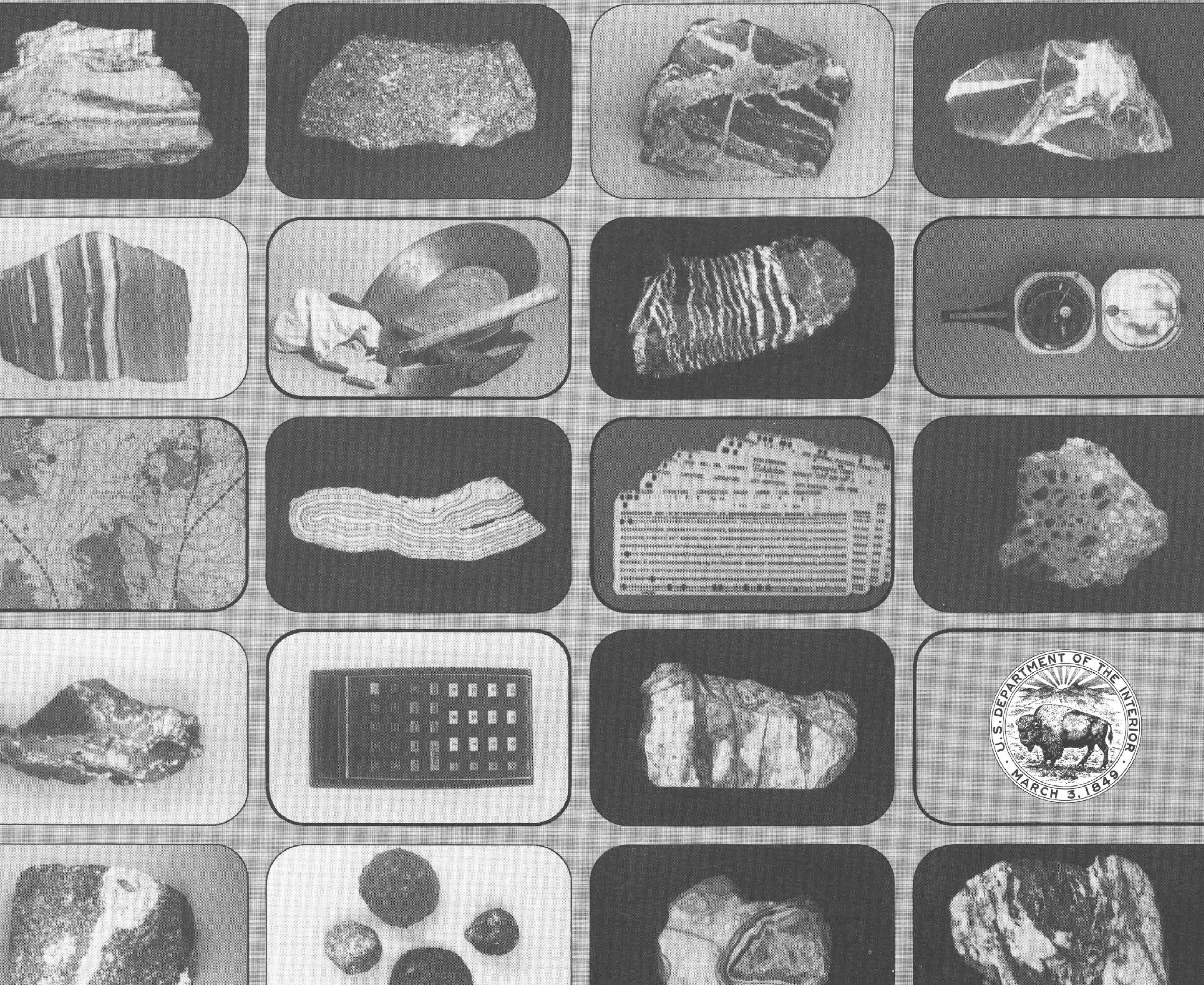
Vanadium Resources in Titaniferous Magnetite Deposits

GEOLOGICAL SURVEY PROFESSIONAL PAPER 926-B



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Vanadium Resources in Titaniferous Magnetite Deposits

By R. P. FISCHER

GEOLOGY AND RESOURCES OF VANADIUM DEPOSITS

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APPRAISAL OF MINERAL RESOURCES

Continuing appraisal of the mineral resources of the United States is conducted by the U.S. Geological Survey in accordance with the provisions of the Mining and Minerals Policy Act of 1970 (Public Law 91-631, Dec. 31, 1970). Total resources for purposes of these appraisal estimates include currently minable resources (*reserves*) as well as those resources not yet discovered or not currently profitable to mine.

The mining of mineral deposits, once discovered, depends on geologic, economic, and technologic factors; however, identification of many deposits yet to be discovered, owing to incomplete knowledge of their distribution in the Earth's crust, depends greatly on geologic availability and man's ingenuity. Consequently, appraisal of mineral resources results in approximations, subject to constant change as known deposits are depleted, new deposits are found, new extractive technology and uses are developed, and new geologic knowledge and theories indicate new areas favorable for exploration.

This Professional Paper discusses aspects of the geology of vanadium as a framework for appraising resources of this commodity in the light of today's technology, economics, and geologic knowledge.

Other Geological Survey publications relating to the appraisal of resources of specific mineral commodities include the following:

Professional Paper 820—"United States Mineral Resources"
Professional Paper 907—"Geology and Resources of Copper"
Professional Paper 933—"Geology and Resources of Fluorine in the United States"

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VANADIUM RESOURCES IN TITANIFEROUS MAGNETITE DEPOSITS

By R. P. Fischer

ABSTRACT

Titaniferous magnetite deposits are magmatic accumulations of magnetite and ilmenite. They commonly contain 0.2 to 1 percent V_2O_5, most of which is concentrated in the magnetite, and they have become the world's principal source of vanadium.

