

UNITED STATES DEPARTMENT OF THE INTERIOR

Harold L. Ickes, Secretary

GEOLOGICAL SURVEY

W. E. Wrather, Director

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Bulletin 940-D

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VANADIUM-BEARING MAGNETITE-ILMENITE  
DEPOSITS  
NEAR LAKE SANFORD  
ESSEX COUNTY, NEW YORK

BY

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Strategic Minerals Investigations, 1943

(Pages 99-123)



UNITED STATES  
GOVERNMENT PRINTING OFFICE  
WASHINGTON : 1943



## CONTENTS

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	Page
Abstract.....	99
Introduction.....	100
Location and accessibility.....	100
History and earlier investigations.....	101
Field work.....	102
Acknowledgments.....	102
Geology.....	103
Regional setting.....	103
Rocks of Lake Sanford district.....	103
Anorthosite-gabbro series.....	104
Anorthosite.....	105
Gabbroic anorthosite.....	105
Gabbro.....	105
Gradation to magnetite-ilmenite rock.....	106
Dike rocks.....	106
Ore deposits.....	106
Classes of ore.....	107
Rich ore.....	107
Lean ore.....	108
Gabbro with disseminated magnetite-ilmenite.....	108
Mineralogy of the ore.....	108
Recovery of vanadium.....	109
Laboratory investigations.....	111
Methods of investigation.....	111
Magnetic concentrate.....	111
Separation of magnetite from other minerals...	111
General quantitative variations.....	113
Titanium and vanadium content.....	114
Ratio of $TiO_2$ to $V_2O_5$ .....	114
Nonmagnetic concentrate.....	114
Significance of laboratory studies.....	116
Localization and origin of ore deposits.....	117
Description of deposits and reserves.....	117
Sanford Hill deposit.....	119
Iron Mountain deposit.....	120
Calamity Mill Pond deposit.....	121
Cheney Pond deposit.....	122
Summary of reserves.....	122

## ILLUSTRATIONS

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	Page
Plate 19. Geologic and topographic map of Sanford Hill magnetite deposit, Essex County, N. Y... In pocket	
20. Isometric block diagram of Sanford Hill mine..... In pocket	
21. Geologic and topographic map of Iron Mountain magnetite deposit, Essex County, N. Y... In pocket	

	Page
Plate 22. Geologic and topographic map of Calamity Mill Pond magnetite deposit, Essex County, N. Y.....	In pocket
23. Geologic and topographic map of Cheney Pond magnetite deposit, Essex County, N. Y....	In pocket
Figure 9. Index map of part of northeastern New York State showing location of the Lake Sanford district.....	100
10. Schematic diagram of mineral composition of rocks in the Lake Sanford district.....	104
11. Diagram showing calculated mineral composition of ore samples in table 3.....	113
12. Diagram showing chemical composition of the magnetic concentrates of ore samples in table 3.....	113
13. Index map showing location of ore deposits in the Lake Sanford district.....	118

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TABLES

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	Page
Table 3. Chemical analyses and calculated mineral com- position of samples of vanadium-bearing mag- netite rock from Lake Sanford district, Essex County, N. Y.....	115
4. Estimated reserves in Lake Sanford district....	122

## CORRECTIONS TO GEOLOGICAL SURVEY BULLETIN 940-D

Bulletin 940-D. Vanadium-bearing magnetite-ilmenite deposits near Lake Sanford,  
Essex County, N. Y. [Published in January 1944.]

Page 112, table. In last column, under  $\text{TiO}_2$ , last line should read 10.04, instead of 10.71.

Page 115, table, footnote 2. Percent of  $\text{V}_2\text{O}_5$  should be 0.71, instead of 0.17.

# VANADIUM-BEARING MAGNETITE-ILMENITE DEPOSITS

NEAR LAKE SANFORD,

ESSEX COUNTY, NEW YORK

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By James R. Balsley, Jr.

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## ABSTRACT

Four deposits of vanadium-bearing magnetite-ilmenite, closely associated with small intrusive bodies of gabbro in the anorthositic core of the Adirondack Mountains, have been found near Lake Sanford, Essex County, N. Y., at the head of the Hudson River. The anorthosite, gabbro, and magnetite-ilmenite rocks form a gradational series and are believed to be related to the same regional intrusion of magma.

The ore consists of intermixed granular ilmenite and magnetite, with a little rutile and varying proportions of silicate minerals. The magnetic concentrate from the ore may contain up to 15 percent  $TiO_2$ , incorporated in ilmenite and rutile that are finely disseminated in the magnetite, and up to 1.7 percent  $V_2O_5$ , possibly in very fine-grained coulsonite, an iron-vanadium oxide, which is also included in the magnetite. Three metals can be produced from the ore—iron and vanadium from the magnetite of the magnetic concentrate and titanium from the ilmenite of the nonmagnetic separate. Laboratory studies indicate that fine-grained lean ore must be crushed to 60 mesh or finer to obtain the most complete magnetic separation, that ore with 10 to 30 percent silicate minerals produces the greatest quantity of ilmenite, and that the richest ore, though it produces the greatest quantity of magnetic concentrate, is the least favorable for recovery of vanadium. To obtain the most favorable balance, therefore, of the three interdependent products, titanium, vanadium, and iron, it is necessary to mill ore of intermediate grade, or an artificial mixture resembling it.

The largest of the deposits, on Sanford Hill, is now being mined by the National Lead Co. It has been proved by diamond drilling to contain, above the level of the lake, 11,500,000 tons of rich ore, which will yield 8,200,000 tons of magnetic concentrate containing, on the average, 0.6 percent  $V_2O_5$ .

Another large deposit, on Iron Mountain, probably contains 7,000,000 tons of rich ore, which will yield 4,550,000 tons of magnetic concentrate with an average content of 0.7 percent  $V_2O_5$ . The district as a whole contains 16,500,000 tons of measured ore, which will yield 10,000,000 tons of magnetic concentrate with an average content of 0.6 percent  $V_2O_5$ ; 12,600,000 tons of indicated ore, which will yield 8,300,000 tons of magnetic concentrate averaging 0.7 percent  $V_2O_5$ ; and 13,900,000 tons of inferred ore, which will yield 2,500,000 tons of magnetic concentrate averaging 0.8 percent  $V_2O_5$ .

