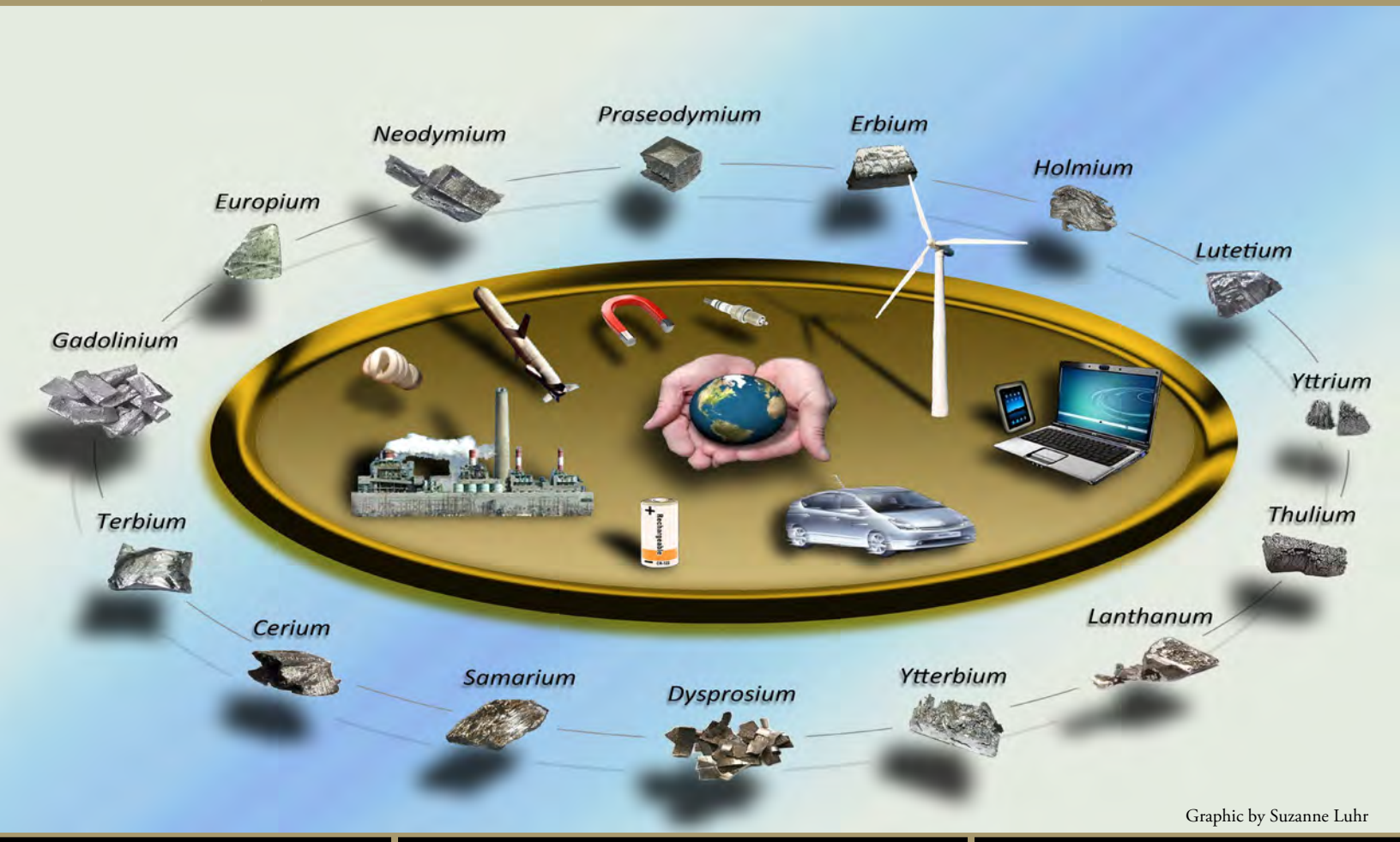
Rare Earth Elements in Wyoming

Wayne M. Sutherland, Robert W. Gregory,
Jacob D. Carnes, and Brett N. Worman



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WSGS geologist Wayne Sutherland investigating the titaniferous black sandstone horizon in the Mesaverde Formation at Cottonwood Creek in the Bighorn Basin. *Photo by Judy Sutherland.*

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Report of Investigations No. 65
2013

Wayne M. Sutherland, Robert W. Gregory, Jacob D. Carnes, and Brett N. Worman

Wyoming State Geological Survey, Laramie, Wyoming 82071

Table of Contents

Abstract 1
Introduction 1
Scope and Results of Project 2
Samples and Analyses 3
Rare Earth Elements Defined 3
REE Uses 7
Politics and Supplies 7
REE Prices. 9
Extraction of REE. 11
General Geology of REE. 11
REE Minerals. 11
REE Production and Exploration in Wyoming. 14
Geologic Occurrences of Wyoming REE 15
Bear Lodge Mountains Rare Earth Element Deposit 16
Precambrian Occurrences 21
Pegmatites 21
Tie Siding Pegmatites. 21
Laramie Range Pegmatites. 27
Big Creek District 29
Many Values Area. 32
Southern Bighorn and Owl Creek Mountains 33
Other Precambrian Occurrences. 34
Union Pass – Warm Spring Area. 34
Clarence Wood Lode Claims. 37
Babbs Mine. 38
Tertiary-aged Igneous Occurrences. 39
Leucite Hills 39
Sediment-hosted Occurrences 39
Flathead Sandstone Paleoplacers 41
Bald Mountain Paleoplacers, Big Horn and Sheridan Counties 41
Rattlesnake Hills. 46
Union Pass – Warm Spring Area. 46
Mesaverde Formation Paleoplacers 48
Separation Rim. 49
Cottonwood Creek 50
Grass Creek 50
Mud Creek 51
Dugout Creek 51
Lovell. 51
Other Potential Paleoplacers 51
Frontier Formation 51
Stump Formation. 54
Other Sandstone Hosted Occurrences 54

Deacon's Prayer Group Claims 55
Phosphate-Rich Sedimentary Occurrences 55
Uraniferous Phosphatic Horizons in the Wilkins Peak Member of the Green River Formation. 55
Phosphorite Beds in Western Wyoming. 60
Dahllite Concretions in the Thermopolis Shale, Big Horn County 62
Occurrences of Other Elements 62
Conclusion 66
Acknowledgements 66
References 67
Index 75

Figures

Figure 1. Sample locations 17
Figure 2. Sample of FMR dike at Bear Lodge REE project. 18
Figure 3. Map of Bear Lodge REE project. 20
Figure 4. Locations of Precambrian samples. 22
Figure 5. Tie Siding area geology and samples. 23
Figure 6. Tie Siding pegmatites. 24
Figure 7. Allanite from the Holiday Place pegmatite. 27
Figure 8. Big Creek area geology and samples. 30
Figure 9. Samples of the Big Creek - Platt pegmatites. 31
Figure 10. Union Pass-Warm Spring area geology and samples. 35
Figure 11. Wildcat Road, iron-rich pod- quartz monzonite contact. 36
Figure 12. Photomicrograph of zircon grain within biotite. 36
Figure 13. Locations of paleoplacer, placer, and other sandstone-hosted samples . . 40
Figure 14. Conglomerate of the lower Flathead Sandstone. 41
Figure 15. Bald Mountain area geology and samples. 43
Figure 16. Gold flake and monazite grains. 47
Figure 17. Mesaverde Formation titaniferous black sandstone outcrops. 48
Figure 18. Cottonwood Creek Mesaverde Formation heavy sand. 50
Figure 19. Spring Gap Frontier Formation outcrop and samples 52
Figure 20. Spring Gap area geology and samples. 53
Figure 21. Locations of phosphate-related samples. 56
Figure 22. South Firehole Canyon lithostratigraphy and samples. 59
Figure 23. South Firehole Canyon UPZ 2a within Wilkins Peak Member. 60
Figure 24. Phosphoria Formation outcrop near Hoback. 61
Figure 25. Dahllite-bearing Thermopolis Shale. 62
Figure 26. Dahllite concretions. 63
Figure 27. WSGS geologist Bob Gregory collecting a REE sample. 66

Tables

Table 1. Periodic table of the elements 4
Table 2. Estimated crustal abundances 6
Table 3. Uses of rare earth elements. 8
Table 4. Prices of REE. 10
Table 5. REE-bearing minerals in Wyoming. 12
Table 6. Tie Siding pegmatites REE concentrations 25
Table 7. Weddle claims pegmatites REE concentrations. 28
Table 8. Big Creek - Platt pegmatites REE concentrations. 32
Table 9. Allie claims pegmatites REE concentrations. 34
Table 10. Union Pass-Warm Spring area Precambrian REE concentrations. 37
Table 11. Clarence Wood lode claims REE concentrations. 38
Table 12. Babbs mine Precambrian REE concentrations. 38
Table 13. Leucite Hills REE concentrations. 39
Table 14. Bald Mountain area REE concentrations. 44
Table 15. Western Rattlesnake Hills Flathead Sandstone REE concentrations. . . . 46
Table 16. Mesaverde Formation paleoplacers REE concentrations. 49
Table 17. Spring Gap paleoplacers REE concentrations. 54
Table 18. Deacon's Prayer claim group REE concentrations. 55
Table 19. Measured section of the lower Wilkins Peak Member. 57
Table 20. Wilkins Peak Member REE concentrations. 60
Table 21. Phosphoria Formation near Hoback REE concentrations. 62
Table 22. Concentration of the REE, P_2O_5, uranium, and thorium in dahllite concretions from the Thermopolis Shale near Greybull. 63

ABSTRACT

Rare earth elements (REE) comprise a group of metals with similar physical and chemical properties that encompasses the lanthanide series elements plus scandium and yttrium. Sixteen REE occur in nature, however, promethium (Pm) is highly-unstable and does not occur naturally on earth. Diverse sectors of the U.S. economy depend upon REE, including energy generation, transportation, data transmission, and national defense. Despite domestic demand for REE, the United States has produced negligible REE since the early 2000s, while China has accounted for 90 to 97 percent of the global supply. Current U.S. production is increasing due to the reopening of Molycorp's Mountain Pass mine in California, the only active REE mine in the country. Exploration and development of new prospects across the United States is on-going and includes the Bear Lodge deposit in northeastern Wyoming, owned by Rare Element Resources, Ltd. The Bear Lodge deposit was not part of Wyoming State Geological Survey (WSGS) field investigations since it is currently under intense exploration by private interests.

Previous investigations identified many potential REE occurrences in Wyoming, but lacked complete elemental analyses. The WSGS collected samples from numerous known, suspected, and potential REE host rocks and analyzed them for REE content as well as for other potential economic metals or elements. The limited timeframe for this project precluded collecting samples from all known or potential REE-hosting sites, however, the WSGS collected a large number of samples. Notable REE enrichment occurs in a variety of geologic environments across Wyoming. These environments include carbonatites, pegmatite pods and lenses, epidosite dikes, calc-silicate pods and dikes, iron-rich silicate pods, paleoplacers in marginal marine sandstones, and phosphatic horizons in marine shales and lacustrine mudstones. For widespread access to the results of this study, the WSGS has developed an online database that contains locations, geologic settings, and analyses for all samples. This database will aid mineral exploration across the state, by identifying not only REE concentrations, but other potentially economic elements and related associations as well.

INTRODUCTION

Rare earth elements (REE) are a group of metallic elements with similar physical and chemical properties. REE are a vital resource to industrialized societies worldwide. Over the last 15 years, REE production and processing have become centered in China, which by 2010 provided 95 to 97 percent of the world's supply (Northern Miner, 2010). A 40 percent reduction in China's REE exports in 2010 compared to 2009 caused world demand to exceed supply (Bradsher, 2010; Davis, 2011; Grace, 2010). Although the United States' supply issues improved during 2012, securing REE resources is in our nation's best interest to maintain national security; diversification of the state's economy is in the best interest of Wyoming.

Minor amounts of REE-bearing minerals were reported in Wyoming as early as the 1930s. Early exploration generally focused first on uranium and thorium, while REE were an interesting association. Marzell (1933) reported production of 408 kg (800 lbs) of samarskite in 1930, but gave no source location. REE mineralization associated with thorium from the Bear Lodge Mountains was reported in 1949 (Rare Element Resources, 2011). Paleoplacers in the northern Bighorn Mountains were found to host radioactive monazite (a thorium- and REE-hosting mineral) in 1950 (Wilson, 1951; McKinney and Horst, 1953). These monazites were subsequently investigated by the U.S. Bureau of Mines (USBM) and the U.S. Atomic Energy Commission (AEC) between 1951 and 1953 (Kline and Winkel, 1952; McKinney and Horst, 1953). No REE analyses were reported with these investigations. Allanite-bearing ore was reportedly mined between 1952 and 1955 in the southern Bighorn Mountains (Bromley, 1955), and a small amount of REE-bearing minerals were mined from a pegmatite in Carbon County in the 1950s (King and Harris, 2002).

Most early REE studies identified the potential for REE occurrences but did not produce detailed analyses due to high analytical costs. Modern technology has significantly reduced the cost of high quality detailed analyses, but follow up studies in Wyoming have been slow due to time and budget constraints. The Wyoming State Geological

Survey (WSGS) compiled an Open File Report on REE and yttrium in Wyoming in 1987, which was updated in 1991 and again in 2002 (King and Harris, 1987; King, 1991; King and Harris, 2002). However, these reports were based on literature searches and did not include any original sampling or analyses.

Between 2009 and 2012, the WSGS began to sample and analyze potential REE host rocks within the state. Using WSGS Open File Report 91-3 (King and Harris, 2002) as a foundation, the WSGS compiled data from existing sources, collected and analyzed a small number of new samples, and re-analyzed some samples collected at earlier dates.

In March of 2012, the Wyoming State Legislature allocated $200,000 of Abandoned Mine Lands Reclamation (AML) funds to the WSGS to conduct a geological and geochemical investigation on potential REE-bearing, as well as other potentially economic deposits in Wyoming, cataloging those deposits, and providing a report on the findings by June 1, 2013. In response to this legislative allocation, the WSGS collected 335 samples from known, potential, and suspected host rocks of REE and other minerals, and analyzed these along with 67 samples previously collected by the WSGS. Additional samples that were collected for REE analyses, or for other projects during 2010 and 2011, are included in the results of this study.

Scope and Results of Project

This report summarizes previous investigations into the occurrences of REE in Wyoming and provides REE and other elemental analyses where such information was absent or incomplete. Samples were collected from numerous known, suspected, and potential REE host rocks and analyzed for REE and other potential economic metals or elements. Although a large number of samples were collected, sampling of all known or potential REE-hosting sites was not possible during the time frame of this project.

Information provided from this project will be useful for individuals, consultants, and industry as a base for initiating exploration not only for REE, but for other industrial/economic metals and elements as well. Anomalous concentrations of certain elements may be pathfinders that lead to the discovery of other economic deposits. For example, an abundance of arsenic in some geological settings is considered a pathfinder for gold. A database of the sample analyses, locations, and geologic settings developed during this project, may aid in exploration to identify not only REE concentrations but other, potentially economic associations.

It is our hope that educational institutions may also use these data to better understand the often complex geologic environments in Wyoming. Decision-makers at state and community levels may find this information useful in identifying potential areas of economic development or environmental concern.

Results from this investigation include this written summary report and related maps, a CD with all raw analytical data in an appendix, and a publicly available online database. The online **W**yoming **D**atabase of **G**eology (Wyo-DOG) includes all elemental analyses along with brief write-ups and photographs for most samples. Wyo-DOG makes the results of this study available to a wide audience for exploration, evaluation, and education. Data from Wyo-DOG can be displayed in several formats including ArcGIS and Google Earth.

The idea for a WSGS online database that presents analytical data relative to Wyoming mineral occurrences began in the late 1990s as discussions between W.M. Sutherland and W.D. Hausel. However allocations of budgets, hardware, software, and time were unavailable until 2009. Between 2009 and 2011, an early attempt to construct this type of database was made by N.R. Jones, with assistance and input by W.M. Sutherland and R.W. Gregory. Construction of this initial database provided building blocks and useful ideas for both interface and database structure that evolved into Wyo-DOG. Using this information and feedback from the authors of this report, S. Parrill was able to use rapid prototyping (rapid application development) with iterative and incremental development (agile software development) methodologies to construct Wyo-DOG during 2012-2103.

Wyo-DOG is a multi-tiered application using a structured, relational database. Data is entered via an application using the traditional client/server (two-tier) model. Data in the relational database can be queried directly by common modeling applications such as ESRI's ArcDesktop or via custom, including Web-based, interfaces. Where appropriate, data can also be made available to other modeling applications through common data exchange formats, such as CSV and XML, to facilitate a variety of uses.

Wyo-DOG can be accessed from the WSGS website at www.wsgs.uwyo.edu/. Wyo-DOG was initiated with this project to fulfill the goal of creating a statewide catalog of REE occurrences, as well as occurrences of other resources. It is our hope that adequate resources, including funding, personnel, and time, will continue to be available to further expand Wyo-DOG to include new data types, investigations, and the many volumes of historical data that reside in paper files at the WSGS.

Samples and Analyses

This investigation is a survey of various sites across Wyoming based on grab samples (i.e., small, unmeasured samples, not necessarily representative of a larger volume of material). Analyses of these grab samples can neither confirm nor deny the presence or absence of economic concentrations of REE or other elements. A grab sample only represents one small piece of evidence for the occurrence of a mineral concentration or deposit. The grab sample is not associated with, nor does it indicate a volume of material greater than the size of the individual sample. The elemental concentrations associated with a grab sample may or may not extend into the outcrop from which the sample was collected.

A thorough evaluation of a deposit, as opposed to a survey of occurrences as presented in this report, requires multiple samples be evaluated across the range of geologic environments that occur at a specific location. Each of those samples must represent a specific volume of relatively uniform material such that elemental concentrations can be converted to tonnage estimates across the deposit. Only then can the economic tenor of the deposit be estimated. No single sample can define or eliminate the possibility of an economic deposit.

Not all samples are equal. The analysis of a panned concentrate from a placer sample is not equivalent to that of a grab sample. A panned concentrate results from washing disaggregated grains in the field with water to separate out the heavy ones from lighter ones. Analytical results may show relatively high values for some elements in the concentrate. However, to provide proper perspective, a panned concentrate analysis must be diluted to represent the original larger volume of material from which the concentrate was derived. This dilution may reduce reported values by a factor of 10 to 100 or more, depending on techniques and equipment used in sampling. Placer samples are appropriately described in both the text of this report and in Wyo-DOG.

All sample analyses collected for this project were completed by ALS Chemex of Reno, Nevada. Analytical methods for historical samples included within Wyo-DOG or this report are referred to as generic if either the laboratory or the method of analysis is not known. Geochemical analyses on samples included whole rock analyses (major element concentrations in the form of oxides) by inductively coupled plasma (ICP), atomic emission spectrometry or mass spectrometry, and atomic adsorption. These methods, when preceded by effective preparation techniques, can generally detect most elements present in a sample from very low concentrations in the range of less than 0.1 to 5 parts per million (ppm) up to ore-grade concentrations. To put this in perspective, 1.0 percent is equal to 10,000 ppm.

Rare Earth Elements Defined

Rare earth elements (a.k.a. rare earth metals) are a group of metallic elements with similar physical and chemical properties. Fifteen of these are listed in the periodic table (table 1) in a series from atomic numbers 57 through 71 known as the lanthanide series. However, one highly-unstable element, promethium, does not occur naturally on earth, has a half-life of 17.7 years, and decays into

PERIODIC TABLE OF ELEMENTS

Physical state of element
@ Standard conditions
0 °C (32 °F), 101kPa (1 atm)

Gas, Solid, Liquid, Unknown

Atomic Number — 79 — Color - physical state
Element symbol (red-Rare earth elements) — Au — Element name
Gold
Atomic Mass - brackets ( ) indicate the mass of the most stable isotope. — 196.9666
0.004 — Crustal Abundance (ppm)

Alkali Metals, Alkaline Metals, Transition Metals, Other Metals, Semi-metals, Unknown, Nonmetals, Halogens, Noble Gases, Lanthanides, Actinides

Note: *If element symbol appears as: Mt - Then the element is Synthetic (artificially prepared)*

1 H Hydrogen 1.00794 1,400																	2 He Helium 4.0026 0.008
3 Li Lithium 6.9411 20	4 Be Beryllium 9.0122 3											5 B Boron 10.811 10	6 C Carbon 12.0107 200	7 N Nitrogen 14.00674 20	8 O Oxygen 15.9994 460,000	9 F Fluorine 18.9984 600	10 Ne Neon 20.1797 0.01
11 Na Sodium 22.9898 23,000	12 Mg Magnesium 24.305 24,000											13 Al Aluminum 26.9815 83,000	14 Si Silicon 28.0855 280,000	15 P Phosphorus 30.97384 1,100	16 S Sulfur 32.066 300	17 Cl Chlorine 35.4527 130	18 Ar Argon 39.948 3
19 K Potassium 39.0983 20,000	20 Ca Calcium 40.078 42,000	21 Sc Scandium 44.9559 23	22 Ti Titanium 47.867 6,000	23 V Vanadium 50.9415 140	24 Cr Chromium 51.9961 110	25 Mn Manganese 54.938 1,000	26 Fe Iron 55.845 58,000	27 Co Cobalt 58.9332 27	28 Ni Nickel 58.6934 80	29 Cu Copper 63.546 60	30 Zn Zinc 65.39 70	31 Ga Gallium 69.723 20	32 Ge Germanium 72.61 4	33 As Arsenic 74.9216 2	34 Se Selenium 78.96 0.05	35 Br Bromine 79.904 2.5	36 Kr Krypton 83.798 trace
37 Rb Rubidium 85.4678 90	38 Sr Strontium 87.62 380	39 Y Yttrium 88.9059 30	40 Zr Zirconium 91.224 160	41 Nb Niobium 92.9064 20	42 Mo Molybdenum 95.94 1.3	43 Tc Technetium (98)	44 Ru Ruthenium 101.07 0.001	45 Rh Rhodium 102.9055 0.001	46 Pd Palladium 106.42 0.01	47 Ag Silver 107.8682 0.07	48 Cd Cadmium 112.411 0.2	49 In Induim 114.818 0.1	50 Sn Tin 118.71 2.1	51 Sb Antimony 121.76 0.2	52 Te Tellurium 127.6 0.001	53 I Iodine 126.9045 0.5	54 Xe Xenon 131.29 trace
55 Cs Cesium 132.9055 2	56 Ba Barium 137.327 400	57-71 Lanthanides	72 Hf Hafnium 178.49 3	73 Ta Tantalum 180.9479 2	74 W Tungsten 183.84 1.4	75 Re Rhenium 186.207 0.005	76 Os Osmium 190.23 0.003	77 Ir Iridium 192.217 0.001	78 Pt Platinum 195.078 0.01	79 Au Gold 196.9666 0.004	80 Hg Mercury 200.59 0.08	81 Tl Thallium 204.3833 0.6	82 Pb Lead 207.2 13	83 Bi Bismuth 208.9804 0.05	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222) trace
87 Fr Francium (223)	88 Ra Radium (226)	89-103 Actinides	104 Rf Rutherfordium (267)	105 Db Dubnium (268)	106 Sg Seaborgium (269)	107 Bh Bohrium (270)	108 Hs Hassium (277)	109 Mt Meitnerium (278)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (281)	112 Cn Copernicium (285)	113 Uut Ununtrium (286)	114 Fl Flerovium (289)	115 Uup Ununpentium (288)	116 Lv Livermorium (293)	117 Uus Ununseptium (294)	118 Uuo Ununoctium (294)

Lanthanides	57 La Lanthanum 138.9055 30	58 Ce Cerium 140.116 60	59 Pr Praseodymium 140.9077 9	60 Nd Neodymium 144.24 30	61 Pm Promethium (145)	62 Sm Samarium 150.36 6	63 Eu Europium 151.964 2	64 Gd Gadolinium 157.25 6	65 Tb Terbium 158.9253 1	66 Dy Dysprosium 162.50 4	67 Ho Holmium 164.9303 1	68 Er Erbium 167.26 3	69 Tm Thulium 168.9342 0.5	70 Yb Ytterbium 173.04 3	71 Lu Lutetium 174.967 0.6
Actinides	89 Ac Actinium (227)	90 Th Thorium 232.0381	91 Pa Protactinium 231.0359	92 U Uranium 238.0289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (251)	99 Es Einsteinium (252)	100 Fm Ferium (257)	101 Md Mendelevium (258)	102 No Nobelium (259)	103 Lr Lawrencium (262)

Table 1. Periodic Table of the Elements with REE outlined in black. (Chart by James R. Rodgers, Wyoming State Geological Survey.)

neodymium-145 through electron capture, a type of radioactive decay.

Two other elements not within this series, scandium (atomic number 21) and yttrium (atomic number 39) are generally included within the group of REE because of their shared occurrence in nature with the lanthanides. Including scandium and yttrium, there are a total of 16 naturally occurring REE.

Rare earth elements received their name from perceived scarcity during the 18th and 19th centuries and from 'earth' as an obsolete term for oxide (Hedrick, 2004; Long, Van Gosen, Foley, and Cordier, 2010). REE are now known to be relatively common within the earth's crust. Even the two least abundant REE, thulium (Tm) and lutetium (Lu) are in the range of 140 to 180 times more common than gold. However, economically mineable concentrations of REE are not common. REE range in crustal abundances from cerium (25th most abundant of the 78 common elements in the earth's crust at 60 parts per million, or ppm, to thulium and lutetium (least abundant REE at about 0.5 ppm). Estimates of crustal abundances vary depending on the reference source.

REE are subdivided into **L**ight **R**are **E**arth **E**lements (LREE) and **H**eavy **R**are **E**arth **E**lements (HREE) based on their atomic weight (table 2) (Hedrick, 2004). LREE include the elements lanthanum (atomic number 57, atomic weight 138.91) through europium (atomic number 63, atomic weight 151.96) while HREE are gadolinium (atomic number 64, atomic weight 157.25) through lutetium (atomic number 71, atomic weight 174.97).

REE in their elemental form are iron-gray to silver, malleable and ductile, soft metals that are unstable in the presence of oxygen, and readily react to form metal oxides. Chemically, REE are generally trivalent, but exceptions occur with cerium, europium, and ytterbium. Cerium forms compounds with a valence of +4. Europium can be divalent and oxidizes much more readily than the trivalent REE, forming a yellow surface coating of Eu (OH) within minutes after exposure to moist air. Ytterbium has a closed-shell electron configuration (reluctant to share electrons with oxygen or other elements) and is thus relatively inert; it can be handled in air and remains stable (Borzone and others, 1999).

The reactivity of most REE is problematic for shipping and long-term storage in elemental form. Because of this, REE are often reported in metric tons (1 tonne = 1000 kilograms [kg]) of **R**are **E**arth **O**xide (**REO**) with all REE lumped together. The designation **T**otal **R**are **E**arth **O**xides (**TREO**) is used in mining and exploration to describe the total REE content in a deposit or samples in an equivalent oxide form even though their mineral occurrence may not be in the form of an oxide. By convention, TREO addresses only 14 lanthanide series elements plus yttrium; scandium is not included in TREO (Rare Element Resources, 2011). A mixture of REE in metallic form (usually admixed with iron) is called misch metal, or mischmetal (Hedrick, 1985).

REE with even atomic numbers, such as Ce and Nd, have greater cosmic and terrestrial abundances than adjacent REE with odd atomic numbers (La and Pr; table 1). Cerium is the most abundant with a continental crustal abundance of about 60 ppm, followed by lanthanum at 34 ppm and neodymium at 33 ppm. The cumulative total abundance of REE in the earth's crust, including scandium and yttrium, ranges from about 20 ppm to 219 ppm, depending on the reference cited (Long, Van Gosen, Foley, and Cordier, 2010; WebElements.com, 2012).

To depict low REE concentrations and compare slight deviations between samples, this report addresses elemental concentrations in ppm. However, commercial REE assay values are, by convention, reported in terms of TREO. The difference between reported ppm in assay values and reported TREO will vary with the specific geochemistry of individual deposits. TREO equivalents found in Rare Element Resources' Bear Lodge project are approximately 15.6 percent higher than the combined raw metal assay values (Rare Element Resources, 2011). However, using the Bear Lodge deposit as a general indication, 3,000 ppm in raw metal assay would give an estimated TREO of

Table 2. Rare earth elements, other elements of interest, and estimated crustal abundances by weight.

Element (chemical Symbol)	Atomic Number	Crustal Concentration[a] (ppm)	Crustal Concentration[b] (ppm)	Five times crustal concentration[a] (ppm)	Element group
Lanthanum (La)	57	34	30	170	LREE
Cerium (Ce)	58	60	64	300	
Praseodymium (Pr)	59	8.7	7.1	43.5	
Neodymium (Nd)	60	33	26	165	
Promethium (Pm)	61	0	-	0	
Samarium (Sm)	62	6	4.5	30	
Europium (Eu)	63	1.8	0.88	9	HREE
Gadolinium (Gd)	64	5.2	3.8	26	
Terbium (Tb)	65	0.94	0.64	4.7	
Dysprosium (Dy)	66	6.2	3.5	31	
Holmium (Hm)	67	1.2	0.8	6	
Erbium (Er)	68	3	2.3	15	
Thulium (Tm)	69	0.45	0.33	2.25	
Ytterbium (Yb)	70	2.8	2.2	14	
Lutetium (Lu)	71	0.56	0.32	2.8	
Scandium (Sc)	21	26	13.6	130	
Yttrium (Y)	39	29	22	145	
Cumulative Total REEs		**218.85**	**181.97**	**1094**	REE
Iron (Fe)	26	63,000.00	-	315,000	Associated Elements
Copper (Cu)	29	68	-	340	
Silver (Ag)	47	0.08	-	0.4	
Platinum (Pt)	78	0.04	-	0.19	
Gold (Au)	79	0.00	-	0.02	
Lead (Pb)	82	10	-	50	
Thorium (Th)	90	6	-	30	
Uranium (U)	92	1.8	-	9	

[a]http://www.webelements.com/periodicity/abundance_crust/; described as estimates of the average composition of continental crust derived by a consensus and averaging process for data abstracted from five different references.

[b]Taylor and McLennan (1985) apply to the upper continental crust.

about 0.34 percent, and 10,000 ppm would be about 1.15 percent TREO.

Total REE values greater than 3,000 ppm may be indicative of potential for an economic deposit, depending on the type of sample. The selection of 3,000 ppm results in part from study of REE reported as TREO grades in various active exploration projects outside of Wyoming (Saywell, 2011; Grace, 2010). Reported TREO in exploration projects varied from 0.33 percent in drill core intercepts (the low end of positive indications for further exploration) to more commonly cited figures in the vicinity of 1 percent. Values of 1 to 2 percent are considered good and values greater than 2 percent are great. This assumes favorable mine-

ability and economic factors, including sufficient deposit size and tenor, consistency of ore grades, uniform mineralogy, favorable chemistry for metal extraction, mine siting, transportation, etc.

In contrast to base metals (such as copper, lead, or iron) and precious metals, REE have very little tendency to become concentrated in exploitable ore deposits (Haxel and others, 2002). LREE are more incompatible because they have larger ionic radii and are therefore more strongly concentrated in the continental crust than HREE. In most rare earth deposits, lanthanum, cerium, praseodymium, and neodymium constitute 80 to 99 percent of the total. Because of this, deposits containing relatively high grades of the less common and more valuable HREE (gadolinium to lutetium, yttrium, and europium) are particularly desirable.

REE Uses

Consumer products that rely on integral use of REE include: catalytic converters, cell phones, digital cameras, and computers. Additionally, Nd, Sm, Gd, Dy, or Pr are used in high power permanent magnets where weight and space are of concern in applications ranging from computer hard drive motors to wind generators. A typical 2-megawatt wind turbine requires 60 kg (132 lbs) of dysprosium and 372 kg (820 lbs) of neodymium, which at October 2011 prices would cost $301,680 just for their REE (Grushkin, 2011). A typical hybrid car, such as a Toyota Prius, contains around 11.3 kg (25 lbs) of REE, mostly lanthanum in its rechargeable battery (McDermott, 2009) and about 2 kg (4.5 lbs) of neodymium and dysprosium in its drive motor (Grushkin, 2011).

Fiber-optic cables that transmit signals over long distances require regularly spaced sections of erbium-doped fiber that function as laser amplifiers. Erbium alone possesses the required optical properties for this application. Europium is used as a phosphor activator. In a color television tube it provides the red color seen by the viewer. The light REE, lanthanum and neodymium, are used as catalysts in the refining of heavy crude oil into usable forms. Gadolinium, which has the highest neutron capture cross section of all the elements, is the material of choice for absorbing high-energy neutrons.

Misch metal is pyrophoric; when scratched it gives off sparks capable of igniting flammable gases. It is used in cigarette lighters and automatic gas-lighting devices. It is also used in making some types of steel, and in aluminum and magnesium alloys.

The United States uses REE in a wide range of applications, including some that are critical to national security. This makes China's control of REE a subject of concern. U.S. Department of Defense uses REE in lasers, precision-guided munitions, communications and radar systems, avionics, night-vision equipment, satellites, range finders, and control systems (Hedrick, 2004; 2010). Various uses of REE, listed by element are shown in table 3.