These deposits are mostly associated with mafic igneous rocks that occur in thick stratiform sheets or complex intrusive bodies of deep-seated origin. The ore minerals crystallized with the rock-forming minerals from the magma, and they commonly occur disseminated in large masses of rock or segregated in extensive layers; some bodies of magnetite and ilmenite occur as plugs or dikes that were injected as solutions or melts into these forms. The deposits vary widely in size; some are very large.

Vanadium can be recovered from titaniferous magnetite ore by either of two processes: (1) precipitating a vanadium salt from a leach of ore roasted with salt, or (2) precipitation from a leach of salt-roasted vanadium-rich slag obtained by smelting the ore to make a vanadium-bearing pig iron, which is then blown in a converter to make the vanadium-rich slag. About 75 percent of the world's supply of vanadium was derived from titaniferous magnetite deposits in 1970; virtually no vanadium was obtained from this raw-material source before the 1950's. The vanadium in known titaniferous magnetite deposits represents several thousands of years supply at the current rate of world consumption, about 25,000 short tons of vanadium yearly.

INTRODUCTION

Titaniferous magnetite deposits are magmatic accumulations of ilmenite and magnetite, or related minerals, that are arbitrarily defined as containing more than about 1 percent TiO_2. Characteristically they are vanadium-bearing, and they have become the world's principal source of vanadium. This report briefly reviews their geology, vanadium production, and resources.

GEOLOGY

Vanadium is considered to be a minor element, but it is a rather abundant one. Its crustal abundance is in the order of 100-150 ppm (parts per million). It is one of the lithophile elements that occur mainly in silicate rocks, but it does not form an important part of any common rock-forming mineral. In igneous rocks, vanadium occurs mainly in the insoluble 3-valent state and substitutes for iron and perhaps aluminum in iron and ferromagnesian minerals. It is most abundant in the mafic igneous rocks (about 200 ppm), less abundant in the ultramafic and intermediate rocks (about 50 ppm), and sparse in the silicic ones (about 25 ppm). Vanadium is concentrated in magmatic titaniferous magnetite deposits, and it commonly constitutes from 1,000 to 5,000 ppm (about 0.2 to 1 percent V_2O_5) in these deposits.

Vanadium-bearing titaniferous magnetite deposits are mainly associated with mafic igneous rocks, most commonly with gabbro and anorthosite; some occurrences are associated with alkalic igneous rocks. The mafic igneous rocks are of deep-seated origin, and they occur in thick stratiform sheets, such as the Bushveld complex in South Africa (Willemse, 1969; Allard, 1970), or in complex intrusive bodies, such as Taberg, Sweden (Hjelmqvist, 1950), Otanmäki, Finland (Pääkkönen, 1956), and Lake Sanford, New York (Gross, 1968). Most of the titaniferous magnetite deposits exposed are in continental shield areas and are of Precambrian age; a few are younger.

Magnetite (Fe_3O_4) and ilmenite ($FeTiO_3$) are the principal ore minerals, but hematite (Fe_2O_3) is present in some deposits as is some rutile (TiO_2) and perovskite ($CaTiO_3$). These minerals occur in medium- to fine-grained intergrowths and in exsolution and solid-solution relations; ulvospinel (Fe_2TiO_4) and titanomagnetite ($(FeTi)_3O_4$ or $(FeTi)_2O_3$) are two mineral names commonly applied to some of these exsolution and solid-solution forms. Small blebs and exsolution blades of coulsonite ($(Fe, V)_3O_4$) have been recognized in magnetite in a few deposits, but no vanadium mineral has been recognized in most deposits. Although some vanadium occurs in ilmenite and other titanium minerals, most of the vanadium in these deposits is in the magnetite (magnetic concentrates).

The ore minerals crystallized with the silicate minerals from the magma, and commonly they occur disseminated in large masses of rock or were segregated by crystal settling into extensive lenses or layers as much as several feet thick. Some bodies of magnetite and ilmenite occur as plugs, dikes, and irregularly shaped masses that presumably were injected into these forms when changing conditions in sites of earlier accumulation caused remobilization of iron and titanium. Vanadium-bearing titaniferous magnetite deposits vary widely in size—from those too small to be mined to those that contain several billion tons of ore containing several million tons of vanadium.

For additional information on the mineralogy and geology of titaniferous magnetite deposits, the reader is referred to reports by Gross (1967), Klemic, Marsh, and Cooper (1973), Lawthers (1957), Rose (1973), Willemse (1969), and to several papers in Visser and von Gruenewaldt (1970).

PRODUCTION

Figure 1 is a generalized graph showing vanadium production by geologic types of deposits for every tenth year from 1910 to 1970 (Fischer, 1973a). The type "Sandstone, and others" represents total vanadium production from the United States, most of which was derived from vanadium-bearing sandstone ores, but some of which was derived from base-metal vanadate deposits, from phosphate rock, from a deposit associated with an alkalic intrusion, and from petroleum residues. The type "Asphaltite" represents total production from the vanadium-bearing asphaltite deposit at Mina Ragra, Peru. The type "Vanadates" represents production from base-metal vanadate deposits, mostly from Namibia (formerly South-West Africa) and Zambia (formerly Northern Rhodesia). And the type "Iron deposits" represents vanadium obtained from titaniferous magnetite deposits in Finland, South Africa, Norway, and the U.S.S.R. The production data for Finland, South Africa, and Norway are published by the U.S. Bureau of Mines; those for the U.S.S.R. are partly estimated by the writer. A little vanadium has been obtained from still other types of raw materials, but the amounts are too small to be shown at the scale of figure 1.

