

**GEOLOGICAL  
SURVEY  
OF  
CANADA**

**DEPARTMENT OF ENERGY,  
MINES AND RESOURCES**

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**ECONOMIC GEOLOGY  
REPORT No. 27**

**GEOLOGY OF VANADIUM  
AND VANADIFEROUS OCCURRENCES  
OF CANADA**

**E. R. Rose**

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**Ottawa  
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**GEOLOGY OF VANADIUM  
AND VANADIFEROUS OCCURRENCES  
OF CANADA**

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Magpie Mountain titaniferous magnetite deposit, Quebec; No. 2 deposit, looking south from No. 1 deposit.



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E. R. Rose

**DEPARTMENT OF  
ENERGY, MINES AND RESOURCES  
CANADA**

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## PREFACE

Vanadium, a rare element with unique properties, is of increasing importance in the industrial world as a ferro-alloy, chemical compound, catalyst, and metal. However, little information has been generally available on occurrences of vanadium in Canada, and no commercial peace-time production of the element has been recorded from any deposit in this country. The following report represents the first major attempt to assemble and add to published information on the geology of vanadium occurrences in Canada and to illustrate their potential economic importance.

Y. O. FORTIER,

*Director, Geological Survey of Canada*

OTTAWA, June 18, 1970



WIRTSCHAFTSGEOLOGISCHE BERICHT 27 —  
Die Geologie von Vanadiumvorkommen und  
vanadiumführenden Gesteinen in Kanada  
Von E. R. Rose

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РАПОРТ ЭКОНОМИЧЕСКОЙ ГЕОЛОГИИ 27 —  
Геология ванадия и его залежей в Канаде  
Э. Р. Роз

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# GEOLOGY OF VANADIUM AND VANADIFEROUS OCCURRENCES OF CANADA

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## *Abstract*

This report deals with the geology and economic potential of vanadium in Canada. It describes the geology of vanadium deposits, outlines their distribution, indicates areas and geological conditions favourable for additional occurrences, and stresses the relationship of vanadium to titaniferous magnetite deposits, as well as to uranium and other deposits, in Canada. It reviews historical and technological progress in the production and use of vanadium and its ores; gives information on the geology, geochemistry, mineralogy, geophysics, and methods of detection of vanadium; outlines the geology of world and Canadian vanadium occurrences; gives significant guides for prospecting for vanadium and its ores; and indicates prospects for the development of vanadium deposits in this country.

Vanadium is a notable constituent of titaniferous magnetite in which it occurs in solid solution. Large deposits of vanadium-bearing titaniferous magnetite are distributed in the Canadian Shield, particularly in the Grenville Province, associated with the gabbroic phases of anorthositic intrusions. Vanadium is dispersed throughout a variety of rocks and minerals elsewhere in Canada, significantly in uranium, iron, manganese, and chromium deposits; in bituminous sandstone, organic shale, asphaltite, lignite, coal, graphite, and phosphate rock; in basic to intermediate volcanic rocks; in alkaline rocks and carbonatites; and in certain other more acidic igneous and metamorphic rocks.

## *Résumé*

L'auteur traite de la géologie et du potentiel économique du vanadium au Canada. Il décrit la géologie des gisements, esquisse leur répartition, indique les régions et les conditions géologiques propices à des venues additionnelles et souligne le rapport entre le vanadium et les gisements de magnétite titanifère, d'uranium et autres minéraux au Canada. Il revoit les progrès historiques et technologiques réalisés dans la production et l'utilisation du vanadium et de ses minerais, donne des renseignements sur la géologie, la géochimie, la minéralogie, la géophysique et les méthodes de détection, esquisse la géologie des venues au Canada et dans le monde, donne des principes pertinents pour la prospection et indique les perspectives de la mise en valeur des gisements au Canada à la lumière de la situation du vanadium dans le monde.

Le vanadium est un composant notable de la magnétite titanifère dans laquelle il se trouve en solution solide. D'importants gisements de magnétite titanifère contenant du vanadium sont répartis dans le Bouclier canadien, particulièrement dans la province de Grenville où ils sont associés aux phases

à gabbro des intrusions d'anorthosite. Le vanadium est réparti dans un éventail de roches et de minéraux ailleurs au Canada, plus particulièrement dans les gisements d'uranium, de fer, de manganèse et de chrome; dans le grès bitumineux, le schiste organique, l'asphaltite, le lignite, la houille, le graphite et les roches phosphatées; dans les roches basiques à volcaniques intermédiaires, dans les roches alcalines et les carbonatites et dans certaines autres roches ignées et métamorphiques plus acides.

## Chapter I

### INTRODUCTION

Vanadium is a trace element that is widely distributed in Canada, but it has not yet been found in a mineable deposit or in a form considered to be economically recoverable here. It is mainly used in the steel and chemical industries, where it is periodically in short supply. In the United States vanadium is classed as a strategic and critical material, and is held in the national stockpile. Since 1963, when import restrictions on vanadium ores and concentrates were lifted, many vanadium producers in the U.S. have been seeking new supplies elsewhere.

Vanadium appears to have been detected for the first time in Canada by F. J. Pope in 1899 in titaniferous magnetite from Eagle Lake, Pine Lake, and the Orton Mine in eastern Ontario. This followed discoveries in titaniferous magnetite made by N. G. Sefström in Sweden in 1831 and by Isidor Walz in the U.S. in 1876. Significant occurrences of vanadium subsequently found in Canada have included: the Seine Bay-Bad Vermilion Lake titaniferous magnetite deposits south of Mine Centre, Ontario, in 1919; the vanadiferous copper-bearing volcanic and sedimentary rocks of Quadra Island, British Columbia, in 1930; the cupriferous vanadium-bearing beds and volcanic rocks near Menzies Bay on Vancouver Island in 1942; the Brazeau-Woods titaniferous magnetite bodies south of Mattawa, Ontario, in 1942; the Steel Mountain titaniferous magnetite in western Newfoundland in 1942; the vanadium in the bitumen of the Athabasca tar sands of Alberta in 1945; the pitchblende-bearing veins of the Beaverlodge area in Saskatchewan in 1955; the titaniferous magnetite of the Lac Doré Complex of Chibougamau, Quebec, in 1967; the uranium-bearing beds in sandstone on Prince Edward Island in 1968; as well as in numerous other occurrences noted by the writer (Rose, 1967) and shown in the report on Map 1321A (*in pocket*).

Until recently the prospects for finding and developing vanadium deposits in this country were generally considered poor. It is hoped that as a result of the investigations covered in this report the outlook for vanadium in Canada will be shown in a better light. World vanadium production and consumption is increasing. The prospects of finding vanadium deposits here appear to be much improved, and the outlook for this rare and useful metal in Canada is promising.

### Previous Work

Vanadium in Canada has received little more than passing geological attention to date. In a Mines Branch report on titanium, A. H. A. Robinson (1922) discussed

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vanadium in titaniferous magnetite, but was apparently not greatly impressed with the suggestions of Pope (1899) that there was a general relationship between titanium and vanadium in titaniferous iron ores. In 1932 H. V. Ellsworth, and in 1933 H. V. Ellsworth and H. C. Gunning, reported briefly on the recently discovered 'carnotite'<sup>1</sup> occurrence on Quadra Island; but after a brief flurry little more was done until 1942, when similar occurrences were discovered near Menzies Bay on Vancouver Island. During World War II vanadium was in critically short supply in North America and it was being recovered from soot scraped from the boilers of oil-burning ships and plants and from the Chromeraïne mine chromite of Quebec. Some tests on the recovery of vanadium from the Athabasca tar sands and on copper and carbon-bearing Upper Carboniferous sandstones of New Brunswick and Nova Scotia were considered disappointing, and no development ensued. In 1943 vanadium was listed in the Mines and Geology Branch publication *Prospectors Guide for Strategic Minerals in Canada*, in an attempt to encourage prospecting for vanadium deposits. Vanadium-bearing titaniferous magnetite prospects were investigated at Mattawa, Ontario (Harding, 1946), and at Steel Mountain, Newfoundland (Baird, 1954).

### Present Work

Work by the writer on titaniferous magnetite deposits in 1952-54 and in 1958-70 suggested their great importance as sources of iron and titanium and eventually led back to the almost forgotten and almost universal association of vanadium with such deposits. In 1963 the present study of the geology of vanadium occurrence in Canada was begun.

Field work on which this report is based was carried out across Canada mainly during the summers of 1963-65, but also during earlier and later years. Many of the samples collected were studied by means of thin and polished sections under the microscope. Tests and analyses of representative material were made; photographs, maps, and illustrations were prepared; and the report was written in 1970.

### Library Research

A search of the literature showed that much was known about the geology of the important uranium-vanadium-producing sandstone deposits in the western United States (Pls. II, III), and that similar deposits were unknown and unlikely to be found in Canada. An investigation of the nature of some of these U.S. deposits and their host rock environment was necessary to estimate the possibility of finding similar deposits in Canada.

The literature also indicated that considerable effort was being made elsewhere to locate and develop sources of vanadium-bearing titaniferous magnetite, particularly in the Republic of South Africa and in the U.S.S.R., which further suggested the possible importance of titaniferous magnetite as well as other potential sources of vanadium here. Subsequent rapid advances in this field, particularly in the development of titaniferous magnetite deposits in both South Africa and Russia, and in the increasing world market for vanadium, have strengthened this suggestion.

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<sup>1</sup>A 'carnotite-like' mineral was identified, and at first was suspected of having not been found in place.

## Foreign Publications

Most of the foreign literature on vanadium readily available to the writer is of American origin. The U.S. Geological Survey and U.S. Bureau of Mines reports are invaluable sources of information, together with reports from individual states and the papers of professional geologists published in mining and scientific journals. The recently issued *Bibliography on the Geology and Resources of Vanadium to 1968* (Fischer and Ohl, 1970) is a good example. Available information on other countries is more limited, but the international scope of the reports used and listed in the References is helpful in giving perspective on the world vanadium situation. This general knowledge concerning world resources and their state of development is useful in assessing future prospects, as well as providing information on otherwise unknown deposits (Nicolini, 1960).

## History of Exploration for Vanadium in Canada

The history of exploration for vanadium in Canada is brief. As previously noted, a number of vanadium occurrences have been found, mainly as a result of laboratory analyses of a variety of materials. Several of the more promising occurrences have been more thoroughly sampled, and a few have been tested by drilling, but none has produced commercially. The demand for vanadium has been sporadic, but during wartime it was in critically short supply in North America, and prospecting for it was encouraged by the American and Canadian governments. Possibly considerable efforts have been made, but there is little evidence of noteworthy success in Canada. It is known that in 1919 Dr. W. L. Goodwin, and later his son, W. M. Goodwin, attempted to explore and develop the vanadium-bearing titaniferous magnetite at Bad Vermilion Lake, south of Mine Centre, Ontario, which for many years was the largest known deposit of its type in Canada. In 1921 W. M. Goodwin and A. F. Cadenhead (Goodwin, 1921) developed and patented a process using silica as a flux to electrically smelt titaniferous ore and recover most of its contained vanadium in the resulting pig iron. They applied the process to several titaniferous ores, among them samples from the Seine Bay-Bad Vermilion Lake and the Orton-Ricketts deposits in Ontario, in an electric furnace at Belleville, Ontario. Although a good recovery of high-quality vanadium-bearing pig iron was obtained neither the process nor the deposits were developed commercially. Nevertheless, the possibilities of the process were demonstrated and several modern methods of processing titaniferous magnetite seem to be based on modifications of the principles described.

During the latter part of 1930 (Ellsworth, 1932), R. Crowe-Swords of Vancouver noticed a soft, greenish yellow material in small fissures in rocks carrying the copper deposits north of Gowlland Harbour on Quadra (Valdes) Island. Samples of the yellowish mineral were subsequently identified as carnotite at the University of British Columbia, and analyses of the mineral showed contents of 19.0 and 21.1 per cent vanadium oxide as well as 27.7 and 28.9 per cent uranium oxide. The reported occurrence was examined by H. C. Gunning in 1932, and was described by Ellsworth and Gunning (1933). They found little of the carnotite-like mineral remaining at the occurrence, but noted a finely banded siliceous, carbonaceous material, 1 inch to 4 inches thick, embedded between two lava flows and carrying some thin greenish copper stains. Five samples taken from this material yielded 0.29, 0.30, 1.60, 2.16,

and greater than 3 per cent  $V_2O_5$ . The occurrence was described by Ellsworth and Gunning as the first discovery of vanadiferous rock of this grade in Canada, and its importance as an indicator of favourable conditions for vanadium and uranium deposition was emphasized. They suggested that these types of rocks as well as the stratigraphically underlying Triassic volcanic and overlying Cretaceous sedimentary ones should be investigated for vanadium. Subsequently Mr. Crowe-Swords found small occurrences in similar rocks about three quarters of a mile west of Menzies Bay on Vancouver Island. Small pits were blasted in these in 1942, but no further development has taken place at either locality. About this time some vanadium was detected in the gold-quartz vein of the Siscoe mine in Quebec.

During World War II when vanadium was in very short supply a number of (titaniferous) magnetite occurrences were sampled and checked for vanadium. In 1942 George Wood of Mattawa reported a showing in Papineau Township about 5 miles south of Mattawa, Ontario, which was drilled and sampled and found to carry about a million tons of titaniferous magnetite averaging about 0.5 per cent vanadium (Harding, 1946). Numerous other occurrences were reported and tested, but none was developed further. In much the same way, in 1942 mineable vanadiferous shale and phosphate rock was located in Idaho. This was the result of traces of vanadium being detected in samples analyzed by the U.S. Geological Survey in 1911.

In 1957 a new vanadium mineral, named nolanite in honour of Dr. Thomas B. Nolan, then director of the U.S. Geological Survey, was described by S. C. Robinson *et al.* from the uranium ore of the Ace Mine at Uranium City in the Beaverlodge area of Saskatchewan. Traces of vanadium were noted in the uranium ores of this district but it has not yet been found practical to recover them. Traces of vanadium were also noted in the Wabana iron ores and in the slag derived from them at Sydney, Nova Scotia, where it has also been considered impractical to recover them.

### Current Developments in Canada

Although there is now no vanadium production from a deposit in Canada, in 1965 Canadian Petrofina Limited began to recover vanadium pentoxide as a byproduct of its petroleum refining operations at Pointe-aux-Trembles near Montreal, Quebec. The imported Venezuelan crude oil carrying 0.01 to 0.06 per cent vanadium is treated according to a process developed at the Mines Branch in Ottawa, and about 600 to 800 pounds of  $V_2O_5$  are recovered daily at the plant. Also, in 1967 G.-O. Allard (1967) reported a significant content of vanadium in analyses of titaniferous magnetite from Rinfret Township, Quebec. In 1968 occurrences of uranium and vanadium were noted in sandstone beds on Prince Edward Island by Prest, *et al.* (1969). With controlled development of the Athabasca tar sands of Alberta taking place on an increasing scale, it seems logical that an attempt will be made to recover the vanadium content of the bitumen there. If the vanadium market continues to grow this could happen soon.

There is also some interest in the intriguing possibility of developing several of Canada's large titaniferous magnetite deposits for the recovery of one or more of the elements iron, titanium, and vanadium. This possibility will come closer to reality when further demands for titanium as well as for vanadium and iron are felt in North America.

## Acknowledgments

The writer wishes to acknowledge the co-operation and courtesy of the then officers of the many mining companies in the United States and Canada who granted access to their properties and took time to provide much valuable information and discussion. In this regard mention should be made of the following: Paul Bethurun, plant manager, and Kent Hudson, geologist, Mines Development Inc., Edgemont, South Dakota; Frank Temple, plant manager, and James Dalrymple, geologist, Union Carbide Corporation, Mining and Metals Division, Rifle, Colorado; L. P. Twitchell, superintendent, Union Carbide Nuclear Company, Grand Junction, Colorado; Paul Wire, plant manager, and Phil Donnerstag, geologist, American Metal Climax, Inc., Climax Uranium Company, Grand Junction, Colorado; Norman B. Schiff, plant metallurgist, Vitro Corporation of America, Vitro Chemical Company, Salt Lake City, Utah; George Atwood, production superintendent, and James Link, geologist, Monsanto Chemical Company, Ballard Mine, Soda Springs (Conda), Idaho; Dr. M. N. Shaw, plant metallurgist, Kermac Nuclear Fuels Corp., Kerr-McGee Oil Industries Inc., Soda Springs, Idaho; J. J. McDougall, geologist, Falconbridge Nickel Mines Limited, Vancouver, British Columbia; George Woollett, geologist, Eldorado Mining and Refining Limited, Uranium City, Saskatchewan; Dr. D. A. Keys, geologist, International Minerals & Chemical Corporation (Canada) Limited, Esterhazy, Saskatchewan; V. S. Colcleugh, geologist, Noranda Exploration Company, Limited, Flin Flon, Manitoba; Dr. G. F. Monture, vice-president, and J. R. Mowat, geologist, Stratmat Ltd., Ottawa, Ontario; Drs. A. E. Buller and Paul K. Geisterfer, geologists, Union Carbide Canada Limited, Toronto, Ontario; Dr. Marcel Vallée, geologist, St. Lawrence Columbium and Metals Corporation, Oka, Quebec; A. V. Southey, superintendent, and W. M. Coughlan, geologist, Dominion Wabana Ore Limited, Bell Island, Newfoundland.

Dr. R. P. Fischer of the U.S. Geological Survey kindly provided the writer with a copy of their Bulletin 1316 in July 1970, just as the present manuscript was completed. The addition of this exhaustive bibliography to the references on vanadium has added much to this report.

During the summer of 1963 the writer was capably assisted by D. E. Rose, and in 1966 by J. C. H. Charette. The co-operation and assistance during the project of many colleagues in the Geological Survey of Canada and elsewhere was of great help in many ways, both in reaching isolated occurrences and in discussions of geological settings and problems. The writer is especially indebted to Drs. J. A. Roddick, W. W. Hutchison, H. Gabrielse, C. K. Bell, G.-O. Allard, J. R. Mowat, George Woollett, D. A. Carson, and D. M. Baird. Dr. J. L. Jambor kindly made a copy of his unpublished thesis on the Menzies Bay vanadium occurrences (1960) available to the writer, and J. J. Lynch was most helpful with advice on field chemical tests for vanadium. The co-operation of officers of many of the provincial departments of mines, and of the federal Mineral Resources Branch and Mines Branch is also gratefully acknowledged.

Analytical results in the reports are mainly from semiquantitative and qualitative spectrographic analyses made on the writer's samples by H. W. Champ, K. Church, and the late W. F. White of the Geological Survey's spectrographic

#### VANADIUM AND VANADIFEROUS OCCURRENCES OF CANADA

laboratory. A number of chemical and X-ray fluorescence analyses for vanadium were made by members of the chemistry and analytical laboratories of the Survey, and several analyses were made by officers of the chemical laboratory of the Mines Branch. A number of analytical results are also given from the literature. Less precise results are estimates based on the writer's qualitative chemical tests for vanadium made in the field. Radiometric determinations of the uranium content of the samples were made by the writer and J. H. C. Charette using the Geological Survey laboratory end window Geiger counter and the methods outlined by Lang, *et al.* (1962, p. 124).

## Chapter II

### VANADIUM AND ITS ORES

#### *Vanadium*

*Vanadium from Vanadis,  
Goddess of Norse folk-lore,  
Strengthen the steel that serves us,  
Toughen our iron ore.  
Go—get the fumes that exhaust us,  
Muffle the mighty jets' roar,  
Crack up the compounds that plague us,  
Help us to find more ore.*

#### Historical Review

The element vanadium is believed to have been first detected in 1801 in brown lead ore from Zamapan, Hidalgo, by Manuel del Rio, a professor of mineralogy at the School of Mines in Mexico City. He called it 'erythronium,' then later decided it was really chromium in the form of a basic lead chromate. Erythronium was further discredited in 1805 by a French professor of chemistry, Collet-Descostils, who agreed that it was chromium. It was not until 1830 that N. G. Sefström, a Swedish chemist, rediscovered the new element in iron made from the titaniferous magnetite of Taberg, Sweden, and named it 'vanadium' after Vanadis, the Norse goddess of mythology (Freya Vanadis, goddess of beauty). Later in 1830 Freidrich Wohler concluded that vanadium and erythronium were the same element, and in 1831 J. J. Berzelius published a description of vanadium compounds. No further progress was made until the 1860s, when Sir Henry Roscoe, after whom the mineral roscoelite was named, produced the first nearly pure vanadium metal. During the next 50 years many unsuccessful attempts were made to produce high-purity vanadium metal. These resulted in hard brittle crystals due to impurities, and vanadium was incorrectly classed in Group VA of the Periodic Table along with arsenic, antimony, and bismuth. In 1923 Hunter and Jones reduced vanadium trichloride with sodium in a steel bomb, producing a fine grey powder of 99.5 per cent vanadium; and in 1927 Marden and Rich (1927) produced the first globules of high-purity ductile vanadium in the form of three eighths of an inch diameter shot. This was done by the calcium reduction of vanadium pentoxide in a steel bomb at 900° to 950°C according to the reaction ( $V_2O_5 + 5Ca + 5CaCl_2 \rightarrow 2V + 5CaO.5CaCl_2$ ). Vanadium was found to be more like tantalum than arsenic, and the method of Marden and Rich became the standard laboratory source of the few hundred grams of the metal that were produced annually.

Poems by E. R. Rose.

Impetus for commercial development of the vanadium alloy industry came in 1896 when the Firming Steel Works in France found that vanadium-bearing steel made superior armour plate; and in 1900 Arnold at Sheffield found that vanadium improved the physical properties of plain carbon tool steels. For a time the sole commercial source of vanadium was the slag produced at the Creusot Steel Works in France, where vanadium-bearing pig iron derived from the oölitic iron ore from Mazonay was made into steel. However, in 1905 prospector-manager Rizo-Patron, searching for fuel, discovered the first large deposit of what proved to be rich vanadium ore, on his employer's property near Quisque, high in the Andes of Peru. This deposit was to supply most of the world's vanadium for more than 25 years. Samples of the red ash derived from this patronite 'coal' were found to be high in vanadium by D. F. Hewett (1909) and were first reduced to metal in 1906 by F. M. Beckett of the Electro Metallurgical Company in Niagara Falls, New York. Dr. W. F. Hillebrand of the U.S. Geological Survey identified nine vanadium-bearing minerals in the Mina Ragra ores, six of which (patronite, pascoite, minasragrite, quisquite, melano-vanadite, and hewettite) were completely new. Subsequently, other important vanadium producers were found in 1906 with uranium in sandstone in Colorado (Pl. II A); in 1910 in Turkestan; in 1909 in lead-zinc-copper ores in Africa, as well as in asphalt in Argentina; and in 1951 in sandstone at Edgemont, South Dakota (Pl. II B). Production has declined from many of the previously noted occurrences and is giving way to increased recovery from titaniferous magnetite in the Republic of South Africa, the U.S.S.R., and Finland; from phosphate rock (Pl. III B) in the western United States (Idaho and Montana); and from the lateritic capping of an altered ultrabasic or carbonatite plug in Arkansas.

### Ore Processing and Extraction

Vanadium is generally extracted from many of its ores by roasting them with common salt to form a water-soluble sodium vanadate. This is leached with dilute acid and filtered, and from this filtrate the vanadium is precipitated by addition of either sulphuric acid, as red or yellow 'vanadium oxide,' or by ammonium chloride as whitish ammonium metavanadate ( $\text{NH}_4\text{VO}_3$ ). These products may be fused and converted to black vanadium pentoxide (high purity  $\text{V}_2\text{O}_5$ ) for use in the production of ferrovanadium (Carvan or Solvan) or vanadium metal.

#### Recovery from Uranium and Base Metal Ores

In uranium and base metal ores carrying vanadium, many other complex factors may be encountered in the recovery process, but vanadium may be selectively separated from the acid solution of uranium and other metals by carefully controlling the pH<sup>1</sup> of the solution, by ion exchange, and solvent-extraction separations. Separation of uranium from vanadium is more difficult in acid than in neutral or basic solutions. The ion-exchange and solvent extraction separations are based on the ability of organic compounds (resins, amines, and organophosphorous acids) to exchange uranium ions selectively from solutions. Vanadium is recovered from solution, after uranium has been removed, by adjusting the pH of the solution to 2.0, adding a solution of 15 parts DEHPA (di-2-ethylhexyl phosphoric acid) and 85 parts kerosene to extract the

<sup>1</sup> pH—hydrogen ion concentration.

vanadium, and then stripping it from this solution with dilute sulphuric acid, as vanadium oxide 'red cake.' The red cake may be redissolved in an ammonium solution from which AMV (ammonium metavanadate) is crystallized. The AMV is calcined and fused to form a vanadium pentoxide product, 98+ per cent  $V_2O_5$ .

#### Recovery from Iron Ores and Titaniferous Magnetite

At Otanmäki, Finland, titaniferous magnetite is crushed and concentrated by wet magnetic separator. The vanadium- and titanium-bearing magnetic concentrate is dried, mixed with sodium sulphate, finely ground, then pelletized and roasted at 1,200°C in a vertical shaft furnace. The pelletized calcine is leached with hot water, washed and sold as iron-ore sinter. The water-leach solution, carrying about 25 grams per litre of  $V_2O_5$ , is treated with sulphuric acid, and vanadium oxide red cake is precipitated. Output has been increased to about 1,000 tons of  $V_2O_5$  per year.

In the Lydenburg district of South Africa, vanadium has been recovered from titaniferous magnetite since 1958 using the salt-roast process. Ammonium chloride was used to precipitate ammonium metavanadate, which in turn was broken down and fused to form a high-grade fused-oxide product. In 1968 a new plant for the integrated production of iron and steel as well as vanadium- and titanium-rich slags and oxides opened at Witbank, about 90 miles east of Pretoria. Vanadium-bearing titaniferous magnetite concentrate is prereduced in coal-fired rotary kilns, then fed into 50-foot-diameter electric furnaces in which first titanium is slagged off, then vanadium, using silicon and oxygen. The remaining hot metal is made into steel using the basic oxygen process. The titanium- and vanadium-rich slags may be sold or processed further into titanium and vanadium oxides or metals. When the plant reaches its capacity it is estimated that 11,000 to 12,000 tons of  $V_2O_5$  will be recovered annually from 480,000 tons of hot metal.

#### Recovery from Phosphate Rock

Western phosphate rock, containing 0.1 to 2.6 per cent  $V_2O_5$ , is first calcined and then reduced to elemental phosphorus in an electric furnace from which a byproduct heavy slag, rich in phosphorus, vanadium, and iron, called ferrophosphorus or 'ferrophos,' is recovered. The ferrophos is treated as a vanadium ore by a modified salt roast followed by solvent extraction of vanadium oxide and sodium metavanadate. These products are further processed to black fused  $V_2O_5$ .

#### Recovery from Petroleum, Oil Shale, Bitumen, Hydrocarbons, Coal, and Lignite

The refining, burning, or destructive distillation of petroleum, oil shale, and bitumen, or the burning of hydrocarbons, coal, and lignite may result in the concentration of vanadium in the coke, ash, soot, and fly-ash to a remarkable degree. The recovered vanadium-rich product is then treated as a vanadium ore, from which vanadium may be extracted by salt-roast, acid-leach, and solvent-extraction processes.

#### Properties of Vanadium

Vanadium is a hard, lustrous, steel-grey metal of high melting point (1,900° ± 25°C), and when pure shows good resistance to salt-water corrosion. Compared with



copper and aluminum it is a poor conductor of heat and electricity. It is malleable and ductile, but may become brittle due to adsorbed hydrogen. It combines with carbon, oxygen, and nitrogen at high temperatures to form carbides, oxides, and nitrides. It is readily machinable, much like cold-rolled steel, and is weldable using the argon-arc process.

The physical properties of vanadium metal, given by Dunn and Edlund (Hampel, 1961) are shown in Table I. Chemically it lies between niobium (columbium) and tantalum, and between titanium and chromium. It is amphoteric, forming bases and acid radicals in different valencies. It is insoluble in hydrochloric acid and in dilute sulphuric acid, but it dissolves in nitric acid, hydrofluoric acid, and concentrated sulphuric acid. It is less resistant than stainless steel and copper in simulated ocean water.

TABLE I *Physical properties of vanadium*

Atomic number	23
Atomic weight	50.95
Crystal structure	Body-centred cubic
Lattice constant	3.034-Å
Density	6.11 gm/cc
Melting point	1,900° ± 25°C (3,452°F) <sup>1</sup> 1,919° ± 2°C (3,486°F) <sup>2</sup>
Boiling point	3,000°C (5,432°F)
Specific heat	0.12 cal/gm/°C
Thermal neutron-absorption cross-section	4.98 ± 0.02 barns/atom
Thermal conductivity	0.074 cal/cc/cm/sec/°C at 100°C
Electrical resistivity	24.8–26.0 microhm-cm at 20°C

<sup>1</sup>Some tables give 1,710° ± 10°C, based on early measurements of impure vanadium carrying carbon.

<sup>2</sup>Higher purity vanadium metal melting point determined in 1954 by R. A. Orioni and J. S. Jones.

## Uses of Vanadium and Its Compounds

Vanadium and its compounds are mainly used in the steel (89 per cent) and chemical (11 per cent) industries. The range and scope of its usefulness as an engineering metal have not yet been fully explored. New applications are constantly being found for its unusual combination of properties.

There is no entirely satisfactory substitute for vanadium in the production of special steels where toughness, resistance to shock or impact, and resilience are involved. Substituting steels may contain molybdenum, chromium, nickel, manganese, titanium, silicon, and aluminum. A small content of vanadium improves the mechanical properties of cast iron and steel. Two main reasons for using vanadium in steel are to reduce grain size and to increase the temperature stability of the steel. Vanadium is usually added to the molten steel bath in the form of ferrovanadium, where the vanadium (in amounts of about 0.25 per cent) acts mainly as a 'scavenger' combining with and removing undesirable impurities such as oxides and nitrides from the steel, thus making it stronger. Ferrovanadium is used in the production of special steels for axles, coil springs, crankshafts, and ball bearings, which contain about 0.15 per cent vanadium.

Nearly all tool steels contain vanadium because of the desirable properties of wear resistance, hardness, and temperature stability that the vanadium carbides formed impart to them. Vanadium contents of 0.2 to 0.4 per cent are used in high-speed cutting steels for the tool and die industry. Vanadium is also useful in the continuous casting of steel, where it overcomes mechanical difficulties in pouring the molten metal, in addition to making better and cleaner steel. This process might use 1 pound to 2 pounds of vanadium per ton of finished steel and create a much larger outlet for the element.

The use of vanadium in low-alloy steels is increasing, as is its use in alloys with titanium and aluminum for aircraft manufacturing. Vanadium foil is used as a bonding material between steel and titanium metal sheets in the cladding of pure titanium metal to steel. High-purity vanadium metal has promising potential for use in space vehicles and in the construction of fast atomic reactors because of its strength at elevated temperatures and its low fission-neutron cross-section. New techniques of ferroalloy manufacture, including vacuum melting of vanadium metal of high purity, are being developed to meet the demanding requirements of the aerospace and atomic energy industries.

Manufacturing oxidation catalysts from ammonium metavanadate and vanadium pentoxide for the chemical industry is the largest single application of vanadium compounds. Vanadium may be substituted for platinum as a catalyst. As such it is used in the manufacture of sulphuric acid, ammonia, xylene, benzene, butadiene, polyethylene plastics, ethylene propylene rubber, and a variety of other products, as well as in the 'cracking' of petroleum and in the purification of ore concentrates. The use of vanadium catalysts for completing the oxidation of hydrocarbon pollutants in automobile exhaust fumes is also being investigated in the United States.

Vanadium has been used in ceramics both as a component of the refractory as well as a colouring material. Added to glass, vanadium produces an almost colourless glass that absorbs ultraviolet light; this glaze may be used to protect foods and juices from the action of ultraviolet radiation which destroys their vitamins.

### World Production, Consumption, and Prices

Western world production and consumption of vanadium have increased markedly since 1950, and especially since 1960, and now approximates 12,000 tons per year. More than one half of this is consumed in the United States (Fig. 1). Little of the vanadium used is recoverable as scrap. In 1960 the major producers of the western world were the sandstone ores of the Colorado Plateau (60 per cent); the lead-zinc-copper ores of the Otavi Mountains of South West Africa (12 per cent); the titaniferous magnetite rubble above plugs in the Bushveld Complex in the Republic of South Africa (9 per cent); and the titaniferous magnetite deposits of Otanmäki, Finland (8 per cent). In 1963 U.S. vanadium production represented 55 per cent of the West's output. In 1966 Canadian Petrofina Limited became a vanadium pentoxide producer from its oil refinery near Montreal, Quebec. Until 1970 half of the western world's vanadium supply was derived from sedimentary rocks and uranium ores of the Colorado Plateau and the western United States. Consumption of vanadium in the U.S. increased by 10 per cent over 1967 to more than 5,500 tons, but prices began to decrease because of heavy imports from Russia and increased South African production in 1968-69. In 1970, with a full year's production of vanadiferous slag from Highveld Steel and Vanadium Corporation Limited at Witbank, South Africa, from Union Carbide's new

vanadium plant at Wilson Springs, Arkansas, and from Atlas Minerals Corporation's uranium-vanadium mill at Moab, Utah, supplies were expected to exceed demand. If this trend continues and prices continue to decline, the lower price for vanadium would make it more competitive with niobium (columbium), molybdenum, and other ferro-alloy metals; and as demand overtakes supply, new sources of vanadium may be required.

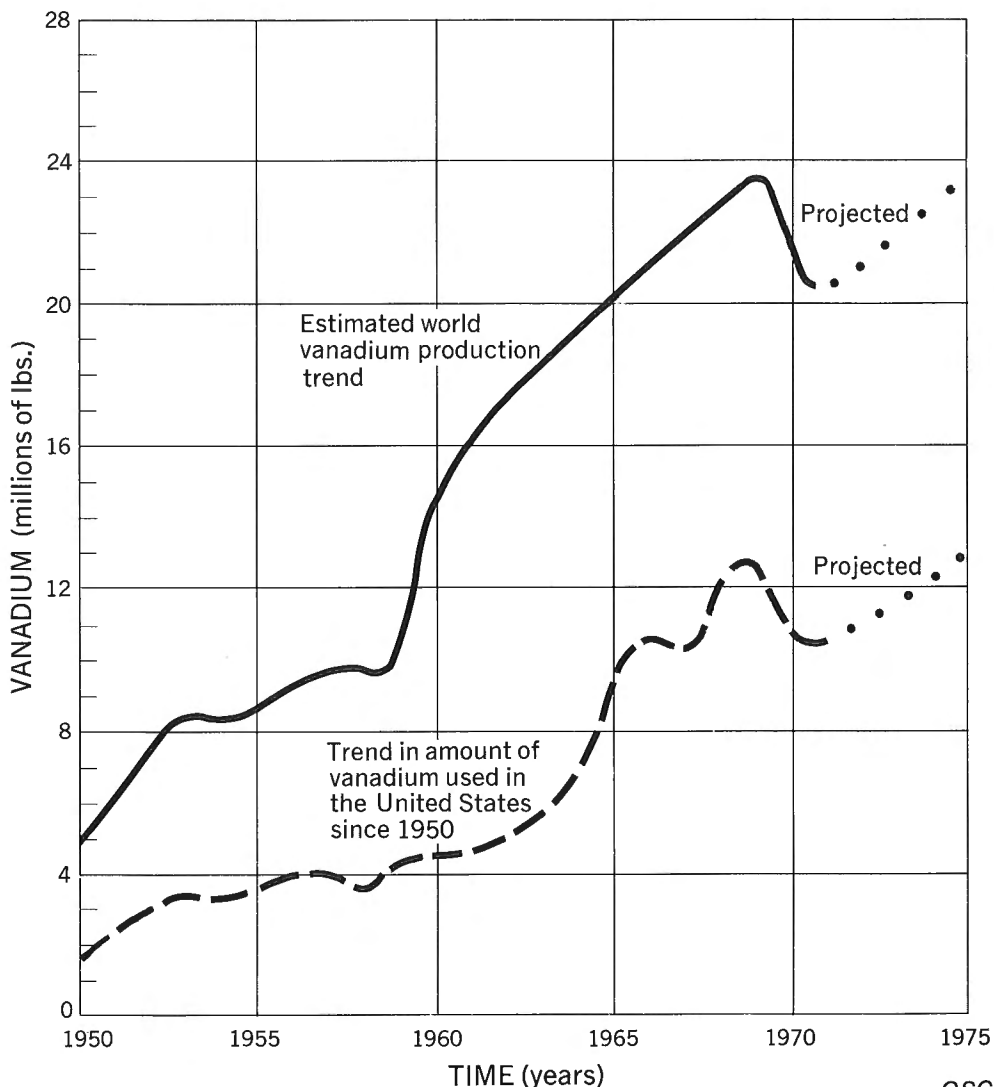


FIGURE 1. Trends in vanadium production and consumption.

GSC

McKenzie and Seybolt (1950) substituted iodine for calcium chloride in the Marden and Rich process and modified the procedure so that massive amounts of ductile vanadium could be produced on a much larger scale. Vanadium thus was changed to a metal of high industrial potential, and its price was greatly reduced.