Politics and Supplies

Prior to the 1990s, the United States produced sufficient REE for domestic use. Low prices and overproduction from the mid-1990s through 2003 closed most mines and plants outside of China (Saywell, 2011). Since 2004, China has supplied 90 to 97 percent of the world's REE, while in 2010, the United States produced none (Northern Miner, 2010). In 2012, China still produced 97 percent of the world's REE (Niles, 2012). Substitutes for many REE applications are available, but they tend to be inferior (Cordier, 2011). Alternative technologies and recycling of REE may help reduce market demand over the next few years (Elmquist, 2011). However, high-technology REE applications are diverse and expanding, driving increasing technological, economic, and strategic needs in the United States (Long, Van Gosen, Foley, and Cordier, 2010). Compounding supply problems, China drastically reduced its REE exports beginning in 2010, and hiked export taxes to a range of 15 to 25 percent (Davis, 2011). These actions resulted in a scramble for these resources in the rest of the world (Bradsher, 2010; Grace, 2010; Davis, 2011). In 2012, China continued to restrict the world supply of REO (U.S. Geological Survey, 2013).

Table 3. Typical uses of the rare earth elements, after Haxel and others (2002), U.S. Department of Energy (2010), Long, Van Gosen, Foley, and Cordier (2010), Hedrick (2010), WebElements (2012).

Element	Typical uses	Element Group
Lanthanum	lanthanum oxide additive in optical lenses increases light refraction and decreases dispersion, catalysts in heavy crude oil reformation, lighting phosphors, batteries, metal alloys, polishing compounds, ceramics	LREE
Cerium	polishing compounds for optical lenses, lighting phosphors, batteries, metal alloys, catalysts, glass additives, ceramics	
Praseodymium	high power permanent magnets, batteries, metal alloys, catalysts, polishing compounds, glass additives, ceramics	
Neodymium	catalysts in heavy crude oil reformation, high power permanent magnets, neodymium-yttrium-aluminum-garnet lasers, neodymium-iron-boron permanent magnets, batteries, metal alloys, glass additives, ceramics	
Samarium	samarium-cobalt permanent magnets, batteries	
Europium	phosphor activator for red color in a color television tube	HREE
Gadolinium	high power permanent magnets, paint or coating against neutron radiation, phosphors	
Terbium	terbium iron-nickel alloy with dysprosium (Terfenol-D) used in stealth technology, lighting phosphors, high power permanent magnets	
Dysprosium	high power permanent magnets, ceramics, nanotechnology research	
Holmium	high power permanent magnets, nuclear control rods, lasers, optical coatings	
Erbium	doped fiber laser amplifiers, metal alloys	
Thulium	Few uses due to rarity and properties similar to other REEs	
Ytterbium	radiation source in portable x-ray equipment, stress gauges, lasers, metal alloys, catalysts	
Lutetium	few uses due to rarity and properties similar to other REEs	
Scandium	high-strength light weight metallurgical applications	Associated Elements
Yttrium	neodymium-yttrium-aluminum-garnet lasers, lighting phosphors, ceramics	

Slow economic conditions worldwide during 2012, combined with more efficient material usage, resulted in a decline in United States REE imports from 7,790 tons in 2011 to 5,700 tons in 2012. The economic slowdown also resulted in a decline in prices for most REE products in the aftermath of significant price increases during 2011. The value of refined REE imported by the United States decreased from $802 million in 2011 to $615 million in 2012 (U.S. Geological Survey, 2013).

The largest known REE deposits occur in China, Australia, and North America, with much smaller reserves found in India, Brazil, Malaysia and South Africa. Production has been dominated by China, with additional production from Australia, India, Malaysia, Russia, and Thailand (Hedrick, 2004). China's reserves are the largest. Estimates project that China has the largest percentage of worldwide REE reserves at about 36 percent, compared to the United States at about 13 percent (Long, Van

Gosen, Foley, and Cordier, 2010). The Commonwealth of Independent States (Azerbaijan, Armenia, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Moldova, Russia, Tajikistan, Turkmenistan, Uzbekistan, and Ukraine) controls about 19 percent, followed by Australia with 5.4 percent and India with 3.1 percent (Long, Van Gosen, Foley, and Cordier, 2010).

China's state-owned mines kept rare earth prices artificially low during most of the past 15 years, which drove other suppliers out of business. The United States had the expertise, but lacked the manufacturing infrastructure to refine rare earth oxides to metals. Rebuilding the U.S. REE supply chain has begun, but could take as long as 15 years to complete (Long, Van Gosen, Foley, and Cordier, 2010; Hsu, 2010). Achieving a secure strategic supply of REE seems to be more important now than the economic impact of developing the necessary supply chain.

The only current REE producer in the United States is the Molycorp mine, producing from a carbonatite, at Mountain Pass, California. Molycorp's production has been from previously mined and stockpiled material. However, completion of their ongoing expansion and modernization project is expected to produce about 19,050 tonnes (21,000 tons) of REO equivalent per year, beginning in mid-2013 (Molycorp, 2013). The company plans to increase production to 40,000 tonnes (44,090 tons) of REO per year when justified by demand, product pricing, capital availability, and financial returns.

REE minerals and deposits are often classified as either LREE or HREE. However, since both types usually occur together, the designation is often a statement relating to the economic dominance of either the light or the heavy elements. LREE deposits are the most common and HREE are generally more valuable than LREE. Molycorp's Mountain Pass deposit is dominated by LREE (Long, Van Gosen, Foley, and Cordier, 2010).

A 2010 study by the U.S. Department of Energy (DOE) addressed the supply of critical minerals in the United States. They used the term critical as a measure of importance to the economy, availability of clean energy, and risk of supply disruption. Among other minerals and elements addressed, they considered five REE (Dy, Nd, Tb, Eu, and Y) as most critical in the short term future of the United States.

Currently, REE projects being investigated for exploration or development in the United States include: the Bear Lodge deposit in Wyoming; Bokan, Alaska; La Paz, Arizona; Diamond Creek, Idaho; Lemhi Pass, Idaho and Montana; Pea Ridge, Missouri; Elk Creek, Nebraska; Thor, Nevada; and Round Top, Texas (U.S. Geological Survey, 2013).

REE Prices

REE prices have risen substantially in the last decade. Between October 2009 and June 2011, prices for all REE rose 1,500 percent, then retreated significantly during the latter part of 2011 (Saywell, 2011). Prices retreated further during 2012, but remained substantially higher than in 2010 (U.S. Geological Survey, 2013). Although there have been major fluctuations, prices are expected to remain high until a chain of supply, processing, and manufacturing has been established outside of China. Table 4 shows the rising prices along with fluctuations in 2008, 2010, and 2011.

Relative market values for REE are highly variable and depend in part on the source quoted. Prices also depend on the level of purity, which is determined by the specifications for any particular application (Lynas Corporation, 2011). Pricing occasionally addresses individual metallic elements. However, most references cite REE in oxide form, reported as REO. REO concentrates vary in their elemental mixes based on those found in their source deposits. REO prices vary accordingly and may not be comparable between one deposit and another. Concentrates range from near 40 percent REO to 99 percent REO. One of the best sources for current REE price information is Metal-Pages (www.metal-pages.com/metalprices/rareearths), which requires a subscription to view.

Table 4. Prices of REO ($US/kg) raw materials from 2000 to 2012, from a variety of sources.
[FOB ex-China indicates that price includes Chinese export taxes and other fees.]

Element/ Mineral	Oxide 2000[a]	Oxide 2006[b]	Oxide FOB ex-China 2007[c]	Oxide FOB ex-China 2008[c]	Oxide FOB ex-China 2009[c]	Oxide FOB ex-China Jan.5, 2010[d]	Oxide FOB ex-China Aug.5, 2010[d]	Oxide FOB ex-China 2010[c]	Oxide FOB ex-China Q2, 2011[c]	Oxide FOB ex-China Q3, 2011[c]	Oxide FOB ex-China Nov. 21, 2011[c]	Oxide Jan. 2012[e]	Oxide Dec. 2012[e]
lanthanum	23.00	1.45	3.44	8.71	4.88	5.60	33.50	22.40	135.02	117.68	65.00		
cerium	19.20		3.04	4.56	3.88	4.15	33.00	21.60	138.29	118.65	55.00		
praseodymium	36.80		29.05	29.48	18.03	21.50	54.50	48.00	220.08	244.73	210.00		
neodymium	28.50		30.24	31.90	19.12	22.50	55.25	49.50	256.15	338.85	240.00	195.00	80.00
promethium	---												
samarium	360.00		3.60	5.20	3.40	3.95	31.80	14.40	125.60	129.45	90.00		
europium	990.00	260.00	323.90	481.92	492.92	485.00	590.00	559.80	1830.00	4900.00	3800.00		
gadolinium	130.00					6.75	40.00						
terbium	535.00	455.00	590.40	720.77	361.67	365.00	605.00	557.80	1659.20	3761.54	2820.00		
dysprosium	120.00		89.10	118.49	115.67	117.25	286.50	231.60	921.20	2262.31	2020.00		
holmium	440.00												
erbium	155.00												
thulium	2500.00												
ytterbium	230.00												
lutetium	3500.00												
yttrium	88.00					10.25	34.50						
bastnasite	5.51												
monazite	0.73												
REO[f]			11.59	14.87	10.32			31.35	173.20	193.21	122.45		

[a]From Hedrick (2002)

[b]From Northern Miner (2008)

[c]From Lynas Corporation, Ltd (2011)

[d]From Rare Earth miner MCP (2010)

[e]From U.S. Geological Survey (2013)

[f]Avg. Mt. Weld, Aust. REE composition

Extraction of REE

Aside from generally low concentrations of REE in their host rocks and minerals, the cost of separation of the individual elements is quite high compared to other metals. REE ores are mineralogically and chemically complex, and are often radioactive (Long, Van Gosen, Foley, and Cordier, 2010). Because of their similar chemical properties, individual REE are difficult to isolate by ordinary metallurgical means. Therefore, separation is a long and complex process that involves multiple and repetitive steps in solvent extraction and/or ion exchange. Other extraction methods may involve iterative fractional crystallization, fusion, volitization, or a combination of selective reduction and vacuum distillation of halides (Hedrick, 1985; Uda and others, 2000).

The presence of two or more mineral phases in many deposits requires a different extraction technology for each mineral, compounding both complexity and cost (Long, Van Gosen, Foley, and Cordier, 2010). The cost of building a plant to separate the individual REE is also high and must be tailored to the unique mineralogy of a specific ore. Construction of a new mine, with attached separation plant, was estimated in 2010 to cost between $500 million and $1 billion (Hsu, 2010), with a lead time up to 15 years for full-capacity completion (Long, Van Gosen, Foley, and Cordier, 2010; Hsu, 2010).

General Geology of REE

Awareness of the diversity of REE deposit types is beneficial to exploration efforts. Economically exploitable concentrations of REE are primarily derived from crystalline igneous rocks (Long, Van Gosen, and Johnson, 2010). REE are more common in alkaline igneous rocks and carbonatites than in mafic rocks (Long, Van Gosen, Foley, and Cordier, 2010). REE typically occur as trivalent cations in rock-forming minerals in carbonates, oxides, phosphates, and silicates (Hedrick, 2004). REE are chemically similar to thorium and are often found in minerals and rocks in association with thorium (Hedrick and Templeton, 1990). Economic concentrations of REE host minerals are known from alkaline igneous rocks, carbonatites, and from a wide variety of dikes and veins that cross-cut alkaline intrusions and surrounding rocks (Long, Van Gosen, Foley, and Cordier, 2010).

Sedimentary rocks that may preferentially contain REE include phosphatic rocks, coarse clastic rocks, and shales (Hedrick, 1985). Phosphate deposits may be sources for yttrium and lanthanum (Long, Van Gosen, and Johnson, 2010). Sediments derived from host rocks that contain even small amounts of REE-bearing minerals may produce both placer and paleoplacer concentrations.

Ion-adsorption clays, or laterites, developed as residuum from chemical weathering, may be enriched in REE from intensive leaching of igneous and other rocks. Economic REE concentrations in ion-adsorption clays, are known from southern China and Kazakhstan (Long, Van Gosen, Foley, and Cordier, 2010). Such clays tend to have a greater enrichment in HREE than other deposit types (Hedrick, 2004).

REE Minerals

Numerous minerals are known to contain REE as essential constituents, and a greater number contain REE as accessory elements. However, only a few of these minerals host large enough concentrations of REE to be considered ore minerals (Hedrick, 1985). Worldwide, the principal commercial sources of REE are the minerals bastnasite, loparite, monazite, and xenotime, and rare-earth ion-adsorption clays (Hedrick, 2004). When discussing principal REE-bearing minerals only in the United States, Long, Van Gosen, Foley, and Cordier (2010) omit loparite and ion adsorption clays, but add euxenite and allanite, although other REE-bearing minerals are also present. Table 5 lists minerals reported in Wyoming that contain REE. Of the principal REE-bearing minerals, allanite, bastnasite, euxenite, monazite, and xenotime are known to occur in Wyoming (King and Harris, 2002). Mineral formulas shown in the following discussions are variable depending on the source cited, and on subvarieties that may contain differing elemental substitutions.

Table 5. REE-bearing minerals that occur in Wyoming.

Mineral	Chemical Formula[a,b]	REE as primary or accessory constituents
Allanite[c]	$Ca(Ce,La,Y,Ca)Al_2(Fe2+,Fe3+)(SiO_4)(Si_2O_7)O(OH)$	Minerals with REE as essential constituents
Ancylite	$Sr_3(Ce,La,Dy)_4(CO_3)_7(OH)_4 \cdot 3H_2O$	
Bastnasite	$(Ce,La,Y)CO_3F$	
Brannerite	$(U,Ca,Y,Ce)(Ti,Fe)_2O_6$	
Brockite	$(Ca,Th,Ce)PO_4 \cdot H_2O$	
Burbankite	$(Na,Ca)_3(Sr,Ba,Ce)_3(CO3)_5$	
Calkinsite	$(Ce,La)_2(CO_3) \cdot 4H_2O$	
Cerianite	$(CeTh)O_2$	
Carbocerianite	$(Ca,Na)(Sr,Ce,Ba)CO_3$	
Euxenite	$(Y,Er,Ce,U,Pb,Ca)(Nb,Ta,Ti)_2(O,OH)_6$	
Ewaldite	$Ba(Ca,Y,Na,K)(CO_3)_2$	
Fergusonite	$(Y,Er,Ce,Nd,La,Fe)(Nb,Ta,Ti)O_4$	
Gadolinite	$(Y,Ce,La,Nd)_2FeBe_2Si_2O_{10}$	
Mckelveyite	$Ba_3Na(Ca,Sr,U)Y(CO_3)_6 \cdot 3H_2O$	
Parisite	$Ca(Ce,La)_2(CO_3)_3F_2$	
Monazite	$(Ce,La,Y,Th)PO_4$	
Rhabdophane	$(Ce,La,Nd)PO_4 \cdot H_2O$	
Samarskite	$(Y,Ce,U,Ca,Th,Fe)(Nb,Ta,Ti)_2(O,OH)_6$	
Synchysite	$(Ce,La,Nd,Y)Ca(CO_3)_2F$	
Xenotime	YPO_4	
Apatite	$Ca_5(PO_4)_3(F,OH,Cl)_3$	Minerals with REE as accessory constituents
Columbite-Tantalite	$(Fe,U,Ca)(Nb,Ta)O_4$	
Fluorite	CaF_2	
Huttonite-thorite	$ThSiO_4$	
Pycrochlore-microlite	$(Na,Ca)_2(Nb,Ta,Ti)O_6(OH,F)$	
Sphene	$CaTiSiO_5$	
Zircon	$ZrSiO_4$	

[a]After King and Harris (2002); Rare Element Resources (2011), formulas vary with citation source

[b]REEs not listed may substitute into some formulas for specific occurrences

[c]Chemical formula after Long and others (2010)

Allanite $Ca(Ce,La,Y,Ca)Al_2(Fe^{2+},Fe^{3+})(SiO_4)(Si_2O_7)O(OH)$

Allanite is a member of the epidote mineral group, where some calcium atoms are replaced by REE, particularly cerium. It is also the only member of the epidote group in which ferrous (Fe^{2+}, reduced) iron is an essential constituent. Cerium- (or REE-) epidotes may contain 0.35 to 2.23 percent radioactive components (Deer and others, 1967). The REE content of allanite is typically about 5 percent REO, but can vary widely from 3 to 51 percent, depending on its geologic source (Gupta and Krishnamurthy, 2005).

Allanite is most commonly found as an accessory mineral in igneous rocks, but rarely in sufficient concentration to be economically mined. Typically these igneous rocks include granites, syenites,

diorites, and their associated pegmatites. The mineral usually occurs as black to dark brown and brownish-violet tabular grains. It has a conchoidal fracture and is often metamict (i.e., its crystal lattice is disrupted while the mineral grain retains its original morphology) due to radioactive decay of thorium, which can weaken the crystal structure. A microscopic dark halo or ring seen inside of allanite mineral grains is also an effect caused by radioactivity (Long, Van Gosen, Foley, and Cordier, 2010). The specific gravity of allanite is 3.4 to 4.2 and its hardness is between 5 to 6.5 Moh's scale (Deer and others, 1967); these characteristics suggest a possibility for placer concentrations. However, metamict varieties may weather rapidly. Weathering of allanite produces a reddish-brown, iron-rich, earthy crust deficient in REE compared to unweathered allanite (Deer and others, 1967).

Bastnasite $(Ce,La,Y)CO_3F$

Bastnasite, also spelled bastnaesite or bastnäsite, is an uncommon REE-bearing carbonate mineral (cerium-lanthanum-yttrium carbonate fluoride) that occurs in a mineral series with hydroxyl-bastnasite [$(Ce,La)CO_3(OH,F)$]. It is also closely related to parisite [$Ca(Ce,La)_2(CO_3)_3F_2$], and may form replacement crystals after allanite (Long, Van Gosen, Foley, and Cordier, 2010). Although bastnasite is not common, it is the most abundant REE-bearing mineral (MinDat.org, 2011).

Bastnasite is primarily mined from rare, carbonate-rich igneous rocks called carbonatites. Carbonatites contain greater than 50 percent carbonate minerals and are usually associated with alkaline igneous complexes. Bastnasite is one of the world's primary sources for REE, and is dominated by LREE (Hedrick, 2004). Bastnasite theoretically can contain about 75 percent REO, but averages about 60 percent. Its yttrium content is generally very low at about 0.05 percent (Hedrick, 1985). In addition to being found in carbonatites, bastnasite is known as an accessory mineral in some alkaline igneous rocks and in some hydrothermal deposits (Hedrick, 2004).

Bastnasite may be massive or granular and typically forms small, rounded hexagonal or short prismatic crystals; it may also occur as spheres or rosettes (Long, Van Gosen, Foley, and Cordier, 2010). It is transparent to translucent, with a vitreous to greasy or pearly luster. Its color varies from colorless to shades of yellow, reddish-brown, and pink. Bastnasite is relatively heavy with a specific gravity of 4.7 to 5.0. However, its low Moh's hardness of 4.0 to 4.5 (MinDat.org, 2011), combined with its brittleness and a prominent basal cleavage, suggest little possibility for placer concentrations.

Euxenite $(Y,Er,Ce,U,Pb,Ca)(Nb,Ta,Ti)_2(O,OH)_6$

Euxenite is a slightly radioactive oxide mineral in a series with polycrase [$(Y,Ca,Ce,U,Th)(Ti,Nb,Ta)_2O_6$]. Euxenite has similar properties to other REE-bearing oxide minerals such as fergusonite and samarskite, both uranium minerals, and to aeschynite, a minor REE-bearing mineral. Euxenite is typically found in granite pegmatites in association with quartz, feldspars, columbite (ferrocolumbite), tantalite (ferrotantalite or manganocolumbite), and monazite (Long, Van Gosen, Foley, and Cordier, 2010; MinDat.org, 2011).

Euxenite generally forms black to yellow- or green-tinged, greasy to submetallic, tabular to prismatic crystals. Metamict crystals are often partially amorphous. The mineral may also be granular to massive, or may form radial aggregates. It is brittle, exhibits a conchoidal fracture, and has no cleavage. Its Moh's hardness of 5.5 to 6.5 and specific gravity of 5.3 to 5.9 facilitate its concentration in placer deposits such as in detrital black sands (Long, Van Gosen, Foley, and Cordier, 2010; MinDat.org, 2011).

Monazite $(Ce,La,Y,Th)PO_4$

Monazite is a REE-thorium phosphate mineral that is similar to bastnasite as a LREE ore. However, it hosts slightly more of the HREE, especially yttrium, dysprosium, and gadolinium (Hedrick, 2004). Monazite can theoretically contain 70 percent REO, including about 2 percent yttrium oxide. In reality, most concentrates contain about 55 to 65 percent REO (Hedrick, 1985), with typical values in the 60 to 62 percent range (Long, Van Gosen, Foley, and Cordier, 2010). Monazite's high thorium content (4.5 to10 percent ThO_2 equivalent) and thorium's naturally occurring radioactivity is

considered an impediment to mining and processing. Because of this, world monazite production is relatively small (Hedrick, 2004).

Monazite forms translucent, brownish-red to yellow, equant to tabular prismatic crystals with wedge-shaped terminations and a vitreous to adamantine luster. It has a good planar cleavage, a conchoidal fracture, and may be found in both granular and massive forms. Metamict alteration due to radioactive decay of thorium is usually present in monazite and shifts its luster to resinous (Hedrick, 2004; Long, Van Gosen, Foley, and Cordier, 2010; MinDat.org, 2011).

Monazite is a rare accessory mineral in alkaline igneous and metamorphic rocks such as granites, syenites, gneisses, and related pegmatites (Deer and others, 1967). However, its economic concentrations are typically in placers and paleoplacers (Hedrick, 1985). Placer occurrences derive from monazite's high specific gravity of 4.8 to 5.5, and a Moh's hardness of 5, which contributes a moderate resistance to weathering. Monazite is recovered from placers as a byproduct during processing for other resistant heavy minerals, including cassiterite, ilmenite, magnetite, rutile, and zircon (Hedrick, 2004; Long, Van Gosen, Foley, and Cordier, 2010).

Xenotime YPO_4

Xenotime is a yttrium-dominated phosphate related to monazite, with possible substitutions of other REE in its structure. It can contain about 67 percent REO, most of which is HREE dominated by Y_2O_3 (Hedrick, 1985; Gupta and Krishnamurthy, 2005). However, xenotime concentrates average about 25 percent REO (Hedrick, 1985).

Xenotime generally forms yellowish- to reddish-brown prismatic crystals with vitreous to resinous lusters. Less commonly, it may be gray, green, or pink and its crystal form may vary to equant, pyramidal, or radial aggregates and rosettes. Xenotime's similarities in crystal habit and overall appearance to zircon confound identification. However, its Moh's hardness is only 4 to 5, compared to zircon's 7.5, and xenotime has a distinct cleavage (Long, Van Gosen, Foley, and Cordier, 2010; MinDat.org, 2011).

Xenotime occurs as an accessory mineral in acidic and alkaline igneous rocks, and in some mica schists and quartz-rich gneisses (Long, Van Gosen, Foley, and Cordier, 2010). As an REE ore mineral, xenotime is a byproduct of tin mining, and to a lesser extent, is recovered as a detrital byproduct from the mining of heavy-mineral sands (Hedrick, 2004). Its specific gravity of 4.4 to 5.1 favors its concentration in placers.

REE PRODUCTION AND EXPLORATION IN WYOMING

REE mineralization in Wyoming was discovered in the Bear Lodge Mountains in 1949 (Rare Element Resources, 2011). A record of a telephone conversation between H.D. Thomas and C.C. Towle of the AEC in 1951 states that the AEC examined the "Sundance deposit," which was first reported in the spring of 1950, and that it was "mainly rare earths" and contained negligible uranium content in the monazite (Thomas, 1951). Wilmarth and Johnson (1953) of the U.S. Geological Survey (USGS) found iron-manganese veins in two locations hosting REO as high as 12.99 percent. However, they authors concluded the limited size of the veins and the high cost of mining prohibited commercial mining of the rare-earth ore, but additional deposits were likely to be found in the area (Wilmarth and Johnson, 1953).

After early interest in the Bear Lodge deposit, exploration was renewed in 1972 by the Duval Corporation. They found high-grade copper, molybdenum, and precious- and rare-earth- metals within an altered carbonatite-alkaline-intrusive complex. Their drilling encountered combined REO intercepts ranging from 1 to 15 percent. In the 1980s, carbonatite-hosted thorium and REE deposits in the Bear Lodge Mountains were thought to be the largest resource of disseminated REE in North America (Staatz, 1983). Exploration involving numerous companies continued in the Bear Lodge through the mid-1990s when lower Chinese prices began to weaken incentive for REE exploration in the United States. In 2004, Rare Element Resources began exploration drilling in the Bear Lodge REE deposit. The Bear Lodge REE deposit northwest of Sundance is the largest known

REE deposit in Wyoming and is currently well-advanced in exploration, including metallurgical and environmental studies directed toward mine development (Rare Element Resources, 2013a).

Exploration in other parts of Wyoming that eventually resulted in identification of REE or REE-bearing minerals similarly focused first on uranium and thorium. Paleoplacers in the Bald Mountain area of the Bighorn Mountains were first examined for low-grade gold in the latter half of the 19th century. During late summer of 1950, these paleoplacers in the lower part of the Flathead Sandstone were found to host radioactive monazite and were investigated by the USBM in 1951 (Kline and Winkel, 1952). Evaluation of the Bald Mountain area paleoplacers for monazite and its thorium content by the AEC in 1952 (McKinney and Horst, 1953) showed a significant resource, but the study concluded that it could only be mined economically if the price per ton for the monazite was significantly higher. No analyses for REE accompanied reports from these investigations. This, and other reports of early exploration, focused on uranium and thorium rather than on REE, which were hosted by some of the same minerals but appeared to be ignored at the time. However, the USBM reported in the 1956 Minerals Yearbook that U.S. Yttrium, Inc. in Laramie, Wyoming was conducting exploration and research in rare earth metals in the Bald Mountain area.

Minor amounts of REE-bearing minerals were reportedly mined in Wyoming from at least three locations. Marzell (1933) reported production of 363 kg (800 lbs) of samarskite from Wyoming in 1930, but left the source of the material unknown. Allanite-bearing ore was reportedly extracted from the Beaver Creek prospect in the Bighorn Mountains in southern Johnson County, between 1952 and 1955, but neither production nor processing records exist (Bromley, 1955; King and Harris, 2002). The Platt mine in the Big Creek district on the west side of the Medicine Bow Mountains, produced approximately 4,500 kg (10,000 lbs) of euxenite from a pegmatite between 1956 and 1958 (Houston, 1961). Other sources reduce this figure to 1,800 kg (4,000 lbs), and state that 5,900 kg (13,000 lbs) of ore produced from this mine in 1956 was for uranium (King and Harris, 2002).

Recent REE exploration in Wyoming, beyond the Bear Lodge deposit, began in 2009 and continues to the present. Targets of renewed interest include placers, paleoplacers of several ages, alkaline igneous complexes, pegmatites, and possible carbonatites.

GEOLOGIC OCCURRENCES OF WYOMING REE

Reported Precambrian REE occurrences in Wyoming are hosted by pegmatites, veins and dikes, faults and shear zones, metacarbonate rocks of uncertain origin, disseminated minerals in generally alkalic igneous rocks, and in metasediments, including paleoplacers (King and Harris, 2002). Paleozoic and Mesozoic occurrences include paleoplacers in both the Cambrian Flathead Sandstone and the Cretaceous Mesaverde Formation, and disseminations within phosphate rock of the Permian Phosphoria Formation. Tertiary REE concentration hosts include alkali igneous rocks, related carbonatite veins, dikes, hydrothermal zones, and some paleoplacers. Quaternary REE hosts are alluvial placers, paleoplacers, and some hot spring deposits.

The most outstanding REE occurrence in Wyoming is the carbonatite-hosted Bear Lodge deposit currently under exploration by Rare Element Resources. The Bear Lodge REE deposit is centered on carbonatite dikes associated with Eocene (46 to 50 Ma) alkalic intrusive rocks. In this deposit, the minerals ancylite and bastnasite contain most of the REE, which are dominated by the LREE cerium, lanthanum, neodymium, and praseodymium. However, at the Whitetail Ridge deposit and the Carbon target, HREE-enrichment primarily occurs as elevated yttrium-HREE in parasite and synchysite; at Taylor Ridge and westward, yttrium-HREE enrichment appears to occur within xenotime and an unidentified yttrium-vanadium phosphate (Jim Clark, Rare Element Resources, personal communication, April 2013). Potential exists in other parts of Wyoming for the discovery of carbonatites that host REE.

All samples analyzed for this study are shown in figure 1. This figure also shows samples with greater than five times average continental crustal abundance of one or more REE. These occurrences do not imply economic deposits. However, they do indicate sites that may be of interest for further exploration with possibilities for locating previously unknown REE deposits. Many samples analyzed for this project yielded low values for REE and other elements of economic interest and were not addressed in the text. The results of these analyses are included on the CD and in the detailed site and sample descriptions in Wyo-DOG.

Bear Lodge Mountains Rare Earth Element Deposit, Crook County, Wyoming

The Bear Lodge Mountains REE deposit was not investigated during this study. However, as the most advanced REE project in Wyoming, an overview of the deposit is appropriate to provide some perspective when comparing other potential deposits.

The Bear Lodge Mountains are located along the northwestern edge of the Black Hills uplift adjacent to the northeastern part of the Powder River Basin. They are the largest of several domal uplifts in the region that are cored by exposed Tertiary alkalic intrusions and flanked by steeply dipping Paleozoic and Mesozoic sediments. These intrusions and resulting uplifts have exposed Precambrian crystalline rocks both in the Bear Lodge Mountains and in the Tinton-Mineral Hill area near the South Dakota border. Other domes in the region, such as Green Mountain, Strawberry Mountain, and Lime Buttes, are thought to have unexposed igneous cores. The area is within the WSGS 30' x 60' Sundance and Devils Tower geologic quadrangles (Sutherland, 2007; 2008).

Prospecting in the Bear Lodge began in 1875, following the discovery of gold in feldspar porphyry near Warren Peak. Recent exploration in the area has been fostered both by historically known mineralization, and by similarities this Tertiary intrusive complex shares with Cripple Creek, Colorado. In addition to gold, historic mineral values have included Ba, Cu, Ag, Pb, Zn, Mn, Nb, Ta, Th, F, P_2O_5, and REE (DeWitt and others, 1986; Hausel and Sutherland, 1988; Hausel, 1989; Hausel, 1997).

REE mineralization in the Bear Lodge Mountains is part of the Paleocene and Eocene alkalic igneous intrusive and volcanic rocks that crop out in northeastern Wyoming. These rocks form sills, plugs, dikes, and irregular bodies intruding rocks ranging from Precambrian to Cretaceous in age. These rocks crop out in the central part of the Bear Lodge Mountains, at Missouri Buttes and Devils Tower to the northwest, and at Mineral Hill, Black Butte, Inyan Kara Mountain, and Sundance Mountain to the southeast. Most of these rocks are porphyritic, exhibit flow banding, and show evidence of shallow emplacement and rapid cooling (Staatz, 1983). Extrusive flows and pyroclastic deposits are found in limited areas where magma reached the surface in the Bear Lodge Mountains.

Magmatism progressed from east to west in three pulses beginning in the South Dakota Black Hills about 58 Ma, with later pulses about 55-54 Ma near the Wyoming-South Dakota stateline, and about 50-46 Ma in the Bear Lodge Mountains, Devils Tower, and Missouri Buttes (Duke, 2005). Carbonatite dikes, which contain rare-earth mineralization, represent the last phase of igneous intrusive activity in the area. Accompanying the east to west trend is a transition from subalkalic magmatism in the east to extremely alkalic in the west. Alteration is common and includes fenitization, silicification, carbonate enrichment, and sericitization (Duke, 2005). The largest volume of intrusive rocks is either trachyte or phonolite, accompanied by lesser amounts of latite, syenite, nepheline syenite, lamprophyre, pseudoleucite porphyry, agglomerate, diatremes, and other intrusive breccias, and carbonatite (Robinson and others, 1964; Staatz, 1983).

