

Phosphate Rock in Wyoming

Jacob D. Carnes

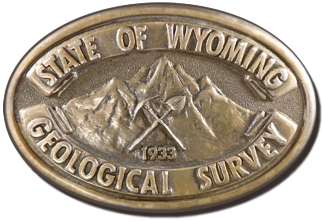


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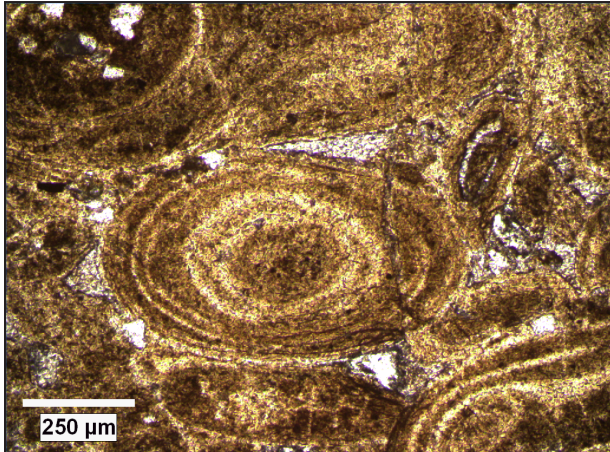


WYOMING STATE GEOLOGICAL SURVEY

Thomas A. Drean, Director and State Geologist



Director and State Geologist Thomas A. Dreaan



Photomicrograph of phosphate rock from the Poison Creek trench in Lincoln County, Wyo., showing the concentric structure of apatite grains commonly found in phosphorites of the Phosphoria Formation. *Photomicrograph by Jacob Carnes, 2015.*

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Cover photo: Outcrop of the Meade Peak Member of the Phosphoria Formation along U.S. Hwy 26, approximately 3 miles southwest of Hoback Junction, in Teton County, Wyo. *Photo by Jacob Carnes, 2015.*

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Wyoming State Geological Survey
Report of Investigations No. 68
2015

Jacob D. Carnes

Wyoming State Geological Survey, Laramie, Wyoming 82071

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ABSTRACT

Phosphorus (P) is a nutrient necessary for all life. It enters the terrestrial food chain when it is absorbed by plants from soil. Soluble phosphorus is often a limiting nutrient in natural ecosystems. Large scale agriculture can rapidly deplete the soluble phosphorus in soil, leading to the need for topical phosphorus fertilizer. Phosphate rock is currently the only source of phosphorus for synthetic fertilizers and other industrial uses.

There are six phosphate rock deposit-types that are typically targeted for economic development: (1) marine phosphorites, (2) igneous apatite, (3) residual phosphorites, (4) river pebble phosphate deposits, (5) phosphatized rock, and (6) guano. Marine phosphorites are well documented within the Permian Phosphoria Formation of western to central Wyoming; these are the only phosphate rock occurrences in Wyoming likely to be of a grade and extent to attract economic interest. Geologic settings favorable to igneous apatite do occur within the central Laramie Mountains, and the Black Hills of Wyoming, but no extensive igneous phosphate rock deposits have been reported in Wyoming. The remaining four deposit types are not found in Wyoming.

Thick, medium- to high-grade occurrences of phosphate rock are most common in western Wyoming, but may extend into central Wyoming. The Meade Peak Member of the Phosphoria Formation in the Overthrust Belt exhibits the highest potential for economically viable phosphate rock deposits with respect to grade and thickness; however, the steep inclination and discontinuity of beds may preclude mineability at many locations.

Southeast of Lander, the Meade Peak Member and, to a lesser degree, the Retort Member of the Phosphoria Formation host important phosphate deposits along the northeastern flank of the Wind River Mountains. The Lander deposits are low- to medium-grade, but the structural geology of the area is relatively simple compared to the Overthrust Belt.

INTRODUCTION

Phosphorus (P) is a nutrient vital for all life. It is a component in DNA and RNA, and also adenosine triphosphate, which facilitates energy transfer within cells (Environmental Literacy Council, 2013). Terrestrial plants incorporate phosphorus from soil, while animals receive phosphorus through their diet. In nature, phosphorus is commonly a limiting factor with respect to the quantity of life an ecosystem can support (Ozanne, 1980). In soil, natural soluble phosphorus that can be taken up by plants typically makes up less than 10 percent of total phosphorus

in the soil (Ozanne, 1980). In agricultural settings, natural availability of soluble phosphorus is often prohibitively low, thus phosphorus must be added to the soil by means of a topical fertilizer (Ozanne, 1980). Similarly, phosphorus feed additives may be required for ruminant livestock (Allaway, 1962; Reid, 1980; Underwood and Suttle, 1999). Phosphate rock is the primary source of phosphorus for these and other industrial applications. Phosphorus makes up around 0.1 percent of sedimentary rocks, and is only the 11th most abundant element in the earth's crust. However, given favorable environmental conditions over a protracted period of time, phosphorus may accumulate at higher rates, leading to concentrations in excess of 13 percent P, or 30 percent phosphorus pentoxide (P_2O_5) by weight (Filipelli, 2011). Phosphorus may also be concentrated in igneous rocks (McKelvey and others, 1953a). In phosphate rock, phosphorus most commonly occurs within the mineral apatite ($Ca_5(PO_4)_3(F,Cl,OH)$), a calcium phosphate with varying amounts of fluoride, chloride, and hydroxide anions. For this report, the term phosphate rock refers to any rock that contains more than 14 percent P_2O_5 . Rocks that contain 14–24 percent P_2O_5 are termed low-grade, 24–30 percent P_2O_5 rocks are termed medium-grade, and rocks that contain 30 percent P_2O_5 or more are termed high-grade.

The United States is the third largest producer of phosphate rock globally (fig. 1). The bulk of domestic production currently occurs in Florida and North Carolina, with remaining production in Idaho and Utah (Jasinski, 2015). Phosphate production in Idaho and Utah occurs from the so-called Western Phosphate Field (fig. 2), which is underlain by the Permian Phosphoria Formation. The Western Phosphate Field extends into western Wyoming, and although the Phosphoria Formation thins eastward from Idaho, notable phosphate rock deposits still exist in Wyoming (fig. 3).

Phosphate rock in Wyoming was first mined in 1907, and production in the western portion of the state was sporadic until the opening of the Leefe Mine in 1947 (Jasinski and others, 2004). The Leefe Mine, located approximately 30 miles west of Kemmerer, produced phosphate rock from the Phosphoria Formation from 1947 to 1977, after which time phosphate rock production in western Wyoming ceased (Wyoming Board of Equalization, 1948–1972; Wyoming Department of Revenue, 1973–1978; Jasinski and others, 2004). Though production in Wyoming has been dormant for more than 3½ decades, the phosphate mining industry has a robust presence in southeastern Idaho and northeastern Utah, and a phosphate processing facility is located near Rock Springs, Wyo. Thus, phosphate rock deposits in western Wyoming are relatively close to existing phosphate processing infrastructure.

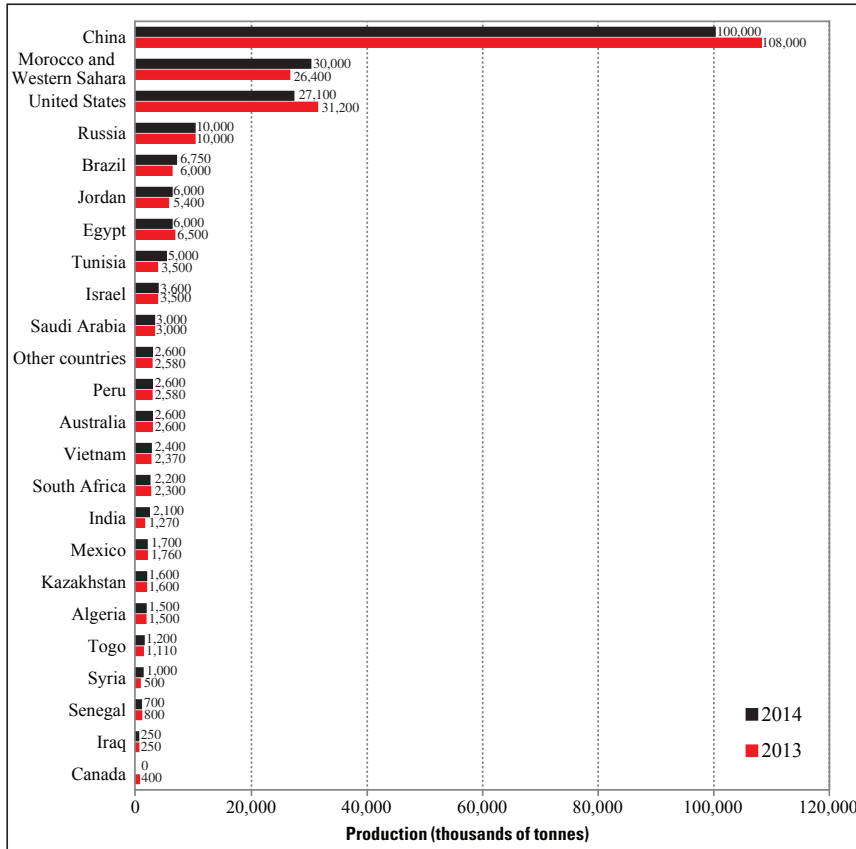


Figure 1. Global phosphate rock production for 2013 and 2014 by country, in thousands of tonnes.

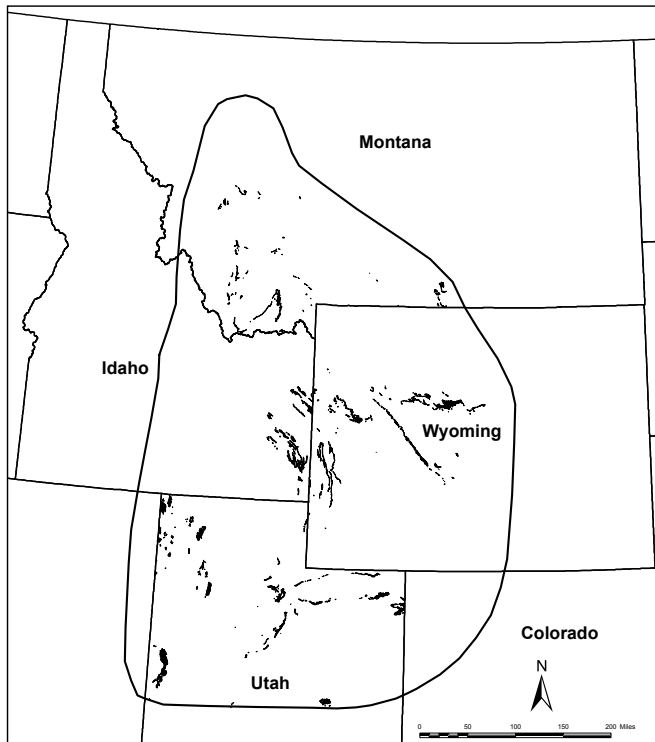


Figure 2. Map showing extent of the Western Phosphate Field and outcrops of Phosphoria-aged rocks. The Western Phosphate Field, outlined, covers a 350,000-km² area. Outcrops of the Phosphoria Formation and related rocks are shown in black. Modified from Hein and others (2004).

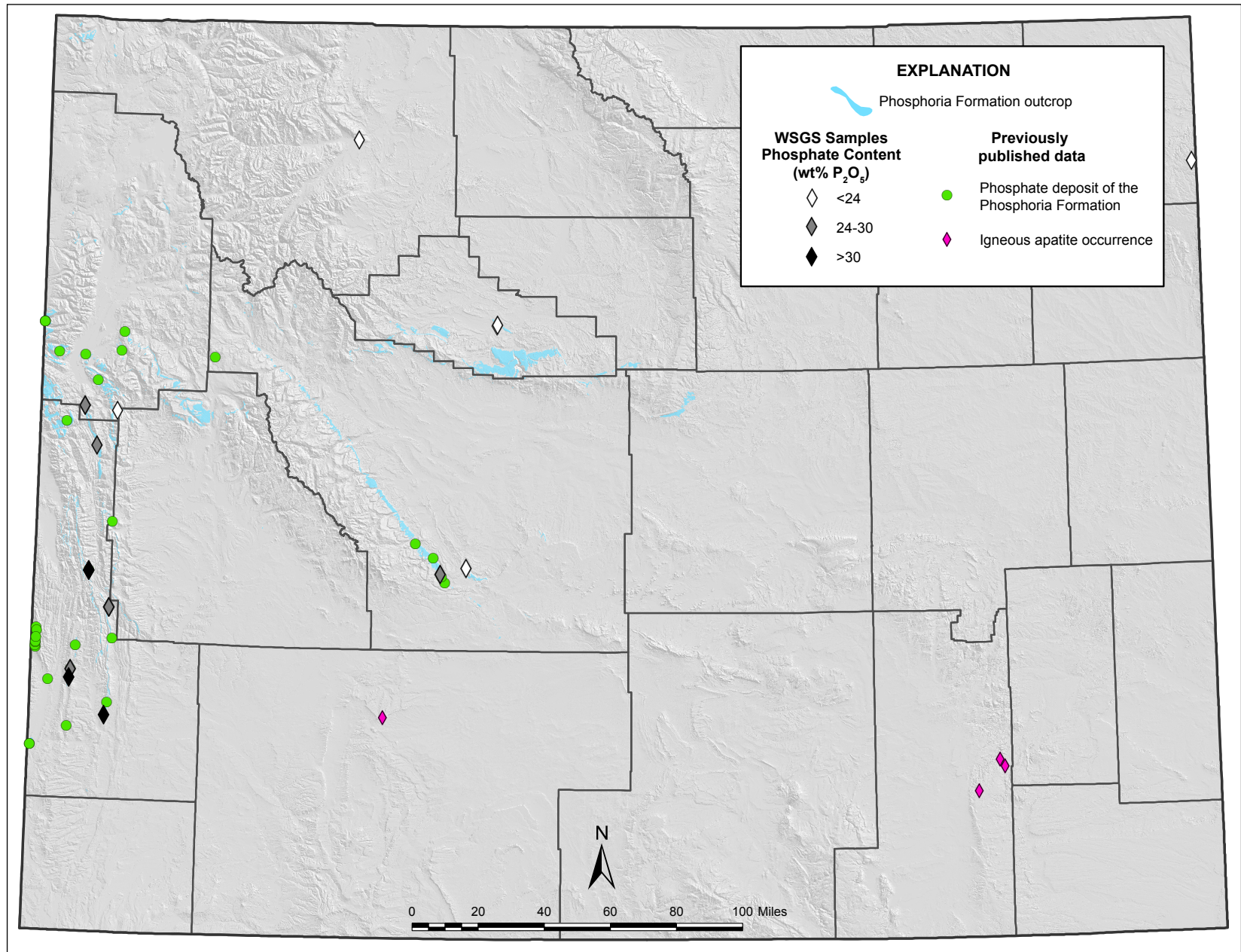


Figure 3. Map of Wyoming showing locations of previously reported medium- to high-grade phosphate rock beds greater than 3 ft in thickness, previously reported occurrences of igneous apatite, and the locations of samples collected and/or analyzed for this report.

A Note About Units

Units of measure for previously published data cited below are given in the same form as the original report without conversion from non-metric to metric, or vice versa. For simplicity and uniformity, measures of thickness and distance obtained during fieldwork for this report are given in the non-metric units of feet (ft) or miles (mi). Units of weight related to mined phosphate rock and estimates of reserves and resources are reported in literature as either non-metric tons or metric tonnes. One ton is equal to 2000 pounds (lb), or approximately 0.907 tonnes. A tonne is equal to 1000 kilograms (kg), or approximately 1.102 tons. In general, historical production figures are reported in tons, while modern estimates of reserves and resources are reported in tonnes.

OVERVIEW

This report aims to highlight the phosphate resources of Wyoming based on both a summary of previously collected data and the presentation of new data. The information included in this report will provide members of industry with a starting point for initiating new phosphate exploration and resource evaluation in Wyoming. Decision makers at state and community levels may also find this information useful in identifying potential areas of economic development.

To determine mining feasibility of a phosphate deposit, additional factors besides grade and bed thickness must be considered, including the extent of the deposit, steepness of dip, thickness of overburden, and accessibility. Complete identification of deposits that fully fit feasibility criteria is beyond the scope and intentions of this report; rather the aim of this report is to provide new and available information as a starting point for interested parties.