Ductile vanadium metal is produced in the United States by Union Carbide Metals Co., and formerly by Vanadium Corporation of America, by the modified calcium-iodine method in 100-pound lots per day, in the form of regulus, ingots, and wrought shapes. Since 1950 the price of vanadium metal has been reduced from \$1,800 per pound to about \$3.45 per pound, but it is still a relatively high priced metal, and is used mainly in the form of ferroalloys and other compounds.

In 1965 the price of vanadium pentoxide ( $V_2O_5$ ) fluctuated around \$1.25 per pound, and that of ferrovandium around \$2.90 per pound. Solvan (Foote Mineral Company) and Carvan (Union Carbide) each sold at \$2.46 per pound. The price of non-ductile vanadium metal, 90 per cent pure and in 100-pound lots was about \$3.45 per pound, and that of ductile vanadium metal ranged from \$30 to \$50 a pound. However, in July 1970, 98 per cent fused  $V_2O_5$  was quoted by *Metals Week* at \$1.64 per pound, and at \$2.40 to \$2.50 by dealers for export. Standard-grade ferrovandium was quoted at \$3.47 per pound, and at \$4.65 to \$5 per pound by dealers for export, with Solvan and Carvan each at \$2.96 per pound. The increased prices of vanadium compounds at this time seem to reflect the present inflationary rise as well as a temporary shortage of the element. Present strong demand and high prices couple to make vanadium attractive financially.

### World Resources

World vanadium resources are known only in a general way, as summarized by R. P. Fischer (1961) and Briscoe (1961). The situation was reviewed more recently by Sage (1969). The metal has been recovered mainly as a byproduct of the mining and refining of other materials. Most of the high-grade vanadium deposits such as the patronite of Peru are rare and of relatively small size, but low-grade sources are larger and more abundant. Titaniferous magnetite deposits carrying more than 0.25 per cent vanadium are abundant in Canada, Finland, Russia, South Africa, and the United States, and these appear to form the world's largest reserves of recoverable vanadium. Canada is particularly well endowed. Her large area of exposed Precambrian Shield includes numerous large bodies of anorthositic and gabbroic rocks with intimately associated deposits and occurrences of vanadium-bearing titaniferous magnetite. Known world vanadium resources, as shown in Figure 2, may be summarized as follows:

#### *Argentina*

Traces of vanadium have been found in the asphaltite or solid bitumens that form seams, veins, and irregular lenses in sedimentary rocks of Middle Jurassic to Upper Cretaceous age, in the Provinces of Córdoba, San Luis, and Mendoza. Small amounts of vanadium have been recovered from the ash produced after burning asphalt.

#### *Peru*

Vanadium-bearing asphaltites in Lower Cretaceous limestone are also widespread throughout the Peruvian Andes. Until 1970, however, about 20 per cent of the world's vanadium came from a deposit of patronite (essentially a black vanadium sulphide) associated with carbonaceous material at Mina Ragra in Pasco Province on the eastern side of the high Andes. About 27,000 tons of vanadium were produced from this deposit (much of the ore carried 6 per cent vanadium) by the Vanadium Corporation of America before the mine closed in 1955.

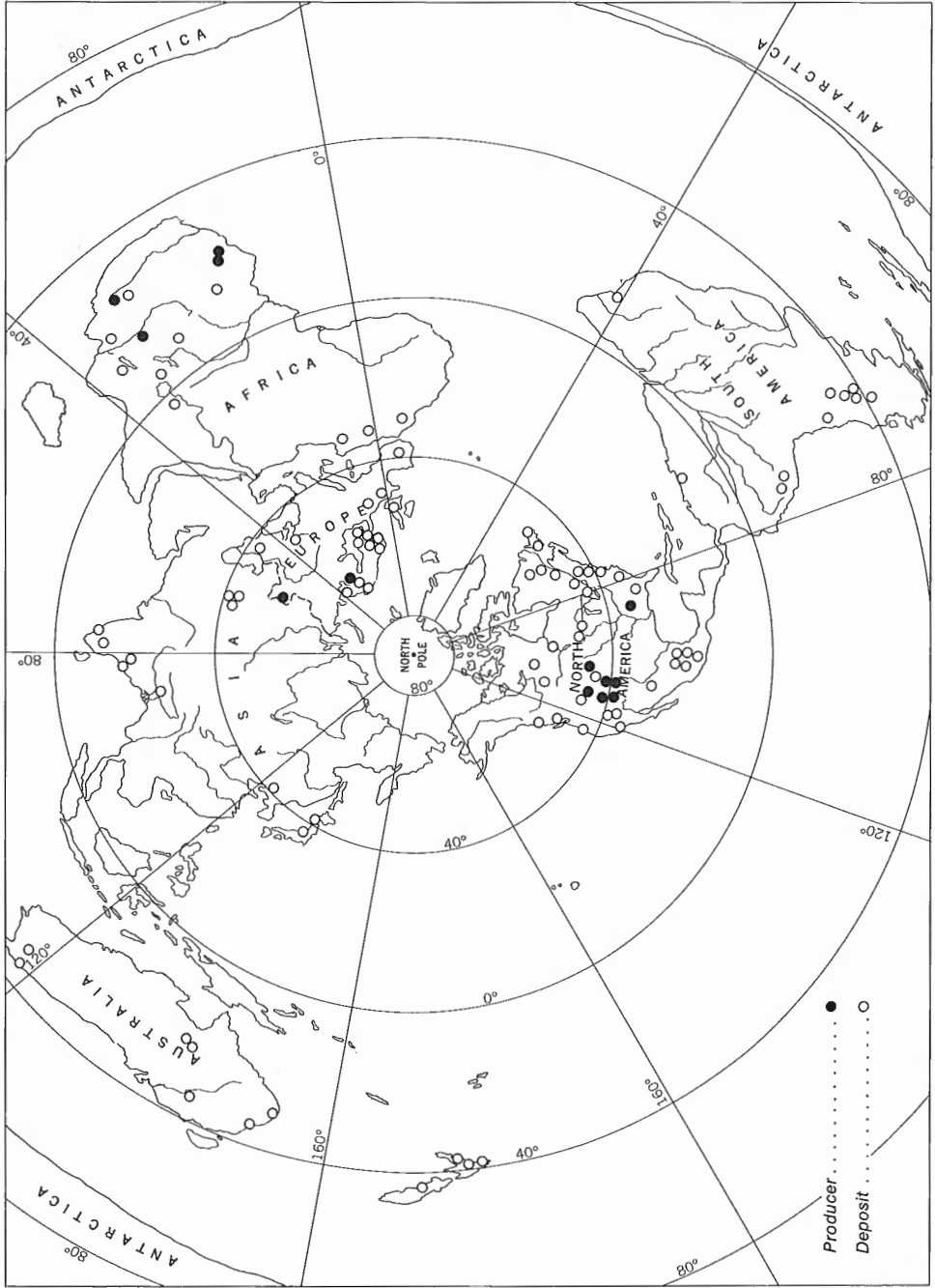


FIGURE 2. Distribution of world vanadium resources.

### *Canada*

In 1965 Canadian Petrofina Limited began to recover small amounts of vanadium from imported Venezuelan crude oil at its refinery at Pointe-aux-Trembles near Montreal. About 100 tons of vanadium pentoxide are produced annually from this plant.

The Athabasca tar sands of northern Alberta also carry faint traces of vanadium that could be recovered from the residue of the oil-refining process. Billions of tons of bitumen carrying from 0.01 to 0.02 per cent vanadium are available for processing. The first commercial production of synthetic crude oil from the Athabasca tar sands began in 1964.

Certain oil shales, lignites, and soft coals in both eastern and western Canada have also been found to be vanadiferous, as are some Canadian uranium and iron ores. Traces of vanadium are in the uranium ore and tailings of the Eldorado mines and mill at Uranium City, Saskatchewan; and in the Wabana iron ore of Newfoundland, as well as in the slag that was derived from it at the steel works in Sydney, Nova Scotia, until the mine closed in 1967.

Millions of tons of vanadium and titanium are locked in Canada's untapped titaniferous magnetite deposits, the largest of which are in the Province of Quebec. A dozen or more of the Quebec deposits probably carry more than half a million tons each of vanadium, as well as much more iron and titanium. Together they form a large potential reserve of these metals, one of Canada's great undeveloped natural resources (Rose, 1969a; 1970).

### *Finland*

The Finnish Government began mining and concentrating vanadium-bearing titaniferous magnetite at Otanmäki in 1954, and has subsequently expanded production to about 1,000 tons of  $V_2O_5$  per year. Reserves are estimated at about 50 million tons of ore carrying about 125,000 tons of vanadium.

### *Soviet Union*

Russia is reported to have in 1963 greatly expanded its vanadium production mainly from a single, large, low-grade titaniferous magnetite deposit on Kachkanar Mountain in the Urals. The deposit is said to contain 80 per cent of the Ural reserves, the ore averaging 16 per cent Fe, 0.1 per cent  $V_2O_5$ , and 1 per cent  $TiO_2$ , and the magnetic concentrate 53 per cent Fe, 0.4 per cent  $V_2O_5$ , and 4 per cent  $TiO_2$ . In 1968 Russia was reportedly building a large new ferrovanadium plant, and was shipping large tonnages of slag containing 15 per cent  $V_2O_5$  into Europe. In 1969 and 1970 Russia also marketed titanium sponge in the United States.

### *Republic of South Africa*

Recovery of vanadium from weathered rubble associated with persistent bands and plugs of titaniferous magnetite near Steelpoort in the stratiform Bushveld Complex of the Transvaal began in 1958; it was increased in 1960 and in 1962, when South Africa contributed 16.6 per cent of world vanadium production for that year. In 1968 Highveld Steel and Vanadium Corporation Limited, brought a new integrated iron, steel, and vanadium complex into operation with a new mine at Mapoch and a smelter at Witbank, intended to produce nearly half a million tons of vanadium-bearing hot metal a year, from which a slag containing about 25 per cent  $V_2O_5$ , 10 per cent  $TiO_2$ , 40 per cent FeO, and 20 per cent  $SiO_2$ , is recovered. Some of this slag is now being

marketed and processed in the United States and Europe for the manufacture of ferrovandium. Ore reserves are reported to be about 200 million tons containing 55 to 57 per cent Fe, 12 to 15 per cent  $TiO_2$ , and 1.4 to 2.5 per cent  $V_2O_5$ . The total titaniferous magnetite reserves of the entire Bushveld Complex are undoubtedly much larger.

#### *South West Africa*

Since 1920 vanadium production of South West Africa has come from lead-zinc-copper mines near Otavi and Tsumeb. Vanadinite, descloizite, and mottramite (all secondary lead-zinc-copper vanadates), with smithsonite, pyromorphite, mimetite, calamine, calcite, and clay, are found in breccias and cavities in the base-metal ores, and in 'sand sacs,'—all of which occur mainly in dolomite of the Precambrian Otavi Series. The Abenab, Abenab-West, and Berg-Aukus mines north of Grootfontein are more recent producers. Many of these deposits are nearly vertical, roughly cylindrical breccia pipes in platy limestone near its contact with massive dolomite.

Somewhat similar deposits are also found at the Broken Hill lead-zinc mine in Zambia (Northern Rhodesia), and in Angola, but vanadium production from these sources has been sporadic. Together these secondary deposits in the lead-zinc-copper ores of southern Africa provide a relatively small source of vanadium production, and they are also an important source of good crystals of vanadium minerals.

#### *United States*

As the leading consumer of vanadium United States has been most active in developing its potential sources. Its main supplies have come from the sandstone-uranium ores of the Colorado Plateau, augmented by recovery from phosphate rock of the Permian Phosphoria Formation in Idaho, lignite in the Dakotas, and more recently from laterite in Arkansas. Other potential sources of vanadium are the oil shales and hydrocarbons, titaniferous magnetite in Wyoming, New York, and Minnesota, and the low-grade uranium ores of New Mexico.

### Chapter III

## GEOLOGY OF VANADIUM

### *Anorthosite*

*Ilmenite and hematite, twin daughters of anorthosite,  
Seldom separated far;  
Keeping close to one another,  
And to their magnetic brother, titanomagnetite.  
Minerals from beneath the cover,  
Of an ancient bedrock mother,  
Born of temperature and pressure,  
At a depth too great to measure,  
Streaming vapours, seeking fissures,  
Striving upward to the light,  
Yield reluctantly their plunder,  
When the rock is torn asunder.  
Swelling the coffers of the country,  
With their abundance and their bounty.*

### General Geological Associations

The general geological associations of vanadium in Canada and elsewhere appear to be with: (1) basic igneous rocks (intrusive and extrusive), including iron- and copper-bearing types; (2) basic alkaline rocks; (3) carbonatite complexes; (4) titaniferous magnetic deposits; (5) chromite deposits; (6) uranium deposits; (7) iron and manganese deposits—marine types in particular; (8) apatite and marine phosphorite occurrences; (9) dark shales and variegated shales; (10) transported clastic, black sand, and sandstone deposits; (11) certain asphalt, asphaltite, bitumen, bituminous sandstone, lignite, coal, oil, oil shale, and graphite occurrences; and (12) residual and secondary occurrences.

Secondary vanadium minerals and vanadium-bearing materials of complex composition are more numerous and commonly much richer in vanadium than primary minerals. Concentrations of secondary minerals form many of the world's most productive sources of vanadium ore. More than 80 per cent of world vanadium has been recovered from secondary deposits, and most of this has come from deposits in sedimentary rocks of Mesozoic age. Nevertheless, vanadium occurrences are spread throughout the geological column in rocks of a wide variety of ages and types. Geological age is therefore not a reliable criterion for judging the prospects of vanadium occurrences in Canada or elsewhere.

The processes by which vanadium deposits are formed are varied and complex, and therefore most difficult to describe in general terms. For millions of years the



primary vanadium occurrences in the oldest igneous and sedimentary rocks have been more or less involved in continental and earth-shaping forces, in places resulting in recrystallization of secondary minerals once derived from primary sources. Not only have conditions of temperature and pressure varied within the earth's crust, but the atmosphere and hydrosphere have been changing, resulting in changes of environment and state of primary occurrences throughout the geological record.

The vanadium deposits of Canada are classified subjectively according to general types and processes in simplified form in Table VII. Beyond this, each occurrence must be considered separately in greater detail. Table II illustrates the geological age range of vanadium occurrences in Canada.

TABLE II *Ages of vanadium-bearing formations*

Era	Period	Age (m.y.)	
CENOZOIC	RECENT AND PLEISTOCENE		Unconsolidated black sands, north shore St. Lawrence River Titaniferous magnetite in anorthositic gabbro, East Sooke, B.C.; lignite, Sask., B.C.
	TERTIARY		
MESOZOIC	CRETACEOUS	100	Soft coal, Alta., B.C.; hematite iron ore, Peace River, Alta.; ferruginous sandstone, Burmis, Alta.; bitumen, Peru; Athabasca tar sands, Alta.; titaniferous magnetite in carbonatite, alkaline complex, Oka, Que. Phosphatic shale, Crownsnest Pass, Alberta; uranium-bearing sandstone, Colorado Plateau, U.S.A.
	JURASSIC		
	TRIASSIC	200	Bituminous sediment and andesite-basalt, Quadra Island and Menzies Bay, B.C.
PALEOZOIC	PERMIAN		Phosphate rock, Phosphoria Formation, Alta., Idaho, Montana.
	PENNSYLVANIAN	300	Spheroids of reduction in 'red beds,' P.E.I.; bituminous coal, New Glasgow, N.S.
	MISSISSIPPIAN		Oil shale and albertite, Albert Mines, N.B.; oil shale, Nfld.
	DEVONIAN	400	Dark shale, Kettle Point, Ontario; red sandstone, Grand Falls, Nfld., Chattanooga shale, Tenn.
	SILURIAN		Chromite in serpentinite, Coleraine Twp., Que.; oölitic hematite, Torbrook, N.S.
	ORDOVICIAN		Dark slate, Gataga River, B.C.
	CAMBRIAN	500	Oölitic hematite, Wabana, Nfld. Manganiferous shale, Manuels, Nfld. Maroon arkose, Elgin, Ont.

TABLE II  
(conc.)

Era	Period	Age (m.y.)	
PRECAMBRIAN		600	
		700	
		800	
		900	Titaniferous magnetite in gabbroic anorthosite, Man., Ont., Que., and Nfld.
		1,000	Logan diabase sills, Nipigon, Ont. Sibley series argillite and nodules, Nipigon, Thunder Bay, Ont.; Muskox Complex and Coppermine basalts, N.W.T.
		1,100	Titaniferous magnetite in gabbroic
		1,200	anorthosite, Magnetite Lake, Labrador, Nfld., and Duluth gabbro, Minn.
		1,300	
		1,400	
		1,500	Nolanite in pitchblende-bearing deposits, Beaverlodge area, Sask.
		1,600	Titaniferous magnetite in gabbro and charnockite, India
		1,700	
		1,800	
		1,900	
		2,000	Titaniferous magnetite, Bushveld Complex, South Africa
		2,100	Titaniferous magnetite in diabase, Angus Twp., Ont.
		2,200	Vanadium in sedimentary rocks, Huronian-Timiskaming, Spanish, Ont. (?)
		2,300	Titaniferous magnetite, Lac Doré Complex, Que. (?)
		2,400	Vanadium in ashrock and iron ore, Steeprock Lake, Ont. (?) Titaniferous magnetite in anorthositic gabbro, Cross (Pipestone) Lake, Man., Bad Vermilion Lake-Seine Bay, Ont. (?)
		2,500	Vanadium in chromite-bearing peridotite, Bird River, Man. (?) Vanadium in graphitic schists, Star Lake, Man. (?)
	2,600		
	2,700	Vanadium in metavolcanic rocks, andesite-basalt (Superior Province), Ont., Que. (?)	

## Geochemistry

Vanadium is one of the most common trace elements, ranking twenty-second in abundance in the earth's crust. Its estimated average distribution in major units is indicated in Table III. It averages about 150 parts per million (0.015 per cent) in igneous rocks (Goldschmidt, 1954), is more abundant than zinc, about twice as much as nickel or copper, about six times as much as niobium (columbium), and about ten times as much as lead or molybdenum. It is three or more times as abundant in basic igneous rocks as in acidic igneous rocks, and is generally less so in sedimentary and metamorphic rocks (with certain exceptions) than in igneous rocks.

Most of the vanadium in igneous rocks is believed to be in the relatively insoluble trivalent cation state ( $V^{+3}$ ). Its ions substitute for and replace those of iron, aluminum, and silicon in ferromagnesian minerals; and those of iron, titanium, and chromium in titaniferous magnetite, ilmenite, and chromite. Vanadium is relatively abundant in magmatic iron ores, especially in titaniferous magnetite, and according to Fischer (Busch, 1961), like titanium also shows a faint tendency to concentrate in hydrothermal veins extending from magmatic activity, and in gold telluride veins. In the  $V^{+2}$  form it is a constituent of certain rare sulphide minerals, in the  $V^{+4}$  form in bituminous deposits, and in the  $V^{+5}$  form in the zone of weathering. The  $V^{+3}$  ion has been identified in the laboratory, but not as yet in nature. Because of the amphoteric nature of vanadium, its four natural states of oxidation ( $V^{+2}$ ,  $V^{+3}$ ,  $V^{+4}$ ,  $V^{+5}$ ), and its ability to form radicals and complex chemical compounds either as an anion or cation, it is also associated with uranium, niobium, and rare earths in more acidic and alkaline rocks, and with phosphorus in phosphate occurrences. Its ability to form a complex porphyrin or organometallic compound with a molecular structure similar to that of chlorophyll may account in part for its association with various types of organic matter, hydrocarbons, and carbon.

During rock weathering, vanadium is commonly incorporated with aluminum in clay minerals. During further decomposition of the clay minerals vanadium and aluminum may be released as soluble hydroxides which may be transported and re-precipitated or incorporated in secondary forms elsewhere. This may occur in either acidic or basic solutions under either oxidizing or reducing conditions, in contrast to uranium which is precipitated almost entirely in neutral or basic environments.

### Geochemical Character

Vanadium is grouped with phosphorus, niobium (columbium), and tantalum in Group V of the Periodic Table, and with titanium, chromium, manganese, iron, cobalt, and nickel, as a member of the iron family, or ferride group of elements, of the fourth period of the Periodic System. It is generally associated with these elements in nature, and becomes partitioned between the structurally compact early oxide minerals, and the less compact structures of the ferromagnesian silicate minerals such as olivine, pyroxene, garnet, amphibole, and mica, in which it may replace aluminum and iron, and to some extent, magnesium and silicon.

Because of its affinity for oxygen, relatively insoluble trivalent vanadium ( $V^{+3}$ ) may be oxidized to the more soluble quinquevalent form ( $V^{+5}$ ) in both acids and

alkalis during the cycle of weathering or during hydrothermal alteration. In this way it may be dissolved and transported, and later precipitated by iron or aluminum hydroxides, by heavy metals, or by other reducing agents such as carbon. It may also be absorbed by clay minerals, absorbed or precipitated by organisms, or combined to form porphyrins or organometallic complexes.

TABLE III *Estimated average vanadium content of material in earth's crust (ppm)*

Rock Material	Turekian and Wedepohl (1961)	Rankama and Sahama (1950)	Krauskopf (1955)	Vinogradov (1956)	Green (1959)	Champlin and Dunning (1960)	Gold-schmidt (1954)
<b>IGNEOUS ROCKS</b>		150-315	150		90		150
Ultrabasic	40	17		140	140		
Basic	250	56-320		200	210		
Acidic	30-88	17-34		100	95		
<b>SEDIMENTARY</b>							
Clay	120	120					
Shale	130	120	50-300	130	90-130		
Carbonate	20	<10	2-20		2-20		
Sandstone	20	20	10-60		10-60		
Iron sand		500					
Green sand		68-220					
Öölitic iron		500					
Bog iron		<10					
Laterite- bauxite		400					
Phosphorite		<10					
Crude oil					30		
Asphaltic oil						23-280	
Asphalt		5,400					
Bituminous phosphates		1,600					
Coal		900				280	
<b>METAMORPHIC</b>							
Orthogneiss		5					
Paragneiss		20-70					
Quartzite		5-34					
Schist		34-56			93		
Carbonate		1.7					
Graphite		200					
<b>OCEAN</b>		0.0003			0.001		
Deep sea sediments					330		
<b>UPPER LITHOSPHERE</b>							150
<b>METEORITES</b>		6-50					

## Biogeochemistry

Vanadium may be beneficial or toxic to life depending on its concentration and on the particular organism. It occurs in soils as vanadates of copper, zinc, lead, uranium, iron, manganese, calcium, and potassium; replaces aluminum in clays; is high in the organic-rich fraction of phosphate rocks, the sapropelite of black organic shales, and in porphyrin complexes of bituminous sediments (Cannon, 1963). According to Vinogradov (1959, p. 183) the average vanadium content of world soils is 100 parts per million. Small amounts of vanadium are stimulating to most plants, but 10 to 20 ppm vanadium in solution is commonly harmful, and concentrations as low as 2.5 ppm may be toxic to some. Specific nitrogen-fixing legumes, however, can tolerate larger amounts, and certain plants such as *Aspergillus niger* require vanadium for growth. Vanadium is essential to the growth of the green algae *Scenedesmus obliquus*, a photosynthetic plant (Aron and Wessel, 1953).

Herbs such as *Allium*, a species of *Astragalus*, *Castilleja*, and *Chrysothamnus* accumulate more vanadium than trees and shrubs in which it accumulates mainly in the roots and old wood. Plants rooted in seleniferous soil have a higher vanadium content than those in calcic soil.

Vanadium is a component of the poisonous *Amanita muscaria* mushroom, the 'Destroying Angel,' which may contain more than 100 ppm of the element and is toxic to humans. Five to six ppm vanadium is toxic to rabbits. Alternatively, a content of slightly more than 0.03 to 0.22 ppm vanadium in water helps prevent dental cavities, and there is evidence that vanadium mine workers in Colorado have a lower blood cholesterol content than control groups elsewhere. Thus vanadium compounds may have medical and pharmaceutical use in the study and prevention of heart disease (Lewis, 1959). Low concentrations of vanadium can apparently partly offset iron-deficiency symptoms in animals and man, especially when these symptoms are aggravated by excess manganese (Gilbert, 1957).

Vanadium is present in certain lichens, mosses, and other plants; in peats, lignites, and coals; and it may be enriched in the ashes derived from them. (Some of this is undoubtedly derived from vanadium-accumulating plants.) The concentration of vanadium in some plant species growing around uranium-vanadium deposits in the western United States is as high as 900 ppm (Cannon, 1960). Vanadium is found in 10 per cent concentration in the blood of marine organisms, holothurians (sea cucumbers) and ascidians (sea-squirts); in certain heavy crude oils (1 to 3 per cent), notably from Persia, Venezuela, and California; in derived bitumens and solid hydrocarbons (quisqueite, shungite, anthraxolite); asphalt and asphaltites (gilsonite, impsomite, albertite); as well as in graphite, graphitic schists, and black shales—all of organic origin—in variable amounts. Bituminous limestones contain more vanadium than other types according to Jost (1932).

## Mineralogy

### Vanadium Minerals

Although more than a hundred vanadium-bearing minerals have been identified, there are probably less than twenty primary vanadium minerals, about 80 per cent of the total being secondary, formed in the zone of weathering and oxidation, or by metamorphic processes. Primary vanadium minerals include: patronite, roscoelite, sulvanite, colusite, davidite, ardennite, bravoite, nolanite, brannerite, coulsonite

(magnetite with 2 to 5 per cent vanadium), sefstromite, vanadium-bearing chromite, and other spinels. All these minerals have been reported in Canada with the exception of patronite, colusite, and ardennite. The secondary minerals, few of which have been found in Canada, include: vanadinite, descloizite, cuprodescloizite, mottramite, brackebuschite, barnesite, hewettite, meta-hewettite, sincosite, pascoite, corvusite, carnotite, tyuyamunite, metatyuyamunite, rauvite, volborthite, calciovolborthite, simplotite, uvanite, rossite, metarossite, montroseite, paramontroseite, vanoxite, doloresite, duttonite, delrioite, alaite, ferghanite, fervantite, turanite, fernandinite, uzbekite, melovanadinite, endlichite, huegelite, tangeite, pyrobelonite, dechenite, gamagarite, kolovratite, minasragrite, pucherite, steigerite, sengierite, sherwoodite, pintadoite, navajoite, haggite, francevillite, vesignieite, hummerite, arseniovanadinite, tanzanite, vanadium-bearing chlorite, clay, and hydromica.

### *Identification of Vanadium Minerals*

Because of the great variety and range of vanadium minerals as well as the marked similarities of some of these minerals to one another and to other non-vanadiferous minerals, they are difficult to identify both in the field and in the laboratory. The precise identification of vanadium mineral species is therefore the task of the well-equipped mineralogy laboratory and mineralogist. Table IV summarizes the chief characteristics and associations of known vanadium minerals, and illustrates some of the complexity of identifying them. In Table IV the names of the main ore minerals of vanadium are set in boldface type, but in nature the ores are commonly mixtures of several of these minerals, and in places they may include many rare varieties.

### *Detection of Vanadium*

The prospector or geologist may be assisted in attempts to detect and identify vanadium-bearing minerals in the field by portable equipment such as pocket knife, hand lens, magnet, radiation detector, blowpipe, and chemical kit. All titaniferous magnetite and iron deposits, radioactive occurrences, phosphate, bituminous, and carbonaceous deposits should be investigated for vanadium content. Traces of brightly coloured secondary vanadium hydroxide blooms should be sought, but they may not always be present. Bleached zones, or zones of reduction, in 'red bed' sequences merit careful examination. In many places little evidence of the presence or absence of vanadium may be available in outcrop or hand specimen, even in potential ore material.

Fortunately, when vanadium is present in amounts of 0.01 per cent or more in rocks, it may usually be detected by chemical tests in the field. Several such tests have been devised. The writer has found the following one to be practical, simple, and useful.

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

TABLE IV | Characteristics and occurrences of vanadium minerals

Mineral	Composition	Properties	Association	Occurrence	Location
SULPHIDES AND SULPHOVANADATES <b>Patronite</b>	Complex V sulphide, a mixture VS <sub>4</sub> or V <sub>2</sub> S <sub>5</sub> +nS+C+Fe	Soft, greenish black, pitchy, coaly mass	With quisquite, pascoite, minasragrite	In asphalt-coke in Cretaceous bleached red shale	Mina Ragra, Andes Mountains, Peru
<b>Colusite</b>	Basemetal, V sulphide	Bronze, metallic (like pyrrhotite)	Enargite, tennantite, chalcocite, pyrite, etc. Quartz	In vein stockworks in quartz monzonite, of Cretaceous age	Colusa Mine, Butte, Montana
<b>Sulvanite</b>	Copper V sulphide, 3Cu <sub>2</sub> S·V <sub>2</sub> S <sub>5</sub>	Bronze, metallic cubic crystals	Quartz	As crystals in quartz veins in Ordovician shale, British Columbia	Burra-Burra, South Australia; Mercur, Utah; British Columbia
<b>Arsenosulvanite</b> <b>Bravoite</b>	Cu <sub>3</sub> (As, V) S <sub>4</sub> (Fe, Ni) S <sub>2</sub> with 5% V in places	Arsenical sulvanite Pale yellow metallic octahedrons	With patronite, etc., in asphalt	In bleached red shale of Cretaceous age	Mina Ragra, Peru
OXIDES <b>Titanomagnetite</b>	Fe (Ti, V) <sub>3</sub> O <sub>4</sub>	Hard, black magnetic	Ilmenite	In basic igneous rocks—Precambrian to Recent	Otanmäki, Finland; South Africa; United States; Canada
var. 'Coulsonite'	(Fe, Ti, V) <sub>3</sub> O <sub>4</sub>	Hard, black, magnetic	Ilmenite	In basic igneous rocks—Precambrian to Recent	Otanmäki, Finland; India; South Africa; United States; Canada
<b>Selströmite</b>	Vanadiferous ilmenite				
<b>Chromite</b>	(Fe, Mg)O· (Cr, Al, V) <sub>2</sub> O <sub>3</sub>	Hard, black, magnetic	Serpentine, talc	In serpentinite	Coleraine, Quebec

<sup>1</sup>Minerals set in boldface type are important ore minerals.

Montroselite	$(V, Fe)O \cdot OH$	Soft, brown-black crystalline aggregates	With pyrite in U-V ores	In sandstone of Mesozoic age	Colorado Plateau
Paramontroselite	$VO_2$	Black velvety powder	With haggite, etc.	In sandstone of Mesozoic age	Colorado Plateau
Alaite	$V_2O_5 \cdot H_2O$	Bluish red, moss-like			Ferghana, Turkistan
Brannerite	$(U, V, Fe, Ce, Y, Th)_5Ti_5O_{16}$	Black heavy, isometric	With Au, monazite, uraninite, etc.	In placer sands and Precambrian conglomerate	Idaho; Elliott Lake, Ontario
Doloresite	$(3V_2O_4 \cdot 2H_2O)$	Green crystals	Red-brown fragments, in U-V ores	In Mesozoic limestone	Colorado Plateau; New Mexico
Protodoloresite	$V_2O_3 \cdot 2V_2O_4 \cdot 5H_2O$				
Duttonite	$VO \cdot (OH)_2$	Light brown, vitreous	With montroselite, etc.	In Mesozoic sandstone	Colorado Plateau; New Mexico
Paraduttonite	$V_2O_5 \cdot H_2O$				
Haggite	$V_2O_2 \cdot (OH)_2$	Greenish yellow crystals	With paramontroselite	On sandstone	Colorado Plateau; New Mexico
Navajoite	$V_2O_5 \cdot 3H_2O$	Dark brown powder and fibres	With rauvite, etc.	In seams and disseminated in Mesozoic sandstone	Colorado Plateau; Arizona
Davidite	Ti, Fe, U, V, RE <sup>1</sup> , bearing mineral	Hard, brittle, black, isotropic	With ilmenite, rutile, and radioactive minerals	In pegmatite, soda-rich granites, veins	Oiary, Australia; Mozambique
Karelianite	$V_2O_3$	Hard, black, hexagonal	With pyrrhotite, chalcopyrite, pyrite, nolanite, and graphite in quartzite	In quartzite and copper ore boulders	Outokumpu, Finland
SILICATES					
Roscoelite	Vanadium mica $(Al, V)_2(Al, Si)_3(K, Na)O_{10}(OH, F)_2$ Sr V Si <sub>2</sub> O <sub>7</sub>	Green, grey; tan, monoclinic plates	With quartz and gold tellurides, etc.	In veins and in Mesozoic sandstone	Colorado Plateau
Haradaite	Hydrous V Al silicate	Grey, scales	With U-V minerals	In Mesozoic sandstone	Colorado Plateau
Vanadium hydromica	Hydrous V Al silicate	Grey-green scales	With U-V minerals	In Mesozoic sandstone	Colorado Plateau
Vanadium chlorite	Hydrous V Al silicate	Grey, earthy	With U-V minerals	In Mesozoic sandstone	Colorado Plateau
Vanadium clay					

<sup>1</sup>Rare earth



TABLE IV  
(cont.) *Characteristics and occurrences of vanadium minerals*

Mineral	Composition	Properties	Association	Occurrence	Location
SILICATES (cont.) Kurumsakite	$(Zn, Ni, Cu)_8 Al_8 V_2 Si_5 O_{35} \cdot 27H_2O$	Greenish yellow		In cavities in bituminous schists	Kara-Tan Mountains, Turkestan
Ardennite	V-bearing epidote	Yellow to brown	With quartz		Salm-Château, Belgium
(Dewalquite)	$8 MnO \cdot 4 Al_2 O_3 (As, V)_2 O_3 \cdot 8 Si O_2 \cdot 5 H_2 O$	Orthorhombic prismatic crystals	With sericite, pyrite		Ala Valley, Italy
Cavansite	$Ca(VO)(Si_4 O_{10}) \cdot 6 H_2 O$	Green-blue	With ruby, corundum, and zoisite	In volcanic rock and gneiss	Arusha, Tanzania
Tanzanite	V-bearing zoisite		With V minerals	In sandstone near diabase sill	Laguna, New Mexico
Goldmanite	V-bearing garnet	Deep green-brown			
(Manganoo goldmanite)	$(Ca_3 V_2 Si_3 O_{12})$ with Mn				
Vanadifolite	Silicate and vanadate of Ca				
Yamatolite	$Mn_3 V_2 Si_3 O_{12}$				
VANADITE					
Simplifite	$CaO \cdot 2V_2 O_4 \cdot 5H_2 O$	Black to yellow green	With U-V minerals	In Mesozoic sandstone	Colorado Plateau
VANADYLVANADATES					
Corvusite	$V_2 O_4 \cdot 6V_2 O_5 \cdot nH_2 O$	Blue-black, powdery crystals	With U-V minerals	In Mesozoic sandstone	Colorado Plateau
Vanoxite (Kensmithite)	$2V_2 O_4 \cdot V_2 O_5 \cdot 8H_2 O$	Black to dark brown	With U-V minerals	In Mesozoic sandstone	Colorado Plateau

Nolanite	$3\text{FeO} \cdot \text{V}_2\text{O}_3 \cdot 3\text{V}_2\text{O}_4$	Black, hard, pitchy	With pitchblende, ilmenite	In veins in Precambrian meta-sediments, and mylonite	Beaverlodge, Sask.
Melanovanadite	$2\text{CaO} \cdot 2\text{V}_2\text{O}_4 \cdot 3\text{V}_2\text{O}_5 \cdot \text{H}_2\text{O}$	Black, velvety crystals	With pascoite, rossite	In veins in Precambrian metasediments; Mesozoic shale	Beaverlodge, Sask.; Peru
Fernandinite	$\text{CaO} \cdot \text{V}_2\text{O}_4 \cdot 5\text{V}_2\text{O}_5 \cdot 14\text{H}_2\text{O}$	Dull green, fibres	With patronite, etc.	In veins in shale	Peru; Colorado
Grantsite	$\text{Na}_4\text{Ca}(\text{V}^{+4}\text{O})_2\text{V}^{+5}\text{O}_{30} \cdot 8\text{H}_2\text{O}$	Blue-green to black plates	With anthraxolite	In oxidized clay beds	Russia
Hendersonite	$\text{Ca}_2\text{V}_{17-18}\text{V}_{6-8}\text{O}_{65-70}(\text{O}, \text{OH})_{24} \cdot 8\text{H}_2\text{O}$	Yellow to orange crystals	With motttramite	In Mesozoic sandstone	Arizona
VANADATES		Deep brownish red			Colorado Plateau; Utah
Alvanite	$3\text{Al}_2\text{O}_3 \cdot \text{V}_2\text{O}_5 \cdot 11\text{H}_2\text{O}$				
Arseniovanadinite	As-bearing vanadinite				
Barnesite	$\text{Na}_2\text{O} \cdot 3\text{V}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$				
Bokite	$\text{K}, \text{Al}_3\text{Fe}_6\text{V}^{+4}\text{V}_6^{+5}\text{O}_{16} \cdot 30\text{H}_2\text{O}$				
Brackebuschite	$2(\text{Pb}, \text{Mn}, \text{Fe})\text{O} \cdot \text{V}_2\text{O}_5 \cdot \text{H}_2\text{O}$	Black, needles	With descloizite	In altered sandstone	Cordoba, Argentina
Calciovolborthite	$(\text{Cu}, \text{Ca})_2 \cdot (\text{VO}_4)(\text{OH})$	Bright yellow-green, scaly	With Cu, Ca minerals	Coatings on Triassic argillite, etc., and Mesozoic sandstone	Menzies Bay, British Columbia; Utah; Colorado Plateau
(Tangeite) (Kalkvolborthite) Carnotite	$\text{K}_2(\text{UO}_2)_2 \cdot (\text{VO}_4)_2 \cdot 3\text{H}_2\text{O}$	Bright yellow powder	With U-V minerals	Coatings on Mesozoic sandstone; on argillite and lava	Colorado Plateau; Quadra Island, British Columbia
Chervette Chileite	$\text{Pb}_2\text{V}_2\text{O}_7$ $\text{Pb}, \text{Cu}(\text{V}, \text{As})\text{O}_4$ OH				
Cuprodescloizite	$4(\text{Cu}, \text{Zn}, \text{Pb})\text{O} \cdot (\text{V}, \text{As})_2\text{O}_5 \cdot \text{H}_2\text{O}$	Greenish black, red-brown cellular	With Pb ores, descloizite	Pb ores and sandstone	Rhodesia; Colorado Plateau
Colliteite	$(\text{Pb}, \text{Ca})_5(\text{P}, \text{V})\text{O}_4\text{I}_3 \cdot \text{Cl}$	Var. of pyromorphite			
Delrioite	$\text{CaO} \cdot \text{SrO} \cdot \text{V}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$	Pale yellow to green	With metarossite	On Mesozoic sandstone	Colorado Plateau

TABLE IV  
(cont.)