Historically, one carbonatite dike that cuts intrusive breccia was exposed in an old exploration trench on top of the Bear Lodge Mountains in the SE¼ sec. 7 and SW¼ sec. 8, T. 52 N., R. 63 W. (Staatz, 1983; Sutherland, 2008). Carbonatite has since been recognized at the surface in trenches

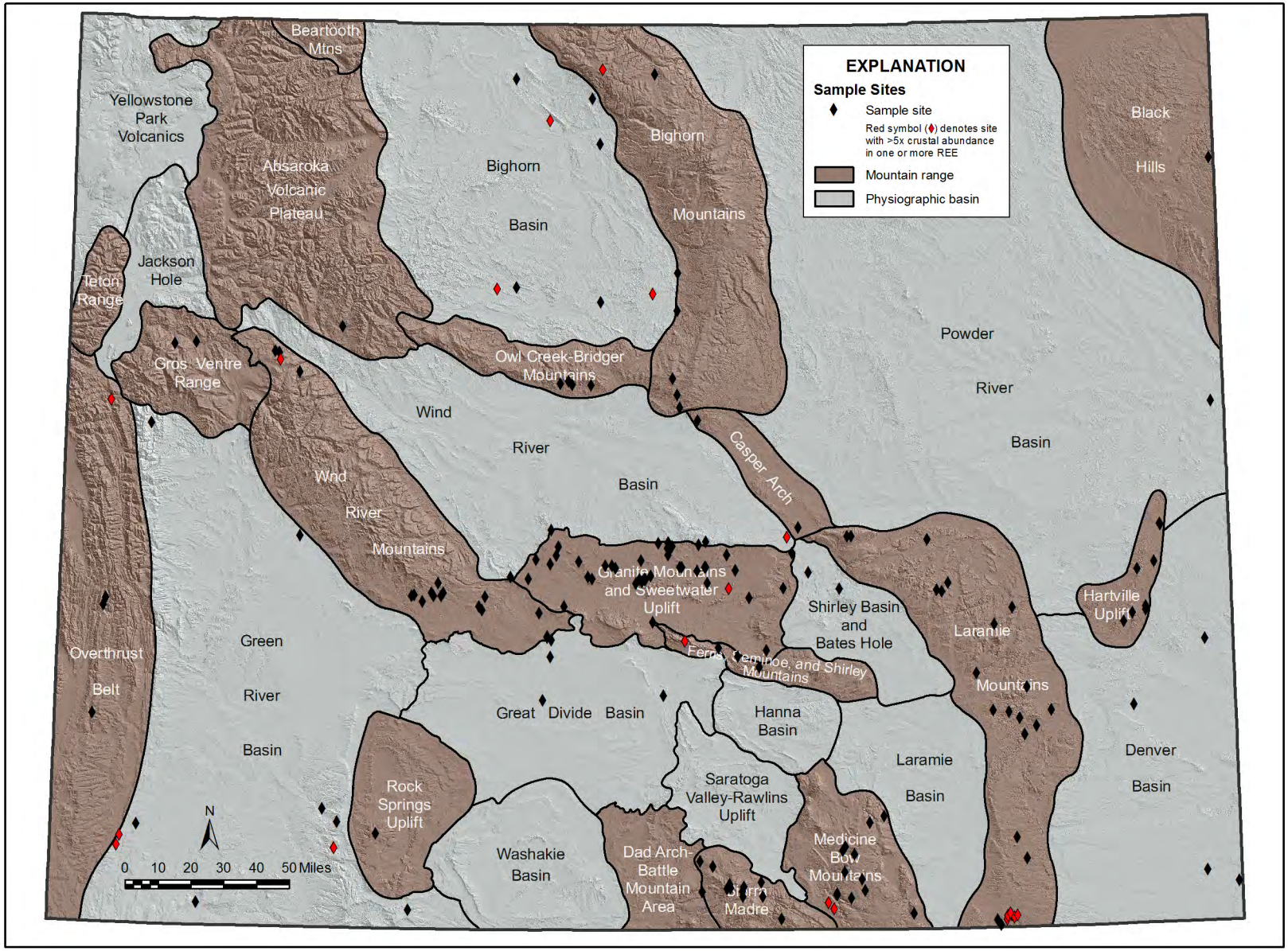

Figure 1. Locations of samples collected and/or analyzed during this project. Sample sites with enrichment to greater than five times crustal abundance in one or more REE are shown in red.

located on Carbon Hill and on the west flank of Bull Hill (Rare Element Resources, 2011).

Figure 2. Sample of FMR dike at the Bear Lodge REE project.

Carbonatite is mostly calcite, but may also contain accessory minerals commonly associated with REE-enrichment, including strontianite, fluorite, biotite, phlogopite, sanadine, apatite, pyrite, pyrrhotite, sphalerite, galena, and locally abundant acmite. Although Thomas (1951) mentioned monazite, the most common REE-bearing minerals reported by Staatz (1983) were brown bastnasite and pink ancylite. The exposed carbonatite is brown to yellowish-brown, and mottled. Unweathered carbonatite encountered in drill holes appears light-gray to white and is banded with accessory minerals. Similar carbonatite dikes were subsequently intersected by drill holes at other locations, and were found to occur in swarms of several closely spaced, relatively narrow dikes accompanied by one thick main dike (Rare Earth Elements, 2011).

REE mineralization occurs in unaltered carbonatite and in deeply weathered carbonatite dikes referred to as FMR dikes. FMR references the major iron-manganese-rare-earth-element constituents of the highly oxidized, carbonatite dikes. These **F** (FeO_x), **M** (MnO_x), and **R** (REE minerals) dikes, veins, and stockworks range in depth from 0 to 150 m (0 to 500 ft) or more as shown by exploration drilling. Carbonatite and FMR dikes encountered in drill holes and trenches range from narrow veinlets to almost 15 m (50 ft) in width and generally dip vertically to steeply southwest along northwest strikes (Rare Element Resources, 2011).

The FMR dikes contain altered silicates, amorphous silica, and variable amounts of REE minerals dominated by bastnasite. Additionally, FMR veins within the oxidized zone host REE mineralization as cerianite [$(CeTh)O_2$], parisite [$Ca(REE)_2(CO_3)_3F_2$], and fine-grained fibrous clusters of synchysite [$Ca(REE)(CO_3)_2F$]. FMR bodies generally have higher concentrations of REE than the carbonatites. The fine grain size and crystal morphology of the bastnasite group minerals in the FMR dikes makes beneficiation easier than in the unoxidized carbonatite dikes; these minerals are amenable to attrition scrubbing and size classification in the physical upgrade process (Jim Clark, Rare Element Resources, personal communication, April 2013). Common accessory minerals in FMR dikes include barite, fluorite, apatite, with varying amounts of sanidine and quartz. The FMR veins are typically vuggy and rusty to black in color and also occur as sheeted zones and stockworks (Rare Element Resources, 2011). Figure 2 shows a hand specimen of an FMR dike from the Bull Hill area. REE mineralization within the dikes ranges from about 0.25 to nearly 20 percent, and appears to be uniform both along strike and at depth. Mineralization within the stockworks varies from about 0.5 percent to 2 percent REO (Rare Element Resources, 2012).

The carbonatite and FMR dikes are classified as either sovite- or silico-carbonatite. REE mineral abundances in both types reportedly range from trace amounts to greater than 50 percent. Sovite-carbonatite consists of fine to coarse crystalline calcite, with accessory biotite, potassium feldspar, augite, strontianite, dolomite, and sulfides. As much as 30 percent sulfide and oxide components include pyrite, pyrrhotite, chalcopyrite, galena, sphalerite, molybdenite, hematite, rutile, and ilmenite. Silico-carbonatite contains more than 30 percent silicate minerals (biotite or phlogopite and potassium feldspar) with calcite and

accessory aegirine, apatite, strontianite, barite, and celestite (Rare Element Resources, 2011).

LREE dominate the Bear Lodge deposit. However, a press release by Rare Element Resources on August 4, 2011 describes high HREE grades in the northern and western portion of their project area. These localities are referred to as their Whitetail Ridge, Taylor, and Carbon target areas (fig. 3). These areas generally host grades greater than 3 percent REO and are also significantly enriched in europium, terbium, dysprosium, and gadolinium, as well as yttrium (Rare Element Resources, personal communication, April 2013).

On March 18, 2013, Rare Element Resources reported an NI 43-101-compliant[1] total high-grade Measured and Indicated (M&I) mineral resource of 13.3 million tonnes (14.7 million tons) grading 3.22 percent REO at a 1.5 percent cutoff grade, which included M&I resources of 5 million tonnes (6 million tons) grading 4.72 percent REO at 3 percent cutoff grade (Rare Element Resources, 2013b). In relative order of decreasing abundance REOs include Ce_2O_3, La_2O_3, Nd_2O_3, Pr_2O_3, Sm_2O_3, Gd_2O_3, Y_2O_3, Eu_2O_3, Dy_2O_3, Tb_2O_3, and others (Rare Element Resources, 2012). The continuing expansion of the identified Bear Lodge REE deposit through drilling seems to confirm Staatz's 1983 claim that Bear Lodge may be the largest resource of disseminated rare-earth elements in North America.

Gold mineralization occurs within the same large alkaline-igneous complex as the REE mineralization. The Taylor target area was primarily a gold exploration area until a thick FMR zone was intersected in 2010. One hole intersected high-grade REE mineralization that also averaged 1.3 g/tonne (0.038 oz/ton) gold[2] from the surface to a depth of 62.5 m (205 ft). On March 15, 2011, the company released an NI 43-101-compliant inferred mineral resource estimate of 26,850 kg (947,000 oz) of gold contained in 69.3 million tonnes (76.4 million tons) averaging 0.42 ppm (0.42 g/tonne; 0.122 oz/ton) using a 0.15 ppm (0.15 g/tonne; 0.004 oz/ton) cutoff grade. A February 27, 2012 news release reported some of Rare Element Resources' best gold drilling assays that included 24.4 m (80 feet) of 4.5 ppm (4.5 g/tonne; 0.131 oz/ton) in one hole (Rare Element Resources, 2012). The 2011 gold drilling results will likely expand the company's gold resource.

Rare Element Resources' REE project totals about 971.2 hectares (2,400 acres) that includes 90 unpatented federal lode claims and one private section of land. Between 2008 and the end of 2012, their drill hole database included 216 core holes and 16,920 assay samples (Rare Element Resources, 2013b). On March 1, 2012, the company announced positive economic results from a prefeasibility study. Projections are for a conventional open-pit mine and an on-site physical upgrade plant using a gravity separation and screening and wash process designed to produce up to 907 tonnes (1,000 tons) of ore material per day. Their nominal operating scenario addresses production of 20,970 tonnes (23,111 tons) per year of 45 percent REO concentrate for a mine life of 19 years. However, continued drilling in outlying areas indicates potential for increased LREE and HREE enrichment that could extend the life of the mine (Rare Element Resources, 2012). In conjunction with a feasibility study commencing in 2013, the company plans to conduct pilot-scale metallurgical testing on more than 19.1 tonnes (21 tons) of mineralized material (Rare Element Resources, 2013b). Details of Rare Element Resources, Ltd. recent activity can be found on their website at http://www.rareelementresources.com.

1 National Instrument 43-101 is a Standards of Disclosure for Mineral Projects rule issued by the Canadian Securities Administrators, which governs the public disclosure of scientific and technical information by publicly-traded mining companies, including oral statements, written documents, and websites. NI 43-101 requires that all disclosure be based on advice by a "qualified person" (engineer or geologist) who, in some cases, must be independent of the mining company and the property. Its purpose is to ensure public confidence in mining-related stocks by enhancing the accuracy and integrity of public disclosure in the mining sector.

2 By convention, ounces (oz) always means Troy ounces when referring to gold or other precious metals.

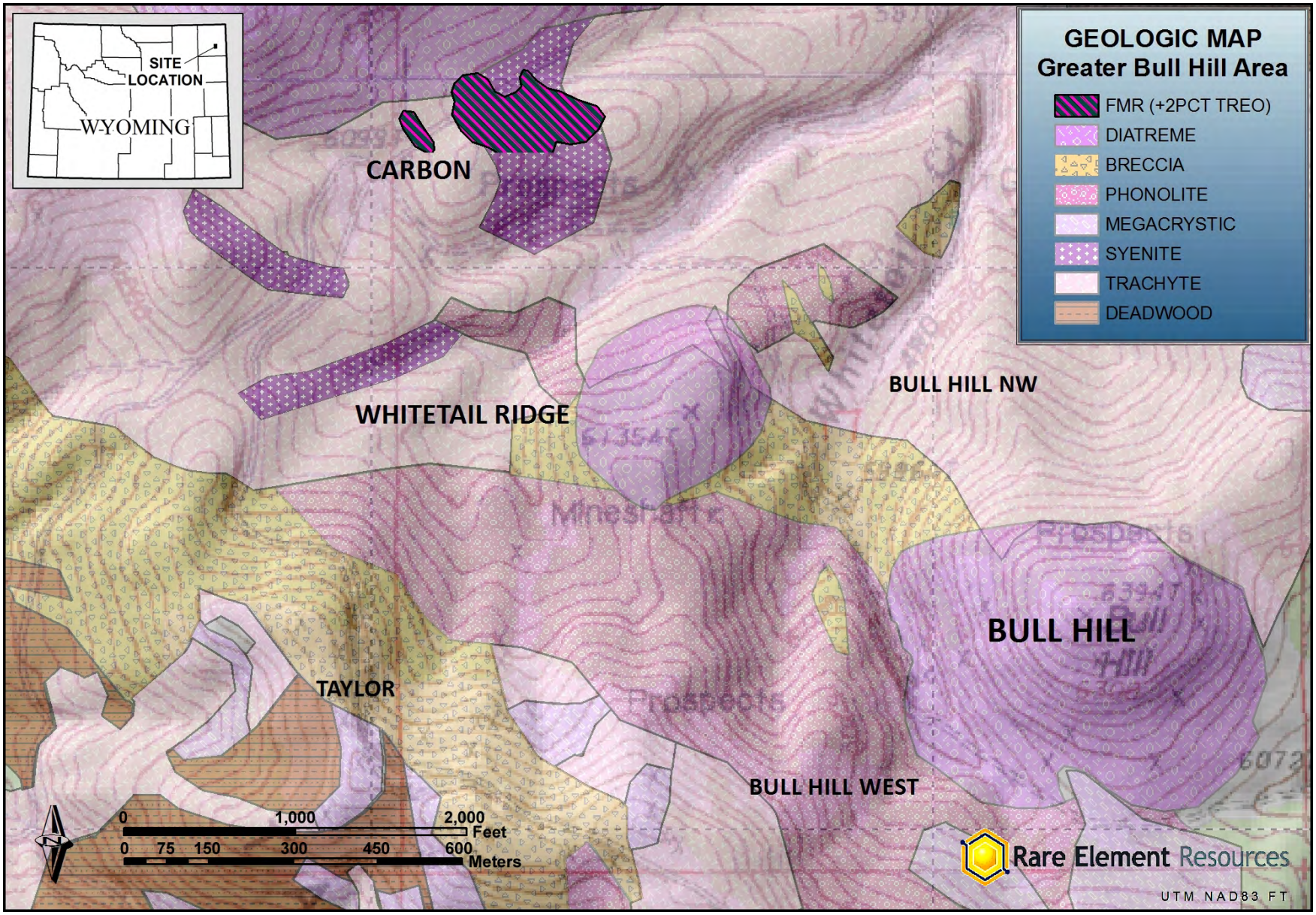

Figure 3. Map of the Rare Element Resources, Ltd. Bear Lodge Project area. (John Ray, Rare Element Resources, Inc.,

Precambrian Occurrences

Precambrian rocks across Wyoming are potential hosts of REE. Known occurrences are present within granitic igneous rocks and within metamorphic rocks of various compositions (fig. 4). The most important Precambrian REE-host rocks in Wyoming are granitic pegmatites and other pods and dikes within granitic igneous and metamorphic rocks. These include granitic pegmatites within the Mesoproterozoic Sherman Granite near Tie Siding in southeastern Wyoming, granitic pegmatites that cut Paleoproterozoic granite gneiss in the Big Creek district on the west flank of the Medicine Bow Mountains, and calc-silicate pods and dikes within Archean granitic gneiss in the southern Bighorn Mountains. Secondary alteration in some pegmatites is apparently important in concentrating REE.

Pegmatites

Globally, granitic pegmatites host important deposits of strategic resources. Strategic resources are elements that are important for a country's economy or defense, but have substantial risk of supply disruptions (Adams and others, 1980; Linnen and others, 2012). Strategic resources commonly hosted in granitic pegmatites include Ta, Nb, Be, Sb, W, Co, and REE. Two general types of pegmatites that are important hosts of strategic resources are: 1) Lithium-Cesium-Tantalum (LCT) pegmatites, which contain high concentrations of Li, Cs, Ta, P, B, Rb, Be, Nb, and Sn; and 2) Niobium-Yttrium-Fluorine (NYF) pegmatites, which are enriched in niobium, yttrium, and fluorine, as well as the REE (Linnen and others, 2012). The LCT pegmatites currently have greater economic importance than the NYF pegmatites (Linnen and others, 2012). However, the economic potential of the NYF pegmatites to produce REE resources is demonstrated by the Strange Lake pegmatite in Canada, which hosts more than 140 million tonnes (154.3 million tons) of ore with an average grade of 0.9 percent TREO (Quest Rare Minerals, 2013).

LCT and NYF pegmatites typically occur within granitic intrusive complexes (Linnen and others, 2012). However, REE-bearing pegmatites are also present within metamorphic terrains, as pods and dikes that can be discordant to foliation, as well as small lenses concordant to foliation (Houston, 1961; Adams and others, 1980).

Across Wyoming, granitic pegmatites are potential hosts for both high- and low-grade REE-mineralization. Significant enrichment is present in the Big Creek and Tie Siding districts, and interesting REE or other element anomalies occur in the Weddle claims, the Many Values area, and in the Allie claims. For granitic pegmatites hosted within intrusive rocks, post-emplacement processes may be important factors controlling the concentration of REE. In the Tie Siding area (fig. 5), post-emplacement hydrothermal activity was apparently responsible for further concentration of REE within alteration zones (fig. 6). In the Weddle claims in the Laramie Range, the only notable REE-enrichment is associated with a granite dikelet, reinforcing the importance of post-emplacement processes in concentrating REE. However, the secondary processes appear to be less important for REE-enrichment in pegmatites hosted by metamorphic rocks. However, in the Allie claims in the southern Bighorn Mountains, field relations suggest that the pegmatite bodies are the product of partial melting of the host-rock gneiss.

Tie Siding Pegmatites

Pegmatite pods within the Sherman Granite southeast of Tie Siding (fig. 5) can be highly radioactive and enriched in some REE (King and Harris, 2002). The Tie Siding pegmatites are typically zoned, and have an overall alkali feldspar granite composition. Zonation consists of an outer zone composed of biotite, microcline, and quartz, a central zone that is more than 90 percent microcline, and an inner core of quartz (Griffin and Warner, 1982). Many of these pegmatites exhibit fresh exposures due to production of potassium feldspar in the 1940s (fig. 6) (Osterwald and others, 1966; Griffin and Warner, 1982).

The REE-bearing minerals within some of these pegmatites are uncertain, but allanite is present in at least one locality, and zones of elevated radioactivity (7 – 500 times background) are present at all of the studied pegmatites (Griffin and Warner, 1982). The highest levels of radioactivity are associated with biotite. Griffin and Warner (1982)

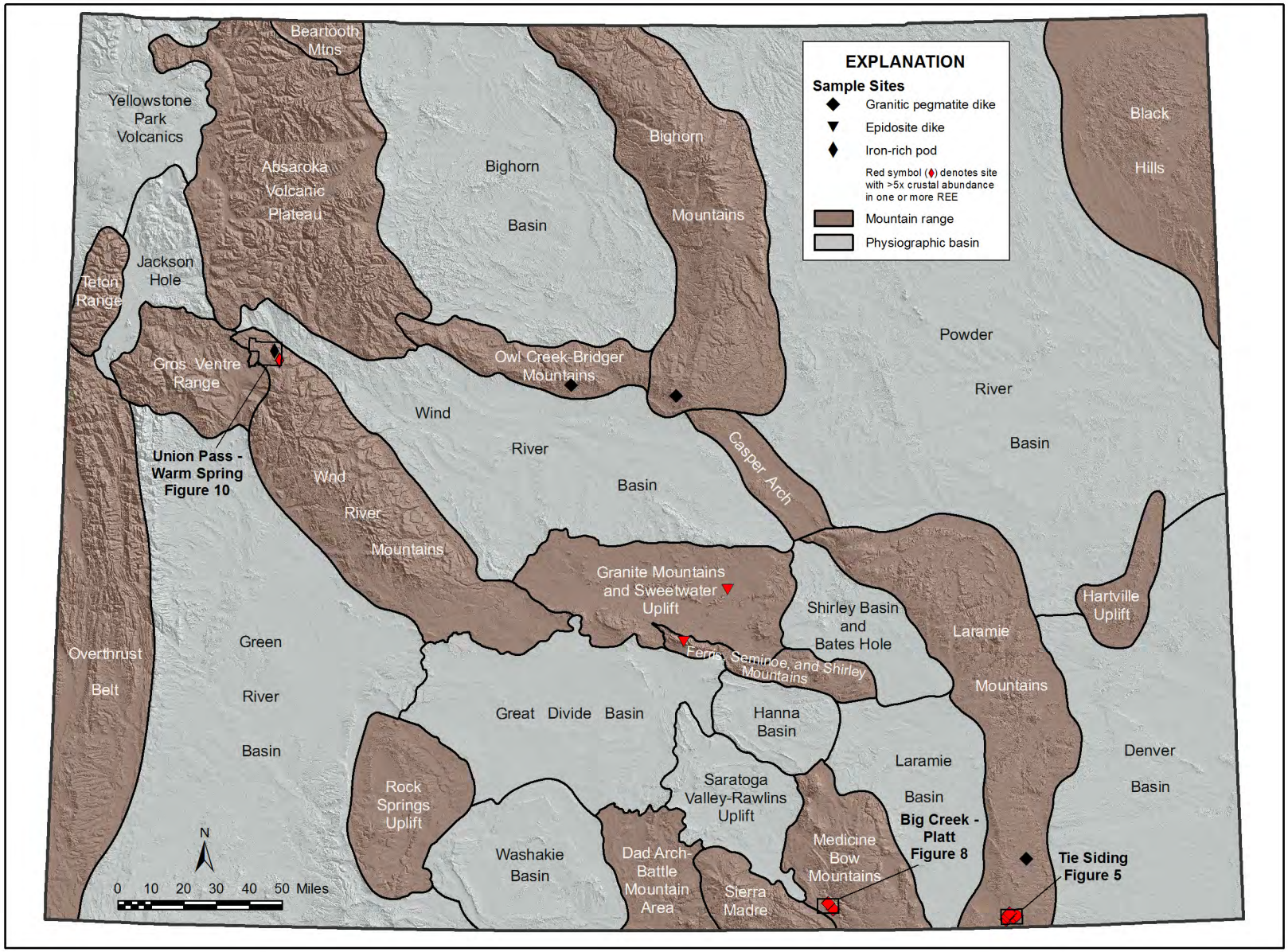

Figure 4. Locations of Precambrian samples included in this report. Sample sites with enrichment of greater than five times crustal abundance in one or more REE are shown in red.

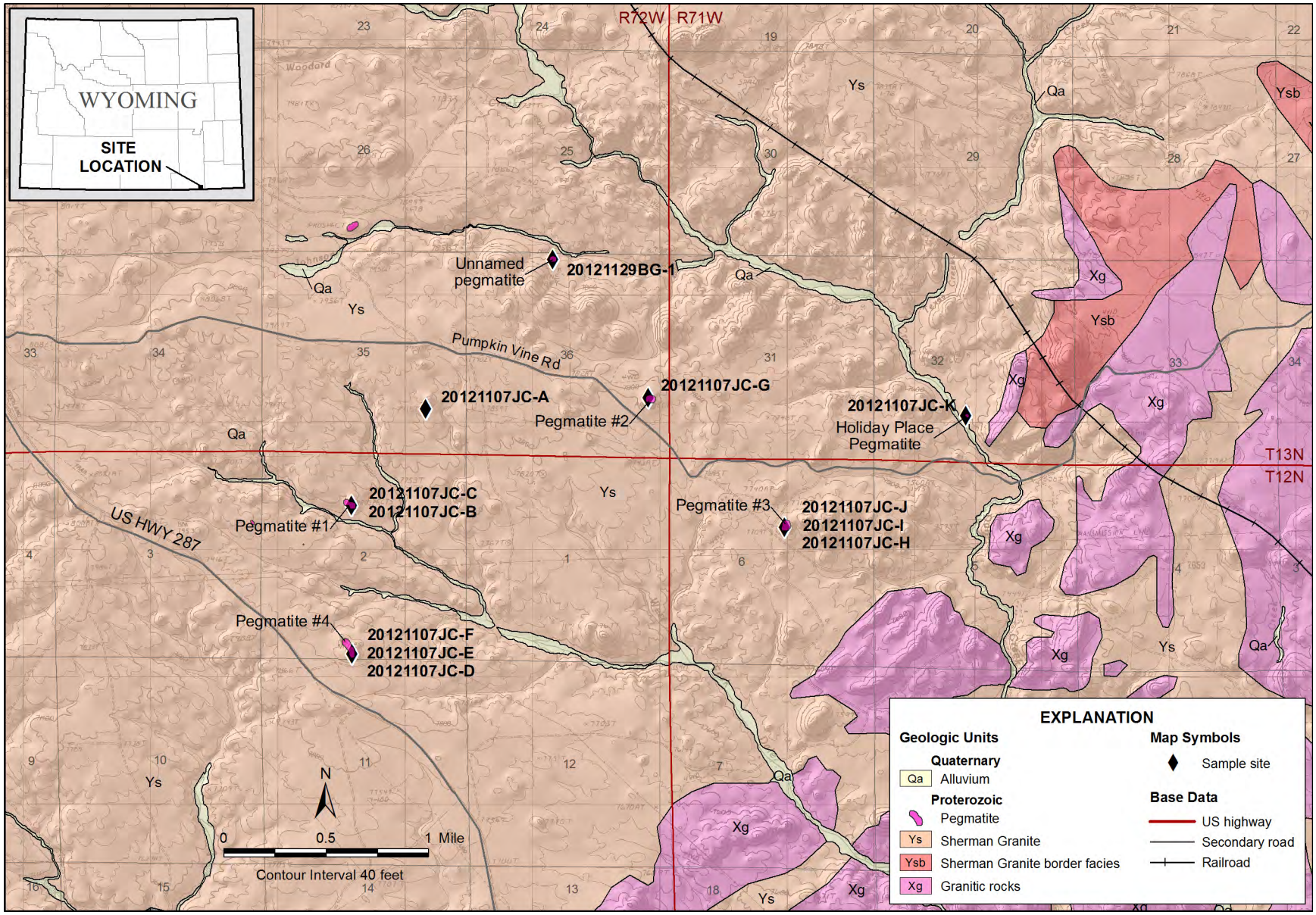

Figure 5. Sample locations and geology of the Tie Siding area, modified from Ver Ploeg and Boyd (2007) and Hausel and others (1981).

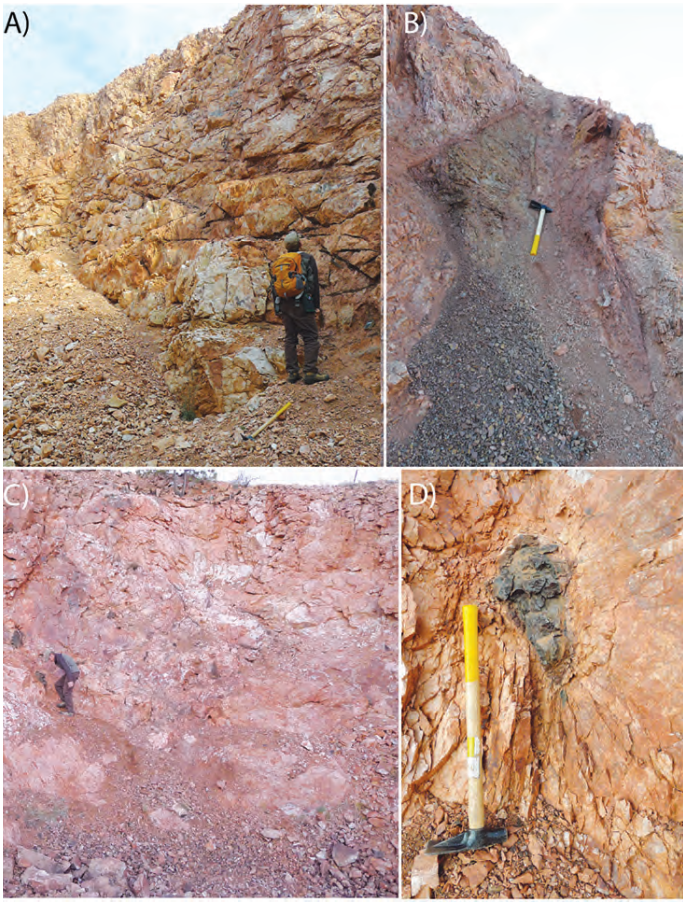

Figure 6. Tie Siding pegmatites. A, mining pit that exposes the granitic pegmatite with large books of biotite of pegmatite #4. B, alteration zone within pegmatite #3. C, Holiday Place pegmatite, exposed within a mine pit; an allanite nodule is present immediately left of the person. D, close-up of an allanite nodule in the Holiday Place pegmatite.

suggest that the source of the radioactivity is zircon hosted within the biotite. However, a sample of biotite (Sample 20121107JC-E) associated with high radioactivity is not itself radioactive and contains very little zircon. Radioactivity associated with several large biotite seams exhibits significant variability along the seam, suggesting that the source of the radioactivity is not disseminated uniformly throughout the seam. Most of the high REE concentrations in the Tie Siding pegmatites are associated with alteration zones on the margins of the pegmatites. However, the highest concentration of REE is found in large, 30 to 60 cm (1- to 2-ft) diameter allanite nodules within alkali feldspar.

Pegmatite #1, Sec. 35, T. 13 N., R. 72 W. and NE¼NW¼ sec. 2, T. 12 N., R. 72. W., Southern Albany County

Outcrops in this area are dominated by pink, very coarse-grained to pegmatitic epidote pyroxene monzonite of the Sherman Granite, with moderate to abundant magnetite, and moderate hematite and limonite staining (Sample 20121107JC-A). This monzonite is enriched in all of the REE, as well as yttrium and niobium (table 6).

Smith (1954) identified pyrochlore in this pegmatite and reported a sample with 4.1 percent ThO_2, 0.35 percent cU_3O_8[3],1.23 percent eU_3O_8. He also noted radioactivity up to 900 times background and a vitreous radioactive mineral (Smith, 1953a). Subsequent workers were unable to locate this pegmatite (Griffin and Warner, 1982) and the reported location in sec. 35, T. 13 N., R. 72 W. (Smith, 1953a; 1954) is probably incorrect. However, a biotite alkali feldspar granite to granite pegmatite is exposed in a group of small prospect pits in the SE¼NW¼ sec. 2, T. 12 N., R. 72 W., to the south of the location cited by Smith (1953a; 1954).

Feldspars in the pegmatite exhibit graphic texture and a zone of feldspar to clay alteration (fig. 6) is associated with radioactivity up to eight times background (380 counts per minute [cpm] with background of 50 cpm). When isolated, a sample of this material (Sample

3 Uranium concentrations are sometimes denoted by cU_3O_8 or cU, which represent assay values as determined by laboratory chemical analysis. The more frequently used denotation eU_3O_8, is a value representing radiometric equivalent U_3O_8, as estimated from gamma ray measurements. Together, cU_3O_8 and eU_3O_8 can then be used to determine the disequilibium of a uranium deposit. As uranium decays naturally, the resulting daughter products are often radioactive as well. That radioactivity can affect gamma ray logging measurements and may lead to a falsely higher estimation of uranium concentration in that deposit, and would be referred to as being in disequilibrium.

Table 6. Concentration of the REE, niobium, uranium, and thorium in the Tie Siding pegmatites. Bold values indicate concentrations greater than five times crustal abundance.

	Tie Siding pegmatites									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121107JC-A	76.4	154.5	20.5	82.1	16.65	4.88	16.05	2.46	14.1	2.82
20121107JC-B	**2110**	**4670**	**384**	**1185**	**122.5**	6.1	**58.8**	**7.44**	**36.2**	**7.33**
20121107JC-C	56.2	105.5	10.4	32.7	4.34	0.75	2.96	0.45	2.6	0.53
20121107JC-D	9.7	14.1	3	13.4	4.87	0.33	7.38	1.59	11.6	2.73
20121107JC-E	27	32	5.2	20.8	5.3	<0.2	7.3	1.26	9.4	2.37
20121107JC-F	4.9	5.9	1.28	6.1	3.15	0.29	6.83	1.59	13	3.56
20121107JC-G	12.4	4.4	2.49	9	1.74	2.29	2.14	0.43	3.27	0.91
20121107JC-H	5.8	29.4	2.37	12.1	7.32	0.16	15.7	4.05	**32.1**	**8.36**
20121107JC-I	29.3	41.9	8.6	36.7	8.67	1.92	9.12	1.39	8.01	1.61
20121107JC-J	**821**	**1285**	**187.5**	**661**	**119**	8.77	**96.2**	**11.65**	**56.9**	**10.25**
20121107JC-K	**23200**	**60300**	**8400**	**35200**	**7800**	**63.7**	**5400**	**674**	**2830**	**437**
20121129BG-1	10.9	17.6	3.28	14.4	6.11	1.96	9.67	2.37	18.3	4.61

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	U (ppm)	Th (ppm)
20121107JC-A	7.71	1.11	6.98	1.18	7	65.7	480.1	42.5	8.72	14.2
20121107JC-B	**22.5**	**3.86**	**28.7**	**5.47**	2	**252**	**8902**	**88.7**	**437**	**651**
20121107JC-C	1.54	0.26	1.71	0.3	<1	16.5	236.7	4.8	8.47	**42.1**
20121107JC-D	9.8	1.97	**16.2**	**2.95**	1	81.9	182.5	**294**	**32.4**	**222**
20121107JC-E	9.5	1.77	**15.5**	2.57	2.2	68	210.2	**842**	**47**	**45.3**
20121107JC-F	13.2	**2.47**	**18.1**	**3.34**	<1	118	201.7	10.1	**24.9**	**343**
20121107JC-G	3.54	0.75	6.53	1.36	<1	23.8	75.1	24.7	**32.4**	**84.1**
20121107JC-H	**28.3**	**4.85**	**32.2**	**5.25**	3	**225**	416.0	48.3	6.31	4.21
20121107JC-I	4.31	0.64	3.95	0.66	22	42	220.8	13.5	3.19	1.88
20121107JC-J	**25.1**	**3.37**	**20.2**	**3.3**	7	**301**	**3617**	51.2	**16.1**	**52.7**
20121107JC-K	**915**	**106.5**	**578**	**83.3**	9	**9540**	**155500**	6	**958**	**18100**
20121129BG-1	**17.3**	**3.43**	**29.1**	**5.31**	1	137	282.3	267	**32.8**	**74**

20121107JC-B) exhibited only slightly anomalous radioactivity. It is enriched in all of the REE, yttrium, and niobium to concentrations greater than five times crustal abundances, except for europium, which is present at more than three times crustal abundance. This sample also contains more than 0.04 percent uranium and 0.065 percent thorium (table 6).