## INTRODUCTION

Location and accessibility

Deposits of vanadium-bearing magnetite-ilmenite rock have been reported to occur at many places in the Adirondack Mountains in northeastern New York (fig. 9). Those near Lake

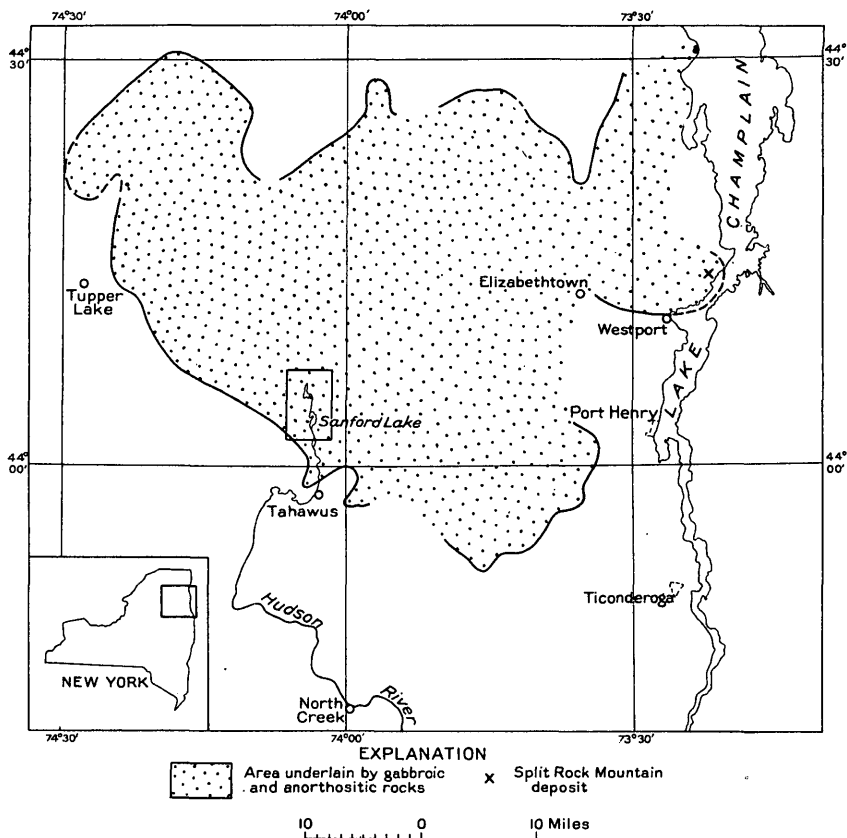


Figure 9.--Index map of part of northeastern New York State showing location of the Lake Sanford district. Adapted from Buddington, A. F., Geol. Soc. Amer. Mem.

Sanford, in Essex County, owned by the National Lead Co., are the largest in the region and include the only deposit of this type that is now being mined in the United States. This property is 32 miles by road north of the village of North Creek, and it probably will be served by a connection to the Adirondack Branch of the Delaware & Hudson Railroad that is now

being built by the U. S. Defense Plant Corporation for operation during the war emergency.

#### History and earlier investigations

Iron ore was first discovered in the Lake Sanford area by Archibald MacIntyre in 1826. MacIntyre purchased the property and founded the Adirondack Iron & Steel Co., which produced iron from 1838 to 1858; but this company failed, and the mine subsequently became the property of the MacIntyre Iron Co., which held it until 1941. Because of the large proportion of titanium in the ore, which made it unsatisfactory for producing the newer types of steel, this company made only sporadic attempts to exploit the deposits.

The National Lead Co. purchased the property in 1941, and began development work in June with a view to producing ilmenite for the manufacture of titanium pigment. After doing 11,000 feet of diamond drilling to outline the ore body, the company began open-cut mining on a series of benches. A 4,000-ton mill was erected at the south end of Sanford Hill, and a small village for the workmen was built on the southeast shore of the lake. Production began in July 1942 and reached full capacity at the end of the year, and it is expected in 1943 to amount to about 200,000 long tons of ilmenite concentrate, containing 48 percent  $TiO_2$ , and 450,000 long tons of magnetite concentrate, containing 60 percent Fe, 9 percent  $TiO_2$ , and 0.7 percent  $V_2O_5$ . Titanium pigment is produced from the ilmenite concentrate by the National Lead Co., and the magnetic concentrate is sold to the Bethlehem Steel Co. for the production of vanadium and iron.

The presence of vanadium in this ore was first mentioned by Rossi in 1898,<sup>1/</sup> but the ore was not considered a source of

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<sup>1/</sup> Rossi, A. J., Iron Age, February 1898.

vanadium until that possibility was suggested in a Geological Survey memorandum of February 25, 1942.

Earlier published reports bearing on the petrology and economic geology of the region include those by Emmons,<sup>2/</sup> Rossi,<sup>3/</sup> Kemp,<sup>4/</sup> Newland,<sup>5/</sup> and Singewald.<sup>6/</sup> R. C. Stephenson,<sup>7/</sup> geologist of the National Lead Co., has recently made a detailed study of the rocks in this district.

#### Field work

This report is based on four weeks of field study made by the author, assisted by J. C. Reinemund, in September 1942, during which four magnetite deposits—those at Sanford Hill, Iron Mountain, Calamity Mill Pond, and Cheney Pond—were mapped with plane table and telescopic alidade on a scale of 250 feet to the inch. Magnetic surveys made in 1908 by F. C. Rolls were made available to the Geological Survey by the National Lead Co., and were used as a guide for a more detailed compass and dip-needle survey made by the writer.

#### Acknowledgments

The writer is indebted to the personnel of the National Lead Co. for its hospitality, courtesy, and assistance, and in particular to I. D. Hager, general manager of the MacIntyre Development, Otto Herres, resident manager, and R. C. Stephenson, resident geologist. J. C. Rabbitt, of the Geological Survey, made more than 150 spectrographic analyses for

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<sup>2/</sup> Emmons, Ebenezer, Survey of the Second Geological District, pp. 244-255, 1842.

<sup>3/</sup> Rossi, A. J., Titaniferous ores in the blast furnace: Am. Inst. Min. Met. Eng. Trans., vol. 21, pp. 832-866, 1893.

<sup>4/</sup> Kemp, J. F., Titaniferous iron ores of the Adirondacks: U. S. Geol. Survey 19th Ann. Rept., pp. 409-417, 1898.

<sup>5/</sup> Newland, D. H., Geology of the Adirondack magnetic iron ores: New York State Mus. Bull. 119, pt. 3, pp. 155-164, 1908.

