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UNITED STATES DEPARTMENT OF THE INTERIOR

Oscar L. Chapman, *Secretary*

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MAGNETIC EXPLORATION FOR CHROMITE

By H. E. Hawkes

ABSTRACT

Present knowledge indicates that the magnetic susceptibility of chromite varies from practically nil, for chromite approaching the composition $MgO.Cr_2O_3$, to high values for chromite approaching magnetite in composition. Magnetic prospecting may be useful in locating ore containing magnetic chromite but is of little help in the direct location of high-grade, nonmagnetic chromite. Under favorable conditions, geological information of value in prospecting for chromite can be obtained by magnetic surveys. However, although magnetic methods appear to give some promise in certain areas, no report of a discovery of commercial-grade chromite directly attributable to a magnetic survey has come to the attention of the author.

INTRODUCTION

This paper is an attempt to summarize the problem of magnetic exploration for chromite. It presents a review of the published literature on the subject together with the results of experimental surveys by the author in 1941 on some of the more important chromite deposits of the western United States.

In many respects, chromite is similar to magnetite. Both minerals are iron-bearing spinels, are black and heavy, and form massive, monomineralic ore deposits. The strongly magnetic character of magnetite is well known, and magnetic methods of exploration for magnetite-bearing iron ores have met with outstanding success. If the mineralogical similarities between magnetite and chromite could be extended to include magnetic properties, magnetic methods of prospecting for chromite might be equally effective.

Chromite, however, is commonly nonmagnetic or only very weakly magnetic. Only in a few localities is it strongly magnetic. Nevertheless, magnetic methods have been applied to chromite prospecting far more often than would seem to be warranted by its relatively undistinguished magnetic properties. The writer knows of at least 30 areas where magnetic surveys have been run, but not a single discovery of primary chromite of commercial value that could be credited to the magnetic data.

GEOLOGY OF CHROMITE DEPOSITS

The geologic occurrence of primary chromite is limited to what are generally regarded as segregation products of ultramafic magmas. Chromite is never found in the form of veins, shoots, or other hydrothermal deposits, lying outside the limits of the ultramafic mass. In this respect the geology of chromite is unlike that of any other common ore mineral, with the possible exception of titaniferous magnetite. The problem of prospecting for primary chromite, therefore, is twofold—first, to locate bodies of the ultramafic host rock and, second, to locate the concentrations of chromite within the ultramafic bodies.

Two quite distinct varieties of chromite deposit are known. These have been called the "sackform" and the "stratiform" types, terms suggested by the characteristic shape of the deposits.

The sackform type is characteristic of the dunites and peridotites of certain geosynclinal belts such as the Coast Range of California. The ore ranges from massive chromite to sparse disseminations of chromite grains in a silicate matrix. In addition to the chromite segregations, the dunite and peridotite country rock may contain about 1 percent chromite as an accessory mineral of no economic importance except as a source of placer ore. Deposits of chromite occur in the enclosing ultramafic rock as clusters, linear zones, or randomly scattered lenticular or irregular bodies. Sackform chromite bodies have been compared to plums in a plum pudding, as the distribution of the deposits in many localities appears to lack any perceptible control. Where the deposits tend to occur in clusters, prospecting may be guided by the probability that new discoveries are more likely to be found in the vicinity of known ore than at a distance from it. Observers have also noted that where the ultramafic mass containing the ore consists of both dunite and peridotite, the ore bodies characteristically occur only in the dunitic phase. Where the local magnetic properties of the dunite are notably different from those of the peridotite, favorable zones for mineralization can be indicated by the data of magnetic surveys. In many areas, however, the occurrence of dunite is limited to a sheath of negligible thickness separating the ore from the main mass of peridotite. In some localities, "ore zones" of unknown genetic significance have been indicated by magnetic surveys. Possibly these are the reflection of variations in the degree of serpentinization that are related in some way to the presence of ore deposits.

The stratiform type of chromite deposit is found only in the lower ultramafic layers of differentiated norite or gabbro sills. Examples are the tabular chromitite bodies of the Stillwater complex in Montana, the Bird River complex in Manitoba, and the Bushveld complex in South Africa. The chromitite layers commonly maintain a fairly consistent stratigraphic relationship to the primary igneous layering and to the marginal contacts of the sill. Prospecting for this type of chromite ore is thus simplified once the stratigraphic relationships have been worked out, and lateral extensions or faulted segments can be located in much the same way that a coal seam is traced through areas of complex structure.

Serpentinization of the primary silicate minerals of the ultramafic country rock of both types of chromite is common. The process of alteration of olivine and pyroxene to serpentine producers very fine grained magnetite as a byproduct. Magnetite originating from processes of serpentinization may cause extraneous magnetic anomalies that interfere with direct magnetic observation of chromite ore. However, the resulting strong magnetism of the ultramafic country rock may be an advantage in prospecting, in that it makes possible the location of small isolated ultramafic bodies or the tracing of the contacts of larger ultramafic masses.

At Casper Mountain, Wyo., and near Red Lodge, Mont., the ultramafic rocks with their included chromite deposits have been invaded by later igneous intrusions and hydrothermal solutions. At Casper Mountain (Stephenson, H. K., 1940), the ultramafic rocks have been stoped out or metamorphosed almost beyond recognition, whereas at least some of the chromite ore has retained its original position and shape. The effect of metamorphism on the ore at this locality has been primarily the addition of iron to the chromite molecule and the alteration of the silicate gangue minerals. The high iron content of some of the Red Lodge chromites, however, is thought to be primary (James, 1946, p. 170).

