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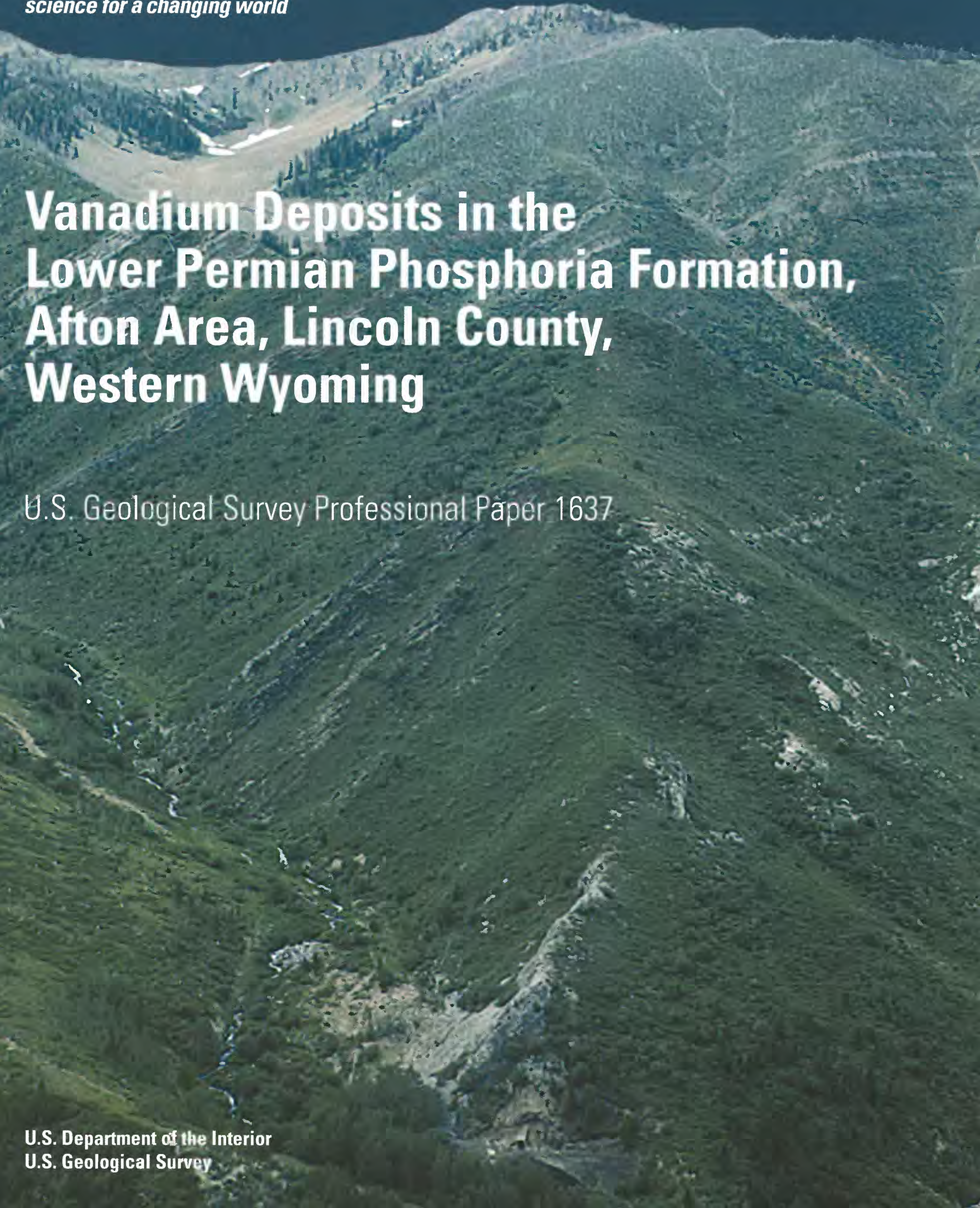
Vanadium Deposits in the Lower Permian Phosphoria Formation, Afton Area, Lincoln County, Western Wyoming

U.S. Geological Survey Professional Paper 1637



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Cover. View south across Dry Creek Canyon. Vanadium Adit 3 in Meade Peak Member of the Phosphoria Formation in center at bottom of photograph. Rex Chert Member forms ragged ledges uphill from adit. Original 35 mm color transparency by J.D. Love, September 1943.

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Based on field work and analysis by U.S. Geological Survey and the (then) U.S. Bureau of Mines during 1942–1944

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[Plates are on enclosed CD-ROM]

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Metric Conversion Factors

Because the data for this report were acquired in the 1940s, all measurements are in feet, miles, inches, short tons, and degrees Fahrenheit; they are published here in those original units. For conversion to metric units, use the following factors:

To convert	Multiply by	To obtain metric units
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
(short) ton (2,000 lb)	0.91	metric ton (t)
degrees Fahrenheit (°F)	5/9 (F-32)	degrees Celsius (°C)

Vanadium Deposits in the Lower Permian Phosphoria Formation, Afton Area, Lincoln County, Western Wyoming

By J.D. Love, L.E. Smith, D.G. Browne[1], and L.M. Carter

Abstract

Vanadium reserves are in the Phosphoria Formation of the Afton area, western Wyoming. The vanadium is in shale and mudstone beds in the Meade Peak Member of the Phosphoria Formation (Permian). Exploration work by the U.S. Geological Survey from the late 1930s to 1943 demonstrated that the vanadiferous zone is remarkably consistent in character, grade, thickness, and lateral continuity throughout the Afton and adjacent 1,000 square mile mountainous area.

During the program of exploration and development, in cooperation with the U.S. Bureau of Mines, 123 trenches were dug across surface sections of the Meade Peak Member. Four shafts and six adits were driven into four lines of outcrop of the vanadiferous zone along Dry Creek. On the basis of these data, reserves of about 30 million tons of "indicated" vanadium ore averaging 1.1 percent V_2O_5 are estimated. The richest central 2.1 feet of the vanadiferous zone is black shale, oolite, and dark-gray mudstone. The tonnage estimate is based in part on ore above main drainage levels and for an arbitrary 500 feet below drainage levels.

Factors favorable to possible economic development of the vanadium deposits in the Afton area are the large "indicated" ore reserves and the topographically high areas above drainage levels. Unfavorable factors are the rough terrain, harsh climate, and narrow width of the ore bed. Nearby sources exist for coal, salt, and sulfur, which at the time of this study were necessary for processing the ore.

This study demonstrates how a successful field exploration program can be completed under Spartan conditions, and a similar program to the north in the future could be immensely rewarding. About 1,000 square miles of similar mountainous terrain north of the Afton area contain many lines of Phosphoria outcrops that have not been explored adequately for vanadium, gold, silver, chromium, zinc, cadmium, and other trace elements known to be present.

Introduction

The U.S. Geological Survey wartime (1942–1944) program of investigation of vanadium resources in the Phosphoria Formation (Permian) in the mountains of western Wyoming, southeastern Idaho, northern Utah, and western Montana, was initiated and directed by W.W. Rubey (fig. 1). He divided the work into three areas: V.E. McKelvey, R.P. Sheldon, and associates were assigned to study and evaluate the deposits in southeastern Idaho, Coal and Raymond Canyons in western Wyoming, and northern Utah. J.D. Love was assigned to investigate the deposits farther north and east in the Afton area of western Wyoming (fig. 2). Roger Swanson and Earl Cressman were assigned to areas in western Montana.

Because of the wartime personnel shortage, the drafting of the original versions of the plates and all clerical work, including the preparation of figures and tables, were accomplished in the field for the final report, thereby significantly delaying its completion. The completed manuscript that forms the basis of this report was submitted to the U.S. Geological Survey on May 25, 1944. The original estimates of tonnage of ore-grade vanadium deposits and associated analytical data have not been changed. Wartime and postwar restrictions, changing governmental priorities, deferred commitments by the authors, and lack of national economic interest in domestic vanadium deposits were responsible for delaying the issuance of this report to the public.

The significance of this investigation still remains the same. It demonstrates (1) the effectiveness of the practical surface exploration techniques used in this rugged terrain; (2) continuity of thickness and economic grade of the principal vanadium ore bed; (3) the feasible underground mining techniques for recovering vanadium from a 3-foot bed of ore; (4) definition of an area containing 30 million short tons of "indicated" vanadium ore[2]; (5) suggestion that adjacent unexplored areas are worthy of a similar type of investigation for vanadium; (6) use of exploration techniques—and possibly their future parallel or coordinated use—to locate and evaluate hitherto unrecognized stratigraphically distributed deposits in the Phosphoria Formation in western Wyoming. These could include gold, silver, chromium, zinc, cadmium, selenium, and other elements known to occur in the Meade Peak Member of the Phosphoria. (See Love, 1961, 1967; Vine, 1969; Vine and Tourtelot, 1970.)

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[1]University of California–Los Angeles.

[2]See the mineral resource classification system of figure 18 (this report).