<sup>6/</sup> Singewald, J. T., Jr., The titaniferous iron ores in the United States: U. S. Bur. Mines Bull. 64, pp. 60-76, 1913.

<sup>7/</sup> Stephenson, R. C., Dissertation in preparation at The Johns Hopkins University; to be published as a New York State Museum bulletin.

vanadium in samples collected by the writer, using laboratory facilities that were generously placed at his disposal by Harvard University. W. T. Pecora and F. C. Calkins, of the Geological Survey, made helpful criticisms of the manuscript.

## GEOLOGY

### Regional setting

The regional geology of the Adirondack Mountains, which has been discussed at length by many investigators—most recently by Balk,<sup>8/</sup> Alling,<sup>9/</sup> and Buddington<sup>10/</sup>—, is so complex that it can be only briefly summarized in this report.

The oldest rocks of the region belong to the Grenville series of metamorphosed sediments, which was successively intruded by (1) anorthositic and gabbroic rocks, (2) syenitic and granitic rocks, (3) diabase dikes, (4) granite, and (5) basalt dikes. The igneous rocks form the central part of the Adirondack Mountains (fig. 9), and the Grenville series—which barely enters the area—forms the periphery. Both the igneous and the Grenville rocks are believed to be of pre-Cambrian age; all of them have been metamorphosed.

All the deposits of vanadium-bearing magnetite-ilmenite described in this report are found in the anorthositic and gabbroic rocks (group 1 above).

### Rocks of Lake Sanford district

The dominant rocks of the Lake Sanford district are divisible into two series, the first ranging from anorthosite to gabbro and the second from gabbro to magnetite-ilmenite rock.

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<sup>8/</sup> Balk, Robert, Structural geology of the Adirondack anorthosite: Min. Pet. Mitt., Bd. 41, pp. 308-434, 1931.

<sup>9/</sup> Alling, H. L., The Adirondack anorthosite and its problems: Jour. Geology, vol. 40, pp. 193-237, 1932.

<sup>10/</sup> Buddington, A. F., Adirondack igneous rocks and their metamorphism: Geol. Soc. America Mem. 7, 1939.

The first series grades into the second, and all gradations exist within each series.

Figure 10 shows the general character of the gradation graphically by means of curves.

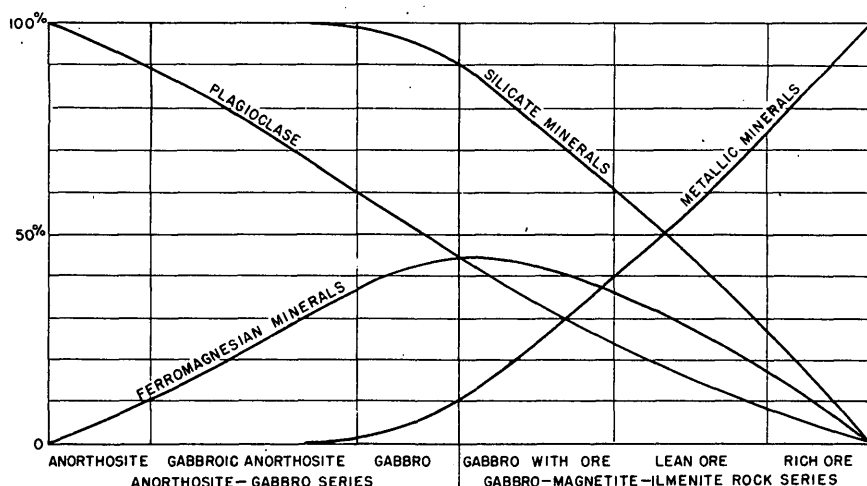


Figure 10.--Schematic diagram of mineral composition of rocks in the Lake Sanford district.

#### Anorthosite-gabbro series

The rocks of the anorthosite-gabbro series consist essentially of silicate minerals—light-colored plagioclase feldspar and the dark-colored ferromagnesian minerals pyroxene, garnet, hornblende, and biotite (fig. 10). Varieties within the series may be distinguished by their differing proportions of feldspar to ferromagnesian minerals or by the resulting differences of color and grain size. Comparatively light-colored, coarse-grained anorthosite with more than 90 percent feldspar grades into dark-colored fine-grained gabbro in which the quantity of feldspar and of ferromagnesian minerals is roughly equal. Magnetite-ilmenite is relatively scarce in this series of rocks; the pure anorthosite contains none and the gabbro only about 10 percent.

Anorthosite.--Anorthosite, the most abundant rock in the district, is a light-to dark-gray coarsely porphyritic rock containing 90 percent or more of plagioclase feldspar (calcic andesine). Blue-gray plagioclase phenocrysts up to 3 inches in length are embedded in white to greenish fine-grained interstitial plagioclase of the same composition.

The large crystals are so dark-colored in places, because of the abundance of minute inclusions, that they might be taken for ferromagnesian minerals. Near contacts with ore, the groundmass of the anorthosite commonly contains moderately coarse grained scapolite, which may be a deuteric alteration product. In the Lake Sanford area the anorthosite, as found by petrographic study, has undergone considerable movement during its solidification. In most places any structure that may be present is generally inconspicuous because of the massive character of the rock, but in some places a poorly developed flow structure is shown by parallel arrangement of tabular feldspar phenocrysts.

Gabbroic anorthosite.--The term "gabbroic anorthosite" is used to designate rock intermediate in composition between the anorthosite and gabbro, and, as would be expected, the rock shows some of the physical characteristics of both end members (fig. 10).

Gabbro.--In this district the term "gabbro" is used to designate a dark-colored, fine-grained rock containing approximately equal amounts of feldspar and dark-colored ferromagnesian minerals. Because of local usage and because these rocks form a mappable unit, no attempt was made to distinguish gabbro, in which the only pyroxene is augite, from norite, which contains hypersthene as well as augite. The gabbro, as thus broadly defined, is a dark-gray to black, fine-grained, equigranular rock. It is composed essentially of andesine and pyroxene (augite and hypersthene) with almandite garnet,

hornblende, and biotite as subordinate constituents, and magnetite-ilmenite, rutile, apatite, and scapolite as accessories. The andesine has a wide range of composition, but is commonly more sodic than that in the anorthosite.

A gneissic structure resulting from a parallel arrangement of the feldspar and ferromagnesian minerals is apparent in most of the gabbro of the district. The banding is generally parallel to the elongation of the lens-shaped masses in which the gabbro is found.