Mineral	Composition	Properties	Association	Occurrence	Location
<i>VANADATES (cont.)</i>					
Dechenite	$PbO \cdot V_2O_5(?)$	Yellow to brownish red, heavy, nodular	With lead minerals	In Pb ores and sandstone	Bavaria, Germany; Carinthia, Austria
<b>Desloizite</b> (Vanadite) (Eusynchite) Schmarrerite Endlichte	$4(Zn, Cu, Pb) O \cdot V_2O_5 \cdot H_2O$ Variety of desloizite $Pb_4(V, AsO_4)_3Pb Cl$	Red to black, crystals (like sphalerite) Yellow tan, heavy hexagonal crystals	With lead minerals	In altered Mesozoic sandstone	Rhodesia; Colorado Plateau
(Arsenovanadinite)	Vanadate and molybdate of lead				New Mexico; South Dakota
Eosite	$3UO \cdot V_2O_5 \cdot 6H_2O$	Yellow scales	With tyuyamunite	In Mesozoic sandstone	Ferghana, Russia
Ferghanite	(With Si in places) $Fe_4V_4O_{16} \cdot 5H_2O$	Golden brown fibres	With hewettite, etc.	In Mesozoic sandstone	Colorado Plateau
(Ferganite)	(Ba, Pb) $(UO_2)_2$	Greenish yellow films	With rauvite in nodules	In Permo-Carboniferous sandstone	Prince Edward Island
Fervantite	$(VO_2)_2 \cdot 5H_2O$ Phosphate and vanadate of Mn and U				
Francevillite (Barium francevillite) Fritzscheite	$Ba_4(Fe, Mn)_2V_4O_{15} \cdot (OH)_2$ (Al, Fe) $_3(V, P)O_4$ $(OH)_3 \cdot 7\frac{1}{2} - 8\frac{1}{2} H_2O$ Ca $V_6O_{16} \cdot 9H_2O$	Dark brown needles	Sitaparite, ephesite	In manganese ore	Postmasburg, South Africa
Gamagarite					
Gutsevichite					
<b>Hewettite</b>		Deep red aggregates	With U-V minerals	In Mesozoic sandstone, etc.	Colorado Plateau; Peru, Baden, Germany
Huegelite	Hydrous Zn, Pb vanadate	Yellow to brown			

Huemulite	$\text{Na}_4\text{MgV}_{10}\text{O}_{28} \cdot 24\text{H}_2\text{O}$	Soft yellow-orange films	With U-V minerals	In sandstone	Mendoza, Argentina
Hummerite	$\text{K}_2\text{Mg}_2\text{V}_{10}\text{O}_{28} \cdot 16\text{H}_2\text{O}$	Bright orange	With hewettite, etc.	In veins and crusts in sandstone	Colorado Plateau
Kolovratite	Ni vanadate (?)	Yellow-green crusts	With U-V minerals	In quartz schist and carbonaceous slates	Ferghana, Turkistan
Metahewettite	$\text{CaV}_6\text{O}_{16} \cdot 9\text{H}_2\text{O}$ (?)	Deep red aggregates	With U-V minerals	In Mesozoic sandstone, etc.	Colorado Plateau; Peru
Metarossite	$\text{CaV}_2\text{O}_6 \cdot 2\text{H}_2\text{O}$	Pale pearly yellow	With U-V minerals	In Mesozoic sandstone	Colorado Plateau; Colorado Plateau; South Dakota;
Metatyuyamunite	$\text{Ca}(\text{UO}_2)_2(\text{VO}_4)_2 \cdot 5\text{H}_2\text{O}$	Yellow scales, powder	With U-V minerals	In Pb ores	Ferghana
Mottramite	$(\text{Cu}, \text{Zn})\text{Pb}(\text{VO}_4) \cdot (\text{OH})$	Green-black crystals	With Cu, Zn, Pb minerals	In sandstone	Africa; Arizona; England
(Ramirite of Mexico) (Psittacinite)	$4(\text{Pb}, \text{Cu})\text{O} \cdot \text{V}_2\text{O}_5 \cdot 2\text{H}_2\text{O}$		In Pb, Cu ores		Africa; Colorado Plateau; Russia
(Vesbine) Pascoite	$\text{Ca}_2\text{V}_6\text{O}_{17} \cdot 11\text{H}_2\text{O}$	Orange to yellow powder	With U-V minerals	In Mesozoic sandstone, etc.	Colorado Plateau; Peru
Pintadoite	$2\text{CaO} \cdot \text{V}_2\text{O}_5 \cdot 9\text{H}_2\text{O}$	Green	With V minerals	In Mesozoic sandstone	Colorado Plateau
Pucherite	$\text{Bi}_2\text{O}_3 \cdot \text{V}_2\text{O}_5$	Red-brown, heavy crystals	With V minerals	In veins and disseminations	Saxony, Germany; California
Pyrobelonite	$4\text{PbO} \cdot 7\text{Mn O}_2 \cdot \text{V}_2\text{O}_5 \cdot 3\text{H}_2\text{O}$	Red needles	With U-V minerals	Coating Mesozoic sandstone, and	Langban, Sweden
Rauvite	$\text{CaO} \cdot 2\text{UO}_3 \cdot 6\text{V}_2\text{O}_5 \cdot 20\text{H}_2\text{O}$	Red to black	With U-V minerals	Permo-Carboniferous sandstone	Colorado Plateau; Prince Edward Island
Robellazite	Vanadate, tungstate, columbate, and tantalate of Fe, Al, and Mn		With metarossite		
Rossite	$\text{CaV}_2\text{O}_6 \cdot 4\text{H}_2\text{O}$	Yellow, vitreous		Coating and veinlets in sandstone	Colorado Plateau
Rusakovite	$(\text{Fe}, \text{Al})_5(\text{V}, \text{P})\text{O}_4\text{I}_2$				
Santafeite	$(\text{OH})_9 \cdot 3\text{H}_2\text{O}$ $\text{Na}_2\text{O} \cdot 6(\text{Mn}, \text{Ca}, \text{Sr})\text{O} \cdot 3\text{MnO}_2 \cdot 8(\text{V}, \text{As})_2\text{O}_5 \cdot 8\text{H}_2\text{O}$	Black needles and rosettes		On limestone joints	Colorado Plateau

TABLE IV  
(cont.)

Characteristics and occurrences of vanadium minerals

Mineral	Composition	Properties	Association	Occurrence	Location
VANADATES (cont.) Safpaevite	$6Al_2O_3 \cdot V_2O_4 \cdot 3V_2O_5 \cdot 30H_2O$	Pearly to dull yellow powder	With anthraxolite, steigerite, hewettite, gypsum	In weathered zones of clay beds and carbonaceous shale	Russia
Sengierite	$2Cu \cdot 2UO_3 \cdot V_2O_5 \cdot 10H_2O$				Congo
Sherwoodite	$Ca_3V_8O_{22} \cdot 15H_2O$	Blue-black tetragonal crystals			Colorado Plateau
Steigerite	$Al_2(VO_4)_2 \cdot 6\frac{1}{2}H_2O$	Yellow, waxy, canary yellow, gumlike coatings	With V minerals	Coating sandstone	Colorado Plateau
Chromsteigerite	$2CaO \cdot 2CuO \cdot V_2O_5 \cdot H_2O$	Dark olive green	With Cu minerals	In sandstone	Colorado Plateau; Turkistan
Tangeite	$5CuO \cdot V_2O_5 \cdot 2H_2O$	Olive green, radial	With Cu minerals		Ferghana, Turkistan
Turanite	$Ca(UO_2)_2(VO_4)_2 \cdot 7H_2O$	Yellow scales, powder	With carnotite, etc.	In Mesozoic sandstone	Ferghana, Turkistan; Colorado Plateau
(Calciocarnotite) Uvanite	$2UO_3 \cdot 3V_2O_5 \cdot 15H_2O$ (?)	Brown-yellow	With U-V minerals	In Mesozoic sandstone, etc.	Colorado Plateau
Uzbekite (?) Vanadinite	$3CuO \cdot V_2O_5 \cdot 3H_2O$ $Pb_4(VO_4)_3 \cdot PbCl$	Green needles	With Pb minerals	In Pb ores in sandstone	Ferghana, Turkistan
(Cuprovanadinite) Vesignieite	$(Pb, Cu)_5(VO_4)_3Cl$ $Cu_3Ba(VO_4)_2(OH)_2$	Red, yellow, brown, hexagonal crystals	and barite		Mexico; Colorado Plateau; Africa
Volborthite	$Cu_3(VO_4)_2 \cdot 3H_2O$ (?)	Vitreous yellow-green lamellar	With gypsum, etc.	In Mesozoic sandstone, etc.	Colorado Plateau; Ural Mts.; Ferghana, Turkistan
Vanuralite	$(UO_2)_2 \cdot Al(VO_4)_2 \cdot 8H_2O$	Dark green-yellow (green like epidote)			

Vanuranlyite	$(\text{H}_3\text{O})_2\text{U}_2\text{V}_2\text{O}_{12} \cdot 3 \cdot 6 \text{H}_2\text{O}$ Vanadate of Pb	Blue, mammillary	On patronite	Alteration product	Mina Ragra, Peru
Wicklowite (Vichlovite)					
SULPHATE Minasragrite	$\text{V}_2\text{O}_4 \cdot 3\text{SO}_3 \cdot 16\text{H}_2\text{O}$	Grey to green to brown Leek green	In phosphorite and veins With V minerals	In black shale and in pegmatites In veins and crusts	Idaho; Ontario; Quebec Colorado Plateau; Peru
PHOSPHATES V-apatite	$\text{Ca}_3[(\text{P}, \text{V})_2\text{O}_3]_2$	Reddish grey, cleaved, orthorhombic crystals	With phosphates	On thin coatings	Cornwall, England
Sincosite	$\text{Ca V}_2\text{O}_2(\text{PO}_4)_2 \cdot 5\text{H}_2\text{O}$ (V, Ce, Ca) $\text{PO}_4 \cdot 2\text{H}_2\text{O}$				
Churchite					
Schoderite	$\text{Al}_2\text{VO}_4 \cdot \text{PO}_4 \cdot 8\text{H}_2\text{O}$				
Metaschoderite	$\text{Al}_2\text{VO}_4\text{PO}_4 \cdot 6\text{H}_2\text{O}$				
ORGANIC MINERAL Rafaelite	Vanadiferous asphaltite				

To ensure 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 ( $K_2S_2O_8$ ) 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 formation of a pale orange solution which deepens to brown with an increasing percentage of vanadium. The test is not entirely satisfactory, particularly for brown organic and some ferruginous solutions that mask the colour; this must be overcome by filtration and dilution. The yellow 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 in 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.

#### *Procedure*

1. Prepare sample by crushing and grinding to powder, using available tools or equipment (e.g., pair of pliers, two hammers, small mortar and pestle).
2. Dissolve a small pea-sized portion of the powdered sample in about 5 cc of 8 normal  $HNO_3$  (1:1) in a pyrex test tube, heating to boiling with a small propane torch.
3. Allow to settle and cool. (Filter if necessary to remove colour or turbidity of solution.)
4. Extract a small amount of clear solution with a dropper or pipette, and place in another test tube or on a spot plate. Dilute with an equal volume of water and mix.
5. Add one to three drops of 1-per-cent hydrogen peroxide with a dropper or pipette. If vanadium is present in amounts of 100 ppm (0.01%) or more, the solution will turn orange within 2 or 3 minutes, if not immediately, depending on its concentration and the acidity of the solution.

*Remarks.* The test may be made quantitatively using measured amounts of sample and reagents, and comparing the intensity of coloration with that of prepared standards. Certain elements such as Fe, Cr, U, Ti, Mo, lignites, and bitumens may interfere to some extent with coloration of the solution, but usually they can be separated or distinguished.

#### *Reagents*

Concentrated  $HNO_3$ ,  $H_2O_2$ ;  $H_2O$

#### *Equipment*

Pyrex test tubes, spot plate, mortar and pestle or hammer, propane torch, test-tube holder, (filter paper and funnel), pipette or droppers.

Reference is also made to more elaborate chemical tests for vanadium given in Hawkes, 1957; Ward, *et al.*, 1963. These more specific tests require more equipment and chemicals than the one described above, and are therefore not as suitable for geological field work.

## Geophysics

### Physical Properties and Geophysical Methods

Several notable physical properties of groups of vanadium-bearing ore minerals and materials make it possible to use certain geophysical methods to advantage in outlining such deposits. As previously described (Rose, 1969a), the remarkable magnetic properties and high specific gravity of iron-titanium minerals mean that magnetic and gravity surveys greatly assist in detecting and delineating titaniferous magnetite deposits. This applies equally to vanadium-bearing titaniferous magnetite. Uranium- and thorium-bearing vanadium occurrences may respond to radioactivity detectors and thus reveal their presence. Therefore, radiation detectors may be used to locate and outline such deposits.

#### *Methods Based on Magnetism*

Aeromagnetic surveys used in conjunction with geological maps are extremely important in outlining favourable areas for locating titaniferous magnetite occurrences and for projecting the extensions of concealed or partly concealed deposits. For ground surveys the portable magnetometer and super-dip needle may be used to add greater sensitivity and refinement of detail. The simple, inexpensive dip needle may also be used to good advantage on vanadium-bearing titaniferous magnetite occurrences.

#### *Methods Based on Radioactivity*

The use on the ground of portable radiation detectors, Geiger counters, and scintillometers, may also be supplemented by airborne scintillometers and spectrometers to obtain quick and extensive areal coverage. Such airborne instruments have been used with some success to detect and outline radioactive occurrences, and methods are now under investigation and development (Darnley, 1968) to detect and differentiate between the radiation of uranium, thorium, and potassium (*see also* Darnley and Grasty, 1970).

#### *Geochemical-Geophysical Methods*

Geochemical methods of measuring uranium and thorium in surface waters and stream sediments have been field tested (Smith, *et al.*, 1968), and a method of collecting and measuring radon gas in surface waters and soils has been developed by the Geological Survey (Dyck and Pelchat, 1969). An airborne instrument is currently under development. All these methods have application in the search for vanadium because of its common association with uranium.



## Chapter IV

### DESCRIPTION OF WORLD DEPOSITS

#### *The Lost Vanadium Lode*

*There's a treasure in the mountains—  
Or, so I have been told—  
That flows from crystal fountains,  
Most scenic to behold.  
And these legends of the mountain,  
In the stories I've been told,  
Originate, I'm certain,  
From the lost vanadium lode.*

### Africa

#### *Republic of South Africa*

A 2-billion-year-old mass of layered, igneous rocks, the Bushveld Complex, intrudes rocks of the ancient Transvaal System and the underlying 'old granite' basement. The pyroxenite, norite, gabbro, and anorthosite that form the lower part of this differentiated mass were formerly believed to underlie a 12,000-square-mile basin occupying an area almost as large as Scotland. Recent geophysical work indicates that the structure is more complex, and that the basin is only partly underlain by the basic rocks which are probably concentrated in three or more main centres of igneous activity each with underlying feeder pipes and dykes extending to great depth (Holmes, 1965). Layers of chromite, some of which are platinum bearing, as well as horizons of vanadium-bearing titaniferous magnetite, form part of the basic layers of the Bushveld Complex. Some of the titaniferous magnetite layers are as much as 6 or 7 feet thick and extend for miles along strike. Some of the seams carry as much as 0.85 per cent V (Schwellnus and Willemse, 1944). Relatively undisturbed seams in the Lydenburg district of the eastern Transvaal near Steelpoort and at Mapoch near Witbank are now being mined (Sage, 1969).

#### *South West Africa*

The vanadium ores, descloizite, cuprodescloizite, mottramite, and vanadinite occur chiefly in oxidized zones of lead-zinc-copper ores and in the dolomite and sandstone of the Otavi System of Precambrian age, all of which rest unconformably on a metamorphic series of rocks that is intruded by granite (Schwellnus, 1946). The Tsumeb lead-zinc-copper mine has been active since 1900, and is the largest lead mine in Africa. The deposit is a cylindrical pipe in the Otavi dolomite in which dolomite breccia and intrusive pseudoaplite are present. The lead-zinc-copper ore, comprising

galena, sphalerite, tennantite, etc., is oxidized to a depth of 1,200 feet, below which the sulphides are dominant. The secondarily enriched upper part of the ore is especially rich in copper, and the vanadium ores occur in the upper part of the oxidized zone. At Tsumeb-West mine the vanadium minerals occur as concretionary nodules or as coatings on dolomite boulders within the sandstone, which occupies irregular and odd-shaped sand-filled depressions on the surface of the dolomite. This type of deposit is widely distributed throughout the area, but the deposits are shallow and generally hold little ore. The Berg-Aukas deposit is an irregular pipe of smithsonite and calamine almost surrounded by a calcareous clay that carries boulders of dolomite encrusted with vanadium minerals. The dolomite walls of the pipe are in places lined with vanadium minerals. The Abenab mine is a steeply dipping cylindrical mass of collapse breccias in platy limestone near its contact with massive dolomite. The breccia cement includes vanadates, calcite, and red clay. The source of vanadium in all the deposits in South West Africa seems to have been the Otavi sedimentary rocks, for the shales of this series generally carry about 0.5 per cent V and the dolomites about 0.2 per cent V, whereas both primary sulphides below the Tsumeb mine and the smithsonite-calamine pipe at Berg-Aukas contain no vanadium.

#### *Angola*

Vanadate minerals have been reported in oxidized base-metal deposits.

#### *Congo (Brazzaville)*

Sulvanite and vanadate minerals are reported in copper-lead-zinc ores.

#### *Mozambique*

Roscoelite has been noted in graphite occurrences.

#### *Morocco*

Vanadinite has been reported in the oxidized parts of lead deposits of Oudjda, and uranium-vanadium-bearing veins in the central massif of Aouliø.

#### *Niger*

Vanadium-uranium-copper-bearing sandstones have been noted in Agadez.

#### *Tanzania*

Vanadium-bearing titaniferous magnetite occurrences have been reported in the Liganga area, and the gem variety of vanadium-bearing zoisite, called tanzanite, occurs with ruby corundum near Arusha.

#### *Tunisia*

Vanadate occurrences are associated with two lead-zinc deposits in Djebba.

#### *Zambia (Northern Rhodesia)*

At Broken Hill vanadinite and descloizite are also associated with lead-zinc-copper ore in fracture zones, collapse breccias, and caverns in massive dolomite of the Precambrian Roan Series (Katanga System) of sedimentary rocks. The deposits generally consist of a core of zinc-lead-copper-iron sulphides enveloped by irregular zones of oxidized ore through which vanadinite and descloizite are irregularly distributed. Oxidized ore ranges from 0.4 to 1.2 per cent vanadium (Lamey, 1966).

## Australasia

### *Australia*

Ores rich in the mineral davidite are mined for uranium at Olary. Roscoelite has been reported in some of the gold telluride deposits at Kalgoorlie, and vanadium may be an important constituent in some of the extensive laterite and bauxite deposits of Australia. A low-grade vanadium deposit in the Jameson Range of Western Australia has been under investigation. Large sedimentary iron deposits of undetermined vanadium content have recently been discovered in northern and western Australia.

### *New Zealand*

The titanomagnetite concentrate made from the iron sands of New Zealand carries about 0.3 per cent vanadium. These unconsolidated sands are derived from the weathering and erosion of basic volcanic rocks and ash deposits from volcanoes of the Southern Alps of Cenozoic, Pliocene to Recent age. Millions of tons of iron sand carrying titanomagnetite and ilmenite are located on both the North and South Islands (Martin, 1955). The oldest iron-sand bed was found as an ancient beach deposit west of Wanganui in the Brunswick Formation which lies on the surface of a Pliocene formation. On the west coast of North Island the Taranaki iron sands are widely distributed for 290 miles about 15 miles west-northwest of Auckland. Both recent beach and dune sands, and Pleistocene raised beach and dune sands contain disseminations and concentrations of dark minerals in andesite, basalt, and volcanic ash deposits. The resistant Fe-Ti-V iron oxide minerals are present and concentrated to some extent, as the associated silicates weather rapidly to clay and carbonates and are removed by percolating groundwater. Further concentration of the hard heavy mineral grains is effected by the sorting action of running water as the unconsolidated materials are eroded and redeposited at the strand. The resulting beach sands may be further concentrated by wave action and shore currents, as well as by the separation and migration of lighter material forming wind-blown dune sands. Large tonnages of dune sands and iron sands are in the Lake Taharoa area of North Island, and lower grade deposits of even greater extent have recently been outlined in the North Head area, in particular at Kawhia North Head and Waikato North Head.

Ilmenite and gold-bearing black beach sands occur along a 250-mile stretch of the west coast of South Island, about 50 miles north of Westport, in the form of recent and raised beach deposits in marginal land. Deposits at Cape Foulwind average 5.5 per cent ilmenite. Except for Gillespie's Beach, where a considerable amount of magnetite sand occurs, the main ore mineral of the black sands of South Island is said to be ilmenite.

## Eurasia

### *Finland*

At Otanmäki, 300 miles north of Helsinki, Finland, an estimated 50 million tons of vanadium-bearing titaniferous magnetite ore occur in nearly vertical lenses in a zone more than a mile long in Precambrian(?) gabbro-amphibolite intrusion. The largest lenses are reported to be about 950 feet long, 12 to 64 feet wide, and 1,700 feet deep. Magnetite and ilmenite, in discrete grains 0.1 to 2 mm in diameter, impregnate the basic host rock; the main gangue minerals being chlorite, hornblende, and basic plagi-

clase feldspar, from which the magnetite and ilmenite are readily separable. The magnetic concentrate from the high-grade material is reported to carry about 0.6 per cent vanadium. The average ore carries about 35 per cent magnetite, about 28 per cent ilmenite, and about 0.25 per cent vanadium.

### *Norway*

Titaniferous magnetite deposits at Rodsand are believed to be vanadiferous. Aplite veins in gneissic granite at Kragerø carry 10 to 15 per cent rutile from which a black concentrate high in vanadium and chromium has been obtained. The productive zone in the granite is flanked by an enormous granite-pegmatite dyke on one side and by an olivine-norite dyke in amphibolite on the other.

### *Sweden*

The titaniferous magnetite deposit at Taberg, in which vanadium was first detected and named by Sefstrom, occurs in a norite hill 400 feet high, in which ilmenite and titanomagnetite are concentrated, forming a mass of ore with some olivine, biotite, and plagioclase. Low-grade vanadiferous alum and oil shales of Cambro-Silurian age in Sweden carry as much as 0.2 per cent vanadium and form another potential source of the element. The uranium-bearing variety of coal or carbon (kolm) in the alum shale of Sweden carries as much as 1 per cent uranium in its ash (Rankama and Sahama, 1950, p. 637).

### *England, France, Belgium, Luxembourg, West Germany*

These western European countries satisfy part of their vanadium requirements by processing vanadium-bearing slag resulting from smelting their low-grade, minette-type, marine, oölitic iron ores of Mesozoic age. The vanadium content of these ores is generally low, averaging about 0.08 per cent, but it may be somewhat concentrated in the slag from which it is economically recovered in stages in Europe.

The metalliferous black shale, the Permian Kupferschiefer of Poland and Germany also carries molybdenum, vanadium, chromium, nickel, cobalt, and copper, etc. Normal sea water is not sufficiently rich in metallic elements to supply the amounts of metals in the Kupferschiefer, but there is a strong probability, according to Wedepohl (1964), that the reduction of iron oxides in the underlying red floor (Rotliegend) sandstone aided in mobilizing the elements characteristic of the Kupferschiefer and in supplying them to the stagnant waters in which the Kupferschiefer formed.

### *Spain*

A small deposit of vanadinite and descloizite near Zafra once made Spain a leading vanadium producer, but reserves were small and production was short lived. The vanadium minerals occur in the oxidized parts of lead-bearing veins that cut vanadium-rich clays.

### *Austria*

Vanadium has been reported in the lead-zinc deposits of the Bleiberg-Kreuth area, Carinthia.

### *Hungary*

Vanadium-bearing titaniferous magnetite occurs in ultrabasic rocks of the Bükk mountains and in uraniferous micaceous chromium ore.

*Bulgaria*

Black sand and titaniferous magnetite deposits are reported in the Black Sea area.

*Italy*

Uranium–vanadium-bearing sandstones are known at Val Rendena, and vanadates have been reported in copper ore at Bena de Padru in Ozieri.

*Union of Soviet Socialist Republics*

The vanadium deposits of Russia include vanadium-bearing titaniferous magnetite deposits in the central Urals (Ilmen Mountains), the sandstone-type deposits of Ferghana district in Turkestan (central Asia), the vanadium-bearing residual Kerch iron ore in the Ukraine, and possibly apatite and sphene deposits of the Kola Peninsula.

The Ural Mountains deposits reportedly carry 400 million tons of ore averaging 0.3 per cent vanadium. Ilmenite concentrate made from ore from the Kussink area contained the following percentages: 45.3 TiO<sub>2</sub>, 35.8 iron, and 0.18 vanadium. The titaniferous magnetite deposits are associated with metamorphosed gabbroic intrusions of Precambrian or Paleozoic age. Deposits are located at Kusa, Pervoural'sk, and Kachkanar Mountain in the Urals, of which the latter is by far the largest (Lamey, 1966).

The Kara-Tan vanadium–mica (roscoelite?) deposit in Turkestan is reported to have been traced for more than 20 miles in a zone 30 to 45 feet thick, in metamorphosed sedimentary rocks of Paleozoic or Mesozoic age. Thin bands of roscoelite (?) bearing sandstone alternate with bands of flint. Vanadium-bearing phosphate rock is also reported in the Kara-Tan Mountains.

At Tyuya Myan, Ferghana, also in central Asia, oxidized uranium, vanadium, and copper minerals are associated with barite, calcite, and quartz in limestone. The ores are pipe-like replacement and cavity-filling deposits of carnotite, tyuyamunite, metatyuyamunite, turanite, ferghanite, volborthite, and uzbekite, in an area of faulting and igneous activity. They have been ascribed to thermal solutions derived from diabase intrusives on the one hand, and to leaching of uranium and vanadium from nearby black bituminous shales, on the other. The latter shales contain about 0.04 per cent uranium and 0.085 per cent vanadium (Rankama and Sahama, 1950, p. 638).

*Iran*

Vanadates have been reported in the oxidized zones of certain lead–zinc deposits.

*India*

Titaniferous magnetite-lode deposits associated with basic, ultrabasic, and charnockitic rocks have been found in Singhbhum, Mayurbhanj, and Chamnapatna areas of Mysore; near Nuasahi in Keonjhar; in Orissa north of Godasahi and Nilgiri, and in Bihar. There are also important titaniferous magnetite concentrations in the black sand beach deposits of Travancore, Quilon, and Kerala. The mineral coulsonite, the vanadium-rich variety of magnetite, was first identified in India by Dunn and Dey (1937). The titaniferous magnetites of India are reported to carry generally from 0.25 to 1.5 per cent vanadium.

*Ceylon*

The black sand beaches of Ceylon at Pullmoddai, Dondra, Beruwala, and Induruwa are richer in ilmenite than in titaniferous magnetite. They also carry monazite, rutile, and zircon.

*China*

Important titaniferous magnetite deposits are believed to occur in Manchuria, in Yunnan and Sinkiang provinces (Hampel, 1961).

*Japan*

The dark beach sands of Japan, derived from the breakdown of basic lavas and volcanic ash rocks, carry much vanadium-bearing titaniferous magnetite. Vanadium has been recovered since World War II from magnetic concentrates made from these sands.

*Korea*

Vanadium-bearing titaniferous magnetite deposits have been reported as well as graphitic schists and gneiss of 0.08 per cent average vanadium content.

## North America

As indicated in Figure 3, vanadium occurrences are widely distributed in North America. Many of these are associated with uranium, iron, titanium, phosphorus, or organic matter. Most of the significant occurrences are in the sedimentary basins of Mesozoic age, particularly in the western United States basin and range province. Vanadium-bearing titaniferous magnetite occurrences are most abundant in eastern Canada.

*Canada*

The best-known vanadium occurrences in Canada are: the Precambrian titaniferous magnetite bodies south of Mine Centre at Bad Vermilion Lake and Seine Bay, those south of Mattawa in Papineau Township, Ontario, and those east of St. George's at Steel Mountain in western Newfoundland; the vanadium-bearing cupriferous sediments and lavas of Triassic age, north of Gowlland Harbour on Quadra Island, and west of Menzies Bay on Vancouver Island; the Precambrian uranium-bearing veins of the Beaverlodge area in Saskatchewan; and the vanadium-bearing bitumen of the Athabasca tar sands of Cretaceous age at McMurray on the Athabasca River in northern Alberta. To these a host of other occurrences must now be added, as subsequently described in Chapter V, all contributing to a rather impressive total of various types of vanadium occurrences and potential in Canada (Rose, 1967).

*Mexico*

Historically, the new element vanadium was first detected in oxidized lead ore in Mexico, in which it occurs as the vanadate minerals, vanadinite, descloizite, cuprodescloizite, and mottramite, as well as in mimetite, all of which are irregularly distributed throughout the oxidized parts of lead-zinc-copper deposits in the main Cordillera of Mexico, from Chihuahua to Hidalgo. The occurrences are small and similar to others in Arizona and New Mexico.

VANADIUM AND VANADIFEROUS OCCURRENCES OF CANADA

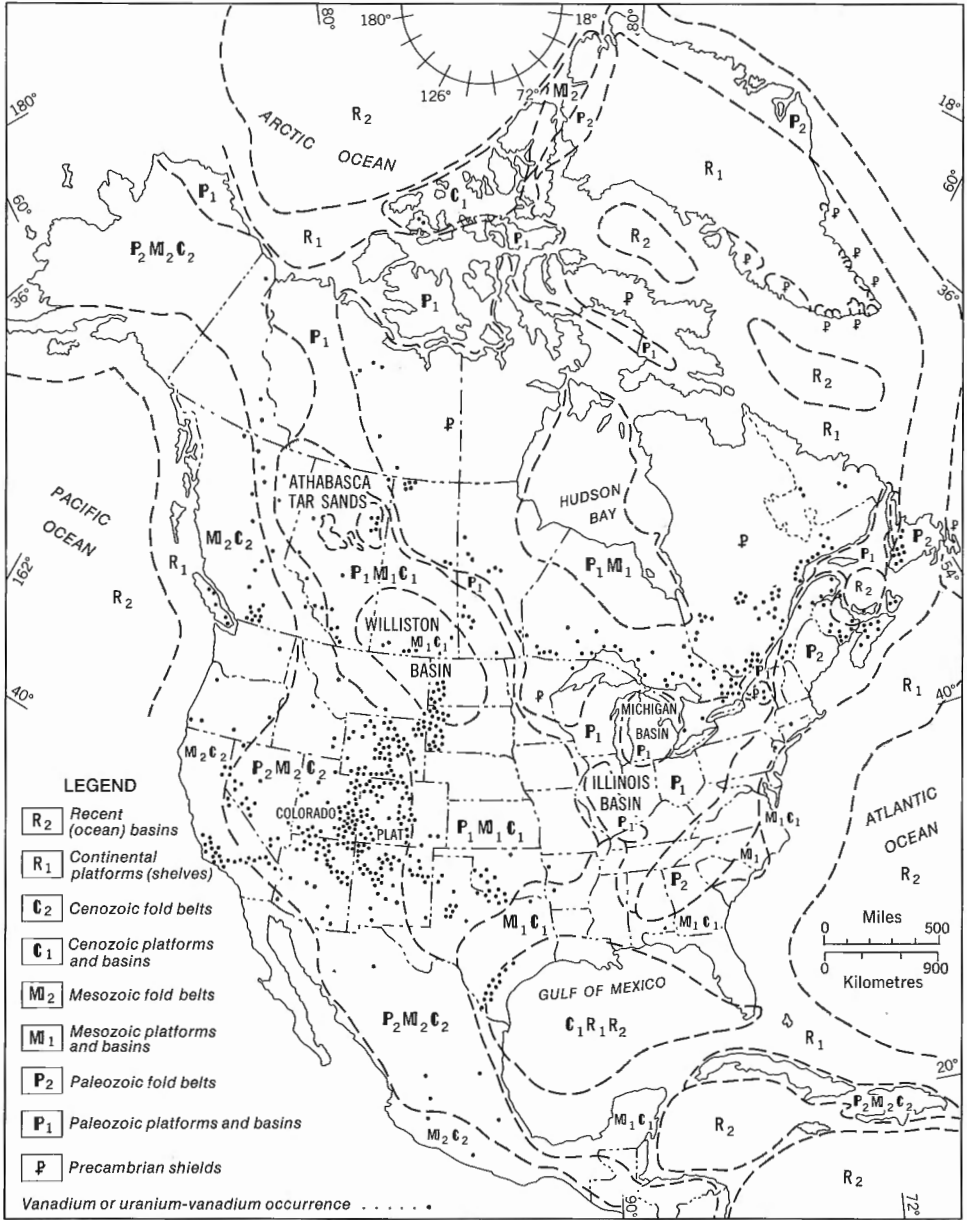


FIGURE 3. Vanadium occurrences in North America in relation to main structural elements.

GSC

**United States**

The main vanadium ores in the United States as shown in Figure 3 are: (1) the sandstone-type uranium ores of Mesozoic age of the Colorado Plateau, Wyoming, the Dakotas, and neighbouring states; (2) the phosphate deposits of the Permian Phosphoria Formation of Idaho, Montana, Wyoming, and Utah; and (3) the lateritic capping of an altered carbonatite complex at Wilson Springs, Arkansas. Other important

potential sources are: (1) titaniferous magnetite deposits in Wyoming, Minnesota, New York, and Montana (Stillwater Complex), etc.; (2) organic shales and solid hydrocarbons in Wyoming, Nevada, Oklahoma, and Colorado; (3) lignite ash from North Dakota and elsewhere; (4) titanium-bearing veins; (5) certain gold-quartz veins; and (6) certain base-metal deposits.

*Sandstone deposits (Colorado Plateau).* Although the average sandstone of the earth's crust and in the western United States is low in vanadium, important vanadium deposits occur in certain sandstones at widespread localities in the Colorado Plateau (in Colorado, Utah, Arizona, and New Mexico), on the flanks of the Black Hills in South Dakota, and in basins in Wyoming. A considerable range of geological time, stratigraphic thickness, and geographic distribution is represented by these ores. Vanadium and uranium deposits were found in the sandstone of western Colorado in 1898 and an extensive literature concerning them has appeared since World Wars I and II. The ores are found within thick, relatively undisturbed formations of sedimentary rock of Mesozoic age. They are largely of nonmarine origin and apparently formed in poorly drained foreland or post-orogenic basins. The ore generally occurs as small and erratic lenses or irregular channels in sandstone.

*Roscoelite and carnotite types.* Two general types of ore were early distinguished, the 'roscoelite' type of Rifle and Placerville, Colorado, and the 'carnotite' type of the Uravan Mineral Belt. In general the roscoelite type of vanadium ore occurs as concordant bands in relatively clean, gently dipping, bleached sandstone beds of the Entrada (Jurassic) and underlying Navajo (Jurassic?) Formations. They are characterized by roscoelite, vanadium-bearing hydromica, chlorite and clay, and montroseite, along with minor calcite, dolomite, galena-clausthalite (with Se and S in solid solution), chalcopyrite, pyrite, marcasite, and coffinite. The ores vary from light to dark shades of grey, tan, or green to almost black, and in vanadium content from 2 per cent to a cut-off mining grade of about 0.84 per cent V. Yellow and orange secondary vanadium minerals enrich the ore in places, but they are neither common nor abundant. At Rifle, Colorado, a persistent bed of this type of ore pinches and swells, varying from a few inches to 20 feet thick, averaging about 6 feet thick, about 0.5 per cent vanadium and 0.05 per cent  $U_3O_8$ , and carrying several million tons of ore. In places the rare uranyl carbonate minerals, bayleyite and swartzite, form light efflorescences on the ore on the mine walls. The vanadium-uranium ratio of these ores is generally high, 15:1 or more, but the ore zone shows a delicate vertical colour and metal zoning, ideally with dark (black) ore at the bottom, enriched in uranium and vanadium, succeeded by a greenish chromium zone, a pale pinkish lead-selenium zone, and a reddish iron zone. In places, this zonation is interrupted and seemingly reversed. About 500,000 tons of ore averaging 1.5 per cent  $V_2O_5$  are in reserve.