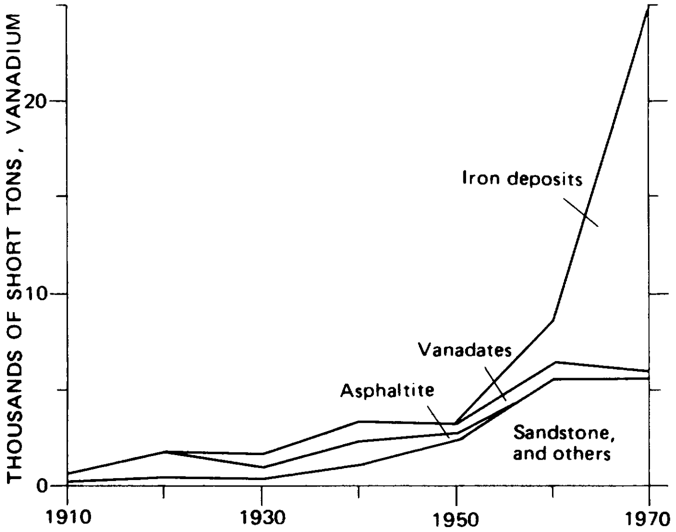

FIGURE 1.—Generalized graph showing vanadium production by geologic types of deposits for every tenth year, 1910–70. (Reprinted from Fischer, 1973a, fig. 76.)

In 1970, about 18,000 tons of vanadium, representing about 75 percent of the world's supply, was derived from titaniferous magnetite deposits; a little vanadium was obtained from this source before the 1950's, but the amount was negligible. The technology of vanadium recovery from titaniferous magnetite ore and the productive deposits are briefly described below.

Vanadium can be recovered from titaniferous magnetite ore or a magnetite concentrate of the ore by either of two general processes. In one process the ore or concentrate is mixed with a sodium salt and roasted, which yields a water-soluble sodium vanadate, which is leached by water and then recovered by precipitation from the solution (Tikkanen, 1956; Guise-Brown and Atmore, 1968). In the second process the ore or concentrate is introduced as iron ore into a blast furnace, which yields a vanadium-bearing pig iron, which is then blown in a converter, yielding a vanadium-rich slag; the slag is then salt-roasted, leached, and a vanadium salt precipitated (Polyakov, 1959; Douglas and others, 1968; Engineering and Mining Journal, 1972). A modification of this process permits the production of ferrovanadium directly from the vanadium-rich slag (Christiania Spigerverk, 1969). Direct smelting of ore in an electric furnace to yield coproduct iron, titanium, and vanadium has been proposed (Udy, 1962).

The titaniferous magnetite deposit at Otanmäki, Finland (no. 58, fig. 2, and table 1), is in a complex group of intrusive rocks consisting mainly of amphibolite, anorthosite, and gabbro. The ore occurs in lenticular bodies of varied size. In the mill, the ore is ground to moderate fineness and magnetically separated to make a marketable titanium concentrate and a vanadium-bearing magnetite concentrate, which is salt-roasted to recover vanadium, and the tailings of this operation are used as an iron ore. Vanadium oxide containing 15,342 short tons of vanadium was recovered in 1956–72. Reserves total about 50,000,000 tons of ore. A similar deposit at Mustavaara, Finland (no. 57, fig. 2, and table 1), is being developed and is expected to yield about 1,700 short tons of vanadium yearly after 1976 (Mining Magazine, 1972).

The stratiform mafic and ultramafic rocks of the Bushveld igneous complex in South Africa (no. 95, fig. 2, and table 1) are host to plugs and extensive layers of vanadium-rich titaniferous magnetite. These plugs and layers crop out for a distance of about 200 miles (300 kilometres), and they have been mined at several localities. Vanadium has been recovered as the principal product of salt-roasting the ore and as a byproduct in slags from pig iron. Reported production from these deposits during 1958–72 totals 30,872 short tons of vanadium in oxide and other vanadium concentrates and about 18,620 short tons of vanadium in slags; a considerable part of these slags have been exported for vanadium recovery in other countries. Reserves that can be mined by opencut methods total more than 200,000,000 tons of titaniferous magnetite ore (Nel and Luyt, 1964), and reserves and resources that can be mined underground are a few times that figure; total resources of at least 2 billion tons of titaniferous magnetite are estimated.

Titaniferous magnetite deposits in the Ural Mountains are the principal source of vanadium in the U.S.S.R. They are associated with mafic and ultramafic intrusive bodies, and they range from moderately small, high-grade, massive deposits to large, low-grade, disseminated deposits. Production probably began in the mid-1930's from the Kusinskoe deposit (no. 48, fig. 2, and table 1) and about the same time or in the 1940's from the Pervoural'sk deposit (no. 47, fig. 2, and table 1), but these operations probably were on a small scale and perhaps desultory until the 1950's. Yearly production from these deposits was about 4,000,000 tons of ore in the mid-1960's (Sokolov, 1970, p. 385). Operations at Mount Kachkanar (no. 45, fig. 2, and table 1) began about 1963, and currently (1974) this deposit probably is being mined at the rate of about 30,000,000 tons of ore yearly (Sokolov, 1970, p. 385). Vanadium is being recovered from pig-iron slags, some of which have been exported. Production records are not available, but it seems likely that the cumulative yield from these deposits probably amounts to about 50,000 short tons of vanadium, and that the current yearly yield is on the order of 8,000 to 10,000 short tons of vanadium. Reserves at Mount Kachkanar total 12 billion tons of ore (Sokolov, 1970, p. 398). The Pudozhgorskoe and Tsagin deposits and deposits in the Keyv intrusive (nos. 55, 52, and 51, fig. 2, and table 1) in the Karelo-Kola region in the northwestern part of the Soviet Union are being considered for exploitation in the future (Yudin and Zak, 1970).

The titaniferous magnetite bodies at the Rodsand mine, Norway (no. 67, fig. 2, and table 1), are lenses and layers in mafic rocks. The current annual yield of the mine is a little more than 1,000 short tons of vanadium in ferrovanadium, which is converted directly from vanadiferous slags. Although vanadium production data for Norway have been reported by the U.S. Bureau of Mines only since 1963, some vanadium had been recovered from vanadiferous slags that were exported to other European countries prior to 1963. Reserves at Rodsand total 10,000,000 tons of ore.