#### Gradation to magnetite-ilmenite rock

Gabbro containing less than 10 percent of magnetite-ilmenite grades into a rock that consists almost entirely of magnetite-ilmenite (fig. 10) but that has the same igneous origin as the gabbro and anorthosite. The rocks containing more than about 10 percent of magnetite-ilmenite are ores of iron, titanium, and vanadium, and are discussed further under "Ore deposits."

#### Dike rocks

Dike rocks are not common in the Lake Sanford district. Some dikes a few inches to a foot wide, composed of plagioclase, pyroxene, and magnetite, crop out near the mouth of Calamity Brook, and two dikes of fine-grained diabase are intruded into the western end of the deposit on Iron Mountain.

#### ORE DEPOSITS

The vanadium-bearing ore mined in the Lake Sanford district consists of rock that contains relatively large proportions of magnetite-ilmenite. It grades in composition from almost pure magnetite-ilmenite to gabbro with less than 10 percent of magnetite-ilmenite. Even the richest of the ore is believed to be an igneous rock genetically related to the

anorthosite-gabbro series, the magnetite-ilmenite having consolidated after the silicate minerals. The magnetite in the rock contains vanadium, a metal that is of strategic significance to the war program, and the vanadium content of the ore is the matter chiefly considered in this report. Titanium and iron also are produced from this deposit, and the mining and milling of the ore must be so adjusted as to give the most favorable balance between three interdependent products—vanadium, titanium, and iron.

Vanadium is at present recovered from magnetite by a metallurgical process whose efficiency is directly proportional to the amount of contained vanadium and inversely proportional to the amount of contained titanium. In an effort to determine the mixture that would be most satisfactory as an ore of both titanium and vanadium, the writer has made special studies of the variations in vanadium content and in ratio of  $TiO_2$  to  $V_2O_5$  in concentrates of metallic minerals produced from ore of different grades.

#### Classes of ore

##### Rich ore

In this district the term "rich ore" is applied to a very heavy, coarse-grained rock composed almost entirely of the metallic minerals, magnetite and ilmenite, in grains up to one-fourth of an inch in diameter. It may contain as much as 25 percent of silicate minerals; biotite and large phenocrysts of andesine are the most abundant and they are accompanied by some pyroxene and hornblende (fig. 10). The magnetic concentrate from this rich ore amounts to from 50 to 80 percent of the rock.

## Lean ore

By local usage the term "lean ore" is applied to that containing more than about 25 percent of silicate minerals. Such ore is a heavy, dark, fine-grained rock composed of small crystals of feldspar and ferromagnesian minerals in a matrix of magnetite-ilmenite. The metallic minerals form 40 to 75 percent of the rock and the magnetic concentrate 15 to 50 percent (fig. 10). The "cut-off" for lean ore is determined by the total recovery of titanium, vanadium, and iron from it, and as there is not at present sufficient information regarding recovery of vanadium to determine the cut-off accurately, it was arbitrarily set at a minimum content in metallic minerals of 40 percent.

## Gabbro with disseminated magnetite-ilmenite

All the gabbro in this district contains at least a few percent of the metallic minerals, and that containing more than 10 percent and less than 40 percent can be considered submarginal ore. Such rock is distinguished on the detailed maps (pls. 19, 20, 21, and 23) as gabbro with disseminated magnetite-ilmenite. It differs from lean ore only in the proportions of its minerals, but, because of the greater abundance of the silicate minerals, it shows in many places the gneissic structure typical of the gabbro.

Mineralogy of the ore

Vanadium is found only in the magnetite of these rocks and titanium only in the ilmenite and rutile. Dunn<sup>11/</sup> reports that in similar but richer ores in India an iron-vanadium oxide, which he has named coulsonite, is intergrown with magnetite. Coulsonite has not been identified in the magnetite

<sup>11/</sup> Dunn, J. A., Vanadium-bearing titaniferous iron ores in Singhbhum and Mayurbhanj, India, Trans. Min. & Geol. Ins. of India, pp. 120-184, February 1937.

from the Lake Sanford district. Minute grains of an unidentified metallic mineral resembling coulsonite as described by Dunn were observed, however, in polished sections of magnetite-ilmenite, containing 1.5 to 1.7 percent  $V_2O_5$ , that were collected from a magnetite-ilmenite deposit on Split Rock Mountain, 35 miles northeast of Lake Sanford (fig. 9). The tiny grains are intimately intergrown with the magnetite and are too small to be isolated for further study. As this mineral is visible only in samples exceptionally rich in vanadium, it is believed to be the vanadium mineral, and it may occur as submicroscopic grains in all the magnetite. It is possible, however, that the vanadium is not all contained in this mineral but is partly in chemical combination with the iron of the magnetite.

Also intimately intergrown with the magnetite are numerous fine laths of ilmenite, a few laths of rutile, and a few irregular blebs of hercynite, which is a dark green iron-rich spinel.

Most of the ilmenite forms separate grains or blebs mixed with grains of magnetite, and it is this granular ilmenite, and not that which is finely intergrown with magnetite, that is largely recovered for use in the manufacture of titanium pigment.

#### Recovery of vanadium

Heretofore the most feasible method of recovering vanadium from these ores has been a pyrometallurgical process involving three steps: (1) production of a vanadium-rich, titanium-poor magnetic concentrate by electromagnetic separation from granular ilmenite and silicate minerals; (2) reduction of the magnetic concentrate, by smelting in a blast furnace, to pig iron containing the vanadium; and (3) concentration of the vanadium in a slag produced from the pig iron in a Bessemer converter.

Successful recovery of vanadium by this method depends in large measure upon both the titanium content and the vanadium content of the magnetic concentrate. An excess of titanium prevents satisfactory smelting: recent tests by the Bethlehem Steel Co. showed that an ore charge containing more than about 2.5 percent  $TiO_2$  could not be smelted in a large blast furnace. High percentage of vanadium, on the other hand, is favorable: the percentage recovery of vanadium in the Bessemer converter is directly proportional to the concentration of vanadium in the pig iron, and varies from about 80 percent at 0.8 percent  $V_2O_5$  to 45 percent at 0.2 percent  $V_2O_5$ . The necessity for keeping the vanadium content of the magnetic concentrate up to a certain level puts a limit on permissible dilution of the blast-furnace charge to reduce the percentage of objectionable  $TiO_2$ , for mere dilution would of course reduce the percentage of vanadium in the same ratio. The two determining factors in the recovery of vanadium by this process are the percentage of  $V_2O_5$  and the ratio of  $TiO_2$  to  $V_2O_5$  in the magnetic concentrate. By the methods employed in the current operations of the Bethlehem Steel Co., vanadium can be recovered from these ores only if the magnetic concentrate contains more than 0.3 percent  $V_2O_5$  and if the ratio of  $TiO_2$  to  $V_2O_5$  is less than 9. This company is now endeavoring, however, to improve the method so that it will be less limited in its application.