This report presents new data on 21 samples from several known, suspected, and potential phosphate deposits in Wyoming collected during field work for this report (table 1). Sampling of all known or potential phosphate deposits in the state was not possible given the time frame of this project. Sample sites for this report fit one of two objectives: (1) to fill in gaps between historical sampling locations, and (2) to confirm previously published values. Samples were analyzed by powder X-ray diffraction (XRD) to identify phosphate minerals, major element whole rock geochemistry to determine phosphate content, and trace element geochemistry for indications of other potential economic elements or metals (table 2, table 3).

PHOSPHATE DEPOSIT TYPES

According to McKelvey and others (1953a), there are six primary phosphate deposit types: (1) marine phosphorites,

(2) igneous apatite, (3) residual phosphorites, (4) river pebble phosphate deposits, (5) phosphatized rock, and (6) guano. Minor phosphate sources include ancient bone piles, glauconitic sedimentary deposits, and slag produced from phosphatic iron ore (Hertzog, 1935), as well as phosphatic lacustrine deposits (Love, 1964). Phosphate minerals can also be found associated with paleo-hot spring deposits, but such occurrences are generally low grade and limited in extent.

The majority of known phosphate deposits in Wyoming are marine phosphorites of the Phosphoria Formation (e.g., Sheldon and others, 1953; Simons and others, 1988; Sheldon, 1989). Gulbrandsen (1966) found that phosphorus in the Phosphoria Formation occurs in the mineral fluorapatite ($\text{Ca}_5(\text{PO}_4)_3\text{F}$). McKelvey and others (1953a) described two depositional facies of marine phosphorite: shallow marine and deep marine. Shallow marine deposits are associated with limestone, glauconitic sandstone, quartz sandstone, and minor clay; phosphate minerals in these deposits occur as nodules and pebbles up to 5 cm in diameter, though most are less than 1 cm in diameter. Shallow marine phosphorite deposits are typically low grade, with phosphate grains disseminated in a matrix of non-phosphate material. Less common high-grade shallow marine phosphate deposits are typically composed of reworked, older phosphatic sediment. Deep marine phosphorites occur as beds of phosphatic peloids (fig. 4) interbedded with black shale, chert, and minor limestone. Phosphatic beds can be 3 or more feet in thickness and can extend in area over thousands of square miles (McKelvey and others, 1953a). The interpreted depositional environment for the marine phosphorites of the Phosphoria Formation is a sediment-starved basin in areas of possible syn-depositional oceanic upwelling (Kazakov, 1937; McKelvey and others, 1953a; Hiatt and Budd, 2003). However, unanswered questions remain about the style and role of oceanic upwelling during deposition (e.g., Hiatt and Budd, 2003; Ketner, 2009).

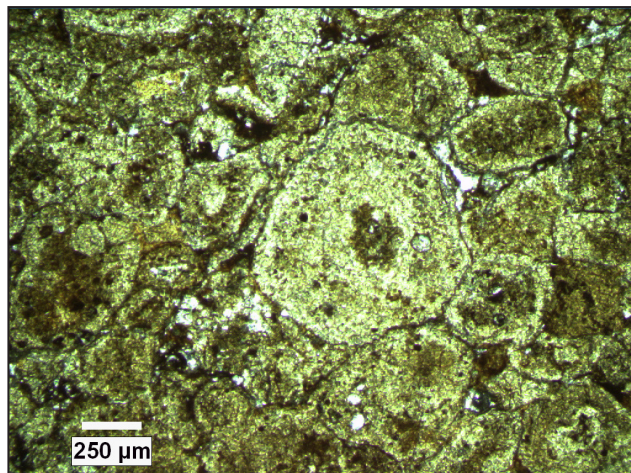


Figure 4. Plane polarized light photomicrograph of sample 20150715JC-C showing peloidal texture of apatite grains.

Table 1. List of samples collected for this report.

Sample number	Lithology	Locality	Latitude	Longitude	Legal Location	County
20150622JC-B	Mudstone	Twin Creek Road	42.6244	-108.4853	NE1/4, NE1/4, sec. 36, T.31N., R.98W.	Fremont
20150622JC-C	Phosphate rock	Twin Creek Road	42.6244	-108.4853	NE1/4, NE1/4, sec. 36, T.31N., R.98W.	Fremont
20150623JC-B	Phosphate rock	Red Canyon	42.5988	-108.6378	NW1/4, SW1/4, sec. 2, T.30N., R.99W.	Fremont
20150623JC-C	Phosphate rock	Red Canyon	42.5988	-108.6378	NW1/4, SW1/4, sec. 2, T.30N., R.99W.	Fremont
20150624JC-A	Tufa(?)	Eagle Ridge	43.6923	-108.3130	NW1/4, SW1/4, sec. 18, T.43N., R.95W.	Hot Springs
20150624JC-C	Mudstone	Eagle Ridge	43.6932	-108.3108	NW1/4, SW1/4, sec. 18, T.43N., R.95W.	Hot Springs
20150713JC-A	Phosphate rock	South Commissary Ridge	41.9481	-110.6044	SW1/4, NE1/4, sec. 29, T.23N., R.116W.	Lincoln
20150714JC-A	Phosphate rock	North Fork Pine Creek	42.1441	-110.8109	NW1/4, NW1/4, sec. 24, T.25N., R.118W.	Lincoln
20150714JC-B	Phosphate rock	North Fork Pine Creek	42.1441	-110.8109	NW1/4, NW1/4, sec. 24, T.25N., R.118W.	Lincoln
20150714JC-C	Phosphate rock	North Fork Pine Creek	42.1435	-110.8114	NW1/4, NW1/4, sec. 24, T.25N., R.118W.	Lincoln
20150714JC-E	Phosphate rock	Middle Fork Pine Creek	42.1076	-110.8172	NE1/4, SE1/4, sec. 35, T.25N., R.118W.	Lincoln
20150715JC-A	Phosphate rock	Poison Creek	42.5797	-110.7222	SW1/4, SW1/4, sec. 13, T.30N., R.117W.	Lincoln
20150715JC-B	Phosphate rock	Shafer Creek	42.4189	-110.5963	NE1/4, NW1/4, sec. 15, T.28N., R.116W.	Lincoln
20150715JC-C	Phosphate rock	Shafer Creek	42.4189	-110.5963	NE1/4, NW1/4, sec. 15, T.28N., R.116W.	Lincoln
20150715JC-D	Phosphate rock	Shafer Creek	42.4189	-110.5963	NE1/4, NW1/4, sec. 15, T.28N., R.116W.	Lincoln
20150715JC-E	Phosphate rock	Poison Creek	42.5797	-110.7222	SW1/4, SW1/4, sec. 13, T.30N., R.117W.	Lincoln
20150716JC-A	Phosphate rock	Hoback	43.3017	-110.7804	SW1/4, NE1/4, sec. 32, T.39N., R.116W.	Lincoln
20150716JC-B	Mudstone	Hoback	43.3017	-110.7804	SW1/4, NE1/4, sec. 32, T.39N., R.116W.	Lincoln
20150716JC-C	Phosphate rock	Hoback	43.3017	-110.7804	SW1/4, NE1/4, sec. 32, T.39N., R.116W.	Lincoln
20150716JC-E	Phosphate rock	Waterdog Lake	43.1274	-110.7025	SW1/4, SE1/4, sec. 36, T.37N., R.116W.	Lincoln
20150717JC-A	Phosphate rock	Buck Creek	43.2805	-110.5864	SW1/4, SE1/4, sec. 1, T.38N., R.115W.	Lincoln

Table 2. Major element geochemistry of samples collected for this investigation. Phosphate contents greater than 24% P₂O₅ and corresponding sample numbers are in bold.

Sample Number	Al ₂ O ₃ (wt%)	BaO (wt%)	CaO (wt%)	Cr ₂ O ₃ (wt%)	Fe ₂ O ₃ (wt%)	K ₂ O (wt%)	MgO (wt%)	MnO (wt%)	Na ₂ O (wt%)	P ₂ O ₅ (wt%)	SiO ₂ (wt%)	SrO (wt%)	TiO ₂ (wt%)	Loss on ignition
20150622JC-B	2.05	0.02	41.4	0.04	1.14	0.84	2.69	0.02	0.37	10.25	15.21	0.04	0.13	24.51
20150622JC-C	2.01	0.02	38	0.04	1.12	0.87	0.54	0.02	1	23.3	22.65	0.09	0.11	7.46
20150623JC-B	3.1	0.04	38.7	0.05	1.68	1.4	1.06	0.05	1.02	21.6	17.96	0.1	0.18	10.14
20150623JC-C	2.01	0.03	43.8	0.04	1.2	0.94	0.63	0.03	1.04	24.2	12.72	0.1	0.12	10.16
20150624JC-A	0.26	0.02	23.8	0.12	2.66	0.06	0.01	0.01	0.04	2.93	29.98	0.02	0.13	9.43
20150624JC-C	0.37	0.01	37.4	0.02	0.87	0.19	13.2	0.03	0.08	3.83	2.55	0.01	0.03	39.93
20150713JC-A	1.09	0.04	46.7	0.06	0.57	0.43	0.2	0.01	1.44	31.1	8.55	0.13	0.09	4.97
20150714JC-A	3.99	0.04	27.1	0.05	4.28	1.16	0.34	0.03	0.43	18.7	38.02	0.07	0.29	3.78
20150714JC-B	1.3	0.01	16.7	0.03	1.44	0.41	0.2	0.04	0.11	5.33	65.74	0.02	0.09	8.08
20150714JC-C	2.14	0.03	36.9	0.13	6.37	0.71	0.48	0.01	0.51	25.7	21.14	0.07	0.16	3.76
20150714JC-E	1.66	0.06	44.5	0.16	1	0.58	0.17	0.03	0.93	30.7	11.04	0.11	0.16	8.95
20150715JC-A	0.67	0.02	47.9	0.07	0.37	0.18	0.07	0.01	0.84	33.7	8.86	0.09	0.05	3.64
20150715JC-E	0.59	0.02	49	0.07	0.29	0.16	0.08	0.01	0.84	34.5	7.79	0.1	0.05	3.52
20150715JC-B	0.23	0.02	52.8	0.1	0.21	0.07	0.02	0.01	0.93	35.2	1.72	0.06	0.03	4.34
20150715JC-C	1.69	0.03	44.5	0.16	0.67	0.49	0.19	0.01	1.1	30.8	11.01	0.07	0.17	5.07
20150715JC-D	1.92	0.02	42.4	0.07	0.8	0.43	0.16	0.01	0.85	29.9	16.92	0.06	0.15	3.66
20150716JC-A	1.29	0.03	42.3	0.12	0.88	0.39	0.29	0.01	1.21	28.8	8.34	0.11	0.09	10.82
20150716JC-B	10.79	0.04	1.62	0.07	3.75	3.13	0.67	0.01	0.13	0.92	67.17	0.05	0.73	9.57
20150716JC-C	1.11	0.02	42.3	0.09	1.06	0.35	0.08	0.01	1.05	29.5	6.15	0.1	0.08	13.94
20150716JC-E	1.23	0.02	37.5	0.05	1.45	0.28	0.01	0.02	0.4	27.2	27.51	0.07	0.09	2.53
20150717JC-A	0.27	0.02	34.9	0.02	0.78	0.14	0.25	0.02	0.83	22.9	33.29	0.09	0.04	4.76
20121214WSGS-A	8.34	0.03	1.62	0.01	14.62	5.47	0.48	0.1	1.12	1.2	62.23	0.03	1.51	2.48
WGS-0684-X	4.67	0.02	0.79	0.1	2.12	1.48	0.04	0.01	0.03	7.17	80.29	0.01	0.06	2.61

Igneous apatite is another potential source of phosphate in Wyoming, though much less significant than marine phosphorites. Igneous apatite can occur in a variety of host rocks, including layered mafic to ultramafic rocks and syenites, in iron- and titanium-rich rocks, and in carbonatites. Apatite-rich layers within these host rocks can be hundreds of feet thick and up to a few miles across. Apatite can also occur in hydrothermal veins, as disseminated replacements, as metasomatic differentiation products near the margins of intrusions, and within pegmatites (McKelvey and others, 1953a). Geologic settings favorable to igneous apatite occurrences that are present in Wyoming include iron-titanium rich rocks in the Laramie Range and nepheline syenite in the Black Hills (e.g., DeWitt and others, 1986, Frost and others, 1993).

Of the primary phosphate deposit types identified by McKelvey and others (1953a), the remaining four are less important in Wyoming. Residual phosphorites result from the chemical erosion of phosphate-bearing limestone in humid climates. Carbonate-fluorapatite in these depos-

its is less soluble than calcite and is left behind as limestone breaks down (McKelvey and others, 1953a). River pebble phosphate deposits are the product of erosion and subsequent deposition by run-off, streams, and rivers of residual phosphate deposits (McKelvey and others, 1953a). Phosphatized rock develops in tropical to subtropical regions where the pH of meteoric water is lowered by abundant decaying organic matter, allowing the dissolution of apatite in sedimentary rocks and removal during runoff. Re-precipitation of the phosphate can occur when the runoff encounters aluminum- or iron-rich rocks, or limestone. The phosphate mineralization may occur along joint surfaces, as replacement of bedrock, or as residual boulders (McKelvey and others, 1953a). Guano phosphate deposits are large accumulations of excrement from sea fowl or bats. Guano is rich in both nitrogen and phosphate. Nitrogen is extremely mobile compared to phosphate, so the nitrogen in these deposits is quickly leached, leaving a phosphate-rich residue behind. Guano phosphate deposits are typically restricted in size and have a complex mineralogy (McKelvey and others, 1953a).

Table 3. Trace element geochemistry of samples collected for this investigation.

Sample	Ba (ppm)	Ce (ppm)	Cr (ppm)	Cs (ppm)	Dy (ppm)	Er (ppm)	Eu (ppm)	Ga (ppm)	Gd (ppm)	Ge (ppm)	Hf (ppm)	Ho (ppm)	La (ppm)	Lu (ppm)	Nb (ppm)	Nd (ppm)	Pr (ppm)
20150623JC-B	211	59.6	350	1.83	7.96	5.41	1.68	4.7	8.92	<5	1.5	1.83	107	0.66	3.6	48.5	13.25
20150714JC-E	406	88.4	1130	3.42	28.8	22.8	5.06	3.8	30.7	<5	3.4	7.4	283	2.99	2.2	141.5	37.1
20150715JC-C	111.5	53.8	1120	1.3	14.7	12.3	2.49	3.9	15.5	<5	3.6	3.91	198.5	1.85	2.4	73.7	19.8
20150715JC-E	50.8	88.5	450	0.26	50.3	35.8	11.4	3.6	61.4	<5	1.1	12.15	491	4.27	0.4	296	75.9
20150716JC-B	334	50.8	440	5.49	3.84	2.47	0.85	9.4	4.26	<5	9.7	0.86	38.5	0.43	12.9	26.2	7.06

Sample	Rb (ppm)	Sm (ppm)	Sn (ppm)	Sr (ppm)	Ta (ppm)	Tb (ppm)	Th (ppm)	Tm (ppm)	U (ppm)	V (ppm)	W (ppm)	Y (ppm)	Yb (ppm)	Zr (ppm)	Ag (ppm)	Cd (ppm)	Co (ppm)
20150623JC-B	36.3	8.38	1	923	0.1	1.24	5.09	0.73	20.4	99	1	129.5	4.35	76	<0.5	5	5
20150714JC-E	22.3	24.1	<1	1020	0.1	4.14	4.74	3.13	31.8	228	10	525	18.2	145	2.8	22.2	<1
20150715JC-C	15.9	11.4	<1	617	0.1	2.06	3.64	1.77	129.5	521	1	310	10.9	164	2.9	84.3	<1
20150715JC-E	5.2	48.6	<1	879	<0.1	7.69	1.88	4.7	53.4	205	<1	790	27.3	64	1.1	26.7	<1
20150716JC-B	84.3	4.96	2	410	0.9	0.6	8.99	0.4	12	381	6	32	2.86	376	8.7	21.8	2

Sample	Cu (ppm)	Li (ppm)	Mo (ppm)	Ni (ppm)	Pb (ppm)	Sc (ppm)	Zn (ppm)	As (ppm)	Bi (ppm)	Hg (ppm)	In (ppm)	Re (ppm)	Sb (ppm)	Se (ppm)	Te (ppm)	Tl (ppm)	
20150623JC-B	9	20	<1	16	27	6	552	13.6	0.19	0.047	0.031	0.002	0.16	4.5	2.4	0.02	0.38
20150714JC-E	15	20	1	51	10	7	644	67.2	0.06	0.119	0.017	0.003	2.65	6.3	6.2	0.06	0.44
20150715JC-C	42	10	16	31	13	5	969	6.6	0.04	0.174	0.013	0.073	1.19	4.6	9.3	0.03	5.66
20150715JC-E	25	10	18	29	12	4	362	5.8	0.02	0.261	0.008	0.093	1.55	3.7	9	0.03	0.27
20150716JC-B	50	60	43	154	17	8	1550	35.6	0.2	0.253	0.021	0.155	9.04	3.7	95.9	0.37	0.09

PHOSPHATE CONSUMPTION AND SUPPLY

More than 95 percent of domestically produced phosphate rock is used in the production of fertilizer. Phosphorus is also essential in the manufacture and production of various products, including food additives, pesticides, matches, flame retardants, and plasticizers (Threlfall, 1951; Greenwood and Earnshaw, 1997). As food production is the dominant application of phosphate rock, both as fertilizer and as additives to livestock feed, population growth will drive increases in phosphate rock demand. The United Nations (UN) predicts a 40 percent rise in global population by 2100 (United Nations, 2004). Increased fertilizer application to boost crop yields will be a potential factor in meeting food production needs with rising population (e.g., FAO, 2008). However, due to diminishing returns, increased crop yields will not be proportional to increases in fertilizer application (Tilman and others, 2002).