Concentrations of chromite in placer deposits have been of commercial interest in at least one locality. Placer chromite commonly occurs in association with other heavy minerals such as magnetite, garnet, zircon, olivine, gold, and platinum.

MINERALOGY OF CHROMITE

COMPOSITION

Both chromite and magnetite are members of the isometric spinel group. The chemical formula for chromite is commonly written $FeO.Cr_2O_3$. Inasmuch as chromite almost invariably contains magnesia, alumina, and ferric iron in addition to chromium and ferrous iron, the formula might more correctly be written $(Mg,Fe)O.(Cr,Fe,Al)_2O_3$. The work of Stevens (1944), involving 52 complete analyses of chromites from the Western Hemisphere, indicates that complete isomorphism apparently does not exist within the limits of this formula. Compositions vary from magnetite, $FeO.Fe_2O_3$; to magnesiochromite, $MgO.Cr_2O_3$; and spinel, $MgO.Al_2O_3$; with small proportions of ferrochromite, $FeO.Cr_2O_3$. Magnesioferrite, $MgO.Fe_2O_3$, is not an end member of naturally occurring chromite. For simplicity, the composition of chromite may be regarded as varying from magnetite to magnesiochromite and spinel, with some substitution of FeO for MgO. As one of these end members is highly magnetic (magnetite) and the other two essentially nonmagnetic (spinel and magnesiochromite), the magnetic properties of chromite may vary widely. This variation should be studied experimentally.

The composition of chromite is closely related to the nature of the ultramafic country rock and its subsequent metamorphic history. Sackform chromites from peridotites and dunites are high in chromium; chromites from feldspar-bearing ultramafic rocks such as troctolite are commonly high in aluminum; stratiform chromites from differentiated norite sills are characteristically high in iron. The metamorphosed chromites from Casper Mountain and the somewhat similar chromites from Red Lodge are extremely high in iron, some specimens approaching the composition of magnetite.

COLOR AND STREAK

The color of chromite in transmitted light varies from light brown or reddish brown to black. Stevens (personal communication) has observed that the streak of chromite may be greenish brown or red brown to black depending on composition. He found that when the composition lies between spinel and magnesiochromite the streak is greenish brown; when the composition approaches magnesiochromite but is intermediate between that and magnetite the streak is red brown; as the composition of magnetite is approached the streak becomes darker. Thus an estimate of the composition of the chromite can be made by observing the color of the streak.

MAGNETIC PROPERTIES

The magnetic properties of minerals can be compared quantitatively by determining experimentally a factor designated as the magnetic susceptibility, equal to the ratio of the intensity of magnetization at the surface of the specimen to the intensity of the imposed magnetic field. Quantitative measurements of the magnetic susceptibility of chromite have been made by a number of investigators (table 1).

In connection with these determinations, it should be noted that many of the susceptibility determinations were made at a magnetizing field strength ranging from several hundred to 5,000 times that of the earth. Slichter (1929) has found that the susceptibility of some minerals can vary within very wide limits as a function of the magnetizing force; his experiments with magnetite and pyrrhotite showed that susceptibilities computed from field-survey data were 10 to 100 times greater than those determined under laboratory conditions. Slichter's findings may not apply to chromite, however, as H. K. Stephenson found that his highly magnetic chromites from Casper Mountain showed considerably higher susceptibilities at field strengths of 200 gauss than at 0.3 to 2.6 gauss (table 2).

TABLE 1.—*Magnetic susceptibility of chromite*

Locality	Reference	Field strength (in gauss [1])	Susceptibility (in c. g. s. units × 10 [6])
Casper Mountain, Wyo.	U. S. Geological Survey (1942)	0. 3–2. 6	94, 000. [2]
Do	do	0. 3–2. 6	64, 000. [2]
Do	do	0. 3–2. 6	61, 000. [2]
Do	do	0. 3–2. 6	55, 000. [2]
Do	do	0. 3–2. 6	27, 000. [2]
Shoal Pond, Newfoundland	Snelgrove (1934)	0. 3–2. 6	15, 500.
Verbliuzhi Mountain (Urals), U. S. S. R. (4 samples).	Andreev (1937)		50 to 10,900.
Casper Mountain, Wyo	U. S. Geological Survey (1942)	0. 3–2. 6	8,800. [2]
Great Dyke of northern Rhodesia	Reich (1930)	0. 5	6,000 to 8,000. [3]
Gei-Dara, Transcaucasia, U. S. S. R. (15 samples).	Andreev (1937)		100 to 900.
Varshavsk (Urals), U. S. S. R. (6 samples).	do		50 to 900.
Selukwe, southern Rhodesia	Reich (1930)	0. 5	600 to 800.[3]
Nadezhdino, Transcaucasia, U. S. S. R. (14 samples).	Andreev (1937)		120 to 674.
Casper Mountain, Wyo	U. S. Geological Survey (1942)	0. 3–2. 6	600. [2]
Bluff Head, Newfoundland	Snelgrove (1934)	1,200–1,400	574.
Casper Mountain, Wyo	Stephenson, H. K. (1940)	2,500	549.
Chrome Point, Newfoundland	Snelgrove (1934)	1,200–1,400	537.
Kutarstan (Urals), U. S. S. R. (4 samples).	Andreev (1937)		200 to 400.
Gologorsk, etc. (Urals), U. S. S. R. (4 samples).	do		370 to 450.
Chrome Point, Newfoundland	Stephenson, H. K. (1940)	2,500	317.
Transvaal (Bushveld complex)	Reich (1930)	0.5	200 to 300.[3]
Asia Minor	Stutzer et al. (1918)	220	244.51.
Casper Mountain, Wyo	Stephenson, H. K. (1940)	2,500	232.
Stowbridge, Newfoundland	do	2,500	227.
Kurdistan, Transcaucasia, U. S. S. R. (5 samples).	Andreev (1937)		100 to 200.
Balsam Gap, N. C	Stephenson, H. K. (1940)	2,500	182.
Bluff Head, Newfoundland	do	2,500	180.
Montana (Stillwater complex)	do	2,500	173.
Newfoundland (Blow-me-down complex).	do	2,500	136.
Burnt Hill, Newfoundland	Snelgrove (1934)	1,200–1,400	127.
Newfoundland (Blow-me-down complex).	do	1,200–1,400	80.
Stowbridge, Newfoundland	do	1,200–1,400	57.