The carnotite ores occur extensively in erratic lenses as much as 20 feet thick in the Salt Wash Sandstone Member of the Morrison Formation (Late Jurassic) and to a lesser extent in the Shinarump Member and other basal sandstones of the Chinle Formation (Triassic) and elsewhere. In the near-surface deposits of the Uravan Mineral Belt (above the 200-foot depth), striking yellow carnotite was the main ore mineral, but this gave way in the water-saturated rocks below to black ores that are mixtures of vanadium and uranium oxides, and silicates in the sandstones. Secondary minerals have now become so rare that even hand specimens are difficult to obtain. In the less oxidized deeper parts of the ore the vanadium occurs mainly in the form



of vanadiferous chlorite, hydromica, and clay, and the uranium as uraninite (pitchblende) and coffinite associated with coalified wood, carbonaceous material, pyrite, and other sulphides. Uraninite selectively replaces wood cell walls and coffinite fills wood cell cavities. As this grey ore material is oxidized above the water table, the black vanadium oxide montroseite begins to appear; doloresite, duttonite, paramontroseite, and simplotite form next; further oxidation produces blue-black corvusite followed by greenish black melanovanadinite and then uranium minerals, brownish rauvite, brownish red hewettite, navajoite, orange pascoite, and finally yellow carnotite, tyuyamunite, metatyuyamunite, volborthite, tangeite (calciovolborthite), rossite, metarossite, santafeite, hummerite, ferghanite, steigerite, ferverite, etc. The vanadium-uranium ratio of these ores is generally between 10:1 and 3:1. Most of the vanadium production of the United States has come from this type of uranium-vanadium ore. In 1960 reserves of the Uravan Mineral Belt were reported to be about 4 million tons of ore averaging 1.3 per cent  $V_2O_5$  (Briscoe, 1961). The V-U ratio in the Morrison Formation is slightly lower than in the Green River and Henry Mountains districts of Utah, and toward the south in New Mexico it is much lower, about 1:2.

Uranium ore was discovered in sandstone of the Dakota Formation (Cretaceous) near Edgemont, South Dakota, in 1951, and a 500-ton-per-day plant was built in 1952 by Mines Development Inc. to recover uranium from the ore. In 1960 the plant was expanded to recover vanadium, and later also molybdenum. The ore occurs intermittently in erratic lenses or channels in gently folded, buff-coloured Dakota sandstone in a belt 35 miles long on the southwest flank of the Precambrian Black Hills metamorphic and granite pluton. The ore is commonly dark grey to black, characterized by finely divided uraninite (pitchblende), 'roscoelite,' and carbonaceous matter—all in the interstices of quartz sand grains, but in places it is light buff and carbon free (Pl. III A). Vanadium-rich parts of the ore are commonly deep violet to mauve, and generally occur in an oxidized zone between a lower, black, uranium-rich part, and an upper, rusty, iron-rich part of the sandstone beds. In most places the beds are almost flat lying and overlain by beds of black, lignite-bearing shale, and by colluvial deposits of orange-red argillite, derived from the Spearfish Formation of Triassic age. The crudely zoned ore occurs in concordant shoots generally within 200 feet or less of the surface, and in a relatively unoxidized state. Many mines and pits in these beds have been opened. Each deposit has yielded from 10,000 to 400,000 tons of ore that averaged from 0.18 to 0.20 per cent  $U_3O_8$  and about 0.5 per cent vanadium. In a few places the dark mauve sandstone carries as much as 6 per cent vanadium.

In northeast Wyoming, near the intrusive columnar plug called the Devils Tower, a similar deposit in the Dakota sandstone is overlain by bentonitic beds. Uranium-vanadium ore from the Haber mine is processed at the Edgemont mill, as is the ash from the uranium-molybdenum-vanadium-bearing lignites of the Bellfield-Bowman area in North Dakota. Some suggest that since bentonitic clays are derived from volcanic ash, there may be a genetic relationship through leaching, between uranium-vanadium deposits in the sandstone and lignites, with associated metal-bearing volcanic ash and tuff, as at the Haber mine, and in the North Dakota lignites. In the Gas Hills area of Fremont County, the Wind River Basin of Natron County, and the intermontane basins in Shirley Basin area, Carbon County, Wyoming, uranium deposits in sandstone are low in vanadium, and among other theories, it has been suggested that the uranium ores there have been deposited from metal-bearing brines associated with the migration and accumulation of petroleum and natural gas.

*Origin of sandstone deposits.* Opinion is still divided regarding the ultimate and precise origin of the sandstone ore deposits. Circulating groundwater, carrying uranium, vanadium, and other metals in solution, seems to have played an important role in their formation. Concentration may also have been effected by organisms. Precipitation may have been accomplished by reducing conditions generated in a euxinic environment by organisms, organic matter, carbon or  $H_2S$ , or by gradual cooling of hot migrating metal-bearing solutions. Secondary enrichment is apparent. The low concentrations of uranium and vanadium required to form the deposits suggest that they might have been formed simply as the result of hot groundwater circulating through permeable sedimentary rocks derived from the underlying uranium-vanadium-bearing complex of igneous and metamorphic rocks. Groundwater temperatures are high even today in various centres of igneous activity in the western United States.

*Phosphate deposits.* Billions of tons of vanadium-bearing phosphate rock have been found in the Phosphoria Formation of Permian age, in Idaho, Montana, Wyoming, and Utah. Traces of vanadium, uranium, rare earths, molybdenum, nickel, fluorine, and selenium commonly occur in the phosphate rock and its associated dark shales. In Idaho, where phosphate rock averaging about 0.1 per cent V is being mined on a large scale for the production of phosphorus, vanadium is recovered as a byproduct in the form of ferrophosphorus containing 3 to 8 per cent vanadium. The black shales in which the phosphate rock occurs in Idaho and elsewhere in the United States are commonly even higher in vanadium (from 0.5 to 2.5 per cent  $V_2O_5$ ), than the phosphate rock itself. The black phosphorite that is associated with black shales, cherts, and carbonaceous sandstone or phosphate rock, seems to be higher in vanadium than the grey type associated with carbonate rocks, chert, and sandstone in both western and eastern United States, although neither is barren of the element. Phosphorite is commonly dark brown-grey to black, fine grained, oölitic, and of marine sedimentary origin. The main phosphate bed at Conda, Idaho, near the footwall of a 100- to 150-foot-thick section of black shales, averages 7.1 feet thick, 32 per cent  $P_2O_5$ , and 0.28 per cent  $V_2O_5$ . The upper or hanging-wall bed averages 7.2 feet thick, and 30.5 per cent  $P_2O_5$ , and 0.11 per cent  $V_2O_5$ . At the Ballard Mine (Pl. III B) north of Soda Springs, Idaho, the section is 260 feet thick, and from this a million tons of phosphate rocks carrying 8 to 15 per cent phosphorus and 0.12 per cent vanadium is mined annually.

*Laterites.* The vanadium mine at Wilson Springs, Arkansas, opened in 1969 by Union Carbide, is reported to use a vanadiferous shale comprising the lateritic capping or weathered zone above an underlying ultrabasic or carbonatite complex. In primary carbonatites vanadium occurs in magnetite, carbonates, phosphates, and possibly also in multiple oxide and ferromagnesian minerals. During lateritic weathering vanadium is commonly incorporated in the derived clay and bauxite products. Secondary concentration of heavy metal vanadates may form within these products of weathering if heavy metals are present, or if they are introduced by migrating solutions. The average laterite and bauxite ore is reported to carry about 0.04 to 0.06 per cent vanadium.

*Titaniferous magnetites.* Important vanadium-bearing titaniferous magnetite deposits are known at Iron Mountain, Wyoming; at Sanford Lake (Tahawus), New York; in Minnesota; and New Jersey (Singewald, 1913). The composition and origin of selected iron-titanium deposits in the United States and Canada have been discussed by Lister (1966). Near Iron Mountain, Wyoming, several anorthosite bodies intrude a Precam-

brian (?) metamorphic complex of gneiss, schist, quartzite, and marble that forms the central core of the Laramie Range. A steeply dipping zone of bodies of titaniferous magnetite is associated with a large anorthosite mass on Iron Mountain. The deposit is estimated to hold 12 million tons of titaniferous magnetite averaging about 0.3 per cent vanadium, and 20 million tons or more of lower-grade material.

At Sanford Lake, New York, a large deposit of titaniferous magnetite being mined by National Lead Company, also occurs in a huge body of Precambrian anorthosite, in the Adirondack Mountains (Kemp, 1898). The ore consists of massive and disseminated titaniferous magnetite in gabbro and anorthosite. The ore averages about 34 per cent iron, 18 to 20 per cent titanium, and 0.13 to 0.23 per cent vanadium. Magnetite and ilmenite are recovered, but vanadium is not.

*Organic shales.* In addition to the vanadium-bearing black shales of the Permian Phosphoria Formation, metalliferous, organic black shales occur in the Comus Formation (Ordovician) near Golconda, Nevada; in the Fish Creek Range (lower Paleozoic) near Eureka, Nevada; in the Deseret limestone (Mississippian) near Tintic, Utah; in the Mahogany Zone oil shale of the Green River Formation (Eocene) near Rifle, Colorado; and in the Chattanooga shale (Mississippian) of the eastern United States.

Ten samples of the Mahogany Zone oil shale of the Green River Formation of Colorado and Utah, taken by the U.S. Bureau of Mines, averaged about 25 gallons of oil per ton of shale and carried about 0.002 to 0.02 per cent  $V_2O_5$ . Ash from six samples of Colorado oil shales ranged from 0.003 to 0.06 per cent  $V_2O_5$  (Briscoe, 1961).

*Asphaltites.* Vanadium-bearing asphalt deposits occur near Temple Mountain, Utah, and in the Piñon Range of Eureka County, Nevada, where asphaltite carrying as much as 1 per cent  $V_2O_5$  cements sheared sandstone and shale. Veins of the native bitumen, impsomite, and grahamite, carrying from 0.1 to 0.3 per cent  $V_2O_5$  have been found in folded beds in Oklahoma and Arkansas, and the coal-like, gilsonite deposits of eastern Utah also contain some vanadium.

*Vanadium-bearing base-metal deposits.* Vanadate minerals have been reported in the oxidized zones of more than four hundred base-metal deposits in the western United States, but little vanadium has been produced from them. In the Mammoth area of Arizona, vanadinite, descloizite, motttramite, and wulfenite ( $PbMoO_4$ ) form crystals and crusts on the leached material in the oxidized part of fissure veins in Precambrian (?) granite, along with some gold, molybdenum, copper, lead, and zinc. In the Good-springs district of Nevada, the vanadate minerals form thin coatings on fragments of dolomite breccia and on fossil corals in the oxidized parts of lead-zinc deposits there (Fischer, 1961). The primary copper-vanadium sulphide mineral, colusite, has been noted in the copper-lead-zinc ores of the Colusa Mine at Butte, Montana, but vanadium has not been recovered from the Butte ores.

*Gold-quartz veins.* There is widespread association of roscoelite with gold telluride minerals in quartz veins in the La Plata district of Colorado, and in the Mother Lode of California. Some vanadium ore was produced in 1910 from the Kekionga claim, Boulder County, Colorado, where roscoelite is associated with gold tellurides in irregular masses from an inch to 8 inches wide, 30 feet long and as much as 100 feet deep, over a length of 1,500 feet and depth of 400 feet. Some of the ore contained as much as 3.2 per cent vanadium, and it probably averaged about 2 per cent vanadium (Fischer, 1961).

## South America

Although the high-grade vanadium deposits of Peru have been largely mined out, low-grade vanadium deposits are probably still to be found there. The heavy Venezuelan crude oils are being processed in Canada to recover their vanadium, and they represent a considerable reserve. Additional but smaller sources of vanadium are known in Argentina and Chile, and it is likely that other sources will be found in Brazil.

### *Argentina*

Asphaltites (solid bitumens) occur as seams, veins, and irregular lenses in beds ranging from Middle Jurassic to Upper Cretaceous age in the provinces of Córdoba, San Luis, San Juan, and Mendoza. Samples from Mendoza indicate a content of about 0.1 per cent vanadium in the asphaltite which is concentrated to about 8 per cent in the ash obtained from burning the asphaltite. A number of occurrences of vanadate minerals in the zones of oxidation of base-metal deposits are also known in Argentina, as are other deposits in sandstone and shale.

### *Bolivia*

Vanadate minerals have been reported in oxidized base-metal ores.

### *Brazil*

Occurrences of zinc, silver, and vanadium have been reported in northern Minas Gerais, and vanadate minerals have been noted in a number of other localities.

### *Chile*

Vanadate minerals associated with silver-lead and copper deposits have been noted in Chile, but reserves appear to be small. There has been little production.

### *Peru*

The Mina Ragra deposit in Pasco Province, once the richest and largest vanadium deposit in the world, is now mined out (McKinstry, 1957). The deposit was an inverted cone-shaped mass of patronite (a complex vanadium sulphide, carbon, sulphur, iron, mixture) and patronite shoots associated with carbonaceous, coke-like material, in a fissure zone transecting enclosing beds of red shale of Cretaceous age. The deposit occupied an area 850 by 180 feet at surface, extended to a depth of 210 feet and tapered to a narrow vein from a depth of 210 to 300 feet (Lamey, 1966). The red shale around the deposit is bleached grey and is locally called 'bronce.' Near the deposits a number of igneous bodies intrude into the shale. The central part of the deposit was natural coke, containing patronite veins, enveloped in quisquite (a lustrous black hydrocarbon), and enclosed in grey shale impregnated with patronite and quisquite. The ore consisted essentially of black, pitchy patronite and quisquite with secondary vanadium enrichment, in the form of vanadates and oxides of striking bright colours in the upper part of the deposit.

### *Venezuela*

Soot, ash, and refinery residues from some Venezuelan crude oils are generally high in vanadium. The crude oil carries about 0.01 per cent vanadium but this may be concentrated to as much as 9 to 10 per cent vanadium in the fly-ash.

## Chapter V

### DESCRIPTION OF VANADIUM OCCURRENCES IN CANADA

#### *Gataga Gossan*

*In a niche in the northern Rockies,  
Where Gataga flows fast and free,  
Near the borders of the Yukon,  
In the northeast of B.C.,  
A gossan of umber and ochre,  
Mantles the scenery.*

*But few have seen this gossan,  
And fewer know its lair,  
For it springs from the side of the mountain,  
And hides its secrets there.  
But few have seen this fountain,  
And fewer know its source,  
It comes from the shale beneath it,  
And the metals in its course.*

*The beauty of these mountains  
Is wondrous to behold.  
'T would be a crime to change it,  
It's worth its weight in gold.  
But we must pass with pleasure,  
A secret I've been told,  
That mountain holds the treasure,  
Of the lost vanadium lode!*

Although vanadium was detected in Canada in titaniferous magnetite from eastern Ontario in 1909 and has subsequently been found in a number of such deposits, as well as in a handful of other occurrences, it has not yet been found here as a commercial deposit. Small occurrences of vanadium-bearing minerals, including some carnotite found in 1932 as secondary mineral efflorescences on interlava sedimentary beds of Triassic age associated with copper mineralization on Quadra Island, and later also near Menzies Bay on Vancouver Island, held promise of production and are among the richest in vanadium yet found in Canada. In 1945 a sample of carbonaceous shale from Macmillan River, Yukon Territory, was tested and found to contain 0.1 to 0.3 per cent vanadium (Kindle, 1946). In 1950 a new vanadium mineral, nolanite, in the uranium-bearing veins and ores of the Beaverlodge area, Saskatchewan, was considered as a possible source (Robinson, 1955). Vanadium was also detected in traces by

spectrographic methods in the Athabasca tar sands, in gold-quartz ore of the Siscoe vein, in the North Sydney slag and in the Wabana iron ore, and elsewhere; but there was little further development at any of these occurrences insofar as vanadium is concerned.

The writer's work indicates that vanadium occurs more commonly in Canada than was formerly recognized. The types and range of ages of these occurrences are indicated on Figure 12. The distribution and size of the occurrences in Canada shown on Map 1321A (*in pocket*) shows their size, grade, type, associated elements, and relation to general geology. Vanadium was detected across Canada in many samples of: (a) titaniferous magnetite, basic and alkaline 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) apatite and dark phosphate rock; (g) lignite and soft coal; (h) oil shale, bituminous sandstone (tar sands), asphaltite and graphitic schists; (i) oölitic hematite; (j) manganiferous rocks; and (k) chromite occurrences. In general, vanadium was found associated with: (1) titanium, iron, manganese, and chromium; (2) uranium and thorium; (3) copper; (4) bitumen, carbon, hydrocarbons, organic complexes; and (5) phosphates. It occurs in rocks ranging in age from Precambrian to Recent. In Canada vanadium occurs abundantly in titaniferous magnetite associated with basic rocks of Precambrian age. Elsewhere it has been concentrated in sedimentary rocks of Mesozoic and younger ages. Similar concentrations should be expected to occur in Canada.

### Northwest Territories

#### *Melville Island Oil Sands* (1)<sup>1</sup> 76°11'05"N, 115°00'W

References: Hodgson, G. W., *et al.* (1963).

Tozer, E. T., and Thorsteinsson, R. (1964).

Trettin, H. P., and Hills, L. V. (1966).

Oil-impregnated sands noted by a Dominion Observatory party near Marie Bay, Melville Island, in 1962 were explored by J. C. Sproule in 1962-63, and were investigated by H. P. Trettin and L. V. Hills of the Geological Survey in 1964. The oil sands are crossbedded, deltaic, shoreline deposits of the Triassic Bjerne Formation, marginal to the Sverdrup Basin of the Queen Elizabeth Islands (Tozer and Thorsteinsson, 1964). According to Trettin and Hills (1966), the oil sands and conglomerate, 0 to 85 feet thick, rest unconformably on Paleozoic rocks and are overlain by Jurassic strata. Oil impregnations are local and controlled by structures. Six oil occurrences have been found in a narrow 40-mile-long belt of sandstone in which the oil migrated to its present position beneath cappings of impermeable Jurassic beds in Middle Jurassic or later time. They suggest that between fifty and one hundred million barrels of heavy oil is indicated, but most of the sand has a content of less than 6 per cent by weight of oil.

According to Hodgson, *et al.* (1963), Melville Island oil differs from Athabasca oil in having little or no vanadyl porphyrin content (0.8 ppm), a lower sulphur content, and a higher content of nickel (81 ppm Ni) than vanadium (15 ppm V). Although the vanadium content of the Melville Island oil is low, the occurrence is of interest because it represents the first report and indication of vanadium in the Arctic Islands.

<sup>1</sup> Numbers in brackets refer to localities shown on Map 1321A.

*Muskox Ingenous Complex* (2) 66°35'N, 115°00'W

Reference: Smith, C. H. (1962).

Strong traces of vanadium have been reported in analyses of chromite associated with the layered Muskox igneous complex of the Coppermine River area 60 miles south of the settlement of Coppermine. A chromite-sulphide layer, 8 to 15 inches thick, similar in nature to the Merensky Reef of the Bushveld Complex in South Africa, occurs in pyroxenite near the upper part of the central layered series. The layer, consisting of as much as 50 per cent disseminated chromite, and 1 to 20 per cent pyrrhotite and chalcopyrite, dips gently northwest. It was traced for 3½ miles along strike. Seven samples from the seam average 15.3 per cent Cr<sub>2</sub>O<sub>3</sub>, 0.25 per cent Cu, 0.15 per cent Ni, 0.1 per cent V, 0.01 per cent Co, 0.4 gm/ton Pd, and 0.16 gm/ton Pt (Smith, 1962).

*Coppermine River Basalts* (3) 67°15'N, 116°00'W

Traces of vanadium also occur in these basalts, which average 0.012 per cent Cu, 0.06 per cent V, and 2.22 per cent TiO<sub>2</sub>, according to Baragar (1969).

*Eldorado Pitchblende Deposit* (4) 66°05'N, 118°04'W

Reference: Marble, J. P. (1939).

Two samples of uranium ore from the early upper workings of the Eldorado Gold Mines, Limited, at LaBine Point, Great Bear Lake, were analyzed and found to hold 61.56 and 34.66 per cent U<sub>3</sub>O<sub>8</sub>, 10.51 and 5.88 per cent Pb, strong traces of rare earths, 1.14 and 0.32 per cent total V<sub>2</sub>O<sub>5</sub> + MoO<sub>3</sub>, and 2.42 and 0.62 per cent NiO + CoO, respectively. Sample No. 1 was from pit No. 1, vein No. 1 near surface, and sample No. 2 was from the 800-foot section of No. 2 vein about 100 feet below ground.

*Yellowknife Bay Gabbro* (5) 62°30'20"N, 114°16'W

Reference: Jolliffe, A. W. (1945).

Traces of nickel, chromium, and vanadium, were found in the olivine-rich base of a gently dipping gabbro dyke a mile east of Yellowknife Bay (Jolliffe, 1945).

*François River Basic Complex* (6) 62°05'N, 112°50'W

Reference: Jolliffe, A. W. (1936).

A layered basic intrusion similar in some respects to the Bushveld Complex was also mapped by Jolliffe (1936) east of François River and near the north shore of Great Slave Lake. A 6-pound channel sample taken by Jolliffe from a 5-foot zone near the southeast border of the mass (Geol. Surv. Can. Map 581A, Beaulieu River) showed 11 per cent TiO<sub>2</sub>, but no vanadium. Although vanadium was not detected in the analysis, its presence is to be expected in this type of occurrence.

## Yukon Territory

Traces of vanadium have been noted in spectroscopic and spectrographic analyses of certain dark shales in the Yukon, tested by Kindle (1946) and by Rio Tinto Canadian Exploration Limited (pers. com., L. B. Gatenby), and an occurrence of carbonaceous shale carrying 0.1 to 0.3 per cent vanadium was reported (Kindle, 1946) from an area 90 miles from mile 238 of the Canol Road on the south bank of the South Fork of Macmillan River (loc. 2, 62°52'N, 130°40'W).

Thirty samples of dark Paleozoic shales collected by H. Gabrielse from areas around Watson Lake (loc. 3, between 60–61°N, 129°W), some from northern British Columbia, and some from the Yukon, were tested by the writer. All were faintly radioactive, showing a radioactive equivalent content of from 0.001 to 0.005 per cent  $U_2O_8$ ; twenty-two samples showed from 0.01 to 0.1 per cent vanadium.

A sample of calcareous shale and overlying gossan collected by D. K. Norris from Barn Mountain (loc. 1, 68°35'N, 138°10'W) showed a trace of vanadium and indications of molybdenum and tungsten. Although these widespread occurrences of uranium and vanadium are much below ore grade they are geologically similar to those in the southwestern United States and elsewhere where uranium–vanadium ore has been found in younger beds, and they suggest the extension of a favourable metallogenic province into the Yukon Territory. Recent surveys of radioactive occurrences in Alaska indicate the uranium possibilities of that state, and an occurrence of tyuyamunite is reported in the Alaska panhandle adjacent to the Yukon and British Columbia (Eakins, 1969).

### British Columbia

Traces of vanadium were noted by the writer in field tests at numerous localities in British Columbia, in a variety of rocks and minerals of diverse origin and age. Dark shale of Devonian (?) age in the northern part of British Columbia (loc. 1, 59°N, 130°30'W) sampled by R. Mulligan showed a trace of vanadium, as did several samples of dark shale of Ordovician (?) age submitted by H. Gabrielse (loc. 2, 58°–59°N, 125°–127°W). Here again are many favourable indications of a vanadium and uranium metallogenic province.

#### *Springiron Lake (Gataga River) (3) 57°58'N, 125°45'W*

On a mountain ridge about  $1\frac{1}{2}$  miles north of Springiron Lake, near the headwaters of the south fork of the Gataga River in a rugged section of northern British Columbia, a striking orange-red gossan of several acres covers the steep, east-facing, treed mountainside (Pl. IVA, B). Specimens of a rare, green-weathering, bronze, copper–vanadium sulphide mineral collected by J. J. McDougall of Falconbridge Nickel Mines Limited, from quartz veins and from a black crystalline limestone band in shale at this locality, were subsequently identified as sulvanite ( $3Cu_2S \cdot V_2S_5$ ) by the late R. M. Thompson at the University of British Columbia. The grey shale which forms the ridge, and with which the gossan is associated, is believed to be of Ordovician age. The shale member is underlain by quartzite, overlain by grey dolomitic limestone, and thrown into a series of northwesterly striking folds cut by numerous faults. In the area of the ferruginous gossan most of the bedrock is covered, but here and there outcrops of soft grey, brown, and black shale with occasional penetrations by small vuggy quartz veins are exposed. The shale contains barium, zinc, silver, manganese, vanadium, and iron, in higher than average amounts, and the zone is weakly radioactive. The gossan forms a coating, generally 1 foot to 4 feet thick, of cellular, vividly coloured limonitic iron oxides spread over the weathered shale rubble on the steep slope from the top of the ridge to the valley of the creek below. In places near the top of the ridge the limonite is encrusted around pockets resembling dried-up pools or springs, around which fragments of bark, needles, and cones from the trees



nearby are cemented in the surface layers. The gossan thickens near the base of the slope where it forms almost flat easterly dipping layers in a linear zone more than 1,000 feet long, 10 to 250 feet wide, and 20 feet or more deep in places.

Frobisher Exploration Company Limited trenched and sampled the gossan in 1958, but attempts to drill through it were unsuccessful because of an underlying zone of sticky, blue-grey, pyrite-bearing, calcareous clay or gyttja. One trench exposes 4 feet of dark red-brown gossan above 4 feet of orange clay with shale fragments; another shows 4 to 5 feet of dark crustified gossan over 4 feet of light coloured limonitic zones, with shale fragments below.

Samples of the dark shale showed a high iron (1 to 10 per cent Fe) and barium (1 to 5 per cent Ba) content, with traces of manganese, zinc, copper, titanium, vanadium, and faint traces of molybdenum, nickel, silver, cobalt, chromium, niobium, uranium, and zirconium.

The gossan also has a high iron content ( $>10$  per cent Fe) and zinc (2 to 3 per cent Zn) and faint traces of other metals including copper (0.01 per cent Cu), nickel (0.01 per cent Ni), silver (0.01 per cent Ag), uranium (0.001 to 0.01 per cent  $U_3O_8$ ), and vanadium (0.01 to 0.02 per cent V). The spring waters issuing near the lower part of the gossan-covered shale ridge are clear, but rather acidic and unusually high in base metals. These waters are actively eroding the layered gossan and re-depositing the dissolved metals at lower levels in their courses.

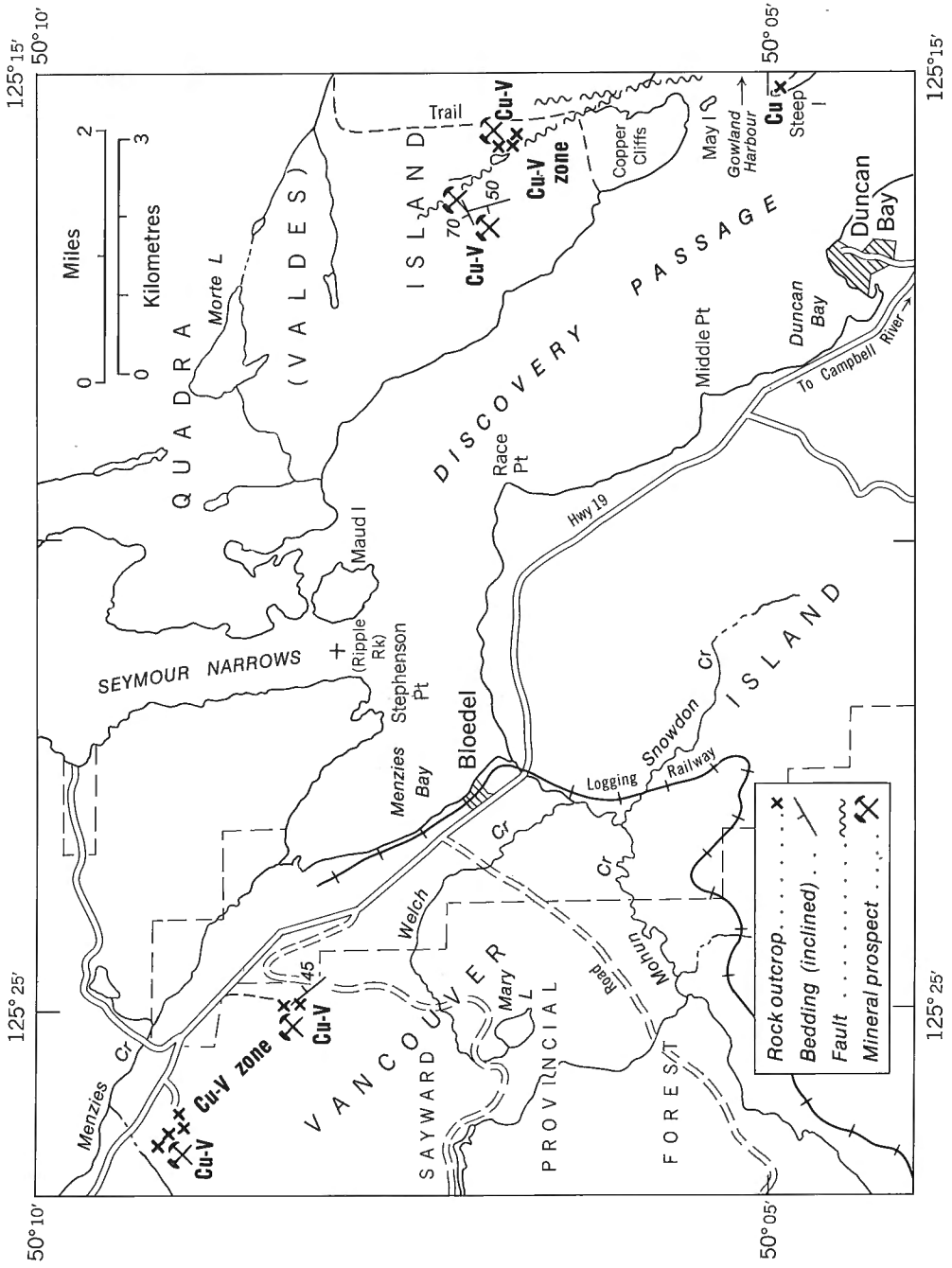
The gossan seems to have been derived locally from metalliferous organic shales, but it has mushroomed down the slope from sources high on the ridge. It seems probable that one or more strongly mineralized zones must occur in the shale underlying this ridge, to account for this unusually large and spectacular, iron- barium- and zinc-rich gossan.

*Quadra Island (17) 50°07'10"N, 125°15'40"W*

- References: Bancroft, J. A. (1913)  
 Carlisle, D., and Susuki, T. (1965)  
 Ellsworth, H. V. (1932)  
 Ellsworth, H. V., and Gunning, H. C. (1933)

The first occurrence of carnotite in British Columbia was discovered by R. Crowe-Swords of Vancouver in 1930 and this was subsequently identified at the University of British Columbia, and described by Ellsworth (1932) and by Ellsworth and Gunning (1933). The carnotite-like mineral was found as a yellow powder in crevices in the copper-bearing volcanic rocks, andesites, and basalts of Bancroft's Valdes Group (1913). These rocks are now included in the Karmutsen Group in which the intercalated sediments and volcanics are included on Quadra Island as an equivalent of the Texada Formation and of Triassic age (Carlisle and Susuki, 1965).

The first vanadium discovery was made in an old open cut on the property of Radium Explorers Incorporated at the north end of the company's showings, described as being about  $1\frac{1}{2}$  miles north of the head of Gowlland Harbour, on Quadra (Valdes) Island (Gunning and Carlisle, 1944). The occurrences located by the writer are about  $2\frac{1}{2}$  miles northwest of the north tip of Gowlland Harbour, about one quarter of a mile east and two fifths of a mile southwest of the north end of a small pond nearby (Fig. 4). At the first exposure east of the pond, hard, fine-grained, amygdaloidal andesite with dark patches of basalt are lightly impregnated in places with chalcocite,



GSC

FIGURE 4. Menzies Bay and Quadra Island vanadium occurrences.

125° 25'

in part altered to malachite. A trench 12 feet deep, 6 feet wide, and 60 feet long has been cut across the ridge, and a shallower trench 80 to 120 feet long runs at right angles to the first along the crest of the southwest-facing outcrop. Sporadic traces of chalcocite and malachite on the joints are shown along the trenches. Samples taken by the writer from the green volcanic rock and copper ore at this locality each showed 0.8% Cu, and 0.14% V, and 1.0% Ti. West of the pond on the northeast side of a wooded ridge three other occurrences were noted, one in a relatively new cut below an old pit in which malachite stains appear in a dark volcanic breccia and in association with a tuffaceous band in volcanic rocks. The strike of this band is 350 degrees; it dips 50 degrees westerly and is crossed by calcite-bearing joints striking 250 degrees and dipping 75 degrees northwest. The main mineralized zone, about 5 feet wide, consists of sheared, chloritic, dark green andesite, feldspar, argillite, and chert with disseminated chalcocite, malachite-azurite, and a trace of yellowish green volborthite. In the newer lower cut, which measures 350 feet long by 50 feet wide by 20 feet deep, a 20-foot-thick zone of soft mauve-brown volcanic rock is exposed above 20 feet of hard green andesite carrying disseminated chalcocite and sporadic malachite. A selected sample taken from the green band showed 0.14% V, 1.1% Ti, and 0.8% Cu; and one from the brown band showed 0.05% V, 1.4% Ti, and 0.01% Cu.

A short distance to the northwest another old cut about 60 feet long, 10 feet wide, and 15 feet deep was found along the strike and dip of a dark sedimentary bed or lens in the grey-green volcanic rocks. The beds strike 50 degrees and dip 70 degrees northwesterly, varying in thickness from 1 foot to 3 feet along the 100-foot exposure. The dark, carbonaceous, cherty, argillite bed carries disseminated chalcocite and secondary bloom of yellow and green, and blue vanadium and copper minerals at both ends of the cut. A zone of breccia 12 inches wide cemented by calcite, runs almost parallel to the sedimentary mineralized band. A sample from the mineralized chert-argillite showed 0.33% V, >0.8% Cu, 0.5% Ti, 0.08% Mn, 0.007% Cr, 0.002% Ni, and 4.1% Fe. A sample of malachite-bearing material showed 0.15% V, >0.8% Cu, 1.0% Ti, 0.17% Mn, 0.017% Cr, 0.007% Ni, <0.002% Co, and >5% Fe; a sample of the volcanic rocks above the mineralized zone showed 0.05% V, 0.06% Cu, 1.1% Ti, 0.15% Mn, 0.024% Cr, 0.009% Ni, and >5.0% Fe; another of the greenish volcanic rocks immediately below the mineralized zone showed 0.14% V, >0.8% Cu, 1.1% Ti, 0.18% Mn, 0.027% Cr, 0.016% Ni, 0.006% Co, and >5.0% Fe; another of the red-brown volcanic rocks 30 feet below the mineralized zone showed 0.05% V, 0.01% Cu, 1.4% Ti, 0.15% Mn, 0.012% Cr, 0.006% Ni, and >5.0% Fe; and another of the weathered volcanic rocks above the mineralized zone showed 0.04% V, >0.8% Cu, 1.5% Ti, 0.2% Mn, 0.03% Cr, 0.007% Ni, 0.002% Co, and >5.0% Fe. These occurrences are within the general area from which the original samples were taken and the descriptions made. Similar occurrences have since been found near Menzies Bay (Pl. V A) on Vancouver Island about 6 miles to the west-northwest of these occurrences on Quadra Island. Although the enriched parts of the deposits are small, the low-grade dissemination of copper and vanadium minerals in the volcanic flows compares favourably in metal content with that of many of the porphyry copper deposits now being prepared for production in British Columbia.

*Menzies Bay (South Location) (16) 50°06'30"N, 125°23'20"W*

Reference: Jambor, J. L. (1960a)

At a point 11.6 miles north on Highway 19 from the bridge over Campbell River, a lane branching off to the left leads south about 0.7 mile to the vicinity of several small cuts in copper-vanadium-bearing volcanic rocks similar to those on Quadra Island. A number of small openings have been made on mineralized zones on each side of the bush road on the Menzies Bay Company Limited claim (Fig. 5).