A sample of biotite granite pegmatite (Sample 20121107JC-C) adjacent to the alteration zone exhibits minor to moderate epidote, hematite, and limonite staining, but no anomalous radioactivity. It is also weakly enriched in lanthanum, cerium, and praseodymium (table 6).

Pegmatite #2, NE¼SE¼ sec. 36, T. 13 N., R. 72 W., Southern Albany County

Uraniferous zircon (crytolite) was reported in this pegmatite (Smith, 1954), as was a vitreous radioactive mineral, and radioactivity up to 35 times background (Smith, 1953b). Griffin and Warner (1982) associated the high radioactivity with biotite and reported an analysis of 200 ppm lanthanum, 50

ppm yttrium, less than 10 ppm niobium, 500 ppm zirconium, and 20 ppm cU_3O_8.

Background radiation in the area is about 50 cpm, and about 165 cpm inside a prospect pit where the pegmatite, similar in composition to pegmatite #1, is exposed. The pegmatite is cut by a small dike of white to pink, medium- to coarse-grained biotite granite (Sample 20121107JC-G) associated with elevated radioactivity more than 15 times background (760 cpm). When isolated, this sample is not anomalously radioactive. The granite is enriched in Eu, Er, Tm, Yb, Lu, and Nb (table 6).

Pegmatite #3, SW¼NE¼ sec. 6, T. 12 N. , R. 71 W., Southern Albany County

Smith (1953c) reported radioactivity up to 35 times background and a vitreous radioactive mineral at this location. Griffin and Warner (1982) associated the high radioactivity with biotite and reported an analysis of 50 ppm lanthanum, 1,000 ppm niobium, greater than 200 ppm yttrium, and 127 ppm cU_3O_8.

This pegmatite is exposed in an abandoned quarry owned by Adventure Stone, LLC., a producer of construction aggregate and decorative stone in the 1990s and early 2000s. Background radiation outside of the quarry is about 50 cpm, but increases slightly to about 165 cpm within the quarry. The exposed pegmatite here is similar to that of pegmatite #1, except that it hosts 2 m (6 ft) long, up to 15 cm (5.9 in) thick seams of biotite associated with hematite. High radioactivity (2,000 cpm), up to 40 times background, is associated with a large biotite seam near a granite pegmatite that exhibits clay alteration of feldspars (Sample 20121107JC-H). The sample itself is not anomalously radioactive.

The contact between the granite pegmatite and enclosing monzonite is filled by a green, fine-grained to aphanitic mafic dike with plagioclase phenocrysts, very-fine grained hornblende, biotite, quartz, and fracture coating dendritic pyrolusite (Sample 20121107JC-I). The monzonite-side margin of the mafic dike hosts a zone where feldspars have been altered to clay (Sample 20121107JC-J) (fig. 6).

The altered pegmatite (Sample 20121107JC-H) is enriched in the HREE (except europium), as well as samarium, yttrium, and niobium, and contains greater than five times the crustal abundance of Dy, Ho, Er, Tm, Yb, Lu, and Y. The mafic dike near the margin of the pegmatite (Sample 20121107JC-I) is enriched in all of the HREE, as well as neodymium, samarium, and yttrium. The altered zone (Sample 20121107JC-J) is enriched in all of the REE as well as yttrium and niobium; only europium and niobium are concentrated less than five times crustal abundance (table 6).

Pegmatite #4, SE¼SW¼ sec. 2, T. 12 N., R. 72 W., Southern Albany County

High radioactivity at this location is associated with biotite, and a biotite-bearing sample of this pegmatite contained 500 ppm lanthanum, 200 ppm niobium, 150 ppm yttrium, and 57 ppm cU_3O_8. A sample of altered granite southwest of the pegmatite yielded 230 ppm lanthanum, 100 ppm niobium, 36 ppm yttrium, and 30 ppm c U_3O_8, and a trace of allanite (Griffin and Warner, 1982).

Background radiation outside of the pegmatite quarry is about 50 cpm, but increases slightly to about 165 cpm within the quarry. The pegmatite is compositionally similar to pegmatite #1, except that biotite is more abundant and, similar to pegmatite #3, occurs both as seams of biotite and hematite, and as radiating groups of biotite books. Elevated radioactivity (500 cpm) is present in an altered, extensively fractured part of the pegmatite associated with a biotite seam and a hematite seam (Sample 20121107JC-D). About 20 m (66 ft) east of this sample, high radioactivity (1,300 cpm) is associated with the west end of a 10 x 60 cm (4 x 24 in) biotite seam (Sample 20121107JC-E). However, the biotite itself did not register above background (approximately 165 cpm); neither did a sample of biotite granite pegmatite from just above the biotite book (Sample 20121107JC-F).

The biotite seam (Sample 20121107JC-E) exhibits weak to moderate HREE enrichment, with ytterbium enriched to greater than five times crustal abundance; furthermore, the biotite contains more than 0.05 percent niobium, the highest value for niobium of any of the samples collected from

the Tie Siding pegmatites. The altered pegmatite (Sample 20121107JC-D) is enriched in all of the HREE (except europium) and yttrium. It is also enriched more than five times crustal abundance in ytterbium and lutetium and contains more than 0.02 percent thorium and nearly 0.03 percent niobium. The unaltered biotite granite pegmatite (Sample 20121107JC-F) is enriched in the HREE (except europium) and yttrium, and contains more than five time crustal abundance of thulium, ytterbium, and lutetium; it also contains more than 0.03 percent thorium (table 6, Tie Siding Conc).

Holiday Place Pegmatite, SE¼SW¼ sec. 32, T. 13 N. , R. 71 W., Southern Albany County
Griffin and Warner (1982) found a trace of allanite here, and reported up to 1,000 ppm lanthanum, greater than 200 ppm yttrium, 50 ppm niobium, and 198 ppm cU_3O_8. This pegmatite is exposed in a prospect pit in a hill on the east side of Dale Creek. Background radioactivity near the pit was about 100 cpm. The pegmatite is similar to pegmatites #3 and #4, but it lacks the radiating biotite books and hosts 30 x 60 cm (12 x 24 in) nodules of allanite (Sample 20121107JC-K) (fig. 7).

The allanite nodules exhibit radioactivity up to 5,000 cpm and are centers for radial fractures that extend into the surrounding alkali feldspar. The sampled allanite nodule contains more than 15 percent REE and yttrium, and also contains nearly 0.1 percent uranium and more than 0.5 percent thorium (table 6). As observed in outcrop, the nodules appear to account for 1 percent or less of the entire volume of the pegmatite.

Unnamed Pegmatite, NE¼NW¼ sec. 36, T. 13 N., R. 72 W., Southern Albany County
A granitic pegmatite, not previously mentioned in the literature, is exposed in a prospect pit at this location. This pegmatite is similar in composition to pegmatite #1, but has biotite- and hematite-rich seams similar to those present in pegmatite #4. These biotite- and hematite-rich seams are associated with altered pegmatitic alkali feldspar with inclusions of hematite, biotite, and a vitreous black mineral (Sample 20121129BG-1) that is enriched to greater than five times crustal abundance in Er, Tm, Yb, and Lu, as well as Nb and Ta (table 6).

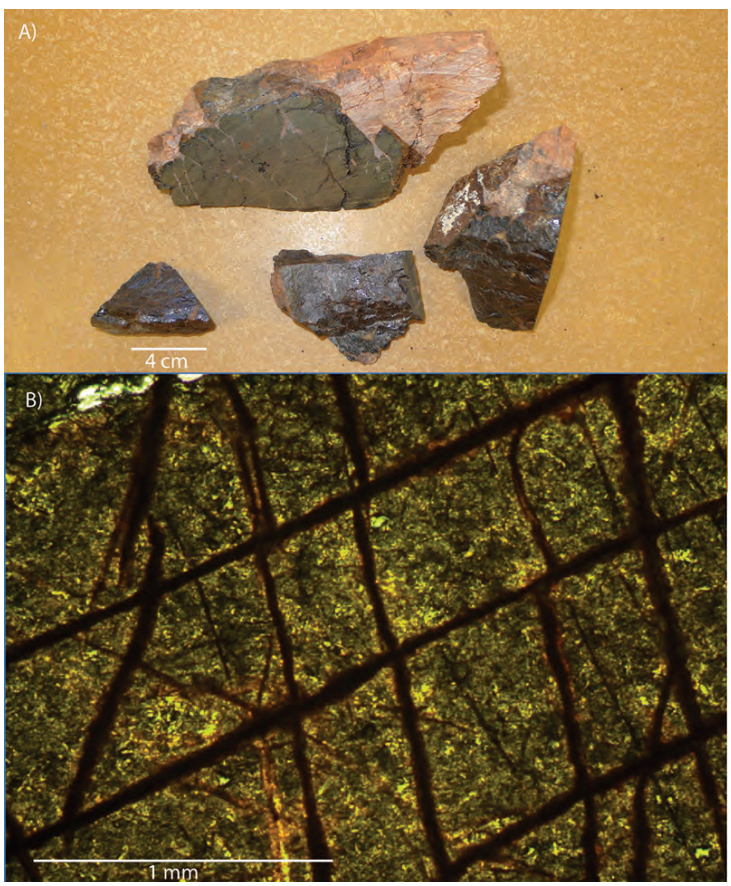

Figure 7. Allanite collected from the Holiday Place pegmatite. A, close-up of allanite; the largest sample exhibits a cut face. B, plane-polarized photomicrograph of the allanite.

Laramie Range Pegmatites

Areas of REE enrichment are present within granitic rocks along the length of the Laramie Range (King and Harris, 2002). Allanite and euxenite have been reported in granitic pegmatites within the Sherman Granite in secs. 1 and 2, T. 15 N., R. 71 W. within the Medicine Bow National Forest (Griffin and Warner, 1982). Additionally, REE-enrichment and REE-bearing minerals, including allanite and xenotime, have been reported within intrusive rocks of the Laramie Anorthosite

Complex in the middle to northern Laramie Range (King and Harris, 2002).

Weddle Claims, Southeastern Albany County
In the SE¼NE¼ sec. 2, T. 15 N., R. 71 W. and SW¼NW¼ sec. 1, T. 15 N., R. 71 W., the Mesoproterozoic Sherman Granite is cut by granitic pegmatite dikes (King and Harris, 2002). Samples of beryl- and possibly euxenite-bearing pegmatite analyzed by Griffin and Warner (1982) showed up to 700 ppm lanthanum, 50 ppm niobium, 367 ppm U_3O_8, and 70 ppm Y. High radioactivity within the pegmatite was found to be associated with biotite. Because of the possible occurrence of euxenite and the association between radioactivity and biotite, King and Harris (2002) suggested that these pegmatites are related to those near Tie Siding.

Two large prospect pits are present within a granitic (QAP: 30% **Q**uartz, 30% **A**lkali feldspar, 40% **P**lagioclase feldspar) pegmatite with abundant biotite in sec. 2. The pegmatite is cut by granite dikes and quartz veins up to 60 cm (24 in) thick. Hematite staining is abundant throughout the pegmatite (Sample 20120921BG-1), but unstained portions are also present (Sample 20120921BG-2). In places this pegmatite is extremely biotite rich (up to 50 percent) (Sample 20120921BG-3). The cross cutting granite dikes are pink, coarse-grained with moderate biotite and Fe-staining, and minor epidote alteration (QAP: 50% Q, 20% A, 30% P) (Sample 20120921BG-4). Two of the samples taken here (20120921BG-1 and 20120921BG-4) are slightly enriched in HREE, but the amount of enrichment found by Griffin and Warner (1982) was not encountered (table 7); neither was beryl nor euxenite observed.

The pegmatite in sec. 1 is similar in composition to the one in sec. 2, but contains biotite pods up to about 30 cm (12 in) across and orange pegmatitic alkali feldspar (Sample 20120921BG-5). A thin biotite granite dikelet that cuts both the pegmatite and a quartz vein includes an unidentified, fine-grained black mineral (Sample 20120921BG-6); this sample exhibits weak enrichment in HREE, notably thulium and ytterbium. A medium- to

Table 7. Concentration of the REE, niobium, tantalum, and thorium in the Weddle claims pegmatites. Bold values indicate concentrations greater than five times crustal abundance.

	Weddle claims									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20120921BG-1	5.4	4.82	6.57	6.1	2.35	0.1	4.32	0.86	6.57	1.7
20120921BG-2	0.8	1.14	0.14	0.4	0.09	0.09	0.1	0.02	0.14	0.03
20120921BG-3	2.5	3.9	0.63	2.7	0.8	0.38	1.07	0.2	1.28	0.3
20120921BG-4	2.8	3.7	0.8	3.7	1.66	0.16	2.51	0.54	3.74	0.82
20120921BG-5	1.1	1.15	0.33	0.6	0.17	0.08	0.27	0.05	0.33	0.08
20120921BG-6	9.5	18.5	2.34	9.4	2.99	0.27	4.79	1.2	9.09	2.21
20120921BG-7	16.6	42.1	4.81	17.6	3.79	0.57	3.96	0.75	4.82	1.16

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	Ta (ppm)	Th (ppm)
20120921BG-1	6.39	1.23	10.4	1.67	0.3	67.5	126.3	6.9	0.91	3.5
20120921BG-2	0.12	0.02	0.17	0.03	0.2	1	4.5	0.4	<0.05	0.2
20120921BG-3	1.14	0.21	1.45	0.25	0	11.5	28.3	47.3	3.5	15.95
20120921BG-4	2.95	0.58	4.17	0.66	0	23.3	52.1	23.3	2.6	5.98
20120921BG-5	0.27	0.05	0.33	0.05	0.1	2.4	7.4	0.8	0.08	0.3
20120921BG-6	8.36	1.6	11.35	1.87	0	63.1	146.6	46.9	5.1	**39.1**
20120921BG-7	4.1	0.73	5.24	0.87	0	35.7	142.8	25	3.6	**352**

coarse-grained granite (QAP: 30% Q, 40% A, 30% P) at this location is weakly enriched in some of the HREE (Sample 20120921BG-7).

Big Creek District

The Big Creek pegmatite district, on the west side of the Medicine Bow Mountains, was investigated and mapped by Houston (1961) and covers an area several miles wide and 3.2 to 10 km (2 to 6 mi) south of the Mullen Creek-Nash Fork shear zone (fig. 8). The Mullen Creek-Nash Fork shear zone is part of the Cheyenne belt suture, which represents a continental-arc collision zone (Graff, 1978; Hills and Houston, 1979) separating the Wyoming Province to the north from cratonized (1.7 Ga) Proterozoic basement of the Colorado Province to the south. The Colorado Province south of the Cheyenne belt consists of volcanogenic island-arc basement rocks, intrusive granites, and gabbroic complexes. The Mullen Creek complex, one of the larger layered mafic complexes in the western United States, lies along the northern edge of the Big Creek pegmatite district. The district is included within the Preliminary Geologic Map of the Saratoga 30' x 60' quadrangle (Sutherland and Hausel, 2005).

Two types of granite pegmatite were described by Houston (1961) that cut Early Proterozoic amphibole gneiss in close proximity to both a medium- to coarse-grained, pink to gray foliated granite intrusion, and a well-foliated amphibolite of the 1778 ± 2 Ma, Mullen Creek layered mafic igneous complex. In the vicinity of known REE occurrences, the amphibole gneiss is dominated by hornblende gneiss and schist, with lesser, alternating layers of feldspar-quartz-biotite gneiss.

The most common pegmatite is an unzoned feldspar-quartz type that is roughly conformable in direction and attitude to the amphibole gneiss. These pegmatites tend to be long and narrow, with widths rarely greater than 3 m (10 ft) and lengths exceeding 0.8 km (0.5 mi). Their contacts with the country rock are sharp and exhibit no decrease in grain size toward the contacts. Mineralogy is simple and is dominated by feldspar accompanied by minor quartz and accessory biotite, muscovite, garnet, magnetite, and ilmenite (Houston, 1961).

The second type of pegmatite may have poorly developed zoning, has cross-cutting relationships with the amphibole gneiss, and tends to be elliptical in plan view, with lengths averaging three times their widths. Similar to the first type, these pegmatites have sharp contacts and show no decrease in grain size toward contact with the country rock. However, the mineralogy is more complicated, and along with feldspar and quartz, includes garnet, biotite, muscovite, tourmaline, fluorite, and rare monazite, allanite, euxenite, and columbite (Houston, 1961).

Economically, these pegmatites can be described as either copper-bearing or REE-bearing. Houston (1961) noted five pegmatites in the district that are known to host one or more of the REE-bearing minerals, monazite, allanite, and euxenite. However, only the Platt pegmatite contained economic quantities of these minerals. Numerous other pegmatites in the district were not examined and have the potential to host REE mineralization (King and Harris, 2002). The nearby Big Creek mine hosted copper mineralization, but no primary REE minerals or columbite. Columbite [$(Fe,Mn)(Nb,Ta)_2O_6$] may contain REE and uranium as accessory constituents (King and Harris, 2002; MinDat.org, 2011).

Platt Mine (Platt Pegmatite, Uranium King Mine), SW¼SE¼ sec. 3, T. 13 N., R. 81 W., Southeastern Carbon County

The Platt mine was excavated to a depth of 23 m (75 ft) in a zoned, cross-cutting type pegmatite 21 m wide by 49 m long (70 x 160 ft). The outer part of the pegmatite is feldspar, and the central part is quartz-mica-feldspar-rare earth minerals. Euxenite is the most abundant REE-bearing mineral followed by monazite, and the least abundant, columbite (Houston, 1961). These occur as large individual crystals and crystal aggregates both in the central pegmatite and in gash fractures. Uranium accounted for most of the production from the Platt mine in 1956 with 12 tonnes (13 tons) of ore (King and Harris, 2002). Approximately 4,500 kg (10,000 lbs) of euxenite were reported to be extracted from the mine between 1956 and 1958 (Houston, 1961; Adams and others, 1980), although the USBM recorded only 1,413 kg (3,115

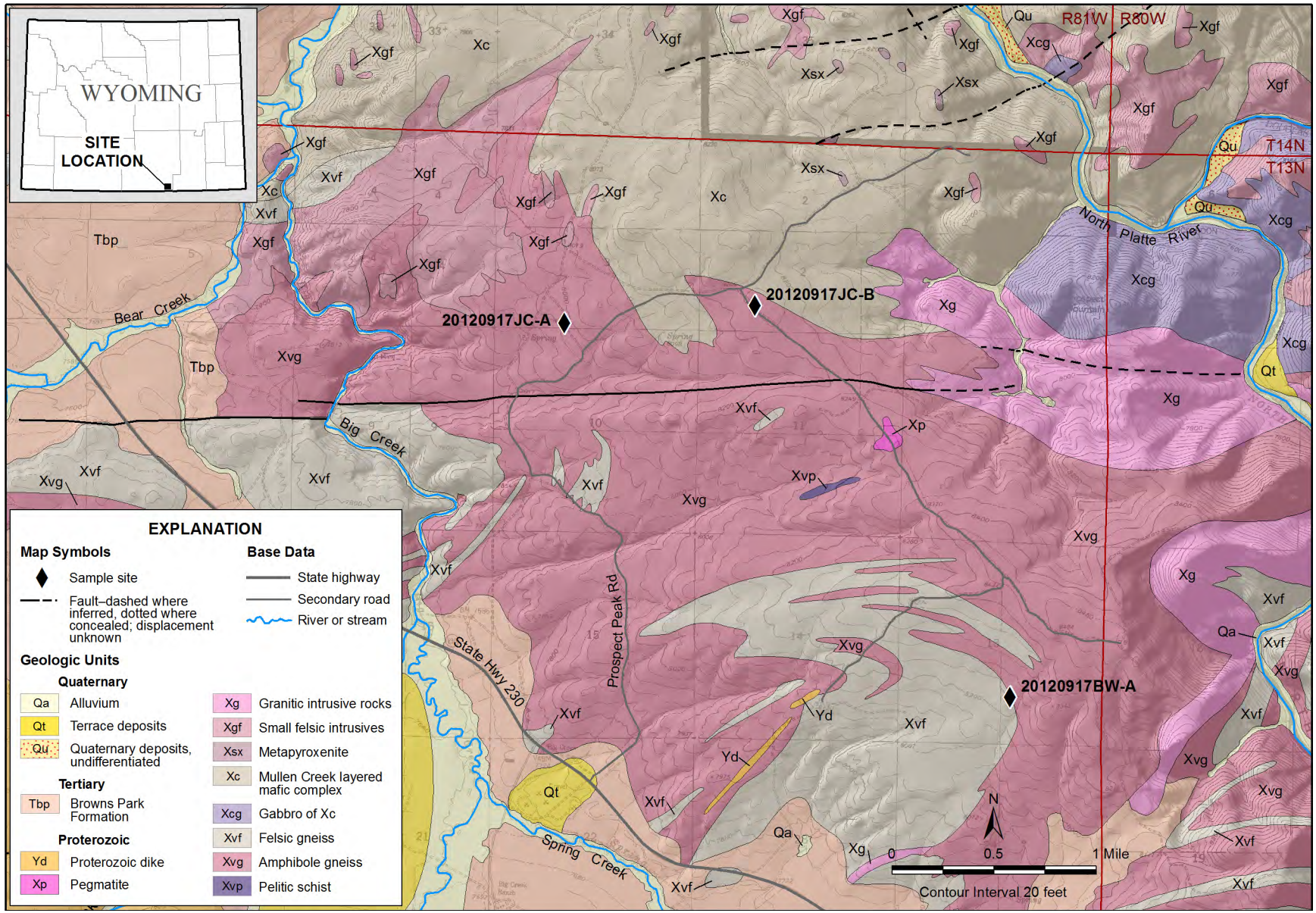

Figure 8. Sample locations and geology of the Big Creek pegmatite district, modified from Sutherland and Hausel (2005).

lbs) for 1957 and 450 kg (1,000 lbs) for 1958 (King and Harris, 2002).

The euxenite was reported by Houston (1961) to be metamict to the extent that it gave no x-ray diffraction pattern. His x-ray fluorescence studies of the euxenite showed, in order of decreasing abundance, the presence of Nb, Y, Fe, Ta, U, and Zr. These were accompanied by minor amounts of Pb, Mn, Zn, Er, Eu, Ac, Ho, Ti, Th, Sm, and Rn. King and Harris (2002) suggested that the euxenite crystals, reported to be up to 7.6 cm (3 in) long, might have been misidentified and were probably samarskite or niobium-rich, yttrium-bearing tantalite.

X-ray fluorescence of monazite from the Platt mine showed, in order of abundance, Ce, Nd, Y, Th, and La. These were accompanied by minor amounts of Pr, Sm, and Gd. Although phosphorus is a major constituent of monazite, its presence could not be shown by the type of analysis used (Houston, 1961).

A 1980 DOE report (Adams and others, 1980) described both euxenite and allanite in several samples from the Platt pegmatite. Sample analyses in that report did not show any lanthanum, or yttrium concentrations higher than average crustal values. Scandium exceeded five times its average crustal value at 200 ppm. No other REE were evaluated in samples from the Platt pegmatite (Adams and others, 1980).

The Platt Mine pegmatite dike trends approximately 50˚. A sample collected for this investigation (Sample 20120917JC-A) is composed of muscovite granite pegmatite dominated by quartz, microcline, and perthite, with moderate plagioclase, and hematite with limonite staining. It contains minor garnet, dendritic pyrolusite, epidote alteration, and a glassy black mineral, possibly euxenite or columbite-tantalite (fig. 9a). The dike intrudes granitic gneiss (Sutherland and Hausel, 2005) with minor biotite; banding in the gneiss trends 342˚, and dips 59˚ E. Analysis of sample 20120917JC-A shows enrichment in lutetium and ytterbium greater than five time crustal abundances; HREE are slightly enriched above crustal abundances. The sample is also enriched in niobium and tantalum. The analyzed values in this sample are a minimum estimate for concentrations in this pegmatite dike because the relatively high silica content of the sample suggests dilution by excess quartz. When the analysis is normalized to the global average silica content of granite, 72.04 percent, (Blatt and Tracy, 1996) Er, Lu, Tm, Yb and Y are enriched above five times crustal abundance, as are niobium and tantalum (table 8). The high niobium and tantalum concentrations suggest that euxenite or columbite-tantalite may be present within the pegmatite.

Figure 9. Samples of the Big Creek – Platt pegmatites. A, Sample 20120917JC-A. B, Sample 20120917BW-A.

Table 8. Concentration of the REE, niobium, tantalum, and uranium in the Big Creek – Platt pegmatites. Bold values indicate concentrations greater than five times crustal abundance.

Big Creek District - Platt Pegmatites										
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20120917BW-A	2	3.8	0.65	3.4	3.18	0.61	12.6	**5.06**	**56.9**	**18.15**
20120917JC-A	27.8	39.2	7.3	28.5	6.91	0.3	6.72	1.31	9.17	2.14
20120917JC-A Normalized	51.4	72.5	13.5	52.7	12.8	0.6	12.4	2.4	17	4

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	Ta (ppm)	U (ppm)
20120917BW-A	**79.2**	**17.25**	**142**	**26.6**	20	**697**	1088.4	**107**	**17.6**	**35.1**
20120917JC-A	8.93	2.17	**19.6**	**3.68**	5	141	309.73	128.5	82.6	**11**
20120917JC-A Normalized	**16.5**	**4**	**36.2**	**6.8**	9.2	**261**	572.8	**237.6**	**152.7**	**20.3**

Platt Pegmatites, T. 13 N., R. 81 W., Southeastern Carbon County

Several pegmatites occur in the N½NE¼ sec. 8, T. 13 N., R. 81 W. (Houston, 1961). One of these was discussed in a 1982 DOE National Uranium Resource Evaluation report (NURE) (Dribus and Nanna, 1982). The report identified a 30- to 91-cm (1- to 3-ft) wide, 30°-trending garnet-bearing granite pegmatite that cut Early Proterozoic biotite schist. The pegmatite exhibited two to 17 times background radioactivity (Geslin, 1954; Dribus and Nanna, 1982), and contained black, metallic minerals identified as euxenite and allanite with the use of Scanning Electron Microscope-Energy Dispersive Spectroscopy (SEM-EDS). Various early analyses reported up to 0.1 percent uranium (King and Harris, 2002). No REE analysis is known from this location.

A similar pegmatite dike in the S½ sec. 13, T. 13 N., R. 81 W., cuts granitic gneiss near its contact with pelitic schist (Sutherland and Hausel, 2005). The pegmatite is exposed in a prospect pit and in outcrop. The dike is granite pegmatite with abundant biotite and hematite, moderate garnet and columbite-tantalite (or possibly euxenite), allanite, and moderate limonite staining (Sample 20120917BW-A) (fig. 9b). This pegmatite sample is enriched in all of the HREE, except for europium. The elements Dy, Er, Ho, Lu, Tb, Tm, and Yb, as well as Y, Nb, and Ta exhibit greater than five times crustal abundances (table 8). Based on the high niobium and tantalum concentrations, the pegmatite also likely hosts euxenite or columbite-tantalite.

In the SE¼SW¼ sec. 2, T. 13 N., R. 81 W., a quartz vein that cuts amphibolite is exposed in a prospect pit. The vein, about 2 m (6 ft) wide, vuggy, and exhibiting abundant hematite and limonite staining was sampled during this investigation. Sample 20120917JC-B is not significantly enriched in any economic elements or minerals (table 8).

Many Values Area

The Many Values area covers the E½ sec. 32 and W½ sec. 33, T. 13 N., R. 78 W., along Forest Service Road 544 in the Medicine Bow National Forest. Local rocks consist of Paleoproterozoic felsic gneiss intruded by Mesoproterozoic Sherman Granite, both of which are cut by granitic pegmatites (Sutherland and Hausel, 2005). Tantalum, mica, and beryl were produced from a mine within the Many Values area in the early 1940s (King and Harris, 2002).

Many Values Mine, SE¼NE¼ sec. 32, T. 13 N., R. 78 W., Southwestern Albany County

Two shallow shafts and several prospect pits developed in Paleoproterozoic tourmaline-rich mica schist and gneiss host rock are cut by granite to granodiorite pegmatites striking 230˚ and dipping 85˚ NW. The pegmatites are muscovite-rich,

granite to granodiorite with rapakivi texture, minor euhedral garnet, and minor iron staining. Through the early 1940s, 18,600 kg (41,000 lbs) of mica, 1.8 tonnes (2 tons) of beryl, and 39 kg (85 lbs) of tantalite were produced from two granitic pegmatites that cut Paleoproterozoic tourmalinized mica schist and gneiss (Osterwald and others, 1966). Additionally, Adams and others (1980) found euxenite, fergusonite, allanite, and cleavelandite within the Many Values pegmatites, and noted that tantalite typically occurs as inclusions in cleavelandite. King and Harris (2002) described this site as an unverified occurrence. A representative sample of the Many Values pegmatite (20120911WS-D) yielded 75.8 ppm niobium (4.5 times crustal abundance) and 10.3 ppm tantalum (6.1 times crustal abundance), but no other significant enrichment is present.

Many Values Prospect Pits, SE¼NE¼ sec. 32 and NE¼SE¼ sec. 33, T. 13 N., R. 78 W., Southwestern Albany County

Prospect pits along US Forest Service Road 544, in the vicinity of the Many Values mine, expose granitic pegmatites within Paleoproterozoic felsic gneiss and Mesoproterozoic Sherman Granite (Sutherland and Hausel, 2005). A prospect pit about 0.8 km (0.5 mi) east of the Many Values mine exposes a granitic pegmatite that cuts gneiss; this pegmatite (Sample 20120911WS-B) is weakly graphitic and exhibits minor epidote alteration but is not enriched in any of the REE or other elements of economic interest. A prospect pit about 107 m (350 ft) east of the Many Values mine exposes a pegmatite that cuts Sherman Granite; the pegmatite (Sample 20120911WS-C) contains 62.7 ppm tantalum (36.9 times crustal abundance).

Southern Bighorn and Owl Creek Mountains

In the southern Bighorn and Owl Creek Mountains, as in the Laramie Range and Medicine Bow Mountains, granitic pegmatites within Precambrian crystalline rocks are potential hosts for REE and associated elements. Allanite-bearing pegmatites are present within Archean gneiss in the southern Bighorn Mountains (King and Harris, 2002). Archean gneiss and tonalite in the Owl Creek Mountains host columbite-tantalite-bearing pegmatites (Hausel and others, 1985).

Whippet and Zimmerman Mines Area, SE¼NE¼ sec. 28 and NW¼ sec. 27, T. 40 N., R. 93 W., Northeastern Fremont County

Dikes of Archean granitic rocks intrude the margins of an Archean supracrustal belt in the Owl Creek Mountains (Thaden, 1980; Hausel and others, 1985). Tungsten, tantalum, beryllium, potassium feldspar, and lithium were produced from pegmatites within these Archean granitic rocks at Whippet mine #8 (Hausel and others, 1985). Due to lack of time and direct access, the Whippet Mine #8 was not sampled.

The Zimmerman beryl mine is 0.5 km (0.33 mi) southeast of the Whippet #8 mine, and targeted a northeast trending felsic dike (Thaden, 1980; Hausel and others, 1985). At the Zimmerman mine, the outcrop is dominated by white granitic rocks, mostly white to light gray, very fine-grained to pegmatitic muscovite tonalite with moderate hematite, epidote, and black tourmaline. One individual tourmaline crystal was at least 9 cm (3.5 in) long. The tonalite is banded in places, and exhibits both modal and size grading (quartz to plagioclase; pegmatitic to very fine-grained) (Sample 20121011JC-F). The tonalite is not significantly enriched in any of the REE, but contains 24 ppm tantalum (more than 14 times crustal abundance), 122.5 ppm cesium (more than 64 times crustal abundance), 12 ppm tungsten (nearly 11 times crustal abundance), and 480 ppm lithium (more than 28 times crustal abundance). The high concentrations of lithium, cesium, and tantalum in this pegmatite suggest that it is an LCT-type pegmatite. If other pegmatites in the Owl Creek Mountains are mostly LCT-type, the prospect of REE-enrichment should be considered relatively low.

Allie (Parlett-Adams) Claims, SW¼NW¼ sec. 12, T. 39 N., R. 88 W., Northwestern Natrona County

Russell and Devore (1948) reported radioactive allanite within lenses of granitic pegmatite enclosed in Precambrian gneiss at this locality. Radioactivity over the pegmatite lenses was reported to be two to

12 times background and the individual radioactive mineral grains ranged from 0.6 to 7.6 cm (0.25 to 3 in) long (Russell and Devore, 1948). King and Harris (2002) listed this site as an unverified occurrence.