[1] One gauss (100,000 gammas) equals 1 oersted or 1 gilbert per centimeter. The strength of the natural magnetic field of the earth is about 0.5 gauss or 50,000 gammas.
[2] See also table 2.
[3] Semiquantitative estimate computed from deflection of magnetic system of magnetometer when specimen is held at fixed distance from magnetometer.

A notable feature of the data of tables 1 and 2 is the apparent variability in the susceptibility of chromite specimens collected from the same area or even from different parts of the same deposit. The susceptibilities of H. K. Stephenson's Casper Mountain suite, all collected within an area half a mile in length, vary widely. Duplicate specimens from Bluff Head, the Blow-me-down complex, Stowbridge, and Chrome Point, Newfoundland, all collected by Snelgrove but determined independently by Snelgrove and Stephenson, differ materially. Hence it is apparent that susceptibility determinations on individual specimens can be misleading.

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TABLE 2.—*Some chemical and physical properties of chromite from Casper Mountain, Wyo.*

[Adapted from U. S. Geol. Survey press release of Sept. 14, 1942; susceptibility at 200 gauss calculated by H. K. Stevenson (1940, table 2)]

Sample No.	Specific gravity	Fe (percent)	Cr_2O_3 (percent)	Color of very fine powder	Relative darkness of color of powder	Susceptibility (in c. g. s. units × 10^6)	
						At field strength of 0.3 to 2.6 gauss	At field strength of 200 gauss
1	4.65	26.76	44.74	Dark brown	1	600	1,600
2	4.73	31.60	42.7	do	3	8,800	14,300
3	4.76	46.00	25.4	Dark reddish brown	2	27,000	44,000
4	4.85	40.52	35.39	Very dark brown	5	61,000	127,000
5	4.92	51.76	18.4	do	4	64,000	216,000
6	4.93	47.19	28.2	Black	6	55,000	117,000
7	4.99	58.40	13.7	do	7	94,000	267,000

GENERAL MINERALOGICAL RELATIONSHIPS

Undoubtedly the magnetic properties of chromite are related either directly or indirectly to its other chemical and physical properties. Although no comprehensive investigation of the mutual relationship of the mineralogical properties of chromite has been reported, scattered observations by many different workers on various aspects of the problem seem to fit into a generally consistent picture.

Several workers have reported qualitative observations on the relation of the magnetic properties of chromite to its chemical composition. Singewald (1919), in a comparative study of the magnetic and nonmagnetic fractions of chrome-bearing sands from Maryland, found that in the magnetic fraction the ratio of chromic oxide to alumina was greater than 1:1, whereas in the nonmagnetic fraction the ratio was less than 1:1. This view has not been supported by most other workers, who have found evidence indicating that the magnetic properties of chromite are related more or less directly to the iron content of the chromite molecule. Stevens (1944, p. 26) observed that in samples high in iron the chromite was magnetic, making magnetic separation of chromite and magnetite impracticable. H. K. Stephenson's data from Casper Mountain (table 2) point toward a definite relationship between increasing iron content and increasing susceptibility, but the problem here is confused by the presence of finely intergrown hematite that could not be mechanically separated from the chromite.

Hitchen (1929), at Unst in Scotland; Dresser (1913), at Thetford, Quebec; Maxwell (1949), in New Caledonia; and the present writer, at Little Castle Creek in California, have observed thin sections of chromite where the grains consist of a core of light-colored chromite surrounded by an opaque rim. The opaque phase may also be developed in a fine lacework pattern along apparent incipient fractures leading into the light-colored core. Observations on some of this material indicate that the opaque phase is not only higher in iron but also relatively more magnetic. Dresser (1913, pp. 76–80) reported that magnetic separation of the crushed ore gave a clean black magnetic fraction and a fairly clean, translucent nonmagnetic fraction. Analysis showed that the magnetic fraction contained 15.66 percent FeO and 48.20 percent Cr_2O_3, whereas the nonmagnetic fraction contained 13.94 percent FeO and 45.30 percent Cr_2O_3. The present writer, in studying chromite from Little Castle Creek, found that the opaque halos were magnetic in contrast to the nonmagnetic character of the translucent cores, but obtained no supporting chemical analyses. H. K. Stephenson (1940), at Casper Mountain, did not observe the halo structure in thin section, but found that acid etching of polished surfaces brought out a similar halo pattern in which the material of the halo was more magnetic and more soluble in acid than that of the core. Bead tests of the halo mineral showed the presence of chromium; the etch reaction suggested a higher iron content in the halo.

James (1946, p. 171), in the Red Lodge district of Montana, observed a variation in the opacity of the chromite, but did not report having seen the halo texture. He examined 14 representative samples and found that 5 were translucent and 9 were opaque. All five of the translucent chromites were nonmagnetic, and all four of the magnetic chromites were opaque. The former were high in chromium and low in iron, whereas the reverse was true of the latter. Table 2 shows a similar relationship between opacity and magnetic properties in samples from Casper Mountain. The same suite of seven samples also shows a parallelism between magnetic susceptibility and specific gravity.