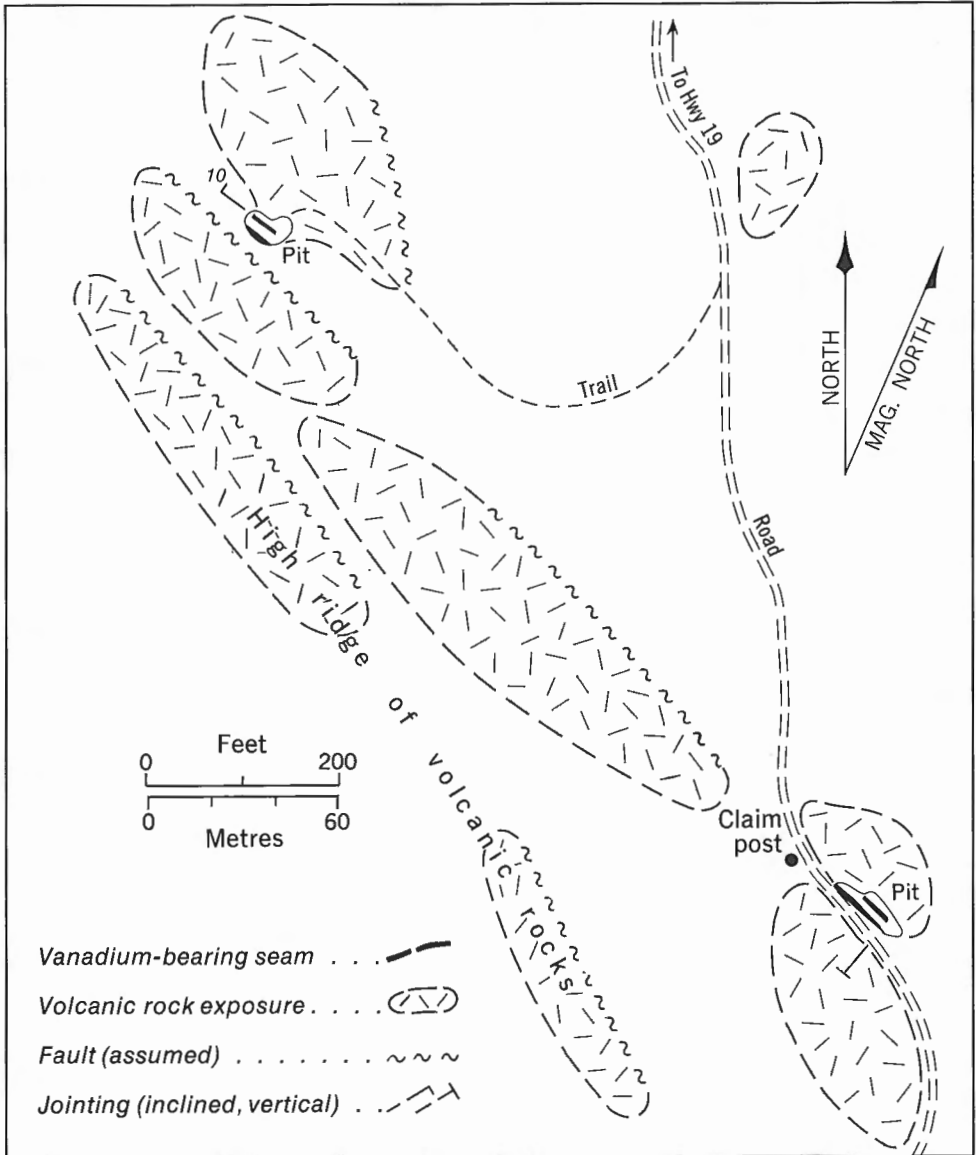


FIGURE 5. Menzies Bay vanadium occurrences, south location.

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The copper-vanadium minerals occur mainly within lenses of sedimentary rock intercalated with the volcanic rocks, but also in the volcanic rocks in a northwesterly trending shear zone at least 1,200 feet long. The sedimentary lens is best exposed southeast of the road where a nearly vertical shear zone in the volcanic rocks strikes at 320 degrees and exposes a rather gently dipping, twisting, pinching seam of mineralized sedimentary rocks resting on brown-weathered, dark green, amygdaloidal andesite, and overlain by a brown-weathered amygdaloidal andesite flow about 6 to 8 feet thick (Pl. V B). The seam is exposed for a length of about 50 feet along the sides of the gulch where it varies considerably in thickness, and is drawn out vertically and dragged along the fault, but generally strikes at 315 degrees and dips 45 degrees northeasterly. The sedimentary seam is about 3.5 feet thick at its widest point, consisting of basal layers of black tuff-argillite 2 to 12 inches thick, overlain by fine-grained grey siliceous, fossiliferous (Triassic) limestone, 4 to 24 inches thick, succeeded in places by a thin zone of greenish shale, 0 to 4 inches thick, carrying carbonaceous remains and brachiopods. Although most of the nearby rocks are more or less stained the black tuff-argillite is most heavily stained yellow, green, and blue, particularly along joints and fractures. On close examination the black tuff-argillite is found to consist largely of altered crystals of feldspar and ferromagnesian minerals, now altered largely to chlorite, with accessory titaniferous magnetite and sphene, some epidote and quartz, in a semi-opaque matrix of dark brown bitumen, greenish volborthite, and opaque dark chalcocite. In places it is fragmented, features a thin wispy banding, and carries replaced carbonaceous and calcareous fossil shells. The rock is obviously derived from the associated lavas, and formed as a bedded sediment with entrapped fossils deposited upon them. The bitumen and organic matter is probably derived from fossil material, but the source of the copper and vanadium is not so clear. Some may have been secreted by the organisms but in part it appears to have been introduced by solutions, for the ore minerals occur both as disseminated irregular groups of crystals, in minute stockworks, and microbreccia cements, as well as in thin veinlets crosscutting the bedding along fractures. Jambor (1960a) identified the secondary yellow vanadium-bearing mineral that accompanies malachite, azurite, and brochantite in these rocks as volborthite, and also detected vanadium there in an organic compound which he called 'golden tan' mineral.

The writer's samples of the black tuff-argillite showed 1.4% V, 2.9% Fe, > 0.8% Cu, 0.12% Ti, 0.019% Mn, 0.002% Cr, and 0.004% Ni; and of the heavily stained material 1.8% V, 4.6% Fe, > 0.8% Cu, 0.42% Ti, 0.057% Mn, 0.018% Cr, 0.007% Ni, and Co was not detected. Dark limestone from the centre of the seam showed 0.09% V, 0.73% Fe, > 0.8% Cu, 0.075% Ti, 0.18% Mn, 0.006% Cr, and Ni and Co were not detected. Soft green shale from the top of the seam showed 0.06% V, > 5.0% Fe, > 0.8% Cu, 0.60% Ti, 0.19% Mn, 0.003% Cr, and Ni and Co were not detected. Green andesite from the footwall below the seam showed 0.08% V, > 5.0% Fe, > 0.8% Cu, 0.99% Ti, 0.17% Mn, 0.02% Cr, 0.01% Ni, and 0.006% Co. Brown stained andesite from the hanging-wall above the seam showed 0.04% V, 0.15% Cu, > 5.0% Fe, 0.8% Ti, 0.23% Mn, 0.009% Cr, 0.09% Ni, and 0.005% Co.

*Menzies Bay (North Location) (15) 50°09'06"N, 125°25'06"W*

At a point 12.3 miles north on Highway 19 from the bridge over Campbell River, a bush road branches to the southwest but curves northwesterly for 0.5 mile to small cuts in copper–vanadium-bearing volcanic rocks similar to those at the south location. As indicated on Figure 6 several small openings have been made in the volcanic rocks along a curvilinear zone about 1,000 feet long on a claim held by Menzies Bay Company Limited in 1963. A light mineralization including small lenses of enriched sediments similar to that at the south location is exposed along joints in the rocks in the cuts along the zone, which strikes about 326 degrees, much the same direction as the mineralized zone at the south location. At the northernmost pit a shallow cut about 300 feet long has been made along the northeast side of an andesite-basalt outcrop. At the northwest side of the cut a red oxidation stain is exposed for 16 feet along a joint surface that strikes about 280 degrees and dips 75 degrees

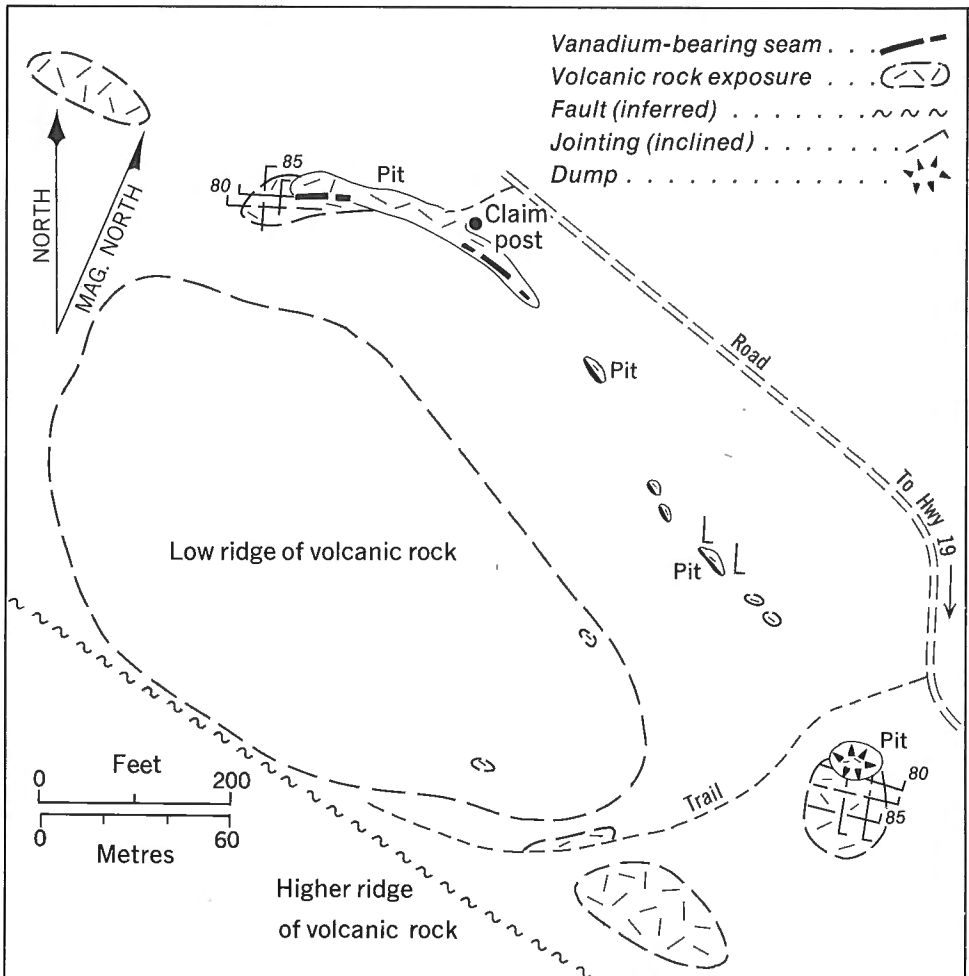


FIGURE 6. Menzies Bay vanadium occurrences, north location.

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northerly. The rock is strongly jointed in two principal directions: one striking northerly (dipping easterly), the other striking westerly (dipping nearly vertically), and a third striking northwesterly (and dipping vertically). A flat erratic lenticular seam of hard, dark, tuffaceous sediment, varying in thickness from 1 inch to 20 inches, and surficially stained with green, blue, yellow, and red secondary iron-copper-vanadium minerals, appears in the bottom of the cut, strikes about 310 degrees and dips 25 degrees northeasterly. The dark seam grades from hard black tuff to fine-grained black limestone, and then to grey fossiliferous limestone as at the south location.

About 200 to 300 feet southeast of this occurrence two small pits expose a 4-inch-thick, nearly vertical band of dark tuffaceous sediments stained with malachite, azurite, limonite, and volborthite, in volcanic rock. Three hundred feet farther east a semicircular pit about 15 feet in diameter and 15 feet deep has been blasted in amygdaloidal andesite carrying sparsely disseminated copper-vanadium stains. The andesite is bluish green to greenish grey, fine grained, pillowform and amygdaloidal, strongly jointed, but almost barren of mineralization and alteration, except for thin films along certain joints, and here and there a speck of native copper, chalcocite, or malachite.

A sample of the mineralized sedimentary seam showed 1.5% V, > 0.8% Cu, 4.0% Fe, 0.16% Ti, 0.02% Mn, 0.05% Cr; Ni and Co were not detected. A sample of brown stained andesite from the hanging-wall above the seam showed 0.045% V, 0.27% Cu, 3.9% Fe, 0.72% Ti, 0.07% Mn, 0.009% Cr, 0.005% Ni, and Co was not detected.

*East Sooke Peninsula* (20) 48°20'30"N, 123°42'W

References: Clapp, C. H. (1912)  
Cooke, H. C. (1919)

Some sporadic attempts were made early in the century to mine iron from a deposit on Iron Mountain (Clapp, 1912). According to Cooke (1919) the Iron Mountain deposit consisted of magnetite and pyrrhotite in a gangue of hornblende, forming broken lenses along a large shear zone, and mineralized later with chalcopyrite.

Narrow bands of massive titaniferous magnetite in a gabbroic intrusion with associated anorthosite are poorly exposed south of East Sooke, on the peninsula which forms the southwest tip of Vancouver Island. The gabbro (Oligocene in age) is intrusive into the basic lavas and sediments that form the Metchosin basalts group of Tertiary (Eocene) age, and is overlain by soft sediments of the Sooke Formation of Miocene age. The magnetite is both titaniferous and vanadiferous, carrying about 5 per cent titanium and 1 per cent vanadium. It occurs sporadically in a zone at least 200 feet wide, striking northeasterly and dipping very steeply toward the northwest, flanked on the east by anorthosite, and on the west by a fault and breccia zone (in rusty pyroxenite-gabbro carrying some chalcopyrite, pyrrhotite, ilmenite, and titanomagnetite) called the Meryth Zone. A sample from the Meryth mineralized zone showed 0.5% Cu, 0.02% V, 0.2% Ti, 3% Fe, 3% Al, 3% Ca, 3% Mg, 15% Si, 0.02% Zr, 0.01% Y, and <0.003% Yb. Dip-needle readings on the titaniferous magnetite occurrence are strongly positive. An oriented specimen taken by the writer from the titaniferous magnetite was reversely polarized and showed a strong component of remanent magnetism gently inclined north-northeast, almost at right angles to the

directions of magnetization of the gabbro and anorthosite. The titanomagnetite occurs as intercrystal cumulates, as a very fine dusty dissemination through pyroxene crystals, as rims around grains of olivine, and as massive bands with salients penetrating the altered gabbroic host rock. In short there is evidence of some redistribution of primary iron oxides. The magnetite is weakly anisotropic in a few patches, but shows exsolution textures only under high magnification. A small amount of ilmenite is present as are a few specks of disseminated sulphides, mainly pyrrhotite and chalcopyrite.

*Banks Island* (10) 53°24'N, 130°00'W

Near the east shore of Banks Island a vertically banded intrusive mass of dark amphibolitic gabbro of probable Mesozoic age, but older than the Coast Range granitic intrusions, forms a conspicuously bare 3,000-foot-high mountain. The gabbro carries disseminations and bands of titaniferous magnetite over a large area (Pl. VI A). The most heavily mineralized banded zone within the gabbro is from 100 to 200 feet wide, more than 1,000 feet long, and is flanked by gabbro carrying somewhat less magnetite. The banding strikes northerly and dips steeply easterly. Dip-needle readings on the outcrops are erratic and positive. The zone is crosscut by faults and joints striking northeasterly and dipping steeply northwesterly. These are commonly zones of alteration, carrying thin seams and dykelets of epidote and other alteration products. The gabbro consists mainly of coarse hornblende and plagioclase with disseminations and bands of intergrown titanomagnetite and ilmenite. Titanomagnetite and ilmenite form a mosaic of interlocking crystals both in bands within, and interstitial to, the silicates. Samples of the hornblendite-gabbro showed from 20 to 25% Fe, 1.1 to 1.9% Ti, and 0.04 to 0.33% V. Magnetic concentrates made by the writer from these samples showed > 50% Fe, 1.5 to 5% Ti, and 0.5 to 1% V. Titanium and vanadium are carried mainly in solid solution in titanomagnetite and both concentrate in the magnetic extract.

These occurrences are on tidewater and could be mined by open-pit methods and readily concentrated. Several million tons of low-grade Fe-Ti-V bearing material are known at this locality.

*Porcher Island* (8) 53°55'N, 130°24'W

On a mountain ridge in central Porcher Island a sill-like complex of interbanded, coarse- and fine-grained, basic to ultrabasic, igneous rocks intrudes into fine-grained dark tuff, or slaty greenstone, and is intruded on the east by granodiorite. The banded complex appears to be more than 100 feet thick and at least 600 feet long, possibly much more. It is composed of interbanded hornblende gabbro, anorthositic gabbro, and pyroxenite, all more or less impregnated with clots and seams of titaniferous magnetite and ilmenite. The bands in the rock strike easterly and dip 45 to 60 degrees northerly but swing northwest and may reappear on the ridge to the north. Titaniferous magnetite is most abundant in two zones about 50 to 100 feet thick near the crest of the ridge, where it forms bands 4 to 8 inches thick carrying white plagioclase and tabular prisms of black hornblende arranged vertically and at right angles to the margins of the bands. Epidote and feldspar are common in seams both in joints parallel to the banding and in nearly vertical, north-south, crosscutting joints. In polished section titanomagnetite and ilmenite form interlocking crystal mosaics that are interstitial to the silicate minerals, together with minor pyrrhotite, pyrite, and chalcopyrite. Samples from the host rock show > 5% Fe, 0.5 to 1.2% Ti, and 0.02



to 0.04% V. Samples from the mineralized zone showed > 5% Fe, 0.14 to 0.3% Ti, and 0.14 to 0.2% V; magnetic concentrates made from these samples showed major iron, 0.3 to 1.5% Ti, and 0.2 to 0.5% V. It is not difficult to make a magnetic concentrate that is relatively high in Fe-Ti-V from this material.

*McCauley Island* (9) 53°40'N, 130°15'W

Titaniferous magnetite occurrences in basic to ultrabasic igneous rocks in the south-central part of McCauley Island are also believed to be vanadiferous. The occurrences are probably similar to those on Banks and Porcher Islands.

*McConnell Creek Placer Deposits* (5) 56°47'N, 126°29'W

Reference: Lord, C.S. (1948)

Gold-bearing gravels on McConnell Creek have received sporadic attention since 1899 (Lord, 1948). The gold occurs as small rounded grains, or as larger flattened nuggets, and is accompanied by abundant black sand and occasional flakes of platinum. A sample of black sand concentrate recovered from sluice-boxes on Olson's claim in 1945 assayed > 0.36 ounces a ton in gold, 0.74 ounces a ton in silver, and showed traces of platinum, palladium, and vanadium.

Lord described a group of well-bedded, continental-type sedimentary rocks consisting of sandstone, shale, conglomerate, and tuff about 3,000 feet thick and carrying fossil plant remains, that he named the Sustut Group and assigned to the Upper Cretaceous and Paleocene (Tertiary). He considered the sandstones of the Sustut Group as a possible source of the vanadium detected in the black sand concentrate from McConnell Creek gravel, and suggested that the yellow stains on rocks of the group should be scrutinized carefully for occurrences of carnotite or other vanadium minerals.

*Tsitsutl Mountain* (11) 54°58'N, 125°37'W

References: Armstrong, J. E. (1949)  
Little, H. W. (1949)

Vanadium has also been noted in analyses from a tin-bearing manganiferous vein carrying rhodonite that cuts metamorphosed sedimentary rocks of the Cache Creek Formation (Permian ?) on Tsitsutl Mountain south of Takla Lake (Armstrong, 1949; Little, 1949). According to H. W. Little, a vein 18 to 24 inches wide, composed of about 70 per cent rhodonite, 2 or 3 per cent arsenopyrite, calcite, garnet (spessartite), and ilmenite, is exposed in an outcrop near the crest on the northwest slope of Tsitsutl Mountain at an elevation of 5,500 feet. The vein strikes northwesterly in slate of the Cache Creek Group between a (Triassic ?) post-Permian intrusion of ultrabasic rocks on the west and a younger, larger, quartz porphyry (granite) stock of possible Tertiary age on the east, and immediately north of the boss of biotite granite that forms the core of Tsitsutl Mountain. Chemical tests by H. V. Ellsworth on specimens from the vein showed "appreciable amounts of manganese, cobalt, and vanadium, with very little copper and hardly more than a trace of nickel." The area was investigated mainly for its tin possibilities by The Consolidated Mining and Smelting Company of Canada Limited who obtained an analysis of 0.65 per cent  $V_2O_5$  from a sample of the wall-rock of the vein in otherwise discouraging assays.

*Lodestone Mountain* (30) 49°27'N, 120°50'W

Traces of vanadium are believed to occur in titanomagnetite associated with ultra-basic intrusions on Lodestone Mountain.

*Copper Mountain* (28) 49°22'N, 120°34'W

Reference: Rice, H.M.A. (1947)

Faint traces of vanadium in samples of Copper Mountain ore were reported by H. M. A. Rice (1947, p. 85). A biotite concentrate made from the ore material showed as much as 0.36 per cent vanadium.

*Cherry Bluff* (24) 50°43'N, 120°36'W

References: Cockfield, W. E. (1948)

Young, G. A., and Uglow, W. L. (1926)

Traces of vanadium and titanium were detected in samples of magnetite submitted by E. D. Kindle from Cherry Bluff 13 miles west of Kamloops and one quarter of a mile south of Kamloops Lake where a number of small vein-like masses and disseminations of magnetite and copper have been found in basic phases of the intrusive Iron Mask batholith and altered rocks of Cretaceous or younger age (Young and Uglow, 1926). The magnetite veins are erratic but in general trend east. In places they carry apatite as well as epidote, tremolite, and serpentine (Cockfield, 1948).

*Other Occurrences*

Graphitic shale and schist that form part of the Hozameen Group of Permian or Carboniferous age east of Hope (loc. 29; 49°24'N, 121°26'W) show faint traces of vanadium (0.057% V), as do certain beds of grey to black, yellowish, and mauve sandstone of Cretaceous age in the Nicola (loc. 25) (0.017% V) and Thompson River (loc. 25) (0.024% V) valleys near Spences Bridge; near Minto (loc. 21) (50°52'N, 122°48'W) (0.17% V) in a 10-foot section of yellow stained sediments; and on Vancouver Island, near Cumberland (loc. 18; 49°38'N, 125°02'W) (0.014% V), and Nanaimo (loc. 19) (0.011% V). Thick sections of interbedded black nodular shale and dark sandstone of Early Cretaceous age exposed along the Alaska Highway on Sikanni Chief River (loc. 6) (57°15'N, 122°42'30"W) (0.017% V) where they are flat lying, and west of Fort Nelson (loc. 4; 58°38'N, 124°25'W) (0.01–0.03% V), where they are vertical (Pl. VI B), also carry faint traces of vanadium, with a slight concentration in places in some of the cherty black nodules. Faint traces of vanadium were also detected in almost flat-lying columnar basalt (0.002%) and chert (0.03% V) of Tertiary age near Quesnel (loc. 13; 53°10'40"N, 122°30'W), in grey shale (0.003% V), on Skeena River near Terrace, and in dark slate or schist of Mesozoic age (0.02% V) south of Prince Rupert (loc. 7; 49°30'N, 120°41'W). A sample of Bowron River coal (loc. 12; 53°50'N, 121°55'W) from central British Columbia taken by A. R. Cameron showed 0.1% V and 0.05% Mo in its ash; another from Merritt (loc. 26; 50°06'N, 120°47'W) showed 0.045% and 0.01% Mo; another from Princeton (loc. 27; 49°30'N, 120°41'W) showed 0.015% V; another from coaly shale on Hat Creek (loc. 23; 50°53'N, 121°30'W) showed 0.025% V; another from a 3-foot lignite seam on Australian Creek (loc. 14; 52°41'20"N, 123°23'35"W) showed 0.035% V and 0.01% Mo; and another from coaly shale at Chu Chua (loc. 22; 51°20'N, 120°10'W) showed 0.025% V; all in ash. The coals from British Columbia tested generally higher than the lignites from Saskatchewan.

## Alberta

*Athabasca Tar Sands* (Abasands) (2) 56°42'N, 111°24'W

References: Ells, S.C. (1926)  
 McConnell, R. G. (1893)  
 Scott, J. *et al.* (1954)  
 Vigrass, L. W. (1965)

The Athabasca tar sands, first noted by the explorer Peter Pond in 1788 and assigned to the McMurray Formation of Lower Cretaceous age (McConnell, 1893) and extensively sampled by Ells (1926), occupy a large area in northeastern Alberta where they outcrop at McMurray and along the Athabasca River for 20 miles to the north (Pl. VII A). The lightly covered undulating Cretaceous sandstone beds are impregnated with heavy bitumen in sections as much as 150 feet or more thick, and underlie more than 1,000 square miles. They are believed to hold several billion barrels of crude oil, constituting one of the world's greatest petroleum resources. Three other large important areas of oil sands have since been discovered in northern Alberta. The distribution of these deposits of heavy oil in Lower Cretaceous sandstones in Alberta is outlined in Figure 3.

In 1952-53 an investigation of the trace metals, vanadium, nickel, and iron, in oil derived from these sands was carried out by the Research Council of Alberta, and a summary of results was published (Scott, *et al.*, 1954). A typical oil-sand analysis was 360 ppm  $V_2O_5$  (0.02% V), 93 ppm NiO (0.007% Ni), and 106 ppm  $Fe_2O_3$  (0.007% Fe). A similar proportion of vanadium and nickel was found in widely separated oil samples from Cretaceous rocks elsewhere in Alberta. In addition, the presence of metal-containing porphyrin compounds was detected in the heavy, black, high-sulphur oils, but not in the light oils. From this it was concluded that the heavy oils are probably of common origin and were derived not from a common light oil source, but that they may be the precursors of light oils. The Athabasca oil sands contain a crude oil which is similar in metal-porphyrin content to other high-sulphur oils. According to Hodgson, *et al.* (1963), oil in the Athabasca tar sands has a predominance of vanadyl porphyrin pigments compared with nickel pigments—in contrast to conventional low-sulphur, low-gravity crude oils, in which nickel porphyrins tend to predominate. Porphyrin pigments (deoxophylloerythroetioporphyrin) are in sediments younger than the Precambrian, and recent sediments show the presence also of chlorin pigments, but according to Hodgson, *et al.* (1963), the younger the sediments the more dominant are the chlorin pigments. Also, vanadyl porphyrin pigments appear to predominate over nickel porphyrin complexes in restricted bay-reducing environment (with high sulphur,  $H_2S$ , pH values as opposed to open-sea type of marine sediment). The development of vanadyl and nickel porphyrin pigments in petroleum appears to start from pigments and chlorophyll or some closely related complex in living organisms. Reducing conditions seem to favour the predominance of vanadyl over nickel porphyrins, and also favour the development of sulphur in the developing crude oil through the action of sulphate-reducing bacteria on decaying organic matter in the sediment.

The raw Athabasca oil sand appears to range from 35 to 400 ppm  $V_2O_5$  (0.002-0.024% V) (Scott, *et al.*, 1954; Hodgson, *et al.*, 1963), but samples taken by the writer from Bitumount, Abasands, McMurray, and north along the east bank of

Athabasca River, ranged from 0.002 to 0.01 per cent V, averaging about 0.004 per cent V, with faint traces of U, Th, Ni, and many other metals. One sample of the tar sands from McMurray showed faint traces of Y, Yb, U, and Th, and another held traces of Pt, W, and Ag. Vanadium was not detected in samples of the grey limestone conglomerate and brown chert lying immediately under the Athabasca tar sands.

Plans for recovery of vanadium as a byproduct of the production of synthetic crude oil and petroleum coke have not been announced by Great Canadian Oil Sands Limited, who first obtained the permission of the Alberta government to exploit the oil sands commercially in 1965 on a controlled lease. Commercial oil recovery by GCOS began in 1967, and is expected to continue at the rate of 45,000 barrels of oil and 3,000 tons of petroleum coke per day. The ash from some of the coke is reported to contain about 4 per cent vanadium (Hodgson, *et al.*, 1963).

Similar oil sands have been found, mainly in three other areas in northern Alberta, at the Peace River, Wabasca, and Cold Lake deposits, as shown on Figure 3. The heavy oil content of these Lower Cretaceous sand reservoirs has been estimated at about 750 billion barrels (Vigrass, 1965).

*Andrew Lake (1) 59°50'N, 110°10'W*

Reference: Godfrey, J. D. (1958)

Yellow stains resembling carnotite have been reported in association with radioactive molybdenite occurrences in mixed Precambrian gneisses, schists, granite, and metasedimentary rocks 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 to 0.1 per cent vanadium respectively according to Godfrey.

*Crowsnest Pass Phosphate Rock (11) 49°37'30"N, 114°42'W*

References: Price, R. A. (1962)

Telfer, L. (1933)

Thin beds and nodules of phosphate rock in dark phosphatic carbonaceous shales have been known for many years near the Alberta-British Columbia border in the Crowsnest Pass area, but attempts to mine them for phosphate have proved uneconomical. Consolidated Mining and Smelting Company of Canada (Cominco Ltd.) mine and import phosphate rock from Montana to supply their fertilizer plant at Trail, British Columbia, and they have examined some of the reported Crowsnest Pass occurrences from time to time (Telfer, 1933). It has not been considered economical to recover the low vanadium content of the imported phosphate rock or to further develop the known phosphate rock occurrences in Canada.

On the south side of the highway near Crowsnest Lake (49°37'N, 114°40'W) an exposure of brown to black fissile shale is sandwiched between massive beds of cherty limestone and nodular phosphatic limestone (Pl. VII B). The shale zone in two bands each about 20 feet thick, separated by a 20-foot-thick band of fossiliferous nodular grey limestone, strikes 315 degrees and dips 45 degrees southwesterly under a hanging-wall of cryptocrystalline grey Palliser limestone (Devonian) carrying black chert lenses. The shale zone is in fault contact with Mississippian limestone on the footwall and is considered by Price (1962) to be of Exshaw (Early Mississippian)

age. The shale is wrapped around discontinuous beds or blocks of dark phosphatic limestone and carries many dark rounded nodules from 1 inch to 3 inches in diameter. A sample of the dark shale taken by the writer showed 0.011% V, 0.28% Ti, 0.026% Mn, 0.019% Cr, 0.0086% Ni, 0.009% Cu, 0.003% Co, and 0.002%  $U_3O_8$  (equiv.); and one of the nodules showed 0.0096% V, 0.19% Ti, 0.016% Mn, 0.015% Cr, 0.011% Ni, 0.019% Cu, and 0.003% Co.

At the old Crowe Mine (loc. 10, 49°38'N, 114°44'W) about half a mile north of the highway and near the provincial boundary an adit (now caved) was once driven eastward in dark phosphatic shale carrying the fossil brachiopods *Gryphae*, of Fernie (Jurassic) age. The shale strikes 310 degrees and dips 75 degrees south-westerly. A sample of this shale taken by the writer showed 0.0036% V, 0.12% Ti, 0.028% Mn, 0.0077% Cr, 0.0073% Ni, 0.0045% Cu, 0.003% Co, and 0.003%  $U_3O_8$  (equiv.).

*Burmis* (12) 49°40'30"N, 114°19'30"W and *Dungarvan Creek* (13)  
*Iron Deposits* 49°12'N, 113°54'W

References: Allan, J. A. (1931)  
Norris, D. K. (1955)  
Mellon, G. B. (1961)

More than twenty-five occurrences of consolidated rusty weathered titaniferous magnetite beds of detrital origin in the upper part of the Belly River Formation (sandstone) of Upper Cretaceous age, have been found in the Rocky Mountain foothills area of southwestern Alberta (Allan, 1931). The occurrences consist of folded and faulted beds of indurated dark magnetic iron sand interlaminated with grey-buff sandstone within a series of soft sandstone, siltstone, and shale, all of which overlie the dark grey marine shales of the Wapiabi Formation and the coarse-grained Crowsnest alkaline volcanic member, and are overthrust by sheets of older limestones and other rocks (Norris, 1955).

About 8 miles northwest of Burmis, near Cow Creek in Township 8, Range 3, the iron-sand beds are 25 feet or more thick and are overlain by a 6-foot-thick band of rusty ironstone; but the beds pinch and swell, and in general the iron sands average about 8 feet thick (Pl. VIII A). The beds strike at 350 degrees and dip 70 degrees westerly. The iron sand is crossbedded, has tops up, and is intersected by a zone of fault gouge 2 feet thick at the top, above which a 12-foot section of less magnetic sandstone and shale is exposed. About 20 miles south of Pincher Creek, near Dungarvan Creek, in Township 3, Range 30, the magnetite-bearing sandstone beds include a thin siltstone or shale containing pelecypod and gastropod remains, indicative of near-shore environment.

Mellon (1961) indicated that not only are the recoverable iron content and grade of ore low and contaminated with titanium, but that reserves are less than two million tons at Burmis and six million tons at Dungarvan, grading between 25 and 30 per cent iron. A sample of the iron sands taken by the writer showed 0.15% V, 5.2% Ti, 0.27% Mn, 0.013% Cr, 0.014% Ni, 0.026% Cu, 0.0098% Co, and faint traces of Y, Yb, U, and Th. A magnetic concentrate made by the writer from another sample of Burmis ore material showed 60% Fe, 9% Ti, 0.2% Mn, > 0.05% Cr, and > 0.05% V.

*Peace River Iron Deposits* (3) 59°00'N, 111°25'W

References: Mellon, G. B. (1962)  
Gross, G. A. (1965)

Minette-type iron deposits in oölitic, sideritic, chamositic shales and sandstones of Mesozoic age are widespread in the Clear Hills area north of Hines Creek in the Peace River district of northern Alberta. The deposits have been investigated by Peace River Mining and Smelting Ltd. who have developed a process for the production of iron powder using scrap iron and low-grade iron ore. Like its European counterparts, the Peace River minette-type iron ore carries traces of vanadium. Laboratory attempts to recover vanadium from the ore in the form of  $V_2O_5$  are reported to have been successful.

*Other Occurrences*

Faint traces of vanadium were found in samples of flat-lying coal and enclosing buff sandstone of Cretaceous age at Edmonton (loc. 6; 53°25'N, 113°38'W) (0.0035% V), west of Edson (loc. 4, 53°32'N, 116°26'W) (0.008% V), and south of Drumheller (loc. 9, 51°25'30"N, 112°36'W) (0.005% V), but vanadium was not detected in a sample of coal from the Kootenay Formation at Crowsnest mine. Traces of vanadium were also found in samples of black carbonaceous shale south of Jasper (loc. 5, 52°50'N, 118°04'W) (0.017% V), east of Banff (loc. 7, 51°11'N, 115°32'W) (0.01% V) and east of Kananaskis River (loc. 8, 51°05'30"N, 115°03'W). The dark shales of the Mississippian Banff and Exshaw Formations from which the samples came are commonly weakly radioactive, averaging about 0.005%  $U_3O_8$  equivalent as well as 0.015% vanadium.

## Saskatchewan

*Beaverlodge Uranium Ores* (1) 59°28'N, 108°24'W

References: Alcock, F. J. (1936)  
Robinson, S. C. (1955)  
Robinson, S. C., *et al.* (1957)  
Lang, A. H., *et al.* (1962)  
Tremblay, L. P. (1968)

The pitchblende-rich uranium ores of Uranium City area near Beaverlodge Lake have been developed near the Goldfields area where gold was once sought. In 1935 a radioactive mineral occurrence, discovered by prospectors at the Nicholson copper property, was examined by F. J. Alcock and a sample was identified by H. V. Ellsworth as pitchblende (Alcock, 1936). At that time there was little demand for pitchblende although there was only one other known deposit in Canada, that being mined at Great Bear Lake. Much geological work has subsequently been done in the Beaverlodge area and a number of mines have been developed (*see* Lang, *et al.*, 1962; Tremblay, 1968). In a detailed mineralogical study of the ores, S. C. Robinson (1955) classified them as: epigenetic, syngenetic, and supergene, of which the epigenetic hydrothermally introduced deposits are the most important. Among many other minerals found, an unknown vanadium-bearing mineral was described, analyzed, and named nolanite (Robinson, *et al.*, 1957) in honour of Dr. Thomas B. Nolan, former director of the United States Geological Survey. Nolanite is a heavy, dark, iron vanadate mineral (essentially  $3 FeO \cdot V_2O_5 \cdot 3 V_2O_5$ , but of rather uncertain composition), resem-

bling magnetite and pitchblende in appearance. It 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 closed), and in the Pitche Group near the Lorado property (now closed). Traces of tyuyamunite and carnotite have been noted in zones of secondary alteration in some of the occurrences. Robinson (1955) noted the presence of 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 footwall remote from the St. Louis Fault and an increase of vanadium with depth. The possibility of recovering vanadium as a byproduct of the 1,500-ton-per-day mill was given serious consideration by Eldorado Mining and Refining Limited (now Eldorado Nuclear Limited), but vanadium values in the lower levels proved 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 company geological records. The new main Verna uranium orebody probably averages 0.12 per cent vanadium or less, according to mine geologist George Woollett. Samples of nolanite and pitchblende-bearing vein material taken by the writer from the Ace mine and from the erratic Fish Hook Bay Zone A showed >3.0 per cent V. A sample of carbonate from the red zone of the abandoned Nicholson mine showed 0.11 per cent V, about the same as the average Verna mine ore, both somewhat lower than the grade now required for economic recovery of vanadium.