The amount of mineable phosphate rock present on Earth has been a point of debate and concern over the last decade (e.g., Cordell and others, 2009; Van Vuuren and others, 2010; Van Kauwenbergh, 2010; Edixhoven and others, 2014). Cordell and others (2009), and Van Vuuren and others (2010), highlighted a then-apparent global shortage of mineable phosphate deposits. Indeed, the world phosphorus market exhibited signs of resource scarcity as early as the mid-1990's, and into the late 2000's (Vaccari and Strigul, 2011). Between 1980 and 1996, the average ore grade of mined phosphate rock decreased from 32.7 percent P_2O_5 to 29.5 percent P_2O_5 (Isherwood, 2000; Liu and others, 2008). Vaccari and Strigul (2011) note a 5.1 percent decline in the average grade of phosphate rock produced in the U.S. between 1991 and 2009, but do not cite specific values. Between 2006 and 2014, after 13 years of relatively stable prices below \$50/tonne, the cost of phosphate rock exhibited volatility (Vaccari and Strigul, 2011; Infomine, 2015), including a price spike in 2008 to \$430/tonne. Prices stabilized at \$115/tonne in late 2014 (fig. 5).

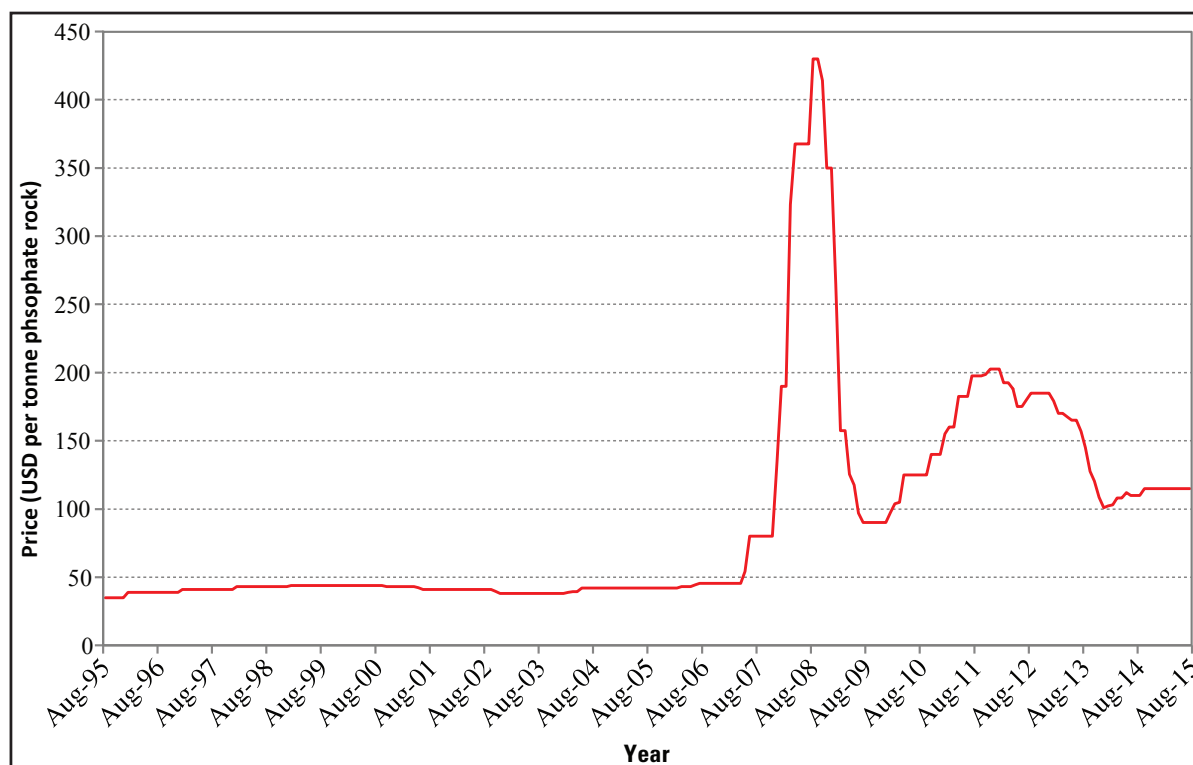


Figure 5. Price of phosphate rock, composed of 70% bone phosphate of lime (32% P_2O_5), in U.S. dollars per tonne from August 1995 through July 2015 (IndexMundi, 2015). Vaccari and Strigul (2011) pointed to the price volatility starting in 2007 following decades of relative stability as a sign of phosphate rock scarcity.

Fears that mineable phosphate deposits may be exhausted by the early 22nd century (Van Vuuren and others, 2010) were countered by revised global phosphate resource estimates that quadrupled previous estimates (Van Kauwenbergh, 2010; Jasinski, 2011). The revised global resource estimates (table 4) rely on data from Moroccan and Western Saharan phosphate deposits that were not included in previous estimates (Van Kauwenbergh, 2010). The revised global phosphate estimates, if accurate, extend the life of mineable phosphates up to 400 years (Van Kauwenbergh, 2010), though the validity of the data used for the revised estimates has been called into question (e.g., Edixhoven and others, 2014). Criticism largely centers on what market conditions the Moroccan phosphate deposits require to be economic. Even if much of the newly reported Moroccan phosphate rock is not economically viable for production under present circumstances, these deposits may still extend the lifetime of global phosphate deposits well into the future. As easily mined phosphate rock becomes scarcer, phosphate prices may increase, resulting in previously uneconomic lower grade deposits becoming more conducive to mining. Additionally, recycling and conservation may reduce overall demand for phosphate rock in the future (Vaccari and Strigul, 2011). The fact remains, however, that there is currently no alternative or substitute for phosphorus in the food supply chain (Jasinski, 2015), and the primary source for phosphorus used in this chain is phosphate rock.

The United States is the third largest phosphate rock producer globally behind China and Morocco (fig. 1). In 2014, phosphate rock mines in the United States produced 27,100,000 tonnes of phosphate rock, down from 31,200,000 tonnes in 2013, and 30,100,000 tonnes in 2012 (Jasinski, 2015). Approximately 80–85 percent of domestic production occurs in Florida and South Carolina; the remaining output is produced from the Western Phosphate Field in southeast Idaho and northeast Utah (Jasinski, 2014, 2015). The drop in domestic production in 2014 is attributed to the closure of a mine in Florida and higher than average stockpiles (Jasinski, 2015). The United States imported 2,570,000 tonnes of phosphate rock in 2014, and a similar amount in 2013. Imports in 2011 and 2012 exceeded 3,000,000 tonnes. Phosphate imports to the United States are sourced from Morocco and Peru (Jasinski, 2014, 2015).

Six phosphate mines are currently in operation in the western United States: five in southeast Idaho and one in Utah. Kiewit Corporation operates the Dry Valley and North Rasmussen Ridge mines in Idaho under contract for Agrium. P4 Production LLC, a wholly owned subsidiary of Monsanto, operates the South Rasmussen and Blackfoot Bridge mines in Idaho. The J.R. Simplot Company oper-

ates the Smoky Canyon Mine in Idaho and the Vernal Mine in Utah.

Agrium ships phosphate rock to its Conda Phosphate plant in Soda Springs, Idaho, where it produces mono-ammonium phosphate, phosphoric acid, and superphosphoric acid (Agrium, 2015). Monsanto ships ore material from South Rasmussen and Blackfoot Bridge mines to its processing facility near Soda Springs, Idaho. Monsanto smelts phosphate rock to produce elemental phosphorus, which is a key component in glyphosate herbicides (Monsanto, 2014). Phosphate rock mined by Simplot is slurried and shipped by pipeline from Vernal, Utah to a processing facility in Rock Springs, Wyo., and from the Smoky Canyon Mine to a plant in Pocatello, Idaho (J.R. Simplot Company, 2008a,b).

Table 4. Global phosphate rock reserves in thousands of tonnes by country, as reported by the USGS (Jasinski, 2015).

Country	Reserves
Morocco and Western Sahara	50,000,000
China	3,700,000
Algeria	2,200,000
Syria	1,800,000
South Africa	1,500,000
Jordan	1,300,000
Russia	1,300,000
United States	1,100,000
Australia	1,030,000
Peru	820,000
Egypt	715,000
Iraq	430,000
Other countries	300,000
Brazil	270,000
Kazakhstan	260,000
Saudi Arabia	211,000
Israel	130,000
Tunisia	100,000
Canada	76,000
Senegal	50,000
India	35,000
Togo	30,000
Mexico	30,000
Vietnam	30,000
World total (rounded)	67,000,000

MARINE PHOSPHORITES

Phosphogenesis

Marine phosphate deposits originate during conditions of rapid biomass production in the water column. High biological activity contributes to the formation of marine phosphorites in two ways: (1) the large amount of organic material serves as a source for abundant phosphorite; and (2) the anoxic to euxinic marine environments produced by high biological activity promote phosphate deposit preservation (e.g., Hiatt and Budd, 2003). Therefore, concentrations of phosphate minerals in the marine sedimentary record result from relatively uncommon environmental conditions that allow high biological production, periodic winnowing, and rapid burial without significant detrital input (Filippelli, 2011).

In Wyoming, the Phosphoria Formation was, in part, deposited at the bottom of the Phosphoria Sea, an epicontinental sea that inundated much of the present-day western United States during the Permian Period, approximately 269–265 Ma (Wardlaw and others, 1995; Wardlaw, 1999). A potential contemporary analog for Phosphoria deposition is occurring off the coast of Peru, where marine phosphate deposition has been linked to large phytoplankton blooms driven by coastal upwelling of cold, nutrient-rich bottom waters (Filippelli, 2011). Kazakov (1937, 1938) first recognized upwelling as an important oceanographic process, and McKelvey and others (1953a) applied Kazakov's models to the Phosphoria Formation to explain high concentrations of phosphate minerals and organic carbon. More recent publications, though, call into question the role of upwelling cold bottom water in the formation of phosphate rock in the Phosphoria. Hiatt and Budd (2003) argued that upwelling water was sourced from the middle of the water column, not the bottom. Ketner (2009) correlated Phosphoria Formation from Utah and Idaho across Nevada to argue that the Phosphoria Basin was shallow with a relatively flat floor over an extensive area, which would prohibit upwelling in the part of the Phosphoria Sea that is now Idaho and western Wyoming.

The Phosphoria Formation

Deposition of the Phosphoria Formation and related Park City Formation occurred within the Phosphoria Basin, off the northwest margin of Pangea, during the first part of the Late Permian, approximately 269–265 Ma (Wardlaw and others, 1995; Wardlaw, 1999). The Milk River Uplift of western Montana bounded the Phosphoria Basin to the north, and the Confusion Shelf and uplifts of the Ancestral Rocky Mountains in Colorado and Utah bounded the basin to the south (Maughan, 1984). The evaporative

Goose Egg Basin bounded the Phosphoria Basin to the east (Maughan, 1984; Perkins, 2003; Hein, 2004).

The source of phosphorus in the Phosphoria Formation was organic matter (Moyle and Piper, 2004). Environmental factors likely drove the rapid accumulation of this organic matter to produce phosphate rock. The paleogeography of the Phosphoria Basin was such that the combination of surface currents flowing along the continental margin and mid-latitude westerly winds may have promoted upwelling of nutrient-rich waters, driving biological productivity and resulting in the accumulation of organic material on the sea floor (McKelvey and others, 1953a; Hiatt and Budd, 2003). Ketner (2009) provides interesting evidence against the occurrence of oceanic upwelling during Phosphoria deposition, but he fails to identify other environmental factors that may have been responsible for elevated biological productivity.

Stratigraphy of the Phosphoria Formation

Sheldon (1963) provides an in-depth description of stratigraphic relationships of the Phosphoria Formation and related rocks; the following is based largely on his work. In Wyoming, the Phosphoria is divided into five units: a lower chert unit, plus the Meade Peak, Rex Chert, Retort, and Tosi Chert members (fig. 6; Sheldon, 1963). The lower chert is an informal unit of the Phosphoria Formation, consisting of a succession of chert beds with minor calcareous, clay-rich, phosphatic, or sandy beds, up to a maximum of 40 ft thick. The lower chert is limited in aerial extent compared to the rest of the Phosphoria Formation (Sheldon, 1963). Outcrops of the lower chert occur in the southern Teton and southeastern Gros Ventre ranges and in the eastern portion of the Wyoming Range. To the north, east, and south, the lower chert grades into the carbonate-rich Grandeur Member of the Park City Formation. To the west, the lower chert grades into the black shale of the Meade Peak Member of the Phosphoria Formation. The Phosphoria Formation intertongues with the laterally equivalent Park City Formation to the east, southeast, and south (fig. 6), and with the Shedhorn Sandstone to the north and northeast.

The dark colored, non-resistant Meade Peak Member of the Phosphoria Formation is up to 250 ft thick, with the thickest portions of the member located in southeastern Idaho, northeastern Utah, and southwestern Wyoming (Tisoncik, 1984). The member consists of interbedded phosphorite, mudstone, and carbonate rock, with minor phosphatic sandstone. Phosphate rock beds in the Meade Peak Member are composed almost entirely of fluorapatite. Fluorapatite in phosphate rock is dominantly peloidal (fig. 4), but also occurs as bioclastic fragments. Most spheroidal

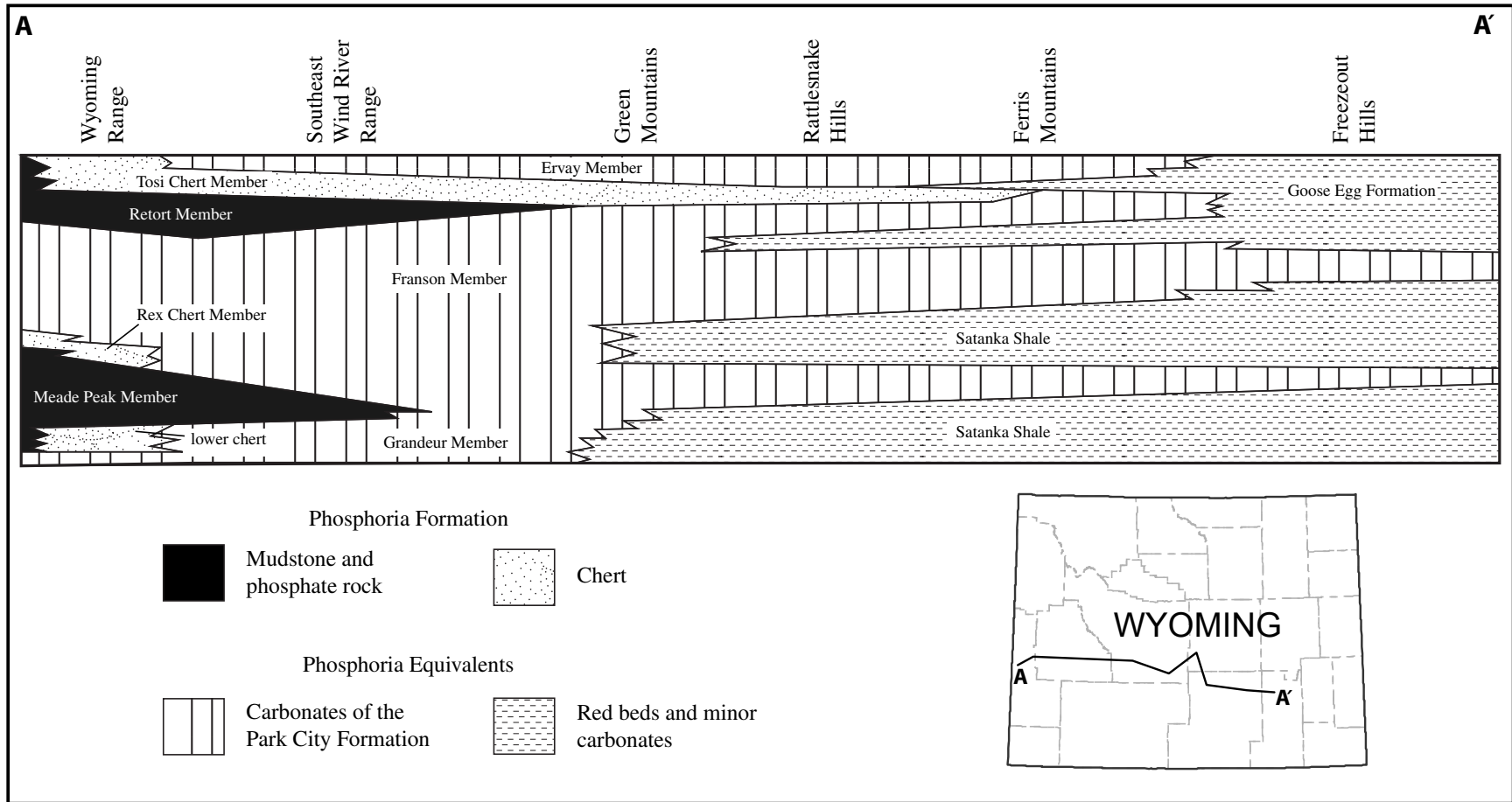


Figure 6. Generalized stratigraphic section of the Phosphoria Formation and related rocks across Wyoming. The approximate line of the section is shown on the location map. Modified from McKelvey and others, 1959.

dal apatite grains range 0.06–4 mm in diameter, but some grains are up to 2 cm across. The Meade Peak Member thins to the north and the east. Much of the thinning into central Wyoming is due to the Meade Peak beds grading into the lower chert and Rex Chert members. In western Wyoming, however, individual beds are persistent, especially along strike, and thinning here is accounted for by the thinning of individual beds, rather than beds pinching out, or grading into separate facies. From western Wyoming into the central part of the state, the Meade Peak Member generally becomes sandier, and carbonate rock and mudstone become less abundant. The highest grade phosphate rock in the Meade Peak Member is commonly located in the upper half of the unit, where the barren rocks grade upward into peloidal phosphate rocks, which in turn, in places, grade into bioclastic phosphorite at the top of the member.

