

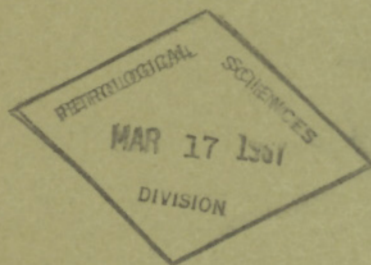
GEOLOGICAL
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VANADIUM OCCURRENCES IN CANADA

(Report and 1 figure)

E. R. Rose



GEOLOGICAL SURVEY
OF CANADA

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DEPARTMENT OF ENERGY, MINES AND RESOURCES

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ABSTRACT

The general nature of vanadium, its uses, occurrences, and types of occurrence are outlined. Methods of identification and a field chemical test for vanadium are described. By means of the latter it has been shown that vanadium is of more widespread occurrence in Canadian rocks than hitherto recognized. The world outlook for vanadium is summarized, and potential sources of vanadium are described by provinces and territories.

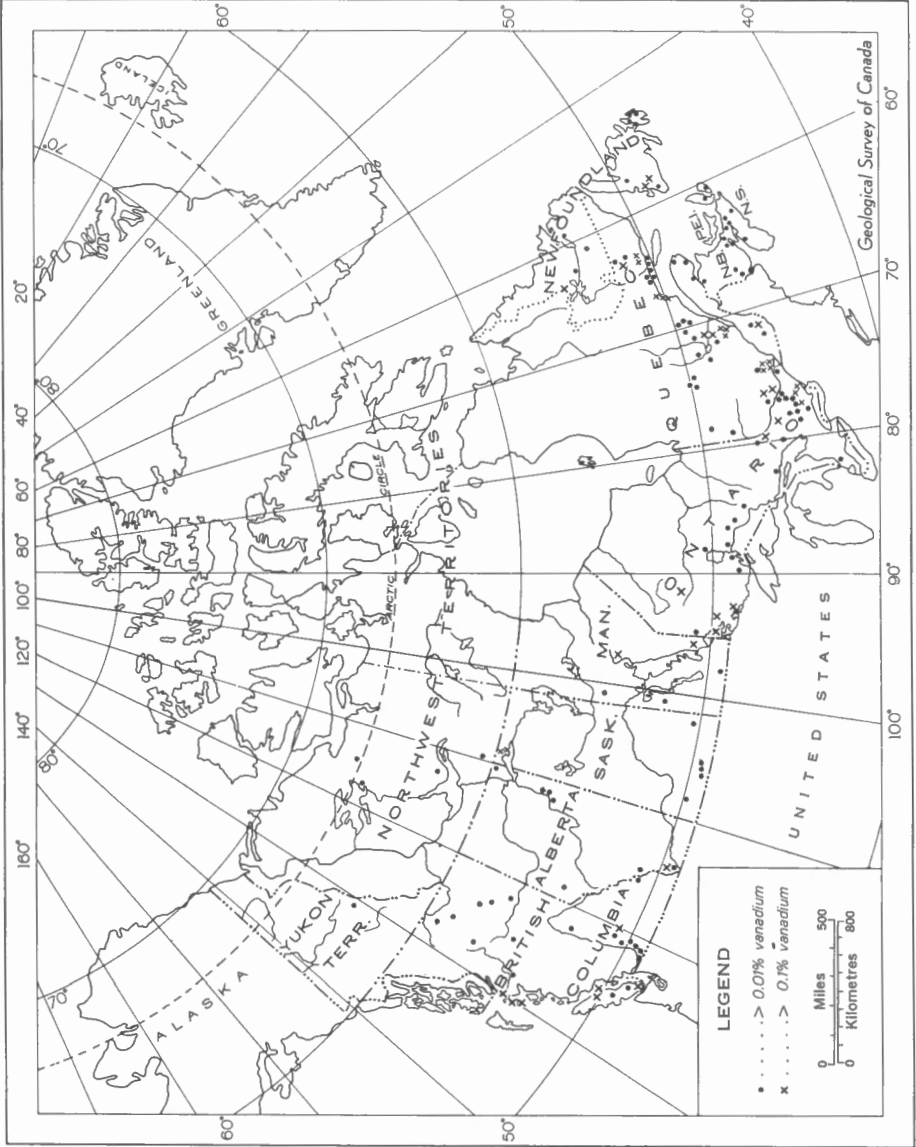


Figure 1. Distribution of vanadium occurrences in Canada.

VANADIUM OCCURRENCES IN CANADA

(Preliminary Report)

INTRODUCTION

Minor occurrences of vanadium in Canada have been known for many years, being found principally in cupriferous beds on Quadra Island, British Columbia (in 1932), in uranium-bearing veins of the Beaverlodge area in Saskatchewan (in 1950), in titaniferous magnetite bodies south of Mine Centre, Ontario (in 1919), south of Mattawa, Ontario (in 1942), and east of St. Georges, Newfoundland (in 1942). However, no vanadium has yet been produced commercially from any deposit in Canada.

Three seasons field work and other investigations by the writer have indicated that vanadium is of more common occurrence than hitherto recognized in Canada, and the number and variety of known occurrences have been greatly increased (Fig. 1). Including the three types noted above, vanadium was commonly found in the following associations, with: (1) titanium, iron, manganese, and chromium; (2) uranium and thorium; (3) copper (lead and zinc); (4) bitumens, carbon, hydrocarbons, organic complexes; and (5) phosphates. In general vanadium was detected across Canada in many samples of: (a) basic igneous rock (intrusive and extrusive); (b) light to dark grey shale, slate, greywacke, and sandstone; (c) light to dark red or violet argillite, shale, and sandstone; (d) yellow stained shale, slate, and sandstone; (e) reddish stained arkose; (f) dark phosphate rock; (g) lignite; (h) oil shale, bituminous sandstone (tar sands) and asphaltite; in formations that range in age from Precambrian to Recent.

The prospects of finding more extensive and higher grade vanadium deposits in Canada appear to be good, and the outlook for this rare strategic metal is promising. Many leading vanadium producers in the United States are now seeking new supplies both within and without the country (see Busch, 1962; and De Huff, 1965).

Canada is currently importing about 400,000 pounds of vanadium per year, mainly in the form of ferrovanadium, and an attempt to meet the demand is being made by Canadian Petrofina Limited by producing vanadium pentoxide (V_2O_5) as a by-product from its crude oil refinery near Point aux Trembles (Montreal). All of this suggests that vanadium ores may find a market and that prospecting for ores of this rare metal in Canada should be encouraged.

Of particular importance in this regard in Canada are deposits of titaniferous magnetite (Rose, 1963) that are commonly associated with mafic and alkalic intrusions and volcanic rocks. Many magnetic concentrates from titaniferous magnetites are known to carry from 0.1 to 0.5 per cent or more of vanadium (Rose, in prep.). Vanadium is recovered from titaniferous magnetite on an increasing scale both in Finland and South Africa.

The association of vanadium with the pitchblende-bearing uranium ores of the Beaverlodge area in northern Saskatchewan, and with the uranium-vanadium sandstone ores of the western United States, suggests not

only that other uranium occurrences in Canada should be investigated for vanadium, but that uranium-vanadium sandstones and shales should be expected in the sedimentary basins of the Great Plains and Cordillera of western Canada (see also Roscoe, 1966), and possibly also in Arctic and eastern Canada.