In summary, it has been found that wherever comparative observations on the various chemical and physical properties of chromite have been made, a rough parallelism exists between increasing iron content and increasing magnetic susceptibility.

INTERPRETATION OF MAGNETIC-SURVEY DATA

The significant measurement in a magnetic survey is the local deviation of the observed magnetic intensity from the average value within the area of the survey. Such deviations are termed "anomalies" in geophysical parlance and are the effect of the distortion of the normal magnetic field of the earth by local concentrations of magnetic minerals.

SUSCEPTIBILITY OF COMMON MINERALS

Magnetite is by far the most strongly magnetic substance that occurs naturally. The susceptibility of magnetite is several times greater than that of the less common magnetic minerals ilmenite, pyrrhotite, and franklinite, and it is some 10,000 times more magnetic than most rock-forming minerals (table 3).

Other factors being held constant, the magnetic anomaly value due to the presence of a given mineral in an underlying deposit is approximately proportional to the product of the susceptibility of that mineral and its concentration in the deposit. Thus a body containing 0.01 to 0.1 percent normal magnetite may give the same anomaly as a body of the same size and shape containing 100 percent normal chromite. By virtue of their magnetite content, serpentinized ultramafic rocks may have susceptibilities as high as $15{,}600 \times 10^{-6}$ c. g. s. units (Heiland, 1940; Haalck, 1934; Snelgrove, 1934).

Besides being the most strongly magnetic natural mineral, magnetite is by far the most common of the magnetic minerals. Except in the presence of large concentrations of one of the other magnetic minerals, therefore, it is safe to assume that the magnetic properties of a rock are controlled almost entirely by its magnetite content.

TABLE 3.—*Magnetic susceptibility of some common minerals*

[Data from Heiland (1940, table 35, pp. 310-311)]

Mineral	No. of specimens	Susceptibility (in c. g. s. units $\times 10^{6}$)	
		Average	Range
Magnetite	10	608,000	151,500 to 1,620,000.
Ilmenite	5	166,000	30,740 to 252,000.
Pyrrhotite	1	125,000	
Franklinite	1	35,640	
Specularite	1	3,200	
Wolframite	1	240.89	
Augite	1	133.13	
Hornblende	1	12.23	
Pyrite	1	4.53	
Quartz	(?)		−1.07 to −1.2.
Chromite	77		57 to 94,000.[1]

[1] Summary of data from table 1.

FIELD DETERMINATION OF MAGNETIC PROPERTIES

A working approximation of the magnetic properties of hand specimens can be made very easily in the field without recourse to tedious laboratory tests. The most commonly used method is to bring the specimen to be tested close to the case of the Schmidt magnetometer and observe deflections of the magnetic system. Specimens of about the same size are rotated in all positions at a point over or under one end of the magnetic system, and the average deflection of the system in scale divisions is noted. This value is a measure of the relative susceptibility of the specimens. Some specimens are magnetically polarized and will deflect the system differently depending on the orientation of the specimen. The magnetic polarity can thus be measured by noting the difference between the maximum and the average deflection of the magnetic system.

In the absence of a magnetometer, very reliable information can be obtained by swinging the hand specimen near the tip of the needle of a standard Brunton compass. Care should be taken to swing the specimen with the same frequency as the natural frequency of oscillation of the needle. The maximum deflection of the compass needle after a number of swings gives a useful measure of the magnetic properties of the specimen.

MAGNETIC FIELD INSTRUMENTS

The magnetic instrument used most commonly in chromite exploration is the Schmidt-type vertical magnetometer. The operation and design of the magnetometer have been described by Joyce (1937); additional descriptive information can be found in most standard texts on geophysical prospecting. The operating sensitivity of the magnetometer is usually between 10 and 50 gammas per scale division. This sensitivity is usually considerably more than is required for the average survey of ultramafic rocks, and field operation may be slowed down by frequent changes of the compensating magnet.

The magnetic dip needle, or mining compass (Stearn, 1929), has been used successfully in magnetic prospecting for chromite. The sensitivity of the dip needle in middle latitudes and at the optimum setting of the counterweight is about 400 gammas per degree. This sensitivity is entirely adequate to detect most of the significant anomalies encountered in chromite prospecting, where the magnetic relief is commonly about 1,000 gammas and may be as great as 20,000 gammas. The very much greater speed and ease of operation of the dip needle as compared with the magnetometer make it thoroughly satisfactory under most conditions, and a more widespread application of the instrument is highly recommended.

The airborne magnetometer has been used with success in locating ultramafic masses (Hurley, 1949), but apparently has never been applied to chromite prospecting. No record was found of the use of any other magnetic instrument in chromite exploration.

RESULTS OF FIELD SURVEYS

Here follows a review of published reports on magnetic prospecting for chromite, together with the results of magnetic surveys by the present writer in some chromite-bearing areas of the western United States. Applications of magnetic methods to chromite prospecting may be considered promising where a direct magnetic indication of the chromite ore itself was found or where an indication of favorable host rock was brought out by the magnetic data. Magnetic surveys are classified as unsuccessful where the chromite could not be detected directly and where the additional geologic information provided by the magnetic data was of no value in prospecting.

DIRECT MAGNETIC INDICATION OF CHROMITE ORE

Positive evidence that a magnetic feature can be correlated directly with chromite ore requires that comparative magnetic observations be made over barren country rock and over known deposits of ore. If the known ore has been largely mined out, the positive evidence may be lacking.