H. A. Taylor, Jr., U.S. Bureau of Mines, has reported (oral commun., 1974) that some vanadium has been recovered in the United States and in Japan from vanadium-bearing residues derived from producing titanium dioxide from titaniferous magnetite ores and titanium-bearing beach-sand deposits.

Plans to recover vanadium from titaniferous magnetite deposits at several other localities have been reported in recent years: Barrambie, Australia (no. 102, fig. 2, and table 1) (Mining Journal, 1971a); Wundowie, Australia (no. 104, fig. 2, and table 1) (Mining Journal, 1971b); Singhbhum-Mayurbhanj, India (no. 78, fig. 2, and table 1) (Mining Journal, 1971c); and Tete, Mozambique (no. 92, fig. 2, and table 1) (Taylor, 1973).

RESOURCES

Figure 2 shows most of the known titaniferous magnetite deposits in the world, and table 1 lists these deposits and gives the available significant resource information regarding them. The resource data have many limitations. Many deposits, including some of the productive ones, are obviously large but have not been thoroughly explored. Many "ore" tonnage estimates are crude, and probably somewhat low, and many grade figures are based on scant sampling. Tonnage estimates for a given deposit commonly vary considerably from one report to another, and generally the later report has the higher estimate; most of the tonnage estimates used are from a report prepared for the United Nations (1970). The qualitative words "small," "medium," and "large" used in the "ore" resources column are those used in the source reports; generally no indication of quantitative significance was given. These same words where used in the vanadium resources column imply the writer's estimates of "less than 100,000," "100,000–1,000,000," and "more than 1,000,000 short tons of vanadium."

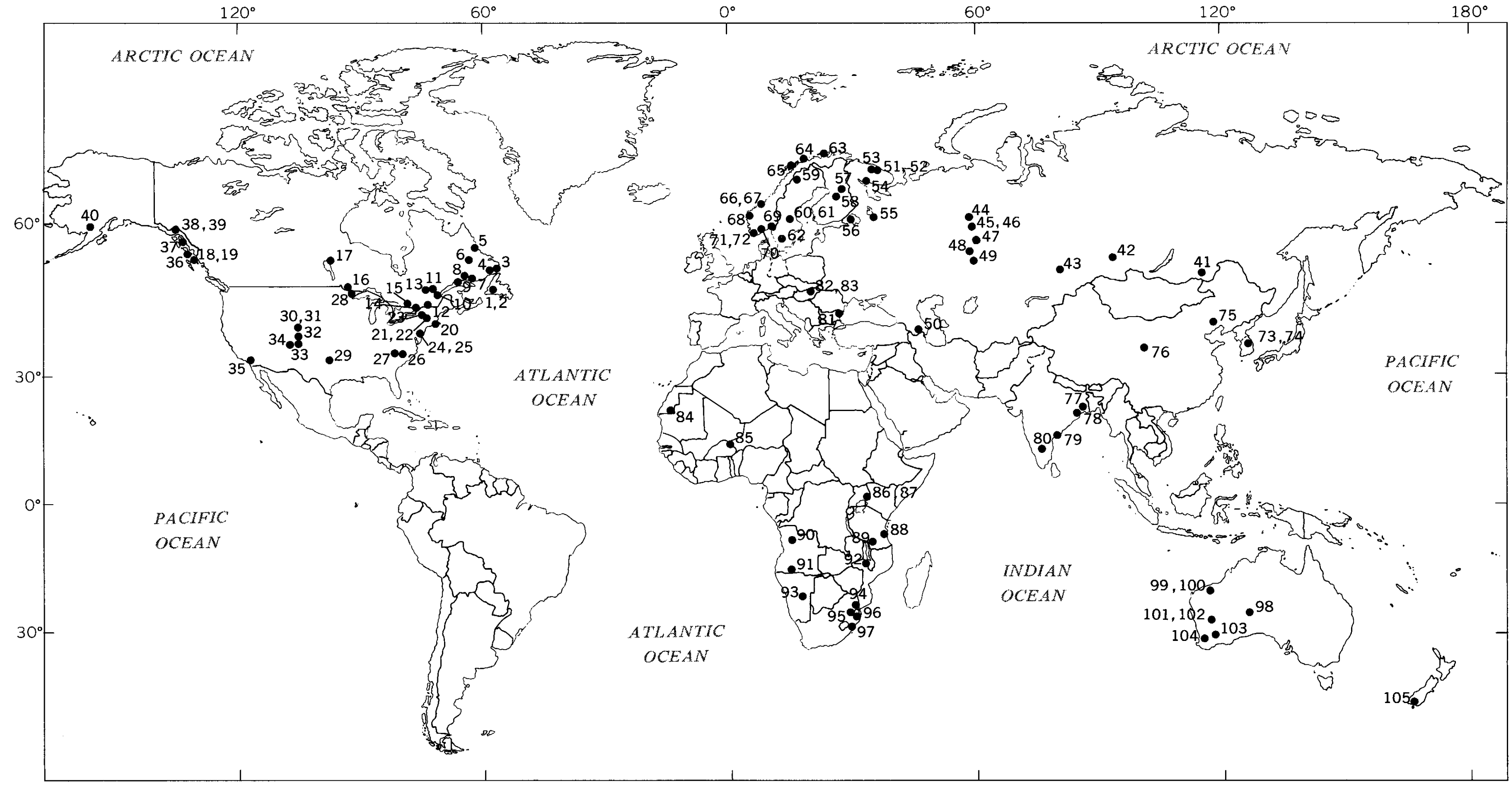

FIGURE 2.—Distribution of known titaniferous magnetite deposits. The numbers identify the deposits listed in table 1.