Concentrations of vanadium associated with both copper and hydrocarbons in basic volcanic rocks and intercalated sedimentary lenses of Triassic age have been noted on Quadra Island and northern Vancouver Island, British Columbia. These rocks carry more than 0.1 per cent vanadium and 0.5 copper in many places, and these, as well as other large areas of Triassic volcanic rocks of British Columbia, are considered to be favourable for prospecting where sediments are intercalated with the flows. Dark grey slate of Mesozoic (?) age in the Prince Rupert area of British Columbia carries 0.5 per cent vanadium in places, and rocks of this type merit attention.

In eastern Canada, some of the manganiferous beds of Cambrian age in Newfoundland, the oolitic hematite beds of Wabana, Newfoundland, and Torbrook, Nova Scotia as well as copper and carbon-bearing sandstones of Carboniferous age, have shown traces of vanadium at numerous localities in New Brunswick, Nova Scotia, and Newfoundland. They should be considered as favourable ground for the occurrence of vanadium.

In central Canada red beds of the Sibley Series (Animikian ?) carry faintly radioactive nodules and they are in part cupriferous and vanadiferous both in the nodules and matrix. Samples of Precambrian greywacke near Spanish, Ontario, and of basal Palaeozoic sandstone and arkoses near Elgin, Ontario, are notably vanadiferous and deserve particular attention.

Certain types of asphalts and heavy oils such as the Venezuelan crude carry about 0.013 per cent vanadium as well as other metals such as uranium, nickel, and molybdenum. The association of vanadium with petroleum and bitumen shown in asphaltites of Peru, Argentina, and elsewhere, and in oil shales such as those in Colorado and Wyoming (see Krauskopf, 1955; Hodgson et al., 1963), has been confirmed by the writer in oil shale from the Humber Valley, Newfoundland, in the oil shales and albertite of Albert Mines, New Brunswick, in dark shales at Kettle Point, Ontario, and Swan River, Manitoba, and in the bituminous Athabasca tar sands of northern Alberta, all of which appear to carry from 0.016 to 0.05 per cent vanadium, i.e. slightly more than Venezuelan crude oil.

Certain lignites are known to be more strongly uraniferous (Denson, 1956) as in North Dakota, than those in Canada (Chamberlain, 1960; Lang, et al. 1962), and samples of lignite and soft coal from western Canada tested by the writer have generally shown both uranium and vanadium, but commonly less than 0.1 per cent vanadium and less than 0.01 per cent uranium. A sample of dark carbonaceous shale associated with lignite lenses in yellow stained conglomeratic Cretaceous sandstone south of Nanaimo, British Columbia, showed a trace of vanadium, as did another of soft coal from New Glasgow, Nova Scotia. Lignite, coal, and carbonaceous material may act both as carriers and as precipitating agents of vanadium and uranium as well as of other metals.

An increasing amount of vanadium is being recovered in the United States as a by-product of the mining and processing of phosphate rock. Dark beds of oolitic phosphorite of the Permian Phosphoria Formation near Soda Springs, Idaho, average from 0.05 to 0.15 per cent vanadium, and from 8 to 12 per cent phosphorus. The associated black shales in places have as much as 0.75 to 1.25 per cent vanadium. Occurrences of phosphate rock, which are in part extensions of the Phosphoria Formation into western Canada, have been found in southern Alberta and British Columbia, but not as yet in commercial quantities and grade (Telfer, 1933). However, prospecting for vanadiferous phosphate rock in western Canada should be encouraged, as well as for other vanadium-bearing, grey to black or maroon shales, sandstones, and other sedimentary rocks, which may be comparable to the uranium-vanadium bearing rocks and ores of Mesozoic age that have been found in the western United States.

General Information on Vanadium

Vanadium is a hard lustrous steel-grey metal, of high melting point ($1900^{\circ} \pm 25^{\circ}\text{C}$)¹ and good resistance to salt-water corrosion. It is used mainly as an alloy and purifying agent in the manufacture of tough steel, stainless steel, high-speed tool and cutting steels, and recently in structural steel, to which it is usually added as a form of ferrovanadium. It is also used as an alloy with other elements such as aluminum, chromium, nickel, manganese, tungsten, boron, and titanium. One of the most recent alloy developments is in the field of titanium-base vanadium alloys now being used in modern aircraft and spacecraft. Vanadium catalysts are important in the production of sulphuric acid and in the refining of petroleum, and they may also find application in the control of the automobile exhaust-smog problem.

Vanadium is a toxic member of the ferride group of elements. Although it forms an estimated 0.011 per cent by weight of the earth's crust, and is the nineteenth element in order of abundance, it is generally widely dispersed and is seldom found in large or concentrated deposits. Its ore deposits generally carry less than 2 per cent of the metal, and are mineable down to grades of slightly less than 1 per cent. In by-product recovery of vanadium the ore materials may average less than 0.1 per cent vanadium.

The most important vanadium ore minerals in the past have been: (a) patronite (a rare black complex vanadium sulphide found in asphaltic veins in red Cretaceous shale in the Peruvian Andes); (b) roscoelite (vanadian mica), vanadiferous hydromica, and vanadium-bearing clay minerals (light to dark grey flakes in the interstices of grey to violet Mesozoic sandstones in the Colorado Plateau and the western United States); (c) carnotite-tyuyamunite and other uranium-vanadium bearing minerals (bright yellow, orange, brown, red, green, and blue-black, secondary hydrous minerals associated with the surface and oxidized parts of the sandstone ores in the Colorado Plateau); (d) mottramite-descloizite-vanadinite (orange-brown crystals in the oxidized zones of lead-zinc-copper deposits in South Africa and elsewhere); and more recently, (f) titaniferous magnetite associated with large bodies of mafic

¹ According to Deardorff et al.; U.S. Bur. Mines R.I. 6594 (1965); and somewhat higher than the normally accepted value of about 1700°C .

igneous rock (in Finland and South Africa). Vanadium is also recovered from the ash of certain crude oils and lignites, from vanadiferous iron ores, slags, and chromite, from the processing of dark phosphate rock (phosphorite) of the Phosphoria Formation in the western United States, and, in a new development, from certain laterites in the southeastern United States. During World War II, as a strategic metal in very great demand, vanadium was recovered also from the soot from the boilers and stacks of the oil-burning ships of North America.

Identification of Vanadium Minerals and Ores

Vanadium occurs naturally in at least three states of oxidation (3, 4, 5), and unites with oxygen and hydrogen, and more rarely with sulphur, to form a multi-coloured variety of minerals. It substitutes for the ferride elements iron, titanium, chromium, and manganese, and combines with calcium, potassium, uranium, thorium, copper, lead, zinc, bismuth, arsenic, phosphorus, and carbon, to form many other rare minerals of a complex chemical composition. It may substitute for magnesium, iron, and aluminum in the formation of chlorophyll-like hydrocarbon molecules and porphyrins in oil, bitumen, asphalt, and other organic substances. It may be adsorbed by finely comminuted or colloidal clay minerals, and also incorporated in their structure as well as in that of the vanadiferous secondary micas, hydromicas, and clay minerals. It may perhaps also substitute for iron and magnesium in the structures of chlorite, biotite, hornblende, and pyroxene, and is a constituent of the rare member of the manganese-bearing, epidote-zoisite group, known as ardenmite.