The dominant lithology in the area is pink to gray, medium- to coarse-grained biotite hornblende quartzofeldspathic gneiss with abundant small, tight folds. Small pockets of biotite granite pegmatite are common within the gneiss and one lens of biotite granite pegmatite (QAP: 20% Q, 60% A, 20% P) contains allanite with some grains up to 1.3 cm (0.5 in) in length (Sample 20121017JC-D). The pegmatite lens is weakly to moderately enriched in all of the LREE and some of the HREE as shown in table 9.

Other Precambrian Occurrences

Beaver Creek Allanite Prospect, Secs. 5 and 6, T. 46 N., R. 83 W. and Sec. 31, T. 47 N., R. 83 W., Western Johnson County

At this location in the southern Bighorn Mountains allanite is present in lenses, bands, and pods of metamorphic calc-silicate rocks. The rocks are composed of a complex assemblage of calcite, diopside, garnet, sodium-rich amphiboles, epidote, oligoclase, magnetite, and allanite. Allanite occurs as irregular masses that interfinger with epidote (Wilson, 1960). The bodies are generally concordant with the 300° trending foliation of the hosting Precambrian quartzofeldspathic gneiss and form a discontinuous zone varying from several centimeters to 2 m (a few inches to 6 ft) wide and 1,143 m (3,750 ft) long (King and Harris, 2002). Marble is adjacent to some of the calc-silicate bodies, and allanite tends to be more abundant in such areas. Individual allanite crystals are as long as 5 cm (2 in) (King and Harris, 2002).

Numerous prospect pits and trenches were cut in the site prior to 1960. In 1955, as much as 544 tonnes (600 tons) of allanite-bearing rock were removed from workings in sec. 31 (Bromley, 1955; Sargent, 1960). Assays reported by Wilson (1960) yielded up to 11 percent CeO_2, 0.7 percent thorium, and 1.5 percent other REO. Access to the Beaver Creek allanite prospect requires passage through private lands, and the WSGS was unable to gain permission to access for this investigation.

Union Pass – Warm Spring Area

The Union Pass – Warm Spring area (fig. 10), is located on the north end of the Wind River Range, approximately 12 km (7.5 mi) due west of Dubois. The area is known to host placer deposits of gold and heavy minerals, and at least one vein- and breccia-hosted uranium deposit. Ullmer (1983) noted a north-northwest trending lineament (fig. 10) that intersects the Dubois claims uranium deposit, which is hosted in a brecciated quartz vein cutting a magnetite- and biotite-rich pod within Archean gneiss (Granger and others, 1971; Ullmer, 1983). Uranium mineralization within the Dubois claims was likely produced through hydrothermal alteration related to the emplacement of granitic dikes (Ullmer, 1983).

Exposed in a road-cut on Wildcat Road near the northwest end of the lineament, and similar to that on the Dubois claims, an iron-rich pod is cut by a biotite granite dike. The pod contains much less biotite, and is dominantly composed of iron-rich

Table 9. Concentration of the REE, niobium, tantalum, and thorium in the Allie claims pegmatites. Bold values indicate concentrations greater than five times crustal abundance.

	Allie claims									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121017JC-D	66.8	174.5	20.6	85.8	27.4	0.85	16	1.89	7.69	1.1

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	Ta (ppm)	Th (ppm)
20121017JC-D	2.67	0.38	2.54	0.39	3.4	29.6	441.6	2.6	0.45	**68.7**

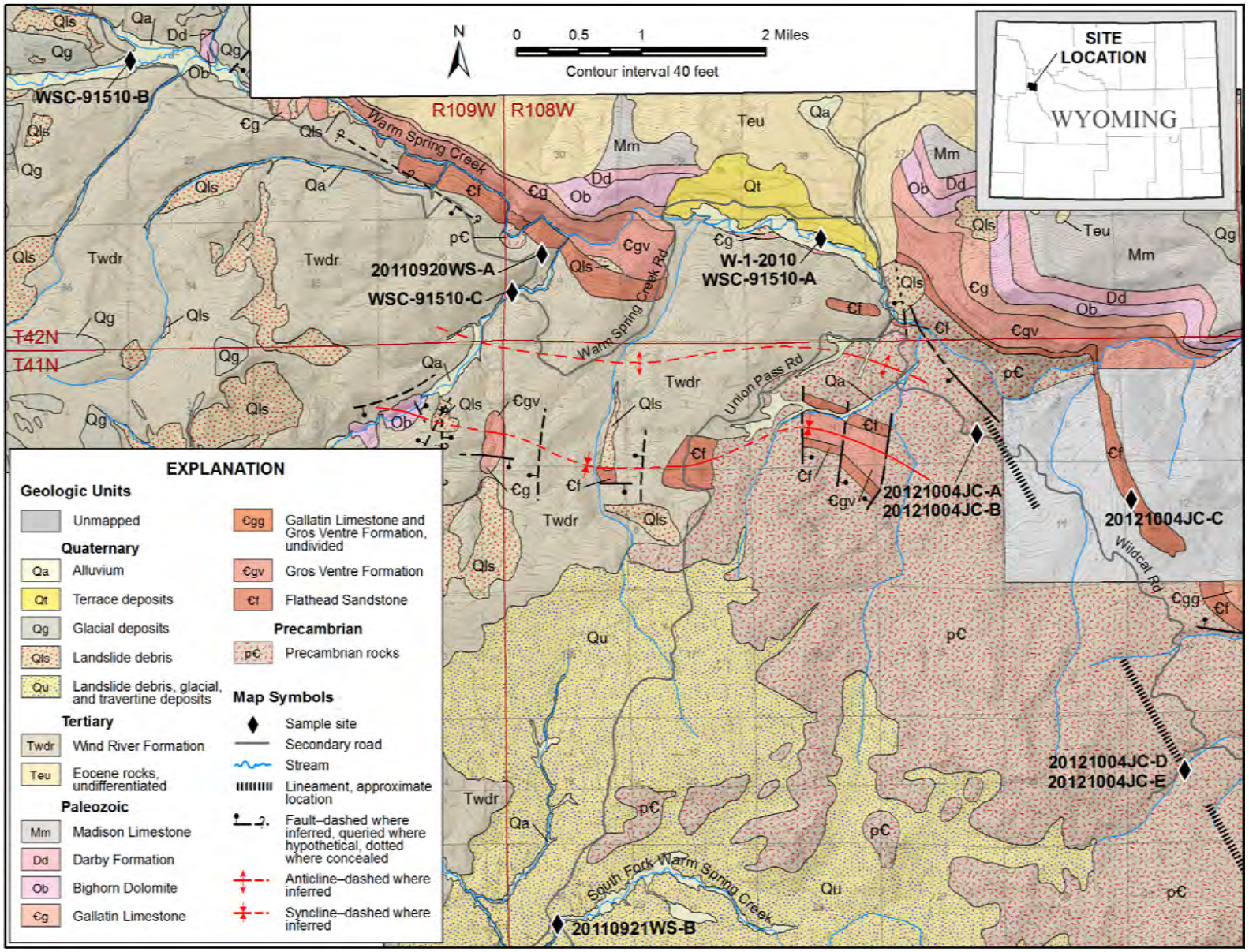

Figure 10. Sample locations and geology of the Union Pass-Warm Spring area, modified from Keefer, 1957; Dunnewald, 1958; Rohrer, 1968; Granger and others, 1971; and Ullmer, 1983.

pyroxenes and olivine. Iron-rich float is present along the length of the lineament. Ullmer (1983) argues that the iron-rich composition and mineral assemblage of the relatively unaltered rocks at the northwest end of the lineament suggest that the iron-rich pods are metamorphosed iron formation, rather than intrusive ultramafic rocks. Granger and others (1971), and Ullmer (1983) refer to the iron-rich pods as biotite gneiss and mica schist, respectively. However, neither banding nor foliation is apparent in outcrop or hand sample.

Figure 11. Contact between the iron-rich pod (left) and quartz monzonite dike (right), along Wildcat Road in the Union Pass – Warm Spring area.

Wild Cat Road, SE¼SE¼ sec. 3, T. 41 N., R. 108 W., Northwestern Fremont County

This locality centers on an iron-rich, weakly altered, granular body composed of hypersthene, ferroaugite, fayalite, magnetite, and quartz, with minor plagioclase, biotite and hornblende. The iron-rich body is on the northwest end of a north-northwest trending lineament, observable in aerial imagery. The lineament intersects the magnetite- and biotite-rich pod that hosts mineralization on the Dubois claims (Ullmer, 1983). The presence of the iron-rich end-members of mafic minerals (i.e. hypersthene, ferroaugite, and fayalite), and the general lack of feldspars led Ullmer (1983) to conclude that this pod, as well as the altered uranium-hosting pod within the Dubois claims, are contact-metamorphosed iron-formation, rather than ultra-mafic plugs.

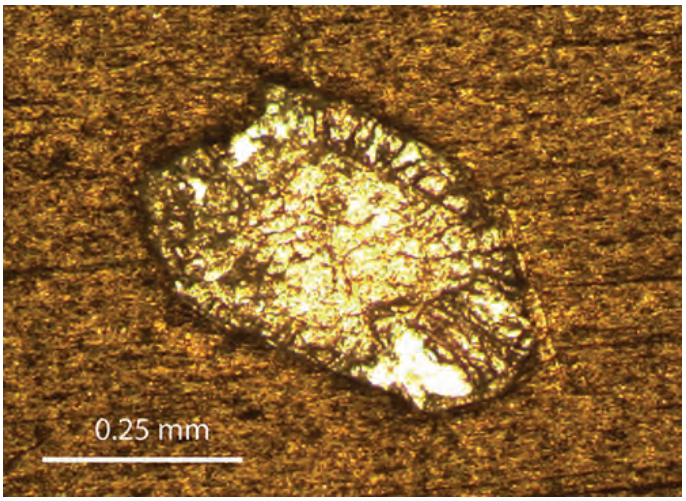

Figure 12. Photomicrograph of a zircon grain within biotite in sample 20121004JC-B.1.

The iron-rich pod (Sample 20121004JC-A) is cut by a very coarse-grained to pegmatitic biotite granite dike with abundant iron-staining (Sample 20121004JC-B) (fig. 11). Sample 20121004JC-B was split into two subsamples for analyses: unaltered granite (20121004JC-B.1), with radioactivity up to three times background when isolated in the lab, and altered, heavily limonite stained granite (20121004JC-B.2) with no anomalous radioactivity. In the unaltered granite, zircon is present within biotite (fig. 12), and is likely the source of the elevated radioactivity and the REE. The presence of moderately radioactive granite supports Ullmer's (1983) assertion that mineralization within the

Table 10. Concentration of the REE, niobium, uranium, and thorium in the Precambrian rocks of the Union Pass – Warm Spring area. Bold values indicate concentrations greater than five times crustal abundance.

	Union Pass - Warm Spring									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121004JC-A	32.6	57.8	5.92	19.2	3.19	0.64	3.63	0.86	7.39	2
20121004JC-B.1	100.5	179	18.6	61.1	9.19	1	6.23	0.73	3.16	0.49
20121004JC-B.2	3.1	4.9	0.57	1.9	0.34	0.04	0.24	0.04	0.22	0.04
20121004JC-D	12.3	29.7	3.09	11.2	2.46	0.45	1.85	0.43	2.88	0.59
20121004JC-E	**821**	**1640**	**143**	**471**	**57.1**	3.01	**28.2**	2.87	12.35	2.31

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	U (ppm)	Th (ppm)
20121004JC-A	6.94	1.24	8.71	1.47	51	52.7	255.3	14.4	1.05	20.3
20121004JC-B.1	1.17	0.15	0.91	0.14	10	12.3	404.7	22.2	3.88	**91**
20121004JC-B.2	0.13	0.02	0.16	0.03	6	1.2	18.9	7.2	1.34	2.5
20121004JC-D	1.85	0.32	2.22	0.36	14	12.4	96.1	6.5	**46.4**	9.31
20121004JC-E	6.29	0.95	6.07	1.05	13	50.8	**3259**	13.9	**10.45**	**436**

Dubois claims is associated with the emplacement of granitic dikes. The unaltered radioactive granite is weakly enriched in the LREE, as well as gadolinium and terbium. The altered granite and the iron-rich pod exhibit no notable enrichment (table 10).

Dubois Claims, SW¼NW¼ sec. 12, T. 41 N., R. 108 W., Northwestern Fremont County

Ullmer (1983) reported that uranium mineralization (up to 2.4 percent U_3O_8) in this area is hosted in a brittle deformation zone within an altered magnetite- and biotite-rich pod in Archean gneiss. The findings of Ullmer (1983) are in agreement with Granger and others (1971), who found pitchblende within a quartz-, hematite-, and magnetite-cemented breccia zone cutting biotite gneiss. Ullmer (1983) interprets the magnetite- and biotite-rich pod as contact-metamorphosed iron formation that was hydrothermally altered. Hydrothermal alteration resulted in chlorite and sericite, as well as the growth of biotite and was likely the source of uranium enrichment (Ullmer, 1983).

The host rock at the surface of the mine site consists of a brecciated quartz vein with moderate biotite and hornblende iron-staining and the occurrence of minor to moderate opaque minerals (Sample 20121004JC-D). The vein cuts an altered black magnetite- and biotite-rich pod (Sample 20121004JC-E). The pod is composed of quartz, magnetite, biotite, hornblende, andradite, and allanite. The iron-rich rock is strongly enriched in the LREE, moderately enriched in gadolinium and thorium, and weakly enriched in the remaining REE and yttrium. The brecciated quartz vein exhibits no significant enrichment of REE or other elements (table 10).

The presence of REE-enrichment at two locations on the lineament described by Ullmer (1983) is significant, and warrants further investigation along its length. In particular, the relationship between the three sampled rock types requires further study to fully characterize this deposit. Enrichment is variable within rock types and in the case of the iron-rich rocks, is apparently associated with hydrothermal activity.

Clarence Wood Lode Claims, SW¼SW¼ sec. 5, T. 29 N., R. 85 W., Southern Natrona County

A moderately radioactive, irregularly shaped epidosite (80 percent epidote) dike is present within Archean quartz monzonite in this vicinity (King and Harris, 2002). Griffin and Milton (1982) re-

Table 11. Concentration of the REE, niobium, uranium, and thorium in the epidosite within the Clarence Wood lode claim. Bold values indicate concentrations greater than five times crustal abundance.

Clarence Wood lode claims										
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121023WS-B	**571**	**944**	**98.6**	**330**	**57.2**	7.1	**33.2**	3.4	15.1	2.5

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	U (ppm)	Th (ppm)
20121023WS-B	5.3	0.62	2.9	0.45	7.7	66	**2145**	5	**182.5**	**64.4**

ported a sample analysis from this dike of 700 ppm La, 100 ppm Y, 200 ppm Zr, 114 ppm eU, and 70 ppm eTh. The epidosite sample (20121023WS-B) showed enrichment at greater than five times crustal abundance in all of the naturally occurring LREE and gadolinium, and weak to moderate enrichment in the remaining HREE, except for ytterbium (table 11). King and Harris (2002) noted that similar dikes are present in the surrounding areas in Carbon, Fremont, and Natrona counties.

Babbs Mine, SE¼ sec. 26, T. 27 N., R. 88 W., Northwestern Carbon County

The Babbs mine, also known as the Weidemeir mine or Cherry Creek prospect, is located near the crest of the Ferris Mountains (Wilson, 1955). It consisted of two adits, three open cuts, and multiple prospect pits that targeted mineralized quartz veins and silicified breccia within Precambrian granitic country rock (Hausel, 1997). The mine is reclaimed, but abundant cupriferous minerals remain in the dump piles. Malachite, chalcopyrite, azurite, and bornite mineralization occurs in quartz veins; disseminated pyrite and chalcopyrite occur within brecciated granite and granodiorite with a silicified matrix (Wilson, 1955; Hausel, 1997). One sulfide-bearing-quartz vein is hosted by a mafic dike (Hausel, 1997). Scheelite and allanite are also reported at the mine site (Wilson, 1955). Massive crystalline epidote with some iron staining, quartz, and jasper (Sample FM8112010-2) is present below the portal of one of the reclaimed adits and is strongly enriched in erbium, thulium, ytterbium, and lutetium (table 12).

REE at the Babbs mine are noteworthy, but the site also hosts significant silver and copper occurrences. A silicified, brecciated granite present at the Babbs mine (Sample Babbs-2) contains 28 ppm (0.82 oz/ton) silver, and 0.43 percent copper; a copper-stained quartz vein (Sample Babbs-1) contains 4 ppm (0.12 oz/ton) silver and greater than 1 percent copper.

Table 12. Concentration of the REE, gold, silver, and copper in the Precambrian rocks of the Babbs mine. Bold values indicate concentrations greater than five times crustal abundance for the REE, greater than 3.429 ppm (0.1 oz/ton) gold and silver, and greater than 0.1 percent copper.

Babbs mine										
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
FM8112010-2	3.1	5.58	0.74	3.8	1.92	1.33	3.83	0.98	9.54	3.14
Babbs-1	23.10	70.60	5.98	23.50	5.84	1.03	6.33	1.31	9.62	2.01
Babbs-2	7.10	7.80	1.74	7.30	1.98	0.42	2.34	0.48	3.62	0.82

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Au (ppm)	Ag (ppm)	Cu (ppm)
FM8112010-2	**16**	**3.71**	**37.5**	**7.06**	2.2	93.5	193.9	--	0.19	196
Babbs-1	6.50	1.13	7.47	1.10	**--**	50.10	215.6	0.78	**4.00**	**>10000**
Babbs-2	2.74	0.47	3.45	0.54	--	26.60	67.4	0.07	**28.00**	**4300**

Tertiary-aged Igneous Occurrences

Leucite Hills

The Leucite Hills in the Green River Basin make up one of the largest lamproite fields in the world (Hausel, 2006). Lamproites are ultrapotassic, mafic to ultramafic volcanic and subvolcanic rocks that can be extremely enriched in the LREE (Kuehner, 1980; Ogden, 1979). Notable REE occurrences in the Leucite Hills are located on Zirkel Mesa, Pilot Butte, and South Table Mountain (table 13). Detailed descriptions of the geology and geochemistry of the Leucite Hills are available in WSGS Report of Investigations 56 (Hausel, 2006).

Zirkel Mesa, NE¼NW¼ sec. 24, T. 22 N., R. 102 W., Northwestern Sweetwater County

Zirkel Mesa is the largest exposure of lamproite in the Leucite Hills, and is dominantly composed of orendite, a diopside-sanidine-phlogopite lamproite (Hausel, 2006). Wyomingite (diopside-leucite-phlogopite lamproite) from Zirkel Mesa (Sample ZM1-WY) is enriched in the LREE, europium, gadolinium, terbium, and dysprosium; lanthanum and cerium are enriched to greater than five times crustal abundance.

Pilot Butte, SE¼NE¼ sec. 10, T. 19 N., R. 106 W., Northwestern Sweetwater County

The Pilot Butte lamproite consists of a volcanic neck, a single lobate lava flow, and two associated small dikes exposed on the southwest flank of the butte. The volcanic and subvolcanic rocks on Pilot Butte are dominantly madupite (diopside-phlogopite-leucite lamproite) with Green River Formation xenoliths (Hausel, 2006). The Pilot Butte madupite (Sample PB1-95) is enriched in the LREE, europium, gadolinium, terbium, and dysprosium; La, Ce, Pr, Nd, and Sm are enriched to greater than five times crustal abundance.

South Table Mountain, SE¼SW¼ sec. 6, T. 22 N., R. 102 W., Northwestern Sweetwater County

South Table Mountain is composed of olivine orendite, and wyomingite. The olivine orendite (Sample STM-1-2010) is enriched in LREE, europium, gadolinium, and terbium; only cerium is enriched to greater than five times crustal abundance.

Sediment-hosted Occurrences

Important REE occurrences in Wyoming are hosted in a number of sedimentary environments. These include fossil beach placers (paleoplacers) within marginal marine sandstones, uranium- and phosphate-rich horizons in Eocene lacustrine deposits in southwestern Wyoming, and phosphorite beds in western Wyoming (King and Harris, 2002). Minor REE occurrences are also present within phosphate concretions in the Bighorn Basin and in alteration zones associated with reduction-oxidation fronts in central Wyoming.

Paleoplacers may host REE-bearing minerals, such as monazite, zircon, and apatite. The Cambrian Flathead Sandstone and the Cretaceous Mesaverde Formation are the most notable REE-bearing paleoplacers in Wyoming; minor paleoplacers are also found in the Cretaceous Frontier Formation (fig. 13). Quaternary alluvial deposits host placers

Table 13. Concentration of the REE, niobium, uranium, thorium and zircon in lamproites from the Leucite Hills. Bold values indicate concentrations greater than five times crustal abundance; scandium was not analyzed for these samples.

	Leucite Hills									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
ZM1-WY	**185.5**	**375**	41.2	150.5	19.75	4.35	13.85	1.49	4.6	0.66
PB1-95	**355**	**700**	**75.4**	267	**33.4**	7.02	23.7	2.23	6.18	0.86
STM-1-2010	151	**308**	34	121.5	15.9	3.48	11.45	1.22	3.87	0.55

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	U (ppm)	Th (ppm)	Zr (ppm)
ZM1-WY	2.05	0.17	1.08	0.15	18.1	818.5	57.4	4.45	21.2	**1400**
PB1-95	2.77	0.21	1.32	0.19	22.5	**1497.8**	**122**	8.98	**40.1**	**1160**
STM-1-2010	1.67	0.14	0.87	0.13	14.8	668.6	49.4	4.76	16.55	**1420**

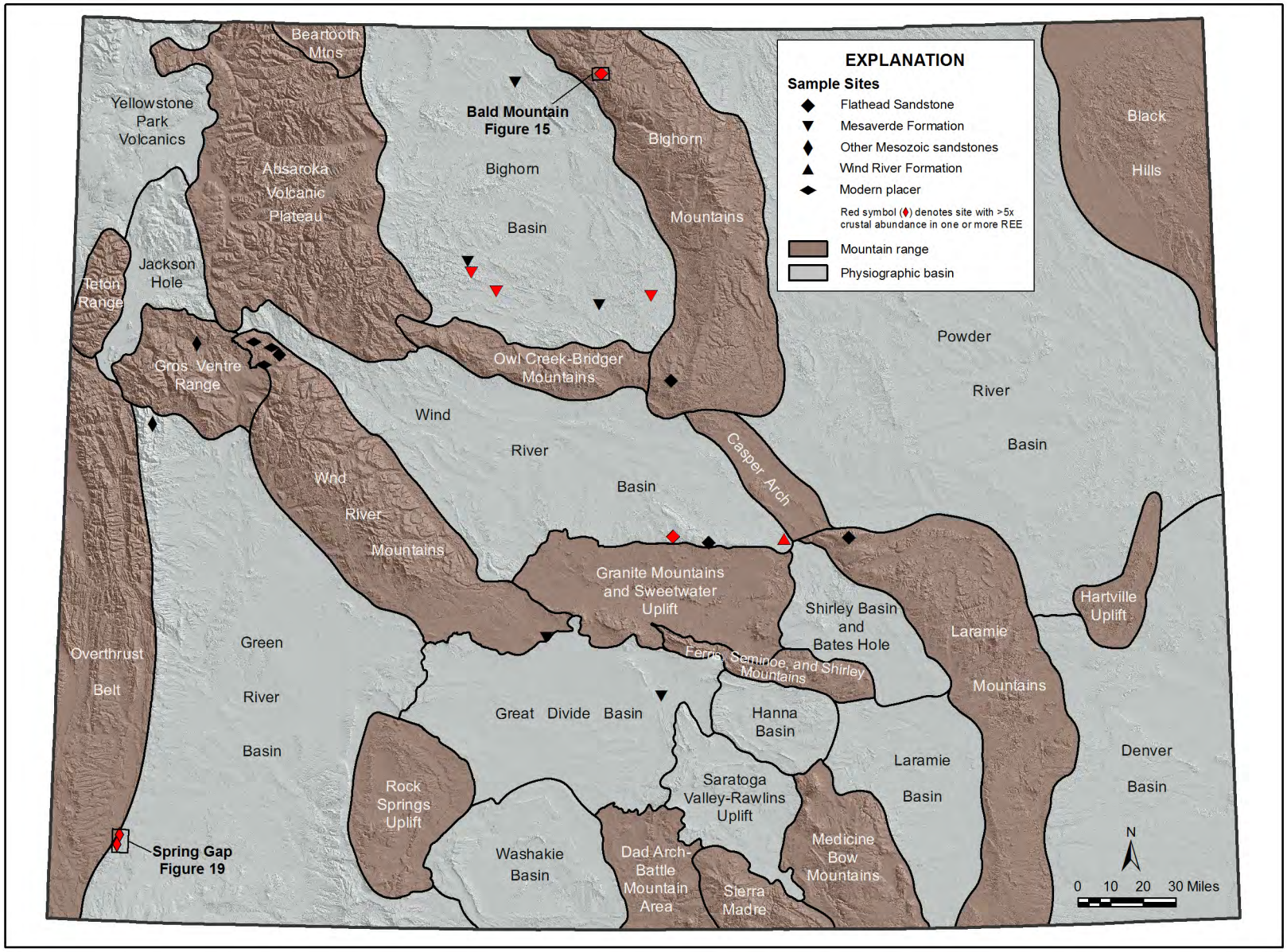

Figure 13. Location of paleoplacer, placer, and other sandstone-hosted samples included in this report. Sample sites with enrichment greater than five times crustal abundance in one or more REE are shown in red.

downstream from older REE mineral concentrations.

Flathead Sandstone Paleoplacers

The Middle Cambrian Flathead Sandstone, referred to by some early workers as the Deadwood Conglomerate, is the oldest sedimentary formation above the Precambrian in Wyoming and has a maximum thickness of about 170 m (560 ft) (Kanizay, 1978). Figure 13 shows the locations of WSGS samples collected from the Flathead Sandstone. The Flathead is dominantly quartz-rich, subangular, medium- to coarse-grained sandstone with large-scale cross-bedding. Non-quartz grains include abundant feldspar and crystalline lithic fragments typical of the underlying granite. Most of the formation is thin- to thick-bedded and well-cemented with a predominant reddish-brown color that grades to purple, rusty-orange, yellow, or gray. The sandstone is interrupted by thin layers of greenish-gray siltstone and shale, particularly in the upper part of the formation. The Flathead represents a fluvial-marine transition zone along a north-south oriented shoreline with braided stream deposits in the conglomeratic base of the formation (Middleton, 1980).

The basal conglomerate (fig. 14) varies from 6 to 15 m (20 to 50 ft) in thickness (McKinney and Horst, 1953). These braided stream deposits are quartz-rich, arkosic conglomerates with subangular to rounded clasts indicative of both a nearby source and a lack of reworking (Middleton, 1980). Clast sizes are up to 5 cm (2 in) in diameter with cementation varying from moderately silicic or limonitic to localized areas of quartzite.

Bald Mountain Paleoplacers, Big Horn and Sheridan Counties

The Bald Mountain area sits along the upper part of the west flank of the northwest-trending, northern Bighorn Mountains at elevations between 2,600 and 2,900 m (8,600 to 9,400 ft). This part of the Bighorn Mountains is an asymmetric, Laramide anticlinal uplift characterized by west-dipping monoclines. Near-horizontal to east-dipping exposures of Lower Paleozoic formations unconformably overlie medium- to coarse-grained, pink to gray, Archean plutonic rocks that generally vary from granitic to quartz dioritic in composition. The granitic rocks locally contain minor pegmatites and are cut by more than one generation of mafic dikes (Osterwald, 1959; Hausel, 1989). Mafic dikes in the Bald Mountain area were mapped as hornblende-diorite by Cardinal (1958).

Figure 14. Conglomerate of the lower Flathead Sandstone. A, outcrop of the basal conglomerate from which sample 20130824WS-D was collected. B, close-up of sample 20110824WS-D, conglomerate from the lower Flathead Sandstone.

Precambrian rocks in the Bald Mountain area are not known to host significant precious metal deposits. However gold paleoplacers within the Flathead conglomerates attracted attention around 1900. The town of Bald Mountain sprang to life for less than a year and then was abandoned when gold values proved insufficient to support commercial mining (McKinney and Horst, 1953; Hausel, 1989). The last gold operation in the area of any size was a mill and jig operation working in disintegrated sandstone and granite, about 3.2 km (2 mi) west of the Bald Mountain townsite in 1903 (McKinney and Horst, 1953). Paleoplacers in the Bald Mountain area occur in the basal part of the Middle Cambrian Flathead Sandstone, near its contact with Precambrian rocks.

Gold in the basal Flathead Sandstone in the Bald Mountain area occurs as fine-grained, flat flakes with jagged edges that suggest a nearby source. The paleoplacer gold is accompanied by other heavy minerals, including ilmenite, magnetite, zircon, and monazite. The monazite attracted interest as a source for thorium in 1951 (Wilson, 1951; McKinney and Horst, 1953; Hausel, 1989; King and Harris, 2002). Heavy mineral concentrates from some of the higher grade samples contained 38.3 percent ilmenite, 8.7 percent monazite, 4.0 percent magnetite, 0.2 percent zircon, and 48.8 percent other impurities (McKinney and Horst, 1953).

Monazite occurs as reddish-brown grains, up to a few millimeters across, within a limonitic matrix of the basal quartz pebble conglomerate. The dense sandstones overlying the basal conglomerate also host notable monazite, but at much lower concentrations than the basal conglomerate (Wilson, 1951). The entire Flathead Sandstone contains some monazite, but significant concentrations are limited to the lower part. Monazite concentrations within the basal Flathead are highly variable laterally, ranging from trace amounts of scattered grains to more than 9.5 kg/tonne (19 lbs/ton). Greater amounts of monazite are generally associated with poorly cemented areas, an abundance of large quartz pebbles, and with a deep yellowish-red color resulting from the strong presence of hematite or limonite (McKinney and Horst, 1953).

The USBM drilled 92 exploration holes in 1952 to test the monazite-bearing conglomerates (fig. 15). Drilling totaled 615.7 m (2,020 ft) from which 24,140 kg (53,214 lbs) of samples were collected for analyses. Depth of drilling was limited by the underlying Precambrian basement. The deepest hole was 14.8 m (48.5 ft), but the average depth was only 6.7 m (22 ft). Some holes were essentially barren, but numerous holes in the area east of Rooster Hill encountered higher-grade, monazite-enriched zones at more than one horizon, with apparent gradations between them. This reinforced the concept of a three-dimensional braided stream depositional environment.

From drilling, the USBM estimated a resource of 18 million tonnes (20 million tons) that averaged 1.25 kg/tonne (2.5 lbs/ton) of monazite (McKinney and Horst, 1953; Borrowman and Rosenbaum, 1962). A high-grade zone was estimated to contain 612,000 tonnes (675,000 tons) of conglomerate that averaged 6.6 kg/tonne (13.2 lbs/ton) of monazite (Borrowman and Rosenbaum, 1962). The average chemical assay value for pure monazite showed 8.8 percent ThO_2 and 0.12 percent U_3O_8. Gold assays taken from six drill holes in the high-grade monazite area varied from 0.034 to 0.172 ppm (0.001 to 0.005 oz/ton), and averaged 0.103 ppm (0.003 oz/ton) (McKinney and Horst, 1953; Hausel, 1989). Ilmenite, which accounted for as much as 38.3 percent of concentrates from higher-grade portions of the deposit, was suggested by Wilson (1951) and by McKinney and Horst (1953) as providing additional economic potential for the paleoplacers.