The Rex Chert Member of the Phosphoria Formation consists of chert beds between the Meade Peak and Retort members. The Rex Chert Member intertongues with the Shedhorn Sandstone and the Park City Formation. In southeastern Idaho, these intertonguing units divide the Rex Chert into three parts. The greatest thickness of the Rex Chert exceeds 110 ft in the Caribou Range of southeastern Idaho; the thickness of the member decreases to the north, east, and southeast as it grades into other rock types. The Rex Chert is predominantly pure chert, with interbedded sandy, dolomitic, calcareous, argillaceous, or phosphatic chert. Apatite grains in the Rex Chert are typically less than 1 mm in diameter; bioclastic fragments account for most of the apatite, though peloidal apatite does occur. The Rex Chert Member is thin-bedded to massive. Except for bedding planes, sedimentary structures are commonly absent, though in places, laminations, nodules, and tubular concretions are present.

The Retort Member of the Phosphoria Formation is a dark, non-resistant, phosphatic, mudstone unit that is widespread throughout the Phosphoria Formation in Wyoming. The Retort Member consists of interbedded, dark gray-to-black mudstone and shale, phosphate rock, and minor carbonate rock. Phosphate rock in the Retort is black to dark gray, thin-bedded, medium-hard argillaceous peloidal rock. Fluorapatite grains can be up to 4 mm in diameter. The Retort Member reaches its maximum thickness of approximately 60 ft in the eastern Gros Ventre Range and in the central to southern Wind River Range. The Retort Member thins to a few feet in thickness in Yellowstone National Park, the northern Wind River Range, and the Owl Creek Mountains. To the south-southwest, in the Wyoming and Snake River ranges, the Retort Member thins to 10–20 ft in thickness. Phosphate rock is most prevalent along the western extent of the Retort Member in the

Wyoming and Hoback ranges, as well as in the Big Hole Range in Idaho. However, Retort Member phosphorites are present as far east as the Owl Creek Mountains, and Conant Creek Anticline in central Wyoming.

The Tosi Chert Member is the uppermost unit of the Phosphoria Formation. The Tosi Chert is lithologically similar to the Rex Chert, and consists of pure chert interbedded with argillaceous, sandy, dolomitic, calcareous, or phosphatic chert. In the northern Teton Range, the Tosi Chert reaches its maximum thickness of 75 ft.

The Park City Formation and Shedhorn Sandstone divide the Phosphoria Formation across much of its extent in Wyoming (Sheldon, 1963). Much academic work has focused on developing sequence stratigraphic models of sedimentation in the Phosphoria Basin during the Permian (e.g., Hein and others, 2004). General agreement exists that the Meade Peak and Retort members, at least in part, represent transgressions of the Phosphoria Sea. For more detailed information regarding the sequence stratigraphy of the Phosphoria and Park City formations, see Hein and others (2004).

Past Production from the Phosphoria Formation in Wyoming

While current production from the Western Phosphate Field is restricted to Idaho and Utah, past production also occurred in Montana and Wyoming (Jasinski and others, 2004). Phosphate rock in the Western Phosphate Field was first discovered in 1889 in Cache County, Utah; mining activities began there in 1904 (Jasinski and others, 2004). In Wyoming, phosphate mining occurred at four facilities: the Cokeville underground mine, the York Canyon underground mine, the South Mountain surface and underground mine, and the Leefe mine, which consisted of two open pits (fig. 7; Jasinski and others, 2004). These mines each targeted phosphate rock in the Phosphoria Formation within the Overthrust Belt in Lincoln County, Wyo.

Cokeville Mine

Production of phosphate rock in Wyoming first occurred in 1907 at the Cokeville underground mine, located just east of Cokeville, Wyo. The Union Phosphate Company/Cokeville Phosphate Company operated the mine intermittently until 1931 (Coffman and Service, 1967). Production information from the Cokeville Mine is not available prior to 1919. From 1925 through 1931, the mine produced over 29,200 tons of phosphate rock (Wyoming Board of Equalization, 1926–1932).

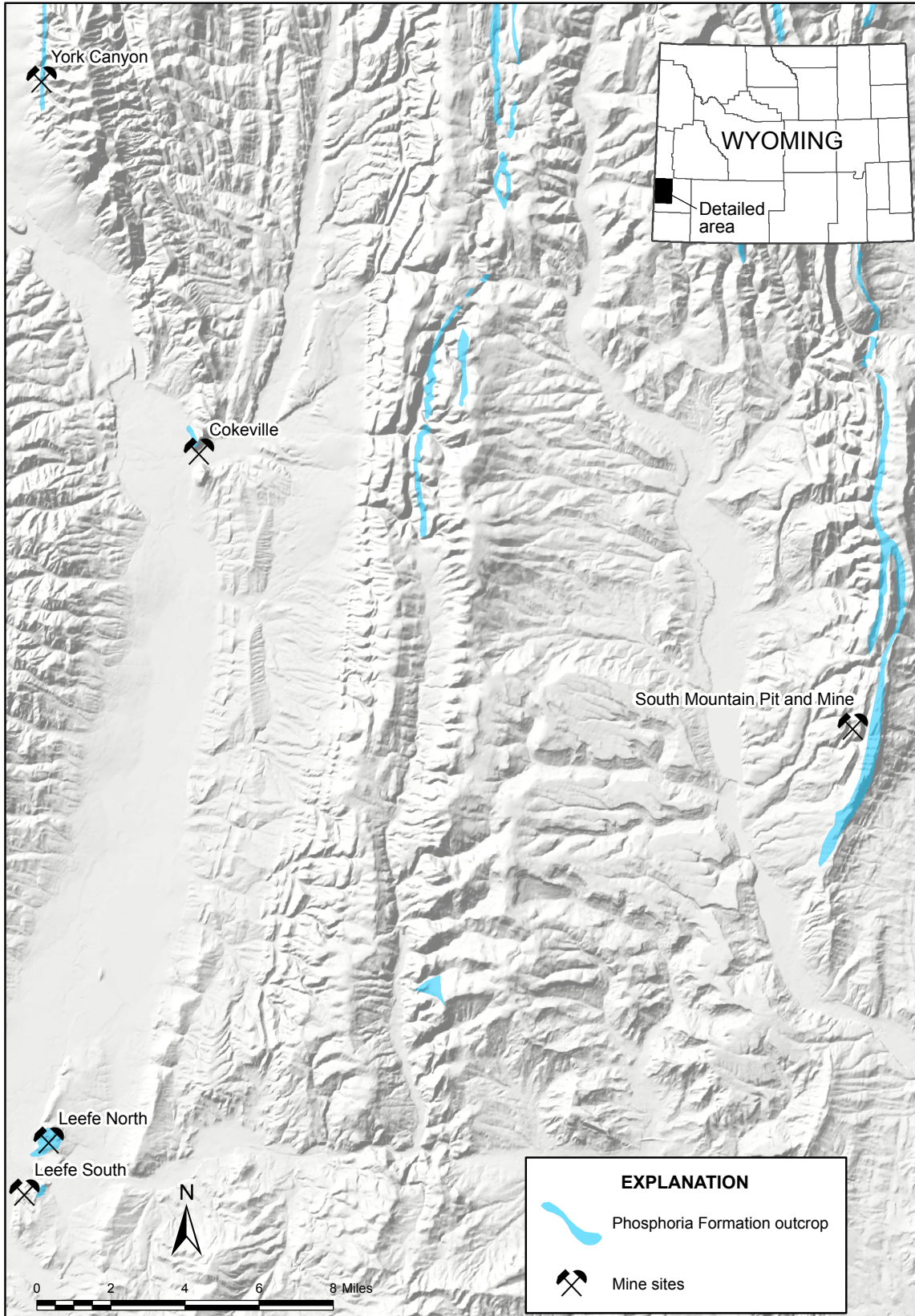


Figure 7. Map showing historic phosphate rock mines in southwest Wyoming.

The Cokeville deposit is on the east limb of a faulted north-plunging anticline where bedding orientation is 330°, 60° E. (Sheldon and others, 1953). Sheldon and others (1953) noted a 4.7 ft thick succession of phosphate rock and phosphatic mudstone in the Meade Peak Member that averaged 30.2 percent P₂O₅.

York Canyon Mine

The York Canyon underground mine northwest of Cokeville operated from 1913 to 1917. The U.S. Phosphate Company mined and pulverized phosphate rock here for direct application to soil. The company guaranteed the crushed rock contained more than 32 percent P₂O₅ (Coffman and Service, 1967). Production figures from the York Canyon Mine are not available. Bedding at the York Canyon mine is nearly vertical and strikes north-northeast; the host bed at York Canyon was 4 ft thick, and averaged 34.4 percent P₂O₅ (Mansfield, 1927).

South Mountain Mine – Commissary Ridge

Near Kemmerer, Phosphate Mines, Inc. operated the open pit and underground South Mountain Mine on Commissary Ridge. In the vicinity of the South Mountain Mine, the Phosphoria Formation overlies the Cretaceous Hilliard Shales along the Absaroka Thrust Fault (Cochran, 1950). At the crest of the Commissary Ridge, bedding orientation is 195°, 45° NW. The target bed at the South Mountain Mine was 4.5 ft thick, and typically contained more than 21 percent P₂O₅. The open pit at the top of the ridge was established first and mining within the pit proceeded until stripping costs became too expensive. An adit was dug into the hill approximately 300 vertical feet below the ridge; the adit intersected the target bed at a distance of 800 ft. Underground, strike and dip of the target bed was 192–200°, 12–20° NW. (Cochran, 1950). Sheldon and others (1954) present a measured section of the Phosphoria Formation from within the open pit and underground mine in 1952. This was completed after mine operations ceased. The most phosphate-rich bed they encountered contained 27.3 percent P₂O₅, but was only 0.5 ft thick; also present were a 1.8-ft-thick bed at the top of the Phosphoria Formation with 22.6 percent P₂O₅, a 1.9-ft-thick bed 17 ft above the base of the Phosphoria with 21.5 percent P₂O₅, and a 2.7-ft-thick bed with 20.7 percent P₂O₅ at the base of the formation (Sheldon and others, 1954).

The mine operated intermittently from 1947 to 1951. By 1950, 8,000 tons of phosphate rock had been mined from the South Mountain Mine (Cochran, 1950); however, annual production data from the Wyoming Board of Equalization or the State Inspector of Mines are not available. Phosphate Mines, Inc. sold the phosphate rock

produced from the South Mountain Mine for direct soil application (Coffman and Service, 1967).

Leefe Mine

The Leefe open-pit mine operated continuously from 1947 to 1977 (Jasinski and others, 2004). The mine included two open pits (Dover, 1995) and yielded more than 4,725,000 tons of phosphate rock (Wyoming Board of Equalization, 1948–1978). The northern pit was located in the SW¹/₄SE¹/₄ sec. 3, and NE¹/₄ sec. 10, T. 21 N., R. 120 W. The southern pit was located in the NE¹/₄ and NE¹/₄NW¹/₄ sec. 15, T. 21 N., R. 120 W. (McKelvey, 1953b; Dover, 1995). The San Francisco Chemical Company developed the mine, and sold it to Stauffer Chemical Company in 1968 (Harris and Hausel, 1984). Construction of phosphate processing facilities began in 1956, and by 1965, the plant at the Leefe site was capable of producing up to 500,000 lb of concentrate and calcined rock per year (Coffman and Service, 1967).

Most of the Phosphoria Formation in the vicinity of the Leefe Mine has been removed, though small remnant outcrops are still present (Dover, 1995). Prior to removal, the Phosphoria Formation at the Leefe Mine occurred along a north-northwest-trending syncline cut by east–west-trending faults. The minor outcrops of the Phosphoria that are still present occur along the flanks of the syncline.

Mining at the Leefe open pit targeted four phosphatic beds in the Meade Peak Member of the Phosphoria Formation (King, 1949, 1967). King (1949) labeled the phosphatic beds A through D, from highest to lowest, and described the beds in detail. The A bed is light colored, oolitic, and massive phosphate rock that averages 5.5 ft thick and ranges from 33.5 to 34.7 percent P₂O₅. Black phosphatic shale of the B bed directly underlies the A bed. The B bed is 5 ft thick with an average phosphate content of 28.0 percent P₂O₅. The C bed is a 6.3-ft-thick black shale with 25 percent P₂O₅, separated from the B bed by 2.0 ft of sandy mudstone. The D bed is lithologically similar to the A bed and contains 33.5 percent P₂O₅, though it is less than 2 ft thick. The D bed is separated from the C bed by 2.0 ft of sandy mudstone, and is underlain by siltstone. Prior to construction of the processing facilities, only the A bed was suitable for mining, as its ore could be shipped without additional processing to increase the phosphate concentration (King, 1967). McKelvey and others (1953b) provide detailed geologic descriptions from both pits at the Leefe mine. They found that in the south pit, the average phosphate content of the A and B beds, combined, was 32.0 percent P₂O₅ over 9.2 ft, while at the north pit, the A and B beds averaged 31.9 percent P₂O₅ over 7.0 ft combined thickness.

During the establishment of the Leefe Mine, the San Francisco Chemical Company recognized the potential value of the phosphatic beds below the A bed, and ensured future minability by disposing of overburden and waste rock outside of the phosphate deposit area (King, 1967). Phosphate ore from the Leefe Mine was used to produce phosphoric acid at facilities in Idaho and British Columbia, Canada (Coffman and Service, 1967; Jasinski and others, 2004). Phosphate rock processed at the Leefe site came from the Leefe Mine itself, as well as mines in Utah and Idaho. The Leefe Mine was the last active phosphate mine in Wyoming, and shut down due to the depletion of phosphate rock resources at the site. After mining operations ceased, phosphate processing continued at the Leefe plant using raw material mined from the Phosphoria Formation in Idaho and Utah into the 1980's (Harris and Hausel, 1984).

Other Significant Occurrences within the Phosphoria Formation

A Note About Sampling

Samples collected and analyzed during this investigation are grab samples (i.e., small, unmeasured samples), and only represent one small piece of evidence for or against the occurrence of a mineral concentration or deposit. The elemental concentrations associated with a grab sample may or may not extend into the outcrop from which the sample was collected. Results reported here are those of a survey, rather than thorough evaluations of individual deposits.