TABLE 1.—*Resource data on the known titaniferous magnetite deposits of the world*

Map No. (fig. 2)	State, Province, or region	Mine, deposit, area, or source rock	Grade of "ore" (percent)			Grade of magnetic concentrate (percent)			"Ore" resources (millions of tons[1])	Vanadium resources (thousands of tons V[1])	Geology									References
											Ore type				Host rock					
			Fe	TiO_2	V_2O_5	Fe	TiO_2	V_2O_5			Disseminations	Layers, lenses	Plugs, dikes	Massive	Gabbroic	Anorthositic	Alkalic	Mafic	Ultramafic	
										Canada										
1	Newfoundland	Steel Mountain	50–55	10±	0.4–0.9	64.5	8	0.75	Small	Small	...	...	×	...	...	×	...	...	...	Gross (1967), Rose (1969, 1970, 1973).
2	do	Indian Head	64	2–6	.2–.7	.....	.....	1.8	Small	Small	×	×	...	...	...	×	...	...	...	Rose (1969, 1970, 1973).
3	Labrador	Sandwich Bay	.....	.....	.....	.....	.....	.....	.....	Small	...	...	...	...	...	×	...	...	...	Rose (1969).
4	do	Mealy Mountains	.....	.....	.....	.....	.....	.....	.....	.....	...	...	...	...	...	×	...	...	...	Rose (1969).
5	do	Nain Mountains	.....	.....	.....	.....	.....	.....	.....	.....	...	...	...	...	...	×	...	...	...	Rose (1969).
6	do	Lake Michikamau	.....	.....	.....	58	9	1.9	Large(?)	Large(?)	×	×	...	...	...	×	...	...	...	Rose (1970).
7	Quebec	Allard Lake	36–40	35	.27–.35	.....	.....	.....	350	500	×	...	...	...	×	×	...	...	...	Hammond (1952), Lawthers (1957), Rose (1969, 1973), Gross (1970), Kish (1972).
8	do	Magpie Mountain	43	10	.2–.35	49	16	.2	2,500	2,500	×	×	...	...	×	×	...	...	...	Rose (1969, 1970, 1973), Gross (1970), Vallée and Raby (1971), Kish (1972).
9	do	Sept Isles	11–42	3–16	.....	55–60	14–18	.25–.8	Large(?)	Large(?)	×	...	...	...	×	×	...	...	...	Lawthers (1957), Rose (1969, 1970, 1973), Kish (1972).
10	do	St. Urbain	35–40	38–45	.17–.34	65	2	.3–.6	40	40	×	×	×	...	...	×	...	...	...	Lawthers (1957), Gross (1967, 1970), Rose (1969, 1970, 1973), Kish (1972).
11	do	Lake St. John	22	5–7	Low	69	.5	.....	320	Medium	×	...	...	...	...	×	...	...	...	Lawthers (1957), Gross (1967, 1970), Rose (1969, 1970, 1973), Kish (1972).
12	do	Morin	25–43	19	.05–.34	60-65	1–4	.4	Large(?)	Medium	×	×	...	×	...	×	...	...	...	Rose (1960, 1969, 1973), Kish (1972).
13	do	Dore Lake	28–53	5–8	.3–1+	62-64	4–5	1.0–2.5	Large	Large	...	×	...	...	...	...	...	...	×	Rose (1970, 1973), Allard (1970, 1973), Kish (1972),
14	Ontario	Matthews, Chaffey	27	6	.1–.55	60–64	4–5	.....	53	Small	×	×	...	...	×	×	...	...	...	Rose (1958, 1969, 1970).
15	do	Mattawa	35	8	.76	60	.....	1.4	Small(?)	Small	...	×	...	...	×	...	...	...	...	Harding (1946), Rose (1970, 1973).
16	do	Vermilion Lake	30–57	10–40	.1±	.....	.....	.....	150	Small(?)	...	×	...	...	×	×	...	...	...	Lawthers (1957), Rose (1969, 1970, 1973), Gross (1970).
17	Manitoba	Cross Lake	28–60	3–10	.02–.5	69	.11	1.6	Small(?)	Small(?)	×	×	...	...	...	×	...	...	...	Rose (1969, 1970, 1973).
18	British Columbia	Banks Island	20–50	1–3	.07–.55	60	1.5–5	.9–1.8	Medium(?)	Medium(?)	×	×	...	...	×	...	...	...	...	Rose (1970, 1973).