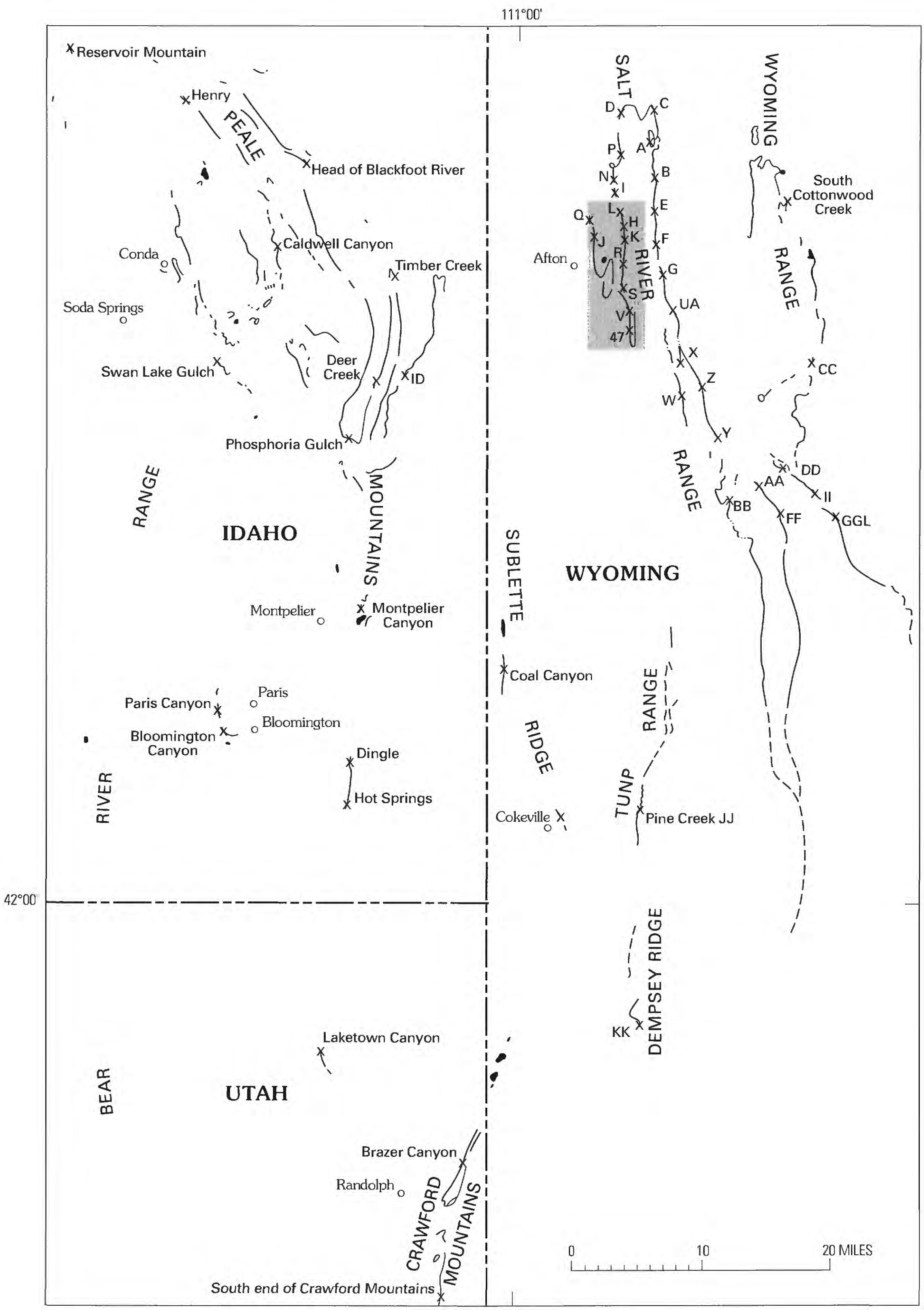


Figure 1. Location of vanadium trenches during initial stage of exploration in the Wyoming-Idaho-Utah area (modified from McKelvey, 1946). Heavy lines, outcrops of the Phosphoria Formation. Box, area of figure 2.

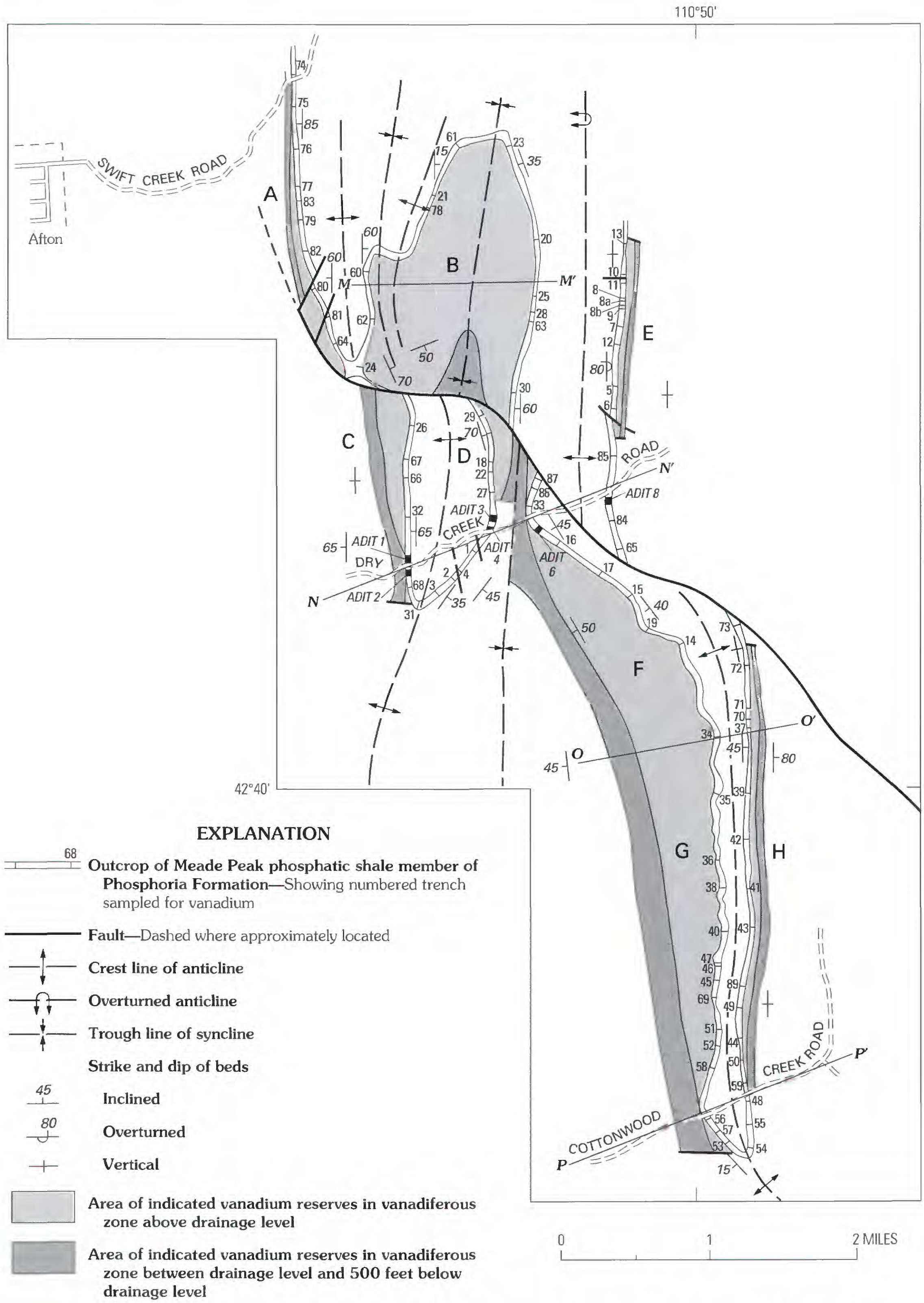


Figure 2. Vanadium trenches and adits at the end of development, boundaries of ore blocks A through G, location of cross sections *M* through *P* (shown on pl. 16), area of vanadiferous beds above drainage level, and for 500 feet below drainage level. Boundaries for blocks A through F and H based on local structures and faults that involve vanadiferous strata; boundary between F and G arbitrarily selected at approximate site of section *O-O'*. Geology by W.W. Rubey, slightly modified by J.D. Love and L.E. Smith.

Figure 3. View south across Dry Creek Canyon. Core of anticline is in Phosphoria and Wells Formations (barely visible). Overlying strata to skyline are Triassic. Vanadium Adit 3 is just out of sight below ledges of Rex Chert Member at right center. Original color transparency by J.D. Love, September 1943.

Acknowledgments

W.W. Rubey first recognized the existence and possible national wartime significance of vanadium deposits in the Afton and adjacent areas. His leadership, vision, and guidance in all phases of exploration of these deposits are deeply appreciated. R.P. Fischer, S.G. Lasky, and D.F. Hewett of the U.S. Geological Survey gave field advice and critically reviewed our interim and final reports. In the development phase of field investigations, we worked with F.H. Majors, Stanford Mahoney, and W.A. Young of the Bureau of Mines.

Cotter Ferguson and Charles Kortes of the Gas Hills Uranium Company were most helpful in providing data of the 60-foot-deep trench, dug in 1961, at the site of our LL trench in Cottonwood Canyon.

We are especially grateful to geologists V.E. McKelvey, J.D. Strobell, Jr., and R.P. Sheldon and chemist Victor North for cooperation in the field and laboratory and for many stimulating discussions about how best to assemble and present the myriads of new data. Roger Swanson and Earl Cressman provided the perspective on the vanadium deposits in Montana.

We are indebted to Elisabeth M. Brouwers and Lorna M. Carter for their encouragement and acumen in steering this manuscript through the editorial process. George Breit's insightful review of an earlier version of the manuscript was particularly useful.

And finally, our respect and appreciation go to the 80 and more resourceful, ingenious, and enthusiastic men of Star Valley, many of whose sons were already in military service, who gave nearly 2 years of their lives to the successful completion of this essential but hazard-filled wartime project.

Climate

The harsh climate of the Afton area is pertinent to year-round mining operations, whether open pit or underground, because it inhibits easy access to areas of operation. The annual precipitation is about 17 inches, but much of it is in the form of snow, which at Afton averages about 81 inches (nearly 7 feet). The depth of snow in the Dry Creek area where all the mining was done, however, was much greater.

Figure 4. View north showing south-facing slope of Dry Creek Canyon. Smooth black outcrop in upper center of photograph is vanadiferous Meade Peak Member, overlain by ragged ledges of Rex Chert Member and underlain by white Wells Formation. Rocks at upper left are all Triassic. Original color transparency by J.D. Love, August 1943.

This operation was complicated by temperatures as low as –47°F (mean annual temperature at Afton was 39°F; Mansfield, 1927, p. 39–41). The record temperature of –65°F was reported at the village of Glover, 5 miles north of Afton. What it was at our mines is not known.

With an average snowfall of nearly 7 feet and strong westerly winds, snow combs over the sharp, bare ridge crests, especially on the south side of Dry Creek Canyon, and slides to the bottom of the canyon where the mines were located. On one day in February 1943, twenty-six snowslides roared down the slopes and buried the access road. Some were more than 20 feet deep and the road had to be built on top of the compacted snow.