Although no analyses were noted for REE in any of the early reports, McKinney and Horst (1953, p. 30) stated that economic conditions at the time "based solely on the rare-earth content of monazite would not allow a commercial stripping operation, such an operation could rapidly produce a significant amount of monazite and, therefore, thorium. It is believed that this deposit could be of definite strategic value." They later mentioned on page 41 that the market price for monazite, at the time their report was written, "…was approximately $375.00 per ton and based solely on the rare-earth

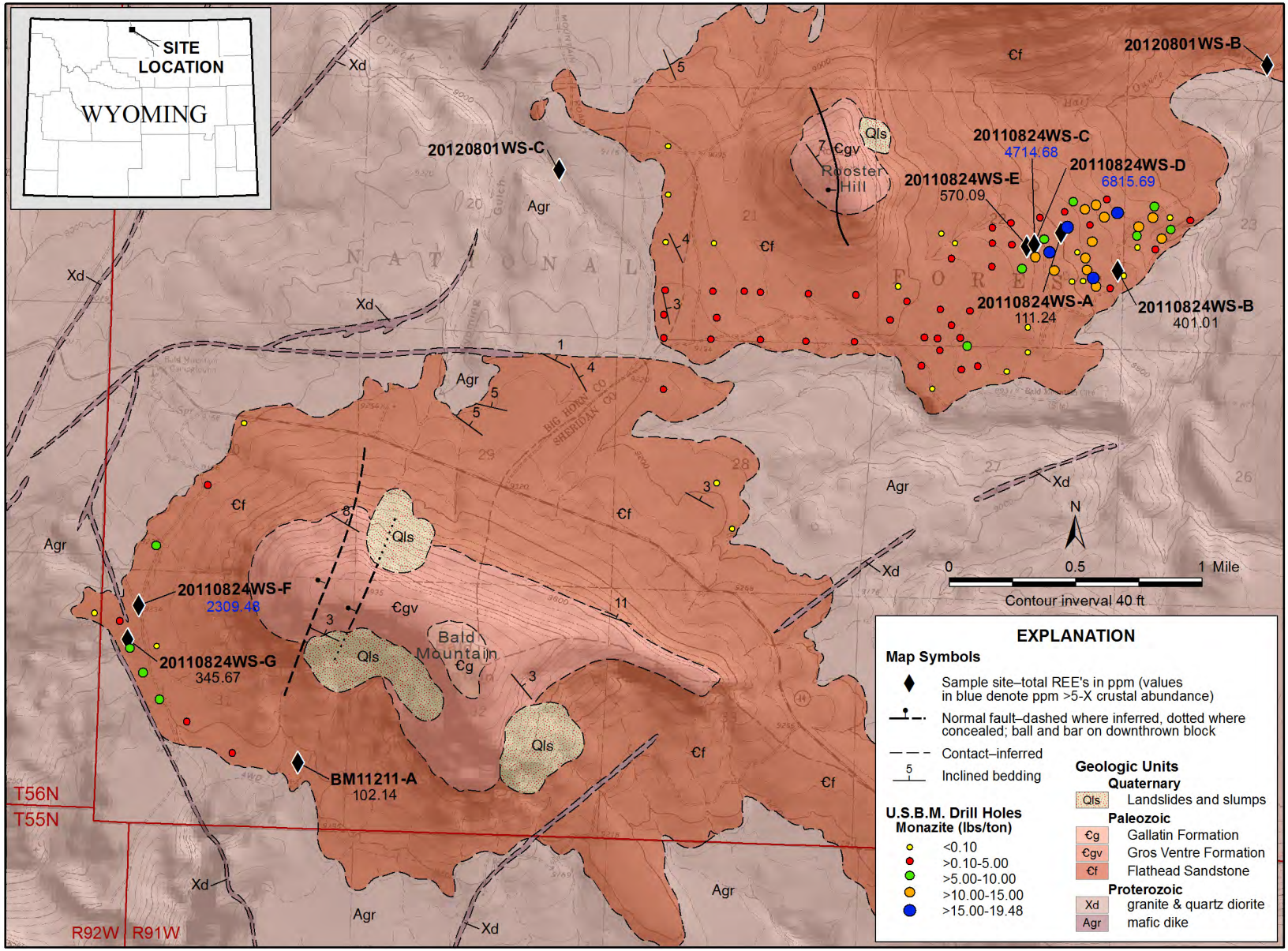

Figure 15. Locations of 1952 USBM drill holes and WSGS Bald Mountain and Rooster Hill samples. Drill data shows maximum grades in pounds of monazite per ton, after McKinney and Horst, 1953. WSGS samples show total REE in ppm. Blue numbers indicate greater than five times average crustal ppm values. Geology modified from Cardinal (1958) and Love and Christiansen (1985).

content of that mineral." Apparently the USBM and AEC were also concerned with the availability of REE in 1953 in addition to thorium.

No published analyses for REE are known for the Bald Mountain area prior to WSGS investigations. However, assuming typical values for monazite concentrates of about 61 percent REO (Long, Van Gosen, Foley, and Cordier, 2010), the average for the estimated Bald Mountain paleoplacer resource as reported by McKinney and Horst (1953) would be 0.7630 kg REO/tonne (1.525 lbs REO/ton) or 0.076 percent REO. The high-grade paleoplacer material would be around 4.02 kg REO/tonne (8.05 lbs REO/ton) or 0.40 percent REO.

King and Harris (2002) argue that the resource interpretations for the paleoplacers in the Bald Mountain area were made with the assumption of a relatively uniform, sheet-like zone of monazite enrichment in the lower Flathead beach deposits. However, the more erratic braided stream depositional environment, now believed to host most of the monazite, suggests that these numbers may be less accurate than originally believed (King and Harris, 2002). The weakly indurated character of this paleoplacer may have some economic advantage over hard rock deposits with similar REE grades. Thin overburden and the potential for easy disaggregation and gravity concentration of high-grade material prior to shipping should be considered in any evaluation.

In 2011, five samples were collected by the WSGS from east of Rooster Hill and three from the west end of Bald Mountain. Samples 20110824WS-C, 20110824WS-D, and 20110824WS-F showed significant REE with total REE contents of 4,714.68 ppm, 6,815.69 ppm, and 2,309 ppm respectively (table 14). These samples were high in most LREE and showed elevated values for HREE and yttrium. They were also significantly high in thorium, and

Table 14. Concentration of the REE, tantalum, uranium, and thorium in the Flathead Sandstone paleoplacers and one Precambrian mafic dike in the Bald Mountain area. Bold values indicate concentrations greater than five times crustal abundance.

	Bald Mountain									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20110824WS-A	27.5	49.8	4.9	15.7	2.2	0.4	1.4	0.2	1.0	0.2
20110824WS-B	94.7	169.5	18.1	61.5	9.6	4.1	7.2	0.9	4.2	0.8
20110824WS-C	**1220.0**	**2230.0**	**220.0**	**695.0**	**103.5**	4.6	**62.0**	**6.6**	27.9	4.6
20110824WS-D	**1790.0**	**3190.0**	**329.0**	**1045.0**	**150.0**	5.0	**77.6**	**7.8**	**36.2**	5.3
20110824WS-E	145.5	260.0	27.0	87.6	12.8	0.8	6.7	0.7	3.9	0.6
20110824WS-F	613.0	**1090.0**	**109.5**	**360.0**	**48.3**	1.7	24.1	2.4	10.6	1.5
20110824WS-G	89.6	159.0	16.0	53.0	7.3	0.7	4.0	0.4	2.2	0.3
BM11211-A	21.6	43.7	4.3	15.2	2.4	0.5	1.6	0.2	1.3	0.3

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Ta (ppm)	U (ppm)	Th (ppm)
20110824WS-A	0.6	0.1	0.6	0.1	0.8	6.0	111.2	0.3	1.5	17.2
20110824WS-B	1.9	0.3	1.4	0.2	7.9	18.8	401.0	0.4	0.5	3.7
20110824WS-C	10.3	1.4	7.3	1.1	4.0	116.5	**4715**	**13.9**	**15.3**	**780.0**
20110824WS-D	11.9	1.3	8.0	1.1	4.1	**153.5**	**6816**	8.0	**19.5**	**1110.0**
20110824WS-E	1.6	0.2	1.3	0.2	1.5	19.7	570.1	0.7	3.8	**101.0**
20110824WS-F	3.2	0.3	1.8	0.3	1.9	40.9	**2309**	2.3	6.0	**380.0**
20110824WS-G	0.8	0.1	0.7	0.1	2.1	9.5	345.7	0.3	6.6	**46.2**
BM11211-A	0.8	0.1	0.9	0.2	1.6	7.6	102.1	0.2	1.9	10.8

samples 20110824WS-C and 20110824WS-D were high in uranium. Some of the other samples showed slightly elevated LREE values, but they did not exceed five times average crustal abundances. WSGS sampling demonstrated the presence of significant REE concentrations, particularly the LREE, associated with thorium-bearing monazite investigated by the USBM/AEC in 1952.

Sample 20110824WS-A is an iron-stained and partially white-banded, cross-bedded, coarse-grained, arkosic sandstone and conglomerate representative of the bottom of the Flathead in what appears to be a paleochannel cut between low outcrops of Precambrian granite and a mafic dike. Only thorium within this sample was slightly elevated.

Sample 20110824WS-C is a poorly cemented, limonitic layer in the basal Flathead Sandstone, collected an unknown distance above the contact with Precambrian crystalline rocks. The sample was collected just below a coarse conglomeratic layer exposed in the west side of an old north-trending exploration trench about 6 m (20 ft) deep. LREE values were significant in this sample and HREE and yttrium values were also elevated.

Sample 20110824WS-D was collected near the east side of the same trench as Sample 20110824WS-C and about 18 m (60 ft) further south. It is a coarse, limonitic, quartz pebble conglomerate (fig. 14) representative of the layer above sample 20110824WS-C. It showed the greatest concentration of REE and thorium of any sample taken in the area. HREE and yttrium values were also elevated in this sample.

Sample 20110824WS-E is a purple, iron-rich sandstone and conglomerate collected about 6 m (20 ft) higher in the Flathead than sample 20110824WS-D, and at the west end of an east-trending trench, west of the trench from which samples 20110824WS-C and 20110824WS-D were collected. This sample hosted elevated LREE values, but none exceeded five times average crustal values. Thorium, however, was notably higher at more than 15 times average crustal values.

Sample, BM11211-A, taken from the middle part of the Flathead on the lower southwestern slope of Bald Mountain showed no anomalous REE, but had slightly elevated thorium values.

Sample 20110824WS-F was collected from the east end of an old exploration trench, about 43 m long by 8 m wide by 4 m deep (140 x 25 x 12 ft). The basal Flathead exposed in this trench is a heavily iron-stained, partly limonitic, coarse sandstone to conglomerate with some very angular clasts. Common, non-magnetic, rounded black pebbles, up to 1.27 cm (0.5 in) diameter, found here crushed easily to a limonite-brown powder, which x-ray diffraction showed to be goethite [$Fe_3(OH)$]. The raw sample contained 2,309 ppm REE, more than 10 times background crustal values. This would be an estimated TREO of about 0.27 percent. The sample was particularly enriched in La, Ce, Pr, Nd, and Sm. Although not as high, values for Eu, Gd, Tb, Dy, and Ho are elevated as well. The sample also contained more than 65 times average crustal abundance of thorium.

Sample 20110824WS-G was collected from excavated material near the center of a 70 m long by 1.2 m wide by 1.2 m deep (230 ft x 4 ft x 4 ft) trench. The sample comprised iron-stained and limonitic sandstone and conglomerate from the lower part of the Flathead. It contained nine times average crustal abundance of thorium, but did not show REE significantly above background crustal values (table 14, p. 41).

Sample 20110824WS-B is from a Precambrian mafic dike in brecciated and rehealed contact with the surrounding granitic rocks. The dike protrudes through part of the lower Flathead. The sample showed slightly elevated LREE values in the dike, which may have contributed to the later Cambrian paleoplacers.

Quaternary alluvial placers in drainages flowing away from the Bald Mountain area are reported to host higher gold values than those found in the Flathead (Hausel, 1989), probably due to further concentration of the paleoplacers. These placers are also reported to host monazite (Wilson, 1951;

King and Harris, 2002), but no historical estimates are known for the monazite concentrations in these modern placers.

Two placer samples were collected from Quaternary alluvium to test for the presence of REE. Sample 20120801WS-B came from Half Ounce Creek, northeast of Rooster Hill, and sample 20120801WS-C was taken from upper Porcupine Creek, northwest of Rooster Hill. Although the concentrates showed cumulative REE of 5,489 ppm and 6,433 ppm respectively, the unconcentrated cumulative REE values were about 46 ppm for Sample 20120801WS-B, and 8 ppm for sample 20120801WS-C.

Rattlesnake Hills

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

The Flathead Sandstone crops out at this locality in the Rattlesnake Hills; the lower Flathead here exhibits REE-enrichment. Tan to pink conglomerate near the base of the Flathead (Sample 20110429BG-A) is enriched above five times crustal abundance in lanthanum and cerium, and weakly to moderately enriched in the rest of the LREE, gadolinium, terbium, dysprosium, and holmium. Five feet above the base of the Flathead is a red conglomerate (Sample 20120429BG-B) that is enriched to greater than five times crustal abundance in the LREE, and weakly to moderately enriched in the HREE and yttrium. Immediately overlying the red conglomerate is dark purple conglomerate (Sample 20120429BG-C) that is enriched in the LREE, gadolinium, terbium, dysprosium, and holmium; lanthanum, cerium, praseodymium, and neodymium are enriched to greater than five times crustal abundances (table 15).

Eastern Rattlesnake Hills, SW¼, T. 32 N., R. 86 W. and SE¼ T. 32 N., R. 87W., Southwestern Natrona County

Flathead Sandstone also outcrops in the eastern Rattlesnake Hills. The upper part of the Flathead in the eastern Rattlesnake Hills is resistant, buff to red sandstone that is locally cemented with hematite and may contain up to a few percent glauconite. A middle nonresistant siltstone separates the upper part of the formation from the lower part, which is a resistant, locally silicified, arkosic pebble conglomeratic, with interbedded sandstone at the bottom (Pekarek, 1977). A sample of quartz-rich, iron-stained Flathead Sandstone from the SW¼NE¼ sec. 29, T. 32 N., R. 86 W. (Sample SR7-30-10-A) is not significantly enriched in any elements of economic interest.

Union Pass – Warm Spring Area, Northwestern Fremont County

Sites with Precambrian REE enrichment are found in the Union Pass – Warm Spring Area (fig. 10; see p. 35). These sites were thought to have potential for paleoplacers in the Flathead, similar to those in the Bald Mountain area in the Bighorn Mountains.

Table 15. Concentration of REE, uranium, thorium and zircon in the Flathead Sandstone along the west side of the Rattlesnake Hills. Bold values indicate concentrations greater than five times crustal abundance.

	Flathead Sandstone, Western Rattle Snake Hills									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20110429BG-A	**165**	**333**	38.1	145	22.6	1.02	13.5	1.62	7.7	1.22
20110429BG-B	**255**	**525**	**59.9**	**229**	**36.5**	1.5	19.75	2.45	11.7	1.82
20110429BG-C	**195**	**395**	**45**	**170**	27.2	1.18	14.8	1.79	8.3	1.28

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	U (ppm)	Th (ppm)	Zr (ppm)
20110429BG-A	2.95	0.39	2.51	0.41	2.6	33.8	771.4	7.93	**125.00**	**904.00**
20110429BG-B	4.18	0.56	3.45	0.57	4.0	50.9	**1206**	**9.51**	**186.50**	**1490.00**
20110429BG-C	2.87	0.39	2.35	0.4	2.7	36.3	904.6	**14.05**	**140.50**	**1120.00**

Samples of the Flathead were collected in the area and analyzed for REE (Samples 20110920WS-A, 20121004JC-C). No elevated values for REE, thorium, or uranium were detected for sample 20121004JC-C. Sample 20110920WS-A was only slightly elevated in thorium, but not in REE.

Placer deposits along Warm Spring Creek, also known as the Clarks Camp-Union Pass gold placers, include monazite-bearing gravels. These gravels are reported to extend 4.8 km (3 mi) up the South Fork (Wilson, 1960; Bolmer and Biggs, 1965; Osterwald and others, 1966; Rohrer, 1968; Hausel, 1989). Rohrer (1968) noted that claims for REE covered the monazite-bearing gravels. The monazite-bearing gravel deposits along Warm Spring Creek range from 0.4 to 1 km (0.25 to 0.6 mi) wide, extend for about 4.8 km (3 mi) in length, and include high terraces more than 30 m (100 ft) above the stream bottom (Hausel, 1989).

The area was mapped by Rohrer in 1968, at which time he sampled and mapped quartzite conglomerate layers in the Wind River Formation containing flour gold within a matrix of fine- to coarse-grained angular quartzite and tuffaceous sandstone. These conglomerate layers, dominated by percussion-marked pebble- to small cobble-sized quartzite round-stones, represent four, 1.6 to 3.2 km (1 to 2 mi) wide, eastward-trending channels. Rohrer (1968) cited gold values (less than 0.009 to 1.777 g/cy (0.0003 to 0.06268 oz/cy as interpreted from 1966 gold value of $35/oz) from the conglomerates as sampled by J.C. Antweiler, but made no mention of monazite or other REE-bearing minerals within them. Rohrer (1968) stated that these auriferous deposits are derived from similar deposits in the Pinyon Conglomerate (occurring about 13 km (8 mi) to the west) which, Love (1973) believed to have originated in the hypothetical, now vanished, Laramide (Late Cretaceous to Paleocene) Targhee uplift west of Jackson Hole.

Modern stream placers at four locations along Warm Spring Creek and the South Fork of Warm Spring Creek were sampled by the WSGS in 2010 and 2011. Monazite and xenotime grains identified in pan samples were generally angular to sub-rounded, suggesting a relatively local source, rather than being reworked from a secondary source in the quartz cobble-rich conglomerates in the Wind River Formation or the Pinyon Conglomerate to the west. Precambrian igneous rocks south of the Quaternary placers are the probable source of the monazite and xenotime.

Although analyses of placer concentrates showed high cumulative REE values, the calculated values for unconcentrated bank cubic yards (BCY) of placer material were all less than crustal abundances. Sample WSC-91510-A showed calculated total REE at 37.28 g/BCY (1.32 oz/BCY), or about 27 ppm, with gold content calculated at 25.3 mg/BCY (0.0009 oz/BCY). See figure 16 for typical monazite and gold flake from Warm Spring Creek. Sample WSC-91510-B showed calculated total REE at 3.84 g/BCY (0.136 oz/BCY), or about 3 ppm, with gold content calculated at 1.9 mg/BCY (0.00007 oz/BCY). Sample WSC-91510-C showed calculated total REE at 51.92 g/BCY (1.83 oz/BCY), or about 37 ppm, with gold content calculated at 2.9 mg/BCY (0.0001 oz/BCY). Sample 20110921WS-B showed calculated total REE at 32.5 g/BCY (1.146 oz/BCY), or about 23 ppm, with no gold.

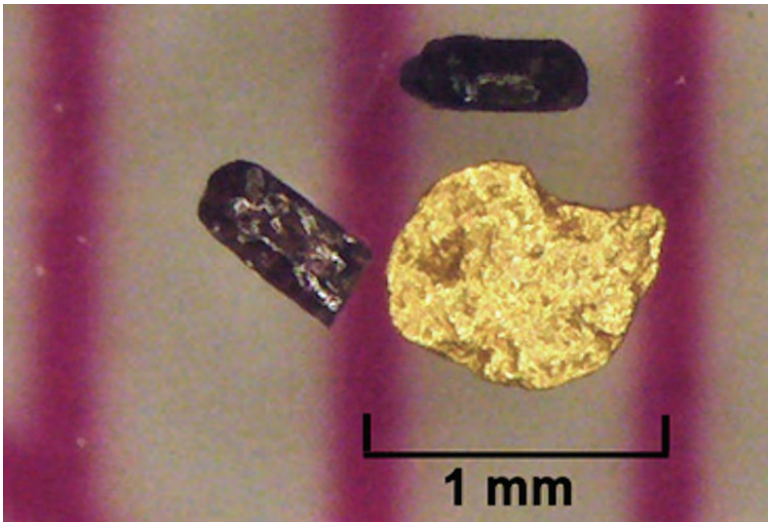

Figure 16. Gold flake and monazite grains from sample WSC-91510-A concentrate.

Oakie Trail, S½NE¼ sec. 15, T. 40 N., R. 88 W., Northwestern Natrona County
The Flathead Sandstone in this area contains up to 134 ppm thorium, but less than 5 ppm uranium, and is likely a typical Flathead Sandstone paleoplacer (Malan, 1972). The Flathead here consists of white to red, quartz pebble conglomerate and medium- to coarse-grained, poorly sorted, subrounded, iron-rich subarkose, with coarse weathered limonite grains (Sample 20121017JC-E). In places where the Flathead Sandstone is weakly brecciated (Sample 20121017JC-F), no elevated REE or thorium values were detected.

Mesaverde Formation Paleoplacers

Titaniferous black sandstone horizons are relatively common in the lower part of the Late Cretaceous Mesaverde Formation across Wyoming, Colorado, and New Mexico, and in the Mesaverde Group in Arizona (Houston and Murphy, 1962; 1970). The Wyoming deposits (fig. 13) occur at the top of the formation's basal sandstone (Houston and Murphy, 1962). The hosting basal sandstone of the Mesaverde is typically a tan to buff, fine-grained sandstone overlain by a succession of interbedded sandstone, shale, carbonaceous shale, and coal or, in some areas, by black shale. The Mesaverde Formation is underlain by black shale of the Cretaceous Cody Shale. Together, the Cody and the Mesaverde represent a generally regressive sequence that transitioned from a deep marine to near-shore terrestrial environment over the depositional history of the two units. The black shale that in places overlies the basal sandstone of the Mesaverde represents a short-lived transgressive event (Houston and Murphy, 1962). Titaniferous black sandstones at or near the top of the basal sandstone are thought to be fossil beach placers analogous to modern heavy mineral-rich black sand beaches found in Australia (Houston and Murphy, 1962; 1970).

The heavy minerals within the titaniferous black sandstones of the Mesaverde Formation (fig. 17) were studied in detail by Houston and Murphy (1962; 1970) and are dominantly volcanic in origin. The heavy mineral fraction of the black sandstone consists of 79 to 97 percent opaque minerals, mostly iron-titanium oxides, but a radioactive niobium-bearing mineral may also be present. The remaining heavy mineral fraction is composed of varying amounts of zircon, monazite, garnet, rutile,

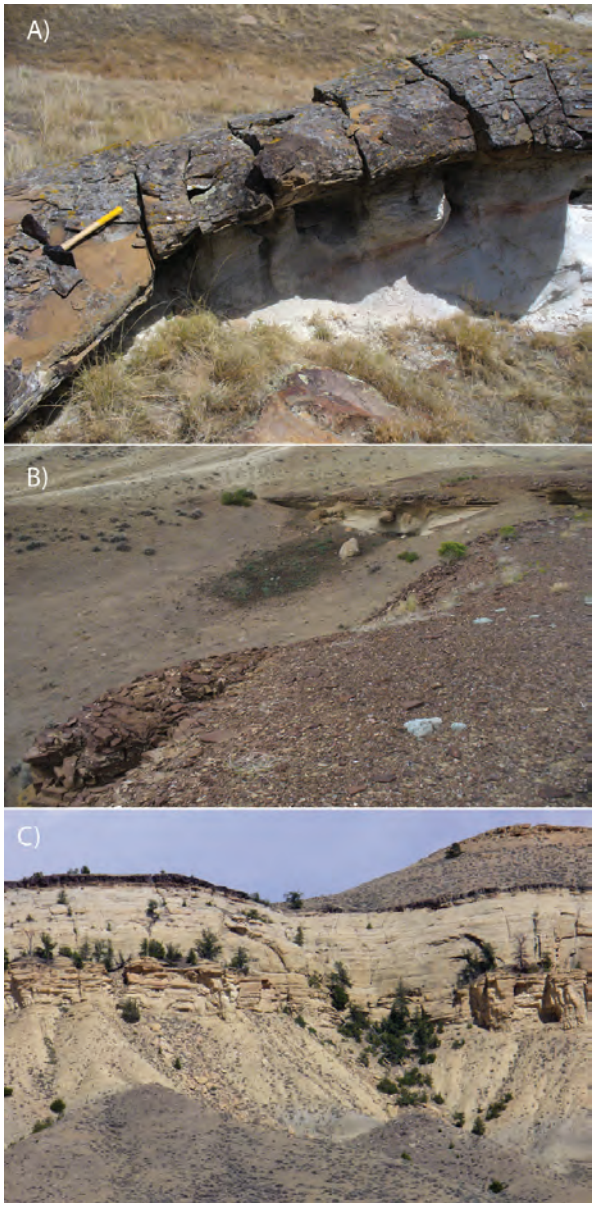

Figure 17. Outcrops of titaniferous black sandstone within the Cretaceous Mesaverde Formation. A, outcrop at Mud Creek, black sandstone overlies tan to buff sandstone of the lower Mesaverde, view is to the northeast. B, outcrop at Dugout Creek, black sandstone overlies tan to buff sandstone of the lower Mesaverde, view is to the northwest. C, outcrop at Grass Creek, north deposit, black sandstone is at the top of the cliff, view is to the northeast.

tourmaline, amphibole, spinel, sphene, epidote, biotite, chlorite, staurolite, and apatite. Zircon and garnet are the most abundant of the translucent heavy minerals (Houston and Murphy, 1962). Analyses of samples collected by the WSGS from the Mesaverde Formation in Wyoming are presented in table 16.

Separation Rim, SE¼NW¼ sec. 22, T. 24 N., R. 89 W., Northwestern Carbon County

A black to dark brown, fine-grained, iron-stained sandstone crops out along the ridge of a Mesaverde Formation hogback in the Separation Rim quadrangle. A sample of this black sandstone (Sample 20120730WS-A) exhibits no enrichment of REE or any other element of economic interest. This black sandstone had not been previously investigated.

Table 16. Concentration of the REE, niobium, zircon, and TiO_2 in the Mesaverde Formation paleoplacers. Bold values indicate concentrations greater than five times crustal abundance.

	Mesaverde Paleoplacers									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20120730WS-A	13.4	23.4	3.21	12.4	2.59	0.66	3.23	0.54	3.22	0.66
20120731WS-A	17.7	29.2	3.7	13.5	2.49	0.55	2.26	0.35	2.13	0.45
20120731WS-B	18.5	30.7	3.95	14.4	2.53	0.55	2.18	0.34	2	0.42
20120731WS-C	**597**	**972**	**108**	**350**	**46.8**	5.64	**29.6**	4.07	22.1	4.42
20120731WS-F	27.3	43.4	4.95	17.2	3.04	0.6	2.67	0.43	2.55	0.54
20120731WS-G	27	47.4	5.86	22.1	4.29	0.9	4.14	0.68	4.16	0.9
20120731WS-H	**408**	**669**	**74.9**	**247**	**35.2**	3.44	23.7	3.53	20.4	4.25
20120801WS-A	87.6	142.5	16.05	52.7	7.57	1	5.21	0.73	4.03	0.84
20120917WS-E	10.6	20.6	2.4	8.6	1.75	0.44	2.37	0.43	3.1	0.73
20120917WS-F	11.5	23.7	2.77	10.2	2.04	0.43	1.92	0.29	1.86	0.41
WMS-GC1-2010	**850**	**1505**	**169.5**	**551**	**80.3**	6.67	**76.8**	**10.35**	**55.8**	**12.5**
WMS-GC2-2010	21.9	39.4	4.5	15.2	2.6	0.37	2.41	0.32	1.61	0.33

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	Zr (ppm)	TiO_2 (%)
20120730WS-A	1.81	0.25	1.46	0.24	2	23.9	93.0	2.3	114	0.1
20120731WS-A	1.33	0.2	1.32	0.22	5	14.6	95.0	4.7	115	0.19
20120731WS-B	1.24	0.18	1.23	0.2	3	13.2	94.6	5.1	212	0.2
20120731WS-C	12.85	1.98	13.95	2.42	15	129.5	**2315.3**	65.3	**4010**	**5.51**
20120731WS-F	1.59	0.25	1.62	0.28	4	16	126.4	8.3	366	0.31
20120731WS-G	2.66	0.38	2.53	0.41	8	27.8	159.2	9.7	281	0.37
20120731WS-H	12.9	2.12	**14.95**	2.7	31	121.5	**1675**	**170.5**	**7240**	12
20120801WS-A	2.46	0.39	2.62	0.44	16	23.8	363.9	35.2	**755**	3.18
20120917WS-E	2.27	0.31	1.87	0.28	4	27.1	86.9	3.3	178	0.15
20120917WS-F	1.22	0.19	1.26	0.19	4	12.8	74.8	4.2	172	0.18
WMS-GC1-2010	**42.8**	**6.93**	**50.9**	**8.99**	43.3	**331**	**3802**	**345**	**10000**	[a]**>10.0**
WMS-GC2-2010	0.99	0.12	0.97	0.16	2	9.2	102.1	6.6	192	[a]0.116

[a]Analyzed for %Ti

Cottonwood Creek, SE¼SE¼ sec. 26 and NE¼NE¼ sec 35, T. 45 N., R. 97 W., Northern Hot Springs County

The titaniferous black sandstone in the Mesaverde Formation at Cottonwood Creek is a dark brown to black and rusty-brown, fine- to medium-grained, cross-bedded sandstone in discontinuous outcrops. Detailed descriptions and analyses of the deposit are found in Houston and Murphy (1962). King and Harris (2002) summarize those findings and include information from more recent studies. The maximum thickness of the black sandstone is reported to be 9 feet, with zircon accounting for 18.5 percent of the heavy mineral fraction, and monazite making up 1.0 percent. Madsen (1978) reported that one sample from this deposit contained 1,687 ppm lanthanum.

Sample 20120731WS-C, of this study, is enriched in all of the REE, as well as yttrium and niobium. La, Ce, Pr, Nd, Sm, and Gd within this black sandstone (fig. 18) are enriched to greater than five times crustal abundances. Several dark brown, iron-rich, fine- to medium-grained, lenticular sandstone bodies are also present in this area. However, two samples (20120731WS-A and 20120731WS-B) showed no significant enrichment in any of the REE or titanium.

Figure 18. Sample 20120731WS-C, dark-brown heavy sand in the Mesaverde Formation at Cottonwood Creek.

Grass Creek, E½SE¼ sec. 8, SW¼SW¼ sec. 9, NW¼NW¼ sec. 16 (North Deposit); and S½NE¼ sec. 33, S½NW¼ sec. 34 (South Deposit), T. 46 N., R. 98 W., Northern Hot Springs County

The Grass Creek area is reported by Houston and Murphy (1962) to host the largest known titaniferous black sandstone deposit in Wyoming. It is exposed in two outcrops, 4.4 km (2.75 mi) apart, on the northeast and south flanks of the Grass Creek anticline in Hot Springs County. Like many other black sandstone deposits in the Mesaverde Formation, the Grass Creek black sandstone is hosted near the top of the basal sandstone of the Mesaverde Formation. However, this deposit differs from other Mesaverde black sandstones in that it is not overlain by marine sediments (Houston and Murphy, 1962).

In the northern exposure, the black sandstone has a maximum width of about 207 m (680 ft), a maximum thickness of about 5 m (16 ft), and an average thickness close to 3.4 m (11 ft). Bedding in the northern outcrop strikes 315°, with a 15° NE dip. The southern outcrop strikes 100° and dips 30° to 35° S along the south flank of the anticline. The black sandstone of the southern outcrop is poorly and sporadically exposed, but can be traced for more than 488 m (1,600 ft) and its maximum thickness is at least 1.5 m (5 ft) (Houston and Murphy, 1962).

A fine-grained, black to red, opaque, mineral-rich sandstone (Sample WMS-GC1-2010), taken from the southern Grass Creek outcrop, is enriched to greater than five times crustal abundance in all of the naturally occurring REE, except for europium; yttrium and niobium are also present at significant levels of enrichment. A red to orange, botryoidal-appearing sandstone (Sample WMS-GC2-2010), collected from the northern outcrop, exhibits no significant enrichment of REE or other elements of economic interest.

Mud Creek, NW¼NE¼ sec. 19, T. 44 N., R. 91 W., Washakie County

The black sands in the Mesaverde Formation just north of Mud Creek were described by Houston and Murphy (1962), with some details added by King and Harris (2002). The titaniferous black sandstone occurs in the uppermost part of the basal sandstone of the Mesaverde and has a maximum thickness of 2.3 m (7.5 ft) and an exposure width of about 460 m (1,500 ft). Houston and Murphy (1962) reported that the heavy mineral suite contains 5 percent zircon. Another sample, collected by Madsen (1978), contained 500 ppm lanthanum.

Recent samples collected from the upper part of the Mesaverde outcrop, about 0.5 km (0.3 mi) northeast of the 1962 and 1978 samples, showed no REE enrichment. These apparently were stratigraphically higher in the formation than the titaniferous black sandstone described by Houston and Murphy (1962). Sample 20120731WS-G is a dark brown, fine- to medium-grained, iron-rich, discontinuous sandstone about 0.9 m (3 ft) thick. Its dark color is mostly due to surface coatings. This iron-rich sandstone is overlain by a thick, white, cross-bedded sandstone near the top of the Mesaverde Formation (Sample 20120731WS-F) that also showed no REE enrichment.

Dugout Creek, NE¼SW¼ sec. 11, T. 44 N., R. 89 W., Eastern Washakie County

The titaniferous black sandstone in the Dugout Creek deposit is in the upper part of the basal Mesaverde Formation and is radioactive in some outcrops. The black sandstone crops out across several sections and its thickness varies from about 0.9 to 7.6 m (3 to 25 ft), but averages 3.0 to 4.6 m (10 to 15 ft) (Houston and Murphy, 1962). This is the most extensive exposure of Mesaverde black sandstone in Wyoming.

Zircon makes up 5 percent of the total heavy mineral content of the black sandstone here and monazite accounts for 1 percent. Uranium content reportedly varies from 0.001 to 0.021 percent eU, depending on which earlier investigation is cited (King and Harris, 2002). Madsen (1978) reported one sample that contained 312 ppm lanthanum.

A recent WSGS sample from this location (Sample 20120731WS-H) consists of fine- to medium-grained, dark-brown to purple and orange, cross-bedded sandstone about 0.9 m (3 ft) thick that overlies a yellowish brown sandstone. The dark-brown sandstone outcrop is about 0.40 km (0.25 mi) in length at this locality. A similar layer is noted about 1.6 km (1 mi) to the north and appears to be continuous for 0.4 to 0.8 km (0.25 to 0.5 mi). Several prospect pits are found near the sample site. Sample 20120731WS-H is 12 percent TiO_2 and slightly enriched in scandium, yttrium, niobium, and all of the REE except dysprosium and holmium. The LREE, ytterbium, and niobium are enriched to greater than five times crustal abundances.