The writer's laboratory studies indicate that these two factors vary systematically according to the grade, that they are not constant in the magnetic concentrate derived from different grades of the ore, and that they vary systematically, in a way that will be described later.

A chemical method for recovering vanadium from the magnetic concentrate produced at the MacIntyre mine has recently been developed by the research department of the National Lead

Co. The concentrate is roasted with 3 percent by weight of salt, and the roasted product is leached to remove the soluble sodium vanadate that is produced. By this process 60 percent of the vanadium in the magnetic concentrate of the ore from Sanford Hill can be economically recovered.

### Laboratory investigations

#### Methods of investigation

The writer has made special chemical and mineralogical studies of the different grades of ore in an effort to determine what mixture of them would give the best recovery of both titanium and vanadium. Samples of several different types of ore were collected, each sample being made up of numerous chips taken at regular intervals from an exposure in which the tenor was approximately constant. The samples were crushed to pass 60 mesh, and then separated by means of a small electromagnet. The silicate minerals were next gravimetrically separated from both the magnetic and nonmagnetic fractions of the samples by means of Clerici solution (specific gravity 4.3), and, finally, the magnetic and nonmagnetic separates were analyzed for Fe,  $TiO_2$ , and  $V_2O_5$ . The separations made with this simple equipment were not as clean as those that could be obtained in a mill, but as all the samples were treated in a similar manner the results have a true relative significance. The analyses for vanadium were made on duplicate samples by two chemical methods and by the spectrograph. There was a constant difference among the results of the methods, but the colorimetric chemical method gave the most consistent results and is believed to be the most reliable.

#### Magnetic concentrate

Separation of magnetite from other minerals.--Magnetite can be separated by means of an electromagnet from nonmagnetic

coarse granular ilmenite and silicate minerals, but the magnetite cannot be ground fine enough to free the intergrown ilmenite and rutile, which are therefore included in the magnetic fraction and tend to impair its value as an ore of vanadium. The effect of grinding varies, however, with the character of the ore; grinding that is sufficient to separate grains of ilmenite from magnetite in coarse rich ore is not sufficient to free the smaller particles in fine-grained lean ore. By way of determining how fine it is worth while to grind ores of different kinds, three samples were crushed to pass 20 mesh and split into two fractions, and one fraction was then recrushed to pass 60 mesh. Magnetic separations were made on both fractions by means of a small electromagnet, and the magnetic concentrates analyzed for Fe and  $TiO_2$ . The results are shown below.

	Mesh	Magnetic concentrate		
		Weight (percent)	Fe (percent)	$TiO_2$ (percent)
Rich ore, Sanford Hill.....	20	79.2	60.10	12.12
	60	78.6	59.12	12.09
Lean ore, Sanford Hill.....	20	48.2	55.93	13.48
	60	42.7	58.72	9.93
Lean ore, Iron Mountain....	20	51.6	52.18	12.71
	60	42.7	55.63	10.71

Grinding to 20 mesh thus appears to be sufficient for coarse-grained rich ore, since finer grinding does not free enough of the intergrown ilmenite to reduce materially the titanium content of the magnetic concentrate. Finer grinding does, on the other hand, improve the magnetic concentrate from lean ore; there is 6 to 9 percent less of this concentrate, but it contains 2 to 4 percent less  $TiO_2$ , for the titanium content of the coarse magnetic fraction is partly due to fine granular ilmenite, which is largely freed by grinding to 60 mesh.

General quantitative variations.--Rich ore yields the highest percentage of magnetic concentrate--80 to 50 percent of the total sample. Lean ore yields from 50 to 15 percent and gabbro with disseminated magnetite-ilmenite less than 15

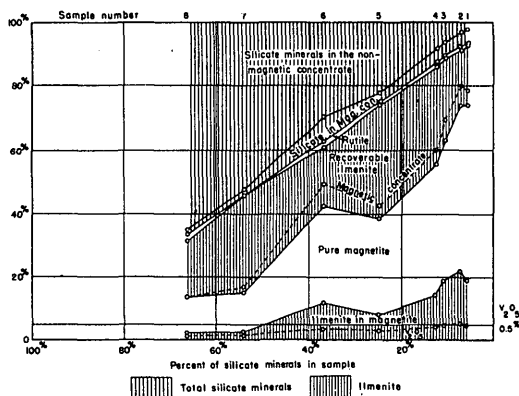


Figure 11.--Diagram showing calculated mineral composition of ore samples in table 3.

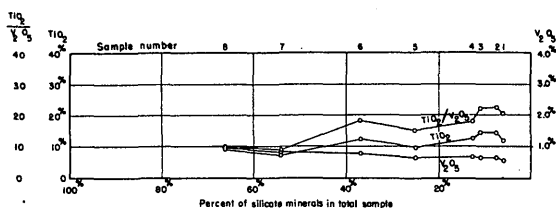


Figure 12.--Diagram showing chemical composition of the magnetic concentrates of ore samples in table 3.

percent (table 3 and fig. 11). But the proportion of magnetic concentrate to the content of metallic mineral in the sample is not constant. In two samples of rich ore, the magnetic concentrate forms 85 and 88 percent of the calculated total content of metallic mineral, and in two samples of lean ore it forms only 36 and 42 percent (table 3 or fig. 11). The most

abundant metallic mineral in rich ore is magnetite, whereas in lean ore it is ilmenite.

Titanium and vanadium content.--The percentages of both titanium and vanadium in the magnetic concentrates are related, in a general way, to the grade of ore from which the concentrate is obtained. The titanium content ranges from 12 to 14½ percent in the concentrate from rich ore, and from 7 to 12 percent in the concentrate from lean ore (table 3 or fig. 12). Vanadium, on the contrary, is much more abundant, relatively, in the magnetic concentrate from lean ore than in that from rich ore (table 3 or fig. 12). The magnetic concentrate of rich ore contains from 0.58 to 0.68 percent  $V_2O_5$  and that of lean ore from 0.65 percent to 0.95 percent  $V_2O_5$ . This difference is of great significance in the recovery of the metal, but it should be noted that the magnetic concentrate from lean ore, though much richer in vanadium, is less than half as abundant as that from rich ore.