Ray mine, John Day area, Oreg.—The ore at the Ray mine consists of a group of small lenses of chromite in dunite and peridotite country rock (Thayer, 1940, p. 102). Field tests of hand specimens with the

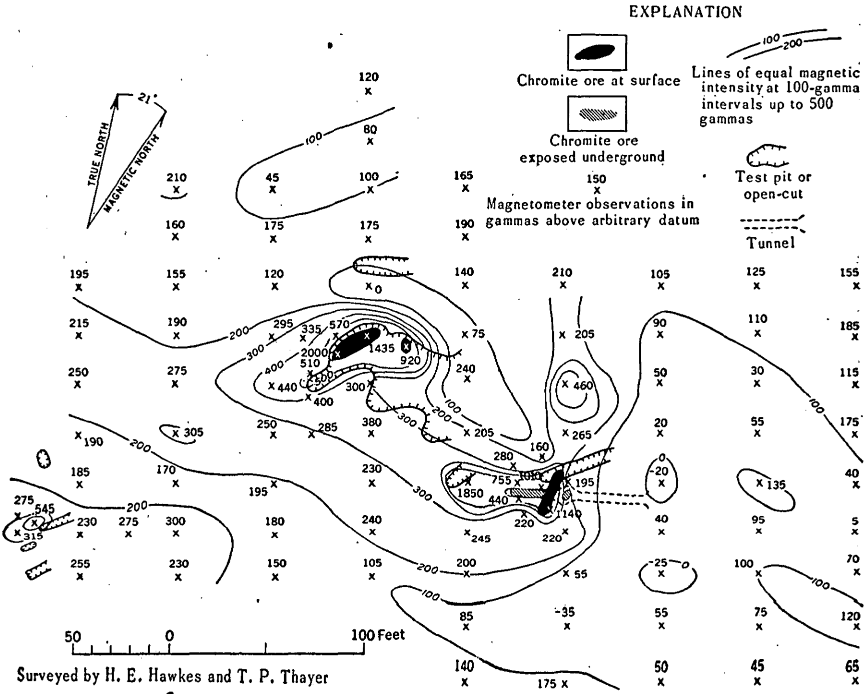

FIGURE 1.—Magnetic map of the Ray chromite mine, John Day area, Grant County, Oreg.

magnetometer showed that the ore was moderately to highly magnetic, whereas the ultramafic country rock was uniformly nonmagnetic. A magnetometer survey of the area by the writer showed positive anomaly values ranging from 500 to 1,800 gammas over known or probable ore. (See fig. 1.) The magnetic relief over the relatively nonmagnetic country rock is about 200 gammas. No evidence of new ore was found except for possible minor extensions of the known lenses in the immediate vicinity of the old workings.

Red Lodge district, Carbon County, Mont.—A magnetometer survey was conducted by the U. S. Geological Survey in three chromiferous areas on Hellroaring Plateau and in one on Line Creek Plateau, near Red Lodge, Mont. (James, 1946). Correlation of magnetic data with known geology showed that very high anomalies were characteristic of known chromite ore, diabase, and magnetite-rich metamorphic rocks, whereas serpentine gave smaller anomalies and granite, quartzite, amphibolite, and porphyry gave still weaker magnetic intensity values. Although the method apparently was well suited to local magnetic and geologic conditions, no new chromite discoveries were made.

Verbliuzhi Mountain, Ural region, U. S. S. R.—Krasulin (1933) reports that a magnetic survey over a known large deposit revealed a well-defined anomaly of about 7,000 gammas above the magnetic background. Chromite bodies of less than 200 tons, however, gave no reaction.

Groenfontein No. 302 farm, Transvaal, South Africa.—Weiss, Simpson, and Paver (1936) describe two 1,000-foot magnetic traverses across a series of thin layers of stratiform chromitite in pyroxenite of the Bushveld complex. Hand specimens of ore from these seams were slightly magnetic. A magnetometer survey showed that one of the three chromitite layers gave an anomaly of about 1,500 gammas on both traverse lines, whereas the other two layers gave no reaction whatever. The average magnetic relief of the pyroxenite country rock was about 500 gammas. The authors conclude that the chromitite layers can be traced magnetically "only in areas where the magnetic intensity values over the country rock are normal or constant." Apparently this preliminary test was not followed up with systematic magnetic surveying, as no new discoveries were reported.

Oregon (*chromite-bearing beach placers*).—E. L. Stephenson (1945) reports the results of magnetometer measurements over marine beach terraces of the Oregon coast near Bandon. The terrace deposits in places contain layers, up to 10 feet thick, of "black sands." These are concentrations of heavy minerals, mainly magnetite, ilmenite, chromite, garnet, olivine, zircon, and pyroxene (Griggs, 1945). Although the principal economic constituent of the black sands is chromite, the deposits are magnetic by virtue of their magnetite content, which commonly ranges from 1 to 7 percent. Magnetometer surveys were run in the vicinity of eight separate black-sand occurrences. Stephenson concludes that "in general the anomalies associated with black sand are stronger and more uniform than other magnetic variations encountered in the immediate area. Exceptions are anomalies due to igneous or metamorphic rocks." The significant magnetic variations range from a few gammas, where the sand is at a depth of 60 feet, up to 250 gammas for black sands within 2 or 3 feet of the surface. Magnetic indications in six localities pointed to the occurrence of previously unknown sand deposits; drilling in three of the areas resulted in the discovery of small new deposits or extensions of known deposits.

Magnetic exploration for placer deposits is an entirely different problem from exploration for primary chromite ore, and this example is included here only because the object of the search was chromite.