*Southern Saskatchewan Lignite Deposits* (4) southern part of Saskatchewan between 49° and 50°N, 104° and 107°W

References: Chamberlain, J. A. (1960)  
Denson, N. M., and Gill, J. R. (1956)

Lignite seams of Cretaceous and Tertiary age are widespread in the Williston Basin and Cypress Hills area of southern Saskatchewan, where they are commonly intercalated with soft buff-yellow sandstone and siltstone, and occasionally with grey shale and granular gritty volcanic ashrock. The general geological setting and distribution of these deposits is shown in Figure 3. Similar lignite deposits north of Belfield in North Dakota, in the North Cave Hills of South Dakota, and in eastern Montana, contain sufficient uranium, vanadium, and molybdenum for economic recovery of these elements (*see* Denson and Gill, 1956), but although lignite is now being strip-mined extensively at Estevan and Bienfait in southern Saskatchewan no comparable rare-metal concentrations have yet been noted (Pl. VIII B). Preliminary investigations of Latour, Lang, and Chamberlain for uranium have given negative results (Chamberlain, 1960). The problem has been investigated by Cameron and Birmingham (1970).

Three samples of lignite from North and South Dakota collected by Cameron were tested by the writer and showed a range of 0.03 to 0.1 per cent  $U_3O_8$  equivalent and from 0.01 to 0.1 per cent vanadium. Vanadium was detected in all but one in a group of twenty-three samples of lignite and associated carbonaceous shale supplied by A.R. Cameron from southern Saskatchewan occurrences; these showed a range of 0.002 to 0.01 per cent  $U_3O_8$  equivalent, and 0.001 to 0.11 per cent vanadium. A sample of volcanic ash from St. Victor showed 0.002 per cent  $U_3O_8$  equivalent, but vanadium was not detected in it. All these samples are lower in uranium and vanadium than those from the Dakotas, and all are below economic grade in these metals. There

is, however, a rather persistent low-grade association of uranium and vanadium in these lignite deposits and in the associated sedimentary rocks, and the possibility of finding local recoverable concentrations of these elements within those formations should not be dismissed. In another group of eleven samples of lignite from southern Saskatchewan taken by A. R. Cameron, vanadium was detected in the ash of each sample, ranging from 0.005 to 0.08 per cent V, compared with a group of six samples of coal from British Columbia, in the ash of which vanadium ranged from 0.015 to 0.1 per cent V (A.R. Cameron, pers. com.).

#### *Other Occurrences*

Traces or faint traces of vanadium in southern Saskatchewan were also noted by the writer in yellowish green sandstone near Verwood (0.007% V), and in reddish shale near Victor (0.016% V); in grey shale from Willow Bunch (0.007% V), all of Cretaceous age; in yellowish Eocene sandstone south of Duncairn (0.006% V); and in a sample of oil shale (0.015% V) and of brick red dolomitic argillite of the Devonian Torquay Formation (0.01% V), from a depth of 1,828 to 1,838 feet in the Yarbo shaft of International Minerals & Chemical Corporation (Canada) Limited potash mine east of Esterhazy (loc. 3, 50°40'N, 102°07'W). Faint traces of vanadium and very faint traces of uranium were detected in samples of graphitic schists of Precambrian age from Granite and Johnson Lakes (loc. 2, 54°40'N, 102°25'W), west of Flin Flon.

### Manitoba

Three types of vanadium occurrences were noted in Precambrian rocks in Manitoba: one in titaniferous magnetite in anorthositic gabbro at Cross (Pipestone) Lake, another in chromite in serpentinized peridotite near Bird River (5) (0.15% V), and the third in graphitic schists near Star Lake (loc. 2, 55°10'N, 100°52'W) (0.01% V) and Wilson Lake (loc. 1, 55°15'N, 101°05'W) (0.01% V). In addition, vanadium was detected at two localities in sedimentary rock of Mesozoic age, one in bentonitic, selenite-bearing, yellow-stained, grey-brown shale in the Pembina valley south of Morden, (loc. 6, 49°05'N, 98°22'W) (0.047% V), the other in dark grey shale south of Swan River (loc. 4, 52°05'N, 101°15'W) (0.023% V).

#### *Cross (Pipestone) Lake (3) 54°30'N, 97°25'W*

References: Bell, C. K. (1962)  
Rousell, D. H. (1965)

Lenses and disseminations of vanadium-bearing titaniferous magnetite in gabbroic anorthosite of Precambrian age outcrop on the south side of an expansion in the Nelson River about 40 miles northeast of Lake Winnipeg (Fig. 7). The area has been mapped by Bell (1962) and Rousell (1965), and the deposit has been under investigation by Noranda Mines Limited. Aeromagnetic Maps 2596G and 2597G, issued by the Geological Survey of Canada in 1965, show a linear belt of positive aeromagnetic anomalies 6 miles long and half a mile wide trending easterly south of Pipestone Lake, including the exposed titaniferous magnetite and gabbro outcrops. The basic igneous rocks bordering the magnetite occurrences extend in an easterly direction, dip nearly vertically, and are crosscut almost at right angles by a late Precambrian diabase dyke. Titaniferous magnetite occurs sporadically in lenses and strong disseminations in a zone 100 feet thick in a band of anorthositic gabbro that is marginal to, and near the



VANADIUM AND VANADIFEROUS OCCURRENCES OF CANADA

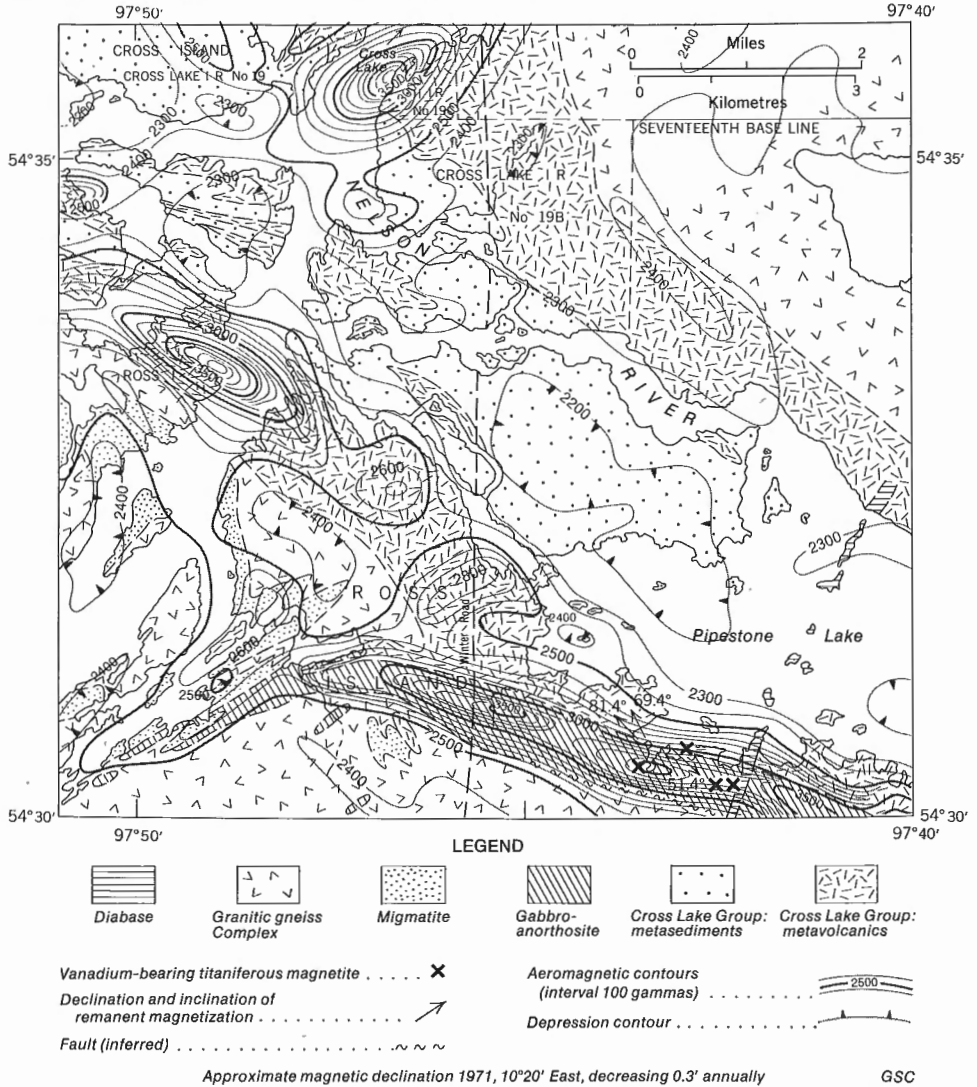


FIGURE 7. Geology, aeromagnetic anomalies and remanent magnetism in titaniferous magnetite, Cross (Pipestone) Lake, Manitoba (geology after C. K. Bell and D. H. Rousell).

top of, a larger, complex, differentiated, sill-like mass of anorthositic rock about 3,000 feet thick (Bell, pers. com., 1971). Rousell (op. cit.) regards this mass as a folded multiple intrusion rather than a layered complex. Further work will be required to resolve this problem. The similarity in geological setting to that of the Bad Vermilion Lake deposit is notable.

Samples taken by the writer from the mineralized zone (P1. IX A, B) showed a range of from 0.01 to 0.3 per cent vanadium, and from 3.2 to 10 per cent titanium; magnetic concentrates made from this material showed more than 60 per cent iron, about 5 per cent titanium, and from 0.5 to 1.5 per cent vanadium. Under a petrographic microscope the opaque iron-titanium oxide minerals are seen to occur interstitially to

plagioclase crystals, together with dark blue-green, pleochroic chlorite and hornblende (Pl. X A). Under a reflecting microscope the opaques are seen as a mosaic of strongly anisotropic titanomagnetite crystals with some intergrown exsolved ilmenite and a few specks of pyrrhotite and chalcopyrite. The strong anomalous anisotropism of the titanomagnetite may in part be due to its relatively high vanadium and titanium content. Titanomagnetite and ilmenite appear to have crystallized from a fluid medium slightly after the plagioclase.

Oriented specimens taken by the writer indicate that the titaniferous magnetite has a component of remanent magnetism directed steeply downward and to the east-south-east, almost at right angles to that of the host rock gabbro, which is steeply inclined to the north-northwest. The remanent magnetism of the magnetite is oblique to the structure and almost at right angles to the earth's present magnetic field.

*Bird River Chromite* (5) 50°25'N, 95°42'W

Reference: Bateman, J. D. (1943)

Chromite was discovered in 1942 in an easterly trending, composite, differentiated, folded sill-like mass of Precambrian basic to ultrabasic rocks, the Bird (Oiseau) River Complex of southeastern Manitoba. The main chromite zone, about 7 feet wide, has been traced intermittently for several miles along strike, in a peridotite zone within a band of gabbro near the middle of the sill (Bateman, 1943). The upper part of the serpentinized peridotite is impregnated and banded with chromite grains and stringers; it averages about 16 to 26 per cent Cr<sub>2</sub>O<sub>3</sub>, and has a chromium-iron ratio of a little more than 1:1. According to Bateman (1943) the dense chromite ore averages from 26.3 to 29.3 per cent Cr. A sample of chromite-rich material taken by the writer from the Bird River sill showed a major content of Cr, Fe, and Al, 10% Si, 7% Mg, 0.3% Ca, 0.3% Mn, 0.2% Ti, 0.15% Ni, and 0.15% V. A part of the Si, Al, Mg, and Ca content of this sample is presumably held in the serpentine and other gangue grains which are intimately associated with the chromite. The vanadium and nickel are held mainly in the chromite.

## Ontario

The best known of the vanadium-bearing titaniferous magnetite deposits in Ontario are those of Bad Vermilion Lake (loc. 3, 48°42'30"N, 92°44'50" W) south of Mine Centre, the Brazeau-Wood property (loc. 23, 46°13'N, 78°42'W) south of Mattawa, the Angus and Flett Township occurrence (loc. 20, 46°51'N, 79°33'W) southeast of Timagami, an occurrence in diabase at Haystack Mountain (loc. 7, 49°59'10"N, 88°W), in occurrences of nickeliferous magnetite associated with an ultramafic body near Puddy Lake (loc. 5, 45°58'N, 89°31'W), and a number of occurrences in eastern Ontario (loc. 21). Occurrences of black sands in Black Bay, Lake Superior (loc. 6, 48°40'N, 88°32'W), of titaniferous magnetite near Bamooos Lake (loc. 9, 48°48'30"N, 86°19'30"W) and on Pic River (loc. 10, 48°42'30"N, 86°17'W) north of Lake Superior, of titaniferous magnetite in Lount Township, Parry Sound district (loc. 22, 45°46'N, 79°40'W), are also reported to be vanadiferous. The Matthews and Chaffey (New Mylamaque; Mymar) (loc. 30, 44°38'N, 76°20'W), Orton and Ricketts (loc. 31, 44°42'N, 77°40'W), Blessington (Eagle Lake) (loc. 29, 44°40'N, 76°42'W), Blithfield (loc. 26, 45°18'N, 76°45'W), Pershing (loc. 32, 44°26'N, 77°51'W), and Pusey or Pine Lake (loc. 25, 44°55'N, 78°23'W) titaniferous magnetite occurrences, all of which are associated with mafic intrusions, were

each found by the writer to be vanadiferous, carrying from 0.1 per cent V in the unconcentrated samples to as much as 0.3 per cent V in the magnetic concentrates made from them (Rose, 1958a). In contrast with this, at least twenty-five deposits of low-titanium magnetite in eastern Ontario, carrying from 0.01 to 0.1 per cent V were found to carry less than 0.01 per cent V in magnetic concentrates made from them. Traces of vanadium have also been found in titaniferous magnetite associated with alkaline-carbonatite complexes as at Nemegos, Nemegosenda River, and Lackner Lake near Chapleau (loc. 11, 47°59'N, 83°07'W), and in the Port Coldwell basic alkaline intrusion near Marathon and Pic River.

In addition to occurrences in titaniferous magnetite, the writer detected traces of vanadium in certain greenstones of Archean (1) volcanic belts in northwestern Ontario (0.01–0.1% V), and in those intercalated with iron-formation north of Timagami (loc. 18, 47°08'N, 79°47'W) (0.01% V); in the dark micaceous greywacke-quartzite beds of pre-Huronian (?) age south of Spanish (loc. 15, 46°11'20"N, 82°21'W) (0.03% V); in the nodules and contact zone of orange-red argillite (0.01% V) of the (post-Huronian, Animikie) Sibley Series and the intrusive diabase sill near Nipigon (loc. 8, 40°01'N, 88°04'W), (0.03% V); in the brown pisolitic 'buckshot' (0.055% V) (Pl. X B) and high-grade ore (0.037% V) paint rock (0.033% V) and ash rocks (0.01%) of Steeprock Lake (loc. 4, 48°48'N, 91°37'W); in rusty gneiss north of Innisville (loc. 27, 45°07'N, 76°14'W) (0.025% V) and near Mattawa (loc. 24, 46°18'N, 78°43'W) (0.01% V); and in the chromite-rich zone of the Gordon Lake (loc. 2, 50°43'N, 95°02'W) copper-nickel deposit (Rose, 1958b). Traces of vanadium were also found by the writer in samples of dark sand (0.02% V) and mottled mauve arkose (0.013% V) at the base of the Paleozoic sandstone section at the Precambrian erosional unconformity near Elgin (loc. 28, 44°36'N, 76°13'W); in tailings from abandoned silver mines and mills at Cobalt (loc. 19, 47°27'N, 79°40'W) (0.013% V); in dark Devonian shale from Kettle Point (loc. 34, 43°13'N, 82°01'W) (0.016% V); in red Silurian shale from Milton (loc. 33, 43°30'N, 79°55'W) (0.013% V); in dark Ordovician shale from Manitoulin Island (loc. 14, 46°58'30"N, 81°55'W) and Sault Ste. Marie (loc. 13, 46°31'N, 84°25'W); in red sandstone north of Sault Ste. Marie (loc. 12, 46°56'30"N, 84°34'W); in dark tuffaceous shale of Precambrian age near Chelmsford (loc. 16, 46°34'N, 81°13'W); in dark weathered gabbro on Veuve River (loc. 17, 46°28'N, 80°30'W); and elsewhere (Rose, 1967, 1969b).

*Seine Bay and Bad Vermilion Lake Titaniferous Magnetite* (3) 48°42'30"N,  
92°44'50"W

- References: Lawson, A. C. (1913)  
Robinson, A. H. A. (1917; 1922)  
Tanton, T. L. (1936)

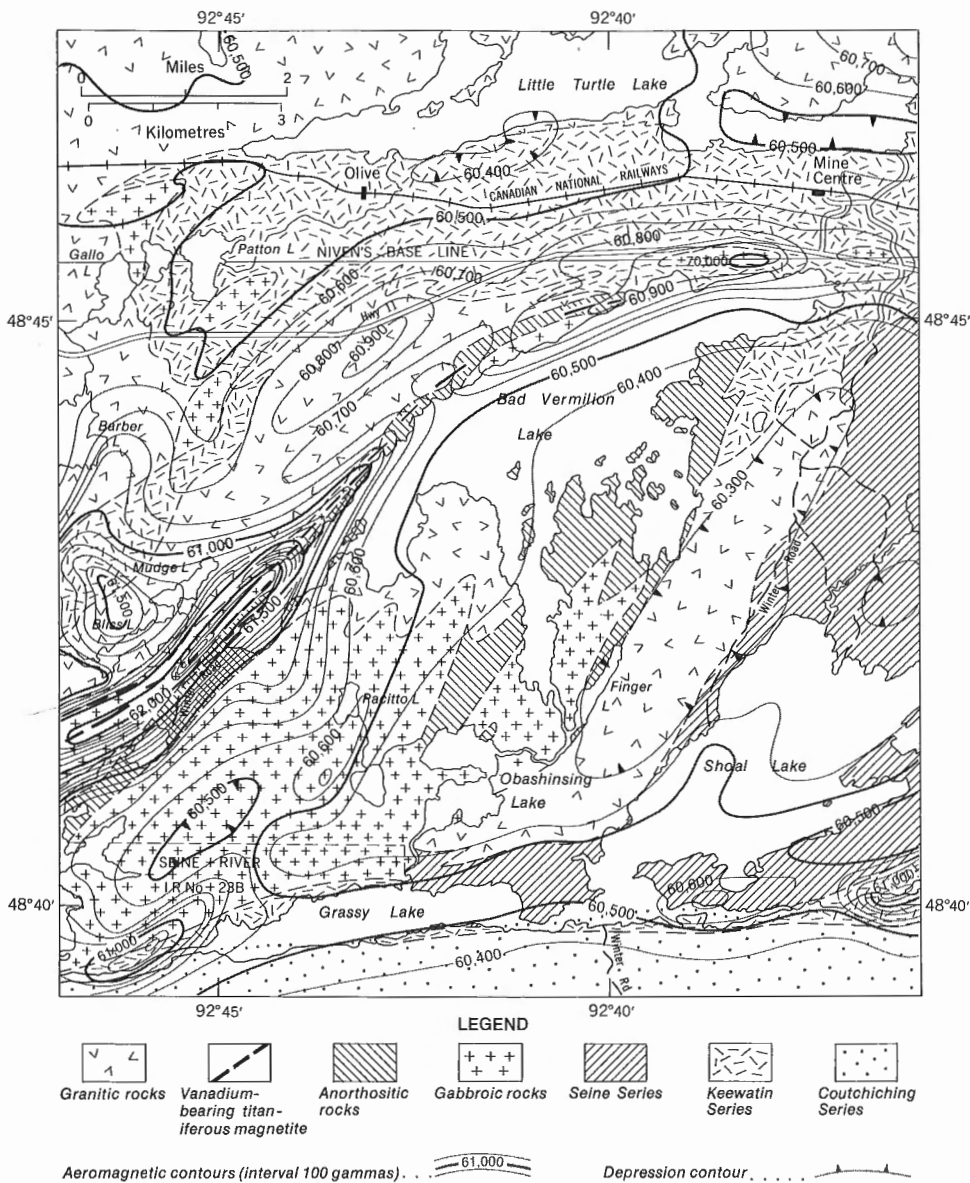
Vanadium-bearing titaniferous magnetite deposits extend in a linear belt from the west shore of Bad Vermilion Lake 3 miles south of Mine Centre, southwesterly for about 14 miles to a point near Seine Bay on Rainy Lake. In 1917 the Mines Branch (Robinson, 1917) made a magnometric survey of the range, and at the same time some diamond drilling of the northeast part of the range was directed by Dr. W. L. Goodwin of Kingston. The results of the work were summarized by Robinson (1922). The material was found to be a phosphatic, vanadium-bearing, titaniferous magnetite with siliceous gangue, unamenable to separation of iron and titanium by mechanical means. Analysis of thirteen outcrop samples reported by Robinson (1922) ranged from 32

to 50 per cent Fe and 6 to 16 per cent Ti. Eight drill-core analyses showed a range of from 25 to 47 per cent Fe and from 4 to 14 per cent Ti. Traces of V and Cr were also detected, and impurities included  $\text{SiO}_2$ , P, and S. A 275-pound sample of high-grade material from outcrops on the shore of Bad Vermilion Lake showed 46.44 per cent Fe and 28.07 per cent  $\text{TiO}_2$  (16.8% Ti) according to Mines Branch analysis in 1918. Mines Branch attempts to eliminate the titanium from this high-grade material by magnetic concentration were unsuccessful, giving a concentrate of 50 per cent Fe and 14.7 per cent Ti.

Geological maps by A. C. Lawson (1913) and T. L. Tanton (1936) indicate that the titaniferous magnetite is associated with a differentiated sill-like body of gabbroic and anorthositic rocks that is intrusive into the older Keewatin-type greenstones, schists, and metasediments of Archean age. The gabbro-anorthosite is in turn intruded by younger granitic rocks that may also be related to the anorthosite body. The titaniferous magnetite occurs in a series of nearly vertical lenses or intermittent bands of both high- and low-grade material within the western part of the gabbroic member of the intrusive body. Exploration by Stratmat Ltd. in 1957 suggested that the magnetite occurs in three main zones along the belt. Aeromagnetic Map 1150G indicates the possibilities of other zones at Grassy Portage to the west and south of Shoal Lake to the east (Fig. 8).

Under the microscope the host anorthositic gabbro is seen to be highly altered: its plagioclase highly saussuritized, generally consisting of a mass of fine-grained clinzoisite, epidote, chlorite, and carbonates; its pyroxenes chloritized and in places peppered, as are the plagioclases, with fine-grained blebs, blades, and needles of opaque iron-titanium oxide minerals arranged along the cleavage planes of the gangue minerals. The ore minerals are commonly rimmed with chlorite and mica where they penetrate the silicates. The ore minerals consist mainly of titanomagnetite and ilmenite in varying proportions, with accessory amounts of pyrite and pyrrhotite. Titanomagnetite is commonly intergrown with a patchwork of ilmenite, and in places appears anisotropic. Here and there the ilmenite is complexly twinned and is unusually magnetic. It will jump to a hand magnet in a manner similar to magnetite. The oxide minerals carry considerable amounts of included gangue minerals, and are invaded and penetrated in irregular fashion by later generation gangue minerals. Both ore and host rock minerals have been fractured and more or less altered as a result of fault movements and hydrothermal metamorphism subsequent to emplacement.

A Mines Branch analysis of a sample taken by the writer from an outcrop on the old portage between Bad Vermilion Lake and Seine Bay showed 27.6% Fe, 3.5% Ti, 0.07% V, 0.91% S, <0.01% P, and Cr was not detected. A magnetic concentrate of this material made by the writer and analyzed by the Geological Survey X-ray fluorescence laboratory showed 61.7% Fe, 10% Ti, 0.25% V, 0.05% Cr, and 0.18% Mn. This illustrates the facility of increasing the iron and vanadium content, and the difficulty of reducing the titanium content of this material. Other samples indicate that vanadium is erratically distributed in the titaniferous magnetite of Bad Vermilion Lake, and that it ranges from 0.012 to 0.3 per cent in the crude ore material and from 0.1 to 0.5 per cent or more in magnetite concentrates made from this material.



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FIGURE 8. Geology and aeromagnetic anomalies, Bad Vermilion Lake—Seine Bay titaniferous magnetite deposits (geology after T. L. Tanton).

**Brazeau-Wood Titaniferous Magnetite (23) 46°13'N, 78°42'W**

Reference: Harding, W. D. (1946)

The old Brazeau (Brazeau-Wood) property in Lot 18, Concession V, Papineau Township, about 5 miles 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. Buckham and Kindle outlined several lenticular deposits, the largest of which, the western, was reported by Buckham

(Harding, 1946) to be 575 feet long and  $12\frac{1}{2}$  feet wide, dipping 75 degrees and carrying about 35% Fe, 4.7% Ti, and 0.4% V, and in magnetic concentrates about 60% Fe and 0.8% V. A second lens, 700 feet east of the first, was found to be 175 feet long and  $12\frac{1}{2}$  feet wide, carrying 35% Fe, 3.9% Ti, and 0.45% V.

The occurrence consists of numerous zones of dissemination and massive lenticular bands of titaniferous magnetite within banded mafic, garnetiferous, hornblende-feldspar gneisses. Exposures are poor but fresh trenching and stripping by Union Carbide Canada Limited, based on a ground magnetic survey, has uncovered several new titaniferous magnetite 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, occur within a 20-foot-wide zone of hornblende-garnet-feldspar gneiss carrying disseminated titaniferous magnetite. The titaniferous magnetite bands strike easterly and dip steeply to the north at a slight angle to the foliation of the mafic host rock gneiss.

Under the microscope the titaniferous magnetite is seen as a mosaic of interlocking crystals of titanomagnetite, titanomagnetite with fine blebs of exsolved ilmenite and spindles of spinel arranged *en echelon* along cleavage planes of the host mineral, and ilmenite, accompanied by disseminated sulphides, pyrite, pyrrhotite, and chalcopyrite, and including considerable unreplaced gangue material. Sulphides occur both in the opaque ore minerals and in the gangue. The oxide-silicate contacts are fretted in places, the magnetite containing included grains of silicates, and the margins of the silicate minerals containing blebs of the oxide minerals. Outstanding corona structures are shown in places in the silicates marginal to the oxides (Pl. XI A,B); the oxide mosaic being rimmed with brown biotite or hornblende, succeeded by pink garnet around a core of highly altered plagioclase that in places is isotropic cloudy glass. Where the opaque iron-titanium oxides are less abundant, ilmenite-hematite intergrowths are more common than magnetite, and the host is much less altered, consisting predominantly of plagioclase, green hornblende, pink garnet, green pyroxene, accessory iron-titanium oxides, pyrite, pyrrhotite, and chalcopyrite.

The known titaniferous magnetite occurrences are on a northeasterly trending positive salient or flexure on the southeast-trending magnetic depression, and the crosscutting strike of the deposits across the regional magnetic trend suggests that they are the cause of the positive magnetic ridge (Fig. 9). Stronger magnetic anomalies to the south and west of the occurrences merit investigation, as they may form part of a folded, faulted complex of anorthositic rocks with associated concentrations of Fe-Ti-V oxide minerals.

Two magnetic concentrates of the ore material made by the writer showed respectively: major iron, 1.5% Ti, 0.7% V, 0.7% Al, 0.5% Si, 0.2% Ca, 0.15% Mg, 0.02% Mn, <0.01% Ni, and, major iron, 1.5% Ti, 1% V, 1.5% Al, 0.7% Si, 0.15% Ca, 0.3% Mg, 0.03% Mn, <0.005% Cu, and <0.01% Co. The residual tailing from the latter sample showed >5% Fe, >7% Ti, 0.3% V, 0.4% Mn, 0.004% Ni, 0.008% Cu, and 0.014% Co.

*Angus and Flett Townships Titaniferous Magnetite (20) 46°51'N, 79°33'W*

Reference: Hurst, M. E. (1931)

Titaniferous magnetite occurs in a tongue of diabase in Angus and Flett Townships, southeast of Timagami. Hurst (1931) reported seven exposures there on two parallel

northwest-trending magnetite-bearing zones about 400 feet apart, each zone being about 400 feet long and entirely within the diabase. A sample of the best material taken by Hurst showed 43.62% Fe, 13.2% Ti, and 0.1% V.

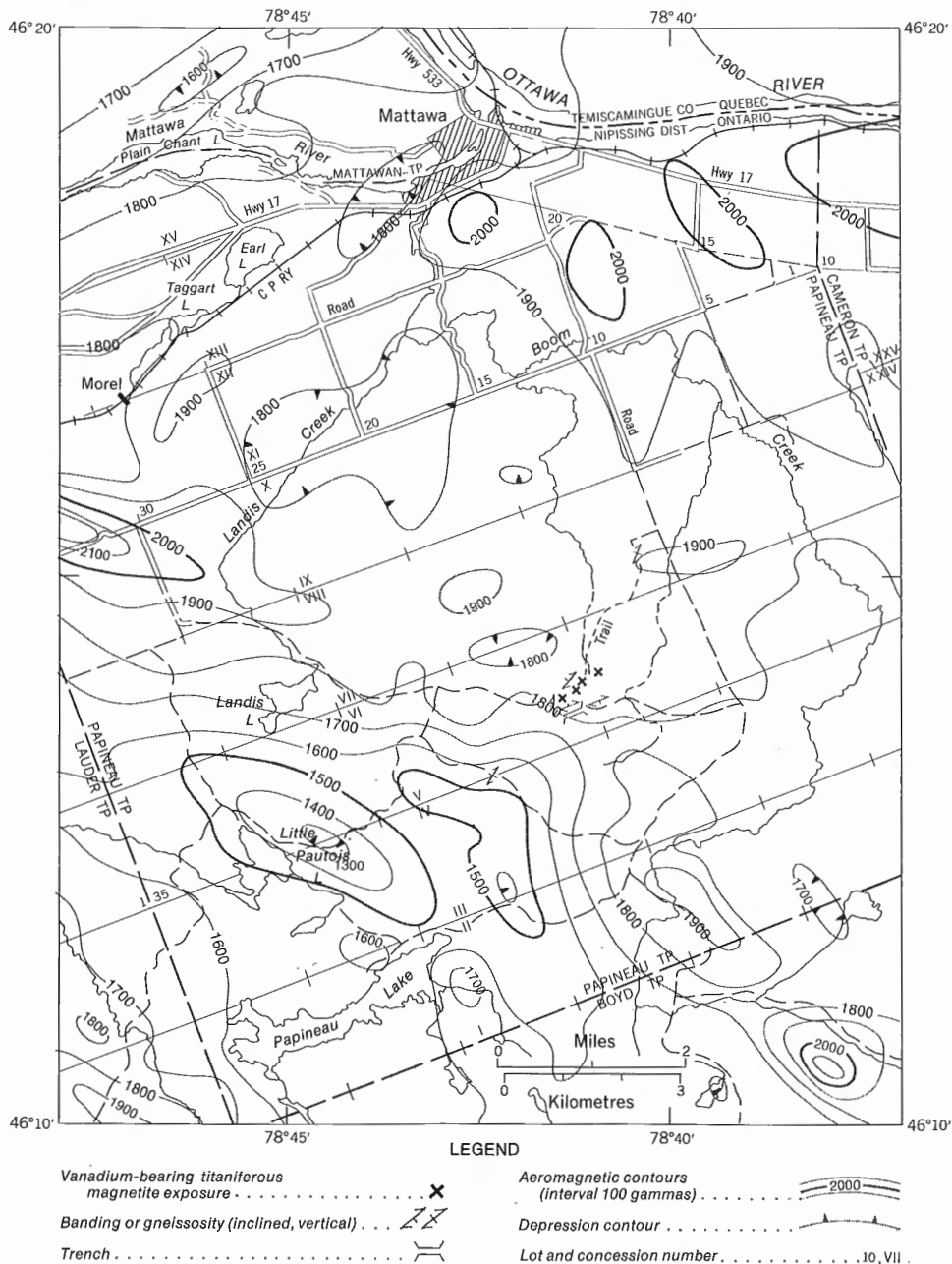


FIGURE 9. Geology and aeromagnetic anomalies, Brazeau-Wood titaniferous magnetite deposit.

GSC

Under the microscope the ore minerals form a granular mosaic of titanomagnetite, titanomagnetite with exsolved ilmenite, and spinels, free ilmenite, with much included and interstitial gangue material, and traces of sulphides, pyrrhotite, pyrite, and chalcopyrite. The occurrences are associated with a weak aeromagnetic anomaly shown on Geological Survey Maps 1480G and 1490G, extending north-northeasterly for more than 2 miles between Fanny Lake and Breadalbane Lake in Flett Township, and another to the east in Angus Township (Fig. 10).

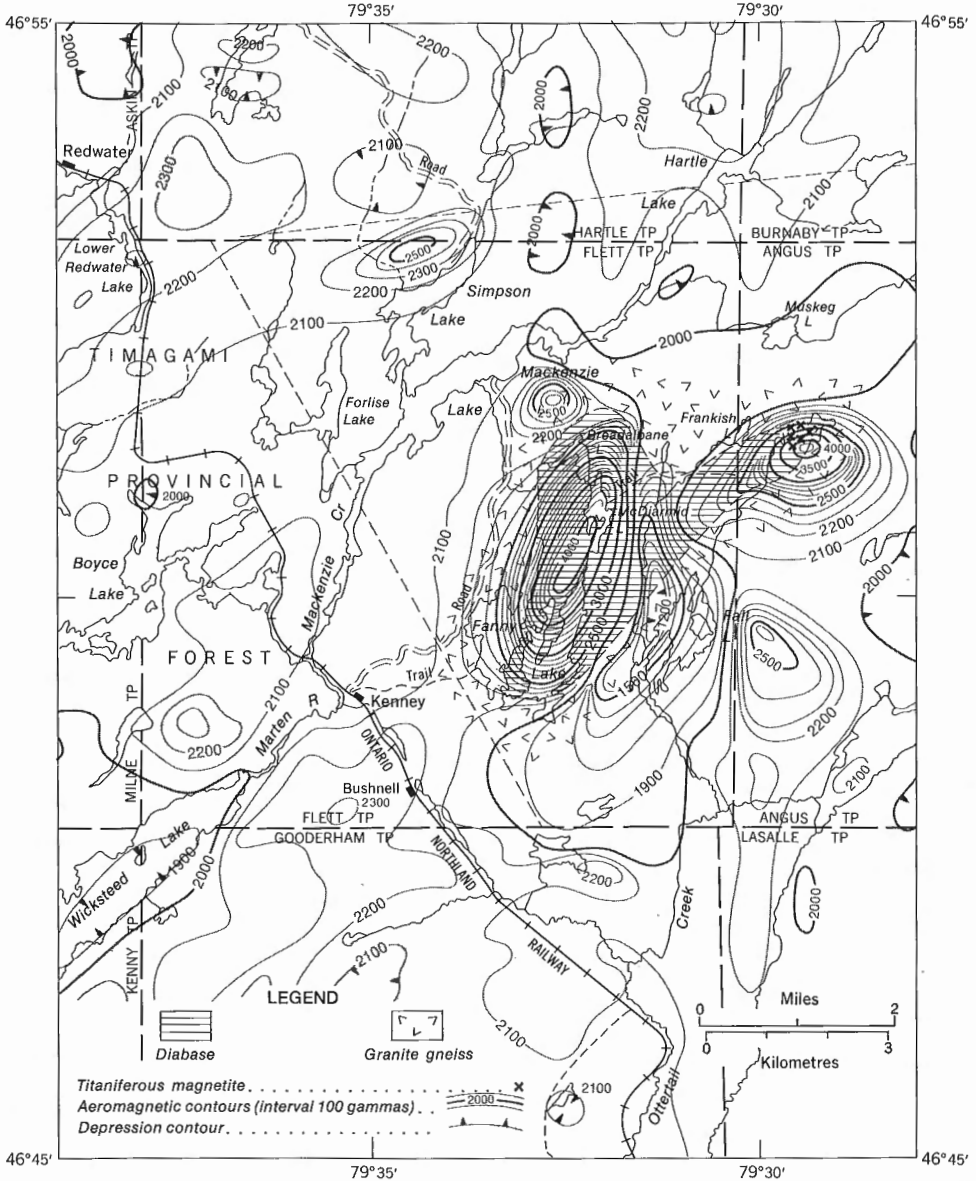


FIGURE 10. Geology and aeromagnetic anomalies, Angus and Flett townships titaniferous magnetite deposits (geology after M. E. Hurst).



The occurrence was investigated in 1966 by Titan Iron Mines Limited and difficulty has been experienced in attempts to reduce the titanium content of the ore material by magnetic separation. The fine-grained intimate intergrowth of the Fe-Ti-V oxide minerals prevents their effective mechanical separation.

*Bamoos Lake* (9) 48°48'30"N, 86°19'30"W

References: Satterly, J. (1968)  
Thomson, J. E. (1931)

Limited occurrences of titaniferous magnetite in dark augite syenite (laurvikite) about 10 miles north of Heron Bay on claims owned by H. England of Port Coldwell, were described by Thomson (1931). A grab sample of magnetite, taken by Thomson from an island in a small lake immediately east of Bamoos Lake, assayed 0.48 per cent vanadium, and traces of a sage-green mineral film on joints in the magnetite were suggested by Dr. T. L. Walker to be pintadoite, a rare calcium vanadate (Thomson, 1931, p. 35). Aeromagnetic maps covering the occurrence show extensive magnetic anomalies.