Powder X-ray diffraction (XRD) analysis allowed for the identification of which, if any, phosphate minerals are present in the samples collected for this report. Twenty-three samples yielded diffractogram patterns that matched phosphate minerals. Twenty of these samples were analyzed for whole-rock geochemistry, along with one sample of barren mudstone, and two samples previously collected by the Wyoming State Geological Survey. ALS Chemex of Reno, Nev. completed all of the geochemical analyses for this project. They used x-ray fluorescence analysis to determine the whole-rock major element composition, as oxides, of each of the 23 samples analyzed. They determined trace element geochemistry for five samples by inductively coupled plasma mass spectrometry for metals, and combustion for carbon and sulfur. Results of the geochemical analyses are shown in tables 2 and 3. Individual results and associated sample sites are discussed below.

Wind River Mountains and Wind River Basin

The Phosphoria Formation crops out in a northwest-trending belt of rock along the northeastern foothills of the Wind

River Mountains (Love and Christiansen, 1985). While the Phosphoria outcrop spans nearly the entire length of the Wind River Mountains, the highest phosphate values reported in the literature from the Phosphoria here are located to the south and west of Lander (e.g., King and Schumacher, 1949; Sheldon and others, 1953). King (1947) provides a detailed description of the physical stratigraphy in the Lander area, with an emphasis on the phosphate rock in the Phosphoria Formation. The total thickness of the Phosphoria Formation in the Lander area is 280–290 ft. The Phosphoria here consists of interbedded mixed argillaceous carbonates, clastic sedimentary rocks, chert, and phosphate rock (King, 1947). Two notable phosphate rock beds are present in the Lander area, a lower bed within the Meade Peak Member, approximately 40–55 ft above the base of the Phosphoria, and an upper bed in the Retort Shale Member, approximately 60–75 ft below the top of the formation (Condit, 1924; King, 1947). The phosphate rock bed in the Meade Peake Member is less persistent than that in the Retort Shale phosphate rock bed, but hosts higher phosphate concentrations. The highest published value for the upper phosphate bed is 22.6 percent P_2O_5 in sec. 25, T. 32 N., R. 100 W., where the bed is 5 ft thick (Condit, 1924). Field investigations for this publication identified a 6-ft-thick bed of low- to medium-grade phosphate rock. A representative sample of the lower half of this bed yielded 24.2 percent P_2O_5 , and one of the upper half yielded 21.6 percent P_2O_5 .

The lower phosphate bed exhibits 27.9 percent P_2O_5 at two locations: Tweed (Usher) Creek, sec 24, T. 30 N., R. 99 W., and Crooked Creek, sec. 21, T. 32 N., R. 100 W (Condit, 1924). At Tweed Creek, Condit reported that the lower phosphate rock bed is 4 ft thick, and at Crooked Creek, the lower phosphate bed is more than 3 ft thick.

The U.S. Bureau of Mines drilled three exploratory core holes on Macfie Ranch in sections 8 and 9, T. 31 N., R. 99 W., and eight core holes 6.5 miles to the southeast near Twin Creek (fig. 8; table 5; King and Schumacher, 1949). The Phosphoria Formation is exposed in a gully cut by the Little Popo Agie River, approximately 1000 ft north of the first drill hole, Macfie 1. Bedding in this area strikes 330°, and dips 8° NE. The core holes ranged in depth from 273 to 321 ft. The first hole, Macfie 1, was drilled past the base of the phosphate rock zone in the Meade Peak Member, while Macfie 2 and 3 finished at the base of the phosphate rock zone. Macfie 1 and 3 were drilled approximately 1000 ft apart along strike, and Macfie 2 was drilled about 1000 ft up dip from the mid-point between Macfie 1 and 3 (fig. 9). The core holes intersected phosphate rock at a depth between 261 and 271 ft. In each of the Macfie core holes, the phosphate rock zone exhibited greater than 25 percent P_2O_5 over an interval of three or more feet. In Macfie 3,

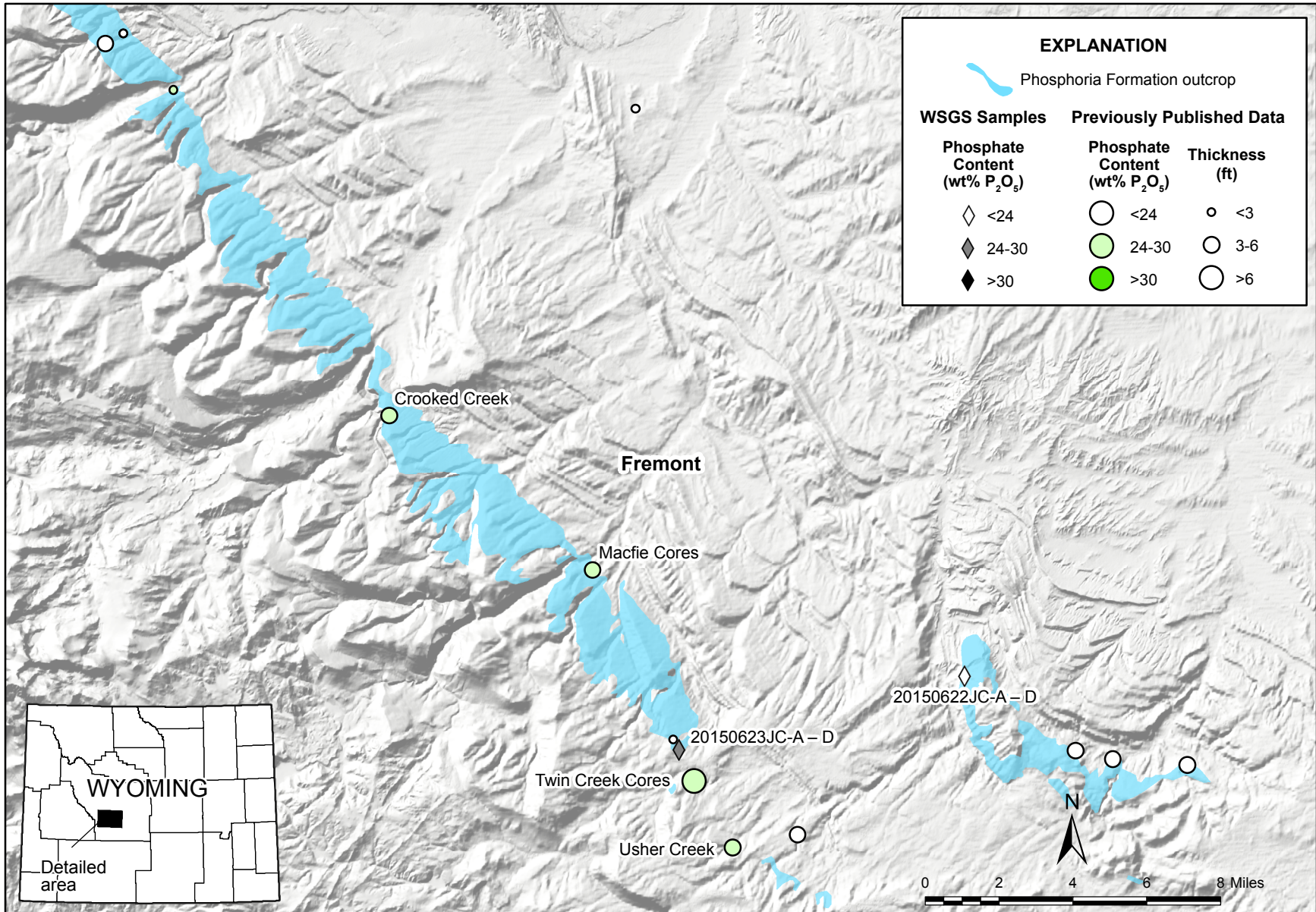


Figure 8. Map showing phosphate rock occurrences and outcrop of the Phosphoria Formation in southwestern Fremont County. Previously reported medium- to high-grade occurrences greater than 3 ft in thickness are labelled, as are samples collected for this report.

the total phosphate rock zone is more than 5 ft thick, but averages less than 21 percent P_2O_5 over that interval (King and Schumacher, 1949).

At Twin Creek (fig. 10), six of the eight exploratory core holes intersected phosphate rock (King and Schumacher, 1949). Where intersected, depth to the phosphate rock ranged from 45–182 ft. At Twin Creek, the phosphate rock zone is generally thicker, but lower grade than at Macfie Ranch. In the six holes where the phosphate rock

was present, the total thickness of the bed was greater than 6 ft; however, only in Twin Creek 1 did the bed average more than 25 percent P_2O_5 . King and Schumacher (1949) also described a shaft driven to the phosphate rock zone at Twin Creek in order to obtain a 50-ton metallurgical sample. This sample yielded a bulk average of 20.7 percent P_2O_5 (Duncan and Fisk, 1957). In comparison, a 1-ton sample taken from a trench near the Macfie Ranch core holes on the Little Popo Agie River yielded a bulk average 27.1 percent P_2O_5 (Duncan and Fisk, 1957).

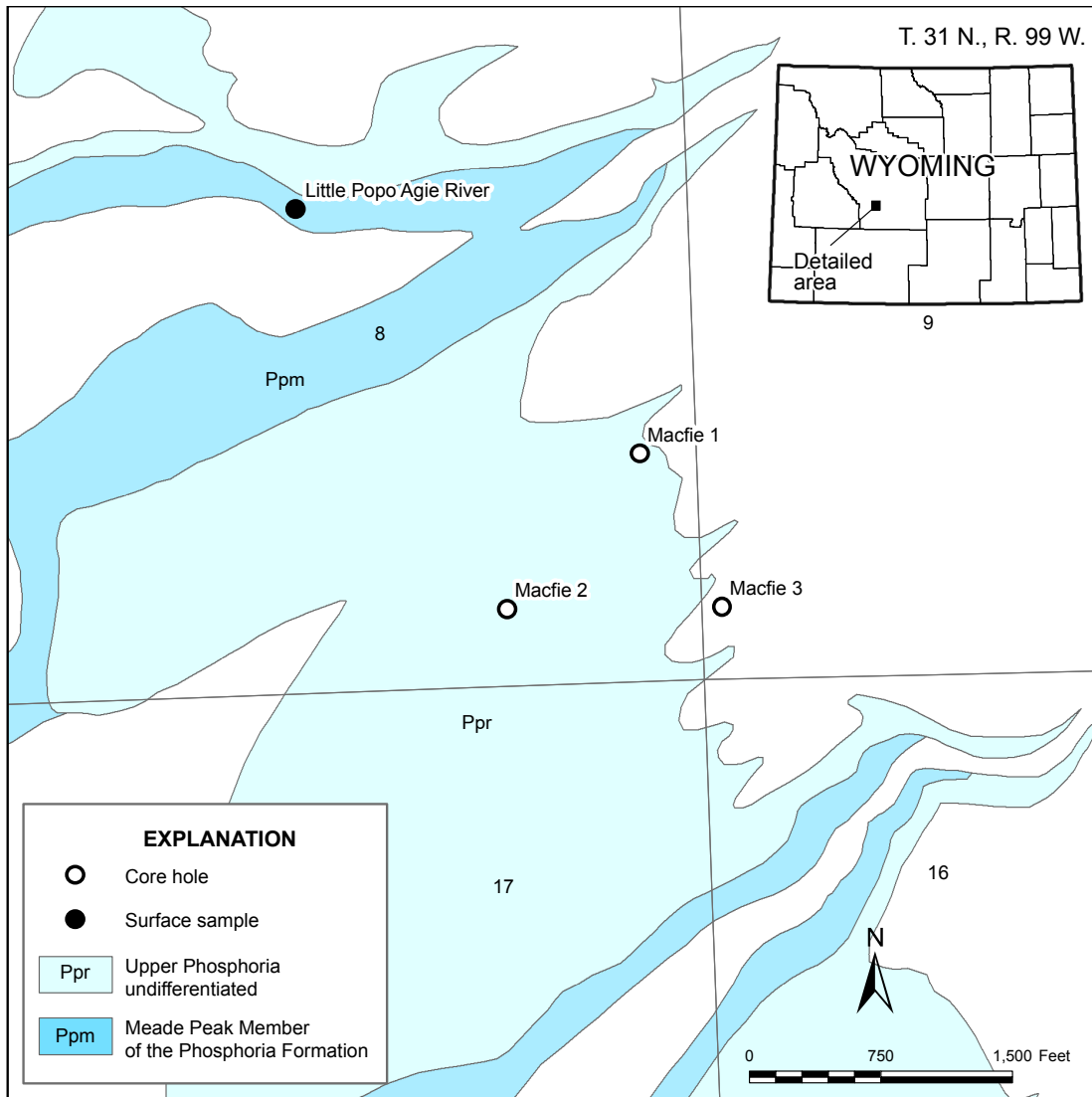


Figure 9. Core hole locations and one surface sample site in the Macfie Ranch area (King and Schumacher, 1949). The extent of surface exposure of the Meade Peak Member of the Phosphoria Formation, and Phosphoria Formation rocks above the Meade Peak Member are also displayed (Johnson and Sutherland, 2009).

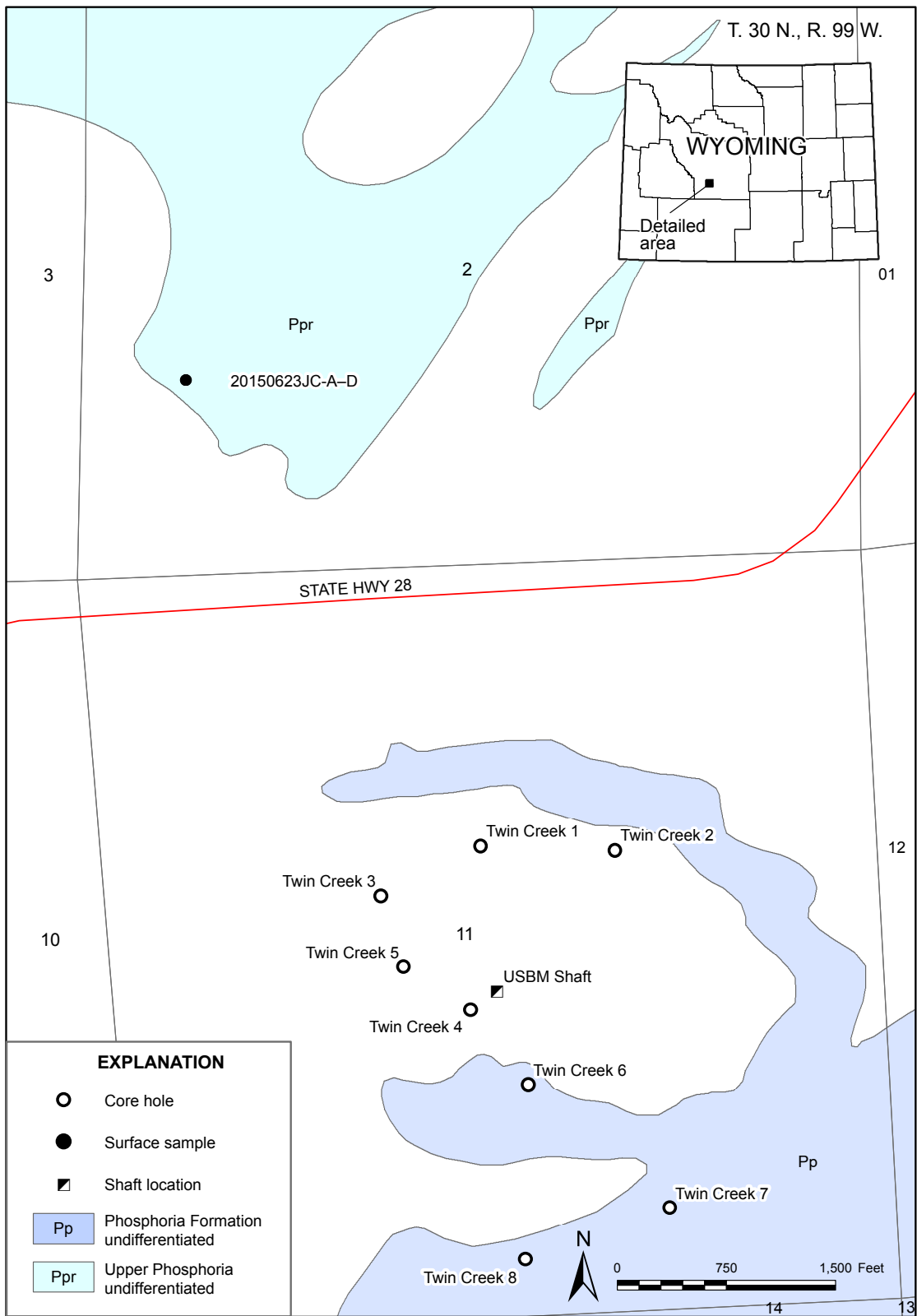


Figure 10. Map showing the locations of core holes and an exploratory shaft in the Twin Creek area (King and Schumacher, 1949). North of the drilling area is the location of four samples collected in Red Canyon during field work for this report. The extent of Phosphoria Formation outcrop is also displayed (Johnson and Sutherland, 2009).