INDICATION OF FAVORABLE HOST ROCK

Serpentinized ultramafic rocks, because of their relatively high magnetite content, can almost always be distinguished from other common rocks by magnetic observations. In most areas, however, the general location and shape of the ultramafic masses are sufficiently well known from geologic observations, and additional magnetic evidence contributes little toward solving the problem of finding chromite. A few exceptions to this rule are noted, together with examples of apparent ore-bearing areas within the ultramafic rocks that can be distinguished magnetically.

Casper Mountain, Wyo.—E. L. Stephenson (1941; see also Stephenson, H. K., 1940; U. S. Geol. Survey, 1942; Horton, 1949) found a well-defined magnetic contrast between a chrome-bearing talc schist and a complex of less magnetic intrusive rocks. The published data (U. S. Geol. Survey, 1942) indicate that the magnetic pattern over the schist is characterized by greater magnetic relief, together with diagnostic contact effects, rather than by a uniformly positive magnetic anomaly. The contacts of the area of chromiferous schist inferred by the magnetic data were closely confirmed by later trenching work. Concentrations of chromite occur throughout the mass of the talc schist in a very irregular pattern. Although laboratory experiments on specimens of chromite showed that the chromite itself at this locality is commonly strongly magnetic (tables 1 and 2), the location and grade of deposits could not be directly correlated with the magnetometer data.

Chrome Point, western Newfoundland.—Snelgrove (1934) presents a geologic map of the Chrome Point chromite area with magnetic dip-needle contours. Eight of the twelve chromite concentrations shown on the map are either enclosed by, or lie within 100 feet of, the —4° dip-needle contour. Susceptibility determinations on hand specimens showed no significant magnetic contrast between ore and country rock.

Shoal Pond area, eastern Newfoundland.—Snelgrove (1934) reports that a dip-needle survey over the area of the chromite deposits at Chrome Hill near Shoal Pond gave a negative anomaly of 15° to 22°. The —10° dip-needle contour encloses an area up to 300 feet wide and at least 1,800 feet long that roughly coincides with the center of a belt of serpentinized dunite 500 feet wide contained in a large pyroxenite mass. Snelgrove's map shows that 12 of the 19 chromite concentrations of the area lie inside the —10° contour; the remainder lie within 100 feet of this contour. No explanation for the negative character of the anomaly is offered. Subsequent laboratory tests showed that a specimen of chromite from this deposit had a susceptibility of

$15{,}500 \times 10^{-6}$ c. g. s. units, as contrasted with 590×10^{-6} for a specimen of pyroxenite from the same ultramafic mass. Although these susceptibility tests showed the ore to be highly magnetic, the field survey served only to outline the general area where chromite concentrations occur.

U. S. S. R.—I͡Unkov (1938) describes the results of four seasons of experimental magnetometer surveys at the Poltavsk, Khalilovsk, Shaidurovsk, Alapaevsk, Verkh-Neivinsk, and Akkarginsk chromite deposits in the Ural region. He concludes that "(1) micromagnetic surveys make it possible to determine rapidly and cheaply the location of the contacts of ultramafic masses, and to distinguish these masses on the basis of their lithologic types (gabbro, peridotite, and dunite). It is also possible to differentiate some vein rocks; (2) ore-bearing zones cannot always be distinguished, as this depends on the geologic setting of the deposit; (3) at none of the deposits examined was it possible to distinguish the ore itself by micromagnetic observations."

Krasulin (1933) reports that, at the Zapivalovsk and Nadezhdinsk deposits in the Urals, the chromite occurs in zones of relatively less magnetic rocks that can be distinguished by magnetometer surveys.

Manitoba, Canada (Bird River complex). The stratiform chromite ore of the Bird River gabbro sill occurs at a fairly constant stratigraphic position in the complex. This igneous complex is faulted and largely covered by a thick overburden, so that it is not always possible to trace the chromite layer by surface exposures. Bateman (1943) reports that exploration for chromite was "facilitated by a magnetometer survey that established the position of the gabbro-peridotite contact and hence of the chromite zone." He does not report any discoveries as a result of this technique.

UNSUCCESSFUL APPLICATION OF MAGNETIC METHODS

Castro mine, San Luis Obispo County, Calif.—Ore at the Castro mine (Smith and Griggs, 1944) occurs as grains of disseminated chromite in a serpentine matrix. The deposits are well-defined, almost horizontal, lenticular masses. Hand specimens of chromite were generally somewhat more magnetic than the ultramafic country rock. Two magnetometer traverses were run by the present author on the hill slope directly overlying the lower ore body, which has the form of a flat lens averaging 12 feet in thickness, most of it in place at the time of the visit. Where the magnetic observations were made, the top surface of the ore was 20 to 25 feet below the surface of the ground. The average of 14 magnetic observations directly over the known ore was 50 gammas lower than the average of 17 observations over barren ground in the immediate vicinity; the total magnetic relief was 200 gammas.

Grey Eagle mine, Glenn County, Calif.—Ore at the Grey Eagle mine (Rynearson and Wells, 1944) occurs as a lens of disseminated chromite, 50 feet in maximum thickness, enclosed in a sheath of serpentinized dunite up to 100 feet thick and 750 feet in total exposed length. The country rock of the chromite-dunite complex is peridotite. Minor faulting has broken the ore complex into a complicated series of fault blocks. Magnetometer field tests of hand specimens by the present author showed that the peridotite and the chromite ore are weakly to moderately magnetic, whereas the serpentinized dunite is relatively nonmagnetic. Generally low magnetic values were observed over and adjoining the ore, possibly as the result of the nonmagnetic character of the dunite as contrasted with the peridotite. This relationship was not sufficiently consistent, however, to be of value in prospecting.