The occurrence forms part of what is now considered to be the Port Coldwell mafic alkalic complex which occupies a crudely circular area about 20 miles in diameter at the northeast corner of Lake Superior. The complex is characterized by alkalic igneous rocks including nepheline syenite and analcite tinguaitite (heronite) dykes, as well as by red syenite and black laurvikite carrying disseminations and local concentrations of vanadium-bearing titaniferous magnetite, as indicated by many relatively strong magnetic anomalies shown in aeromagnetic maps covering the area. The Port Coldwell alkaline complex may be related to other such complexes and carbonatites as indicated by Satterly (1968). A relationship with the Duluth gabbro is also possible.

#### *Other Occurrences*

Alkaline and carbonatite complexes in other parts of Ontario and Quebec may also be carriers of vanadium in the form of titaniferous magnetite and apatite, although it is generally regarded as subordinate to other elements such as niobium, tantalum, uranium, thorium, and rare earths in such occurrences. Further investigation of such complexes may reveal important occurrences for further development.

## Quebec

The vanadium occurrences in Quebec are almost entirely within substantial deposits of titaniferous magnetite in Precambrian gabbroic anorthosite. More than twenty such occurrences have been tested by the writer in which the vanadium content of the magnetic concentrate is greater than 0.2 per cent V. Many of these magnetite-ilmenite deposits are very large, forming extensive zones in mafic rocks associated with huge anorthositic intrusions. Similar ilmenite-hematite deposits 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 north of Havre-St-Pierre is reported to average about 0.15 per cent V, ranging from about 0.05 to 0.21 per cent V. The writer found that ilmenite-hematite of the Ivry deposit north of Montreal carried 0.1 per cent V, and that of the Furnace deposit north of Baie-St-Paul holds 0.17 per cent V.

*Oka Alkaline Intrusion-Carbonatite Complex (5) 46° 30' N, 74° 05' W*

Five samples of titaniferous magnetite taken with the assistance of Marcel Vallée from the columbium (niobium)-bearing alkaline intrusions of probable Mesozoic (Late Cretaceous) age, on the property of St. Lawrence Columbium and Metals Corporation at Oka, also carried from 0.18 to 0.3 per cent V, probably averaging close to 0.25 per cent. Magnetite is being recovered from the columbium (niobium) ores there and is being stockpiled for possible future use.

*St-Urbain Anorthosite Area (15) 47° 33' N, 70° 32' W*

Reference: Rose, E. R. (1961, 1969a)

The St-Urbain anorthosite body is almost surrounded by a zone of positive aeromagnetic anomalies, associated with gabbroic, anorthositic, and charnockitic rocks marginal to the anorthosite intrusion (Rose, 1961, 1969a). The anomalous zone merits investigation because of the common association of vanadium-bearing titaniferous magnetite with such rocks elsewhere. Samples of titaniferous magnetite concentrated by the writer from occurrences in the magnetic zone west and east of the St-Urbain anorthosite showed respectively, 65 to 67% Fe, 4.0 to 4.1% Ti, 0.16 to 0.1% V, 0.07 to 0.13% Mn, and >0.05% Cr. Ilmenite from the Furnace deposit, immediately west of St-Urbain, showed a content of 0.17 per cent V, but an ilmenite concentrate made from it by Continental Iron and Titanium Mining Limited showed only 0.05 per cent V.

*Morin Anorthosite Area (6) 46°05'N, 74°21'W*

Reference: Rose, E. R. (1960, 1969a)

Many disseminations and concentrations of titaniferous magnetite occur in the gabbroic rocks associated with the Morin anorthosite intrusion. The general distribution of magnetic zones there, indicated by aeromagnetic maps now covering the area, suggests the areas favourable for investigation (Rose, 1960, 1969a). Twenty-four samples of titaniferous magnetite occurrences taken by the writer in this area showed from 0.01 to 0.1 per cent V, and magnetic concentrates made from them showed from 0.1 to 0.3 per cent V.

Magnetic concentrates made by the writer from seven of eight bulk samples collected from along the titaniferous magnetite belt in Wexford Township centred near Lac du Pin Rouge (45°58'N, 74°02'W) ranged in composition (in per cent) from 62 to 65 Fe, 0.4 to 2.3 Ti, 0.15 to 0.24 V, 0 to 0.024 Ni, 0 to 0.017 Co, 0 to 0.057 Cr, 0 to 0.007 Cu, 0.25 to 0.56 P<sub>2</sub>O<sub>5</sub>, and 0.11 to 0.3 S. By contrast, a sample of magnetite from a small iron deposit in granitic gneiss and monzonite west of St-Jérôme showed major iron, 0.29% Ti, 0.3% Mn, 0.005% Cr, 0.006% V, and less than 0.001% each of Ni, Co, and Cu. A sample of ilmenite from the Ivry mine (loc. 6, 46°03'45"N, 74°22'W) showed (in per cent) 38.2 Fe, 19.7 Ti, 0.098 V, 0.01 Cr, 0.03 P, and 1.05 S. From the nearby titaniferous magnetite deposit at Degrosbois (46°05'30"N, 74°21'40"W) a magnetic concentrate showed 0.29 per cent V.

*Lac St-Jean Anorthosite Area (16) 48° 16' N, 71° 25' W*

References: Dulieux, E. (1913)

Jooste, R.-F. (1958)

Osborne, F. F. (1928, 1944)

Robinson, A. H. A. (1926)

The titaniferous magnetite deposits near St-Charles-Boromée described by Dulieux (1913), Robinson (1926), Osborne (1944), Jooste (1958), and others, were known

before 1884, and a number of other occurrences have since been located within the anorthositic mass. Aeromagnetic surveys made by the Crane Company in the south-eastern part of the massif revealed many strong magnetic anomalies, both positive and negative, which were investigated by Louis Moyd and W. P. Agocs. Moyd (pers. com.) reported that most of the investigated anomalies were found to be associated with disseminations of titaniferous magnetite and ferriferous ilmenite in noritic to gabbroic phases of the anorthosite.

*St-Charles Titaniferous Magnetite* (19) 48°31'N, 71°28'W

References: Bourgoin, L. (1943)  
Dresser, J. A. (1916)  
Jooste, R.-F. (1958)  
Osborne, F. F. (1944)  
Stansfield, A. (1916)

The St-Charles titaniferous magnetite deposits lie north of the Saguenay River on Lots 44 and 48, Range I, Bourget Township near the village of St-Charles-Boromé. The general geology of the area was described by Dresser (1916), and a detailed description of the deposits was given by Jooste (1958). The possibility of utilizing the deposits by electric smelting was discussed by Stansfield (1916), and some good quality steel was produced in pilot plant tests (Bourgoin, 1943). Extensions along the strike of the deposits were noted by the writer on the southwest side of Saguenay River in Lot 44, Range A, Kenogami Township (16). The deposits are lenticular and in part apatite and olivine bearing. The phosphorus-rich occurrences are mainly in the north part of the zone.

The low phosphorus occurrences average about 46% Fe, 19% TiO<sub>2</sub>, 0.13% P, and the high phosphorus occurrences about 35% Fe, 15% TiO<sub>2</sub> and 3 to 5% P. Magnetic concentrates made from the high phosphorus material showed 60.8% Fe, 10% Ti, 0.22% Mn, <0.05% Cr, 0.05% V, and traces of Y, Yb, and Sc; another showed major iron, 9.8% Ti, 0.28% Mn, 0.26% Cr, 0.011% Ni, 0.014% Co, 0.002% Cu, and 0.3% V.

*Moquin Titaniferous Magnetite* (18) 48°25'N, 71°25'W

A magnetic concentrate made from a sample of titaniferous magnetite from an occurrence in banded gabbro near Moquin, in Kenogami Township, showed major iron, 2.8% Ti, 0.079% Mn, 0.089% Cr, 0.036% Ni, 0.019% Co, 0.005% Cu, and 0.44% V. A trap dyke that intrudes the banded gabbro at Moquin showed traces of Y, Sc, and Zr.

*Lyonne Township Titaniferous Magnetite* (17) 48°25'30"N, 72°37'W

References: Gross, G. A. (1967)  
Waddington, G. W. (1960)

In Lyonne Township, about 18½ miles west of Roberval, a titaniferous magnetite deposit in a mile-long belt of banded anorthositic gabbro has been reported to carry 90 million tons averaging 23.6 per cent Fe and 6.8 per cent TiO<sub>2</sub> to a depth of 500 feet (Waddington, 1960). Additional reserves are present in four other lenticular deposits. Laboratory tests showed that this material could be concentrated to a product carrying 69.7 per cent Fe and 0.51 per cent Ti (Gross, 1967). A vanadium analysis for this material is not available. Another similar occurrence of titaniferous magnetite has been reported in Hubert Township (49°15'N, 72°35'W) (Gross, 1967).

*Baie des Sept-Îles Anorthosite Area (20) 50°16'30"N, 66°25'W.*

- References: Dulieux, E. (1912, 1915)  
 Faessler, C. (1942)  
 Faessler, C. and Schwartz, G. M. (1941)  
 Rose, E. R. (1969a)

Baie des Sept-Îles, an almost circular indentation about 8 miles in diameter on the north shore of St. Lawrence River, is developed mainly in anorthosite and gabbroic anorthosite that outcrops in a semicircular ring, the southern half of which is concealed by the river (Faessler, 1942; Rose, 1969a). A thick layer of dark, troctolitic, ferriferous anorthositic gabbro carrying disseminations and concentrations of titaniferous magnetite and ilmenite and interlayered with anorthosite, curves around the northwest side of the bay and dips gently bayward. Regional aeromagnetic and gravity surveys suggest that the basic intrusive mass extends for about 40 miles south under the St. Lawrence River (pers. com., A. S. MacLaren, 1970).

Concentrations of titaniferous magnetite and ilmenite were opened or mined on a small scale at several places in the body, the W. M. Molson mine at Chute du Cran de Fer, the Gagnon deposit, the Chute aux Outardes deposit, all on Rivière des Rapides, and the Clarke City deposits near the falls on Rivière Ste-Marguerite (Dulieux, 1912, 1915; Faessler and Schwartz, 1941). The dark anorthositic gabbro is now being quarried as a source of road and construction material in the Sept-Îles area. This rock carries much disseminated titaniferous magnetite and averages 20 per cent or more iron over large areas. It is composed largely of twinned plagioclase, pyroxene, olivine, titanomagnetite, and ilmenite. It varies considerably in grain size, and in places grades into less mafic anorthosite or into darker titaniferous magnetite. Pockets of titanomagnetite and ilmenite are distributed through the rock in irregular and vein-like forms. The rock is generally coarse grained, but it is penetrated by both coarser and finer grained dyke-like phases of the same rock type, and by a few dykes of granite, and veins of calcite, chlorite, and glass. Magnetic concentrates from five samples of titaniferous magnetite extracted by the writer from the anorthositic gabbro on the northwest side of Baie des Sept-Îles showed a range of 7 to 11 per cent Ti, and from 0.16 to 0.48 per cent V.

*Lac-Allard-Rivière Romaine Area (22) 50°33'N, 63°25'W*

- References: Hammond, P. (1952)  
 Retty, J. A. (1944)  
 Rose, E. R. (1969a)

Much of the area is occupied by large bodies of anorthositic and gabbroic rocks carrying several large ilmenite deposits and many titaniferous magnetite occurrences (see Retty, 1944; Hammond, 1952; Rose, 1969a). The many strong magnetic anomalies shown on recently issued aeromagnetic maps of the area suggest the distribution of the occurrences. The ilmenite deposits are generally associated with negative or low magnetic anomalies; they are generally low in magnetite and lower in vanadium than titaniferous magnetites. The titaniferous magnetite deposits are generally associated with strong positive magnetic anomalies, and they are generally higher in vanadium. The Lac Tio ilmenite ore averages 32 to 36 per cent TiO<sub>2</sub>, 39 to 43 per cent Fe, and 0.16 per cent V.

A sample of oxide-bearing gabbroic anorthosite that is associated with a strong positive aeromagnetic anomaly in gabbroic anorthosite near Lac Ellen south of the Lac Tio ilmenite deposit was found to carry about 22 per cent recoverable magnetic oxides, about 10 per cent being highly magnetic titanomagnetite and another 10 per cent weakly mag-

netic ilmenite. An X-ray fluorescence analysis showed the strongly magnetic concentrate to be pure, carrying 71.8% Fe, 0.2% Ti, 0.2% V, 0.02% Mn, <0.05% Cr, and <0.01% each of Co and Ni.

### *Maggie Mountain*

*Where mighty Maggie rears its crest,  
A mining man was most impressed,  
He muttered low, perhaps in jest,  
I know it's big, but farther west  
There will be more, or I'll eat my vest.*

### *Maggie Mountain Titaniferous Magnetite (23) 51°24'N, 64°05'W*

The titaniferous magnetite deposits discovered by Awater and Lapointe in 1953, probably form one of the largest deposits of this type in Canada, if not in the world. Much of the ore material is an intrusive, dyke-like mass of oxide-rich gabbroic anorthosite that cuts discordantly through complexly folded granitic gneisses of the Grenville (structural) Province, and is itself intruded by smaller bodies of late granite and diabase. Deposits 1 and 2 are relatively massive homogeneous titaniferous magnetite, and deposits 3 and 4 are composed of interbanded titaniferous magnetite, gabbroic anorthosite, and anorthosite (*see* Fig. 11). With the exception of No. 3 deposit, which lies a few hundred feet east of the south end of No. 2 deposit, all the deposits occur in a linear zone at least  $4\frac{1}{2}$  miles long and about 2,000 feet wide. A belt of strong positive aeromagnetic anomalies is associated with these deposits (Fig. 11). A dip to the west is indicated. Millions of tons of titaniferous magnetite are exposed. An average analysis of deposits 1, 2, and 3, made from twenty-one chemical analyses is given by J. R. Mowat, Stratmat Ltd. (unpubl. rept., 1960), as 43.69% Fe, 10.91% TiO<sub>2</sub>, 5.95% SiO<sub>2</sub>, 5.78% MgO, 0.60% CaO, 11.57% Al<sub>2</sub>O<sub>3</sub>, 0.1% V, 1.45% Cr, 0.027% S, and 0.078% P. Of these, the No. 1 deposit averaged 43.7% Fe, 10% TiO<sub>2</sub>, 0.87% Cr, 9.9% SiO<sub>2</sub>; No. 2 deposit 43.7% Fe, 10.6% TiO<sub>2</sub>, 1.55% Cr, and 6.6% SiO<sub>2</sub>; and No. 3 deposit 40.7% Fe, 10.3% TiO<sub>2</sub>, 2.48% Cr, and 5.7% SiO<sub>2</sub>. Magnetic concentrates of five samples taken by the writer showed a range of V content from 0.25 to 0.30%. Of these, one from No. 1 deposit showed 9.0% Ti, 5.0% Al, 2.6% Si, 2.5% Mg, 0.71% Ca, 0.58% Cr, 0.28% V, 0.19% Mn, 0.098% Ni, 0.023% Co, and 0.004% Cu; one from the north end of No. 2 deposit showed 8% Ti, 4.9% Al, 1.8% Si, 2.9% Mg, 0.24% Ca, 1.0% Cr, 0.25% V, 0.17% Mn, 0.11% Ni, 0.023% Co, and 0.003% Cu; and one from the south end of No. 2 deposit showed 9.2% Ti, 5.2% Al, 3.0% Si, 2.4% Mg, 0.87% Ca, 1.2% Cr, 0.29% V, 0.22% Mn, 0.08% Ni, 0.022% Co, 0.007% Cu; one from the east side of No. 3 deposit gave 7.6% Ti, 5.1% Al, 3.1% Si, 1.9% Mg, 0.91% Ca, 1.5% Cr, 0.29% V, 0.17% Mn, 0.07% Ni, 0.02% Co, and 0.003% Cu; and one from the west part of No. 3 deposit gave 8.4% Ti, 4.3% Al, 1.2% Si, 2.6% Mg, 0.3% Ca, 1.8% Cr, 0.3% V, 0.2% Mn, 0.1% Ni, 0.022% Co, and 0.003% Cu. These results are shown in Table V.

Magnetic concentrates from these deposits are notably richer in chromium than vanadium, but cell edge measurements on five samples of titanomagnetite from chromium-rich and chromium-poor parts of the deposits varied only from 8.388 to 8.395 Å, being slightly greater than that of pure magnetite (8.38 Å), and falling within the general range found by the writer for titanomagnetite from deposits elsewhere in Canada. The titanomagnetite seems to be of fairly uniform chemical composition throughout these deposits.

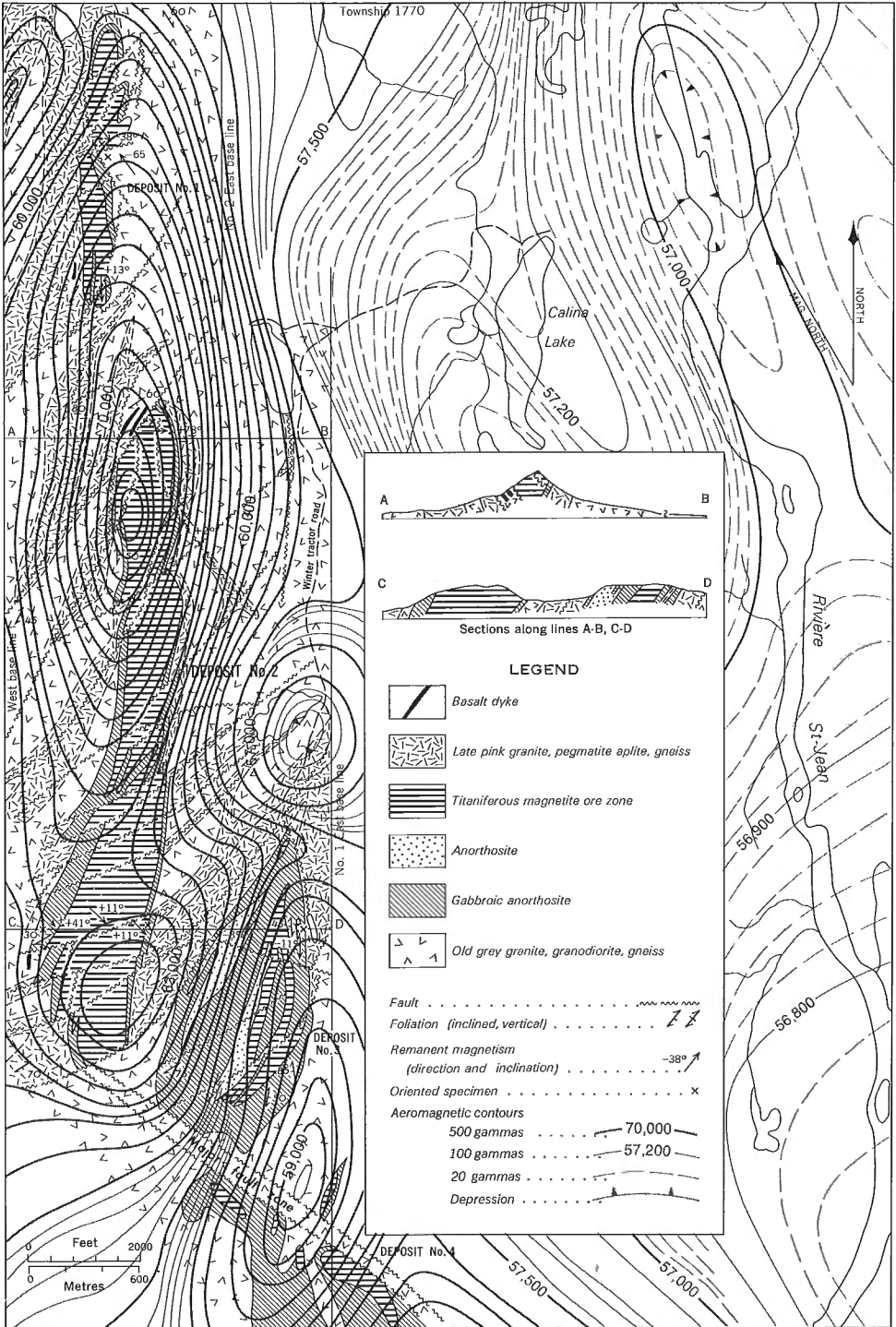


FIGURE 11. Geology and aeromagnetic anomalies, Magpie Mountain titaniferous magnetite deposits (geology after J. R. Mowat, Stratmat Ltd., 1960).

TABLE V  
Analyses of Magpie Mountain titaniferous magnetite

	Fe	Ti	V	Cr	Mn	Co	Ni	Cu	Si	Mg	Ca	Al	S	P
No. 1 deposit	o	43.7	6.5						2.9	3.5				
	c	>60	9.0	0.28	0.58	0.19	0.02	0.10	0.004	2.6	0.71	5.0		
No. 2 deposit (north end)	o	43.7	6.4	1.55										
	c	>60	8.0	0.25	1.0	0.17	0.02	0.11	0.003	1.8	0.24	4.9		
	c	>60	9.2	0.29	1.2	0.22	0.02	0.08	0.007	3.0	2.4	0.87	5.2	
No. 3 deposit (east side)	o	40.7	6.2	2.48					2.8					
	c	>60	7.6	0.29	1.6	0.17	0.02	0.07	0.003	3.1	0.91	5.1		
	c	>60	8.4	0.3	1.8	0.2	0.02	0.1	0.003	1.2	2.6	0.3	4.3	
Nos. 1, 2, 3 deposits (average analyses)	o <sup>1</sup>	43.69	6.5	0.1	1.45				2.97	3.47	0.4	5.8	0.027	0.078
	o <sup>2</sup>	42.7	6.3		1.66				3.55					

o—ore material

c—magnetic concentrate

o<sup>1</sup>—average ore analysis (21 chemical analyses, J. R. Mowat, 1960)

o<sup>2</sup>—average ore analysis (701 spectrographic analyses, J. R. Mowat, 1960)

*Chibougamau Anorthosite Area (11) 49°–50°N, 74°–74°30'W*  
*Chibougamau Complex*

References: Allard, G.-O. (1967)

Mawdsley, J. B., and Norman, G. H. W. (1935)

Smith, J. R., and Allard, G.-O. (1960)

A belt of altered anorthositic rocks on the north side of Lac Chibougamau is 20 miles long and about 2 miles wide (Mawdsley and Norman, 1935; Smith and Allard, 1960). It is associated with sill-like masses of basic to ultrabasic igneous rock, and together with some of these masses appears to form part of a large layered igneous complex with more basic differentiates within it, and near its base. Some of the gabbros and peridotites are themselves differentiated and intrusive into the anorthositic complex as well as into the chloritic schists of the Superior Province to the north. Disseminations of titaniferous magnetite commonly occur in the basic and ultrabasic rocks of the complex, and aeromagnetic surveys made in 1957 by Dominion Gulf Company as part of Operation Overthrust<sup>1</sup> revealed many strong magnetic anomalies in the Chibougamau area in association with these rocks, as well as with those of the Lac Doré Complex in Lemoine and Rinfret Townships south of Lac Chibougamau (Allard, 1967).

Titaniferous magnetite occurs in gabbro on the peninsula separating Lac Doré and Lac Chibougamau; in serpentinized peridotite and dunite at Baie de la Magnétite (loc. 14, 49°53'25"N, 74°07'W) on Lac Chibougamau 6 miles to the east, and in gabbroic anorthosite and pyroxenite bands in anorthosite near Lac Caché about 10 miles to the southwest.

*Baie de la Magnétite titaniferous magnetite (14) 49°53'25"N, 74°07'W.* Disseminations and stringers of titaniferous magnetite occur in a thick zone of serpentinized peridotite and dunite forming Magnetite Mountain and Mont du Sorcier north of Baie de la Magnétite on the northeast end of Lac Chibougamau. The ultrabasic rocks form a band which, although separated by faults from the Chibougamau anorthosite, may be related to it. Samples of the rock from the mineralized zone showed a content of 7 to 10% Si, 5 to 10% Mg, 0.1 to 0.3% Ca, 0.5 to 0.7% Ti, 0.2% V, 0.07% Mn, <0.002% Cr, 0.03 to 0.05% Ni, 0.002% Co, and <0.001% Cu; magnetic concentrates made from these samples showed much the same range of composition. Titanium and chromium are conspicuously low in these samples of ultrabasic rock.

*Lac Doré titaniferous magnetite (9) 49°54'N, 74°15'W.*

Reference: Allard, G.-O. (1967)

A 2-mile-long drift on the 900-foot level under Lac Doré between the Jaculet and Bateman Bay shafts is almost entirely in altered chalky white anorthosite that is inter-banded in places with darker metagabbro and gabbroic anorthosite. A section of anorthositic rocks more than 10,000 feet thick, cut by the drift, is flanked on both sides by bands of metagabbro carrying disseminations of titaniferous magnetite. In places the anorthosite is well banded, and shows a typical cumulate differentiate texture with a gradation from anorthosite to gabbroic anorthosite in bands a foot or less thick.

The banding in these rocks strikes generally northeasterly and dips moderately steeply northwesterly. A sample of the white anorthosite taken by the writer showed 10% Ca, 7% Si, 0.5% Mg, 0.15% Ti, 0.07% Mn, 0.01% Cr, 0.01% V, and 0.001% Cu.

<sup>1</sup>Operation Overthrust was the name given to the geological-geophysical project conducted by private enterprise to locate mineral deposits in this area.



*Île du Portage titaniferous magnetite* (8) 49°53'45"N, 74°14'10"W. A sample of titaniferous magnetite in gabbro from Île du Portage showed 53.2% Fe, 8.2% Ti, and 0.12% Cr, and a magnetic concentrate made from this material gave 64.7% Fe, 4.1% Ti, and 0.84% V (Allard, 1967).

*Lac Caché titaniferous magnetite* (10) 49°49'N, 74°24'W. A zone of banded titaniferous magnetite in gabbro-anorthosite west of Lac Chibougamau near Lac Caché has recently been mapped by G.-O. Allard, who considers it to be probably continuous with his Lac Doré Complex to the south (pers. com., 1969). Two samples from the magnetite-bearing zone here showed 5 to 15% Si, 1.5 to 15% Ca, 3.5% Mg, 1.5 to 5% Ti, 0.15 to 0.2% Mn, 0.0015 to 0.002% Cr, 0.15 to 0.3% V, 0.002 to 0.005% Ni, 0.007 to 0.02% Co, and 0.01% Cu; and magnetic concentrates made from these showed 5 to 10% Si, 1 to 3% Ca, 2 to 3% Mg, 1.5 to 5% Ti, 0.1 to 0.2% Mn, 0.002 to 0.007% Cr, 0.3% V, 0.002 to 0.005% Ni, 0.005 to 0.02% Co, and 0.01 to 0.02% Cu.

*Lac Doré Complex* (11) 49°–50°N, 74°–74°30'W

References: Allard, G.-O. (1967)  
Assad, R. (1968)

The Lac Doré Complex has been named and mapped south of Lac Chibougamau by Professor Allard, for the Quebec Department of Mines and Natural Resources. As a result of his detailed mapping and long experience in the Chibougamau area, Allard considered the Lac Doré Complex to be part of a much larger layered igneous mass, closely related to the Chibougamau Complex and similar to the Bushveld Complex of South Africa, although the former are more deformed and altered.

*Lemoine Township* (12) 49°47'N, 74°07'W and *Rinfret Township* (13) 49°49'25"N, 74°00'40"W. Following Operation Overthrust in 1957, a strong positive aeromagnetic anomaly extending for several miles in a northeasterly direction through Rinfret and Lemoine Townships was investigated by Jones & Laughlin Steel Corporation, and a program of exploration and diamond drilling was carried out during the summer of 1958. The occurrence was described as titaniferous magnetite in which the magnetite-ilmenite mineralization occurs in banded form as segregations in the enclosing anorthosite-gabbro complex. The investigation was abandoned, and for several years the property was dormant, until the presence of vanadium was noted by Allard (1967) in analysis of the material made by the Quebec Department of Mines and Natural Resources, during which time mineral rights for the property were secured for the Province of Quebec.

Subsequent mapping in 1968 and 1969 by Allard has shown that the titaniferous magnetite occurs as faulted, but extensive and persistent zones, within ancient and metamorphosed interbanded pyroxenite, gabbro, and anorthosite, in the northeast-trending south limb of the anorthosite member of the Lac Doré Complex. Allard has mapped three separate but closely associated zones of very basic layered rock in this complex, within which the titaniferous magnetite occurs in concordant, nearly vertical discontinuous bands as much as 5 feet or more wide and hundreds of feet long, as well as in disseminations throughout these rocks. The strongly mineralized zone within the basic rocks is from 100 to 400 feet wide and is exposed intermittently in three main lenses (each about 3 miles long) for a distance of more than 10 miles along strike. This magnetite-bearing zone probably averages about 20 to 25 per cent Fe, 3 to 5 per cent Ti, and 0.15 to 0.2 per cent V.

Eight samples of magnetic concentrates reported by Allard (1967, p. 14) showed a range of from 0.29 to 0.84 per cent vanadium, which he suspected to be about 15 per cent too high (*see also*, Assad, 1968). Four samples of magnetite-rich material taken by the writer from the southwest zone showed a range of 0.3 to 0.5 per cent V, and magnetic concentrates made from them ranged from 0.3 to 0.7 per cent V; a sample of the ilmenite-bearing anorthosite immediately south of the magnetite-bearing zone showed 0.07 per cent V, and a magnetic concentrate made from it showed 0.3 per cent V. Under the microscope the ore material forms an interlocking mosaic of titanomagnetite, ilmenite, and composite grains of each showing complex very fine grained exsolution textures and intergrowths, all distributed interstitially to altered pyroxene, amphibole, plagioclase, and olivine crystals, forming irregular networks and clots, as well as fine dustings throughout (Pl. XII A,B). A few grains of pyrite are present and the ore minerals are corroded by, and in places traversed by, veinlets carrying chlorite, carbonates, limonite, goethite, and other secondary alteration products. Plagioclase is altered almost completely to a zoisite-epidote aggregate, pyroxene to chlorite with sphene, and olivine to serpentine.

The intensity of the alteration of the basic and anorthositic rocks in which these Fe-Ti-V magnetite deposits lie is characteristic of both the Chibougamau and Lac Doré Complexes. It is a reflection of the great age of these rocks and the intensity of the metamorphism they have experienced since their formation. Large granitic batholiths forming the core area under Lac Chibougamau and intruding the complexes, are a probable source of much of the alteration.

#### *Other Occurrences*

Traces of vanadium have been noted in several other titaniferous magnetite occurrences in lode and beach sand deposits in Quebec, in particular along the north shore of St. Lawrence River (21). Titaniferous magnetite occurrences in Precambrian anorthositic gabbro northeast of Fort-Coulonge (loc. 2, 45°51'30"N, 76°37'40"W), are intersected by a radioactive pegmatite dyke that carries a mixture of several rare, dark, rare-earth-bearing minerals including allanite, chevkinite (the rare-earth-bearing variety of sphene or titanite), keilhauite (ytrotitanite; yttrium-bearing titanite) and dark purple fluorite. Samples of the titanomagnetite and of the dark radioactive pegmatite minerals showed 0.3 V and 0.2 per cent V respectively. Titaniferous magnetite occurrences associated with the Bell River basic intrusions (loc. 1, 49°40'N, 77°30'W) and the Shawinigan anorthosite (Grondin mine) (loc. 7, 46°30'N, 72°53'W) are also believed to be vanadiferous, as are several small occurrences in the gneisses of the Gatineau Hills (3). A small occurrence of vanadium-bearing titaniferous hematite and magnetite has also been noted at the Haycock mine (loc. 4, 45°34'N, 75°44'W).

Vanadium was recovered from chromite of the Chromeraie mine in Coleraine Township during World War II. Chromite samples collected by the writer from serpentinitized peridotite of Silurian (?) age near Coleraine (loc. 24, 45°59'N, 71°21'W) south of Thetford Mines showed 0.2 per cent V. Traces of vanadium were once noted in gold-quartz ore of the old Siscoe mine.

Faint traces of vanadium were also detected in samples of Devonian (?) maroon argillite near Rivière-du-Loup (loc. 25, 47°49'N, 69°30'W) and north of Gaspé (loc. 28, 48°54'N, 64°42'W), of orange-red stained Silurian volcanic rocks near Port-Daniel (loc. 27, 48°11'N, 64°56'W), and of dark brownish Carboniferous conglomeratic sandstone near Pointe-à-la-Garde (loc. 26, 48°07'N, 66°35'W) in the Gaspé

Peninsula. Traces of vanadium were also reported in gold ore from the Siscoe vein of the old Siscoe mine in Dubuissou and Vassan Townships, Abitibi district ( $48^{\circ}08.6'N$ ,  $77^{\circ}52.2'W$ ).

### New Brunswick

Traces of vanadium were detected by the writer at ten localities in New Brunswick, seven in sedimentary rock, one from interbedded sediments and volcanic rocks, one from the hydrocarbon albertite and associated shales, and one from the nickeliferous gabbro intrusion at St. Stephen (loc. 7,  $45^{\circ}13'N$ ,  $67^{\circ}15'W$ ). The vanadiferous sedimentary rocks include dark Ordovician (?) shale at Cocks Landing (Cocks Brook) (loc. 1,  $47^{\circ}51'N$ ,  $66^{\circ}56'W$ ) (0.015% V), red Carboniferous argillite and sandstone west of Fredericton (loc. 4,  $45^{\circ}58'N$ ,  $66^{\circ}50'W$ ) (0.04% V), ochre with lignite in sandstone near Boiestown (loc. 3,  $46^{\circ}26'N$ ,  $66^{\circ}23'W$ ) (0.013% V), grey Carboniferous sandstone near Hopewell Cape (loc. 11,  $45^{\circ}47'N$ ,  $64^{\circ}37'W$ ) and grey-brown bituminous shale also of Carboniferous age at Albert Mines (loc. 10,  $45^{\circ}54'N$ ,  $64^{\circ}47'W$ ) (0.01% V).

Albertite extracted from veins in the shale showed 0.05 per cent V. Interbedded, mottled sandstone, conglomerate, felsite, and volcanic breccia of Silurian (?) age, west of Harvey Station (loc. 5,  $45^{\circ}43'N$ ,  $67^{\circ}09'W$ ) was found to carry about 0.03 per cent V.

Faint traces of vanadium were detected in samples of black radioactive hydrocarbon (0.003% V), and the dark Carboniferous shale (0.005% V) in which it occurs, near Hampton (loc. 8,  $45^{\circ}30'N$ ,  $65^{\circ}50'W$ ). Faint traces of vanadium were also noted by the writer in the orange-red Carboniferous sandstone of Shippegan Island (loc. 2,  $47^{\circ}50'N$ ,  $64^{\circ}34'W$ ), and in weakly radioactive reddish argillite from York Mills (loc. 6,  $45^{\circ}40'N$ ,  $67^{\circ}07'W$ ). Two samples of heavy minerals collected by C. R. McLeod (McCartney and McLeod, 1965) from stream gravels in the Upham (loc. 9,  $45^{\circ}29'N$ ,  $65^{\circ}40'W$ ) area of Carboniferous rocks south of Sussex showed strong traces of vanadium (1–0.5%) and very faint traces of uranium (0.002%  $U_3O_8$  equivalent).

*Albert Mines Albertite and Oil Shale* (loc. 10,  $45^{\circ}54'N$ ,  $64^{\circ}41'W$ )

References: Norman, G. W. H. (1941)  
Wright, W. J. (1922)

A vein-like mass of the rare hydrocarbon mineral albertite, discovered in 1820 in Albert County, was mined between 1850–84 and sold at \$15 to \$20 a ton as illuminating oil and fuel. The albertite vein occurs in grey-brown bituminous shales of the Albert Formation of early Carboniferous age. The vein, from 0 to 17 feet wide, was mined for a length of 2,800 feet and to a depth of 1,500 feet where it passed into a shale breccia cemented with albertite. Samples of shale from several points in the Albert Mines area yielded from 32 to 52 imperial gallons of crude oil and 38 to 92 pounds of ammonium sulphate per long ton (Wright, 1922). In 1940 A. W. G. Wilson tested samples of oil shale and albertite from Rosedale, for vanadium, with negative results. In 1942, two samples of albertite and oil shale from Albert Mines were analyzed by the Mines Branch for Sylvanite Gold Mines, Limited, and found to contain 0.01 and 0.02 per cent V respectively, together with three samples of chalcocite-bearing sandstone from New Horton which were found to carry 0.02 per cent V.

A sample of albertite collected by the writer was analyzed spectrographically and found to carry major Si, minor Al, minor Ca, 3% Fe, 0.5% Mg, 0.3% Ti, 0.3% Mn,

0.05% V, 0.05% Cr, 0.05% Ni, 0.01% Sr, 0.02% Ba, and faint traces of Cu, Co, B, Nb, Sc, and Zr, and a very faint trace of Ag (<0.0005%). The enclosing oil shale was found by spectrographic analysis to carry 0.23% Ti, 0.13% Mn, 0.004% Cr, 0.01% V, 0.004% Ni, 0.009% Cu, and <0.001% Co, and by radiometric analysis to have 0.006%  $U_3O_8$  equivalent.

*Hampton Hydrocarbon* (8) 43°30'N, 65°50'W

References: Gross, G. A. (1957)  
Johnston, R. A. A. (1915)

An occurrence of dark hydrocarbon in dark shale near Norton was mentioned by Johnston (1915), and was described later by Gross (1957). The occurrence is about half a mile northwest of No. 2 Highway, and may be reached on foot along a brook which crosses the highway at a point 4 road miles northeast on the highway from the CPR station in Hampton. The main seam of fissile, black, shaly hydrocarbon as exposed in some small overgrown pits, strikes northeasterly, dips 50 degrees northwesterly, is about 8 to 10 feet wide, and lies mainly between a hanging-wall of dark brown sandstone and a footwall of grey sandstone, both of which are intercalated with dark shale. The hydrocarbon seam twists and in places penetrates the footwall rocks.