Topography

Topography was a significant factor in both exploration and development of the vanadium deposits. Elevation on the floor of Star Valley near Afton ranges from 6,100 to 6,600 feet, but the Salt River Range in which much of the vanadium exploration and development took place rises precipitously along a fault line on the east side of the valley to more than 10,000 feet (fig. 3). All of the adits and all but the northernmost trenches are above 7,000 feet (cover photograph). Most trenches are on outcrops near the angle of repose (about 32°) (figs. 4 and 5). Another complicating terrain factor is that timber on many of the canyon slopes has been burned off by forest fires or devastated by clearcuts.

Local Economic Resources Pertinent to Development of Vanadium Resources

The economy of Star Valley has always been agricultural, chiefly dairy farming, because the average growing season is so short (average 46 days). Sawmills in the area harvest local as well as outside timber and for our work or future projects could be used for obtaining mine timbers. Rural Electrification Administration (REA) electricity is available now, although it was not when our work was done. Rock salt

Figure 5. Exploration trenches across the vanadium bed in the Meade Peak Member, south side of Swift Creek Canyon. Original color transparency by J.D. Love, August 1943.

and sulfur were used at the time of our study in the extraction of vanadium from low-grade ores (Argall, 1943; Gupta and Krishnamurthy, 1992), although more modern extraction techniques do not require the use of salt and sulfur (Russell and others, 1982; Judd and others, 1986). These were found within a radius of 12 miles from the vanadium deposits. Rock salt and brines were produced on Stump, Tygee, and Crow Creeks, which drain into Star Valley from the west. The monthly production from the general area in 1877 was 200,000 pounds (Peale, 1879, p. 645). Native peoples likewise quarried salt here. In the subsurface sections, south of Afton, one well showed 5,500 feet of salt in the Preuss Formation (Jurassic) near where a normal section of salt in adjacent wells was 300 feet (Love, 1989, p. 75–76). Sulfur has been mined from open pits at the Auburn Hot Springs 8 miles northwest of Afton. Between 1947 and 1949, about 900 tons of sulfur was mined (Rubey, 1958). A good grade of bituminous coal has been mined for many years at the Blind Bull mine on Greys River northeast of Afton.

Preliminary Investigations

Mansfield (1927, p. 212) first reported vanadium from the Phosphoria Formation in the Teton area about 50 miles north of Afton, along the Wyoming-Idaho State line. In 1941, Anaconda Copper Mining Company began recovering vanadium as a byproduct from phosphate rock in their processing plant at Conda, Idaho. W.W. Rubey had previously spent many years mapping the rocks in the Afton area (fig. 6), as well as most of the mountains in this part of Wyoming (Rubey, 1943, 1958, 1973; Rubey and others, 1975, 1980). Prior to 1942, he had dug 11 trench sections across the black shales of the Meade Peak Member of the Phosphoria Formation. On the basis of chemical analyses of samples from these trenches, he recognized that most but not all of the vanadium was concentrated in a single bed of black shale and mudstone. From Rubey's 11 sampled sections in the Salt River Range, plus 1 in the Wyoming Range farther east, all samples contained some vanadium and six had 0.5 percent or more.

Because of the German blockade during World War II, foreign sources of vanadium used in the manufacture of steel armor plate were severely restricted; as a result, many U.S. tanks, ships, and airplanes of that war were having to go into battle without adequate armor plate. Therefore, the U.S. Geological Survey program to find, develop, and process vanadium deposits was given special priority.

Exploration Phase

Rubey was assigned to other wartime work in 1942, so he transferred the exploration phase of the Afton project to J.D. Love in August 1942. Love's mission was three-fold: (1) to follow the north-south outcrops of the Phosphoria Formation along the "thrust belt" of western Wyoming, in a mountainous area of about 1,500 square miles, with only one road across it[3]; (2) to determine the number, thickness, and grade of significant vanadium-bearing beds in the Meade Peak Member; and (3) to define the richest area for the start of a development phase.

As the area to be explored was almost roadless, horses were used throughout the exploration phase of the program. From August 1942 until November 10, 1942, two packers, four trenchers, 12 pack and saddle horses, and pack equipment were used (fig. 7). We hand dug and sampled inch-by-inch about 20 trenches across the black shales and mudstones of the Meade Peak Member in the Salt River Range and Wyoming Range and as far south as the Tunp Range and Dempsey Ridge (fig. 1; table 1). The airline distance, north-south, was about 70 miles, and the east-west distance was about 20 miles. Because of wartime food rationing, only limited amounts of food could be obtained on any one trip to Afton. Therefore, replenishing these supplies had to be carefully coordinated with the packhorse trips with a load of rock samples.

The samples were taken to Afton where Victor North, the U.S. Geological Survey chemist, analyzed them chemically. However, it was imperative while in the field to determine which of several black shale and mudstone beds contained the most vanadium and which line of outcrop was richest, so we would know in what direction to dig the next trenches. Therefore, every night JDL would run field tests on the samples collected during the day. Each sample was powdered in a cast iron mortar, a specific amount of powder was measured into a test tube, mixed with potassium nitrate and sodium hydroxide, and fused, using a small propane burner. The intensity of yellow color (if any) was then compared visually with a standard sample of known composition (for procedure see North, 1946, and Axelrod, 1946). As the reader can see by comparing field test values with chemical values in the Appendix (on CD-ROM), the field tests were remarkably accurate.

In the beginning of this phase of exploration, it was not known if the vanadium in these new areas was present as a syngenetic deposit. Another question was whether the most vanadiferous samples, from sections several miles apart, were from the same bed, and if the grade increased in one direction. During this phase, the following trenches were dug, measured, and sampled (figs. 1 and 8; table 1): E, G, K, P, R, S, V, W, X, Y, Z, AA, BB, CC, DD, EE, FF, GGL, HH, II, KK, TT, and CL. It should be noted that although locations of all the trenches dug in the Wyoming-Idaho-Utah area are shown in figure 1, and the trenches are described in table 1, the remainder of this report will concern itself solely with exploration in the Afton, Wyo., area (fig. 2). Inasmuch as most trenches were on unsurveyed Forest Service land and no modern topographic maps or aerial photographs existed, the described locations in the Appendix are only approximate.

Data from these trenches demonstrated conclusively that the highest amount of vanadium was concentrated in one zone of black shale and mudstone near the top of the Meade Peak Member of the Phosphoria Formation in the Afton area. The zone was recognizable, however, in all other areas sampled. No lithologic characteristics were recognized that make this zone visually distinctive.

Development Phase

The development phase began in November 1942 after severe weather made impractical any further reconnaissance surface work with the horse-supplied party in the roadless areas. On December 10, 1942, cooperative work with the U.S. Bureau of Mines began in the Afton area. However, the Bureau of Mines part of the cooperative work was suspended abruptly on February 20, 1943, and was not reactivated until July 27, 1943. Then it was continued until December 15, 1943, at which time it was terminated. During our cooperative investigation, the Bureau of Mines staff consisted of F.H. Majors, project chief, and Stanford Mahoney and W.A. Young, mining engineers. Eighty-nine new surface trenches were dug and four shafts sunk along 18 miles of surface outcrops of the Meade Peak Member (pls. 5–16, fig. 2, table 1).

Before underground operations could begin, and because of wartime restrictions on machinery and gasoline, horses were used in logging operations as much as possible. We had

[3] The area had already been mapped by Rubey (1958, 1973; Rubey and others, 1975, 1980), but these maps were not published until long after our work was completed in 1943. However, they were available in manuscript to us.

Figure 6. Generalized geology of Afton area (modified from Rubey, 1973).

EXPLANATION

Qal — **Flood-plain and alluvial fan deposits (Holocene)**—Gravel, sand, silt, and clay; poorly sorted, unconsolidated

Qd — **Rock debris, including hill wash, talus, and landslide deposits (Holocene)**—Angular rock fragments; unstratified

Qtg — **Terrace gravels and older alluvium (Holocene and Pleistocene)**—Partially dissected remnants of gravel, sand, and silt; chiefly in two levels along major streams, one 15–40 feet, the other 100–150 feet above present stream grades, and a few remnants about 100 feet still higher

Qm — **Glacial till (Pleistocene)**—Unsorted rock fragments, silt, and clay; ground moraine of local mountain glaciers

Tsl — **Salt Lake Formation (Pliocene)**—Pale-reddish-gray and tuffaceous conglomerate, grit, sandstone, siltstone, and clay; includes beds of white volcanic ash

Jp — **Preuss Redbeds (Upper Jurassic)**—Dull-reddish- to purplish-gray sandy siltstone and silty claystone; thinly and regularly bedded

Jt — **Twin Creek Limestone (Upper to Middle Jurassic)**—Distinctive unit of thin-bedded somewhat sandy argillaceous limestone and calcareous siltstone, with layers of more massive oolitic limestone below; thin-bedded limestone and siltstone weather light gray and form conspicuous bare slopes

JŦn — **Nugget Sandstone (Triassic(?) and Jurassic(?))**—Quartzite and slightly calcareous sandstone, buff to pinkish-tan, crossbedded, massive, fine- to medium-grained; forms prominent ridges and mountain crests

Ŧa — **Ankareh Redbeds (Upper Triassic)**—Red and purplish sandy calcareous mudstone and red to white fine-grained quartzite; a few beds of dense red to greenish-gray limestone, and discontinuous lentils of gritsized conglomerate; beds of Early Triassic age are absent

Ŧt, **Ŧty**, **Ŧtb** — **Thaynes Limestone (Lower Triassic)**—Alternating layers of gray somewhat sandy limestone and greenish-gray calcareous siltstone with some greenish clay. Ŧty, yellowish-gray-weathering upper member; contains larger proportion of limestone; Ŧtb, dark-brown-weathering lower member; contains fewer thick limestone beds and with numerous manganese stains

Ŧw — **Woodside Redbeds (Lower Triassic)**—Red siltstone and shale; a few thin beds of sandstone and gray limestone

Ŧd — **Dinwoody Formation (Lower Triassic)**—Alternating thin layers of dull-greenish-gray calcareous siltstone and shale and of argillaceous sandy limestone, all of which weather to tan or buffy gray

