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STRATEGIC MINERAL RESOURCES IN WYOMING - TITANIUM

by

W. DAN HAUSEL

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This report has not been reviewed for conformity with the editorial standards of the Geological Survey of Wyoming.

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Introduction

In the past several years, the Metals and Precious Stones Division of the Geological Survey of Wyoming has made a concerted effort to examine and explore for strategic mineral deposits in the State of Wyoming. It is apparent, our state hosts a wide variety of strategic mineral deposits, some of which are of significant grade and size. Some selected reports on strategic minerals published by the Survey include Hausel (1987, 1989), and Hausel and others (1985). This report describes titanium.

Titanium is an important metal that has many industrial applications and several important commercial and military uses. Because of its high strength-to-weight ratio and its ability to retain its mechanical properties at elevated temperatures, titanium is widely used in the aerospace industry, for example in the manufacture of structural components in supersonic aircraft, jet engine parts, and guided missiles. Because of these important military, commercial, and aerospace uses, and because there is only minor titanium production in the United States, titanium is ranked as a strategic metal for the United States.

The principal titanium-bearing minerals include the three polymorphs rutile, anatase, and brookite, all which have the same chemical composition (TiO_2); ilmenite ($FeTiO_3$); leucoxene (Fe_2TiO_5); sphene ($CaTiSiO_5$); perovskite ($CaTiO_3$); and titanomagnetite ($TiFe_2O_4$). Potentially commercial titanium deposits occur as magmatic deposits, placers, and laterites. Worldwide, the greatest amount of production and largest resources are associated with magmatic deposits, followed by placers and then laterites (Towner and others, 1988).

World cumulative production from magmatic deposits totals 57 million tons. Placers produce about 42 million tons, and laterites produce only about 30,000 tons. Known exploitable titanium reserves are reported by Towner and others (1988) to include 630 million tons in magmatic deposits, 235 tons in placers, and 96 million tons in laterites. These resources are primarily located in Australia, Canada, India, Sierra Leone, Italy, Norway, the Republic of South Africa, the United States, the U.S.S.R., Brazil, and China (Lynd, 1985).

Although, Wyoming does not currently produce titanium, titanium deposits are widespread and the potential for commercial mines in the future seems high under favorable conditions. The known deposits range from relatively small placers to sizable placers and magmatic deposits. Additionally, each titanium deposit has accessory metals as potential by-products. Some potential by-product metals include gold, vanadium, iron, zirconium, chromium, and rare earth elements.

Essentially all of the titanium placers in the state are Mesozoic paleoplacers. These are black sandstones that were deposited along beaches in the geologic past. The deposits contain large tonnages of heavy minerals, and together they make up one of the largest reserves of titanium- and iron-oxides and zircon in the Rocky Mountain region (Houston and Murphy, 1962). The heavy-mineral suite includes titaniferous magnetite, ilmenite, altered ilmenite (leucoxene?), rutile (see Harris, 1990), zircon, garnet, tourmaline, sphene, chromite, spinel, monazite, apatite, staurolite, kyanite, epidote, anatase, brookite, pyroxene, amphibole, chlorite, biotite, glauconite, allanite, niobium-bearing opaque minerals, and gold (Houston and Murphy, 1970).

All of the known deposits occur in outcrops of shallow dipping strata along the margins of the Wyoming basins. Madsen (1978) recognized that the paleoplacers are associated with influxes of sediments, suggesting successive periods of uplift at 70, 75, and 82 million years ago. This influx was also responsible for the greater abundance of gold, rutile, garnet, and well-rounded zircon in these black sandstone deposits. In particular, the younger deposits in northeastern Wyoming and at Sheep Mountain, southeastern Wyoming, are enriched in gold (Madsen, 1978). Houston and Murphy (1970) reported that gold makes up as much as 1.3 ppm of samples from the eastern Wyoming deposits.

Magmatic deposits of titaniferous magnetite and magnetite-ilmenite occur in the Laramie Mountains anorthosite complex and in the Lake Owen layered mafic complex in the Medicine Bow Mountains. Other possible magmatic sources of titanium, for which essentially no information is available, include the Mullen Creek layered intrusive in the Medicine Bow Mountains, possibly the Tertiary porphyry copper deposits in the Absaroka mountains and the Proterozoic copper-gold porphyry in the Laramie Mountains. Although the Wyoming porphyry deposits have not been evaluated for titanium resources, some porphyry deposits are sufficiently enriched in titanium oxides to be considered potential resources of the metal (Force and Lynd, 1984).

The best known of the magmatic deposits is the titaniferous magnetite resource in the Laramie Mountains anorthosite complex. Hagner (1968) reported more than 30 deposits of massive titaniferous magnetite occur in this anorthosite complex. This region was examined as a potential source of aluminum during the Second World War, and the titaniferous magnetite deposits have attracted the attention of many researchers and mining companies as a possible source of titanium and other metals. For example, before mining, a portion of this intrusive included 178 million tons of ore containing 90 billion pounds of iron, 20 billion pounds of titanium metal, and 600 million pounds of vanadium metal. Pinnel and Marsh (1957) also reported the anorthosite complex included at least 30 million tons of ore at an average grade of 20 percent TiO_2.

The U.S. Geological Survey estimated Wyoming's potential economic titanium resources at 5.94 billion pounds of contained titanium in titaniferous magnetite deposits and 1.1 billion pounds of titanium in titaniferous black sandstone deposits (Force and Lynd, 1984). Only those deposits that met the following criteria were considered: (1) sufficient grain size (>0.02 mm), (2) easily separable magnetite-ilmenite intergrowths, and (3) inseparable intergrowths with more than 25 percent TiO_2. Thus, the actual titanium resource (including both potentially economic deposits and all deposits deemed uneconomic) is huge.

There was some production of massive magnetite-ilmenite during the late 1950s to the early 1970s. Production reports from the Wyoming State Mine Inspector and the Ad Valorem Department of Taxation indicate 1,091,452 tons of titaniferous magnetite were mined from the Iron Mountain district in the south-central Laramie Mountains. The material was shipped to New Orleans for use as a heavy mineral aggregate in concrete in submerged pipelines. The pipelines serviced offshore oil wells in the Gulf Coast region (Hagner, 1968, p. 667).