Lovell, secs. 7 and 12, T. 55 N., R. 95 W., Northwestern Big Horn County

This slightly radioactive, titaniferous, black sandstone deposit averages 0.9 m (3 ft) thick, with a maximum thickness of 1.2 m (4 ft). The outcrop extends along an 11° SW dipping hogback for 914 to 1,524 m (3,000 to 5,000 ft) (King and Harris, 2002). Houston and Murphy (1962) reported zircon in the heavy mineral fraction, but no monazite. A sample from this deposit by Garrand and others (1982) showed 50 ppm lanthanum, greater than 20 ppm niobium, 40 ppm yttrium, 200 ppm zircon, and 8 ppm cU_3O_8 (20 ppm eU_3O_8). Madsen (1978) reported 316 ppm lanthanum in a sample from this deposit.

A recent WSGS sample (20120801WS-A) from the Lovell deposit represents a dark brown to purple, thin-bedded, fine-grained sandstone up to 1.2 m (4 ft) thick. Analysis of this sample showed more than 3 percent TiO_2 and weak enrichment in the LREE, gadolinium, and niobium.

Other Potential Paleoplacers

Frontier Formation

Frontier Formation, Spring Gap, SE¼NW¼ sec. 30, T. 16 N., R. 117 W., Uinta County

Madsen and Reinhart (1982) reported up to 1,000 ppm lanthanum, 80 ppm yttrium, less than 100

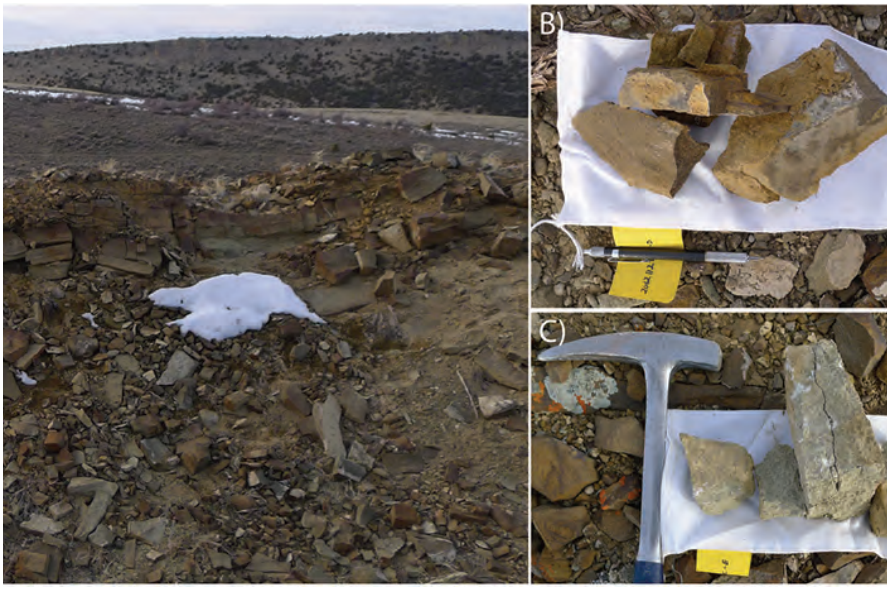

Figure 19. Outcrop and samples of the Frontier Formation in the southern Spring Gap area. A, outcrop of green to yellow barren sandstone overlain by dark-green to dark-brown radioactive, REE-rich sandstone. B, sample of the upper dark-green to dark-brown REE-rich sandstone (20121128JC-D). C, sample of the green to yellow barren sandstone (20121128JC-E).

ppm niobium, and 660 ppm eTh within altered sandstone in the Cretaceous Frontier Formation. This sandstone exhibits a mineralogical assemblage typical of beach placer deposits and contains limonite, pyrite, leucoxene, and an unidentified REE-bearing mineral. The stratigraphy of samples reported by Madsen and Reinhart (1982) is ambiguous (King and Harris, 2002). Recent mapping (M'Gonigle and Dover, 2004) and field investigations from this study show that this sandstone is within the lower third of the Frontier Formation (figs. 19 and 20).

An exploration trench near the area sampled by Madsen and Reinhart (1982), exposes light green to yellow (weathered), angular to subangular, medium- to coarse-grained sandstone, with approximately 25 percent weathered plagioclase, 40 percent quartz, 35 percent mafic minerals, 5 percent biotite, and minor limonite and hematite staining (Sample 20121128JC-E). This weathered sandstone unit is overlain by a dark green to dark brown, angular, medium- to coarse-grained laminated sandstone (fig. 19) with approximately 40 percent mafic minerals, 25 percent limonite, 20 percent weathered plagioclase, 10 percent quartz, 5 percent black opaque minerals, and calcite fracture fills (Sample 20121128JC-D). In places, the mafic minerals in the upper portion of the exposure appear to have grown around plagioclase. Background radioactivity in the area is 90 cpm and the upper mafic-rich unit exhibits up to three times the background 260 cpm; the lower unit exhibits no anomalous radioactivity. The bedding here strikes 202° and dips 55° NW. The lower, light green sandstone (Sample 20121128JC-E) is not significantly enriched in any of the REE. However, the upper, dark green to dark brown sandstone (Sample 20121128JC-D) is enriched in all of the REE as well as scandium, yttrium, and niobium; only europium, lutetium, and scandium are enriched at less than five times crustal abundances (table 17).

Frontier Formation, Spring Gap, NE¼SW¼ sec. 8, T. 16 N., R. 117 W., Uinta County

The same altered Frontier Sandstone as that was sampled in sec. 30 crops out here and is reported by Madsen and Reinhart (1982) to contain 650 ppm lanthanum, 50 ppm yttrium, 120 ppm niobium, 600 ppm eTh, 25 ppm eU, and an elemental assemblage typical of beach placer deposits. The sandstone exposed in a prospect pit at this locality is similar to that of sample 20121128JC-D. It is dark green to dark brown, angular, and medium- to very coarse-grained, with approximately 40 percent mafic minerals, 20 percent limonite, 20 percent weathered plagioclase, 10 percent quartz, 2.5 percent black opaque minerals, 2.5 percent hematite,

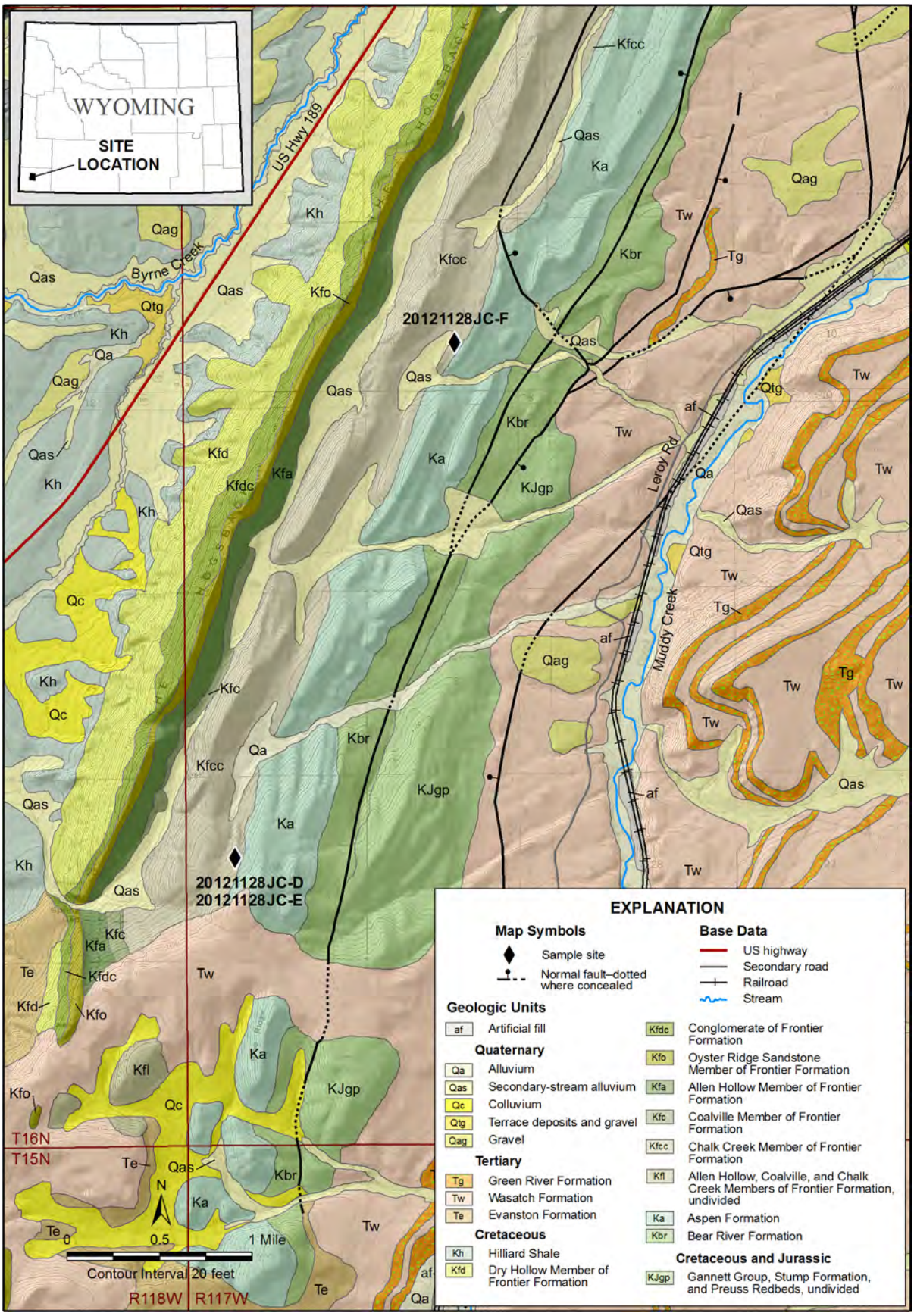

Figure 20. Sample locations and geology of the Spring Gap area, Uinta County, modified from M'Gonigle and Dover (2004).

Table 17. Concentration of the REE, niobium, uranium, and thorium in the Spring Gap paleoplacers within the Frontier Formation. Bold values indicate concentrations greater than five times crustal abundance.

	Spring Gap									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121128JC-D	**2430**	**4110**	**395**	**1225**	**145.5**	5.39	**69.6**	**8.35**	**41.1**	**7.23**
20121128JC-E	40.8	72.8	8.49	32.7	6.4	1.7	5.66	0.85	4.88	0.98
20121128JC-F	**990**	**1650**	**160.5**	**499**	**57.4**	3.06	25.7	2.73	12.55	2.09

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	Nb (ppm)	U (ppm)	Th (ppm)
20121128JC-D	**18.1**	**2.54**	**14.75**	2.26	85	**184**	**8744**	**117**	**9.2**	**387**
20121128JC-E	2.76	0.41	2.38	0.36	10	29.1	220.3	14.9	1.55	5.57
20121128JC-F	5.1	0.73	4.29	0.67	37	53.8	**3505**	68.5	7.29	**186.5**

and calcite fracture fillings (Sample 20121128JC-F). Some mafic minerals appear to have grown around plagioclase grains and are thus probably alteration products. Background radioactivity at this location was 65 cpm away from the outcrop, 100 cpm near the outcrop, and up to five times background (330 cpm) at the point of sampling. This sample (20121128JC-F) is enriched in all of the naturally occurring REE, as well as scandium, yttrium, and niobium; the LREE (except promethium) are all enriched to greater than five times crustal abundances (table 17). Monazite is identifiable in thin-section in sample 20121128JC-F, and is likely present in sample 20121128JC-D.

Stump Formation

Cliff Creek, center S½S½ sec. 33, T. 38 N., R. 114 W., Northwestern Fremont County

In this area, the Jurassic Stump Formation is reported to be weakly radioactive, with zones of up to 90 percent heavy minerals (Houston and Love, 1956). But unlike the Late Cretaceous fossil beach placers (e.g., Mesaverde Formation, Frontier Formation), the Stump contains no monazite (Houston and Love, 1956). King and Harris (2002) noted that this unit may be favorable for REE-enrichment; however, the absence of monazite greatly reduces its potential to host REE.

At this location, the Stump Formation is dark gray to red (weathered), very fine- to coarse-grained calcite cemented sandstone with multiple upward-fining sequences, and trough cross-bedding with conglomerate at the base of the troughs. Grains are 50 percent quartz, 30 percent oolitic calcite, and the remainder is composed of hematite, limonite, and glauconite. Sample 20121003JC-D is representative of the fine-grained material and 20121003JC-E is coarse-grained sandstone. Neither sample is enriched in REE.

Bacon Ridge Sandstone, Dry Cottonwood Creek, SW¼SE¼ sec. 27, T. 42 N., R. 112 W., Teton County

Houston and Murphy (1970) reported a fossil beach placer at this location, but gave no further information. King and Harris (2002) listed this site as a potential host of REE-bearing heavy minerals due to their presence in other Cretaceous beach deposits across Wyoming. The Cretaceous Bacon Ridge Sandstone here is a white to tan, medium- to coarse-grained, well-rounded, cross-bedded quartz sandstone with moderate to abundant lithic fragments and moderate limonite staining (Sample 20121003JC-G). A gray, slope forming bentonitic mudstone (Sample 20121003JC-H) underlies the sandstone at this location. Neither sample exhibits significant REE concentrations.

Other Sandstone Hosted Occurrences

In addition to paleoplacer deposits, sandstones can potentially host REE and other minerals in reduction-oxidation fronts associated with the

interaction between oxidized groundwater and reduced geologic environments. Such deposits are known sources of uranium (e.g., Smith Ranch mine, Wyoming) and a silver and copper (e.g., Paoli deposit in Oklahoma; Thomas and others, 1991). These geological environments potentially host other metals as well.

Deacon's Prayer Group Claims, SE¼SE¼ sec. 18, T. 32 N., R. 82 W., Southern Natrona County

Griffin and Milton (1982) reported 90 ppm cU_3O_8, 250 ppm lanthanum, 70 ppm yttrium, 3,000 ppm titanium, and 300 ppm zirconium within a coarse-grained to conglomeratic arkosic sandstone in the basal Wind River Formation. The area sampled by Griffin and Milton (1982) is located on private land, but the Wind River Formation crops out on adjacent public land to the north (Hunter and others, 2005).

An arkosic, coarse-grained sandstone interbedded with a cobble- to boulder-conglomerate supported by a coarse grained arkosic matrix crops out here on a ridge top that trends about 320°. Clasts in the conglomerate are dominantly felsic igneous rocks but mafic, metamorphic, and sedimentary clasts are also present. The sandstone hosts large iron concretions greater than 2 m (6 ft) across (table 18). Rinds on the concretions, 10 to 20 cm (4 to 8 in) thick, are composed of dark brown to yellow, very coarse-grained, subangular, limonite-cemented lithic arkose (Sample 20121031JC-C). The insides of the concretions are tan to yellow, very coarse-grained, subangular, calcite cemented, limonitic lithic arkose (Sample 20121031JC-D). The interiors of the concretions are not significantly enriched in any of the REE or any other elements of economic interest. However, the concretionary rind (Sample 20121031JC-C) contains 152.2 ppm yttrium, greater than five times its crustal abundance, and is weakly enriched in all of the naturally occurring REE except europium and scandium (table 18). In addition, the rind contains nearly 63 ppm uranium and 0.094 percent titanium. When compared to the results of Griffin and Milton (1982), recent sampling indicates that high concentrations of REE, yttrium, titanium, and uranium within the Deacon's Prayer claim group may be isolated occurrences.

Phosphate-Rich Sedimentary Occurrences

Phosphatic shales and mudstones across Wyoming are potential REE-hosts. Known REE occurrences are hosted by phosphatic shale and mudstone in western and southwestern Wyoming, and by phosphate concretions within black shale in northern Wyoming (fig. 21).

Uraniferous Phosphatic Horizons in the Wilkins Peak Member of the Green River Formation

Love (1964) identified 32 uraniferous phosphatic horizons within the Wilkins Peak Member of the Green River Formation in the Green River Basin. He also described in detail the lower 32.6 m (107 ft) of the Wilkins Peak in a measured section on Lulu claim #2 that includes 13 lithologically

Table 18. Concentration of the REE, uranium, thorium, and titanium within the Wind River Formation in the Deacon's Prayer claim group. Bold values indicate concentrations greater than five times crustal abundance.

	Deacon's Prayer group									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121031JC-C	66.1	111.5	13.8	48.1	11.25	1.82	19.35	3.03	18.8	4.11
20121031JC-D	32.1	53.1	6.42	21.4	4.64	0.68	5.23	0.77	4.44	0.85

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y(ppm)	Cumulative REE (ppm)	U (ppm)	Th (ppm)	Ti (%)
20121031JC-C	12.05	1.52	8.34	1.33	12.3	**152.5**	485.9	**62.7**	26.5	0.09
20121031JC-D	2.43	0.32	1.91	0.3	7.9	26.2	168.7	**35.5**	14.6	0.08

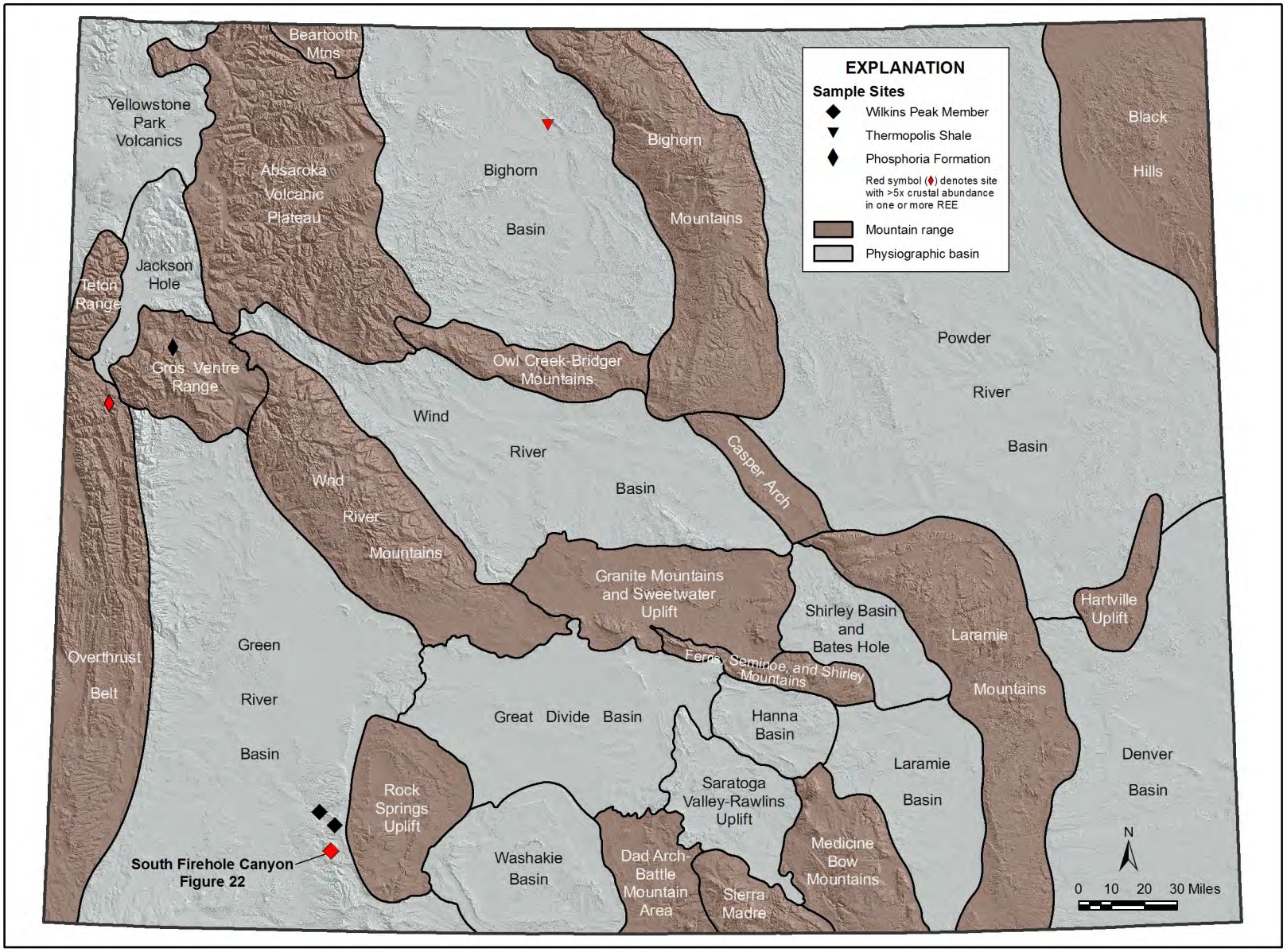

Figure 21. Location of phosphate-related samples included in this report. Sample sites with enrichment of greater than five times crustal abundance in one or more REE are shown in red.

distinct horizons (plus one unit within the underlying Tipton Shale Member), and four uraniferous phosphatic zones (UPZs) in the NE¼SW¼ sec. 10, T. 17 N., R. 106 W. (table 19). The UPZs in the lower part of the Wilkins Peak tend to be more enriched in uranium and phosphate (up to 0.15 percent uranium and 18.2 percent P_2O_5) than those higher in the member. Scarce, dark green to black, REE-bearing carbonate minerals within the Wilkins Peak Member include burbankite, mckelveyite, and ewaldite (Milton and others, 1965; Milton, 1971). Love (1964) noted the presence of REE-bearing minerals in his UPZs 1, 2, and 2a (numbered from the bottom), as well as in a trona bed. The lower UPZs commonly host greater than 0.1 percent REE, but the enrichment is not homogenous and significant lateral variation is observed (King and Harris, 2002).

UPZs are not lithologically distinct from the surrounding rocks and are best identified through the use of radiation detecting equipment. A Geiger counter was not available during sampling of the I-80 on-ramp and Lulu claims (see below); therefore, field identification at those sites was based

Table 19. Measured section of the lower part of the Wilkins Peak Member of the Green River Formation by Love (1964), Lulu claim #2, southwest of Rock Springs.

Bed	Description	Thickness (m)	Thickness (ft)
14	Oil shale, dark-brown, laminated, hard; weathers white; **UPZ 3**	0.15	0.5
13	Shale, gray, soft, fissile	3.35	11.0
12	Gray, very hard, massive, medium-grained sandstone; weathers rusty brown; out crops as ledge that breaks into angular blocks that are conspicuous down slope; regionally identifiable, known as the Firehole bed.	0.12	0.4
11	Shale, claystone, and siltstone, gray to greenish-gray, chippy; moderately hard, but forms slope	4.88	16.0
10	Dolomitic marlstone, tan, slabby, hard, fissile; forms ledge	0.61	2.0
9	Claystone and silstone, green, blocky, slightly radioactive near top; **UPZ 2a** occurs about 1 m below the top, but is not lithologically distinct	2.74	9.0
8	Dolomitic marlstone, tan, hard, slabby, fissile; weathers gray; forms ledge	1.52	5.0
7	Claystone and silstone, green, blocky; forms slope; **UPZ 2** occurs about 1 m below top, but is not litholigically distinct	3.35	11.0
6	Shale and marlstone, greenish-gray, hard, fissile; forms slope	1.52	5.0
5	Dolomitic marlstone, gray, hard, thin-bedded, fissile; weathers tan; interbedded with gray, soft, fissile calcareous shale; forms slope broken by thin ledges	9.14	30.0
4	Dolomitic marlstone, bluish-gray; weathers rusty brown at top; top 1.5 m forms widespread hard brown ledge that comprises most radioactive part of **UPZ 1**	2.44	8.0
3	Shale, gray, marly, soft, fissile	0.91	3.0
2	Marly sandy siltstone, gray, hard slabby, fissile; weathers brown, forms weak ledge; base of Wilkins Peak Member	1.83	6.0
1	Oil shale, dark brown, fissile, thin bedded; weathers gray; top of Tipton Shale	4.3+	14+

entirely on descriptions of field relations provided by Love (1964).

I-80 On-ramp Area, Exit 91, East of Green River, NW¼SE¼ sec. 23, T. 18 N., R. 107 W., Sweetwater County

Mudstone and limestone of the Wilkins Peak Member crops out at this location between the on-ramp and east-bound driving lane of I-80. The units exposed here match the descriptions of horizons 6 through 10 on Lulu claim #2 (Love, 1964), which include UPZ 2 and UPZ 2a. UPZ 2 is hosted within a green, blocky, calcareous mudstone (Sample 20120928JC-A) about 1 m (3 ft) below the base of the overlying tan to gray, thin-bedded to laminated marlstone. UPZ 2a is hosted within a green, blocky, calcareous siltstone and shale (Sample 20120928JC-B), about 1 m (3 ft) below the overlying tan, slabby, dolomitc marlstone. Neither of these samples is significantly enriched in REE or other elements of economic interest.

Lulu claims, NE¼SW¼ sec. 10, T. 17 N., R. 106 W., Southern Sweetwater County

In this area, the uppermost Tipton Shale Member and lower Wilkins Peak Member of the Green River Formation are exposed. The Tipton Shale is composed of a brown to gray, well-indurated oil shale. The lower 3 m (10 ft) of the Wilkins Peak Member consists of marly, sandy siltstone, and marly shale (horizons 2 and 3 of Love, 1964). UPZ 1 is hosted in the upper 2 m (6 ft) of horizon 4, which includes a lower gray to red, irregularly bedded, blocky, slope forming, dolomitic marlstone with a white powdery fracture coating mineral (Sample 20120928JC-E). Horizon 4 also includes an upper gray to brown, interlayered sandy siltstone and marlstone (Sample 20120928JC-C). A blocky, green mudstone to siltstone (Sample 20120928JC-D) that may contain UPZ 2 or 2a crops out about 15 m (50 ft) above horizon 4; this layer is similar to the two rock units of samples 20120928JC-A and 20120928JC-B. REE enrichment is not present in any of these samples, but all three are enriched in lithium, five to 6.5 times crustal abundance.

South Firehole Canyon, NW¼SE¼, sec. 20, T. 16 N., R. 106 W., Southern Sweetwater County

At South Firehole Canyon (fig. 22), Love (1964) reported the presence of UPZs 1, 2, 2a, 3, 3a, and possibly 4, with up to 0.016 percent eU, 0.009 percent uranium and 10.56 percent P_2O_5 in UPZ 2a. The Wilkins Peak Member here is similar to the section described by Love (1964) at Lulu claim #2, except that beds 2 through 6 (Love, 1964) are replaced by about 12 m (39 ft) of resistant ridge-forming, gray to tan, platy to fissile, dolomitic siltstone, with thin interbeds of non-resistant mudstone and shale. This unit exhibits lateral variations in color, including bright red and rusty areas. Background radioactivity at the site was 56 cpm.

About 3 m (10 ft) above the base of the Wilkins Peak Member is a radioactivity anomaly up to 2.5 times the background (140 cpm). The anomaly is within gray to tan (weathered), thin-bedded (about 1 cm or 0.4 in) to fissile, limonite-bearing dolomitic siltstone (Sample 20121129JC-A); the stratigraphic position of the anomaly is equivalent to bed 4 (table 19, Love, 1964, Measured Section), which contains UPZ 1. Bedding at the sample site strikes 295° and dips 4° SW.

A radioactivity anomaly up to 2.3 times background (130 cpm) occurs within bed 7 (table 19), about 15 m (50 ft) above the base of the Wilkins Peak Member. Bed 7 consists of green, slope forming interbedded mudstone and shale. The radioactivity anomaly is associated with UPZ 2, which is hosted in a layer of green, weakly calcareous shale (Sample 20121129JC-B), about 0.5 m (20 in) below the base of bed 8, which is composed of gray to tan, fissile, dolomitic siltstone.

Uraniferous phosphatic zone 2a, hosted in bed 9 (table 19), is associated with a radioactivity anomaly up to 10.6 times background (590 cpm) about 19 m (62 ft) above the base of the Wilkins Peak Member. Bed 9 consists of green, slope forming, interbedded mudstone and shale; UPZ 2a occurs within green, blocky, noncalcareous mudstone (Sample 20121129JC-C), about 0.5 m (20 in) below the base of the gray to tan fissile calcareous siltstone of bed 10 (fig. 23).

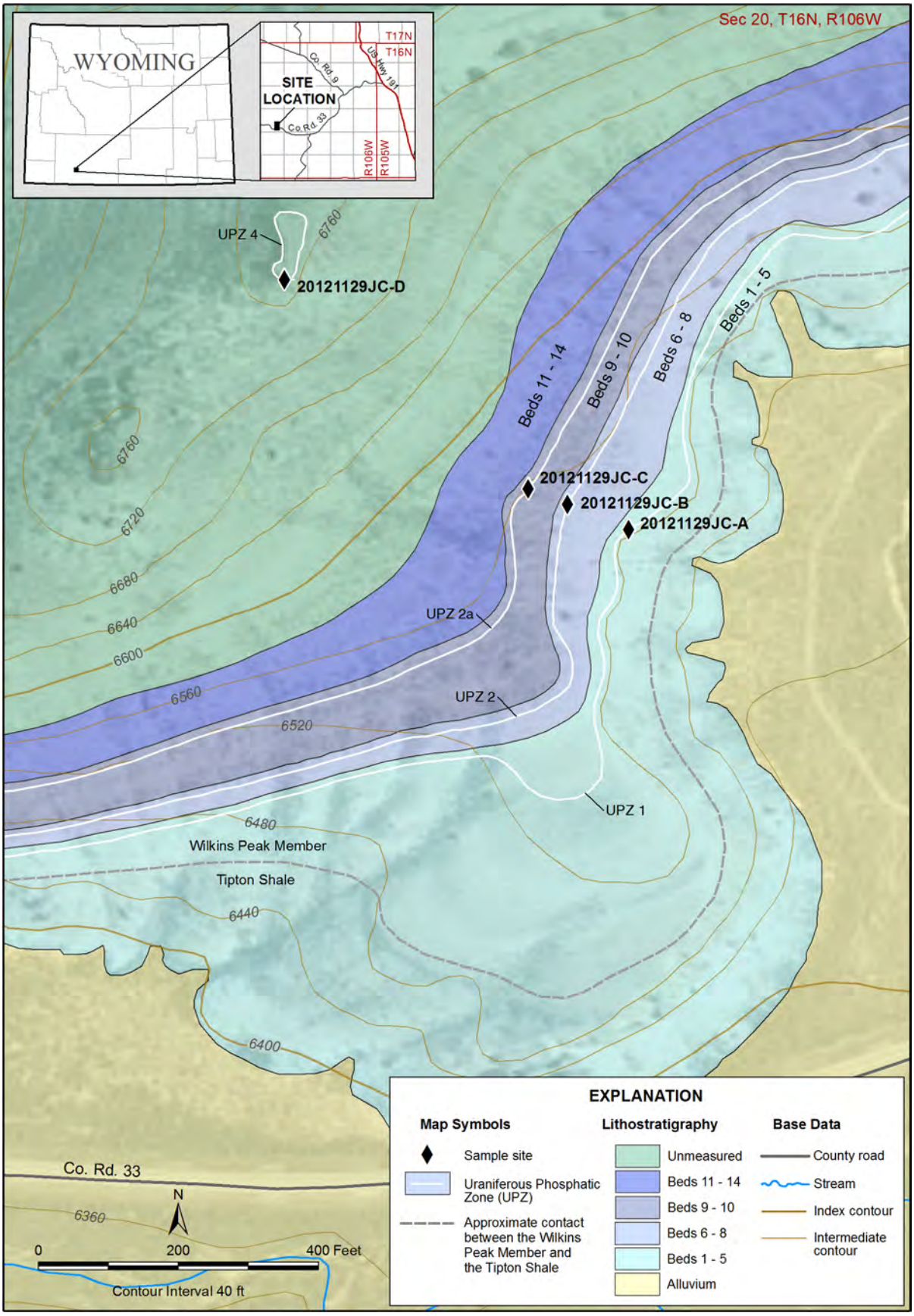

Figure 22. Sample locations and lithostratigraphy in the South Firehole Canyon area. Beds and uraniferous phosphatic zones were identified based upon the descriptions by Love (1964). Table 19 includes descriptions of the individual lithostratigraphic units.

Figure 23. Uraniferous phosphatic zone 2a within the Wilkins Peak Member in the South Firehole Canyon area. A, stratigraphic position of UPZ 2a. B, sample of green, blocky, noncalcareous mudstone that comprises UPZ 2a (20121129JC-C).

The next 65 to 70 m (213 to 230 ft) above bed 9 consist of interbedded ridge forming gray to tan siltstone and dolostone and slope forming green shale and mudstone with no anomalous radioactivity. About 88 to 90 m (289 to 295 ft) above the base of the Wilkins Peak Member, higher than the uppermost unit in Love's (1964) measured section (table 19), is a succession of ridge forming interbedded green calcareous mudstone and limestone, and green to gray, laminated to cross-laminated siltstone overlain by a medium- to coarse-grained, cross-bedded sandstone. UPZ 4 is associated with a radioactivity anomaly up to 5.9 times background (330 cpm) and occurs about 1.5 m (5 ft) above the base of this interbedded succession within a green, well-indurated, bulbous, thin-bedded calcareous mudstone (Sample 20121129JC-D).