Ppr, **Ppp** — **Phosphoria Formation (Permian)**—Ppr, Rex Chert Member; as mapped, includes also Franson Tongue of Park City Formation and Retort Phosphatic Shale and Tosi Chert Members of Phosphoria Formation. Less resistant dark-gray siltstone, thin-bedded black chert and limestone, and a few thin beds of phosphate rock in upper part; resistant ledges of gray cherty dolomitic limestone and some bedded chert in middle and lower parts. Ppp, Meade Peak Phosphatic Shale Member; as mapped, includes also lower chert member of Phosphoria. Nonresistant dark phosphatic siltstone, gray dolomite, dark cherty siltstone, several beds of phosphate rocks, and one vanadiferous carbonaceous siltstone

PIPw — **Wells Formation (Pennsylvanian and Permian)**—As mapped, includes tongue of lower part of Park City Formation at top. Pale-buff fine-grained quartzite and sandstone throughout, with alternating beds of dolomitic limestone and hard siltstone in upper part and a few thin limy beds in middle and lower portions. Forms bold ridges and mountain crests

IPMa — **Amsden Formation (Mississippian and Pennsylvanian)**—Heterogeneous unit of gray, red, and black cherty limestone, fine-grained quartzite and sandstone, red to yellowish siltstone, limestone breccia, quartzose conglomerate, and pisolitic iron oxide; cherty gray limestone most abundant above and sandstone and quartzite below

EXPLANATION (continued)

Contact—Dashed where approximately located; dotted where concealed

High-angle fault—Dashed where approximately located; dotted where concealed; U, upthrown side; D, downthrown side

Holocene or Pleistocene fault—Displaces alluvium or Salt Lake Formation; dashed where approximately located; dotted where concealed; hachures on downthrown side

Fault—Dashed where approximately located; dotted where concealed; barbs show relative movement

Anticline—Showing trace of axial plane; dashed where approximately located

Syncline—Showing trace of axial plane; dashed where approximately located; dotted where concealed

Overturned anticline—Showing trace of axial plane; dashed where approximately located

Overturned syncline, approximately located—Showing trace of axial plane and direction of plunge; dotted where concealed

Strike and dip of beds

- **Horizontal**
- 45 **Inclined**
- **Vertical**
- 50 **Overturned**

Prospect pit or mine

Phosphate trench

Figure 8. Geologist measuring vanadiferous zone in Meade Peak Member at future site of adit. White gloves mark top (left) and bottom (right) of bed. Photograph by J.D. Love, November 9, 1943.

to assemble our own sawmill, cut timber from the adjacent forest, saw mine timbers and lumber for shelter cabins (figs. 9, 10, and 11) and build them before snow got too deep. Roads had to be constructed to the mine sites. We were forced to employ an RD–8 bulldozer each day during the winter to keep the road open to the mines (figs. 12 and 13). Figures 14 and 15 are included to show field conditions that have to be considered as part of any future development here—as well as the difficulty in recording those conditions photographically. Six adits were driven into the Meade Peak Member along the bottom of Dry Creek Canyon along 4 miles of outcrop (fig. 2). Six hundred and six feet of underground work was completed (Allsman and others, 1949, p. 5). The surface trenches were spaced approximately 1,000 feet apart and extended along the lines of outcrop from Swift Creek south to Cottonwood Creek (see sections in Appendix and notes on quality of data).

Figure 7 (facing page). View of (left to right) J.D. Love, Will Hebdon, Jake Miller, and Larell Hebdon at the Swift Creek Camp—the first one at the beginning of the exploration phase of trenching. Original color transparency by J.D. Love, August 1942.

U.S. Geological Survey geologist L.E. Smith joined JDL on May 11, 1943, and stayed on the project until the final report was completed on March 3, 1944. Our report was classified for many years by wartime restrictions. In the late 1990s JDL enlisted D.G. Browne to help him update the manuscript and get it ready for the USGS publication process. L.M. Carter assembled all the pieces, prepared the digital appendix and final plate files, and edited the report.

Summary of Geology

The stratigraphy and structure of the Afton area were mapped by Rubey between 1931 and 1942 and described in a series of classic studies (Rubey, 1958, 1973). The following descriptions are summarized from his work, plus a minor amount of detail from our own work on the Phosphoria Formation. Descriptions of formations older and younger than the Phosphoria are not repeated here. Table 2 summarizes the pertinent data.

Phosphoria Formation

The Phosphoria Formation has been studied extensively, described in detail, analyzed, regionally correlated, and subdivided into many members in most parts of the Western Phosphate Field and adjacent areas (McKelvey and others, 1986; McKelvey and others, 1959; Sheldon, 1957, 1963; and many other publications cited in their bibliographies). For this report, only the data on the Meade Peak Member (named by McKelvey and others, 1959, p. 22–25) are pertinent. However, McKelvey (1946; this report, pls. 1–4)[4] plotted north-south correlations and analyses of unpublished field data supplied by J.D. Love (see sections in Appendix) in the Afton area. McKelvey was also the first to correlate these sections with his own data in Idaho (McKelvey, 1946, pls. 5, 6, and 7).

Table 3 shows representative trench sections of the Meade Peak Member about 5,000 feet apart on the east and west limbs of the Cottonwood Creek anticline. Trench 42 is on the east limb and trench 47 is on the west limb (pls. 14, 12; fig. 2). Figure 16 shows the visual appearance of the vanadiferous zone and adjacent rocks in a bulldozer trench (trench 74, fig. 2) on the north side of the road along the north side of Swift Creek.

Structure of the Vanadiferous Beds

The regional structure involving the Phosphoria Formation is shown on the maps of the Bedford and Afton quadrangles (Rubey, 1958, 1973). The detailed structure involving

[4] On V.E. McKelvey's original (1946) plates 1, 2, 3, and 5, reproduced herein as plates 1–4, "phosphatic shale member" in the title has been updated to "Meade Peak Member."

Table 1. List of trenches and adits dug in the Afton, Wyo., area and areas of adjacent western Wyoming and eastern Idaho, 1942–1943.

USGS	USBM	Figure 1	Figure 2	Pl. No.	Plate 15	Date	Blk No.	Logger	Page No.
A	–	x		1				Gooldy	
B	–	x		1				Gooldy	
C	–	x		1				Gooldy	
D	–	x		2				Gooldy	
E	–	x		1		8-29-42		Love	55
F	–	x		1				Gooldy	
G	–	x		1				G&L	
H	–	x		2				G&R	
I	–	x		2,3				G&R	
J	–	x		2				G&R	
K	–	x		2,4				Rubey	
K	–	x		2,4		8-28-42		Love	32
L	–	x		2				Rubey	
M	–							Rubey	
N	–	x		2				Rubey	
O									
P	–	x		2		9-42		Love	71
Q	–	x		2				Rubey	
R	13	x		2		8-42		Love	22
R	13	x		2		43		Love	28
S	–	x		2		8-42		Love	8
T	–	x				8-42		Love	34
U								Love	
U_A				1				Rubey	
V	34	x		2		9-10-42		Love	14
V	34	x		2		43		Smith	17
W	–	x		1		9-42		Love	60
X	–	x		1		9-42		Love	65
Y	–	x		1,3		9-42		Love	110
Z	–	x		1		9-42		Love	116
AA	–	x		1		9-42		Love	74
BB	–	x		1		9-42		Love	79
CC	–	x				9-42		Love	84
DD	–	x		1		10-42		Love	92
EE	–					10-5-42		Love	43
FF	–	x		1		10-42		Love	96
GG_L	–	x		1		10-42		Love	100
HH	–					10-42		Love	103
II	–	x		1		10-42		Love	106
JJ	–	x							
KK	–	x		3		10-42		Love	446
KK	–	x		3		7-43		Love	446
LLa	–							Smith	413
TT	–					10-6-42		Love	39
–	1		x	8	x		D		
–	2		x		x		D		
–	3		x	8	x		D		

Table 1. List of trenches and adits dug in the Afton, Wyo., area and areas of adjacent western Wyoming and eastern Idaho, 1942–1943.—Continued

USGS	USBM	Figure 1	Figure 2	Pl. No.	Plate 15	Date	Blk No.	Logger	Page No.
BD	4		x	8	x		D	Smith	128
BE	5		x	9	x	8-2-43	E	Love	131
BF	6		x	10	x		E	Smith	134
BG	7		x	9	x	8-3-43	E	Love	137
BH	8		x	9	x	8-3-43	E	Love	140
BHa	8a		x	9	x	11-9-43	E	Smith	142
BHb	8b		x	9	x	9-29-43	E	Smith	146
BI	9		x	9	x	8-3-43	E	Love	150
BJ	10		x	9	x	8-3-43	E	Love	153
BK	11		x	9	x		E	Smith	156
BL	12		x	9	x		E	Smith	159
–	13		x	9	x		E		
BN	14		x	11	x		F	Love	162
BO	15		x	11	x		F	Smith	165
BP	16		x	6	x		F	Love	168
BQ	17		x	6	x		F	Smith	171
BR	18		x	8	x		D	Love	175
BS	19		x	11	x		F	Smith	178
BT	20		x	6	x	8-9-43	B	Love	181
BU	21		x	5	x		B	Love	184
BV	22		x	8	x	8-10-43	D	Love	187
BW	23		x	6	x	8-10-43	B	Smith	189
BX	24		x	5	x		B	Love	192
BY	25		x	6	x	8-14-43	B	Smith	195
BZ	26		x	7	x		C	Love	199
BAA	27		x	8	x		D	L&S	202
BBB	28		x	6	x	8-17-43	B	Smith	206
BCC	29		x	8	x	8-17-43	D	Love	210
BDD	30		x	6	x		B	Love	213
BEE	31		x	8	x	8-31-43	D	Love	216
BFF	32		x	7	x	8-25-43	C	Love	224
BGG	33		x	6	x		F	Smith	226
V	34		x	11	x		G	Smith	14
CB	35		x	11	Note		G	Love	283
CC	36		x	11	x		G	Love	286
CA	37		x	10	x	8-43	H	Smith	276
CD	38		x	11	x		G	Love	288
CE	39		x	13	x	9-8-43	H	Smith	291
CG	40		x	11	x		G	Love	294
CI	41		x	13	x	9-9-43	H	Smith	303
CH	42		x	13	x	9-9-43	H	Smith	297
CJ	43		x	13	x	9-10-43	H	Smith	307
CK	44		x	13	x		H	Love	311
CM	45		x	12	x		G	Love	328
–	46		x	11	x		G		
CL	47		x	2,3,11	x		G	Love	319
CP	48		x	13	x		H	Love	337
CO	49		x	13	x	9-17-43	H	Smith	334
CQ	50		x	13	x	9-15-43	H	Smith	339
CS	51		x	12	x	9-18-43	G	Smith	345
CR	52		x	12	x	9-18-43	G	Smith	342