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Titanium deposits and occurrences in Wyoming

(see **Figure 1**)

Albany County

Iron Mountain district (Laramie Range)

The extent of the Iron Mountain district is not well-defined. It is here defined to include all titaniferous magnetite deposits found within the 350-square-mile Laramie Mountains anorthosite complex (**Figure 1,** no. 1). These deposits range from massive ore to disseminated ore with lenses of ilmenite, magnetite, and magnetite-ilmenite intergrowths containing minor to accessory olivine, apatite, spinel, mica, and sulfides. The magnetite-ilmenite intergrowths form a fine interpenetrating network of ilmenite lamellae along octahedral partings in magnetite (Diemer, 1941). The titaniferous magnetite is late in the paragenetic sequence and often exhibits small stringers that extend out into the anorthosite country rock. In some samples, titaniferous magnetite is seen to partially replace feldspar and pyroxene.

Sulfides occur as accessory minerals in some deposits. Trace to minor amounts of pyrrhotite, chalcopyrite, pyrite, and sphalerite have been reported in norite, hypersthene syenite, and anorthosite of the Laramie Mountains anorthosite complex (Sargent, 1970, p.11). In 1983 and 1984, U.S. Chrome drilled norite in the Strong Creek (Greaser Ranch) area north of the Buttes, near Albany County Highway 12, and recovered core containing abundant sulfides (principally pyrrhotite).

The titaniferous magnetite is interpreted to have formed by replacement of anorthosite. Geochemical evidence indicates titanium and iron were leached from the anorthosite during metamorphism and dispersed into the adjacent fractures and trapped in antiformal structures. Anorthosite adjacent to fractures at Iron Mountain is depleted in both iron and titanium compared to the relatively undisturbed anorthosite. Devore (1955) showed nongranulated plagioclase contained an average of 0.11% TiO_2 compared to 0.06% for granulated plagioclase, and Reinking and Hagner (1969) reported a similar loss for iron. Reinking and Hagner (1969) showed an average loss of 0.15% iron from titanohematite needles in granulated plagioclase.

In addition to titanium and iron, some of these deposits contain anomalous vanadium and chromium (**Table 1**). Vanadium contents are about 0.07 to 0.46% V_2O_5 for the Iron Mountain mine, and about 0.66% to 0.78% for titaniferous magnetite at the Shanton deposit. Chromium varies from 0.03% to 2.45% Cr_2O_3.

Separation of titanium, iron and vanadium metals from the titaniferous magnetite deposits is commercially viable according to metallurgical research conducted by the Colorado School of Mines. Additionally, marketing research by Union Pacific Railroad Company showed that commercial markets were available for these products. (John P. Simons, personal communication, 1990.)