Ratio of  $TiO_2$  to  $V_2O_5$ .--In the magnetic concentrate derived from lean ore the ratio of  $TiO_2$  to  $V_2O_5$  is about half what it is in rich ore (table 3 or fig. 12), so that lean ore is the more suitable material for the metallurgical process currently used to recover vanadium. The ratio ranges from 22.6 in rich ore to 8.7 in lean ore. In all but one of the samples tested the ratio is above the maximum set by the Bethlehem Steel Co. The better separation obtainable in a mill tends to reduce—and hence to improve—the ratio; in the magnetic concentrate produced in the National Lead Co.'s mill from combined ores during November and December 1942, the ratio of  $TiO_2$  to  $V_2O_5$  ranged from 13 to 13.7, considerably below the average obtained in the laboratory.

#### Nonmagnetic concentrate

All the ilmenite recovered is in the nonmagnetic concentrate, mixed with silicate minerals, from which it is



separated in the mill by means of jig tables and high-intensity magnetic separators. The highest percentage of ilmenite is recovered from ore containing roughly 10 to 30 percent of silicate minerals (table 3 or fig. 11). A sample (No. 7, table 3) collected from the Calamity Mill Pond deposit is exceptional in this regard; it is a lean ore and yet it contains an extraordinarily high percentage of ilmenite.

#### Significance of laboratory studies

The laboratory studies led to four significant results:

(1) Rich ore contains the greatest percentage of metallic minerals and of magnetite, and the highest total vanadium content; (2) the magnetic concentrate of rich ore has a lower percentage of  $V_2O_5$  and a higher ratio of  $TiO_2$  to  $V_2O_5$  than that derived from lean ore; (3) intermediate-grade ore has the highest percentage of recoverable ilmenite; (4) crushing to 20 mesh is satisfactory for rich ore but is insufficient to separate the granular ilmenite from the magnetite in lean ore.

These results help to solve the two-fold problem presented by these ore deposits—that of determining the mixture of ore that will (1) give maximum recovery of ilmenite in the mill and (2) produce a magnetic concentrate most favorable for the recovery of vanadium and iron.

In order to recover the greatest percentage of vanadium from ore mined it is necessary to mix rich ore with lean—the rich ore to supply quantity of magnetic concentrate and the lean ore to improve its quality. The greatest percentage of ilmenite from ore mined is recovered from ore of intermediate grade, containing 90 to 70 percent of metallic minerals. The naturally occurring intermediate-grade ore and the artificial mixture resembling it are therefore most favorable for the production of both vanadium and titanium, for their magnetic concentrate is believed to be the optimum mixture for vanadium

recovery, and their nonmagnetic concentrate produces the greatest quantity of ilmenite.

#### Localization and origin of ore deposits

Magnetite-ilmenite is closely associated with gabbro, either in conformable lenses of "lean ore" within the gabbro or in irregular masses of "rich ore" between gabbro and anorthosite. The contact of ore with anorthosite is sharp, but its contact with gabbro is in most places gradational.

The anorthosite, gabbro, and magnetite-ilmenite rocks are believed to be related to the same regional intrusion of magma, as is evidenced by the orderly variations in the relative abundance of the minerals and by their similar modes of occurrence. Anorthosite was the first rock to crystallize from the magma. Residual segregations of iron-rich liquid then accumulated to form masses of gabbro. Continued crystallization of the silicate minerals formed a residual liquid of nearly pure magnetite-ilmenite, which was partly trapped between the interstices of the crystals in the gabbro and partly forced into the still plastic anorthosite. These periods of rock formation overlapped, and all the rocks remained plastic during the process of segregation, so that in some places certain intrusive relations are reversed. Movement contemporaneous with, or slightly later than, the formation of the rocks crushed and recemented the grains of the essentially monomineralic anorthosite and rich magnetite-ilmenite rock, and it also produced gneissic structure in the gabbro and lean ore.

#### DESCRIPTION OF DEPOSITS AND RESERVES

The MacIntyre Development of the National Lead Co. includes four deposits of vanadium-bearing magnetite-ilmenite in the vicinity of Lake Sanford. These are called the Sanford