Little Castle Creek valley, Shasta County, Calif.—In the spring of 1941 the author conducted a magnetometer survey of the area southwest of the Castle Crags mine on the south side of the Little Castle Creek valley. Chromite ore in the Little Castle Creek area occurs as lenses or irregular masses of disseminated to massive ore, scattered over a linear distance of almost a mile in a general southwesterly direction. The deposit at the Castle Crags mine, which is the southernmost deposit of the group, was a 15,000-ton lens of massive chromite that was almost entirely mined out in 1917. Thus it was not possible to make trial magnetic observations over known ore.

Tests of hand specimens showed that massive ore from the main deposit is relatively magnetic as compared with most specimens of country rock. Thin-section study showed that the grains of chromite consisted commonly of opaque, magnetic halos surrounding cores of translucent nonmagnetic chromite.

The survey revealed a fairly complex pattern of anomalies, with a total relief of about 5,000 gammas. A prominent feature of the area is a zone of positive magnetic intensity extending for at least 800 feet southwest of the Castle Crags mine and almost coincident with the continuation of the line along which the known deposits of the area are distributed. On the chance that this anomaly might be the indication of a chromite-bearing zone, an extensive program of surface trenching was recommended and carried out. Except for a few tons of disseminated chromite uncovered 50 feet to one side of the magnetic zone, the results of the surface work were entirely negative (Matson, 1949). No work has been done to check the possibility of a chromite deposit at depth.

Cyclone Gap mine, Siskiyou County, Calif.—Ore at the Cyclone Gap mine occurred as a cluster of six closely spaced pods in serpentinized peridotite and dunite. These pods yielded a total of 2,000 tons of chromite. Many short gash dikes of diorite cut the ultramafic rocks; in one place a dike was seen cutting a chromite pod (F. G.

Wells, personal communication). Magnetometer tests of hand specimens showed that the country rock is generally highly magnetic, whereas the chromite ore is nonmagnetic. It is possible that some magnetite may have been developed by metamorphism along the diorite dikes. In 1941, when the author examined the deposit, the ore was almost mined out, so that no magnetic readings could be made directly over known ore. A magnetometer traverse passing within a few feet of the end of one of the deposits gave a highly irregular curve with a magnetic relief of over 4,000 gammas, but it showed no apparent relation to the position of the ore.

Sourdough mine, Curry County, Oreg.—In the Sourdough area, massive chromite occurs as layers from a few inches to several feet thick in a matrix of dunite, which in turn is contained in peridotite (Wells, Page, and James, 1940). The degree of serpentinization of both dunite and peridotite ranges from slight to intense. According to Lee (1938), "the dunite and chromite were not magnetic; on the other hand the peridotite was very highly magnetic and much of it was magnetically polarized." Lee found "similar magnetic anomalies" over the zone of mineralization on three profile traverses, but was unable to distinguish individual lenses of ore. Additional magnetometer observations by the present author showed that these anomalies consisted of a zone 50 to 100 feet wide of relatively high magnetic relief. Similar areas of high relief were observed over barren peridotite country rock, so that their value as a guide to chromite ore is questionable.

John Day area, Oreg.—The southwest ore body at the Chambers mine (Thayer, 1940, pp. 96–98) is a somewhat irregular lens of medium-grade to massive chromite in a matrix of serpentinized dunite. The dunite in turn is enclosed in serpentinized peridotite, which comprises the bulk of the ultramafic mass. Magnetometer measurements over this deposit were made by the present author in 1941, at which time virtually none of the ore had been removed. A magnetic map of the area of the southwest ore body (fig. 2) showed a complex distribution of anomalies, but no apparent correlation between the magnetic pattern and the location of the ore body. A single magnetic traverse across the center of the northwest ore body, which also has been drilled but not mined, likewise showed no magnetic indication of the ore.

The author ran magnetometer traverses across known ore at the Iron King mine, the Marks and Thompson mine, and the upper and lower deposits at the Dry Camp mine. Specimens of slightly or moderately magnetic ore were found at all these deposits, although in each area specimens of serpentinized peridotite and dunite from the immediately adjacent country rock were as magnetic as the ore speci-

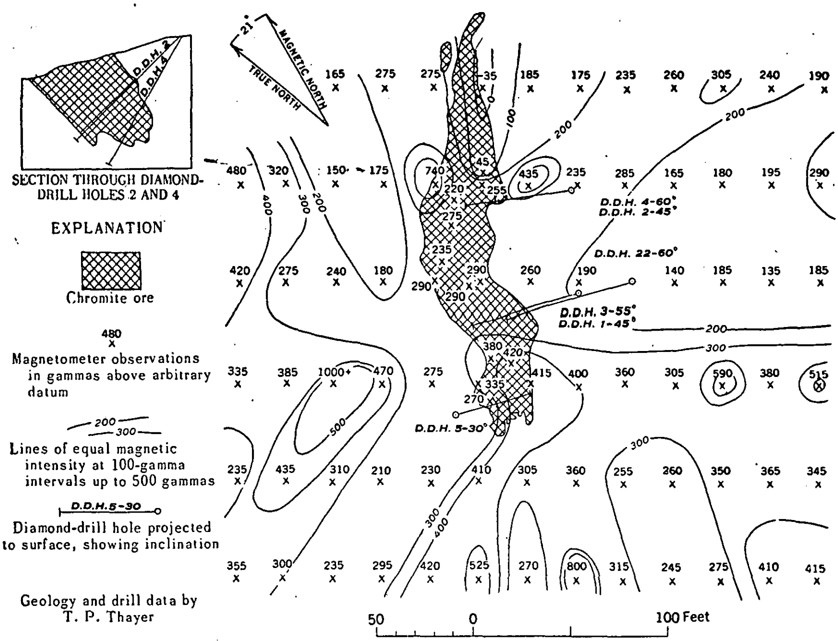

FIGURE 2.—Magnetic map of the southwest ore body, Chambers chromite mine, Grant County, Oreg.