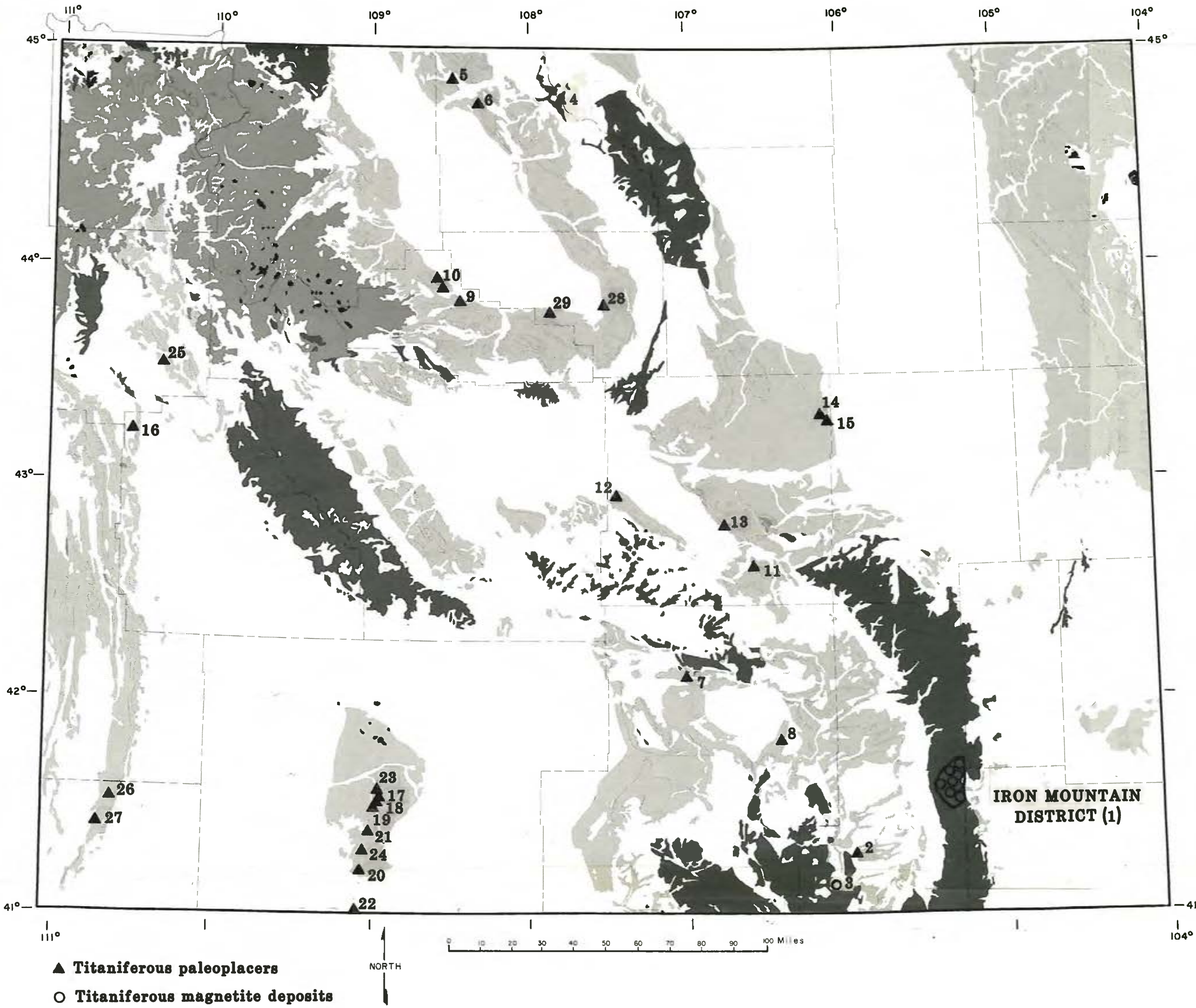

Figure 1. Location map of Wyoming titanium deposits. Numbers refer to deposits described in text. Black=Tertiary intrusives; medium screen=Tertiary volcanics; light screen=Cretaceous sedimentary rocks; dark screen=Precambrian rocks.

Table 1. Published chemical analyses of titaniferous magnetite for the Iron Mountain district (weight percent). 1 = massive titaniferous magnetite sample (from Hagner, 1968). 2 = sample composed of 40% magnetite-ilmenite, 40% olivine, and 20% plagioclase (from Hagner, 1968). 3 - 16 = titaniferous magnetite samples (Diemer, 1941).

	Sample number															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO_2	0.0	17.64	-	-	-	0.76	-	2.15	1.21	-	-	-	-	1.64	4.00	0.54
TiO_2	19.3	10.75	28.0	27.0	27.0	23.49	23.32	23.18	22.43	21.75	19.47	21.85	20.68	14.06	22.85	23.0
Al_2O_3	8.12	-	-	-	-	3.98	-	-	-	-	-	-	-	-	7.25	6.79
Fe_2O_3	26.26	-	-	-	-	45.03	-	48.97	47.21	-	-	-	-	83.43	36.24	45.26
FeO	41.8	-	-	-	-	17.96	-	24.55	25.80	-	-	-	-	-	28.18	23.21
MnO	0.09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
MgO	3.62	-	-	-	-	1.56	-	-	-	-	-	-	-	-	-	-
CaO	0.0	-	-	-	-	1.11	-	-	-	-	-	-	-	0.22	-	-
Na_2O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
K_2O	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
P_2O_5	-	0.0	0.0	0.0	0.0	-	-	-	-	-	-	-	-	-	0.0	0.0
V_2O_5	-	0.07	0.37	0.35	0.46	-	-	-	-	-	-	-	-	-	0.40	0.37
S	-	-	-	-	-	1.44	-	0.03	1.14	-	-	-	0.04	0.03	0.06	0.03
Fe_{total}	-	37.8	50.0	52.0	52.0	45.49	50.83	53.33	51.72	52.31	54.48	51.93	49.66	58.40	47.27	49.7
ZnO	-	-	-	-	-	0.47	-	-	-	-	-	-	-	-	-	-
Mn_2O_3	-	-	-	-	-	1.53	-	-	-	-	-	-	-	1.14	-	-
Cr_2O_3	-	-	-	-	-	2.45	-	-	-	-	-	-	0.16	-	0.03	0.03

Individual deposits

Cobar#1 mine; sec. 2, T.20N(?), R.71W. Magnetite Products Corporation mined 308,000 tons of ore from this property from 1957 to 1963. In 1963, the company name changed to Plicoflex, Incorporated, and operations were moved to the Iron Mountain mine to the south (Osterwald and others, 1966, p.108.). The location (T.21N, R.71W) given by Osterwald and others (1966) for the Cobar#1 is probably incorrect because it would place the mine in the gneiss complex to the north of the anorthosite batholith.

Heviwate Corporation mine; sec. 20, T.20N, R.71W(?). The Heviwate Corporation recovered 93,950 tons of titaniferous magnetite from this mine between 1967 and 1969.

Iron Mountain mine; secs. 22, 23, 26, and 27, T.19N, R.71W. Plicoflex, Incorporated mined 674,336 tons of ore from the Iron Mountain mine between 1963 and 1969. The deposit consists of several en echelon lenses or dike-like masses of massive titaniferous magnetite that are conformable to the compositional layering of the host anorthosite.

In places, the massive ore grades into disseminated ore. The lenses occur in an antiform in the anorthosite where the country rock is fractured and highly granulated. Reinking and Hagner (1969) report the mineralogy of the deposit changes markedly along strike, dip, and plunge. The massive ore is concentrated along the fold axis of the antiform, whereas olivine-rich disseminated ore occurs in the limbs of the fold.

The mineralogy of the Iron Mountain deposit consists of the ore minerals magnetite, ilmenite, and spinel. Olivine, small amounts of biotite, hornblende, plagioclase, orthopyroxene, hematite after magnetite, and rare grains of pyrrhotite are found with the ore. The magnetite, ilmenite, and spinel occur as discrete grains, intergrowths, and overgrowths (Frey, 1946a; Hagner, 1968).

The titaniferous magnetite lenses include two large masses, located along Strong Creek to the south and at the peak of Iron Mountain (7,502 feet) to the north.

The southernmost titaniferous magnetite mass at Strong Creek is 1,200 feet long. Including the disseminated ore, the deposit is about 250 feet thick where it has been structurally thickened by faulting. Drilling has verified a downdip extension of over 800 feet (Dow, 1961).

The northern titaniferous magnetite mass occurs where Iron Mountain reaches its maximum elevation. The massive ore is about 375 feet long, with a maximum thickness of 100 feet where it also has been structurally thickened by faulting (Hagner, 1968). Much of this deposit has been removed by mining (Reinking and Hagner, 1969). Including the disseminated ore surrounding the massive ore, the deposit is nearly 1,700 feet long, as much as 200 feet thick, and has a downdip extension of at least 700 feet (Dow, 1961). Both of these large masses are arcuate and plunge steeply to the southeast (Hagner, 1968).