Table I illustrates the manner of occurrence of the main vanadium ore minerals. Most of these minerals and ores are difficult to detect or identify as many of them are inconspicuously grey-black or brownish red and visually indistinguishable from the ubiquitous iron oxides. The presence of bright yellow, greenish yellow, and orange-coloured secondary powders on weathered surfaces is strongly suggestive of the presence of vanadium and/or uranium, but is not an infallible guide. Some of the hydrated oxides of vanadium such as rossite, navajosite, doloresite, duttonite, fervantite, and haggite are of brownish colour similar to limonite, and a few of the vanadates such as hewettite, meta-hewettite, rauvite, and pucherite have the appearance of earthy red hematite. Other hydrated oxides such as montroseite, vanoxite, and corvusite, and the sulphide, patronite, are soft and black. Nolanite and vanadiferous magnetite ("coulsonite") are hard and black. Roscoelite and vanadiferous hydromicas and clays are commonly pale grey-green to grey-brown and are almost impossible to identify visually. Fortunately vanadium may be detected by a simple chemical test in the field and in some places it also occurs in association with uranium, which may be detected by its radioactivity.

Chemical Field Tests For Vanadium

Hydrogen Peroxide Test

In its simplest form the hydrogen peroxide test may be made as follows: dissolve a small amount of the powdered rock or mineral in nitric

TABLE I
Principal Vanadium Ore Minerals, Their Occurrence and Properties¹

Group	Name	Composition	Locality	Occurrence	Properties
Sulphides	PATRONITE	Complex vanadium sulphide	Minas Ragra, Peru	In asphaltic veins in Cretaceous shale	Pitchy
	Cobaltite	Base metal, vanadium, sulphide	Butte, Montana	In copper ores	Grey-brown metallic
	Sulvanite	$3Cu_2S \cdot V_2S_5$	Burra Burra, Australia; Utah	In oxidized shale and quartz veins	Bronze cubic crystals
Oxides	TITANOMAGNETITE	$Fe(Ti, V)_3O_4$	Finland, South Africa	In basic intrusions	Hard, magnetic
	"Coulsonite"	$(Fe, Ti, V)_3O_4$	India	In titaniferous magnetite	Rare, "
	Navajoite	Hydrous vanadium oxides	Colorado Plateau	In oxidized zones of Mesozoic sandstone	Soft, yellow brown
	Montroseite	" "	" "	" "	Soft, brown
Hydrous oxides	Vanoxite	" "	" "	" "	Brown-black
	CORVUSITE	" "	" "	" "	Blue-black
Vanadates	Volborthite	$(Cu, Ba, Ca)O \cdot V_2O_5 \cdot 15H_2O$	U.S., Russia	With copper minerals	Yellow to green
	Finadoite	$2CaO \cdot V_2O_5 \cdot 9H_2O$	Colorado, Peru	With patronite and sandstone	Green
	CARNOTITE	$K_2O \cdot 2UO_3 \cdot V_2O_5 \cdot 4H_2O$	Colorado	In oxidized U-V sandstone ores	Yellow
	Tyuyamunite	$CaO \cdot 2UO_3 \cdot V_2O_5 \cdot 4H_2O$	" "	" "	" "
	Pascoite	$2CaO \cdot 3V_2O_5 \cdot 4H_2O$	" "	" "	Orange
	HEWLETTITE	$CaO \cdot 3V_2O_5 \cdot 9H_2O$	" "	" "	Red-brown
	(Metawanerite)	$(Cu, Zn)PbVO_4 \cdot OH$	Rhodesia, Africa	Capping Cu-Pb-Zn deposits	Yellow to red
	MOTIKAMITE - DESCLOIZITE	$(Zn, Cu, Pb)_4V_2O_5 \cdot H_2O$	" "	" "	" "
	Cuprescolozite	$(Cu, Zn)O \cdot (V, As)_2O_3 \cdot H_2O$	Arizona, South Africa	With Ag-Pb-Mo and Cu-Pb-Zn ores	Green-brown
	Brackebuschite	$(Pb, Mn, Fe)_2V_2O_8 \cdot H_2O$	Argentina	Capping " "	Brownish black crystals
	NOLANINITE	$Pb_4(VO_4)_3 \cdot P_2O_8 \cdot H_2O$	Rhodesia	" "	Yellow to red crystals
	Nolanite	$3FeO \cdot V_2O_3 \cdot 3V_2O_4$	Beaveridge, Saskatchewan	With hydrothermal pitchblende	Hard, black
Silicates	ROSCOEITE	$2K_2O \cdot 2Al_2O_3 \cdot (Mg, Fe)3V_2O_5 \cdot 10SiO_2 \cdot 4H_2O$	Colorado Plateau	Flake mica in sandstone	Grey-green brown
	Hydromica and clay	" "	" "	Secondary flakes in matrix	Grey to black
Sulphates	MINASRAGRITE	$V_2O_4 \cdot 3SO_3 \cdot 16H_2O$	Peru	Alteration of patronite	Granular, blue
	PHOSPHORITE ² , Apatite	$Ca_3(P, V)PO_3 \cdot 4CaV_2O_7(PO_4)_2 \cdot 5H_2O$	Idaho Peru, Colorado Plateau	In Permian phosphorite	Dark, oolitic Soft, green

¹See Hambley, C.A. (1961); Rare Metals Handbook, 2nd ed; for complete lists of vanadium minerals and their properties.

²Phosphat rock.

acid or aqua regia, evaporate to dryness, add as much water as original acid, and then a few drops of hydrogen peroxide. The presence of vanadium is indicated if the solution turns an orange colour.

In order to insure a more complete solution of the vanadium in unknown and refractory minerals such as titaniferous magnetite and chromite, they should be first fused with potassium pyrosulphate, soda, or salt. The method suggested is as follows: a measured amount of finely powdered sample (25 mgm. scoop) is mixed with potassium pyrosulphate ($K_2S_2O_6$) and heated on charcoal. The powdered fusion product is dissolved by heating in 1:1 nitric acid (HNO_3) in a test tube; the resulting solution is filtered, cooled, and a measured amount of the filtered solution is mixed with an equal volume of water, either in a test tube or on a spot plate. A few drops of 1 per cent hydrogen peroxide (H_2O_2) are added, and the presence of vanadium is revealed by the formation of a pale orange solution, the colour of which deepens to brown with increasing percentage of vanadium in the solution. The test is not entirely satisfactory, particularly for brown coloured organic and some ferruginous solutions, which mask the colour, and this must be overcome by filtration and dilution. The yellow-coloured solutions yielded by tungsten and molybdenum in this test are similar to the amber of faint vanadium tests, so other tests for tungsten and molybdenum should be made when there is doubt. The hydrogen peroxide test is sensitive and will generally detect less than 0.01 per cent vanadium, i.e. much less than ore grade material.

Reference is also made to the more elaborate chemical tests for vanadium given by Hawkes (1957) and by Ward et al. (1963). These tests require more equipment and chemicals than does the one described above.

World Outlook

The chief vanadium ore producing countries in the past have been Peru, South West Africa, Rhodesia, and the United States. Since 1940 world vanadium production has been dominated by that of the United States, but significant production is now developing in South Africa and Finland, whereas that in Peru and Rhodesia has declined. Both the production and export of vanadium and vanadium oxide from the United States have declined somewhat since 1961, and legislation was passed there in 1963 to permit vanadium ore and concentrates to enter the United States duty free. Vanadium is classified in the United States as a strategic and critical material, and is held in the national stockpile.