mens or more so. The data failed to show any systematic correlation between magnetic anomalies and the location of known ore. Even where small anomalies occurred over ore, still higher values were usually found over barren country rock in the immediate vicinity. At the Iron King mine, for instance, the average of eight readings over known ore was only 270 gammas higher than the average of 36 readings over barren country rock, whereas the total magnetic relief was more than 3,200 gammas. Similarly, at the Dry Camp mine, the average of 13 readings over known ore was 40 gammas higher than the average of 25 readings over barren country rock, where the total relief was 560 gammas. It seems safe to conclude, therefore, that with the exception of the Ray mine, mentioned previously, the chromite deposits of the John Day area do not lend themselves readily to magnetic exploration.

Wood mine, Lancaster County, Pa.—Ore at the Wood mine (McIntosh and Mosier, 1948) occurs as nodules and pockets of massive, compact chromite in serpentinized ultramafic rocks. A magnetometer and gravimeter survey by the Geological Survey over an area measuring 6,000 by 2,000 feet indicated several anomalies. These were subsequently diamond-drilled, with negative results.

Thetford district, Quebec.—Miller (1932) reports that magnetometer surveys at Caribou Lake near Thetford, Quebec, showed high anomalies in the vicinity of chrome ore. The magnetic properties of two dozen hand specimens were tested with a pocket magnet, and "in every case the effect produced by the country rock was larger than that by the chromite." Miller expressed considerable doubt, therefore, as to whether the anomalies can be related directly to the chromite. Experimental surveys were run at the Beaver mine and at Black Lake with similar negative results.

U. S. S. R.—Bagratuni (1933), in a description of the Gei-Dara chromite deposits in Kurdistan, reports that hand specimens of gabbro, peridotite, and dunite caused deflections of the magnetic balance of one scale division or less when brought close to the magnetometer case, whereas specimens of chromite caused a deflection of several scale divisions. On this evidence a magnetometer survey in the Gei-Dara area was recommended, and several anomalies were found and interpreted as the effect of buried chromite deposits. Bagratuni did not report on the success of the project, as the anomalies were being drilled at the time the report was written. In a later report Andreev (1937) cites susceptibility data for samples from Gei-Dara, expressed as c. g. s. units times 10^6, as follows: chromite, 270 (average of 15 determinations); serpentinized dunite, 1,530 (average of 11 determinations); serpentinized peridotite, 2,200 (average of 17 determinations). Inasmuch as Andreev makes no mention of any discoveries at Gei-Dara as a result of the earlier work, it might safely be presumed that none were made.

Speaking in general, Andreev (1937) states that "trial magnetic surveys over many magnetite deposits of the Urals and Transcaucasia, to test the possible application of the method for direct detection of chromite, have led to the definite conclusion that magnetic prospecting methods cannot be used for this purpose. Observations taken directly over known chromite outcrops show that the majority of ore bodies give no magnetic indication. In some other cases, ore bodies give both positive and weakly negative anomalies, where the character and sign of the anomaly is not consistent even within the limits of the same mining district. This variability may be explained by the extremely variable magnetic susceptibility of chromite and its country rock together with the factor of permanent magnetization."

Montana (Stillwater complex).—The stratiform ore of the Stillwater igneous complex generally lies near the center of the ultramafic zone in the lower part of the complex (Peoples and Howland, 1940). In the West Benbow area, Mont., the ore occurs as a single seam of chromitite about 10,000 feet in strike length and commonly ranging from 2 to 6 feet in width. Experimental magnetic and resistivity surveys over the western end of this area were conducted in 1941 by Hans Lundberg, consulting geophysicist. According to Wimmler (1948), "the results of these surveys showed that the chromite bands gave no specific indications by either method. Faults could, however, be recorded where serpentinization had occurred along them, but that information was of little value." The magnetic relief in the West Benbow area is about 20,000 gammas, and from a study of hand specimens it appears to be entirely the effect of secondary magnetite developed along serpentinized faults and fissures.

SUMMARY

From a review of the literature and from field investigations by the author it is apparent that magnetic methods of exploration for primary chromite can be successfully applied only under very special geologic conditions. The magnetic indication may take the form of a direct magnetic response from the chromite ore itself or of an indication of favorable host rock which may serve as an indirect guide in the search for ore.

For the direct detection of chromite it is necessary that the chromite be characteristically magnetic and that the country rock be uniformly nonmagnetic. These conditions presuppose a rare combination of circumstances that can be expected only in exceptional cases.

Ultramafic rocks can usually be distinguished from other common rock types by magnetic methods. Thus, if a knowledge of the location, contacts, or shape of the ultramafic host rocks is helpful in prospecting, magnetic methods can be of indirect help in chromite exploration. In some areas ore-bearing zones within the ultramafic mass can apparently be located and mapped by magnetic methods, providing the prospector with another clue.

In the majority of areas described in the literature or examined by the author, magnetic methods showed no promise as a means of locating chromite bodies. Even in the areas where "successful" results were reported, the surveys apparently were successful only in that the method showed promise. The author knows of no discovery of a commercial deposit of primary chromite resulting either directly or indirectly from magnetic-survey work.

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