Chemical analyses of the titaniferous magnetite indicate the massive ore has 16 to 23% titanium. Small amounts of vanadium are also present (Diemer, 1941). Frey (1946a) reported the Iron Mountain deposits averaged about 0.5% V_2O_5.

Several estimates of the resources of titaniferous magnetite at Iron Mountain have been made. Dow (1961) recognized two types of ore: (1) massive titaniferous magnetite (Class I of Pinnell and Marsh, 1957), and (2) disseminated ore (Classes II and III) (see **Table 2**). Pinnell and Marsh (1957) based their ore calculations (**Table 2**) on drilling, mapping, and a magnetometer survey. However, this estimate was made before the deposit was mined by Plicoflex, Incorporated. According to the available production figures, less than 1 million tons were mined.

Table 2. Resource estimates for the Iron Mountain deposit (Pinnell and Marsh, 1957).

Ore class	Tons	Fe (%)	TiO_2(%)	V_2O_5 (%)	SiO_2 (%)
I	30 million	46.0	19.0	1.09	10.05
II	28 million	34.0	16.0	0.99	21.0
III	120 million	17.0	7.0	0.61	39.0
Total	178 million				

The estimate made for the Class III ore (120 million tons) was inferred from a large, positive, low-intensity, magnetic anomaly and may not be reliable. The 178 million tons of total estimated ore would contain 90 billion pounds of iron, 20 billion pounds pounds of titanium, and 600 million pounds of vanadium (Pinnell and Marsh, 1957).

Shanton mine; NE/4 SW/4 sec.8, T.18N, R.71W. The deposit consists of two massive ore bodies approximately 400 feet long by 60 feet wide. The lenses strike northeasterly with a near vertical dip (Dow, 1961).

From 1972 to 1974, U.S. Aggregate Company mined titaniferous magnetite from the Shanton property. A total of 14,500 tons of ore were mined. Megascopically, the titaniferous magnetite at the Shanton property is identical to the Iron Mountain deposit. The ore is massive magnetite intimately associated with ilmenite. No disseminated ore is found.

Assays reported by Frey (1946b) from 71 jack-hammer drill hole samples showed the ore was quite uniform. The assays ranged from 49.8 to 53.0% Fe, 15.6 to 21.4% TiO_2, 0.66 to 0.78% V_2O_5, and 0.01 to 0.09% P_2O_5. Diemer's (1941) analyses of titaniferous magnetite ore from the Shanton deposit are listed in **Table 3**.

Table 3. Chemical analyses of some titaniferous magnetite ore from the Shanton deposit (from Diemer, 1941).

Sample #	1	2	3
TiO_2	25.00	21.08	19.98
Fe	51.00	51.50	52.98
V_2O_3	0.53	---	---

Diemer (1941) estimated the Shanton deposit contained 11,890 tons of titaniferous magnetite ore per foot of depth.

Strong Creek (Greaser Ranch); sec. 24, 26, T.19N, R.72W. This prospect encloses a relatively large, disseminated, titaniferous magnetite deposit with associated sulfides (pyrite, pyrrhotite, chalcopyrite) and pods of massive ore. Oxide lenses in the deposit are dominated by ilmenite (Kling, 1986).

The Strong Creek deposit is the largest known titaniferous deposit in Wyoming. Based on drilling, about 300 million tons of titaniferous magnetite are present (John P. Simons, personal communication, 1990). Assays range from 13.2 to 45.8% Fe, 5.79 to 30.2% TiO_2, and 0.07 to 0.2% P (anonymous, 1964). Beneficiation tests conducted on the ore indicated it was feasible to upgrade the ore and separate it into titanium, iron, and vanadium ore.

Taylor deposit; SE1/4 sec. 35, T.21N, R.71W. Eight outcrops of titaniferous magnetite protrude slightly above the surrounding anorthosite at the Taylor deposit. The titaniferous magnetite is enriched in apatite; locally, the ore may contain as much as 60% apatite. A sample of selected apatite-rich rock assayed 0.32% V_2O_5, 5% TiO_2, 32% Fe, and 12.8% P_2O_5 (Diemer, 1941). The property is estimated to contain about 238,000 tons of ore to a 100-foot depth.

Middle Sybille Creek; SW1/4 SE/4 sec. 20, T.20N, R.71W. Disseminated magnetite-ilmenite was found during mapping by members of the Geological Survey of Wyoming (Hausel and others, 1981). The deposit is scattered over a 1,000-foot length with a maximum width of 400 feet.

SW1/4 sec. 22, T.21N, R.71W. An irregular lens of titaniferous magnetite strikes north for about 400 feet along the crest of a high ridge. The lens ranges from 5 to 100 feet wide, and encloses one small anorthosite xenolith. The titaniferous magnetite is apatite-rich locally and has small amounts of biotite and spinel. An average sample contained 47% Fe, 19% TiO_2, 0.34% V_2O_5, and 2.12% P_2O_5 (Diemer, 1941, p. 14-15).

NW1/4 sec. 26, T.21N, R.71W. This is a small titaniferous magnetite dike or lens that lies 50 feet south of the section boundary between secs. 23 and 26. The lens trends easterly for about 600 feet along the crest of a low ridge of anorthosite. The dike varies from 5 to 20 feet wide (Diemer, 1941, p. 15).

NE1/4 sec. 1, T.20N, R.71W. A small, poorly defined titaniferous magnetite lens strikes N70°E on the east flank of a low hill of anorthosite. The length of the lens probably does not exceed 20 feet long by 3 feet wide (Diemer, 1941, p. 15).

SW1/4 sec. 2, T.20N, R.71W. The deposit consists of two lenses in anorthosite that strike N80°E. The larger lens is 75 feet long and 10 feet wide. The smaller lens is 8 feet long and 5 feet wide (Diemer, 1941, p.15).

SE1/4 sec. 32, T.20N, R.72W. A small lens about 30 feet by 1 or 2 feet occupies the crest of a small hill of anorthosite (Diemer, 1941).