World vanadium production has been on the increase, particularly during the past fifteen years, and is now of the order of about 10,000 tons of the metal per year. It seems unlikely that this well-established trend will change significantly in the near future, but because of the relatively limited world market for vanadium it would be possible for a few new large-scale producers to change the picture to one of over-production. However, new and emerging uses for vanadium suggest that such a situation would be temporary. Moreover, as high-grade deposits of vanadium are rarely found, it seems likely that future large-scale developments will come from low-grade and by-product sources.

TABLE II

Classification of Vanadium Occurrences in Canada ^{x, xx}

Geological Process	Occurrence	Host Rocks	Examples
1. Magmatic concentration	Titaniferous magnetite	Gabbro-anorthosite, Fe ^{xxx}	Mine Centre, Ontario
(a) Intrusion	Titaniferous magnetite dyke	Gabbro-anorthosite, Palaeocene	East Sooke, B. C.
(b) Extrusion	Vanadiferous silicates, titaniferous magnetite	Gabbro-anorthosite, Fe Andesite-basalt, Triassic	Magpie Mountain, Quebec Quadra Island, B. C.
2. Replacement and fissure filling	Nolanite and pitchblende Patronite and asphalt	Veins in metasediments, Fe Veins in red shale, Cretaceous	Fish Hook Bay, Sask. Minas Ragra, Peru, no example known in Canada
3. Sedimentation and secondary enrichment	Vanadium silicates, oxides, hydroxides and vanadates	Clastic sediments, sandstones, shales, greywacke, Fe to Mesozoic	Spanish and Elgin, Ontario Colorado Plateau, U.S.A.
4. Sedimentation and biochemical enrichment	Oolitic hematite Manganiferous nodules	Shale and sandstone, Ordovician Dark shale, Cambrian	Wabana, Newfoundland Avalon Peninsula, Newfoundland.
5. Sedimentation, replacement and secondary enrichment	Vanadates, silicates, volborthite, etc. Uraniferous nodules	Cu-C bearing siltstone and limestone in andesite-basalt, Triassic Red sandstone, argillite, Fe	Menzies Bay, Vancouver Island, B. C. Nipigon, Ontario
6. Sedimentation, organic, secondary, and biochemical concentration	Vanadiferous bitumen, lignite, organic shale, phosphorite	Sandstone, shale, oil shale, phosphate rock, Mesozoic-Palaeozoic	Athabasca tar sands, Alta. Phosphoria Fm., Alta. Soft coal, New Glasgow, N. S.
7. Mechanical concentration, clastic sedimentation	Titaniferous magnetite in black sands and sandstone	Sandstone, Cretaceous; unconsolidated beach sands, Recent	Burmis-Dungarvan, Alta. Northshore St. Lawrence R., Quebec.
8. Metamorphism	Chlorite, graphite, etc.	Altered mafic rocks, crystalline limestone, greenstone, Fe	Timagami, Ontario
9. Sublimation	Vanadium pentoxide (V ₂ O ₅) crystals	Fumerole vent in intermediate lavas, Recent	El Salvador, Central America, no example known in Canada
10. Oxidation and supergene enrichment	Vanadates	Oxidized, deeply weathered Pb-Zn-Cu-Mo deposits	Arizona, Mexico, Africa; Gataga gossan(?), B. C.
11. Residual concentration	Bauxite, laterite, weathered mafic rock	Deeply weathered mafic rocks Recent	Hawaii, Arkansas, Veuve River, Ontario

^x Deposits of types 1-4, 6 and 10 have been important producers of vanadium in countries other than Canada prior to 1967.

^{xx} The origin of many of the occurrences is more complex than indicated.

^{xxx} Fe indicates Precambrian

A price of 31 cents per pound of contained V_2O_5 is quoted for domestic vanadium ore, and of about \$1.00 to \$1.25 per pound for technical grade V_2O_5 (E. & M. J. Metal and Mineral Markets, 1965). The price of ferrovanadium declined in 1964 to about \$2.50 per pound of contained vanadium, making it more competitive with other alloying elements, but it is now quoted (idem., vol. 37, no. 44, 1966) at from \$2.83 to \$3.75 per pound, depending on purity. Vanadium metal of 90 per cent purity is quoted at about \$3.45 per pound (idem., vol. 37, no. 22, 1966), and high-purity vanadium metal has sold for \$30.00 to \$40.00 per pound since 1954 (DeHuff, 1965).

Acknowledgments

The writer is indebted to the officers of many mining, milling, and exploration companies in both the United States and Canada for unstinted assistance in the provision of information on vanadium and vanadium occurrences. The cooperation and assistance during the project of many colleagues in the Geological Survey of Canada was generously given and was of great help in many ways, both in reaching isolated occurrences and in discussions of geological settings and problems. John Lynch of the Survey's Geochemistry Section was most helpful with advice on field chemical tests for vanadium. John Jambor of the Survey's Mineralogy Section kindly made a copy of his unpublished thesis (1960) available to the writer. The cooperation of officers of many of the provincial Departments of Mines, and of the federal Mineral Resources Division and Mines Branch is also acknowledged with gratitude.

Precise analytical results given in the report except where otherwise indicated are from semi-quantitative spectrographic analyses made by H.W. Champ and the late W.F. White, of the Geological Survey's Spectrographic Laboratory. Less precise results are estimations based on the writer's qualitative chemical tests for vanadium.

DESCRIPTION OF OCCURRENCES

Northwest Territories

Traces of vanadium were reported by A.W. Jolliffe (1936) in analyses of titaniferous magnetite within an intrusion of gabbro near François Lake, and by C.H. Smith (1962) in chromite associated with the layered ultramafic Muskox intrusive complex of the Coppermine River area. No occurrences of vanadium have as yet been reported in the Arctic Islands.

Yukon Territory

Traces of vanadium have been noted in spectrographic analyses of certain dark shales in the Yukon (personal communication from L.B. Gatenby of Rio Tinto Canadian Exploration Limited, Vancouver office). Twenty-two samples of dark Palaeozoic shales submitted by H. Gabrielse from an area near Watson Lake in northern British Columbia and the Yukon were tested by the writer and these all showed from 0.01 to 0.1 per cent of vanadium, and all were faintly radioactive.

British Columbia

Traces of vanadium were noted by the writer in chemical tests in the field at numerous localities in British Columbia in a variety of rocks and minerals of diverse origin and age. The best known occurrences are those associated with cupriferous Triassic lava flows and intercalated carbonaceous sediments a mile north of Gowland Harbour on Quadra Island (Ellsworth, 1932; Ellsworth and Gunning, 1933; Gunning and Carlisle, 1944), and 11 miles north of Campbell River near Menzies Bay on Vancouver Island (Jambor, 1960).

Titaniferous magnetite associated with gabbro and anorthosite near East Sooke on the southwest tip of Vancouver Island was sampled with the assistance of D.L. Carson, and found to be vanadiferous. Two samples of magnetite from Cherry Bluffs west of Kamloops, submitted by E.D. Kindle, were both found to be vanadiferous as well as titaniferous. Titaniferous amphibolite and magnetite occurrences that were reported by J.J. McDougall (1961) on Banks and Porcher Islands of the coastal islands south of Prince Rupert were examined with helicopter aid from J.A. Roddick. The titaniferous magnetite occurrences were found to be associated with coarse-grained stratiform intrusions of anorthositic hornblende gabbro, and both titaniferous magnetite and hornblende-rich gabbro were found to be vanadiferous, ranging from 0.02 to 1.5 per cent vanadium and from 0.5 to 5 per cent titanium. From Banks Island three samples of host rock showed from 1 to 2 per cent titanium, and from 0.04 to 0.15 per cent vanadium; four samples of magnetite-rich material showed from 3 to 5 per cent titanium, and from 0.29 to 0.5 per cent or more vanadium; four magnetic concentrates made from these materials showed from 1.5 to 5 per cent titanium, and from 0.5 to 1 per cent or more vanadium. From Porcher Island three samples of host rock showed from 0.5 to 1.2 per cent titanium, and from 0.02 to 0.04 per cent vanadium; four samples of magnetite-rich material showed from 0.7 to 2.3 per cent titanium, and from 0.03 to 0.21 per cent vanadium; four magnetic concentrates made from these materials showed from 0.3 to 3 per cent titanium, and from 0.2 to 0.5 per cent or more vanadium. Titaniferous magnetite occurrences on McCauley Island are also believed to be similar.