Table 5. Phosphate content and stratigraphic data of phosphate rock beds in the Lander area from USBM coring project.

Drill Hole	Starting depth (ft)	Ending depth (ft)	Thickness	Wt% P ₂ O ₅
Macfie 1	261.2	266.0	4.8	25.85
Macfie 2	261.5	265.4	3.9	25.35
Macfie 3	273.3	276.35	3.05	26.60
Twin Creek 1	86.0	92.0	6	25.10
Twin Creek 2	182.4	188.0	5.6	23.20
Twin Creek 4	45.0	51.1	6.1	23.50
Twin Creek 6	50.75	57.1	6.35	22.70
Twin Creek 7	53.7	59.7	6.0	22.90
Twin Creek 8	29.75	35.85	6.1	23.00

Approximately half a mile north-northwest of the Twin Creek core holes, phosphate rock of the Retort Member of the Phosphoria Formation is exposed in outcrop along the side of a gully (fig. 11). Approximately 20 ft below the upper dip slope surface of the Phosphoria Formation is a 6-ft-thick bed of low- to medium-grade phosphate rock. Apatite peloids are most abundant at the base of the phosphate rock bed, and diminish upwards. Underlying the phosphate rock is a pale yellow, fine-grained, calcite cemented quartz sandstone with minor medium- to coarse-grained apatite peloids and shell fragments. The phosphate rock is overlain by barren, light olive-brown limy mudstone. Geochemical analysis of two samples of the phosphate rock bed, one from the bottom of the bed, and one from the top, indicated that the bed grades from 24.2 percent P₂O₅ near its base, to 21.6 percent near its top.

Overthrust Belt: Sublette Range

The Sublette Range is an approximately 20-mile-long, north-northwest-trending ridge, partially bounded on the east by a thrust fault (Love and Christiansen, 1985). The Phosphoria Formation is exposed in a narrow band on the western side of the range. The Sublette Range is the steeply dipping eastern limb of a strongly asymmetrical anticline (McKelvey and others, 1953b). The Phosphoria Formation in the Sublette Range consists of the Meade Peak, Rex Chert, and Retort members; the Tosi Chert is absent in this part of Wyoming (Sheldon, 1963). High-grade phosphate rock is present within the Meade Peak Shale Member in the Sublette Range, and was mined at York Canyon by the U.S. Phosphate Company from 1913 to 1917. The host bed at York Canyon was 4 ft thick and contained 34.4 percent P₂O₅ (Mansfield, 1927). Phosphate rock commonly more than 3 ft thick and greater than 30 percent P₂O₅ persists north and south of York Canyon (table 6; fig. 12).



Figure 11. Outcrop of low- to medium-grade phosphate rock of the Retort Member of the Phosphoria Formation at the Red Canyon locality in the Lander area. a) Outcrop of phosphate rock bed and sample locations 20150623JC-A through 20150623JC-D, from bottom to top, marked by sample bags. Sample 20150623JC-B is at the base of the phosphate rock bed, and 20150623JC-C is at the top of the phosphate rock bed. b) Phosphate rock near the base of the bed. c) Close-up photograph taken near the base of the phosphate rock bed. Individual apatite grains are visible in the muddy matrix, along with shell fragments.

McKelvey and others (1953b) provide a composite measured section of the Phosphoria Formation exposed in two canyons in the S½SE¼, sec. 19, and N½NE¼, sec. 30, T. 27 N., R. 119 W. McKelvey and others (1953b) refer to this location as Layland Canyon; however Layland Canyon is actually 6 miles south of this site. For this report, these two canyons are referred to as Schieffer North and Schieffer South, after the current landowner. The full thickness of the Phosphoria Formation ranges from 155 ft at the Schieffer localities to 268 ft at Coal Canyon, where it has likely been thickened by faulting (McKelvey and others, 1953b). At the Schieffer sections, bedding orientation is 340°, 34° E. near the base of the Meade Peak Member, and 347°, 80° E. at the top of the Retort Member (McKelvey and others, 1953b). To the south, at Coal Canyon and York Canyon, bedding dips nearly vertical, and strikes north-northeast (Mansfield, 1927).

Overthrust Belt: Tunp Range

The Tunp Range is an approximately 40-mile-long, north-northeast-trending mountain range in the Overthrust Belt. The Phosphoria Formation crops out along much of the north half of the Tunp Range, and over a restricted area near Rock Creek at the southern

end of range (fig. 12; Rubey and others, 1980; Love and Christiansen, 1985). At Basin Creek, near the north end of the Tunp Range, the Phosphoria Formation is 243 ft thick, and bedding orientation is 150°, 45° W. (Sheldon and others, 1954). In the central Tunp Range, on the Middle Fork of Pine Creek, the Phosphoria is 292 ft thick and bedding orientation is 190°, 26° W. (McKelvey and others, 1953b). At the southern end of the Tunp Range, near Rock Creek, the exposed thickness of the Phosphoria Formation is approximately 113 ft (Kivi, 1940). Similar to the Sublette Range, the Phosphoria Formation in the Tunp Range consists of the Meade Peak, Rex Chert, and Retort Shale members, with the Tosi Chert absent (McKelvey and others, 1953b; Sheldon and others, 1954). McKelvey and others (1953b) provide measured sections of the Phosphoria Formation in the middle part of the Tunp Range. At the Rock Creek exposure, Kivi (1940) identified a 7-ft-thick bed of phosphate rock that averaged 35 percent P₂O₅. At the Middle Fork of Pine Creek locality, they measured and sampled the entire thickness of the Phosphoria in natural exposures and hand trenches, and at the North Fork Pine Creek locality they measured and sampled the Meade Peak Member in a bulldozer trench. A stock pond is now present at the site of the North Fork of Pine Creek bulldozer trench, and scree covers most of the Meade Peak Member where

Table 6. Phosphate content and stratigraphic data of phosphate rock beds in the Sublette Range from USGS measured sections of the Phosphoria Formation and other field investigations.

Location Name	Legal Location	Latitude	Longitude	P ₂ O ₅ (wt%)	Thickness (ft)	Stratigraphic height above base of Meade Peak Member (ft)
Keystone Ranch (Mansfield, 1927)	NW¼, NE¼, sec. 19, T. 27 N., R. 119 W.	42.3201	-111.0208	38.8	6.0	unknown
Schieffer North (McKelvey and others, 1953)	S½, SE¼, sec. 19, T. 27 N., R. 119 W.	42.3103	-111.0182	30.1	3.8	48
				30.1	5.1	19
Schieffer South (McKelvey and others, 1953)	N½, NE¼, sec. 30, T. 27 N., R. 119 W.	42.3062	-111.0182	30.5	6.8	108
				26.6	7.9	98
Raymond Canyon (Sheldon and others, 1953)	NW¼, NE¼, Sec. 6, T. 26 N., R. 119 W.	42.2764	-111.0208	25.4	3.5	unknown
Coal Canyon (McKelvey and others, 1953)	SW¼, NE¼, sec. 7, T. 26 N., R. 119 W.	42.2578	-111.0216	30.7	5.6	112
				25.9	3.6	105
				26.4	7.8	19
Jackson Canyon (Mansfield, 1927)	NW¼, SE¼, sec. 7, T. 26 N., R. 119 W.	42.2558	-111.0216	32.8	4.5	unknown
York Canyon (Mansfield, 1927)	NE¼, SW¼, sec. 18, T. 26 N., R. 119 W.	42.2417	-111.024	34.4	4.0	unknown
Francis Canyon (Mansfield, 1927)	NW¼, NE¼, sec. 19, T. 26 N., R. 119 W.	42.2329	-111.0209	32.7	3.3	unknown

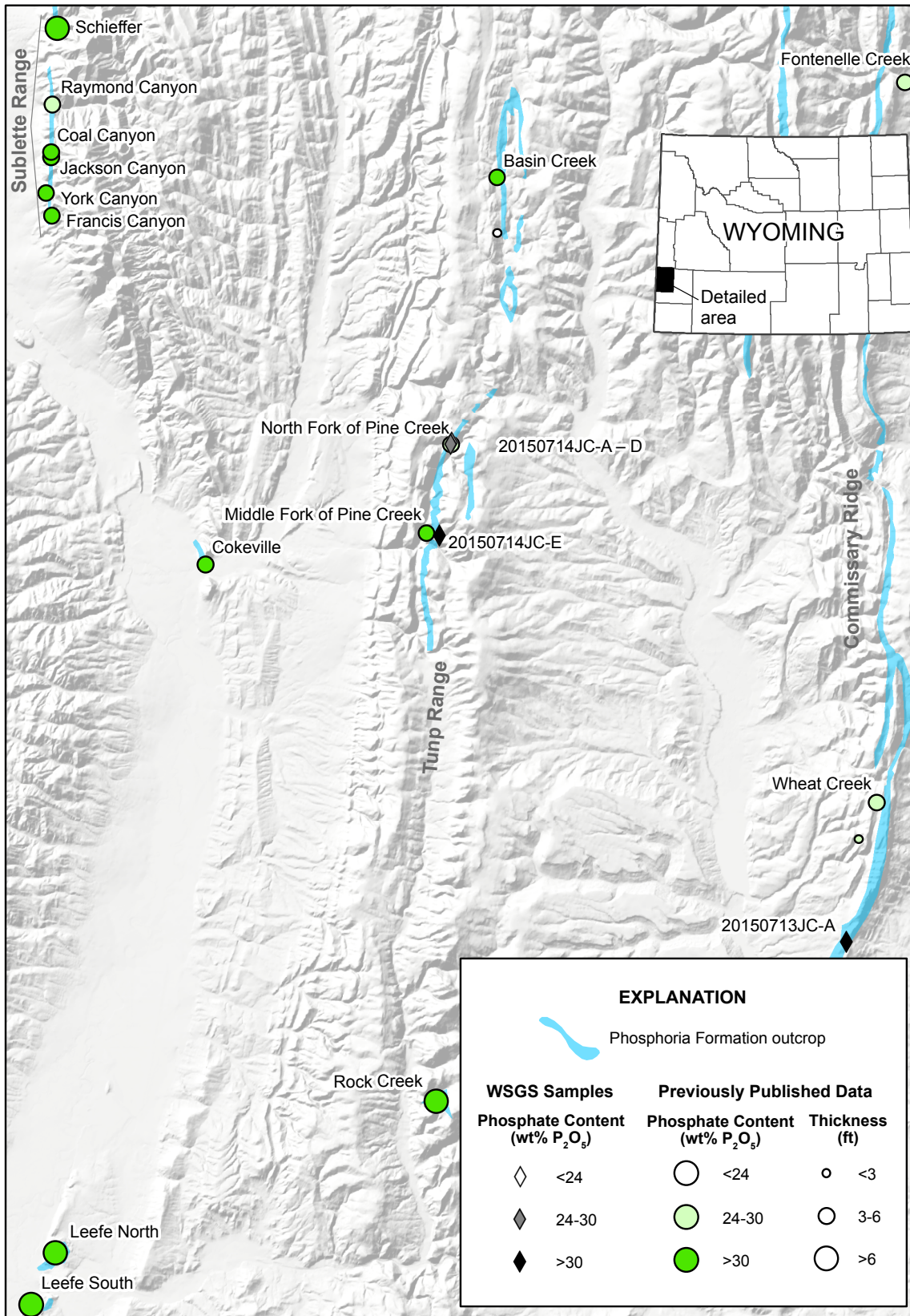


Figure 12. Map showing phosphate rock occurrences and outcrop of the Phosphoria Formation in the southern to central portion of the Overthrust Belt in Wyoming. Previously reported medium- to high-grade occurrences greater than 3 ft in thickness are labelled, as are samples collected for this report.

it would otherwise be exposed in this area. Two phosphate rock beds greater than 3 ft thick occur in the upper third of the Meade Peak Member (McKelvey and others, 1953b); at both locations the uppermost phosphate rock bed contains more than 30 percent P_2O_5 . A medium-grade phosphate rock bed occurs in the lower portion of the Meade Peak Member at the North Fork of Pine Creek locality (table 7). McKelvey and others (1953b) reported minor phosphate rock within the Retort Member at the Middle Fork of Pine Creek, and thin, low-grade phosphate rock was observed at the top of the Retort Shale at North Fork of Pine Creek during field investigations for this report. A sample of phosphate rock collected from float over the Meade Peak Member contained more than 25 percent P_2O_5 , in agreement with McKelvey and others' (1953b) data.

A sample collected from the Meade Peak Member in the Middle Fork of Pine Creek area yielded 30.7 percent P_2O_5 ; only the upper surface of this bed is exposed, and the bed thickness could not be measured (fig. 13; table 2). A sample collected from float over the Meade Peak Member at the North Fork of Pine Creek location yielded nearly 26 percent P_2O_5 . A sample of pisolitic sandstone from the very top of the Retort Member at the North Fork of Pine Creek contained nearly 19 percent P_2O_5 ; the pisolitic sandstone bed is less than 1 ft thick, and the mudstone it overlies only yielded 5.3 percent P_2O_5 (fig. 14; table 2).

At Basin Creek, the Meade Peak Member is significantly thinner than at the Middle and North Forks of Pine Creek, but three thick, high-grade phosphate rock beds occur at

similar relative stratigraphic positions (Sheldon, 1954). A thick, medium-grade phosphate rock bed occurs in the Retort Shale at Basin Creek as well (table 7).

Overthrust Belt: Commissary Ridge

Commissary Ridge is an approximately 40-mile-long, north-trending mountain range that roughly parallels the Tunp Range. Phosphoria Formation outcrops occur along nearly the entire length of Commissary Ridge (fig. 12). Sheldon and others (1954) document two medium-grade phosphate deposits along Commissary Ridge in the Meade Peak Member at Fontenelle Creek and Wheat Creek (table 8). At Fontenelle Creek, bedding orientation is 165° , 55° W., and two phosphate rock beds occur in the Meade Peak Member. The lower bed is more than 5 ft thick with 25.4 percent P_2O_5 ; the upper bed hosts 29.6 percent P_2O_5 over more than 3 ft (Sheldon and others, 1954). At Wheat Creek, the phosphate rock bed is nearly 4 ft thick, and averages 24.3 percent P_2O_5 . The attitude of bedding at Wheat Creek is 180° , 60° W. (Sheldon and others, 1953). Four miles to the south-southwest, in the vicinity of Muddy Creek, 3 miles southeast of Lake Viva Naughton, the phosphate rock bed is less than 2 ft thick, where it is exposed in several old exploration trenches. A sample collected at the Muddy Creek location, though, yielded more than 31 percent P_2O_5 (table 2; fig. 15). Between the Muddy Creek and Wheat Creek localities is the site of the abandoned South Mountain Mine, where Phosphate Mines, Inc. produced low-grade phosphate rock in the late 1940's and early 1950's.