Sec. 4, T.19N, R.72W. Five separate titaniferous magnetite lenses crop out in sec. 4. One lens in the NW/4 is 300 feet long by 100 feet wide and trends northwest. The remaining four lenses are in the NE1/4 and strike northwest. These four are 40 feet by 2 feet; 500 feet by 250 feet; and the remaining two are 50 feet by 3 feet.

The lenses consist of dark bands of anorthosite with a high percentage of titaniferous magnetite, and lighter bands with a relatively larger amount of anorthosite consisting of labradorite, pyroxene, and considerable apatite. The titaniferous magnetite occurs interstitially between anhedral labradorite and pyroxene grains and partially replaces them, indicating the titaniferous magnetite was the last mineral to crystallize. Apatite occurs as euhedral grains enclosed by the other minerals, indicating early crystallization (Diemer, 1941, p.15-16).

S1/2 NE1/4 sec. 7, T.19N, R.72W. This deposit extends 1,500 feet along the southeast flank of an northeast trending ridge. It is not continuous, but consists of four lenses trending along a straight line. A trench in the northernmost lens shows a sharp contact between the titaniferous magnetite and anorthosite. A polished thin section of material from one of the lenses contained coarse-grained magnetite with subordinate limonite and no ilmenite (Diemer, 1941, p. 16).

Secs. 14 and 15,T.19N, R 71W. Six titaniferous magnetite lenses lie along the boundary between secs. 14 and 15. The lenses occur in massive anorthosite. The largest two lenses form a 250- by 50-foot lens on the crest of an east trending ridge in sec. 15, and a nearly 100-square-foot lens in sec. 14 (Diemer, 1941, p. 16-17).

Goat Mountain; NW1/4 sec. 4, T.18N, R.71W and SW1/4 sec. 33, T.19N, R.71W. Massive titaniferous magnetite occurs on the crest of a high knob of anorthosite in sec. 33 (Diemer, 1941, p. 17). The deposit consists of two parallel lenses of massive and disseminated ore separated by 100 feet of granite. Both lenses strike northwesterly, dip to the southwest, and are approximately 600 feet long by 150 feet wide (Dow, 1961).

Sec. 4, T.18N, R.71W and sec. 33, T.19N, R.71W. One lens in the SW/4 of sec. 33, approximately 400 feet long and 200 feet wide, is separated by a granite dike from a smaller lens 200 feet long by 100 feet wide.

In sec. 4, another lens of massive magnetite-ilmenite strikes northeast into the southern edge of sec. 4. This lens is 500 feet long and about 100 feet wide (Dow, 1961).

Sec. 4, T.18N, R.71W. Dow (1961) described another deposit in sec. 4. This deposit consists of massive and disseminated titaniferous magnetite that strikes northeast for 600 feet with a steep northwest dip. The width of the deposit is up to 60 feet.

Sec. 5, T.18N, R.71W. Three parallel lenses of disseminated titaniferous magnetite with subordinate massive ore strike northwest and dip southwest. The largest deposit is 2,500 feet long and as much as 300 feet thick (Dow, 1961).

NW1/4 sec. 3, T.18N, R.71W. Diemer (1941, p. 17) reported two lenses of titaniferous magnetite were found in anorthosite country rock. One lens, located on a crest of a hill, strikes northeast, dips steeply southeast, and is 150 feet by 8 feet. The smaller lens is 15 feet long and only 1 to 2 feet wide. Dow (1961) reported the large deposit to be 325 feet by 25 feet. The same area also includes disseminated lenses, the largest of which is 500 feet long with an average thickness of 35 feet.

NW1/4 sec. 15, T.18N, R.71W. A 30-foot-long titaniferous magnetite lens ranges in width from 2 to 25 feet. The lens strikes north across a low ridge of anorthosite. The southern end of the lens (which is only 2 feet wide) increases in width at depth (based on the outward dipping contacts) (Diemer, 1941, p. 17).

SE1/4 sec. 17, T.18N, R.71W. A titaniferous magnetite lens strikes N20°E. From south to north, the lens is 180 feet long and tapers to 10 feet wide from 40 feet wide (Diemer, 1941, p. 17).

Spring Creek; secs. 13 and 14, T.18N, R.71W. Diemer (1941, p. 18) recognized several lenses of northeast trending magnetite-ilmenite. The deposits consist of both massive titaniferous magnetite with lenses up to 400 feet long and 10 to 60 feet thick, and a large disseminated deposit 1,200 feet long by 700 feet wide and 250 feet thick. A few deposits in the area do not outcrop and were discovered by magnetometer surveys followed by drilling (Dow, 1961).

SE1/4 sec. 31, T.18N, R.71W. A titaniferous magnetite lens in anorthosite is 50 feet long by 2 to 3 feet wide (Diemer, 1941, p. 18).

Centennial Valley

Sheep Mountain titaniferous black sandstone (**Figure 1**, no. 2); SE1/4 sec. 10, and NW1/4 sec. 14, T.15N, R.77W. An outcrop of titaniferous black sandstone lies near the base(?) of the Mesaverde Formation (Upper Cretaceous) where it crops out along the northeastern edge of Sheep Mountain. The deposit trends N45°W and is a maximum of 17 feet thick and 50 feet wide (Houston and Murphy, 1962, p. 103-106). Scattered outcrops of the black sandstone can be traced for nearly 4,300 feet along strike. Based on proton precession magnetometer profile surveys across two exposures, the black sandstone continues downdip (25° to 30°NE) for only a short distance (Hausel and Jones, 1982, p. 35-40).

Chemical analyses of seven samples collected along 2-foot intervals from a prospect pit on the northeastern exposure averaged 15.6% TiO_2 and 40.4% total iron as Fe_2O_3 (Houston and Murphy, 1962, p. 105). The TiO_2 content of these samples ranged from 0.26 to 23.68%. Houston and Murphy (1970) and Madsen (1978) reported this deposit to have anomalous gold.