Table 1. List of trenches and adits dug in the Afton, Wyo., area and areas of adjacent western Wyoming and eastern Idaho, 1942–1943.—Continued

USGS	USBM	Figure 1	Figure 2	Pl. No.	Plate 15	Date	Blk No.	Logger	Page No.
CW	53		x	12	x	10-21-43	H	Smith	357
CV	54		x	12	x		H	Love	354
CU	55		x	12	x		H	Love	351
CZ	56		x	12	Note		H	Love	364
CT	57		x	12	x	9-17-43	H	Love	349
CY	58		x	12	x		G	Love	362
CX	59		x	13	x	9-20-43	H	Smith	359
BJJ	60		x	5	x	9-24-43	B	Smith	235
BMM	61		x	5	x	9-27-43	B	Love	246
BKK	62		x	5	x	9-27-43	B	Smith	238
BOO	63		x	6	x	9-30-43	B	Love	252
BLL	64		x	4	x		A	Smith	242
BNN	65		x	10	x	9-30-43	E	Smith	249
BPP	66		x	7	x	10-2-43	C	Smith	254
BQQ	67		x	7	x	10-2-43	C	Smith	258
BHH	68		x	7	x		C	Love	229
CN	69		x	12	x	9-14-43	G	Love	331
CAA	70		x	10	x	10-6-43	H	Love	367
CBB	71		x	10	x		H	Love	371
CCC	72		x	10	x	10-9-43	H	Love	374
CDD	73		x	10	x		H	Love	377
M*	74		x	4	x		A	Love	380
SA	75		x	4	x	10-11-43	A	Smith	382
SB	76		x	4	x	10-12-43	A	Smith	386
SH	77		x	4	x	10-15-43	A	Smith	409
BII	78		x	5	x		B	Love	232
SF	79		x	4	x		A	Love	401
SD	80		x	4	x		A	Love	395
SC	81		x	4	x	10-13-43	A	Smith	391
SE	82		x	4	x	10-14-43	A	Smith	398
SG	83		x	4	x	10-14-43	A	Smith	405
BRR	84		x	10	x	10-2-43	E	Smith	262
BSS	85		x	10	x	10-4-43	E	Smith	268
BTT	86					11-9-43		Smith	271
BUU	87		x		x	11-12-43	B	Smith	274
	88		x						
LL	89		x	13	x	7-23-43	H	Love	314
Adit 1+				7			C	Love	220
Adit 2				7		12-42	C	Love	435
Adit 3				8		12-42	D	L&S	415
Adit 4				8		12-42	D	Love	424
Adit 5						Abandon			
Adit 6				6		12-42	F	Love	425
Adit 7						Abandon			
Adit 8				10		12-42	E	Love	440
South Cotton-wood Creek								Rodgers	
1D								Deiss	
Conda								Rubey	

Notes:

Loggers: G&L=Gooldy and Love
G&R=Gooldy and Rubey
L&S=Love and Smith

Figure 9. Woodcutters at beginning of logging operation to obtain timber for mine studs and lumber for mine buildings, Dry Creek Canyon. Original color transparency by J.D. Love, December 1942.

Figure 11 (above). Blizzard conditions while horses are dragging logs toward sawmill. Bulldozer at back is clearing Dry Creek Road. Snow at this time is about 5 feet deep. Photograph by J.D. Love, December 1942.

◄ **Figure 10 (left).** Loading area in bottom of Dry Creek Canyon. Horses are dragging logs to sawmill at upper left. Photograph by J.D. Love, December 1942.

Figure 12 (above). Bulldozer bucking 10-foot-deep snowslide that buried road in Dry Creek Canyon. Photograph by J.D. Love, February 1943.

Figure 14 (right). View north showing shelter tent ► at Adit 3. Wall of Rex Chert Member is at top left. Photograph by J.D. Love, February 1943.

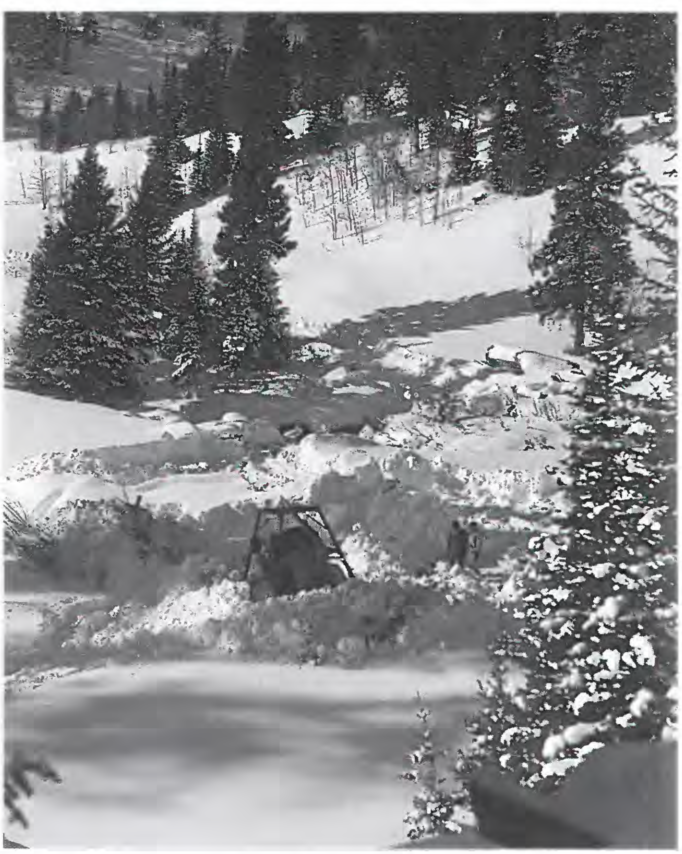


Figure 13. View west down Dry Creek Canyon between Adits 1 and 4, showing problem of clearing 7 feet of snow in order to keep road open to the mines. Men at right of bulldozer show scale. Photograph by J.D. Love, February 1943.

Figure 15. Portal of Adit 1 partly blocked by snowslide, being hand cleared with shovels during blizzard. Photograph by J.D. Love, February 1943.

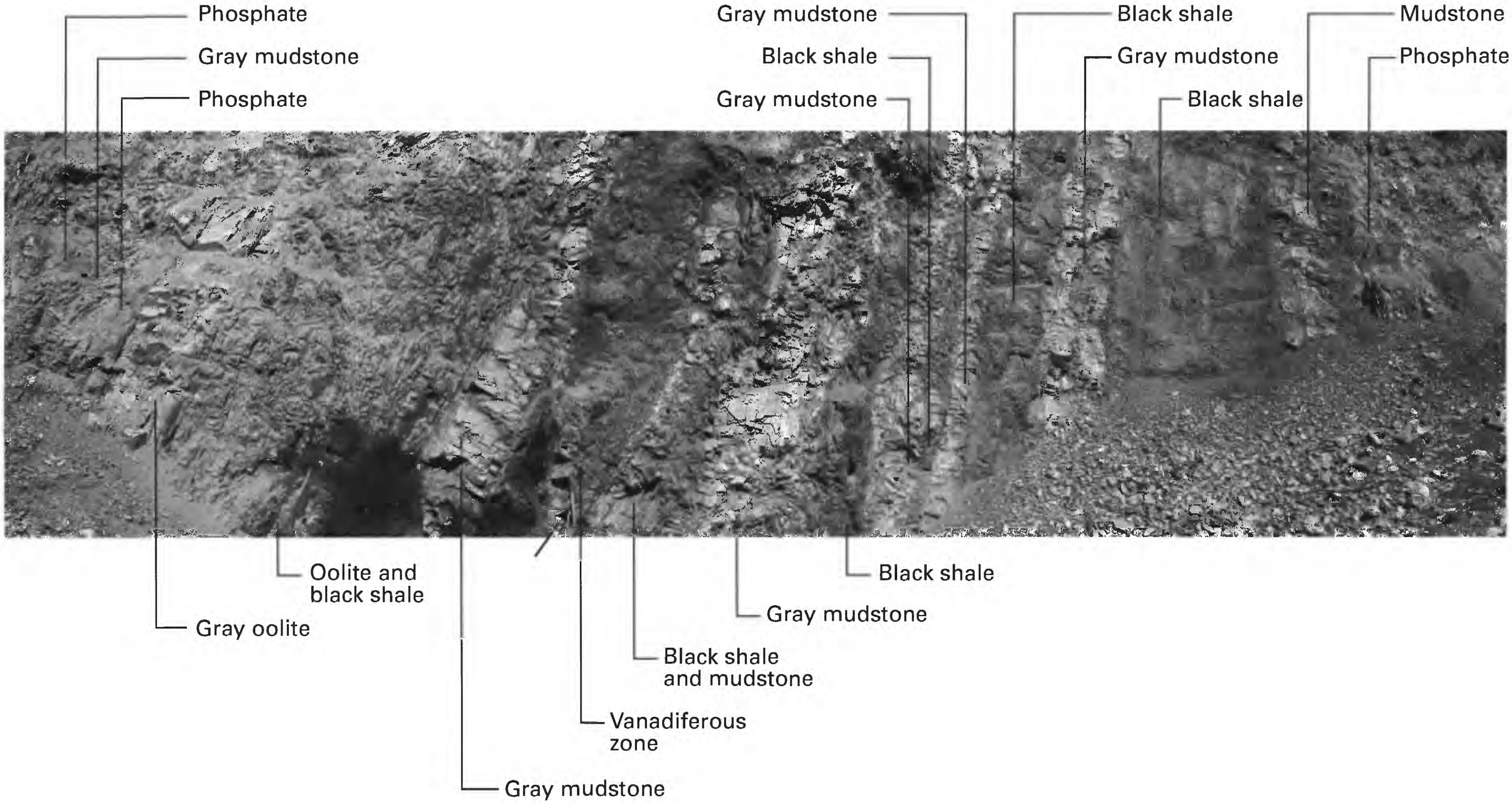


Figure 16. Trench 74 on Swift Creek, showing exposure of Meade Peak Member of the Phosphoria Formation. Oldest beds are at right; base of Rex Chert Member is at extreme left. Shovel (arrow) on vanadiferous zone indicates scale.