Table 7. Phosphate content and stratigraphic data of phosphate rock beds in the Tunp Range from USGS measured sections of the Phosphoria Formation and other field investigations

Location Name	Legal Location	Latitude	Longitude	P_2O_5 (wt%)	Thickness (ft)	Stratigraphic height above base of Phosphoria (ft)
Rock Creek (Kivi, 1940)	sec. 16, T. 22 N., R. 118 W.	41.8861	-110.8194	36.0	7	unknown
Middle Fork of Pine Creek (McKelvey and others, 1953)	sec. 35, T. 25 N., R. 118 W.	42.1085	-110.8239	30.5	3.4	76
				27.3	4.4	71
North Fork of Pine Creek (McKelvey and others, 1953)	NW¼, NW¼, sec. 24, T. 25 N., R. 118 W.	42.1431	-110.811	34.7	3.5	90
				26.7	5.4	83
				26.3	3.95	38
Basin Creek (Sheldon and others, 1954)	secs. 12 and 13, T. 26 N., R. 117½ W.	42.2475	-110.7863	24.3	5	237
				35.2	3.1	62
				30.1	4.3	54
				30.3	3	14

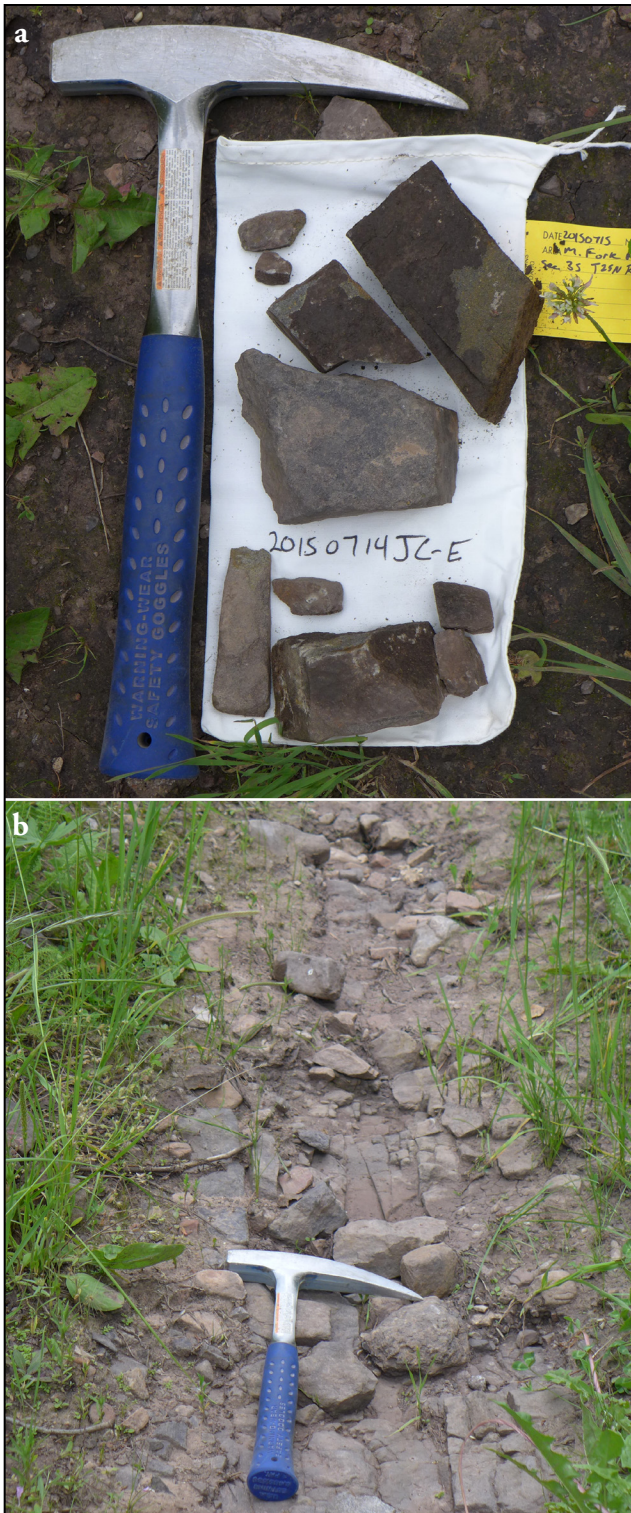


Figure 13. Phosphate rock at the Middle Fork of Pine Creek location. a) Photograph of sample 20150714JC-E. b) Outcrop of phosphate rock in the Meade Peak Member of the Phosphoria Formation at the sample location. The outcrop is on a dip slope, and only the top of the phosphate rock bed is exposed.



Figure 14. Samples of phosphate rock from the North Fork of Pine Creek locality. a) Sample 20150714JC-A, limonite-stained mudstone with common pisoids of apatite, and pebble-sized fragments of phosphate rock. This sample was collected from the top of the Retort Shale Member of the Phosphoria Formation. b) Sample 20150714JC-C, phosphate rock collected from float over the Meade Peak Member of the Phosphoria Formation.

Table 8. Phosphate content and stratigraphic data of phosphate rock beds on Commissary Ridge from USGS measured sections of the Phosphoria Formation and other investigations.

Location Name	Legal Location	Latitude	Longitude	P ₂ O ₅ (wt%)	Thickness (ft)	Stratigraphic height above base of Phosphoria (ft)
Fontenelle Creek, Wyoming, lot 1379 (Sheldon and others, 1954)	Sec. 35, T27N, R116W	42.2841	-110.5712	29.6	3.1	unknown
				25.4	5.4	unknown
Wheat Creek, Wyoming, lot 1378 (Sheldon and others, 1954)	Sec. 4, T23N, R116W	42.0024	-110.588	24.3	3.8	4
South Mountain Mine (Cochran, 1950)	Secs. 8 and 9, T23N, R116W	41.988	-110.5975	>21.0	4.5	unknown

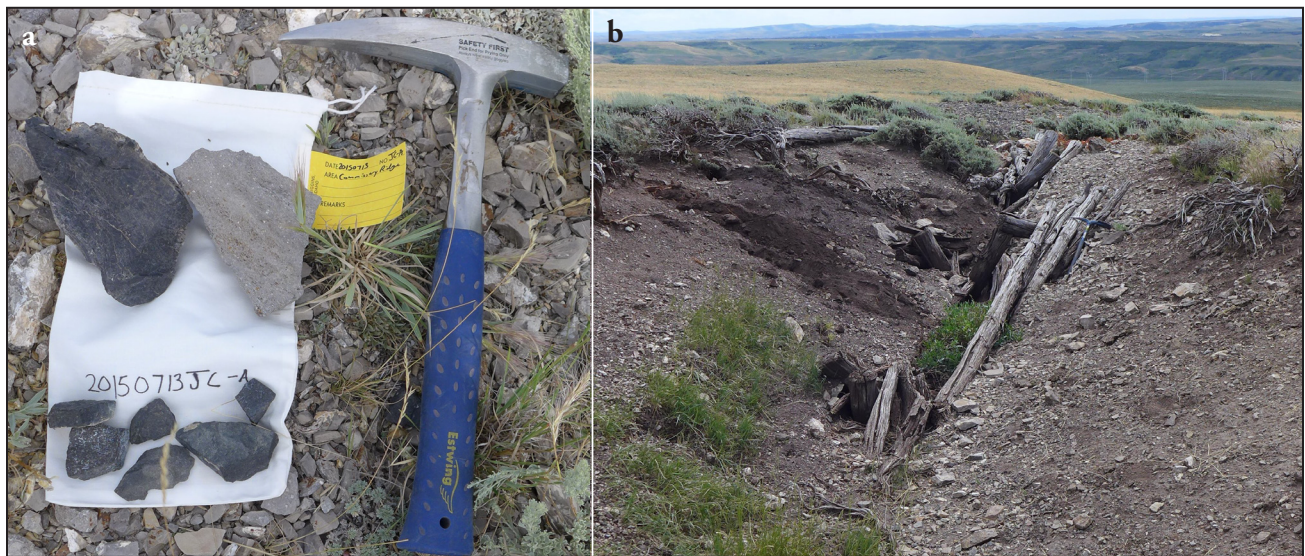


Figure 15. Hand samples and exploration trench at the Muddy Creek Locality. a) Hand samples of black mudstone, gray fossiliferous limestone, and fragments of black phosphate rock (clockwise from upper left). Samples were collected from an exploration trench at the Muddy Creek locality. b) The largest of three exploration trenches at the Muddy Creek locality.

Near the northern end of Commissary Ridge, above Schafer Creek, is a potentially significant phosphate deposit in the upper portion of the Meade Peak Member. The Meade Peak, Rex Chert, and Retort members of the Phosphoria Formation are exposed in a road cut along Forest Service Road 10166 at this location above Shafer Creek (fig. 16). The strike and dip of bedding within the Wells Formation immediately below the Phosphoria Formation is 152°, 48° SW. The Meade Peak Member is more than 50 ft thick here. The lower 40 ft of the Meade Peak Member consists of mudstone and shale with no notable phosphate rock observed. In the upper 13 ft of the Meade Peak Member are three beds of phosphate rock (table 2) separated by tan-to-brown mudstone, siltstone, and sandstone. The lowest phosphate rock is a 1.2-ft-thick bed of dark gray to very dark gray packstone composed of fine- to medium-grained apatite pellets, and coarse- to very

coarse-grained concentrically ringed apatite-mud ooids in a muddy, weakly calcareous to non-calcareous matrix. Above this bed is 1.7 ft of brown-to-tan interbedded mudstone and sandstone. The interbedded mudstone and sandstone is overlain by a 4.7-ft-thick bed of black phosphate rock that consists of fine- to medium-grained apatite pellets and a weakly calcareous muddy matrix. The top approximate 5 ft of the Meade Peak Member consists of a 2.6-ft-thick bed of tan-to-brown fossiliferous mudstone, overlain by 2.2 ft of very dark gray phosphate rock. The uppermost phosphate rock bed consists of fine- to medium-grained apatite pellets and a non-calcareous muddy matrix; abundant bioclastic material is present at the very top of this bed. The Rex Chert Member of the Phosphoria overlies the upper phosphate rock bed. The Retort Shale Member overlies the Rex Chert, but no significant phosphate rock occurs within the Retort Member.

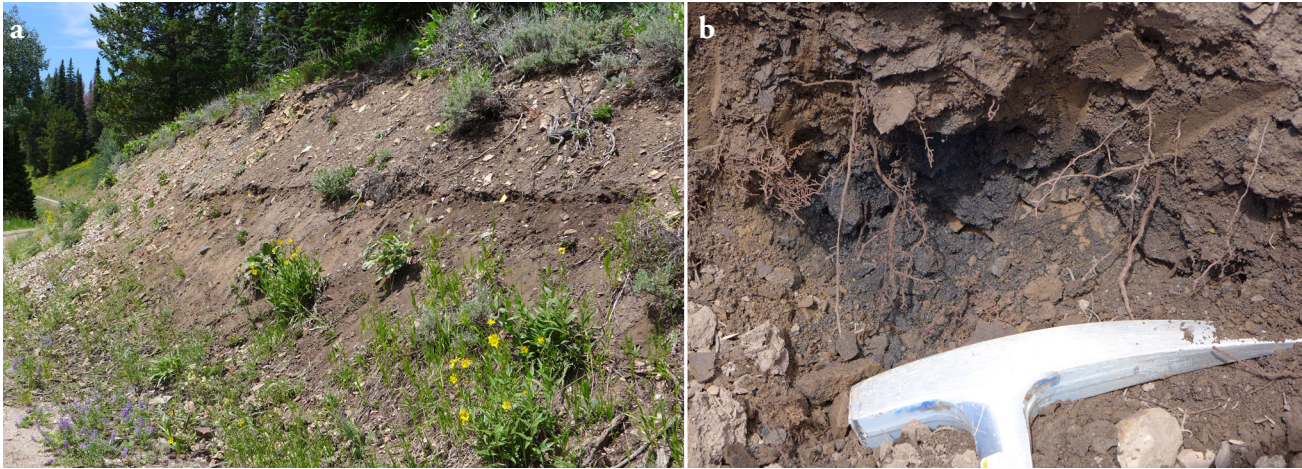


Figure 16. Shafer Creek phosphate rock occurrence. a) Outcrop of the Meade Peak Member and overlying Rex Chert Member of the Phosphoria Formation. Representative samples of the phosphate rock beds at this location were collected from the small trench visible in the photograph. b) Close-up photograph of friable phosphate rock in the lower-most phosphate rock bed at this location.

Overthrust Belt: Salt River, Wyoming, and Snake River Ranges

One potentially significant phosphate deposit near the southern end of the Salt River Range, at Poison Creek (fig. 17) was described by Sheldon and others (1953). Two medium- to high-grade phosphate rock beds are present in the upper half of the Meade Peak Member exposed in a bulldozer trench. Bedding at Poison Creek strikes 344°, and dips 44° W. The lower of the two phosphate rock beds contains more than 31 percent P₂O₅ (table 9). Geochemical analysis of samples collected at this location during fieldwork for this report (fig. 18; table 2) confirms the high grade reported by Sheldon and others (1953).

Mansfield (1927) identified two locations in the middle portion of the Salt River Range where phosphate rock beds contain greater than 30 percent P₂O₅, but did not provide measurements of bed thickness. At the boundary between the Salt River and Snake River ranges, the Meade Peak Member is well exposed in a road cut on U.S. Highway 26, near the historic Hoback town site, along the Snake River (fig. 19). Two thin, medium- to high-grade phosphate rock beds are present in this outcrop (McKelvey and others, 1953b). The beds are both less than 1 ft thick, and separated by a 4-ft-thick, black mudstone bed. The lower bed contains 34.8 percent P₂O₅, and the upper bed 28.9 percent P₂O₅ (McKelvey and others, 1953b). A sample of the lower bed collected for this study yielded 29.5 percent P₂O₅, while one of the upper beds yielded 28.8 percent P₂O₅.

Table 9. Phosphate content and stratigraphic data of phosphate rock beds in northern half of the Wyoming Overthrust Belt from USGS measured sections of the Phosphoria Formation and other field investigations.

Location Name	Legal Location	Latitude	Longitude	P ₂ O ₅ (wt%)	Thickness (ft)	Stratigraphic height above base of Phosphoria (ft)
Poison Creek (Sheldon and others, 1953)	SW¼, SW¼, sec. 13, T. 30 N., R. 117 W.	42.5797	-110.7222	24.8	3.4	80
				31.3	3.4	45
South Cottonwood Creek - Sheep Creek divide (McKelvey, 1946)	SW1/4, SE1/4, Sec. 29, T33N, R115W	42.7956	-110.595	25.9	4.9	9
Dry Fork - Wolf Creek (Benham, 1984)	SW¼, sec. 28, T. 38 N., R. 117 W.	43.2315	-110.8884	31.1	9.4	29
				29.5	11.2	15
Mosquito Creek (Gere and others, 1966)	NW¼, sec. 36, T41N, R118-¼W	43.4769	-110.9561	33.5	3.5	0

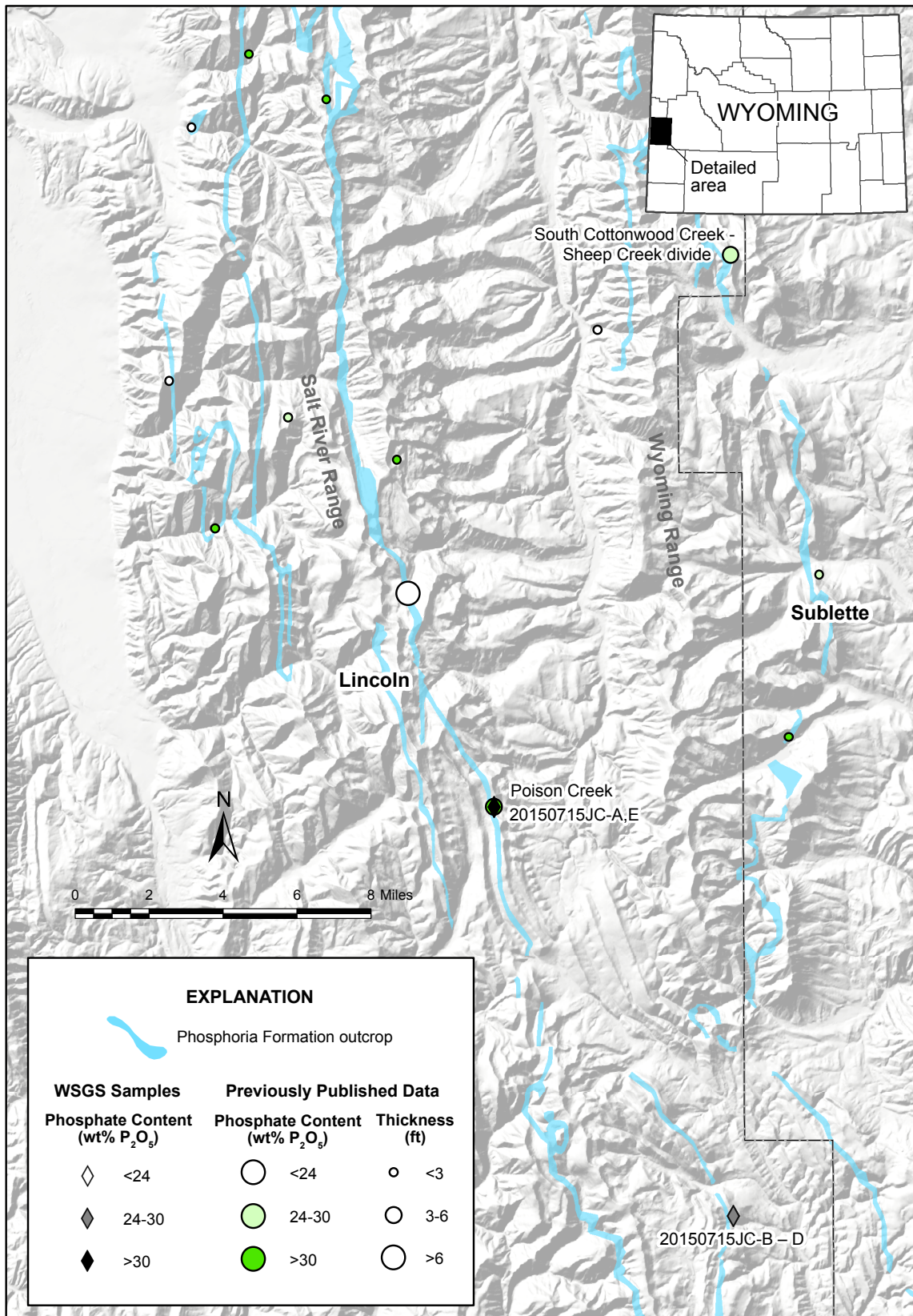


Figure 17. Map showing phosphate rock occurrences and outcrop of the Phosphoria Formation in the central to northern portion of the Overthrust Belt in Wyoming. Previously reported medium- to high-grade occurrences greater than 3 ft in thickness are labelled, as are samples collected for this report.