Samples of dark slate and schist of extensive outcrop immediately south of Prince Rupert were also found to be vanadiferous, carrying about 0.5 per cent vanadium in one place. Very faint traces of vanadium were detected in samples of dark shale and in an associated porous, orange-red, recently formed, limonite-goethite gossan that partly covers a steep mountainside slope, near the headwaters of Gataga River in northern British Columbia. Specimens of a rare copper-vanadium sulphide mineral, sulvanite ($3\text{Cu}_2\text{S} \cdot \text{V}_2\text{S}_5$) were discovered by J.J. McDougall of Falconbridge Nickel Mines Limited in this locality in 1957 and were subsequently identified by R. M. Thompson of the University of British Columbia (McDougall, 1958). The gossan is unusually rich in iron, lead, and zinc, according to Falconbridge analyses. The shale there is believed to be of Ordovician age, an extension along strike from the northwest of a sedimentary series in Kechika map-area (H. Gabrielse, 1960). The shale is underlain by quartzite and overlain by grey dolomitic limestone. Gabrielse (personal communication) reports that small areas of gossan are commonly developed on the shale elsewhere, and that most of these gossans appear to have been formed close to their source. For example, near Deadwood Lake he noted a gossan, which was investigated by drilling (Consolidated Mining and Smelting Company) and was found to be

underlain by a system of weathered veins in the shale carrying marcasite, pyrite, sphalerite, galena, and barite. The gossan near the headwaters of Gataga River is unusual in its size, thickness, and degree of enrichment, however, and, if it was formed in situ would suggest the existence of a ferruginous base-metal zone or vein system in the shale immediately underlying the gossan capping. The Gataga gossan appears to be thickest and best developed on small terraces on the mountain slope, where it has accumulated in rough layers and crusts formed both by chemical and mechanical action. In places pieces of shale, pre-existing gossan, and small bits of organic material, such as twigs, cones, and needles from the present forest cover, are cemented in freshly deposited layers of limonite-geothite. In this there is evidence that there has been some migration and redistribution of the gossan, and as no indigenous limonite is visible, it seems likely that the gossan has been at least partly removed from its bedrock source. However, since it occurs on a steep slope rather than in the valley bottom and lake bed below, it seems probable that it is not far removed, but has mushroomed from its source. Although the base-metal content of the gossan gives some promise for an associated lead-zinc occurrence, the vanadium content appears to be too low except possibly for by-product recovery. The association of vanadium with lead and zinc, however, has previously been noted in large deposits in Rhodesia, South-West Africa, Arizona, and Mexico, as well as in dolomitic limestone in other parts of the world, and its possible importance should be mentioned here.

Graphitic shale and schist that form part of the Sicker Group of Carboniferous age east of Hope show faint traces of vanadium, when tested chemically, as did certain beds of grey to black, yellowish and mauve sandstone of Cretaceous age in the Nicola and Thompson River valleys near Spence's Bridge, and on Vancouver Island, near Cumberland and Nanaimo. Thick sections of interbedded black nodular shale and dark sandstone of Early Cretaceous age exposed along the Alaska Highway on the Sikanni Chief River, where they are flat-lying, and north of Fort Nelson, where they are vertical, also carry faint traces of vanadium, with a slight concentration in places in some of the cherty black nodules. A trace of vanadium was also detected in almost flat-lying columnar basalt of Tertiary age near Quesnel, and in grey shale on the Skeena River near Terrace.

In addition, vanadium has been noted in analyses of heavy minerals in placer gold concentrates from the McConnell Creek area (Lord, 1948), and from a tin-bearing manganiferous rhodonite vein that cuts metamorphosed sedimentary rocks of the Cache Creek Formation in the Tsitsutl Mountains south of Takla Lake (Armstrong, 1949).

Alberta

Faint traces of vanadium were found in samples of flat-lying coal and buff sandstone of Cretaceous age west of Edson and south of Drumheller, in dark carbonaceous shale near the Kananaskis River, in dark titaniferous magnetite-bearing sandstone of Cretaceous age north of Burmis, in dark phosphatic shales near Crows Nest Lake, as well as in bituminous sandstone and sideritic chert of the Athabasca tar sands near Fort McMurray. In addition to these, yellow stains resembling carnotite have been reported in association with radioactive, molybdenite deposits in mixed Precambrian

gneisses, schists, granite, and metasedimentary rock near the southwest arm of Andrew Lake in the northeast corner of Alberta (Godfrey, 1958). However, spectrographic analyses of two samples of the mineralized rock were reported to show only 0.15 and 0.1 per cent vanadium respectively (Godfrey, 1958).

Although the vanadium content of the Athabasca tar sands is generally probably less than 0.05 per cent (Hodgson, Peake, and Baker, 1963), the content of some of its ash is about 4 per cent, and since billions of tons of bitumen are available for processing, large potential reserves of vanadium are contained in these deposits.

Saskatchewan

The most important known vanadiferous occurrences in Saskatchewan are the uranium (pitchblende) ores of the Goldfields area of the north shore of Lake Athabasca, the geology of which was described by A. M. Christie (1953), and the mineralogy by S. C. Robinson (1955). An unknown vanadium-bearing mineral in the ores was described, analyzed, and named nolanite (Robinson, et al., 1957). Nolanite is a heavy, dark iron vanadate mineral ($3\text{FeO} \cdot \text{V}_2\text{O}_3 \cdot 3\text{V}_2\text{O}_4$), much like magnetite and pitchblende in appearance, which occurs in massive aggregates and hexagonal plates, associated with pitchblende, chalcopyrite, hematite, ilmenite, and dolomite in ores of the Ace-Fay mines, and notably in occurrences in the Fish Hook Bay, Zone A deposit (undeveloped), as well as in the old Nicholson No. 2 mine (now abandoned), and in the Pitche Group or Lorado property (now closed). Robinson (1955) noted nolanite on the fifth and sixth levels of the Ace mine, and suggested that there was an increase in vanadium content in veins in the foot-wall remote from the St. Louis fault, and an increase of vanadium with depth. The possibility of recovering vanadium as a by-product of the 1,500-ton-per-day mill was given serious consideration by Eldorado Mining and Refining Limited, but vanadium values in the lower levels have proven to be erratic, ranging from 0.92 per cent on the fifth level to 0.07 per cent on the seventeenth level and probably averaging about 0.09 per cent or less according to geological records (George Woollatt, personal communication). The new main Verna orebody probably averages about 0.12 per cent vanadium or less according to the mine geologist, George Woollatt. Although no attempt is presently being made to extract vanadium, the ores and mill tailings represent a potential reserve from which vanadium might be recovered if required in an emergency.