Medicine Bow Mountains

Lake Owen layered complex (**Figure 1**, no. 3); The Lake Owen layered complex is a large, 20- to 25-square-mile, funnel-shaped mafic complex estimated to be approximately 1.8 billion years old (Houston and others, 1968). Cumulus titanomagnetite is found near the tops of some cyclic layers and may represent a sizable resource considering the strike extent (~ 1 mile) of some of the layers (Patchen, 1987).

Big Horn County

Bald Mountain paleoplacer (**Figure 1**, no. 4); S1/2 sec. 21, sec. 22, W1/2 sec. 23, S1/2 sec. 30, and sec. 31, T.56N, R.91W. Heavy-mineral concentrations are found in the basal Flathead Sandstone (Middle Cambrian). This area was initially prospected for gold near the turn of the century, but the grade was too low to mine commercially at $20 per ounce. In addition to gold, the conglomerate is enriched in other heavy minerals including monazite and ilmenite. Ilmenite concentrations are 4.5 to 5 times those of monazite (McKinney and Horst, 1953).

Cowley black sandstone (**Figure 1**, no. 5); sec. 1, T.56N, R.97W. The deposit is found in the first prominent sandstone scarp 2 miles south of the town of Cowley and about 1/2 mile west of the dirt road that runs south from town. The deposit averages about 1 foot thick with a maximum thickness of only 3.5 feet. The outcrop trends N60°W and is exposed over a 900-foot length. To the south, the deposit continues under alluvium. The titaniferous sandstone is located near the contact of the Mesaverde Formation with the underlying Cody Shale and is interpreted to be hosted by the Mesaverde Formation.

A chemical analysis of a single sample produced 3.0% TiO_2 and 33.85% iron as Fe_2O_3. This particular sample contained only 10.5% heavy minerals (Houston and Murphy, 1962, p. 78-80).

Lovell deposit (**Figure 1**, no. 6); sec. 7, T.55N, R.95W and sec. 12, T.55N, R.96W. The deposit crops out along a N34°W trend crossing the section line about 6 miles south of Lovell. Stratigraphically, the sandstone lies near the base of the Mesaverde Formation and has about 5,000 feet of exposure with a average thickness of 3 feet. The extent of the deposit downdip (11°SW) is unknown.

Three samples collected from the Lovell deposit yielded 2 to 59% heavy minerals. One selected sample contained 53.9% heavy minerals and assayed 15.1% TiO_2 and 71.09% iron as Fe_2O_3 (Houston and Murphy, 1962, p. 80-82).

Carbon County

Seminoe deposit (**Figure 1**, no. 7); sec. 35, T.25N, R.85W, and secs. 15 and 28, T.24N, R.85W. A black sandstone deposit is hosted by Cretaceous rocks (Houston and Murphy, 1970). No other information is available.

Fiddlers Green (**Figure 1**, no. 8); sec. 21, T.21N, R.80W. The Lewis Shale hosts a black sandstone with an outcrop exposure of 2,600 feet. The maximum thickness is 13 feet (Houston and Murphy, 1970).

Hot Springs County

Bighorn Basin

Cottonwood Creek black sandstone (**Figure 1**, no. 9); SE1/4 sec. 26, T.45N, R.97W, located on the northern flank of the Waugh anticline about 21 miles northwest of Thermopolis and east of State Highway 120 where it crosses Cottonwood Creek. The black sandstone is visible from the highway. The deposit caps the back slope of a scarp formed by the basal sandstone of the Mesaverde Formation. The deposit is 300 feet long and is a maximum of 9 feet thick.

Four samples collected from the outcrop averaged 9.7% TiO_2 and 38.4% iron as Fe_2O_3. A high-grade sample collected 3 feet below the top of the deposit contained 16.8% TiO_2 and 47.2% iron as Fe_2O_3 (Houston and Murphy, 1962, p. 94-95).

Grass Creek deposits (**Figure 1**, no. 10); T.46N. R.98W, 35 miles northwest of Thermopolis. Two deposits of titaniferous black sandstone are located in the basal sandstone member of the Mesaverde Formation along the flanks of Grass Creek anticline. The northern deposit crops out in secs. 8, 9, and 16, and the southern deposit in secs. 33 and 34.

Houston and Murphy (1962, p. 91-94) reported this to be the largest high-grade black sandstone deposit in the state. The northern deposit crops out for 5,600 feet with a maximum width of 680 feet, and the southern deposit sporadically crops out for more than 1,600 feet. Houston and Murphy (1962) found the geological evidence sufficient to show the deposit was at one time connected in a north-south direction over a distance of 4 miles. Erosion has since removed the central portion and exposed older rock units of the Cody Shale.

The black sandstone to the north averages 10 to 12 feet thick with a maximum thickness of 16 feet. Farther north, the deposit continues under younger strata. The southern deposit has a maximum thickness of 5 feet or more. Drilling and outcrop sampling of the northern deposit delineated a 3-million-ton ore body with an average of 21.0% TiO_2 and 4.8% $ZrSiO_4$ at a cutoff of sandstone less than 4 feet thick (William H. Graves, personal communication, 1990).

Twelve samples analyzed petrographically averaged 44% acid-soluble matrix, 26% light minerals, and 30% heavy minerals. As much as 18% of the heavy mineral fraction is comprised of zircon. Chemical analyses of 25 samples averaged 16% TiO_2 and 23% total iron as Fe_2O_3 (Houston and Murphy, 1962). Selected samples of both the northern and southern outcrops collected by the author were analyzed for gold, but none was detected.

Natrona County

Wind River Basin

Clarkson Hill titaniferous sandstone (**Figure 1**, no. 11); NE1/4 NE1/4 sec. 20, T.31N, R.82W, about 26 miles southwest of Casper. This deposit occurs in the Parkman Sandstone Member of the Mesaverde Formation. It has an exposed area of 150 feet by 20 feet, with a maximum thickness of 5.5 feet. One sample contained 4.8% TiO_2 and 26.1% total iron expressed as Fe_2O_3 (Houston and Murphy, 1962, p. 100-101).