19	do	Porcher Island	25+	2	.2–.35	60	.3–1.5	.3–.9	Medium(?)	Medium(?)	×	×	...	...	...	...	...	×	...	Rose (1970, 1973).
										United States										
20	Rhode Island	Iron Mine Hill	33	9	.22	.....	.....	.....	7	10	×	...	...	...	×	...	...	...	...	Singewald (1913), Lawthers (1957).
21	New York	Elizabethtown	24–44	10–19	.04–.62	.....	.....	.....	21	Small	...	...	...	...	...	...	...	...	×	Newland (1908), Lawthers (1957).
22	do	Lake Sanford	34	19	.45	56	9–10	.7	122	300	...	×	...	...	×	×	...	...	...	Balsley (1943), Stephenson (1945), MacMillan and others (1950, 1952).
23	do	Diana Complex	20	7	.05	65	4	.15	Large	Small(?)	×	...	...	...	...	...	...	...	×	Leonard and Buddington (1964).
24	New Jersey	Hager	60	6	.....	.....	.....	.4	Small(?)	Small	...	...	...	...	...	...	...	...	...	Bayley (1910).
25	do	Van Syckle	50	10–15	.13–.38	.....	.....	.5	Small(?)	Small	...	×	...	...	...	...	...	...	...	Bayley (1910).
26	North Carolina	Piedmont province	40–65	12±	.....	.....	.....	.6	Small(?)	Small	...	×	×	...	...	...	...	×	...	Singewald (1913), Bayley (1921, 1923).
27	North Carolina-Tennessee	Appalachian province	40–60	5–7	.....	.....	.....	.2–.4	Small(?)	Small	...	×	×	...	...	...	...	×	...	Singewald (1913), Bayley (1921, 1923).
28	Minnesota	Duluth Complex	30	14	.1–.2	.....	.....	.....	94	90	×	×	×	...	×	×	...	...	...	Grout (1949-50), Lawthers (1957).
29	Oklahoma	Wichita Mountains	45-54	14–18	.....	.....	.....	.....	1	Small	...	×	×	...	×	...	...	...	...	Carr and Dutton (1959).
30	Wyoming	Iron Mountain	17-45	10-20	.17–.64	.....	.....	.....	178	250	×	...	...	×	...	×	...	...	...	Pinnell and Marsh (1954), Dow (1961), Harrer (1966).
31	do	Owen Lake	29	5	.02–.2	.....	.....	.....	Small(?)	Small	×	×	×	...	...	×	...	...	...	Harrer (1966).
32	Colorado	Caribou	36-59	2-36	.....	.....	.....	.....	Small	Small	×	×	×	...	...	...	...	...	×	Harrer and Tesch (1959).
33	do	Iron Mountain	45-50	14	.41–.45	.....	.....	.....	Small(?)	Small	×	×	×	...	×	...	...	...	...	Harrer and Tesch (1959).
34	do	Cebolla Creek	9-30	4-32	.1	.....	.....	.....	100	50	×	...	×	...	...	...	...	×	...	Larsen (1942), Rose and Shannon (1960), Harrer and Tesch (1959).
35	California	San Gabriel Mts.	46	20	.53	.....	.....	.....	10	30	×	...	×	...	×	×	...	...	...	Oakeshott (1948).
36	Alaska	Union Bay	18-20	.....	.....	.....	.....	.....	1,000	Large(?)	×	...	...	...	...	...	...	×	×	Kennedy and Walton (1946), Klemic (1970).
37	do	Snettisham	19	2.6	.09	64	3.5	.7	450	225	×	...	...	×	...	...	...	×	...	Thorne and Wells (1956), Klemic (1970).
38	do	Klukwan	15-20	2	.2	62-64	2-4	.3-.4	13,000	13,000	×	×	...	...	...	...	...	×	...	Wells and Thorne (1953), Klemic (1970).
39	do	Klukwan fan	15(?)	2	.05	.....	.....	.....	Medium(?)	Medium(?)	...	...	...	...	...	...	...	...	...	Wells and Thorne (1953).
40	do	Iliamna Lake	12-19	1.3	.02	40-60	3.1	.3-.5	7,000	7,000	×	...	...	...	...	...	...	×	...	Reed and Determan (1965), Klemic (1970).