In southern Saskatchewan, traces of vanadium were noted by the writer in yellowish green sandstone near Verwood and reddish shale near Victor, both of late Cretaceous age, as well as in a sample, supplied by Wolfgang Wiens of the Geological Survey of Canada, of brick red dolomitic argillite of the Devonian Torquay Formation, from a depth of 1828-1838 feet in the new shaft of International Minerals and Chemical Corporation (Canada) Limited potash mine, near Sharbo east of Esterhazy. Faint traces of vanadium were also detected in samples of grey Cretaceous shale from Willowbunch, and yellowish Eocene sandstone south of Duncairn. Lignite of late Cretaceous age from East End, Bienfait, and elsewhere in southern Saskatchewan also shows faint traces of vanadium and very faint radioactivity.

Manitoba

Three occurrences of vanadium were noted in Precambrian rocks, one in titaniferous magnetite in anorthositic gabbro at Cross (Pipestone) Lake, another in chromite in serpentized peridotite near Bird River, and the third in graphitic schists near Star Lake. In addition, two occurrences are known in sedimentary rocks of Mesozoic age, one in bentonitic, selenite-bearing, yellow-stained, grey-brown shale in the Pembina Valley south of Morden, the other in dark grey shale south of Swan River.

The most promising of these is the vanadium occurrence on the south shore of Cross (Pipestone) Lake, where a band of anorthositic gabbro carrying fine-grained disseminations and massive segregations of titaniferous magnetite forms a zone marginal to a larger, sill-like mass of anorthositic rock, which is intrusive into the amphibolitic greenstone country rock. Both the amphibolitic greenstone and anorthositic gabbro trend in an east-west direction, dip nearly vertically, and are cross-cut by a northerly trending diabase dyke, as indicated by the geological mapping of Bell (1962). The titaniferous magnetite is not well exposed, but has been traced magnetically in a zone about 100 feet wide for several thousand feet along strike south of the lake by Noranda Exploration Company under the direction of V.D. Colcleugh. Vanadium occurs sporadically in the magnetite and host rock of this zone, and samples taken by the writer from this magnetite-ilmenite occurrence have shown a range from 0.01 to 0.3 per cent vanadium. Magnetic concentrates of this material have shown more than 60 per cent iron, about 5 per cent titanium, and from 0.5 to 1.5 per cent vanadium.

A chromite-rich sample taken by the writer from the Bird River sill was found to carry more than 10 per cent each of chromium and iron, as well as 0.15 per cent each of nickel and vanadium. The dense chromite ore is reported by Bateman (1943) to average from 26.3 to 29.3 per cent chromium.

Ontario

Vanadiferous titaniferous magnetite occurrences on Bad Vermilion Lake and Seine Bay of Rainy Lake, south of Mine Centre, were investigated many years ago by W.M. Goodwin, who developed a process (1921) to smelt these ores in an electric furnace. In pilot plant tests he was successful in recovering most of the vanadium and the iron in the pig, and eliminating titanium in the siliceous slag. These magnetite-ilmenite deposits extend for 14 miles in an elongate, narrow zone within a sill-like body of anorthosite and gabbro, which is intrusive into Keewatin type greenstones, schists, and metasediments, as shown by the geological mapping of Tanton (1936). In many ways the occurrence is similar to that on Cross Lake, Manitoba. Results of the writer's sampling of various outcrops suggest that vanadium is erratically distributed in the magnetite of Bad Vermilion Lake, and that it ranges from 0.012 to 0.3 per cent in the crude ore, and from 0.1 to 0.5 per cent or more in magnetic concentrates made from this material.

Two other deposits of vanadiferous titaniferous magnetite that have been known for many years are currently being investigated by private companies. One of these, the old Brazeau (Brazeau-Wood) property in lot 18,

Concession V, Papineau township south of Mattawa, was investigated in 1942 by M.E. Hurst and J. Satterly of the Ontario Department of Mines, and by A.F. Buckham and E.D. Kindle of the Geological Survey of Canada. The deposit was reported by Buckham (Harding, 1946) to carry in the unconcentrated sample about 35 per cent iron, 4.7 per cent titanium, and 0.4 per cent vanadium, and in the magnetic concentrates about 60 per cent iron and 0.8 per cent vanadium. The magnetic concentrate made from a sample taken by the writer showed as much as 1.3 per cent vanadium. The occurrence consists of numerous zones of dissemination and massive lenticular impregnation of titaniferous magnetite within bands of mafic, garnetiferous, hornblende-feldspar gneisses, which generally trend in a northeasterly direction and dip northwesterly. Exposures are poor, but fresh trenching and stripping by Union Carbide (Canada) Limited, under the direction of A.E. Buller and Paul K. Geisterfer, based on a ground magnetic survey, have uncovered several new titaniferous magnetite-rich zones on lot 15, Concession V of Papineau township. In one of these trenches two bands of massive titaniferous magnetite, each about 2 feet wide, are exposed within a 20-foot-wide zone of disseminated material, all striking easterly and dipping steeply to the north at a slight angle to foliation of the host rock hornblende-garnet-feldspar gneiss. The investigation to determine the tonnage and grade of the deposit is continuing.

The other is an occurrence of titaniferous magnetite within a tongue of diabase in Angus township, southeast of Timagami. Hurst (1931) reported seven exposures there on two parallel northwest-trending, magnetite-bearing zones about 400 feet apart, each zone about 400 feet long and entirely within the diabase. A sample of the best material taken by Hurst showed 43.62 per cent iron, 13.2 per cent titanium, and 0.1 per cent vanadium. The deposit is now being investigated by Titan Iron Mines Limited.

Occurrences of black sands in Black Bay, Lake Superior, of titaniferous magnetite on Bamoose Lake and on Pic River north of Lake Superior, and of titaniferous magnetite in Lount township, Parry Sound district, are also reported to be vanadiferous. The Matthews and Chaffey (New Mylamaque), Orton, Ricketts, Blessington (Eagle Lake), Blithfield, and Pershing titaniferous magnetite occurrences, all of which are associated with mafic intrusions, were each found by the writer (in 1953) to be vanadiferous, carrying from 0.1 per cent vanadium in the outcrop or drill core sample and as much as 0.3 per cent in magnetic concentrates (Rose, 1958). The writer also found (1958) that most of the low-titanium magnetite deposits in eastern Ontario (at least 25 of the deposits) carry from 0.01 to 0.1 per cent vanadium, but less than 0.01 per cent vanadium in the magnetic concentrates made from them. This is in marked contrast to the high-titanium deposits in which vanadium is characteristically concentrated in the magnetic extract.

In addition to these occurrences in titaniferous magnetite, the writer detected traces of vanadium in other rocks and minerals in Ontario as in certain greenstones of northwestern Ontario and those intercalated in the iron-formation north of Timagami, in the dark micaceous greywacke-quartzite beds south of Spanish, in the siderite iron ore of Michipicoten, in the contact zone of orange-red argillite of the Sibley Series and the intrusive diabase sill near Nipigon, in the brown pisolitic "buckshot" ore of Steeprock Lake, in rusty gneiss near Innisville, and in the chromite-rich zone of the Gordon Lake copper-nickel deposit. Strong traces of vanadium were also

found by the writer in samples of dark sand and mottled mauve arkose at the base of the Palaeozoic sandstone section at the Precambrian contact near Elgin. Faint traces of vanadium were also detected in samples of dark shale from Kettle Point.