Coalbank Hills (**Figure 1**, no. 12); center sec. 5, T.34N, R.88W, near the northern end of the Rattlesnake Hills about 15 miles southwest of Waltman. The deposit is less than 1,400 feet long and up to 5 feet thick. This titaniferous black sandstone occurs in the basal sandstone of the Mesaverde Formation. One sample examined petrographically contained 54.1% heavy minerals, 2.3% light minerals, and 43.6% acid-soluble matrix (Houston and Murphy, 1962, p. 95-97).

Poison Spider black sandstone (**Figure 1**, no. 13); NE1/4 NE1/4 NE1/4 sec. 1, T.33N, R.84W and SE1/4 SE1/4 SE1/4 sec. 36, T.34N, R.84W, 12 miles south of Natrona. This deposit is at least 7 feet thick with a 300-foot outcrop exposure in the Lewis Shale. An average of five samples of the black sandstone contained 40.3% acid-soluble matrix, 25.6% light minerals, and 34.1% heavy minerals. An average of 13 samples assayed 5.2% TiO_2 and 21.7% Fe_2O_3 (Houston and Murphy, 1962, p. 101-103).

Salt Creek (northern segment) (**Figure 1**, no. 14); secs. 24, 25, and 36, T.39N, R.78W, and sec. 31, T.39N, R.77W. A black sandstone deposit with 8,976+ feet of outcrop exposure was reported by Houston and Murphy (1970). The sandstone is probably in the Mesaverde Formation.

Salt Creek (southern segment) (**Figure 1**, no. 15); secs. 19 and 30, T.38N, R.77W. An outcrop of black sandstone has an exposure length of 5,280+ feet and width of 750 feet (Houston and Murphy, 1970). The deposit is probably in the Mesaverde Formation.

Sublette County

Cliff Creek black sandstone (**Figure 1**, no. 16); sec. 33, T.38N., R.114W, 30 to 32 miles southeast of Jackson. The Cliff Creek deposit occurs in the Stump Sandstone of Late Jurassic age. A petrographic analysis of a high-grade sample contained 26.7% matrix and 71% heavy minerals. A sample of the highly ferruginous portion of a 0.6-foot section assayed 20.15% TiO_2 and 54.93% Fe_2O_3. Another 0.4-foot section, located stratigraphically below the first one, assayed 13.4% Fe_2O_3 and 7.66% TiO_2 (Houston and Love, 1956). Houston and Murphy (1962, p. 114-115) pointed out that the deposit varies greatly in composition.

Sweetwater County

Black Butte Creek (Zelanka deposit) (**Figure 1**, no. 17); SE1/4 sec. 30, T.18N., R.101W, about 20 miles southeast of Rock Springs. The deposit is exposed in a ledge along a steep brush-covered slope and has good exposures in prospect pits at each end of the deposit. It is about 1,500 feet long in a east-northeast direction and is 3 to 4 feet thick. The stratigraphic positions of the Black Butte titaniferous sandstone is in a littoral sequence (McCourt Sandstone Tongue) of the Rock Springs Formation (Houston and Murphy, 1962; Roehler, 1989).

Samples analyzed petrographically averaged 34.5% acid-soluble matrix, 41.5% light minerals, and 24.0% heavy minerals. Chemically, the samples contain an average of 14% TiO_2 and 15% total iron as Fe_2O_3 (Houston and Murphy, 1962, p.110-111). A composite of three samples collected by Dow and Batty (1961) averaged 27.3% TiO_2, 2.0% ZrO_2, and 22.9% Fe.

Brady Road deposit (**Figure 1**, no. 18); SW1/4 sec. 11 and NW1/4 sec. 14, T.17N, R.102W, 20 miles southeast of Rock Springs. Titaniferous black sandstone caps a ridge for nearly 2,500 feet with widths of 50 to 100 feet. The average thickness is 4 feet. The deposit is in the Ericson Sandstone according to Dow and Batty (1961), although Roehler (1989) placed it within the McCourt Sandstone Tongue of the Rock Springs Formation. Assays of three samples collected from the black sandstone averaged 22.2% TiO_2, 1.4% ZrO_2, and 18.4% Fe (Dow and Batty, 1961, p.21-22).

Cooper Ridge deposit (**Figure 1**, no. 19); SE1/4 sec. 1, T.17N, R.102W. An outcrop of titaniferous black sandstone is located in the Ericson Sandstone (McCourt Tongue according to Roehler, 1989) between the Black Butte Creek and Brady Road deposits (Houston and Murphy, 1962). The heavy-mineral placer crops out over 120 feet, with an average thickness of only 3.3 feet (Roehler, 1989). A chemical analysis of one sample contained 28% TiO_2 and 35.8% total iron as Fe_2O_3 (Houston and Murphy,1962, p. 110-111).

Murphy No. 1 (Salt Wells Creek) (**Figure 1**, no. 20); SE1/4 sec. 7, T.14N, R.103W, about 35 miles southeast of Rock Springs. The titaniferous black sandstone deposit occupies a channel in the basal member of the Ericson Sandstone and has an outcrop width of 200 feet with an average thickness of 3 feet (Dow and Batty, 1961; Houston and Murphy, 1962). Roehler (1989) placed the deposit in the McCourt Sandstone Tongue of the Rock Springs Formation rather than in the Ericson Formation.

A composite of three samples averaged 17.4% TiO_2, 1.9% ZrO_2, and 14.6% iron (Dow and Batty, 1961, p. 16-19). Two other samples averaged 22.5% TiO_2 and 25.5% total iron as Fe_2O_3 (Houston and Murphy, 1962, p. 108-109).

Murphy No. 2 (**Figure 1**, no. 21); sec. 8, T.16N, R.102W, nearly 20 miles southeast of Rock Springs and a short distance southeast of Camel Rock. The Murphy No. 2 occupies a channel in the basal member of the Ericson Sandstone on the north slope of a mesa. The deposit crops out for 450 feet and has an average width of 3 feet. Samples collected from the deposit average 19.7% TiO_2, 2.0% ZrO_2, and 15.4% Fe (Dow and Batty, 1961, p. 20).