See footnotes at end of table.

TABLE 1 —*Resource data on the known titaniferous magnetite deposits of the world*—Continued

Map No. (fig. 2)	State, Province, or region	Mine, deposit, area, or source rock	Grade of "ore" (percent)			Grade of magnetic concentrate (percent)			"Ore" resources (millions of tons[1])	Vanadium resources (thousands of tons V[1])	Geology									References
											Ore type				Host rock					
			Fe	TiO_2	V_2O_5	Fe	TiO_2	V_2O_5			Disseminations	Layers, lenses	Plugs, dikes	Massive	Gabbroic	Anorthositic	Alkalic	Mafic	Ultramafic	
U.S.S.R.																				
41	East Transbaikalia	Charskoe	18-41	.....	.....	.....	.....	.....	20	Small(?)	...	...	...	...	...	...	...	...	...	Sokolov (1970).
42	Kuznetsk-Sayan	Lysanovskoe	21	.....	.....	.....	.....	.....	1,200	Large(?)	...	...	...	...	...	...	...	...	...	Sokolov (1970).
43	Gorny Altay	Kharlovskoe	17	.....	.....	.....	.....	.....	900	Medium(?)	...	...	...	...	...	...	...	...	...	Sokolov (1970).
44	Ural	Yubryshkinskoe	27	.....	.....	.....	.....	.....	8,000	Large(?)	...	...	...	...	...	...	...	...	...	Sokolov (1970).
45	do	Mt. Kachkanar[2]	16-17	1.5	.10-.12	60	.66	3.3	13,000	7,000	×	...	...	...	...	...	...	×	×	Polyakov (1959), Bardin (1957), Zakharov (1964), Sokolav (1970).
46	do	Guseva Gora	17	.....	.....	.....	.....	.....	3,194	Large(?)	×	...	...	...	...	...	...	×	×	Myasnik and others (1966).
47	do	Pervoural'sk	16-35	3(?)	(?)-.4	.....	.....	.....	140	Medium(?)	×	...	...	...	...	...	...	×	×	Lawthers (1957), Polyakov (1959), Bardin (1957), Sokolov (1970).
48	do	Kusinskoe	48-51	13-14	.68	.....	.....	.95-1	3	12	×	...	...	...	...	...	...	×	×	Lawthers (1957), Polyakov (1959), Bardin (1957), Sokolov (1970).
49	do	Visean	.....	10.8	.73	.....	.....	.....	Large	Large(?)	...	...	...	...	...	...	...	×	...	Fominykh (1963).
50	Caucasus Minor	Svorantskoe	16	.....	.....	.....	.....	.....	800	Medium(?)	...	...	...	...	...	...	...	...	...	Sokolov (1970).
51	Karelo-Kola	Keyv intrusive	29-45	5-10	.15-.75	66-69	.....	1.1-1.4	Large(?)	Large(?)	×	×	...	...	...	...	...	×	...	Yudin and Zak (1970).
52	do	Tsagin	36	7	.26	58	.....	.5-.6	Large	Large(?)	×	×	...	...	×	×	...	...	...	Polyakov (1959), Kavardin (1906a, 1960b), Yudin and Zak (1970).
53	do	Afrikanda	11-18	8-18	Low	50-61	9	.11	Large(?)	Medium(?)	...	...	×	...	...	...	×	...	×	Yudin and Zak (1970).
54	do	Yelet'ozero	13-37	8-26	.13	58	.....	.6	Large(?)	Medium(?)	×	×	...	...	×	...	×	...	...	Yudin and Zak (1970).
55	do	Pudozhgarskoe	28	6.2	.4	52	.....	1.12	517	1,300	×	×	...	...	...	...	...	×	×	Bardin (1957), Polyakov (1959), Yudin and Zak (1970), Sokolov (1970).
56	do	Koykara	22-32	5.5-8.5	.25-.47	.....	.....	.....	300	Medium	...	×	...	...	×	...	...	...	...	Yudin and Zak (1970), Sokolov (1970).
Finland																				
57		Mustavaara	.....	.....	.....	.....	.....	.....	.....	Medium(?)	...	×	...	...	...	...	...	×	...	Mining Magazine (1972).
58	Kemijarvi	Otanmäki	40	12.3	.47	67	.....	1.05	50	130	...	×	...	...	...	...	...	×	...	Paarma (1954), Pääkkönen (1956), Outokumpu and Otanmäki Cos. (1960) Marelle (1970).
Sweden																				
59	Kvikkjokk	Routivare	55	11	.1	.....	.....	.....	33	18	...	×	...	...	...	×	...	...	...	Lawthers (1957).
60	Järvsö	Kramsta	25	5	.4	.....	.....	.....	27	56	...	×	...	...	×	...	...	...	...	Lawthers (1957).
61	Nordingrå	Ulvö	35	8	.5	.....	.....	.....	22	64	...	×	...	...	...	...	...	×	...	Lawthers (1957).
62	Småland	Taberg	32	6	.3	.....	.....	.....	165	280	...	•	×	...	...	...	...	×	...	Hjelmqvist (1950), Lawthers (1957).
Norway																				
63		Stjernöy-Seiland	.....	.....	.....	.....	.....	.1-1	Medium(?)	Medium(?)	×	...	×	...	...	...	...	×	×	Geis (1971).
64	Malselv	Hattevarre	.....	.....	.....	.....	.....	.56	1	10	...	×	...	...	...	...	...	×	...	Geis (1971).
65	Lofoten	Selvåg	35	4	.4	60	5	.7	20-44	50	×	×	...	...	×	...	...	...	...	Lawthers (1957), Marelle (1970), Geis (1971).
66	Möre	Solnör, etc	.....	.....	.....	.....	.....	.5-1.2	Medium(?)	Medium(?)	...	×	×	...	×	...	...	...	...	Geis (1971).
67	do	Rödsand	35	6	.5	62	2	.9	10	30	...	×	...	...	...	...	...	×	...	Lawthers (1957), Marelle (1970), Geis (1971).
68		Sogn	10–30	.5–50	.1–1	.....	.....	.....	Small(?)	Small(?)	×	×	...	...	×	×	...	...	...	Geis (1971).
69		Oslo	55	Low	.4	.....	.....	.....	Small(?)	Small(?)	...	×	...	...	×	...	...	...	...	Geis (1971).
70		Bamle	.....	.....	.8-.9	.....	.....	.....	Small(?)	Small(?)	...	×	...	...	×	...	...	...	...	Geis (1971).
71	Ergersund	Tellnes	.....	17.9	.....	65	.....	.....	300	Small(?)	...	...	×	...	...	×	...	...	...	Lawthers (1957), Geis (1971).
72	do	Storgangen	5	17	.14	65	43	.73	33	30	...	...	×	...	...	×	...	...	...	Lawthers (1957), Geis (1971).
Republic of Korea																				
73	Seoul	Soyonpyongdo	50	17	.4(?)	65	.....	.....	4	Small(?)	...	×	...	...	×	...	...	...	...	Gallagher and others (1962), Nishiwaki (1970).
74	Kyonggi	Porum-do	60	10	.15-.4	.....	.....	.....	1	Small	...	...	×	...	...	...	...	×	...	Gallagher (1963).
China (Mainland)																				
75	Hopei (Manchuria)	Luanping	53	11	.48	.....	.....	.....	6	15	...	×	...	...	×	...	...	...	...	U.S. Bureau Mines (1945), Muraoka (1953), Nishiwaki (1970).
76	Ssuchuan	Panchihua	20-45	10(?)	High	.....	.....	.....	650	Large(?)	...	...	...	...	...	...	...	×	...	Hsing (1959), Nishiwaki (1970).
India																				
77	West Bengal	Shaltora	.....	.....	.....	.....	.....	.....	.....	.....	...	...	...	...	...	×	...	...	...	Chakravarty, Roy, and Banerjee (1960).
78	Bihar and Orissa	Singhbhum-Mayurbhanj	47-57	14-25	.7-4.8	.....	.....	.....	20	200	...	×	×	...	×	×	...	...	...	Dunn (1942), Krishnan (1954), S. Roy (1954), B.C. Roy (1969), Mukherjee (1958), Nishiwaki (1970), Mining Journal (1971c).