Quebec

The vanadium occurrences in Quebec are almost entirely within substantial deposits of titaniferous magnetite in Precambrian gabbroic anorthosite. More than 20 such occurrences have been tested by the writer in which the vanadium content of the magnetic concentrate is greater than 0.2 per cent, and although the vanadium content is probably more than 0.5 per cent in several of these, it commonly averages about 0.25 per cent. Many of these magnetite-ilmenite deposits are very large, forming extensive zones in mafic rock associated with huge anorthositic intrusions, and they constitute large undeveloped potential reserves of iron and titanium, as well as of vanadium. Ilmenite-hematite deposits of a similar nature also carry traces of vanadium, but commonly in smaller amounts than in the magnetite-ilmenite occurrences. Ore from the large ilmenite-hematite deposit at Lac Tio is reported to average about 0.15 per cent vanadium, ranging from about 0.05 to 0.21 per cent. The writer found that ilmenite-hematite of the Ivry deposit north of Montreal carried 0.1 per cent vanadium, and that of the Furnace deposit north of Baie St. Paul holds 0.17 per cent. An unusually high vanadium content of 1.1 per cent was noted in a sample from a deposit in the Gouffre River valley (Rose, 1961). Certain deposits that are transitional between magnetite-ilmenite and ilmenite-hematite deposits may also be potential sources of iron, titanium, and vanadium.

The writer's samples of titaniferous magnetite taken with the assistance of mine geologist Marcel Vallee from the columbium (niobium)-bearing intrusions of probable Mesozoic (late Cretaceous) age on the property of St. Lawrence Columbium and Metals Corporation Limited at Oka, also carries vanadium in amounts ranging from 0.18 to 0.3 per cent, again probably averaging close to 0.25 per cent. Magnetite is being recovered at present from the mining and milling of the columbium (niobium) ores by St. Lawrence Columbium and Metals Corporation Limited, and it is being stockpiled for possible future use.

Chromite samples collected by the writer from serpentinized peridotite of Silurian(?) age near Coleraine, south of Thetford Mines, showed 0.2 per cent of vanadium upon analysis, and faint traces of vanadium were also detected in samples of Devonian(?) maroon argillite north of Gaspé, of orange-red stained Silurian volcanic rock near Port Daniel, and of dark brownish Carboniferous conglomeratic sandstone near Pointe à la Garde in the Gaspé peninsula.

An occurrence, in pegmatite north of Fort Coulonge, of the rare radioactive rare-earth bearing varieties of sphene, chevkinite, and keilhauite (yttrotitanite), was found to carry 0.2 per cent vanadium. The pegmatite dyke in which it occurs intersects Precambrian anorthositic gabbro that carries small concentrations of titaniferous magnetite, samples of which show 0.3 per cent vanadium.

New Brunswick

Traces of vanadium were detected by the writer in six localities in New Brunswick, three in sedimentary rock, one from interbedded sedimentary and volcanic rocks, one from the hydrocarbon albertite and associated shales, and one from the gabbro intrusion at St. Stephen. The sedimentary rocks include dark Ordovician(?) shale at Cox's Landing, red Carboniferous argillite and sandstone north of Fredericton, grey Carboniferous sandstone near Hopewell Cape, and grey-brown bituminous shale of Carboniferous age at Albert Mines. Interbedded mottled sandstone, conglomerate, felsite, and volcanic breccia of Silurian(?) age west of Harvey Station was found to carry about 0.03 per cent vanadium, the red beds north of Fredericton about 0.04 per cent, and the albertite about 0.05 per cent. A sample of black radioactive hydrocarbon near Hampton (see Gross, 1957), and the dark shale in which it occurs, were however found to carry only about 0.003 per cent and 0.005 per cent vanadium respectively. Faint traces of vanadium were noted in the orange-red radioactive sandstone of Shippigan Island, and in radioactive red argillite from York Mills (see Gross, 1957).

Nova Scotia

Traces of vanadium were detected in three localities in Nova Scotia, one in a flat-lying soft coal seam near New Glasgow, another in the fine-grained hematite iron-ore of Torbrook, and the other in grey-brown, malachite-bearing, Carboniferous sandstone, north of Baddeck in Cape Breton. Faint traces of vanadium were also detected in soft blotchy dark red argillite and sandstone in the Gravois Point-Malagash Point area and in siderite of the Londonderry area.

Prince Edward Island

Only very faint traces of vanadium were noted by the writer in samples of the red soil and sandstone from Prince Edward Island.

Newfoundland

Traces of vanadium were noted by the writer in eight localities on the Island of Newfoundland. Titaniferous magnetite occurrences of the Steel Mountain area, north of Flat Bay Brook and east of Bay St. George, in which vanadium was noted by D.M. Baird in 1942 (Baird, 1954) were examined, as were those at Indian Head described by Heyl and Ronan (1954). Magnetic concentrates made by the writer from titaniferous magnetite of the Bishop North and Hayes deposits were found to carry 0.41 and 0.43 per cent vanadium respectively. A similar concentrate from titaniferous magnetite at Indian Head on the United States air base of Harmon Field, was found to carry 1.1 per cent vanadium. Samples of titaniferous magnetite disseminated in anorthositic gabbro near Labrador Pond were reported to carry from 0.02 to 0.14 per cent vanadium (Heyl and Ronan, 1954). Red-stained granitic rocks east of Stephenville also showed traces of vanadium in places. It seems likely that other titaniferous magnetite occurrences may also be vanadiferous. The occurrences are all of Precambrian age.

It has been known for some time that the oolitic hematite iron-ore of Ordovician age of Wabana, Bell Island, is vanadiferous, and it is believed that some vanadium was recovered from Wabana ore in Germany during World War II. Mine records supplied in 1964 by company geologist W.M. Coughlan, courtesy of Mr. A.V. Southey, Mine Superintendent, indicated however, only a trace of vanadium in a representative sample of ore. With the assistance of W.M. Coughlan selected samples along the strike and across the stratification of the three main ore-beds and the dark shales and sandstones with which they are interbedded, were taken. Of the 30 samples taken, 14 were of oolitic hematite ore, in which a range of 0.004 to 0.093 per cent vanadium was shown upon analysis, 9 were of dark shale, which showed a range of 0.009 to 0.033 per cent vanadium, 5 were of sandstone, which showed a range of 0.0034 to 0.007 per cent vanadium, one was of oolitic pyrite and one of dark nodules, which showed less than 0.001 per cent and 0.007 per cent vanadium, respectively. In the samples taken, vanadium appears to be highest, at 0.093 per cent, in the bottom part of the Scotia Bed (range 0.038% to 0.093%) as compared with 0.053 per cent in the Upper Bed (one sample), and 0.031 to 0.054 in the Dominion (Lower) Bed. Slag from the Sydney smelter is also believed to be vanadiferous (Janes, 1956), and although there appears to be insufficient vanadium in the Wabana ore to permit its direct economic recovery by present methods, it seems possible that it could be recovered by chemical treatment of the ore or slag.

It may be of interest to note here that the manganese content of the three ore beds at Wabana showed a range from 0.022 to +3.0 per cent, reaching its highest value in the upper part of the Scotia bed at its eastern-most outcrop. The dark sandstone immediately above the Scotia bed also carries more than 3.0 per cent manganese. Titanium ranges from 0.07 to 0.55 per cent in the hematite ore, from 0.37 to 0.77 per cent in the dark shale, and from 0.09 to 0.36 per cent in the sandstone.