Table 2. General section of rocks exposed in vanadium areas near Afton, Wyo.

System	Formation	Character and topographic expression	Feet
Quaternary	Hill wash and mantle	Silt, sand, gravel, and boulders, unconsolidated, derived locally or from slopes above.	0-10
	Talus	Accumulations of angular boulders at base of cliffs.	0-100
	Alluvium	Silt and gravel deposits in canyon bottoms, rounded and partly sorted.	0-50
		Unconformity	
Tertiary	?	Conglomerate of unsorted silt, sand, gravel, and subrounded boulders; consolidated.	0-100(?)
		Unconformity	
Triassic (lower)	Thaynes	Limestone, gray to buff, platy to massive, fossiliferous, *Meekoceras* in lower 100 feet; forms ridges.	1,000–1,200
	Woodside		
	Upper	Shale and siltstone, red, (maroon), soft, thin-bedded. Contains gray mudballs; silty limestone at top. Forms gullies.	200-215
	Lower	Siltstone, shaly, interbedded red and greenish gray, some limestone in upper part. Forms gullies.	70-140
	Dinwoody	Siltstone, gray to greenish gray, parts shaly or limy, includes limy siltstone near base; fossiliferous, reef-forming limestone in parts.	600-930

Table 2. General section of rocks exposed in vanadium areas near Afton, Wyo.—Continued

System	Formation	Character and topographic expression	Feet
		Disconformity	
Permian (Upper)	Phosphoria		
	Rex Chert Member	Massive chert, cherty limestone, and quartzite. Chert gray to black, bedded to nodular; limestone massive, at places phosphatic; at base of member limestone contains *Productus* brachiopods. Forms reefs.	112-150
		Disconformity (?)	
	Meade Peak Member	Siltstone, mudstone, shale, and oolitic phosphate rock, black, rich in organic matter, thin bedded. Siltstone at top siliceous and cherty; phosphate near top and bottom thick bedded; mudstone limy in places; shales fissile to plastic. Forms saddles and gullies.	90-120
		Disconformity (?)	
Carboniferous			
Pennsylvanian	Wells	Limestone and sandstone, limestone at top and bottom, gray, some crinoidal; some nodular chert; sandstone white to reddish, sugary texture, thin bedded to massive, some beds contain nodular chert. Forms ridges and peaks.	100-1,250

Table 3. Representative section of the Meade Peak Member of the Phosphoria Formation in the Cottonwood Creek area.

	Trench 42[1] (upper part not measured)	Trench 47[1] (upper part not measured)
Rex Chert Member		
Limestone, gray, hard, cherty, *Productus*.		
Meade Peak Member		
Mudstone, dark-gray, banded, thin-bedded, siliceous.	18.0	20.8
Phosphate and mudstone, black, massive, *Lingula*.	1.5*	8.2
Mudstone, dark-gray, thin-bedded, with thin oolite beds.	3.2*	4.7
Oolite, black, coarse; and mudstone, gray, thin.	1.4	1.9
Shale, black, soft; and black mudstone; oolitic at top. Vanadiferous zone.	5.9*	5.0
Mudstone, gray, limy; thin oolitic shale bed in upper half.	6.9	8.3
Shale and mudstone, shale black, soft, fissile; mudstone dark-gray, hard, limy, thick-bedded.	14.2	14.4
Mudstone and oolitic shale, mudstone dark-gray, hard, limy, thick-bedded; shale black, fissile.	9.8*	15.6
Phosphate, black, hard, massive.	1.6*	3.2
Mudstone, dark-gray to black, hard, thick-bedded, some cherty; a few scattered thin shale and phosphate beds.	12.3	26.1
Total	63.8	108.2
Unconformity		
Wells Formation		
Limestone, gray, hard, massive.	Not measured	Not measured

[1]Trench 47 is a typical section on the west limb of the Cottonwood Creek anticline. Trench 24 is on the east anticline limb of the Cottonwood Creek anticline. Trenches are 5,000 feet apart. Thicknesses are in feet.

*Crushed, probably faulted.

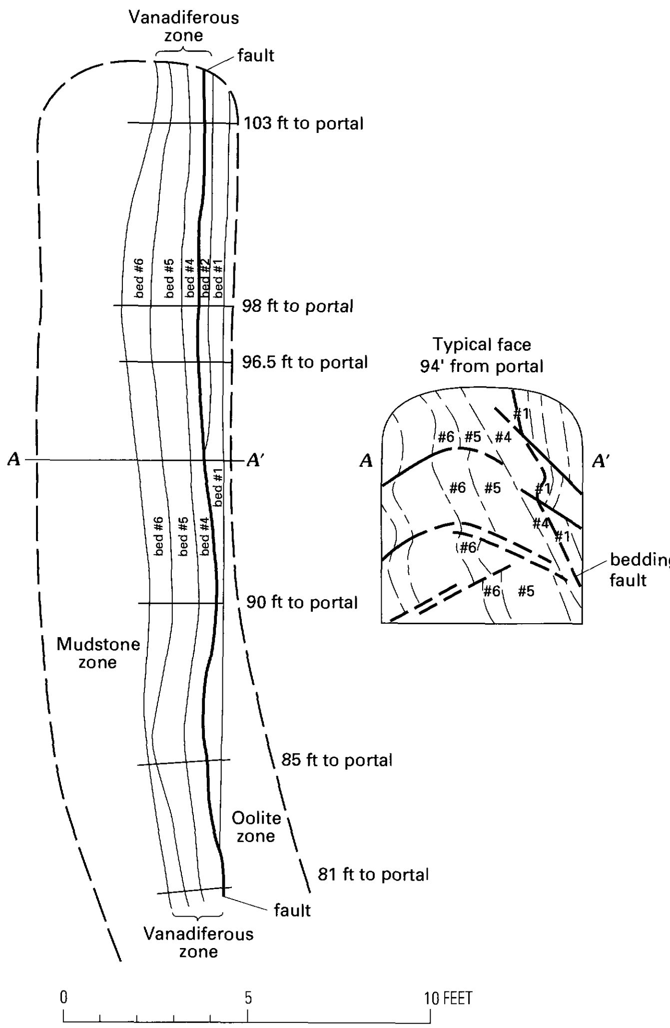


Figure 17. Bedding fault in the vanadiferous zone in Adit 3, Dry Creek Canyon. Fault dashed where inferred.

the major vanadiferous bed is more complex than the regional structure. Two sharp asymmetrical anticlines and a shallow syncline trend north and plunge 5° –10° south. Dips on the limbs of the folds are steep, varying from 60° to vertical. In places, the east limb of the east anticline is slightly overturned. The east limb of the west anticline is complicated by a minor fold in the northern part of the area. The Phosphoria Formation along the west anticline plunges below the surface south of Dry Creek Canyon, and along the east anticline it plunges below the surface south of Cottonwood Creek. (See geologic map, fig. 6.)

A major transverse fault strikes northwest across the area, offsetting the folds as much as 4,000 feet. Several smaller transverse faults offset the Phosphoria outcrop 50–200 feet. In 17 percent of the trench exposures and in the adits, minor transverse and bedding faults are visible. Typical of these is the one found in Adit 3 (fig. 17).

Vanadiferous Zone

The vanadiferous zone is a 3.5- to 5-foot thickness of black shale and mudstone about 35 feet below the top of the Meade Peak Member. This sequence of beds persists at the same stratigraphic horizon and with only slight changes in thickness and vanadium content throughout 20 miles of outcrop (figs. 2, 6). This zone is also believed to correlate with a zone of similar lithology in the Coal Canyon and Cokeville areas 30 miles south of the Afton area (pl. 3). McKelvey (1946, pls. 5 and 6) correlated the vanadiferous beds in the Afton area with similar beds in the Paris-Bloomington area in southeastern Idaho, 40 airline miles to the southwest.

The shales of the vanadiferous zone are black, soft and structureless or fissile and brittle, with laminae generally less than 1 inch thick. In many sections they have an oil odor from contained organic matter. In fact, at several localities these shales in mine dumps have been ignited by brush fires. The mudstones within the vanadiferous zone are typically fine grained, micaceous, hard, very dark metallic gray, and thin bedded (1–4 inches). The vanadiferous zone is divided into six relatively continuous beds, as shown in table 4.

The stratum directly overlying the vanadiferous zone is a coarse-grained black phosphatic oolite. This is the basal bed of 1–3 feet of interbedded gray mudstone and oolite. Above this is 3–8 feet of gray, massive hard limy mudstone with thin partings of oolite (fig. 16). These two units are distinctive horizons, traceable throughout the Afton area; they have low vanadium contents (pls. 1–3). They are especially important, however, in underground mines because they form a stable roof. Similar beds above the vanadiferous zone in the Paris-Bloomington area to the southwest in Idaho are probably correlative but contain significant quantities of vanadium. As is shown in figure 17, the footwall below the vanadiferous zone is a gray, hard, thick-bedded limy mudstone 4–7 feet thick, containing oolitic black shale partings near the top (table 4).