79	Andhra Pradesh	Tiruvuru	55	14	1.7	.....	.....	.....	Medium(?)	Medium(?)	...	...	×	...	...	...	...	×	...	Bhimasankaram (1963).
80	Mysore		55-60	Up to 12	Some	.....	.....	.....	131	Medium(?)	...	×	...	...	...	...	...	...	×	Krishnan (1954).
Bulgaria																				
81	Strandzha Planina	Kosti	.....	6-7	.56-.63	.....	.....	.....	.....	.....	×	...	...	...	×	...	...	...	...	Vasilev and Stanisheva (1963).
Hungary																				
82		Bukk Mountains	.....	.....	.....	.....	.....	.....	.....	.....	...	×	...	...	×	...	...	...	...	Lengyel (1961).
83		Szorvaskő	.....	Up to 25	.09-.17	.....	.....	.....	.....	.....	...	×	...	...	...	...	...	...	×	Lengyel (1957).
Spanish Sahara																				
84	Río de Oro	Agracha	54	14	.....	.....	.....	.....	150	.....	...	...	...	...	...	...	...	...	...	Marelle and Abdulla (1970).
Upper Volta																				
85	Dori	Tin Edia	58	12	.6	.....	.....	.....	50	150	...	...	...	×	×	...	...	...	...	Marelle and Abdulla (1970).
Uganda																				
86	Bugisu	Sukulu	62	.....	.....	.....	.....	.....	45	.....	×	...	...	...	...	...	×	...	...	Barnes (1961), Baldock (1969), Marelle and Abdulla (1970).
87	do	Bukusu	.....	10-20	.....	.....	.....	.....	23	.....	...	×	...	...	...	...	×	...	...	Barnes (1961), Baldock (1969), Marelle and Abdulla (1970).
Tanzania																				
88	Uluguru Mountains	Hundusi	40	8±	.....	.....	.....	.....	8	.....	×	×	...	...	...	×	...	...	...	Harris (1961), Marelle and Abdulla (1970).
89	Eastern Upangwa	Liganga	49	13	.67	.....	.....	.....	45	160	...	×	×	...	×	×	...	...	...	Carter (1960), Harris (1961).
Angola																				
90	Luando	M'Bassa	56-60	5	.....	.....	.....	.....	6	.....	...	×	...	...	...	...	...	...	...	Marelle and Abdulla (1970).
91		Gambos, Chiange, and Chitado	48±	25±	.....	.....	.....	.....	.....	.....	...	...	...	×	...	...	...	...	...	Marelle and Abdulla (1970).
Mozambique																				
92	Tete	Muande, Machedua, Massamba, Inhantipissa, and Txizita	50±	20±	.6	.....	.....	.....	250	800	...	...	...	×	...	×	...	...	...	Marelle and Abdulla (1970), Putzer (1970).
Namibia (South-West Africa)																				
93		Orkorusa	.....	.....	.....	.....	.....	.....	40	.....	...	...	...	...	...	...	...	...	...	Marelle and Abdulla (1970).
South Africa																				
94	Transvaal	Rooiwater Complex	.....	.....	.....	.....	.....	.....	.....	.....	...	...	...	...	...	...	...	...	...	South Africa Geological Survey (1959).
95	do	Bushveld Complex	42-60	14-20	1.5-1.7	.....	.....	.....	2,000	17,000	...	×	×	...	...	...	...	×	×	Nel and Luyt (1964), Willemse (1969), Marelle and Abdulla, (1970).
96	do	Piet Retief	30-39	.....	.....	.....	.....	.....	5	.....	...	×	...	...	×	...	...	...	...	South Africa Geological Survey (1959).
97	Natal	Tugela River	42-54	9-19	.....	.....	.....	.....	15	.....	...	×	...	...	×	×	...	...	...	Wagner (1928), Lawthers (1957).
Australia																				
98	Western Australia	Jameson Range	48	20±	.57-2.4	.....	.....	.....	100	Medium	...	×	...	...	...	...	...	×	×	Mining Journal (1967), Daniels (1967).
99	do	Balla Balla	.....	.....	.75	.....	.....	.....	[2]2	[2]6	...	×	...	...	×	...	...	...	...	Jones (1965).
100	do	Andover	51	18	.92	.....	.....	.....	[3]3	[3]15	...	×	...	...	...	...	...	×	×	Connolly (1959), Jones (1965).
101	do	Gabaninthe-Yarrabudda	60±	15.7	.9-1.3	.....	.....	.....	6	45	...	×	...	...	...	...	...	×	×	Gardner (1951), Jones (1965), Western Australia Department of Mines (1966).
102	do	Barrambie	.....	.....	.4-.5	60	.....	.6-.7	[4]240	[4]600	...	×	...	...	×	...	...	...	...	Rausch (1971), Pratt (1971), Mining Journal (1971a).
103	do	Southern Cross	.....	.....	.....	.....	.....	.....	.....	.....	...	...	...	...	...	...	...	...	...	Mining World (1961, 1962).
104	do	Wundowie	.....	.....	.47-.65	.....	.....	2	40+	140	...	×	...	...	×	...	...	...	...	Western Australia Department of Mines (1966), Hudson (1967), Mining Journal (1971b).
New Zealand																				
105	South Island	Doubtful Sound	.....	.....	.....	.....	.....	.....	50	.....	...	...	...	...	×	...	...	...	...	Engineering and Mining Journal (1971).

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[1]Many source reports do not designate whether the tonnage figures are in "short," "long," or "metric" tons. Furthermore, most tonnages are estimated and the figures are rounded, and generally they are considered to indicate only orders of magnitude; the inaccuracies of the figures are judged to be greater than the differences among these units, hence the kind of tons is not specified.

[2]Estimated only to a depth of 15 ft (4.5 m).

[3]Estimated only to a depth of 75 ft (23 m).

[4]Estimated only to a depth of 100 ft (30 m).

Ore grades in the titaniferous magnetite deposits from which vanadium is being recovered vary widely: 16-60 percent Fe, 1.5-38 percent TiO_2, and 0.1-2 percent V_2O_5. This wide range indicates that technologically it is possible to obtain vanadium from all or almost all of the deposits listed in table 1. Other factors—such as economics, mining technology, and politics—also influence the successful exploitation of a mineral deposit, and generally these factors cannot be appraised for the deposits listed on the basis of published information. Nevertheless, it is obvious that the titaniferous magnetite deposits contain enormous vanadium resources, representing thousands of years' supply at the current rate of world consumption, about 25,000 short tons of vanadium yearly. Titaniferous magnetite deposits will continue to be the principal source of vanadium, unless the economics and technology of recovery of vanadium from petroleum and petroleum products (Fischer, 1973b) favor this possible alternative source in the future.

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