Samples of manganiferous black shale of middle Cambrian age from Manuels River and from Topsail Head showed vanadium contents of 0.052 and 0.0079 per cent respectively; dark shale of Carboniferous age from the Humber Valley north of Deer Lake showed 0.018 per cent vanadium; and micaceous red and green sandstone of Mississippian age from Crabbes River showed 0.015 per cent vanadium.

Little is known of vanadium in the Coast of Labrador, but the prospects appear to be good for its occurrence in titaniferous magnetite deposits associated with large bodies of anorthositic rocks there, such as those in the Mealy Mountains, in the Nain-Hopedale area, and in the Lake Michikamau area where Emslie (1964) has recently reported large disseminated ilmenite deposits in the gabbroic phase of the Michikamau anorthosite intrusion.

CONCLUSIONS

Vanadium has been detected across Canada throughout the geological column, in rocks and minerals that range in age from Precambrian (+2 billion years) to Oligocene (+25 million years). The most common associations of vanadium in Canada appear to be those with titanium and iron (to a lesser extent with chromium and manganese); with uranium (and to a lesser

extent thorium and rare earths); with copper (and to a lesser extent lead and zinc); with bitumens, carbon, hydrocarbons, organic complexes; and with phosphates. In these associations vanadium is generally concentrated in amounts greater than that of the world crustal average of 0.011 per cent by a factor of 2 to 30 times, in which range it is readily detectable by a simple chemical test. A concentration of more than 80 times the crustal average is required to form ore grade material of about 0.85 per cent vanadium, but in many of the occurrences noted by the writer a concentration of from 2 to 40 times would be sufficient to bring most of the samples to ore grade. This may have been accomplished by natural processes in many places within and near the occurrences noted in the report.

Association With Titanium and Iron

Vanadium occurs persistently in titaniferous magnetite of widely divergent ages in various parts of the country. In these occurrences the iron-titanium oxide minerals - titanomagnetite and the ilmenite-hematite series - predominate, and they are characteristically associated with gabbroic, anorthositic, and alkalic intrusions. Although the vanadium is not restricted to one mineral it is characteristically selectively concentrated in the titanomagnetite-rich fraction of this aggregate, in which it may average from 0.1 to 1.5 or more per cent, as compared to 0.01 to 0.2 per cent in the weakly magnetic ilmenite-hematite fraction, and commonly less than 0.01 per cent in the non-magnetic fraction. The vanadium appears to occur mainly in solid solution within the crystal lattice of the titanomagnetite, and more rarely as the vanadian magnetite, "coulsonite", which may be intergrown with, or exsolved from the former. Vanadium is also found in the mafic minerals, pyroxene, hornblende, biotite, and chlorite, that are associated with the iron-titanium oxides. In certain places these iron-titanium-oxide minerals may be separated by mechanical magnetic methods to form concentrates that are of ore grade vanadium.

The marine oolitic iron ores of Mesozoic age of Europe are faintly vanadiferous, as are those of Palaeozoic age at Wabana, Newfoundland (Ordovician), and Torbrook, Nova Scotia (Silurian). At Wabana the vanadium content of samples selected by the writer from the oolitic hematite iron-ore showed a range from 0.004 to 0.093 per cent vanadium, averaging slightly higher than the overlying black shale and underlying grey sandstone, and coming close to the average of the younger European oolitic iron-ores reported by Landergren (1948).

Association With Uranium and Thorium

Vanadium is also commonly associated with uranium in deposits of both sedimentary and igneous (hydrothermal) origin, and of various ages. The secondarily enriched sedimentary sandstone ores of Mesozoic age in the western United States carry as much as 10 per cent vanadium in places, but probably average less than 2 per cent combined vanadium and uranium, and they pass gradationally into sandstone that carries much less than 0.1 per cent vanadium. Some of the Cretaceous sandstones and shales of Western Canada in places carry more than 0.1 per cent vanadium, as do several other sedimentary formations of Palaeozoic and Precambrian age in both Eastern

and Western Canada. Favourable zones for secondary enrichment should be searched for within these rocks.

The Precambrian radioactive pitchblende ores of the Ace-Fay mine at Beaverlodge (Eldorado) carry sporadically distributed vanadium, mainly in the form of the mineral nolanite, and these uranium ores appear to average about the same vanadium content as do the Wabana iron-ores. Certain undeveloped vanadium-rich veins on the Fish Hook Bay, Nicholson, and Bolger properties in the Beaverlodge area carry vanadium in nolanite as well as in other minerals. Many of the rare, uranium-bearing, multiple oxide minerals of pegmatites also carry vanadium, as do many of the secondary hydrated uranium-bearing minerals.

Association With Copper, Lead, and Zinc

As much as 0.3 per cent or more vanadium is associated with copper in the basaltic lavas and intercalated chalcocite-bearing sedimentary lenses of Triassic age on Vancouver and Quadra Islands of British Columbia, and in lesser amounts with malachite-bearing sandstone of Mississippian age in New Brunswick, Nova Scotia, and Newfoundland. Some form of carbon or hydrocarbon is commonly present in all of these vanadiferous rocks, and this may have acted both as a source medium and precipitating agent of vanadium. The association of vanadium and the complex ores of copper, lead, and zinc as shown by deposits in South Africa, Rhodesia, and at Butte, Montana has not been demonstrated in Canada, but remains a possibility for prospecting and investigation.

Association With Bitumens, Carbon, Hydrocarbons, Porphyrins, and Organic Complexes

Bituminous and petroliferous shales of various ages commonly carry vanadium, as do the Athabasca tar sands of Cretaceous age of northern Alberta, and various hydrocarbons such as the albertite in the Mississippian shales of Albert Mines, New Brunswick. Certain heavy oils, lignites, soft coals, and graphites also may carry appreciable amounts of vanadium concentrated perhaps both by biochemical and secondary processes.

Association With Phosphates

The black shales and associated phosphate-rock of the Permian Phosphoria Formation of the western United States are strongly vanadiferous, as are some of the dark shales and slates of various ages in Canada. In many of these rocks the vanadium may be carried in several forms, such as in comminuted titanomagnetite and in other heavy multiple oxide and radioactive minerals, in graphite, bitumen, carbon, hydrocarbons, and organic complexes, in primary and secondary vanadium-bearing clays and micas, in substitution for phosphorus in phosphates and shells, or in substitution for dispersed uranium, iron, titanium, chromium, and manganese oxides and hydroxides. The vanadium content commonly ranges from 0.01 to 0.1 per cent, but may reach 1 per cent or more in places in these dark shales,

slates, and phosphorites largely of marine origin, and in which vanadium has been concentrated by marine organisms.

Association With Bauxite and Laterite

Bauxites and laterites developed from basic rocks commonly carry more vanadium than those derived from acidic rocks, and in places these may approach ore grade. There is little hope of finding such occurrences in Canada except possibly in a high-grade metamorphic, completely recrystallized form, but large quantities of bauxite are being processed at Arvida and Kitimat for the production of aluminum, from which vanadium might possibly be recovered.

A trace of vanadium was detected by the writer in a sample of rather deeply weathered, friable, bronzite gabbro or pyroxenite south of Veuve River and about a mile west of the village of Hagar, in Hagar township, Ontario. This leucoxene-ilmenite-bearing mafic rock may be removed by pick or shovel from the outcrop to an exposed depth of at least 15 feet. This deeply weathered mafic rock provides information on a type of occurrence seldom seen in the heavily glaciated terrain typical of the Canadian Shield or in this part of Canada.

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