In the main part of the Afton area, individual beds within the vanadiferous zone were sampled for vanadium analysis in 123 surface trenches and four shafts. Six adits with a total length of 605 feet were driven into four lines of outcrop of the vanadiferous zone. These assays show that the vanadiferous zone has remarkable continuity and averages about 0.7 percent V_2O_5 for the full 4.15 feet average thickness (fig. 2; tables 5, 6). The central shale (bed No. 4) is richest (about 1.6 percent V_2O_5). Beds above and below bed No. 4 contain successively less vanadium (tables 3, 4). The assays (see Appendix and pls. 15 and 16) also show that variations of as much as 30 percent in grade may occur between apparently undisturbed sections of the vanadiferous zone at sample intervals of less than 10 feet. The variations are believed to result in part from undetected minor faulting, or squeezing of plastic shales. The individual assays are considered significant only at the actual sample point and are treated as random assays in calculating the average grade and thickness along each outcrop and in each adit. These average grades (weighted against thickness)

Table 4. Typical detailed section of the vanadiferous zone.

Bed (top)	Description		Thickness (Feet)
1	Shale, black, oolitic, soft to brittle, more shaly at top; some mudstone, gray, blockier near base; lenses of coarse black oolite.		0.55
2	Shale, black, soft, lightly oolitic in upper part; blocky in some places; greasy and shiny in part.		0.65
3	Mudstone, dark-gray to black, hard, micaceous; in beds 1–3 inches thick.		0.65
4	Shale, black, soft; in places grades laterally to thin-bedded gray mudstone.		0.75
5	Mudstone, black to dark-gray, hard, micaceous; weathers with a spheroidal, rusty surface; black shale parting in middle in some places.		1.20
6	Shale, black, soft to brittle, oolitic in most places; locally blocky in part.		0.45
		Total	4.25
(bottom)	Mudstone, gray, limy, thick-bedded		7.20

and thicknesses (arithmetic) are considered representative of the ore blocks underlying the outcrops, as shown in figure 2 and in table 6 and in the ore block profiles on plate 16.

To avoid attaching too much importance to the extreme variations of thickness and grade found in a few sections in which bed boundaries and correlations are uncertain because of interbed squeezing or minor faulting, the average thicknesses and grades of undistorted beds in each ore block are used (fig. 2; table 5).

Preliminary studies of the mineral composition so far have not satisfactorily determined the mode of occurrence of the vanadium. Mica in flakes as much as 0.05 inch in diameter and phosphatic oolite grains as much as 0.1 inch in diameter can be seen. As a result of microscopic examinations of samples from the vanadiferous zone at Coal Canyon, Wyo., 30 miles south of Afton (fig. 1), the U.S. Bureau of Mines identified quartz, orthoclase, and plagioclase in fine particles and pyrite or marcasite in extremely fine particles. Investigations by the U.S. Geological Survey have shown that the vanadium is not combined with the carbonaceous matter that makes up about 30 percent of the rock in some places (Wells and Brannock, 1943). Analyses by the Bureau of Mines of four samples of high-grade ore from the vicinity of Afton are shown in table 7, together with the ratios between vanadium and molybdenum, carbon, sulfur, and phosphorus in table 8. The ratios shown in table 8 indicate a moderately close relationship between the V_2O_5 and Mo, C, and S contents, but no close relationship between the P and the V_2O_5. However, from the fragmentary data, no opinion as to the mineral relationship of the vanadium can be drawn.

In years subsequent to 1944, much geochemical work was done on vanadium and other trace elements in the vanadiferous zone in the Afton area and others in the region by many researchers, chiefly in the U.S. Geological Survey. Published and open-file reports by Gulbrandsen (1960, 1966, 1975), Desborough (1977), Davidson and Larkin (1961), Vine (1969), and Vine and Tourtelot (1970), and references cited by them supply more up to date and more detailed information on spot samples; but these do not change the estimates of grade and tonnage of vanadium in the Afton area presented in this report.

Origin of Vanadium Concentrations

According to Mansfield (1927), the rocks of the Meade Peak Member were probably deposited in cold, relatively stagnant waters of a shallow, widespread sea. Organic matter and fine silt were deposited very slowly, and at times small phosphate oolites were formed in the ooze. The vanadium may possibly have originated as a component of the fine clastics; it may have been absorbed by the clastics from marine solutions during deposition, or it may have been deposited in the organic matter and later changed to a fine secondary mineral or absorbed into a silicate.

McKelvey and others (1986, p. 19–25) presented a thorough review of the many ideas concerning the origin of the vanadium in the Meade Peak Member. Their review is especially recommended to readers interested in this subject, and their reference list is extensive. They summarized the current thinking: "The extraordinary concentration of vanadium in the richest part of the vanadium zone (an order of magnitude higher than the ordinary black shale highs) seems to require conditions or processes not yet identified" (McKelvey and others, 1986, p. 24).

A 635-page volume (Hein, 2004) details the most recent (1997-2002) USGS program of research on the Phosphoria Formation. For discussion relating to origin and residence of elements, including vanadium, in the Meade Peak Phosphatic Shale Member, see, for example, Chapter 4, "The Meade Peak Member of the Phosphoria Formation: Temporal and spatial variations in sediment geochemistry"; Chapter 8, "Petrogenesis and mineralogic residence of selected elements in the Meade Peak Phosphatic Shale Member of the Permian Phosphoria Formation, southeast Idaho"; and Chapter 12, "Lithogeochemistry of the Meade Peak Phosphatic Shale Member of the Phosphoria Formation, southeast Idaho."

Effects of Weathering

As the vanadium in the Afton area is in a region of rapid erosion, and the climate is harsh, weathering is limited to very shallow depths. The adits were examined especially for possible leaching or secondary concentration of vanadium minerals. None was found. Near-surface weathering rarely was noticeable below 25 feet. Above this depth, the only effect was a slight increase in fissility of shales and ferruginous coating along fractures, but no redistribution of vanadium. However, in the Paris-Bloomington area of Idaho, 40 miles southwest of Afton, McKelvey and others (1986, p. 11–16) reported considerable secondary enrichment of V_2O_5 below the unconformity between the Meade Peak Member below and the overlying Tertiary rocks (Eocene). No Tertiary rocks of this type were found in the Afton area. The Star Valley sequence (informal name) is Pliocene and is in contact with the Phosphoria in only a few and limited outcrops, and the lithology is very different, being chiefly plastic clays in the lower part and poorly consolidated, locally derived conglomerates in the upper part.

Reserves

Inasmuch as the reserve estimates presented herein are based on a realistic downdip projection of ore proven to be uniform in thickness and grade over wide areas of outcrop and in adits, all ore in this report is classified as "indicated" (pls. 5–16). No "measured" ore is estimated, as underground exploration has been very limited. The terms "indicated" and "measured" are used in the sense of that defined by the U.S. Bureau of Mines and the U.S. Geological Survey (1980) (fig. 18).

The estimation of reserves requires somewhat arbitrary assumptions as to the grade cutoff, mining thickness, and mining depth of the ore. These reserves are divided on the basis of geologic structure into eight ore blocks (figs. 2, 19; pl. 16; table 6). The boundary between blocks F and G was arbitrarily selected at the approximate site of cross section *O–O′* in figure 2 and is more precisely shown on the index map of plate 16. The boundaries for blocks A through F and H are based on local structures and faults that involve the vanadiferous strata. The percent recovery of vanadium falls off rapidly in the milling of ore containing less than 0.5 percent V_2O_5, so for this report reserves are calculated for the part of the vanadiferous zone (beds 3, 4, and part of 5) with 0.5 percent V_2O_5 assay boundaries (table 6). Reserves are also calculated for a sequence of the richest vanadiferous beds totaling 3 feet (fig. 20), a thickness likewise found practicable for mining in similarly steeply dipping beds in Raymond Canyon (McKelvey and others, 1986). The 3-foot thickness does not follow either stratigraphic or assay walls but shifts within the vanadiferous zone from trench to trench (see pls. 5–14). Depth of reserves is limited to 500 feet below drainage level. Reserves are stated separately for ore above drainage level and ore between drainage level and 500 feet below drainage level (table 6). The ore underlying significantly faulted portions of the outcrop has been omitted from the reserves.

Ore Blocks Most Favorable for Mining

The uniformity of grade and thickness in the beds of the vanadiferous zone is such that selection of the most favorable area for mining is dependent on a realistic and precise knowledge of the relative mining costs for ore in various thicknesses (1.9–3 feet or more), the cost of milling, and the percentage of recovery of vanadium. This information is at present lacking, but we conclude that the Dry Creek area, particularly blocks D, F, and B, has a slight superiority in grade and thickness (table 5).

Epilog

When the World War II German blockade of the Atlantic was broken and vanadium from overseas became more readily available and cheaper, there was no need to continue the Afton project and the companion studies in Idaho and Montana. The Afton project was therefore terminated in March 1944. More than 2 years of work was not in vain, however, for in addition to our data, McKelvey, Sheldon, Cressman, Swanson, and associates in Idaho, Montana, and Wyoming amassed an enormous amount of new data on the occurrence, evaluation, and chemistry of deposits of phosphate, vanadium, and other elements; they also worked out the lateral and vertical relations of various tongues of the Phosphoria Formation and its equivalents. Also, experimental mining gave new information of the economics of underground exploration for vanadium in complex structural areas (McKelvey and others, 1986). Perhaps at some future time when economic constraints are fewer, the 30 million short tons of "indicated" vanadium ore averaging 1.1 percent V_2O_5 in the Afton area may be important.

Table 5. Distribution of vanadium in the individual beds of the vanadiferous zone.