REE enrichment is only found in UPZ 2a (Sample 20121129JC-C) and is restricted to the HREE and yttrium. This is similar to Love's (1964) results, in which he reported high concentrations of yttrium and neodymium. Notably, the enrichment of neodymium in UPZ 2a reported by Love (1964) is not present in sample 20121129JC-C. This indicates that relative enrichment between the LREE and HREE may vary laterally or vertically across UPZ 2a in the Fire Hole Canyon area (table 20).

Phosphorite Beds in Western Wyoming

Phosphorite beds within the Phosphoria Formation are possible sources of REE and other metals (King and Harris, 2002) and some sites have been confirmed to host metal deposits (Gulbrandsen,

Table 20. Concentration of the REE, P_2O_5, uranium, and thorium in the Wilkins Peak Member of the Green River Formation at South Firehole Canyon. Bold values indicate concentrations greater than five times crustal abundance.

	South Firehole Canyon									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121129JC-A	41	83.4	10	38.9	7.93	1.6	7.18	1.18	6.87	1.33
20121129JC-B	42.5	80.6	9.29	33.1	5.8	1.14	4.73	0.8	5.05	1.12
20121129JC-C	55.4	131.5	18.65	87	25.4	6.44	**32.5**	**6.67**	**44.1**	**9.75**
20121129JC-D	24	49	6.01	22.8	4.35	0.91	4.46	0.97	8.28	2.39

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	P_2O_5 (%)	U (ppm)	Th (ppm)
20121129JC-A	3.63	0.52	2.9	0.42	9	41.3	257.2	0.21	**13.9**	**44.4**
20121129JC-B	3.44	0.54	3.08	0.44	8	36.4	236.0	0.32	**15.05**	**48.7**
20121129JC-C	**29.7**	**4.67**	**28.2**	**4.25**	13	**300**	797.2	**8.72**	**90.4**	**373**
20121129JC-D	8.49	1.42	7.71	1.01	7	79.5	228.3	**0.55**	**31.7**	**94**

1977; Love, 1984). REE concentrations are typically correlated with phosphorus content, due to an association with apatite. Despite its promise as a host of REE, the Phosphoria Formation has been the subject of few REE analyses (King and Harris, 2002).

Hoback, SW¼NE¼ sec. 32, T. 39 N., R. 116 W., Southwestern Teton County

The Phosphoria Formation crops out along US 89, near the historic town site of Hoback, in extensively folded and faulted terrain, and was the target of a phosphate exploration trench (Albee, 1968). The Phosphoria overlies the Mississippian and Pennsylvanian Wells Formation and is overlain by the Triassic Dinwoody Formation. The northeastern margin of this outcrop is cut by a high-angle fault that places the Phosphoria Formation in fault contact with the Wells Formation (Albee, 1968). The Astoria mineral hot spring is located 340 m (1,100 ft) east-southeast of this outcrop (Breckenridge and Hinckley, 1978), and indicates that the overall area may have experienced hydrothermal activity in the past.

The Phosphoria Formation in this area (fig. 24) includes the Meade Peak Phosphatic Shale Member and an overlying, unnamed tan mudstone interbedded with chert-bearing limey mudstone (Sample 20121003JC-A). The Meade Peak Member is composed of black, moderately- to well-indurated, massive mudstone (Sample 20121003JC-B), interbedded with black, fissile, poorly indurated shale (Sample 20121003JC-C). The Meade Peak Member is about 15 m (50 ft) thick at this locality, and the overall thickness of the Phosphoria Formation is about 55 m (180 ft). Bedding within the Phosphoria strikes 288° and dips 21° NW. The upper black shale of the Meade Peak Member is the most phosphatic unit sampled at this location, with 10.4 percent P_2O_5. Significant REE-enrichment is only observed within the black phosphatic shale at this location; lanthanum and yttrium are the only REE enriched greater than five times crustal abundances (table 21). The black shale is also enriched in various metals, most notably chromium, nickel, cadmium, and molybdenum.

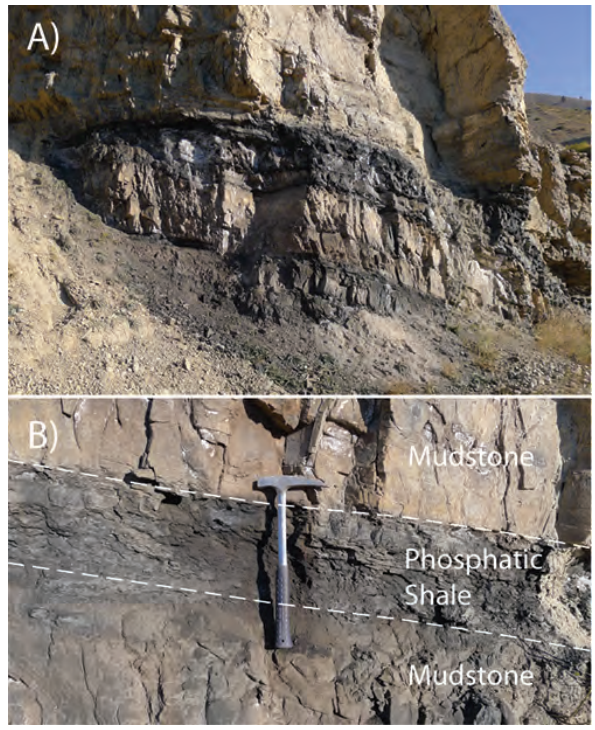

Figure 24. Phosphoria Formation outcrop near Hoback. A, interbedded black mudstone, black phosphatic shale, and tan mudstone of the Meade Peak Member, overlain by interbedded tan limestone and mudstone of the upper Phosphoria Formation. B, bed of REE-rich black phosphatic shale, underlain by black mudstone and overlain by tan mudstone; Sample 20121003JC-C location.

Crystal Creek Canyon, NW¼SW¼ sec. 34, T. 42 N., R. 113 W., Southern Teton County

Simons and others (1988) reported samples with up to 700 ppm lanthanum, 300 ppm yttrium, and 31.5 percent P_2O_5 from the Phosphoria Formation in the Crystal Creek Canyon area. The Meade Peak Phosphatic Shale Member of the Phosphoria Formation does not appear to crop out in this area. At this location the Phosphoria consists of gray to tan, extensively fractured limestone and limey mudstone, with nodules of chert and yellow to brown, radiating-bladed carbonate crystals (Sample 20121003JC-F). This unit is not significantly enriched in any REE or other elements of economic interest.

Table 21. Concentration of the REE and P_2O_5 in the Phosphoria Formation near Hoback. Bold values indicate concentrations greater than five times crustal abundance.

	Phosphoria Formation; Hoback, WY								
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)
20121003JC-A	5.7	3.7	0.85	3.2	0.52	0.14	0.62	0.1	0.64
20121003JC-B	37.4	53.2	7.48	28.3	5.6	1.1	5.09	0.81	4.69
20121003JC-C	**218**	67.9	26.8	105.5	17.1	3.62	19.65	2.85	18.7

Element	Ho (ppm)	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	P_2O_5 (%)
20121003JC-A	0.14	0.47	0.07	0.45	0.08	<1	8.8	25.5	0.46
20121003JC-B	1.02	3.1	0.47	3.32	0.54	8	34.6	194.7	0.93
20121003JC-C	4.59	14.1	2.07	12.05	2.01	9	**306**	829.9	10.4

Dahllite Concretions in the Thermopolis Shale, Big Horn County

The Thermopolis Shale (fig. 25) at the Wyoben bentonite mine near Greybull (NW¼NE¼ sec. 14, T. 53 N., R. 94 W.) is 76 to 91 m (250 to 300 ft) thick and consists of black to gray, bentonitic shale interbedded with thin yellow to brown siltstone, grading to sandstone beds near its base (Kozimko, 1985; Ladd, 1985). Dahllite [$Ca_5(PO_4,CO_3)_3(OH,O)$] concretions (fig. 26) are present near the base of the Thermopolis Shale in the Bighorn Basin (Moberly, 1962) and have also been noted in southwestern Montana (Dyman and others, 2000). The concretions are gray, spheroidal, have a rough surface, and have a radial fibrous texture in cross-section. A sample of these concretions (20121018JC-E) is enriched in all of the REE plus yttrium; gadolinium, terbium, and yttrium are enriched greater than five times crustal abundances (table 22).

Figure 25. Dahllite-bearing, lower part of the Cretaceous Thermopolis Shale (Kt), overlying the Cretaceous Sykes Mountain Formation (Ksm; a local term for the upper Cloverly Formation), near the Wyoben bentonite mine, northwest of Greybull.

OCCURRENCES OF OTHER ELEMENTS

This WSGS investigation for REE included analyses for other elements as well, from both current samples and samples retained by the WSGS from previous investigations. Significant concentrations of elements other than REE are described in this section.

Hub Prospect, E½NE¼ sec. 6, T. 15 N., R. 87 W., Southern Carbon County

The Hub prospect targeted a 0.5 m (1.5 ft) thick quartz vein that cuts sheared amphibolite of the Late Archean Silver Lake Metavolcanics. Hausel (1986) reported a sample of this quartz vein that yielded 0.41 percent copper, 150.8 g/tonne (3.99 oz/ton) silver, and no gold. Visible gold was reported in a separate sample (Hausel, 1997), and a sample of limonite

Figure 26. Dahllite concretions from the Cretaceous Thermopolis Shale near the Wyoben bentonite mine, northwest of Greybull., A, sample 20121018JC-E. B, interior of a dahllite concretion.

stained vein quartz, mineralized with chalcopyrite, pyrite, bornite, malachite, and hematite, analyzed for this report yielded 17.25 ppm (0.50 oz/ton) gold, 41.3 ppm (1.20 oz/ton) silver, and 2.62 percent copper.

Gold Coin Mine, SW¼ sec. 11, T. 15 N., R. 87 W., Southern Carbon County

The Gold Coin mine targeted copper, lead, gold, and silver mineralization within a 0.3 m (1.0 ft) wide quartz vein (Beeler, 1902; Hausel, 1997). The vein is concentrated within a fissure that trends 75° and dips to the south at a high angle (Spencer, 1904). The vein cuts the regional foliation of the hosting Late Archean black diorite (Beeler, 1902; Spencer, 1904). A sample of vein quartz with abundant limonite (possibly replacing sulfides), galena, chalcopyrite with chalcocite rims, and minor malachite (Sample 20121203WSGS-B) from the Gold Coin mine yielded 318 ppm (9.27 oz/ton) silver, 0.11 ppm (0.003 oz/ton) gold, 0.11 percent copper, and 14.6 percent zinc.

Section 8 Mine, S½SE¼ sec. 8, T. 14 N., R. 85 W., Southern Carbon County

The Section 8 mine targeted copper mineralization hosted in pyritized banded chert within amphibolite of the Silver Lake Metavolcanics, though the exact field relationship between the amphibolite and chert is unknown. In addition to the amphibolite, chlorite garnet schist is also present in the Silver Lake Metavolcanics in the vicinity of the Section 8 mine. The banded chert has a trend of 81° and dips 52° SE. Mineralization is concordant with the local banding in the chert. A sample from the mine yielded 2.61 percent copper but no detectable gold (Hausel, 1986; 1997); no silver was reported. A sample of pyrite- and chalcopyrite-bearing banded chert (Sample 20121203WSGS-D) yielded 27.4 ppm (0.80 oz/ton) silver and 6.75 percent copper.

Table 22. Concentration of the REE, P_2O_5, uranium, and thorium in dahllite concretions from the Thermopolis Shale near Greybull. Bold values indicate concentrations greater than five times crustal abundance.

	Wyo-Ben mine dahllite									
Element	La (ppm)	Ce (ppm)	Pr (ppm)	Nd (ppm)	Sm (ppm)	Eu (ppm)	Gd (ppm)	Tb (ppm)	Dy (ppm)	Ho (ppm)
20121018JC-E	65.4	135	20.1	93.2	24.4	6.32	**31.9**	**4.83**	26.7	4.96

Element	Er (ppm)	Tm (ppm)	Yb (ppm)	Lu (ppm)	Sc (ppm)	Y (ppm)	Cumulative REE (ppm)	P_2O_5 (%)	U (ppm)	Th (ppm)
20121018JC-E	10.8	1.15	5.56	0.72	9	**187.5**	627.5	**33.6**	3.75	1.03

Black Rock Gap prospect, SE¼SW¼ sec. 32, T. 31 N., R. 91 W., Southeastern Fremont County
The Black Rock Gap prospect is located along an east-trending shear zone in the north-central Granite Mountains. Intensive potassic and propylitic alteration surrounds the prospect with a 4.6 m (15 ft) long adit in the center of a north-trending antiformal structure just west of Black Rock Gap. The adit follows a 95° trending, near vertical shear zone, which cuts mafic and ultramafic rocks and granite gneiss. Brecciation accompanies shearing in some areas. Abundant jasper and epidote are present near the adit, as is some copper staining. Epidotization is spread across a wide area near the prospect and is easily seen in aerial imagery. A sample of sheared ultramafic rock with copper staining (20121009WS-A) yielded 0.5 ppm (0.015 oz/ton) gold, 318 ppm cobalt, 516 ppm chromium, and 1.15 percent copper. A sample of iron-stained fault gouge from the shear zone (20121009WS-B) yielded 0.51 ppm (0.015 oz/ton) gold, 318 ppm cobalt, 515 ppm chromium, and 1.575 percent copper. Two additional samples from the prospect, 20121009WS-C (brecciated mafic rock with $CaCO_3$ cement) and 20121009WS-D (severely altered and brecciated felsic gneiss) yielded 1,200 ppm and 1,630 ppm chromium, respectively.

UT Creek - Lost Muffler Fault Prospects, NW¼NW¼ sec. 22, T. 32 N., R. 87 W., Northwestern Natrona County
The UT Creek Formation is generally east-trending and inclined steeply south to near vertical, in the northern part of the Saddle Rock quadrangle (Sutherland and others, 2012). The Archean UT Creek Formation is dominated by fine- to medium-grained metagreywackes and tuffaceous metagreywackes separated by a relatively thick metavolcanic member that is locally dominated by foliated to massive, black, fine-grained to aphanitic metabasalts (Hausel, 1996).

The Lost Muffler fault parallels the general east trend of the UT Creek Formation and carries anomalous gold values west of UT Creek (Hausel, 1996) where it is dotted with small prospects. Near the north side of the fault, east of UT Creek, and near a contact between metabasalt and metagreywacke, a prospect pit is dug into sheared metabasalt cut by iron-stained quartz veins adjacent to an outcrop of minor black schist. Sample 20120607WS-B is representative of the sheared metabasalt and associated quartz veins. Analysis of this sample showed 1.84 ppm (0.05 oz/ton) gold and no anomalous REE.

Wagon Bed Formation NW¼SE¼ sec. 30, T. 32 N., R. 88 W., Southwestern Natrona County
The Wagon Bed Formation crops out south of the North Granite Mountains Fault in the northern part of the Blackjack Ranch 7.5' quadrangle. The Wagon Bed Formation was described by Van Houten (1964) in the Beaver Rim area, about 55 km (34 mi) west of the Blackjack Ranch quadrangle. Love (1970) further described the Wagon Bed in the central Granite Mountains. Regionally, it varies from pale-olive and greenish-gray, tuffaceous sandstone, siltstone, and mudstone with some zeolitic ash layers to a highly variable coarse conglomerate. Outcrops of the Wagon Bed in this area are poorly exposed due to weathering and slope wash. However, ground disturbances such as excavations or drill holes provide opportunities to examine the lithology of the formation. At this site, a very recent (2012) drill hole provided subsurface material from the Wagon Bed Formation. Three samples were collected here (20121031WS-E, 20121031WS-F, and 20121031WS-G). Cream to greenish and rusty-orange, very-fine grained sandstone and ash (Sample 20121031WS-F) contained 3.15 ppm (0.09 oz/ton) gold.

Wagon Bed Formation Ash Layer, NE¼SE¼ sec. 32, T. 32 N., R. 87 W., Southwestern Natrona County
The Wagon Bed Formation crops out in this vicinity, where it is dominated by conglomerates, sandstones, and ash layers, along with minor silicified limestone. Conglomerate typical of the Wagon Bed caps the ridge above and immediately to the northwest of this location. A tufa deposit from a paleo-hot spring (Sample 20120613WS-A) is underlain by 5- to 10-foot thick ash layer (Sample 20120613WS-B). The tufa (Sample 20120613WS-A) contains 3.68 ppm (0.11 oz/ton) gold, but the ash layer contains no gold. No anomalous REE were detected in either sample.

Moonstone Formation Reefs, SW¼SE¼ sec. 24 and NE¼NW¼ sec. 25, T. 30 N., R. 90 W., Southeastern Fremont County

Sandy, calcareous, partly silicified tuffaceous knobs or humps that project above the relatively flat-lying Moonstone Formation are present in this vicinity. Love (1961; 1970) suggested these knobs were possible algal reefs. However, they contain no fossil material and appear to be hot-springs-related tufa deposits. Several small, historical prospect pits are dug into the mounds that exhibit radioactivity that is notably higher than the local background; the radioactivity appears to be concentrated along silicified fractures. Brecciation along apparent fractures is evident in two of the largest knobs. Sample 20120918WS-D, collected from a knob in sec. 25, contains greater than 1,000 ppm Thorium. Sample 20120918WS-G, collected from a large knob in sec. 24, contains 213 ppm thorium. No anomalous REE were detected.

Strong Mine, Sec. 4, T. 16 N., R. 71 W., Southern Albany County

The original mine included a 110 m (360 ft) shaft with five levels totaling at least 399 m (1,308 ft) of tunnels by 1907 (Beeler, 1907). The shaft was sunk into fractured diabasic and gabbroic dikes hosted by layered gneiss and schist in granite and anorthosite (Hausel, 1997). Tungsten was targeted in scheelite deposits at the 106.7 m (350 ft) level. One hundred tons of scheelite ore was shipped to Boulder Colorado, and yielded 0.2 to 0.6 percent WO_3 (Hausel, 1997). Gold, silver, and nickel were also recovered from the mine (Beeler, 1942). A grab sample of sheelite- and pyrite-bearing quartz-potassium feldspar-biotite gneiss (Sample 19710416ST-3) contains 5,820 ppm tungsten, but no REE enrichment.

Unnamed Location, South Pass Area, SE¼ sec. 23, T. 29 N., R. 98 W., Southwestern Fremont County

A sample of black, very fine- to fine-grained quartz biotite schist, cut by a white, fine-grained quartz vein with epidote, chlorite, and scheelite (Sample 20121212WSGS-B) contains 5,190 ppm tungsten, 0.15 ppm gold (0.004 oz/ton), and 0.23 ppm (0.007 oz/ton) silver.

Broadway Mine, SW¼ sec. 32, T. 13 N., R. 83 W., Southeastern Carbon County

Reclamation efforts at the Broadway mine site have destroyed observable field relationships and vehicle access to the mine site (Hausel, 1992). Production at the Broadway mine targeted a sheared zone at the contact between granite and a complex of gneiss, amphibolite, pyroxenite, gabbro, and diorite that dips from 50° SE to 50° NW (Osterwald, 1947; DeNault, 1967). Sample 20121203WSGS-A from this mine is a green, medium- to coarse grained diopside spessertine hornfels with minor actinolite, and moderate to abundant limonite staining and grain-coatings. The sample contains 2.75 percent zinc but no REE enrichment.

Figure 27. WSGS geologist Robert Gregory collecting sample 20120913BG-3 from altered, brecciated granite, a road cut along the Leo-Shirley Basin Road; details are in the Appendix CD and on Wyo-DOG. *Photo by Wayne M. Sutherland.*

CONCLUSION

This investigation confirms REE occurrences in a variety of geologic settings across Wyoming and provides a large amount of easily accessible analytical data through the WSGS's new on-line database (Wyo-DOG). Dikes and pods that cut Precambrian igneous and metamorphic rocks host high REE concentrations in some areas. Phanerozoic coarse-grained sandstones and conglomerates, as well as phosphatic shales and mudstones also host localized high REE concentrations. No interpretations resulted from this investigation concerning the potential for economic development of these occurrences. However, the information provided to the public through Wyo-DOG will foster exploration and lead to greater knowledge and better understanding of REE and other potentially economic minerals in Wyoming.

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INDEX

A

Abandoned Mine Lands 2
acmite 18
actinolite 65
aeschynite 13
Albany County 24, 25, 26, 27, 28, 32, 33, 65
alkaline igneous complex 13, 15
allanite 1, 11, 12, 13, 15, 21, 24, 26, 27, 29, 31, 32, 33, 34, 37, 38
Allie (Parlett-Adams) claims 21, 33, 34
alteration 14, 16, 21, 24, 25, 26, 28, 31, 33, 34, 37, 39, 54, 63
amphibolite 29, 32, 62, 63, 65
ancylite 12, 15
andradite 37
anorthosite 27, 65
apatite 12, 18, 19, 39, 49, 61
Astoria mineral hot spring 61
azurite 38

B

Babbs mine 38
Bacon Ridge Sandstone 54
Bald Mountain 15, 41, 42, 43, 44, 45, 46
bastnasite 10, 11, 12, 13, 15, 18
Bear Lodge 1, 5, 9, 14, 15, 16, 18, 19, 20, 66
Beaver Creek allanite prospect 34
beryl 28, 32, 33
berylium 33
Big Creek district 15, 21, 29, 30, 32
Big Creek mine 29
Big Horn County 51, 61
Bighorn Basin 39, 62
Bighorn Mountains 1, 15, 21, 33, 34, 41, 47
Black Butte 16
Black Hills 16
Blackjack Ranch quadrangle
Black Rock Gap 63
black sand 13, 48, 49, 50, 51
bornite 38, 62
breccia 16, 34, 37, 38, 45, 48, 64, 65, 66
Broadway mine 65
Bull Hill 18
burbankite 12, 57

C

cadmium 61
calcite 18, 34, 52, 54, 55
calc-silicate 1, 21, 34
Carbon County 1, 29, 31, 38, 49, 62, 63, 65
Carbon Hill 18
Carbon target area 19
carbonatite 1, 9, 11, 13, 14, 15, 16, 18
cerianite 12, 18
cerium 5, 7, 8, 10 12, 13, 15, 25, 39, 46
chalcopyrite 18, 38, 62, 63
chert 61, 63
Cheyenne Belt 29
chlorite 37, 49, 64, 65
chromium 61, 64
Clarence Wood Lode claims 37, 38
Clarks Camp-Union Pass gold placers 47
cleavelandite 33
Cliff Creek 54
cobalt 64
Cody Shale 48
Colorado Province 29
columbite 13, 29, 31, 32, 33
conglomerate 41, 42, 45, 46, 47, 48, 54, 55, 64, 65
copper 7, 14, 29, 38, 55, 62, 63, 64
Cottonwood Creek 50, 54
Crystal Creek Canyon 61

D

Dahllite 61, 62, 63
Deacon's Prayer Group claims 55
Deadwood Conglomerate 41
Devils Tower 16
Dinwoody Formation 61
diorite 13, 32, 38, 41, 63, 65
Dry Cottonwood Creek 54
Dubois Claims 34, 36, 37
Dugout Creek 48, 51
dysprosium 7, 8, 10, 13, 19, 39, 46, 51

E

epidote (also epidotization and epidosite) 1, 12, 24, 25, 28, 31, 33, 34, 37, 38, 49, 64, 65
erbium 7, 8, 10, 38
europium 5, 7, 8, 10, 19, 25, 26, 27, 32, 39, 50, 52, 55
euxenite 11, 12, 13, 15, 27, 28, 29, 31, 32
ewaldite 12, 57

F

fergusonite 12, 13, 33
Ferris Mountains 38
ferrocolumbite 13
ferrotantalite 13
Flathead Sandstone 15, 39, 41, 42, 44, 45, 46, 48
fluorite 12, 18, 29
FMR dike 18
fossil beach placer 39, 48, 54
Fremont County 33, 36, 37, 46, 54, 63, 64, 65
Frontier Formation 39, 51, 52, 54

G

gadolinium 5, 7, 8, 10, 12, 13, 19, 36, 37, 39, 46, 51, 62
galena 18, 63
garnet 6, 29, 31, 32, 34, 49,
glauconite 46, 54
goethite 45
gold 2, 5, 15, 16, 19, 34, 42, 47, 62, 63, 64, 65
Gold Coin mine 63
Grass Creek 48, 50
Green Mountain 16
Green River Basin 39, 55
Green River Formation 39, 55, 57, 58, 60

H

Half Ounce Creek 46
heavy rare earth elements (HREE) 5, 7, 9, 11, 13, 14 , 15, 19, 26, 27, 28, 31, 32, 34, 37, 44, 45, 46, 60
hematite 18, 24, 25, 26, 27, 28, 31, 32, 33, 37, 42, 46, 52, 54, 62
Hoback 61, 62
Holiday Place pegmatite 24, 27
holmium 8, 10, 45, 51
hornblende 26, 29, 34, 36, 37, 41
hornfels 65
hot spring 15, 50, 61, 64
Hot Springs County 50
Hub prospect 62
hydrothermal alteration 34, 37

I

I-80 On-ramp Area, Exit 91 58
Inyan Kara Mountain 16
ion adsorption clays 11
iron concretion 55

J

jasper 38, 64
Johnson County 15, 34

L

lacustrine 1, 39
lamproite 39
lamprophyre 16
lanthanide series 1, 3, 5
lanthanum 5, 7, 8, 10, 11, 13, 15, 25, 26, 27, 28, 31, 39, 46, 50, 51, 52, 55, 61
Laramie Anorthosite Complex 27
Laramie Range 21, 27, 33
laterites 11
latite 16
LCT pegmatite 21
lead 6, 7, 11, 24, 63, 65
Leucite Hills 39
leucoxene 52
light rare earth elements (LREE) 5, 7, 9, 13, 15, 19, 34, 36, 37, 39, 44, 45, 46, 51, 54, 60
Lime Buttes 16
limestone 58, 60, 61, 64
limonite 24, 25, 31, 32, 36, 42, 45, 48, 52, 54, 55, 58, 62, 63, 65
lineament 34, 36, 37
lithium 21, 33, 58
loparite 11
Lost Muffler fault 64
Lovell 51
Lulu claims 57
lutetium 5, 7, 26, 27, 31, 38, 52

M

madupite 39
mafic dike 26, 38, 41, 44, 45
magmatism 16
malachite 38, 62, 63
manganocolumbite 13
Many Values area 21, 32
marble 34
marine 1, 39, 41, 48, 50
mass spectrometry 3
mckelveyite 12, 57
Medicine Bow Mountains 15, 21, 29, 33
Medicine Bow National Forest 27, 32
Mesaverde Formation 15, 39, 48, 49, 50, 51, 54
metabasalt 64
metagreywacke 64
metamict 13, 14, 29
metavolcanic 62, 63, 64
microcline 15, 21, 29, 31, 32
misch metal 5, 7
Missouri Buttes 16
molybdenum 14, 61
Molycorp 1, 9

monazite 1, 11, 12, 13, 14, 15, 18, 19, 29, 31, 39, 42, 43, 44, 45, 47, 49, 50, 51, 54
monzonite 24, 26, 36, 37
Moonstone Formation 64
Moonstone Formation Reefs 64
Mud Creek 48, 51
mudstone 1, 54, 55, 58, 60, 61, 64, 65
Mullen Creek complex 29
Mullen Creek-Nash Fork shear zone 29
muscovite 29, 31, 32, 33

N

National Uranium Resource Evaluation (NURE) 31
Natrona County 33, 37, 46, 48, 55, 64
neodymium 5, 7, 8, 10, 15, 26, 46, 60
nepheline syenite 16
NI 43-101 19
nickel 61, 65
niobium 21, 24, 25, 26, 27, 28, 31, 32, 33, 48, 50, 51, 52, 54
North Granite Mountains Fault 64
NYF pegmatite 21

O

Oakie Trail 48
oil shale 58
orendite 39
Owl Creek Mountains 33

P

paleoplacer 1, 11, 14, 15, 39, 40, 41, 42, 44, 45, 46, 48, 49, 51, 54
parisite 12, 13, 18
pegmatite 1, 13, 14, 15, 21, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 41
Pegmatite #1 24, 25, 26, 27
Pegmatite #2 25
Pegmatite #3 24, 26
Pegmatite #4 26, 27
perthite 31
phonolite 16
phosphate 11, 13, 14, 15, 39, 55, 56, 57, 61
Phosphoria Formation 15, 60, 61, 62
Pilot Butte 39
Pinyon Conglomerate 47
placer 1, 3, 11, 13, 14, 15, 34, 39, 45, 46, 47, 48, 52, 54
Platt 15, 29, 31, 32
polycrase 13
Porcupine Creek 46
Powder River Basin 16
praseodymium 7, 8, 10, 15, 25, 46
prices 7, 8, 9, 10, 14

production 1, 7, 8, 9, 14, 15, 19, 21, 29, 65
promethium 1, 3, 54
pseudoleucite 16
pyrite 18, 38, 52, 62, 63, 65
pyrolusite 26, 31
pyrrhotite 18

Q

quartz pebble conglomerate 42, 45, 48
Quaternary alluvium 46

R

rare earth elements (REE) 1, 3, 5, 17, 18, 22, 28, 32, 34, 38, 39, 40, 43, 44, 46, 49, 52, 54, 55, 56, 60, 61, 62, 63
Rare Element Resources 1, 5, 12, 14, 15, 18, 19, 20, 65, 66
Rattlesnake Hills 46
reduction-oxidation front 39, 54
REO 5, 7, 9, 12, 13, 14, 18, 19, 34, 44
Rooster Hill 42, 43, 44, 46

S

Saddle Rock quadrangle 64
samarium 6, 8, 10, 26
samarskite 1, 8, 10, 12, 13, 15, 31
sandstone 1, 39, 41, 42, 45, 46, 47, 48, 49, 50, 51, 52, 54, 55, 60, 62, 64, 65
Saratoga 30’ x 60’ quadrangle 29
scandium 6, 15, 31, 39, 51, 52, 54, 55
scheelite 38, 65
schist 14, 29, 32, 36, 63, 64, 65
Section 8 mine 63
Separation Rim 49
Separation Rim quadrangle 49
sericite 37
shale 48, 55, 58, 60, 62
shear zone 15, 29, 63, 64
Sheridan County
Sherman Granite 21, 24, 27, 28, 32, 33
silicified 38, 46, 64, 65
silver 5, 6, 38, 55, 62, 63, 65
Silver Lake Metavolcanics 62, 63
South Firehole Canyon 58, 59, 60
South Fork Warm Spring Creek
South Table Mountain 39
sphalerite 18
Spring Gap 51, 52, 53, 54
Strange Lake pegmatite 21
Strawberry Mountain 16
Strong mine 65

strontianite 18, 19
Stump Formation 54
Sundance Mountain 16
Sundance 30' x 60' quadrangle 16
Sweetwater County 39, 58
syenite 12, 14, 16
synchysite 12, 15, 18

T

tantalite 28, 31, 32, 33, 34, 44
tantalum 28, 31, 32, 33, 34, 44
Taylor Target Area 19
terbium 6, 8, 10, 19, 26, 27, 36, 37, 39, 46, 62
Teton County 54, 61
Thermopolis Shale 61, 62, 63
thorium 1, 11, 13, 14, 15, 26, 27, 34, 37, 42, 44, 45, 47, 48, 65
thulium 5, 6, 8, 10, 27, 28, 38
Tie Siding 21, 23, 24, 25, 26, 27
Tinton-Mineral Hill area 16
Tipton Shale Member of the Green River Formation
titaniferous black sandstone 48, 50, 51
titanium 48, 50, 55
tonalite 33
tourmaline 29, 32, 33, 49
trachyte 16
TREO 5, 6, 21, 45
trona 57
tufa 64, 65
tungsten 33, 65

U

U.S. Atomic Energy Commission 1, 14, 44
U.S. Bureau of Mines 1
U.S. Department of Energy 8, 9, 31
Uinta County 51, 52, 53
Union Pass – Warm Spring Area 34, 35, 36, 37, 46, 47
Unnamed Location, South Pass area 65
Unnamed pegmatite 27
UPZ 57, 58, 60
uranium 1, 13, 14, 15, 24, 25, 27, 29, 31, 32, 26, 37, 39, 45, 47, 47, 51 62, 63
uses 3, 7, 8
UT Creek - Lost Muffler fault prospects 64
UT Creek Formation 64

W

Wagon Bed Formation 64
Warm Spring Creek 47
Washakie County 51

Weddle claims 21, 28
Wells Formation 61
Whippet and Zimmerman Mines Area 33
Whitetail Ridge target area 15, 19
Wild Cat Road 36
Wilkins Peak Member of the Green River Formation 55, 57, 58, 60
Wind River Formation 47, 55
Wind River Range 34
Wyo-DOG 2, 3, 16, 65, 66
Wyoming Province 29
wyomingite 39

X

xenolith 39
xenotime 11, 12, 14, 15, 27, 47

Y

ytterbium 5, 6, 8, 10, 26, 27, 28, 31, 37, 38, 51
yttrium 1, 2, 5, 6, 7, 8, 10, 11, 13, 14, 15, 19, 21, 24, 25, 26, 27, 31, 37, 44, 45, 46, 51, 51, 52, 54, 55, 61, 61, 62

Z

zinc 63, 65
zircon 12, 14, 24, 25, 36, 39, 42, 46, 49, 50, 51, 55
zirconium 12, 25, 55
Zirkel Mesa 39

Notes

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