Red Creek (Richards Gap) (**Figure 1**, no. 22); sec. 22, T.12N, R.105W. Houston and Murphy (1962) reported the black sandstone to be in the NE/4, whereas, Roehler (1989) reported it to be in the SE/4 sec. 22. The deposit is found at the top of a tan, cliff-forming, littoral marine sandstone of the McCourt Tongue of the Rock Springs Formation just a few hundred feet north of the Wyoming-Utah State Line (Houston and Murphy, 1962; Roehler, 1989). The titaniferous black sandstone fills a channel cut in the underlying white sandstone. The deposit is 800 feet long and averages 6 feet thick (Houston and Murphy, 1962, p.106-108).

Two additional thin titaniferous sandstones occur in the area. One is a 0.4-foot-thick, 250-foot-long ferruginous sandstone. The other is a 0.6-foot-thick lens of ferruginous sandstone near the base of the Gottsche Tongue (Roehler, 1989).

An average of five samples collected from the principal black sandstone deposit contained 25.5% TiO_2, 1.5% ZrO_2, and 15.4% Fe (Dow and Batty, 1961, p. 16). Houston and Murphy analyzed eight samples that averaged 14.3% TiO_2 and 19.0% total iron as Fe_2O_3.

Union Pacific No. 1 (**Figure 1**, no. 23); sec. 19, T.19N, R.101W, located on Union Pacific Railroad property. This titaniferous black sandstone is exposed in a 2,700-foot by 150-foot area and averages 7 feet thick. A fault, normal to the N40°E trend of the deposit, has lowered the northeastern third of the deposit by about 60 feet relative to the main body. The deposit is in the Rock Springs Formation.

A shaft was sunk by Union Pacific on the property and samples were collected from the shaft and nearby outcrops. The samples contained an average of 21.1% TiO_2, 3.4% ZrO_2, and 20.2% Fe (Dow and Batty, 1961).

Yenko (**Figure 1**, no. 24); sec. 13, T.15N, R.103W. Exposed on the west wall of a mesa in the Ericson Sandstone. This titaniferous black sandstone is 250 feet long with an average width of 5.5 feet. A composite sample averaged 22.4% TiO2, 2.1% ZrO2, and 16.3% Fe (Dow and Batty, 1961, p. 19).

Teton County

Dry Cottonwood Creek (**Figure 1**, no. 25); sec. 27, T.42N, R.112W. Black sandstone was reported in Bacon Ridge Sandstone by Houston and Murphy (1970). No details were given.

Uinta County

Cumberland Gap (**Figure 1**, no. 26); secs. 25 and 36, T.18N, R.117W and secs. 7, 18, 19, and 30, T.18N, R.118W, about 17 miles south of Kemmerer. Deposits of titaniferous black sandstone occur in a ridge-forming sandstone in the lower part of the Frontier Formation (Late Cretaceous) (Houston and Murphy, 1977). The titaniferous sandstones are intermittently exposed for more than 22,000 feet. The average thickness of the deposit is only 5 feet, but it obtains a maximum thickness of 13 feet (Dow and Batty, 1961).

Samples average 41.4% acid-soluble matrix, 49.4% light minerals, and 9.2% heavy minerals. The heavy minerals include 10.6% zircon, 7.2% chlorite, 1.6% anatase, 1.0% garnet, 1.0% rutile, 1.0% tourmaline, 1.0% apatite, 1.0% monazite, 1.0% epidote, 1.0% sphene, and 78.4% opaques. Rock analyses averaged 9.5% TiO_2 and 20% Fe_2O_3 (Houston and Murphy, 1962, p. 111-114).

Spring Gap (**Figure 1**, no. 27); sec. 30, T.16N, R.117W. This deposit was exposed in a uranium prospect trench dug in the Frontier Formation (Cretaceous) in the upper plate of the Darby Thrust. The paleoplacer was traced along strike for 900 feet and has an average thickness of 2.5 feet.

The sandstone has some disseminated pyrite and is pervasively stained by limonite with subordinate pyrolusite. Emission spectrographic analyses of one sample contained 21% Fe, 0.27% Mn, 22.0% Ti, 0.16% W, and 0.4% Zr (Madson, 1982).

Washakie County

Bighorn Basin

Dugout (Buffalo) Creek (**Figure 1**, no. 28); secs. 34 and 35, T.45N, R.89W and secs. 2, 3, and 11, T.44N, R.89W, 28 miles southwest of Tensleep. The deposit forms a channel in a sandstone member of the Mesaverde Formation that trends N10°E and dips 4°W. The Dugout Creek deposit is one of the largest black sandstone deposits in the western United States, covering an area of about 2.7 miles by 1,500 feet.

The black sandstone deposit is divided into two segments by Dugout Creek. The northern segment is exposed for a length of 5,300 feet and a width of 1,000 feet with an average thickness of 20 feet. The southern portion of the titaniferous sandstone is exposed for a 6,400-foot length with a 1,900-foot width and a 18-foot average thickness. Both the northern and western extensions of this deposit continue under younger sediments for an unknown distance.

Assays of samples collected by the U.S. Bureau of Mines averaged 4.2% TiO_2, 0.4% ZrO_2, and 26.1% Fe (Dow and Batty, 1961, p. 27-28). Samples collected by Houston and Murphy (1962, p. 82-88) averaged 5.9% TiO_2 and 38.9% Fe_2O_3. A grab sample of ore yielded 1.7 ppm gold (William H. Graves, personal communication, 1990).

Mud Creek deposit (**Figure 1**, no. 29); center sec. 19, T.44N, R.91W, 26 miles southeast of Worland. This deposit occupies a channel in a sandstone member of the Mesaverde Formation. Exposures occur on both the north and south sides of Mud Creek. Outcrops have lengths of 175 feet and 350 feet, with a maximum width of 200 feet and average thickness of 6 feet. A composite of three samples tested by the U.S. Bureau of Mines contained 8.0% TiO_2, 0.5% ZrO_2, and 30.0% Fe (Dow and Batty, 1961, p. 28-30).

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