Figure 18. Samples of phosphate rock collected from the Poison Creek locality. a) Sample 20150715JC-A, phosphate rock collected from float in the bulldozer trench cut for a measured section (McKelvey and others, 1953). b) Phosphate rock collected in place from side of bulldozer trench.

In the northeastern portion of the Salt River Range, near Water Dog Lake, phosphate rock is present in float material, though exposure in this area is poor. A sample of phosphate rock from float yielded 27.2 percent P_2O_5 .

The Wyoming Range roughly parallels the Salt River Range to the west. McKelvey (1946) reports one notable phosphate rock occurrence in the Wyoming Range, along the divide between South Cottonwood Creek and Sheep Creek (fig. 17). A nearly 5-ft-thick bed of medium-grade phosphate rock occurs in the lower part of the Meade Peak Member at this location (table 9).

In the southern portion of the Snake River Range, southwest of the Hoback outcrop, Benham (1984) reported two >9-ft-thick, medium- to high-grade successions of phosphate rock in the Meade Peak Member, exposed on a ridge between Dry Fork and Wolf Creek (table 9; fig. 19). The Meade Peak Member here is 37 ft thick; the phosphate rock occurs in the upper 22 ft of the member; the phosphate-rich zones are separated by approximately 3 ft of mudstone.

Eighteen miles north-northwest of the Dry Fork–Wolf Creek site, on the northeast flank of the Snake River Range, a high-grade phosphate rock bed occurs near the base of the Meade Peak Member (table 9; fig. 19; Gere and others, 1966). The Meade Peak Member here is 44 ft thick. The Retort Member is also present at this location, but no geochemical data are available. The Shedhorn Sandstone separates the Meade Peak and Retort members at this location; the Tosi Chert Member is absent (Gere and others, 1966).

Teton Range

Several medium- to high-grade phosphate rock deposits occur in the south part of the Teton Range (fig. 19; Gere and others, 1966). Outcrops of the Phosphoria Formation in the Teton Range are restricted to the southern half of the western flank and the southern end of the range (Love and Christiansen, 1985). The Phosphoria Formation across the Teton Range includes the lower chert unit, the Meade Peak Member, the Retort Member, and the Tosi Chert Member; the Rex Chert Member is replaced by tongues of the Franson Member of the Park City Formation and the Lower Member of the Shedhorn Sandstone (Gere and others, 1966). Two sites at the south end of the Teton Range, separated by 3.5 miles, host phosphate rock at differing stratigraphic locations. At Talbot Creek, a nearly 5-ft-thick bed of medium-grade phosphate rock occurs 4 ft above the base of the Meade Peak Member, while at the Teton Pass Mountains site to the east, a greater than 9-ft-thick bed of high-grade rock is present 22 ft above the base of the Meade Peak (table 10). At Sorensen Creek,

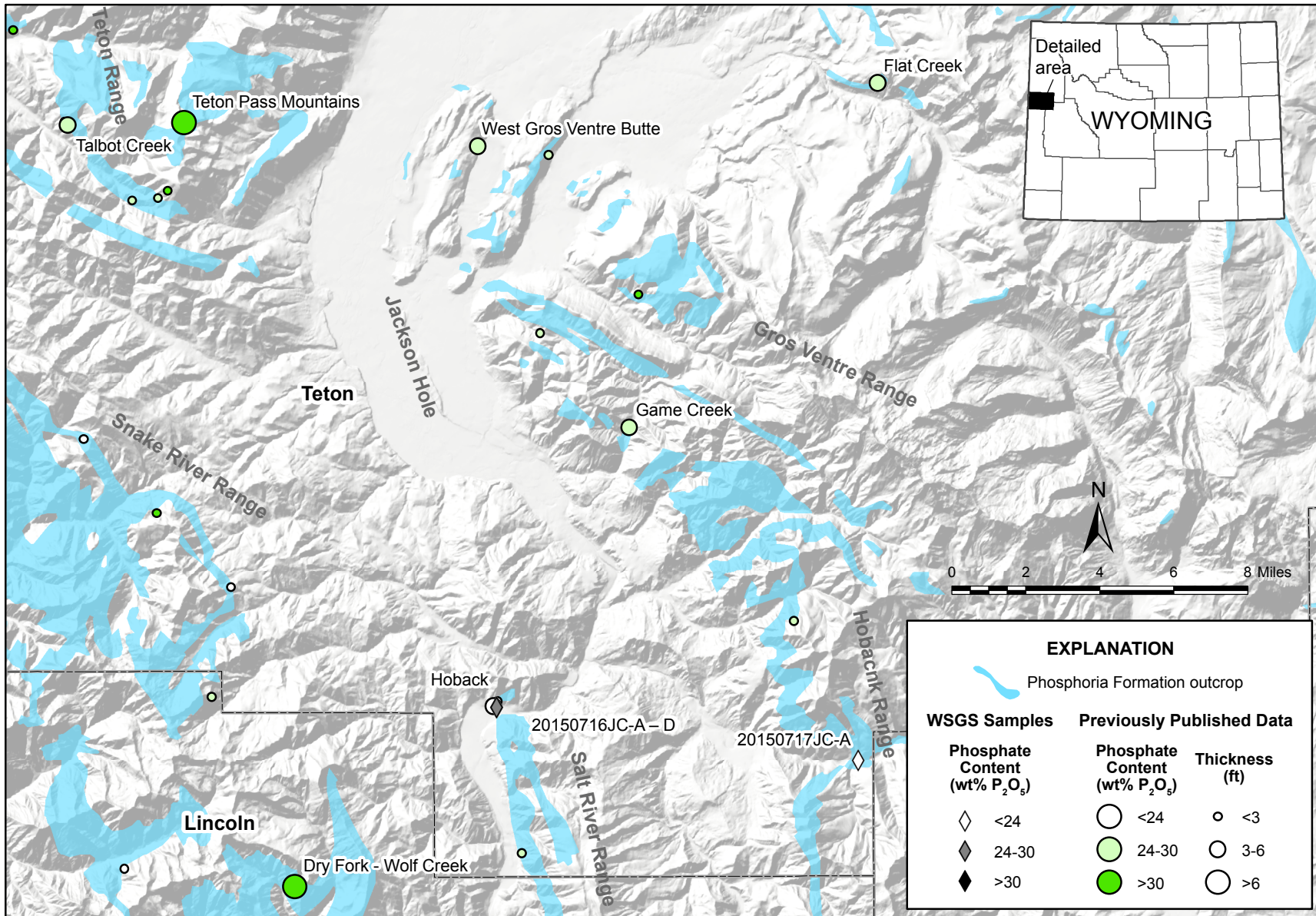


Figure 19. Map showing phosphate rock occurrences and outcrop of the Phosphoria Formation in the northern portion of the Overthrust Belt in Wyoming, the southern end of the Teton Range, Jackson Hole, and the Gros Ventre Range. Previously reported medium- to high-grade occurrences greater than 3 ft in thickness are labelled, as are samples collected for this report.

Table 10. Phosphate content and stratigraphic data of phosphate rock beds in the Teton Range from USGS measured sections of the Phosphoria Formation.

Location Name	Legal Location	Latitude	Longitude	P ₂ O ₅ (wt%)	Thickness (ft)	Stratigraphic height above base of Meade Peak (ft)
Talbot Creek	SE¼, NE¼, and NE¼, SE¼, sec. 9, T. 41 N., R. 118-¾ W. (Unsurveyed)	43.5297	-111.0102	24.4	4.7	4
Teton Pass Mountains	E½, sec. 12, T. 41 N., R. 118-¾ W. (Unsurveyed)	43.5305	-110.9476	31.7	9.35	22
East Darby Creek	NW¼, sec. 34, T. 43 N., R. 118-¾ W.	43.6487	-110.9958	26.0	3.5	0
Sorensen Creek	SE¼, NE¼, sec. 30, T. 43 N., R. 118-¾ W.	43.6605	-111.0438	28.5	3.4	0

(Gere and others, 1966)

and 2.5 miles east-southeast at East Darby Creek, a medium-grade phosphate rock bed, approximately 3.5 ft thick, occurs at the base of the Meade Peak Member. Both locations are situated on a dip slope on the western flank of the Teton Range, with the East Darby Creek site being the up-dip location (table 10). Bedding orientation near the Sorensen Creek site is 200°, 10° W. (Pampeyan and others, 1967).

Gros Ventre Range and Jackson Hole

Gere and others (1966), and Sheldon and others (1953) documented medium-grade phosphate rock in the Meade Peak Member in Jackson Hole and along the adjacent western edge of the Gros Ventre Range (table 11). In this region, all four formal members of the Phosphoria Formation are present, as well as the lower chert unit. The Rex Chert is discontinuous across the area; the lower chert was not identified at the Gros Ventre Slide locality, though Sheldon and others (1953) may have grouped it with the Meade Peak Member. A 3–5 ft thick, medium-grade phosphate rock bed commonly occurs at or near the base of the Meade Peak Member in this region, ranging in phosphate content from 24 to 28 percent P₂O₅. At the Gros Ventre Slide, Sheldon and others (1953) identified a phosphate rock bed nearly 25 ft above the base of the Meade Peak Member; the lower 25 ft may in fact belong to the lower chert unit, which would place the phosphate rock at the base of the Meade Peak Member.

IGNEOUS APATITE

Igneous apatite deposits occur worldwide. Common host rocks include layered syenite, layered mafic and ultramafic rocks, iron- and titanium-rich igneous rocks, and carbonatites. No high-grade igneous phosphate deposits are known in Wyoming, but the typical host rock-types are not uncommon to the state, and anomalously high

concentrations of igneous apatite have been recognized in the state (e.g., fig. 3; Osterwald and others, 1966). In the central Laramie Range, apatite is associated with magnetite-ilmenite deposits within the Laramie Anorthosite Complex (Diemer, 1941; Osterwald and others, 1966). Magnetite-ilmenite bodies at the Taylor Deposit host up to 60 percent apatite (Diemer, 1941). Diemer (1941) also identified apatite at two other magnetite-ilmenite deposits, which he labeled deposits #1 and #6. At deposit #1, varying amounts of apatite occur within iron-rich lenses. At deposit #6, apatite is abundant within an irregular dike, though a sample of this dike yielded only slightly greater than 2 percent P₂O₅.

On Steamboat Mountain in the Leucite Hills, Kemp and Knight (1903) noted the presence of apatite associated with rutile, though they did not give an estimate of the modal abundance. Tertiary intrusive rocks in the Black Hills of northeastern Wyoming include potential phosphate host rocks, including carbonatites and nepheline syenites. A sample analyzed for this report yielded only 1 percent P₂O₅.

PALEO-HOT SPRINGS

Phosphate minerals are present in at least two paleo-hot spring deposits in Wyoming. One occurrence is on Eagle Ridge, northwest of Thermopolis, the other is on Cedar Mountain, west-southwest of Cody. The Eagle Ridge paleo-hot spring was recognized during field work for a WSGS investigation of rare earth elements in Wyoming (Sutherland and others, 2013). The paleo-hot spring lies at the contact between the Phosphoria Formation and a gypsum bed of the overlying Dinwoody Formation(?). Powder XRD analysis identified the phosphate mineral taranakite ((K,Na)₃(Al,Fe³⁺)₅(PO₄)₂(HPO₄)₆·18(H₂O)) in a sample taken from Eagle Ridge. Whole rock geochemical analysis performed for this project indicated that a taranakite-rich sample contains less than 3 percent P₂O₅.

Table 11. Phosphate content and stratigraphic data of phosphate rock beds in the Jackson Hole area and the Gros Ventre Range from USGS measured sections of the Phosphoria Formation.

Location Name	Legal Location	Latitude	Longitude	P ₂ O ₅ (wt%)	Thickness (ft)	Stratigraphic height above base of Meade Peak (ft)
West Gros Ventre Butte (Gere and others, 1966)	NW¼, NE¼, sec. 17, T. 41 N., R. 116W.	43.5213	-110.7895	24.1	4.9	0
Snow King Mountain (Gere and others, 1966)	NE¼, NE¼, sec. 9, T. 40 N., R. 116 W.	43.4481	-110.7561	27.5	3.6	0
Game Creek (Gere and others, 1966)	SW¼, sec. 24, T. 40 N., R. 116 W.	43.411	-110.7084	25.2	3.3	2
Flat Creek (Sheldon and others, 1953)	sec. 6, T. 41 N., R. 114 W.	43.5454	-110.5743	27.1	4.1	0
Gros Ventre Slide (Sheldon and others, 1953)	SW¼, sec. 5, T. 42 N., R. 114 W.	43.6299	-110.5589	24.9	3.4	27

At Cedar Mountain, hydrothermal mineralization occurs within sandstone, likely the Tensleep Sandstone, that included the phosphate mineral minyulite (KAl₂(OH,F)(PO₄)₂·4(H₂O)), as identified by powder XRD analysis. The minyulite occurs as irregular masses along fracture surfaces, and sparsely disseminated in the sandstone. Minyulite itself is more than 38 percent P₂O₅, but a sample of the sandstone with disseminated minyulite yielded only 7.2 percent P₂O₅.

CONCLUSIONS

Thick, medium- to high-grade occurrences of phosphate rock are not uncommon in Wyoming. The Meade Peak Member of the Phosphoria Formation in the Overthrust Belt exhibits the highest potential for economically viable phosphate rock deposits with respect to grade and thickness. The structural geology of the Overthrust Belt is complex and steep inclination and discontinuity of beds may preclude mineability at many locations. Relatively thick, medium- to high-grade phosphate rock beds are present over much of the length of the Sublette Range, though the orientation of bedding is likely too steep to accommodate open pit mining. To the east, in the Tunp Range, thick, medium- to high-grade phosphate rock crops out at several locations; however, sample spacing is too large to indicate whether these occurrences are all within one continuous bed, or multiple discontinuous beds. To the north and east of the Tunp Range, grade and thickness of phosphate rock beds generally decrease. Notable exceptions are the Dry Fork–Wolf Creek locality in the Snake River Range, and the Teton Pass Mountains location in the southern Teton Range.

Southeast of Lander, the Meade Peak Member and, to a lesser degree, the Retort Member host important phosphate deposits along the northeastern flank of the Wind River Mountains. The Lander deposits are low- to medium-grade, but the structural geology of the area is relatively simple compared to the Overthrust Belt.

While phosphate mineralization occurs in other geologic setting in Wyoming, only mineralization of the Phosphoria Formation is likely to be of a grade and extent to attract economic interest. Concentrations of igneous apatite have been identified in southeastern Wyoming; however, to date these occurrences show little potential for economic viability. Phosphate mineralization is also associated with paleo-hot spring deposits in at least two locations in the state, but these occurrences are extremely low-grade and limited in extent.

SUGGESTIONS FOR FUTURE INVESTIGATIONS

With the data contained in this report the next step for investigating Wyoming's phosphate resources is to determine the extent of individual phosphate deposits. Detailed field mapping will reveal the degree of continuity of phosphate rock, as well as structural relationships that can be either beneficial or detrimental to the economic feasibility of a deposit. Detailed mapping may be most beneficial across the Tunp Range and the southern half of the Salt River Range. In this region, several high-grade occurrences have been observed at relatively wide spacing, and available geologic mapping is only at a scale of 1:62,500. Furthermore, detailed geologic mapping will allow for estimations of overburden thickness; where large-scale geologic mapping is currently available (e.g., Snake River Range, southern Teton Range) this may already be possible.

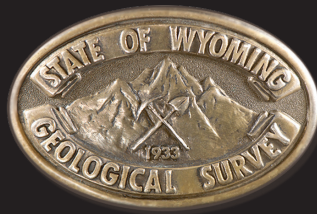
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