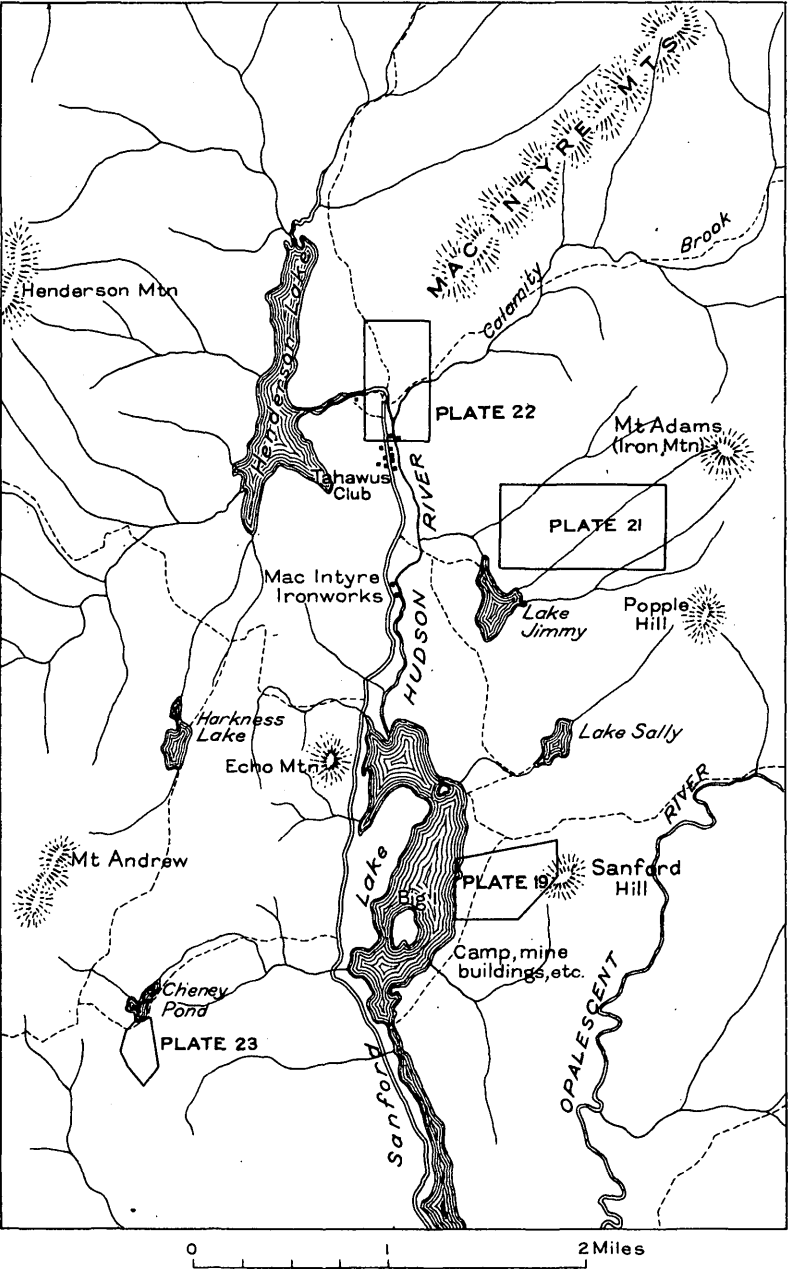


Figure 13.--Index map showing location of ore deposits in the lake Sanford district.

Sanford Hill, the Iron Mountain, the Calamity Mill Pond, and the Cheney Pond deposits (see fig. 13).

Sanford Hill deposit

On the western slope of Sanford Hill (pls. 19 and 20), a deposit of magnetite-ilmenite-bearing gabbro at least 1,800 feet long and 600 feet wide is now being mined by open-cut methods. At the east contact of the gabbro are two large bodies of rich ore, and a third extends 1,000 feet southwestward from the main mass, but it cannot be mined, because the mill has been built upon it. Within the mass are numerous lenses of lean ore and two lenses of moderately rich ore, conformable to the general N. 35° E. strike and steep east dip of the gabbro.

Lens No. 1 is a body of rich ore in the northeast corner of the gabbro mass. It is poorly exposed, but the magnetic survey and eight diamond-drill holes indicate that it is about 1,000 feet long and 400 feet wide, with an average depth to the level of the lake of 350 feet. Two drill holes, (21) and 37, show that the ore continues unchanged to about 200 feet below the level of the lake, making a total depth of 550 feet. The contact is exposed only at the north end of bench No. 5, but the diamond-drill holes indicate that the ore body has a very steep dip to the west (pl. 20). Within this mass, to the level of the lake, are about 7,000,000 tons of rich magnetite-ilmenite rock, which yields 70 to 80 percent of magnetic concentrate containing 0.6 percent of  $V_2O_5$ .

Lens No. 2 is a body of rich ore in the southern part of the main gabbro mass. Its south end is well exposed on benches 1, 2, and 3, and eleven diamond-drill holes show that the ore body is about 800 feet long, 300 feet wide, and 150 feet deep. The contact between ore and anorthosite exposed on the benches is vertical, but the drill holes show that the bottom contact with anorthosite is horizontal (pl. 20), so the mass is cigar-shaped. This body contains about 3,600,000 tons

of ore, which would yield 65 to 75 percent of magnetite concentrate containing 0.6 percent of  $V_2O_5$ .

Lenses No. 3 and 4 are small masses of moderately rich ore in the northwestern part of the gabbro mass. They are well exposed on benches 1, 2, and 3, where it is seen that their contacts with localized patches of anorthosite are sharp but that in most places the ore grades into gabbro. Lens No. 3 contains about 400,000 tons, and lens No. 4 about 500,000 tons of ore, which yields 45 to 55 percent of magnetic concentrate containing 0.7 percent of  $V_2O_5$ .

The remainder of the gabbro mass exposed or proved by diamond drilling comprises about 10,000,000 tons, about half of which can be regarded as lean ore. Much of this ore occurs in small moderately rich lenses, but a large mass of lean ore is bounded by the tongue of anorthosite and by lenses No. 3 and 4. The 5,000,000 tons of ore from this source would yield, on the average, 30 percent of magnetic concentrate containing 0.7 percent of  $V_2O_5$ .

Three estimates of the total tonnage of this deposit have been made:

MacIntyre Co., 1908 (from magnetic survey, assuming 700 feet depth).	.....	24,263,772 gross tons of rich ore (average 45 percent Fe).
National Lead Co., 1942 (to level of lake).	.....	15,000,000 tons.
Geological Survey, 1942 (to level of lake).	.....	12,700,000 tons of ore, with 55 percent magnetic concentrate containing 0.6 percent $V_2O_5$ .

#### Iron Mountain deposit

On the southwestern flank of Mount Adams, near a knob locally referred to as Iron Mountain, a long narrow lens of magnetite-ilmenite-bearing gabbro crops out for a distance of 4,000 feet (pl. 21). A mass of rich ore is poorly exposed

along the northern contact of the gabbro, but the magnetic survey shows that it has a length of 2,100 feet and a width of 50 to 200 feet. A vertical contact of ore against anorthosite is exposed at each end of the ore body, which, as the magnetic survey indicates, is a thin sheet that dips steeply like the main gabbro lens. Six diamond-drill holes were put down here in 1908, but all information regarding them has been lost. The cores from holes 3 and 4 are still on the ground, however, and, though both have been scattered and mixed, enough of them is left to show that practically pure magnetite-ilmenite extends to a depth of at least 150 feet. Assuming an average depth of 200 feet, there are in the deposit about 7,000,000 tons of ore that would yield 60 to 70 percent of magnetic concentrate containing 0.7 percent  $V_2O_5$ .

The remainder of the gabbro yields 10 to 15 percent of magnetic concentrate containing up to 1.0 percent of  $V_2O_5$ , but the amount of vanadium recoverable from this rock is too small to justify considering the rock as ore.

#### Calamity Mill Pond deposit

The geology of the Calamity Mill Pond deposit is complex and, being of little economic significance, will not be considered in detail.

Two hundred feet west of the junction of Calamity and Henderson Brooks, very coarse grained magnetite-ilmenite rock is exposed in an old water-filled excavation 100 feet long and 20 feet wide, locally called the "Mill Pond" (pl. 22). The ore is overlain by anorthosite, with the contact striking north and dipping  $15^\circ$  E., so that ore may possibly extend for a considerable distance under the hill to the west. Diamond-drill hole (1), however, shows only 70 feet of ore, underlain by anorthosite which extends 130 feet to the bottom of the hole, and, as the magnetic survey indicates that the ore does not

continue to the west, the ore body must be small. A small mass of rich ore crops out 400 feet south of the "Mill Pond."