Ore blocks	Oolitic shale (1)	Slightly oolitic shale (2)	Mudstone (3)	Shale (4)	Mudstone (5)	Oolitic shale (6)	Vanadium zone (weighted average)
			Average grade (percent V_2O_5)				
A	0.17	0.24	0.69	1.52	0.60	0.22	0.61
C	.30	.21	.83	1.65	.65	.38	.76
D	.21	.30	.64	1.83	.79	.58	.79
B	.23	.37	.87	1.56	.49	.24	.65
F	.19	.38	.78	1.73	.68	.25	.74
E	.26	.38	.77	1.52	.71	.23	.71
G	.18	.36	.75	1.52	.58	.28	.65
H	.18	.40	.90	1.64	.52	.22	.71
Average	.21	.33	.78	1.63	.60	.30	.69
			Average thickness (feet)				Total (feet)
A	0.55	0.45	0.70	0.55	1.45	0.30	4.00
C	.50	.50	.60	.80	.80	.40	3.60
D	.55	.65	.70	.80	.65	.45	3.80
B	.60	.55	.70	.80	1.70	.55	4.90
F	.55	.65	.60	.85	1.15	.50	4.30
E	.50	.45	.60	.70	1.15	.45	3.85
G	.60	.50	.55	.75	1.35	.45	4.20
H	.70	.60	.65	.65	1.35	.50	4.45
Average	.55	.55	.65	.75	1.20	.45	4.15

Average vanadium content (lb V_2O_5 contained in a 1 foot square column across the vanadiferous zone normal to the bedding):

A	3.7
C	4.1
D	4.5
B	4.8
F	4.8
E	4.1
G	4.1
H	4.3
Average	4.3

Resources of (commodity name)

[A part of reserves or any resource category may be restricted from extraction by laws or regulations]
Area: (mine, district, field, State, etc.) Units: (tons, barrels, ounces, etc.)

Cumulative Production	Identified Resources			Undiscovered Resources	
	Demonstrated		Inferred	Probability Range (or)	
	Measured	Indicated		Hypothetical	Speculative
Economic	Reserves		Inferred Reserves		
Marginally Economic	Marginal Reserves		Inferred Marginal Reserves		
Sub-economic	Demonstrated Subeconomic Resources		Inferred Subeconomic Resources		
Other Occurrences	Includes nonconventional and low-grade materials				

Figure 18. Major elements of mineral-resource classification system (modified from U.S. Bureau of Mines and U.S. Geological Survey, 1980).

Table 6. Reserves of "Indicated" ore near Afton, Wyo.
[In millions of short tons]

	With 0.5% V_2O_5 assay walls				Within 3 feet mining thickness		
	Above drainage level	500 feet below drainage level	Average percent V_2O_5	Average thickness (ft)	Above drainage level	500 feet below drainage level	Average percent V_2O_5
West Swift Creek area							
Block A	1.5	0.5	1.0	1.9	2.5	1	0.7
Subtotal	1.5	.5	1.0	1.9	2.5	1	0.7
Dry Creek area							
Block B	6	.5	1.2	2.0	9	.5	0.9
Block C	1	.5	1.2	1.9	1.5	1	0.9
Block D	.5	.5	1.2	2.2	.5	.5	1.0
Block E	1.5	.5	1.1	2.2	2	.5	0.8
Block F	5	1.5	1.2	2.3	7	2	0.9
Subtotal	14	3.5	1.2	2.1	20	4.5	0.9
Cottonwood Creek area							
Block G	4.5	2	1.1	2.1	6.5	3	0.9
Block H	2.5	1	1.1	2.1	4	1.5	0.9
Subtotal	7	3	1.1	2.1	10.5	4.5	0.9
Total	22.5	7	1.1	1.1	33	10	0.9
Combined total (rounded to the nearest 5 million)	30				45		

Table 7. U.S. Bureau of Mines analyses of four high-grade samples taken from the Afton vanadium areas.

Sample No.	V_2O_5	Mo	C	S	P
H-889	1.975	0.05	15.20	5.90	0.095
H-890	1.34	.03	10.67	4.55	.214
H-888	1.32	.03	9.90	4.70	.269
H-847	1.925	.02	10.10	4.00	1.220

Table 8. Ratios of major elements to V_2O_5 in four high-grade vanadium samples from the Afton area.

Sample No.	V_2O_5	Mo	C	S	P
H-889	1.00	0.03	7.69	2.98	0.048
H-890	1.00	.02	7.96	3.39	.159
H-888	1.00	.02	7.50	3.56	.204
H-847	1.00	.02	10.91	4.32	1.32

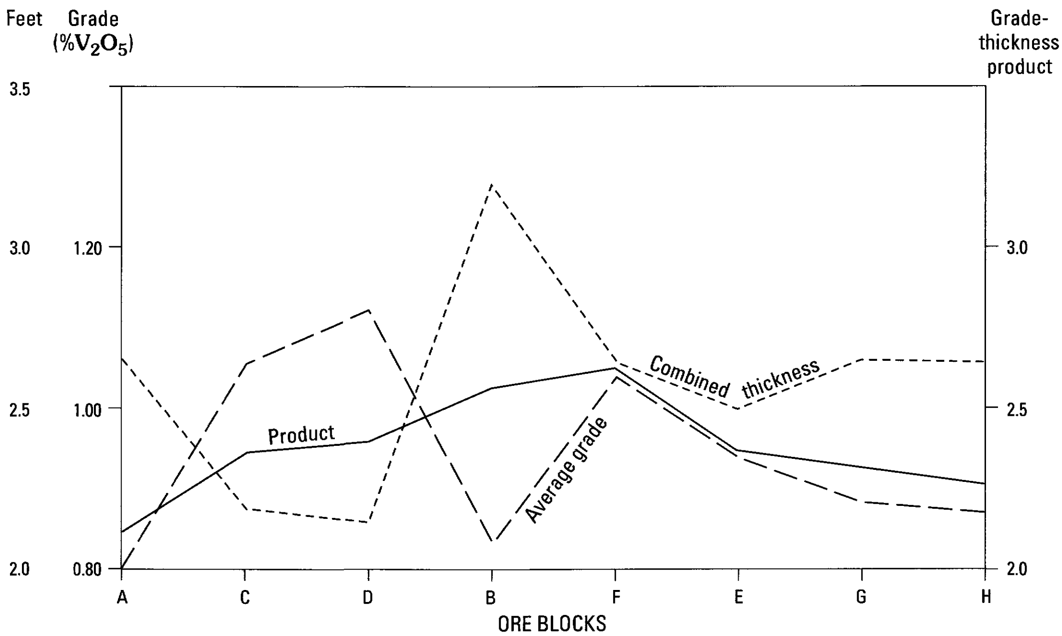
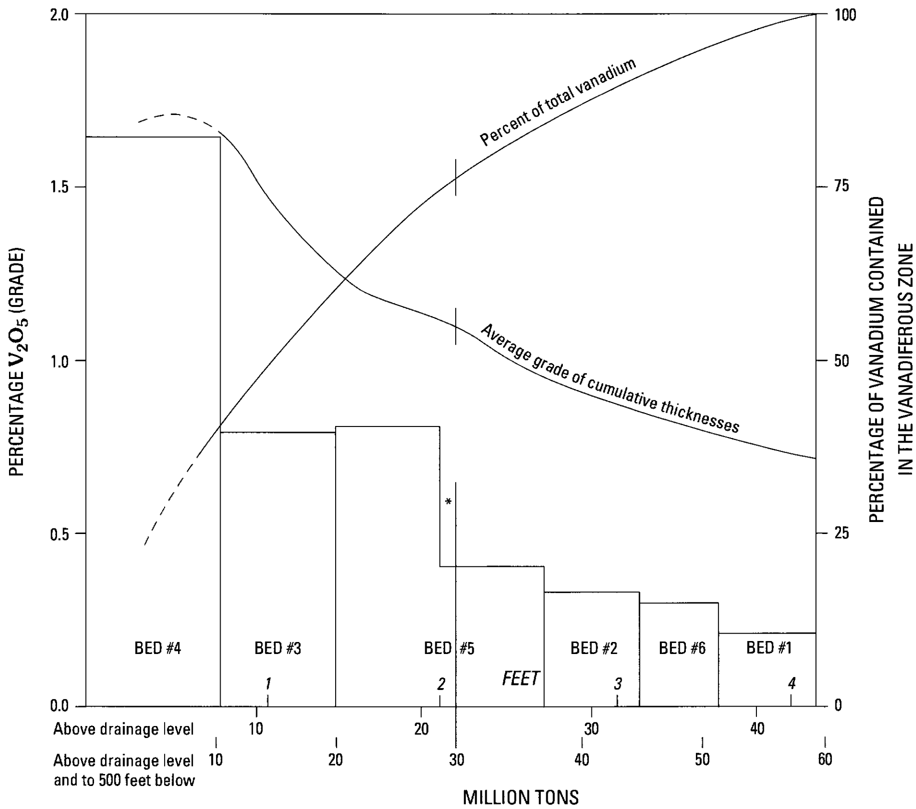


Figure 19. Average grade, combined thickness, and grade-thickness product of beds 3, 4, and 5 of the vanadiferous zone in each block.

The vanadium studies also indicate many economic possibilities for future field research. Studies proven successful in the search for vanadium in the Afton area could serve as an example for regional reconnaissance studies. These could possibly determine the stratigraphic occurrence of gold, silver, chromium, zinc, cadmium, and other trace elements known to be present in the Meade Peak Member and overlying beds in the Phosphoria Formation, which is only about 100–250 feet thick in most areas.

Present and future exploration conditions to be encountered in the field investigations of these additional trace elements would be about the same as they were for vanadium in 1942, but the cost would probably increase by many fold. All the 1942–1943 trenches are caved as of 1997, and all mine entrances were obliterated as public hazards by the USDA Forest Service.

The actual trench sites in the Afton area, because the stratigraphy is already known, should be reexcavated and resampled for trace elements other than vanadium. The sampling program should be extended northward into unsampled territory as far north as Jackson Hole, where significant amounts of gold and silver and other trace elements are already known (Love, 1984; Oriel and others, 1985; Oriel and Moore, 1985) from just a few sites. Random sampling such as we have done in this northern area, however, will not adequately define the economically interesting areas. The need is for a much more sophisticated program, and the rewards may well be worth the effort—and money expended—from both scientific and economic resource standpoints.



Example: A thickness of 2.1 feet of the highest grade beds averages 1.1 percent V_2O_5, contains about 77 percent of the vanadium in the zone, and will yield 22.5 million tons of ore from all areas to drainage level, and 30 million tons to a depth of 500 feet below drainage level.

*In 20 percent of the trenches, the lower part of bed # 5 assayed within the 0.5 percent assay walls, hence was included in the calculated reserves.

Figure 20. The beds of the vanadiferous zone arranged in order of decreasing grade, showing cumulative thickness and tonnage and showing the average grade and percentage of total vanadium in any number of the richest beds.

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