On the ridge between Calamity and Henderson Brooks is a large mass of well-foliated gabbro enclosing many small lenses of magnetite-ilmenite an inch to a foot thick. Two bulk samples of the ore yield only 15 percent of magnetic concentrate, containing 0.8 percent  $V_2O_5$ , but they are noteworthy in that the two together contain 30 percent of recoverable ilmenite. Assuming a depth of 200 feet, there are 8,000,000 tons in this mass.

Lean ore and very small masses of rich ore are exposed in Calamity Brook but have no economic importance.

Diamond-drill hole (2) shows 145 feet of mixed rich and lean ore, and the magnetic survey indicates that there may here be an ore body somewhat larger than the ore at the Mill Pond; but the area is in a swamp and no bedrock is visible.

#### Cheney Pond deposit

Six hundred feet south of Cheney Pond, a lens of gabbro rich in magnetite-ilmenite is intermittently exposed over a distance of 1,000 feet (pl. 23). The lens is 10 to 50 feet thick, strikes approximately north, and dips  $30^\circ$  to  $35^\circ$  W., conformably with the gabbro, into which it grades. The lens evidently dips into the hill, but the magnetic survey gives no conclusive evidence as to how deep it extends. If it extends 100 feet below the surface, the deposit contains 800,000 tons of ore, which would yield 35 percent of magnetic concentrate with 0.7 percent of  $V_2O_5$ .

#### Summary of reserves

The reserves in the district are divided into three classes according to the degree of accuracy with which they can be estimated. "Measured ore" is that whose tonnage has

Table 4.--Estimated ore reserves in the Lake Sanford district  
(Assuming 100 percent recovery of vanadium)

A. Estimates by the Geological Survey, September 1942

	Rich ore (More than 45 percent magnetic concentrate)					Lean ore (35-15 percent magnetic concentrate)					Total ore (weighted average)				
	Ore (short tons)	Weight (per- cent)	Short tons	V <sub>2</sub> O <sub>5</sub> (per- cent)	Vanadium (pounds)	Ore (short tons)	Weight (per- cent)	Short tons	V <sub>2</sub> O <sub>5</sub> (per- cent)	Vanadium (pounds)	Ore (short tons)	Weight (per- cent)	Short tons	V <sub>2</sub> O <sub>5</sub> (per- cent)	Vanadium (pounds)
Sanford Hill:															
Measured (above lake level).	11,500,000	70	8,200,000	0.6	59,000,000	5,000,000	35	1,750,000	0.7	14,000,000	16,500,000	55	10,000,000	0.6	73,000,000
Indicated (below lake level).	4,200,000	70	3,000,000	.6	20,000,000	.....	.....	.....	.....	.....	4,200,000	70	3,000,000	.6	20,000,000
Iron Mountain:															
Indicated.....	7,000,000	65	4,550,000	.7	36,000,000	.....	.....	.....	.....	.....	7,000,000	65	4,600,000	.7	36,000,000
Inferred.....	.....	.....	.....	.....	.....	5,000,000	15	700,000	.9	8,000,000	5,000,000	15	700,000	.9	8,000,000
Calamity Mill Pond:															
Indicated.....	600,000	70	400,000	.6	2,700,000	.....	.....	.....	.....	.....	600,000	70	400,000	.6	2,700,000
Inferred.....	900,000	70	600,000	.6	4,000,000	8,000,000	15	1,200,000	.8	11,000,000	8,900,000	20	1,800,000	.8	15,000,000
Cheney Pond:															
Indicated.....	.....	.....	.....	.....	.....	800,000	35	300,000	.7	3,000,000	800,000	35	300,000	.7	3,000,000
TOTALS FOR DISTRICT:															
Measured.....	11,500,000	70	8,200,000	.6	59,000,000	5,000,000	35	1,750,000	.7	14,000,000	16,500,000	55	10,000,000	.6	73,000,000
Indicated.....	11,800,000	65	8,000,000	.7	59,000,000	800,000	35	300,000	.7	3,000,000	12,600,000	65	8,300,000	.7	62,000,000
Inferred.....	900,000	70	600,000	.....	4,000,000	13,000,000	15	1,900,000	.8	19,000,000	13,900,000	15	2,500,000	.8	23,000,000

B. Estimates by the MacIntyre Iron Co., 1908  
(From magnetic survey, assuming 200 feet depth)

	Gross tons of rich ore (Average 45 percent Fe) [About 60 percent magnetic concentrate]
Sanford Hill.....	24,263,772
Iron Mountain.....	17,415,914
Calamity Mill Pond.....	9,101,872
Total, including Cheney Pond.....	63,000,000

C. Estimated ore reserves in Sanford Hill  
Estimates by the National Lead Co., September 1942

"The results of the drilling program to August 12, 1941, outline a minable ore body averaging 550 feet in width and 1,500 feet long with an average depth of 181 feet [to the level of the lake]. Using these figures, the indicated volume of the ore body is 150,000 cubic feet, which at 10 cubic feet per ton gives an indicated reserve of 15,000,000 tons."

been calculated from the surface area outlined by exposures and whose average depth has been determined by numerous diamond-drill holes. "Indicated ore" is that whose surface area has been determined from exposures and magnetic surveys but whose depth must be estimated from geologic evidence and relatively few drill holes. "Inferred ore" is that which is poorly exposed, or whose extent is inferred entirely from the results of magnetic surveys, and whose depth is estimated solely from geologic evidence. In estimating tonnages, the number of cubic feet to a ton was assumed to be 7 for rich ore, 9 for ore yielding 35 percent of magnetic concentrate, and 10 for ore yielding 15 percent of magnetic concentrate.

The percentage of magnetic concentrate was determined by grinding the samples to pass 60 mesh and separating them by means of a small electromagnet. The amount of vanadium in the magnetic concentrates was determined by more than 100 spectrographic analyses, checked by chemical analyses of 21 samples, in each of which the vanadium was determined by two methods.

No "cut-off" grade is assumed in table 4, for sufficient data are not yet available as to costs for recovering vanadium or as to percentage of recovery. "Pounds of vanadium" is calculated on the assumption of 100-percent recovery.