Weak radioactivity is associated with the hydrocarbon seams in the shale. Samples of hydrocarbon and shale taken by the writer showed contents of 0.05% Ti, 0.05% Mn, 0.01% Cr, 0.003% V, 0.005% Cu, and 0.02% Pb; and 0.41% Ti, 0.15% Mn, 0.003% Cr, 0.005% V, 0.0026% Ni, 0.002% Cu, and 0.003% Co, respectively. A content of 0.015 to 0.023%  $U_3O_8$  equivalent is indicated by radiometric analysis of the samples.

## Nova Scotia

Traces of vanadium were detected in three localities in Nova Scotia: one in a flat-lying soft coal seam near New Glasgow (loc. 5, 45°35'N, 62°37'W), another in fine-grained oölitic hematite iron ore of Torbrook (loc. 1, 44°55'N, 64°58'W) (0.08% V) (Pl. XIII A), and the other in grey-brown, malachite-bearing Carboniferous sandstone, south of Baddeck (loc. 7, 46°08'N, 60°48'W) in Cape Breton (0.011% V). Faint traces of vanadium were also detected in soft blotchy red argillite and sandstone, of Carboniferous age in the Gravois Point-Malagash Point area (loc. 3, 45°48'N, 63°20'W) (0.0075% V), and in copper-bearing green sandstone from Oliver (loc. 4, 45°39'N, 63°19'W) (0.0064% V), and in siderite of the Londonderry area (loc. 2, 45°29'N, 63°36'W) (0.0024% V).

Traces and faint traces of vanadium were found in heavy mineral concentrates made from samples of stream gravels in areas of Carboniferous rocks around West River St. Mary's (loc. 6, 45°17'N, 62°26'W) and from Salmon River, Cape Breton (loc. 8, 45°52'N, 60°25'W) in Nova Scotia (McCartney and McLeod, 1965). Faint to very faint traces of uranium were noted in twelve of these samples. In an additional group of forty-five heavy mineral samples submitted by C. R. McLeod from the Truro-New Glasgow Carboniferous area stream gravels, from which the magnetic minerals had been removed, faint traces to traces of vanadium were detected in all but one, and very faint traces of uranium were detected in thirty-four of the samples. Sixteen of these heavy mineral samples showed strong traces of vanadium (0.1-0.5%), of which five were >0.2 per cent V. These five samples came from an area of Carboniferous sediments of East River St. Mary's.

## Prince Edward Island

In 1963 very faint traces of vanadium were detected by the writer in samples of red soil and sandstone of Permo-Carboniferous age from Prince Edward Island. In September 1968 a small dark-stained specimen collected by V. K. Prest from sandstone beds a mile north of Little Miminegash Pond and submitted to H. R. Steacy for identification, was observed to be weakly radioactive. Further study revealed that the specimen was both uraniferous and vanadiferous, and an investigation of the occurrence was made and reported by officers of the Geological Survey in support of its uranium program (Prest, *et al.*, 1969).

### *Little Miminegash Pond* (1) 46°42'N, 64°12'W

The rare uranium vanadate minerals, rauvite ( $\text{CaO}\cdot 2\text{UO}_3\cdot 6\text{V}_2\text{O}_5\cdot 20\text{H}_2\text{O}$ ) and francevillite [(Ba,Pb)  $(\text{UO}_2)_2(\text{VO}_4)_2\cdot 5\text{H}_2\text{O}$ ], identified in samples collected from the outcrop north of Little Miminegash Pond from which Prest had taken the original sample. The presence of the soft dark vanadium oxide, doloresite ( $3\text{V}_2\text{O}_5\cdot 4\text{H}_2\text{O}$ ) was also tentatively identified as a constituent of the black matrix of certain greenish grey ellipsoidal areas within the red mudstone and sandstone beds. Selected samples of the most strongly radioactive ellipsoids showing in the discovery outcrop showed 0.042 to 0.075%  $\text{U}_3\text{O}_8$ ; 0.003 to 0.009%  $\text{ThO}_2$ ; and 5.0 to 3.92%  $\text{V}_2\text{O}_5$ .

Radioactivity slightly above normal background level, representing faint traces (<0.01%) of  $\text{U}_3\text{O}_8$ , was found in several sections of available oilwell core that were monitored by Beta counter. The best of these results were obtained on a well drilled near the village of Kelly Cross (loc. 2, 46°16'N, 63°30'W) in which weak radioactivity is associated with sections of core as much as 2 feet long in which the sandstone is greenish rather than the normal red.

The highest vanadium analysis shown here by Prest, *et al.* (1969), was 0.92%  $\text{V}_2\text{O}_5$  (about 0.5% V) in a 2-inch section of grey-green streaked sandstone at a depth of 911 feet in the Kelly Cross well. At a depth of 716.5 feet a 6-inch section of interbedded grey sandstone and red mudstone showed 0.68%  $\text{V}_2\text{O}_5$  (about 0.4% V) together with 0.029%  $\text{U}_3\text{O}_8$  and 0.001%  $\text{ThO}_2$ . A 12-inch section of grey sandstone at a depth of 763 feet showed 0.13%  $\text{V}_2\text{O}_5$  (about 0.07% V), 0.004%  $\text{U}_3\text{O}_8$ , and 0.002%  $\text{ThO}_2$ . Ninety-nine feet down a 4-inch section of red and grey sandstone showed 0.001%  $\text{U}_3\text{O}_8$ , 0.002%  $\text{ThO}_2$ , and 0.1%  $\text{V}_2\text{O}_5$  (about 0.06% V). Sparse yellowish grains of vesignieite [ $\text{Cu}_3\text{Ba}(\text{VO}_4)_2\cdot \text{OH}_2$ ] were also noted by Prest, *et al.* (1969), in the sandstone at and near its contact with underlying mudstone at a depth of 99.5 feet in the Kelly Cross well.

## Newfoundland

Traces of vanadium were noted by the writer in eight localities in Precambrian rocks on the Island of Newfoundland. Titaniferous magnetite occurrences of the Steel Mountain area north of Flat Bay Brook, in which vanadium was detected by D. M. Baird in 1942 (Baird, 1954) were examined and found to be vanadiferous as were those at Indian Head described by Heyl and Ronan (1954). The titaniferous magnetite from Indian Head was found to be strongly vanadiferous, and red stained; altered granitic rocks east of Stephenville also showed traces of vanadium in places.

Traces of vanadium were detected also in samples of dark oil shale of Carboniferous age from the Humber valley north of Deer Lake (loc. 4, 49°18'N, 57°27'W)

(0.018% V), and in friable, micaceous red and green sandstones of Mississippian age from Crabbes River (loc. 12, 48°10'30"N, 58°46'W) (0.015% V). Traces or faint traces of vanadium were detected in samples of manganese black shale of Middle Cambrian age from Manuels River (0.052% V) and from Topsail Head (0.008% V), in oölitic hematite (0.004–0.093% V), and enclosing sandstone (0.003–0.007% V) and shale (0.009–0.033% V) of Lower Ordovician age at Wabana, Bell Island. Faint traces of vanadium were also detected in samples of ultrabasic igneous rock from the Bay of Islands igneous complex (loc. 5, 48°50'N, 58°30'W).

#### *Steel Mountain Anorthosite Area*

*Bishop North titaniferous magnetite* (9) 48°24'N, 58°18'W. A dyke-like body of coarse-grained titaniferous magnetite as much as 50 feet wide and 650 feet long, striking north-northeasterly and dipping steeply westerly, cuts through anorthosite in the Steel Mountain area north of Flat Bay Brook. The deposit and host rocks are truncated by east-trending faults and a similarly oriented diabase dyke. The deposit is estimated to hold about a million tons of titaniferous magnetite, averaging about 54% Fe, 7.5% Ti, 0.2% V, 0.008% S, and 0.1% Si. A magnetic concentrate made from a sample of the deposit showed 65.5% Fe, 6.6% Ti, 0.25% V, 0.1% Cr, 0.13% Mn, and 0.01% Ni.

Under the microscope the ore material appears as an interlocking mosaic of titanomagnetite crystals, with a few included grains of plagioclase, pyroxene, and green spinel. Most of the titanomagnetite grains show well-developed octahedral cleavage and an almost submicroscopic intergrowth of ilmenite, which forms a rectangular pattern outlined by elongated tiny spindles of spinel. The spinel spindles follow parting planes parallel to the octahedral cleavage planes in the titanomagnetite. Some free grains of ilmenite occur interstitially to the titanomagnetite, and in a few of these, exsolution lamellae of hematite occur outlining the rhombohedral planes of the ilmenite host. Relict grains of spinel are extensively replaced by titanomagnetite. Because of the intimacy of the intergrowth of the Fe–Ti–V oxide minerals it is improbable that Ti can be significantly reduced by magnetic methods.

*Bishop South titaniferous magnetite* (10) 48°24'N, 58°35'W. A smaller exposure of titaniferous magnetite similar to the Bishop North deposit, outcrops on an anorthosite hill about 2,000 feet south-southeast of the former, and may be its faulted extension or a separate lens along the general strike of the Bishop North vein. The Bishop South deposit, striking northeasterly and dipping steeply northwesterly, about 40 feet wide by 400 feet long, is estimated to hold about half a million tons of titaniferous magnetite, averaging about 54% Fe, 7% Ti, 0.25% V, 0.006% S, and 0.1% Si. Under the microscope the ore material appears almost identical with that of the Bishop North. Gangue grains contain fine-grained stringers and blebs of titanomagnetite and ilmenite, and in places both ore minerals and gangue minerals are fractured and penetrated by veinlets carrying ilmenite, hematite, and gangue.

*Hayes Prospect titaniferous magnetite* (11) 48°23'N, 58°24'W. A vein-dyke of coarse-grained titaniferous magnetite from 3 to 10 feet wide cuts with sharp contacts through grey anorthosite on the crest of a ridge overlooking Flat Bay Brook north of Skull Hill. The vein strikes northerly toward the Bishop occurrences and dips steeply westerly. It is exposed along strike intermittently for about 800 feet, and is associated with a circular, positive, aeromagnetic anomaly. The ore material is similar to that at

the Bishop occurrences, and has a reversed component of remanent magnetism that detracts from its magnetic anomaly. The deposit is estimated to hold about 30,000 tons of titaniferous magnetite averaging about 54% Fe, 9% Ti, and 0.2% V. A magnetic concentrate of this titaniferous magnetite showed 68.5% Fe, 3.5% Ti, 0.28% V, 0.15% Cr, 0.05% Mn, and 0.01% Ni.

#### *Indian Head Anorthosite Area (6)*

*Indian Head mine titaniferous magnetite (6)* 48°30'N, 58°30'W. The deposit of titaniferous magnetite on the west side of Indian Head east of Stephenville Pond, was opened in 1941 by Dominion Steel and Coal Corporation, Limited (DOSCO), and a few hundred tons of ore were removed. The pit was later reopened by the USAAF to provide rock for construction of Harmon Base, and it now consists of three quarry benches from 180 to 300 feet long, totalling 78 feet deep. The rock exposed is grey-green gneissic gabbroic (noritic) anorthosite (norite-gneiss), with gently dipping concordant bands, from one quarter inch to 1½ feet thick, and disseminations of black titaniferous magnetite. Irregular stringers of granite pegmatite cut both the rock and titaniferous magnetite bands. A sample of biotite collected by the writer from one of these pegmatite dykes was dated at  $900 \pm 45$  m.y. by the K/Ar method, thus placing the age of the magnetite deposit as Precambrian.

A considerable tonnage of low-grade, readily concentratable material is exposed, that probably averages about 20% Fe, 0.5% Ti, and 0.1% V, but no conspicuous aeromagnetic anomalies are shown. The deposit is probably of limited extent. A magnetic concentrate made from a sample of this material showed 69.3% Fe, 0.73% Ti, 1.1% V, 0.003% Cr, 0.14% Mn, 0.01% Co, and 0.017% Ni.

Other titaniferous magnetite occurrences are reported at Labrador Pond (loc. 8, 48°30'N, 58°29'W) on the east side of Indian Head; titaniferous magnetite with hematite occurs at the Upper and Lower Drill Brook mines north of Oxback Pond, and the Cliff mine north of Gull Pond, as bands in gneissic anorthositic gabbro and granite. Two samples of the Lower Drill Brook magnetite showed 0.07 and 0.38 per cent V according to the Newfoundland Government Laboratory.

*Upper and Lower Drill Brook mines (7)* 48°32'N, 58°29'W. In 1942 DOSCO opened a pit about 200 feet long by 50 feet wide by 15 feet deep along Drill Brook between Oxback and Gull Ponds (Lower Drill Brook mine) and another on a bench 50 feet above and 100 feet north of Oxback Pond (Upper Drill Brook mine). Both occurrences are mixtures of titaniferous magnetite and hematite which form thin, deformed bands, streaks, and disseminations in gneissic anorthositic gabbro, which is intimately penetrated by small seams and dykelets of granite-pegmatite and granite. Considerable pyrite with some chalcopyrite and molybdenite occurs in the Lower Drill Brook mine. Extensive diamond drilling was done around these occurrences by the Geological Survey of Newfoundland, and mineralized bands were found to be numerous and widespread. Representative samples of the Lower Drill Brook mine were analyzed in the Newfoundland Government Laboratory and found to carry 60.5 to 64.0% Fe, 3.48 to 4.32% Ti, 0.07 to 0.38% V, 3.8 to 0.44% S, P nil, and 0.47% SiO<sub>2</sub>. An analysis of Upper Drill Brook mine titaniferous magnetite showed 64.4% Fe, 2.99% Ti, 0.23% V, 0.07% S, P nil, and 1.86% SiO<sub>2</sub>. An estimate of 57,000 tons of ore averaging 54.8 per cent Fe was made for the Upper Drill Brook mine.

*Wabana Iron Mines Oölitic Hematite* (13) 47°36'N, 52°56'W

Reference: Hayes, A. O. (1915)

The Wabana iron deposits were discovered on Bell Island in Conception Bay, Newfoundland, in 1892, and produced 70 million tons of oölitic hematite iron ore from surface cuts and submarine mines before they were closed in 1966. Five main bands and many thin seams of oölitic hematite are intercalated with fossiliferous sandstones and dark shales of Lower Ordovician age on Bell Island. They dip gently beneath Conception Bay, appearing to lie conformably above the Cambrian strata exposed along the south shore of Conception Bay, and they form an outlying basin, truncated by faults, underlying the bay. Three of the oölitic hematite bands, separated by 240 and 58 feet of strata, have been mined—the Lower (Dominion), Middle (Scotia), and Upper (Little Upper) beds. Most production has come from the Lower bed which is 40 feet thick in places and has been mined down dip for almost 2 miles and along strike for about 3 miles. The submarine ore was mined by room and pillar method, about 40 per cent being left as roof supporting pillars.

The ore beds are composed essentially of sand-like grains of concentrically banded hematite, siderite, chamosite, quartz, and an occasional shell fragment, set in a matrix of siderite and a paste of comminuted quartz (chert), chamosite, hematite, shell fragments, manganese oxides, and carbonates—a mixture of chemically and biochemically precipitated and subordinate clastic material (Pl. XIII B). The oölitic grains are formed by precipitation and accretion of hematite about nuclear, clastic grains. In places they are penetrated by coiled tubules of boring algae (Hayes, 1915). Penecontemporaneous erosion, transportation, and deposition of oölitic grains are shown by crossbedding, interformational conglomeratic beds carrying oölitic hematite, and an off-shore bar arrangement in the ore zones. Ripple-marks, raindrop impressions, cut-and-fill structures, algal structures, worm burrows, and abraded clastic materials in the ore, all suggest shallow-water deposition. The top of the Lower bed is eroded and overlain by a persistent conglomerate carrying pieces of hematite and shale. The immediately overlying bed, as much as 1½ feet thick, consists of granular, oölitic pyrite, carries graptolites, and is succeeded by dark shale with dolomite nodules. The texture of the oölitic pyrite is similar to that of the ore beds, but in contrast to the ore beds, it appears to have formed in a reducing environment, as did the black shales. Thin, nodular, phosphatic beds composed of shell fragments, nodules and oölitic grains of calcium phosphate, siderite and pyrite, also occur in the shale above the Middle bed.

The Lower and Middle beds have yielded ore that ranged from 45 to 57 per cent iron. Silica, at 12 per cent, and phosphorus at 0.85 per cent are the most objectionable impurities; sulphur is less than 0.03 per cent and calcium less than 2 per cent. A trace of vanadium is in the ore, and in the slag at Sydney, and it is believed that some vanadium was recovered in Germany during World War II from Wabana ore shipped before the outbreak of war.

To learn more about the vanadium content of the ore the writer, with the assistance of mine geologist W. M. Coughlan, collected thirty-one samples along strike and across the stratification of the three main ore-beds and the dark shales and sandstones with which they are interbedded. On analysis, fourteen samples of the oölitic hematite showed a range of 0.0042 to 0.093 per cent V, and an average of about 0.05 per cent V; nine samples of dark shale showed from 0.003 to 0.033 per cent V; six samples of sandstone showed from 0.004 to 0.053 per cent V; one of oölitic pyrite and one of dark dolomitic nodules showed <0.001 and 0.007 per cent V respectively. In the samples



taken, vanadium is highest, at 0.093 per cent in the lower part of the Scotia (Middle) bed, but it varies slightly within each bed, both along strike and probably also down dip. The vanadium content of the oölitic hematite (0.05% V) is appreciably higher than that of the enclosing shale (0.009%–0.033% V) and sandstone (<0.001–0.053% V), which average 0.018 and 0.014 per cent V respectively. Titanium was highest and was fairly constant in the black shales, ranging from 0.37 to 0.77 per cent. Manganese exceeded 3 per cent in the upper part of the east end of the Scotia bed and in the associated hanging-wall dark sandstone from east to west. The Cr, Ni, Co, and Cu contents of these rocks and ores ranged up to a maximum of 0.03 per cent for Cu.

By comparison, the minette ores of eastern France, of Cretaceous age, are reported to carry from 0.06 to 1.2 per cent V; the oölitic chamosite–limonite–siderite ironstone of Northamptonshire, England, 0.05 per cent V; the sideritic Liassic Series of Southern Sweden, 0.009 per cent V; the bog iron ore of Finland, <0.001 per cent V; the average shale, 0.0120 per cent V; and the average sandstone, 0.002 per cent V.

*Manganiferous Shale, Avalon Peninsula (15) 47°–48°N, 63°–64°W*

Reference: Dale, N. C. (1915)

Manganese-bearing seams occur in limestone, breccia, and shale of Cambrian age, mainly within a zone at the contact of Lower and Middle Cambrian beds, at numerous localities in the Avalon Peninsula, and particularly around the southern end of Conception Bay (Dale, 1915). Manganese carbonates and oxides occur as nodules, disseminated lenticles and bands in the dark shales.

The manganese-bearing rocks are essentially calcareous or dolomitic argillites with carbonates and oxides, or carbonate-oxides of manganese, hematite, barite, and tri-calcium phosphate (collophane?) as the chief accessories. The primary manganese and barium-bearing carbonates in these beds are more or less superficially altered to pyrolusite, and in some places secondary enrichment in manganese oxides has occurred; but for the most part the manganiferous zone seldom exceeds 12 feet thick and 12 per cent of manganese. Traces of vanadium were noted in some of these occurrences.

*Manuels River, Conception Bay (14) 47°27'N, 52°55'W*

Reference: Rose, E. R. (1952)

On Manuels River, below the cascade over the basal Cambrian conglomerate, a zone of manganiferous shale about 13 feet thick succeeds Lower Cambrian limestone; it strikes northeasterly and dips about 10 degrees northwesterly under fossiliferous Middle Cambrian shale. The manganese-bearing zone at Manuels River contains from 8 to 11.5 per cent Mn. It extends from Topsail Head past Manuels to beyond Kelligrews River. A sample of the manganiferous shale from Manuels River showed >3.0% Mn, 0.052% V, 0.094% Ti, 0.008% Cr, 0.005% Ni, 0.006% Co, and 0.03% Cu; another from Topsail Head showed >3.0% Mn, 0.008% V, 0.13% Ti, 0.005% Cr, 0.009% Ni, 0.008% Co, and 0.02% Cu. Weak indication of radioactivity associated with these beds on Manuels River suggested a content of about 0.004% U<sub>3</sub>O<sub>8</sub> equivalent.

A large tonnage of manganese-bearing material underlies the Paleozoic lowland at the south end of Conception Bay. The mineralized zone also carries variable amounts of calcium, barium, phosphorus, vanadium, and other trace elements, and may become a future source of some of these elements (Rose, 1952).

Twelve samples of manganese occurrences from other localities in the Avalon Peninsula, submitted by W. D. McCartney, were tested by the writer and found to show from 0.001 to 0.006 per cent  $U_3O_8$  equivalent. Six samples showed traces of vanadium as well.

TABLE VI Ferride element<sup>1</sup> content of Wabana iron ore, shale, and sandstone (percentage weight)

		Lower (Dominion) Bed	Middle (Scotia) Bed	Upper (Little Upper) Bed	Black Shale Interbeds	Grey Sandstone Interbeds
Iron (Fe)		> 50	> 50	> 50		
Titanium (Ti)	r	0.14-0.20	0.07-0.16	0.17	0.37-0.77	0.014-0.36
	a	0.17	0.12		0.55	0.017
Vanadium (V)	r	0.0042-0.05	0.038-0.093	0.053	0.009-0.033	<0.001-0.053
	a	0.037	0.064		0.022	0.013
Chromium (Cr)	r	0.003-0.01	0.002-0.009	0.011	0.007-0.021	0.0005-0.007
	a	0.007	0.004		0.011	0.002
Manganese (Mn)	r	0.033-0.14	0.022-> 3.0	0.029	0.039-0.28	0.028-> 3.0
	a	0.086	0.766		0.115	1.02
Cobalt (Co)	r	<0.001-0.007	<0.001-0.008	<0.001	<0.001-0.005	<0.001-0.014
	a	0.005	0.005		0.002	0.007
Nickel (Ni)	r	0.004-0.009	<0.001-0.006	<0.001	0.002-0.017	<0.001-0.015
	a	0.007	0.003		0.009	0.006
Copper (Cu)	r	<0.001-0.015	<0.001-0.002	0.011	<0.001-0.01	<0.001-0.016
	a	0.006	0.001		0.004	0.013

<sup>1</sup>Including copper

r= range

a= average

### Coast of Labrador

Reference: Emslie, R. F. (1963, 1970)

Little is known of vanadium on the coast of Labrador, but the prospects appear to be good for its occurrence in titaniferous magnetite deposits that presumably occur around many of the large bodies of anorthositic rocks there, such as in the Mealy Mountains (loc. 3, 53°30'N, 59°30'W) and Nain-Hopedale areas.

*Michikamau Lake anorthosite area* (1) 54°12'N, 63°48'W. Emslie (1963,1970) recently mapped and described in detail the large differentiated Precambrian anorthositic intrusions near the Quebec-Labrador boundary at Michikamau Lake where ilmenite was reported by Low as early as 1897.

*Magnetite Lake titaniferous magnetite* (2) 54°12'N, 63°50'W. Emslie (1970) reported concentrations and disseminations of magnetite and ilmenite in marginal zone gabbros, and a broad zone carrying layers, pods, and disseminations of magnetite and ilmenite measuring 300 metres wide by several kilometres long, and extending west from Magnetite Lake in the southeast part of the intrusion. Magnetite separated from the oxide concentrations in this zone was analyzed spectrographically and reported by Emslie (1970) to contain as much as 1.5%  $V_2O_5$  (1.02% V).

## *Chapter VI*

# GEOLOGICAL INTERPRETATION AND CLASSIFICATION OF DEPOSITS IN CANADA

### Summary

In the preceding account, widespread traces of vanadium have been shown to occur in a great variety of rocks and minerals of diverse ages across Canada. The distribution of known vanadium occurrences in Canada is indicated on Map 1321A, and their range of geological age and types is illustrated in Tables II, VII and VIII. An age range from Precambrian (+ 2 b.y.) to Oligocene (+ 25 m.y.) and Recent (<10,000 years) is represented. The most common chemical associations of vanadium in these occurrences in Canada appear to be with titanium and iron (to a lesser extent with chromium and manganese, and other ferride elements); with uranium (and to a lesser extent with thorium, and rare earths); with copper (and to a lesser extent with lead and zinc); with bitumen as hydrocarbons, porphyrins, and metallo-organic complexes in tar, asphalt, heavy oil, and solid hydrocarbons; with carbon (graphite, coal, lignite); and with phosphorus, apatite, collophanite, and phosphate rock. These associations appear generally to hold in occurrences of a great range of ages and geological types, but with various and numerous exceptions.

### Host Rocks and Associations of Vanadium

Vanadium has been detected across Canada in many different kinds of rock, but most commonly in the following: (1) basic igneous rock (intrusive and extrusive); (2) basic alkaline igneous rock (intrusive and extrusive); (3) carbonatite complexes; (4) titaniferous magnetite occurrences associated with (1), (2), and (3); (5) chromite deposits; (6) uranium deposits; (7) iron and manganese deposits; (8) heavy, dark, clastic iron sands and sandstones; (9) light grey to dark shale, slate, greywacke, and sandstone; (10) light to dark red or violet argillite, shale, and sandstone; (11) yellow stained shale, slate, and sandstone; (12) reddish stained arkose; (13) dark phosphate rock, collophanite, and apatite; (14) lignite and soft coal; (15) oil, oil shale, bituminous sandstone (tar sands), and asphaltite—all in a wide variety of geological ages.

### Association with Iron

The iron ores and iron-formations of Precambrian age in Canada are generally considered to be below the crustal average in vanadium, as evidenced by analytical data given by Gross (1965). This is rather strange because vanadium may substitute for iron in the structure of many of the common oxide, carbonate, and sulphide ore minerals. It is possible that trace amounts of vanadium in many of these iron ores have

TABLE VII

*Classification of vanadium occurrences in Canada***A. IGNEOUS OR MAGMATIC****I Intrusive bodies****(a) Basic and ultrabasic rocks**

Massive—disseminations and segregations of vanadium-bearing titaniferous magnetite in anorthosite, gabbro, diabase; massive dyke-like deposits, Magpie Mountain, Quebec.

Layered—bands and disseminations of vanadium-bearing titaniferous magnetite; Lac Doré Complex, Quebec; Bad Vermilion Lake, Ontario; Cross (Pipestone) Lake, Manitoba.

**(b) Alkaline rocks—disseminated vanadium-bearing titaniferous magnetite in essexite, yamaskite, etc., of Monteregeian intrusions; Mount Yamaska, Mount Brome.****(c) Acidic rocks—disseminated allanite, titanite, etc., in granitic rocks of Coast Range, northern British Columbia.****II Replacement deposits (aqueo-igneous)****(a) Pegmatite dykes**

Basic rocks—vanadium-bearing apatite in phlogopite-apatite-calcite pyroxenites in eastern Ontario and western Quebec.

Acidic rocks—vanadium-bearing allanite, titanite, zircon, uranium, etc., in radioactive pegmatite dykes in eastern Ontario and western Quebec.

**(b) Carbonatite complexes—vanadium-bearing titaniferous magnetite and apatite in carbonatite complex; Nemegos, Ontario; Oka, Quebec.****(c) Hydrothermal deposits—nolanite in pitchblende in veins and disseminations in metasediments and mylonite at Fishhook Bay and Ace-Fay-Verna mines, Beaverlodge area, Saskatchewan; tin-vanadium-bearing rhodonite vein, Tsitsutl Mountain, British Columbia; gold-silver-tungsten-vanadium-bearing quartz vein, Siscoe mine, Quebec.****III Extrusive bodies****(a) Volcanic and pyroclastic rocks—copper and vanadium-bearing andesite and basalt on Banks Island and Menzies Bay, British Columbia; Coppermine Group basalts, Northwest Territories; and Keewatin greenstones in Ontario, Quebec, and Manitoba.****B. SEDIMENTARY****I Mechanical****(a) Residual (eluvial)—vanadium-bearing titaniferous magnetite rubble in metagabbro on Banks area and Porcher Islands, British Columbia.****(b) Transported (alluvial)—dark sandstone, Burmis and Dungarvan Creek, Alberta; dark sands, St. Lawrence River, Quebec.****II Chemical****(a) Continental—limonite iron ore north of Peace River, Alberta; lignitic sandstone and shale, British Columbia, Alberta, Saskatchewan.****(b) Marine—phosphatic shale, Alberta, and British Columbia; marine oölitic iron ore, Wabana, Newfoundland.****III Biochemical—oil shale and albertite, Albert Mines, New Brunswick; lignite, East End and Bienfait, Saskatchewan.****IV Combinations—vanadium-bearing bitumen Athabasca tar sands, Alberta; soft coal, Alberta, British Columbia, Nova Scotia.****C. METAMORPHIC—vanadium-bearing graphite in graphitic schists in Manitoba, Saskatchewan; and chlorite in schists and iron-formation at Timagami, Ontario.****D. SECONDARY—limonite-goethite gossan, Gataga River, British Columbia****E. COMPLEX—volborthite-bearing sediments and volcanics, Menzies Bay and Quadra Island, British Columbia.**

not been reported, and that close investigation may reveal their presence. Traces and faint traces of vanadium were detected by the writer in samples of Precambrian (Keewatin ?) hematite iron ore from Steeprock Lake, Ontario; from Precambrian (Keewatin ?) hematite-magnetite iron-formation at Timagami, Ontario; from oölitic hematite of Ordovician age at Wabana, Bell Island, Newfoundland; and from oölitic hematite of Silurian age at Torbrook, Nova Scotia. Traces of vanadium have also been reported from limonite-hematite ores of Cretaceous age from the Peace River district-Hines Creek area of northern Alberta. The marine sedimentary iron ores are noteworthy for their vanadium content.

#### Association with Titanium

Vanadium occurs persistently in magmatic deposits of titaniferous magnetite of widely divergent ages in various parts of the country. In these 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 magnetic titanomagnetite in which it may average from 0.1 to 1.5 per cent or more, compared with 0.01 to 0.2 per cent in the weakly magnetic ilmenite-hematite, and commonly less than 0.01 per cent in the nonmagnetic gangue. 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 titaniferous magnetite. Traces of vanadium are also found in the mafic minerals, pyroxene, hornblende, biotite, and chlorite, that are commonly associated with the iron-titanium oxides. Despite the persistent association of vanadium with titaniferous magnetite of all ages, there does not appear to be any constant relationship between the titanium and vanadium content of these occurrences.

#### Association with Uranium, Thorium, and Rare Earths

Vanadium is also commonly associated with uranium in deposits of both sedimentary and hydrothermal origin, and of various ages. It has been noted in the form of nolanite in hydrothermal pitchblende veins of Precambrian age in the Beaverlodge area (Robinson, 1955), and it has been detected by the writer in samples of the Blind River-Elliot Lake uraniumiferous conglomerate of Huronian age. Many of the rare, uranium, thorium, and rare-earth-bearing, multiple oxide minerals of pegmatites also carry vanadium, as do many of the secondary hydrated minerals.

Small amounts of a new secondary yttrium vanadate mineral have recently been identified by Miles and Hogarth (pers. com., 1969), and described as a buff powder associated with allanite in a radioactive pegmatite dyke north of St-Pierre-de-Wakefield, Quebec. Traces of vanadium may also be found in the iron-titanium-niobium-rare earth-uranium-thorium minerals associated with alkalic intrusions and carbonatite complexes, as at Oka, Quebec.

#### Association with Copper

Strong traces of vanadium are associated with copper sulphides in the basaltic lavas and intercalated chalcocite-bearing sedimentary lenses of Triassic age on Vancouver and Quadra Islands of British Columbia. A strong trace of vanadium was

reported by Rice (1947) in biotite concentrates made from samples of the Copper Mountain ore in southern British Columbia. Traces of vanadium are also reported in the Precambrian Coppermine River basalts (Baragar, 1969). Vanadium, uranium, and copper-bearing nodules, and reduced areas in the red sedimentary beds associated with basic volcanic rocks have been noted in the Sibley Series near Nipigon, Ontario, and also in the Permo-Carboniferous 'red beds' of Prince Edward Island where volcanic rocks are not known to be present. Traces of vanadium have also been detected by the writer in cupriferous and other sandstones of Mississippian age in New Brunswick, Nova Scotia, and Newfoundland. Some form of carbon or hydrocarbon, as well as copper, is commonly present in these vanadiferous sediments, and may have acted both as a source medium and precipitating agent of vanadium.

#### Association with Bitumen, Hydrocarbons, Carbon, Porphyrins, and Organic Complexes

Vanadium shows a strong association with bituminous and petroliferous shales and sandstones of various ages, as in the Mississippian shales of Deer Lake, Newfoundland, the Albert shales of New Brunswick, and the Athabasca tar sands of Cretaceous age in northern Alberta. Various hydrocarbons such as albertite in the Mississippian shales of Albert Mines, New Brunswick, and forms of carbon such as graphite from Precambrian schists in Manitoba, soft coal from Stellarton, Nova Scotia, and lignite from British Columbia and Saskatchewan, also carry traces of vanadium, concentrated in places perhaps both by biochemical and secondary processes. In these associations the vanadium may have been precipitated from solutions by living organisms, by dead and decaying organic matter, or by the reducing activity of carbon or carbonaceous material. During these processes some vanadium may be incorporated by the organism, plant or animal, in a chlorophyll-like substance in plants, or as a metallo-organic complex in animals, later to be converted into vanadium-bearing porphyrins, and eventually into other vanadium-bearing minerals by geological processes.

#### Association with Phosphates

Vanadium is also commonly found in the marine phosphorites, phosphatic nodules, and associated black shales of various ages and areas. In many of these rocks the vanadium may be carried in several forms, such as in comminuted titanomagnetite and other heavy multiple oxide and radioactive minerals; in graphite, bitumen, carbonaceous matter, and organic complexes; in vanadium-bearing clays and micas; in substitution for phosphorus in phosphates (collophanite and apatite) and shells; and in dispersed secondary minerals.

Faint traces of vanadium have also been detected in samples of apatite from a number of occurrences in Precambrian rocks in eastern Ontario and north of Ottawa in Quebec; from metamorphic pyroxenite and crystalline limestone; from magnetite occurrences in gabbroic rocks; and from granitic pegmatite dykes.

#### Interpretation of Geological Data

Vanadium is dispersed throughout a great variety of rocks in the earth's crust. Much of the vanadium in Canada is distributed in intrusive gabbroic-anorthositic rocks and associated titaniferous magnetite deposits, as well as in the belts of basic extrusive

volcanic rocks of Precambrian age that form large segments of the Canadian Shield. These ancient rocks provided a primitive source of primary vanadium-bearing material early in the geological history of the earth, in close association with iron and titanium, and formed the first crude metallogenic provinces of these elements. The processes of fractional crystallization and magmatic differentiation appear to have been most effective, at this early and prolonged period in earth history, in concentrating vanadium in titaniferous magnetite segregations within the basic rocks of the crystallizing crust. During the evolution of the Shield areas of the crust these processes seem to have operated periodically, perhaps cyclically, until the continents were formed. These processes appear to have culminated in the formation of the great layered complexes and the anorthositic intrusions of the Shield. Although these magmatic processes have been repeated subsequently many times, they have apparently never functioned on such a large scale over such a long period of time.

Sedimentary and metamorphic processes do not appear to have been comparably effective in concentrating vanadium in this early period of geological time. The sketchy record of Precambrian sedimentation does show examples of minor concentrations of vanadium here and there, as in certain iron-formations, iron ores, slates, and greywacke sandstones (quartzites), but it is not until the Paleozoic and later eras that sedimentary concentrations of vanadium began to be more significant. With the development of the earth's hydrosphere (water), and atmosphere (oxygen), the evolution of organisms, intermittent igneous activity, metamorphism, and orogeny, the relative importance of sedimentary, metamorphic, and secondary processes of concentrating vanadium increased in time, culminating in post-Cretaceous time in the formation of the richest deposit of vanadium ever found: the patronite ore at Mina Ragra, Peru, and in the concentration of other extensive vanadium-uranium ores in the Mesozoic sandstones at widespread localities in the western United States, and elsewhere.

The anatomy and origin of orogenic zones are not readily comprehensible. The (metallogenic) processes that combine to produce metallogenic provinces and periods are likewise poorly defined and only partly understood. It is therefore difficult to generalize about the existence or otherwise of vanadium provinces and periods in Canada. It is perhaps sufficient to note that primary vanadium-bearing source rocks of Precambrian age are plentiful in certain parts of Canada, and possibilities of other occurrences in these areas are good.

## Metallogeny

Map 1321A illustrates the main known primary occurrences of vanadium in Canada and areas in which vanadium is either a common or an outstanding constituent of the bedrock. These areas may be considered to be metallogenic regions or provinces, in which the prospects of finding additional occurrences of vanadium are relatively good. On theoretical grounds the areas in which two or more metallogenic or geological provinces contact one another or overlap are most favourable for the formation of vanadium deposits. In addition to the geological features controlling the development of metallogenic provinces, the effect of geological structures, large and small, may play an all important role in the solution and transfer of vanadium by fluids migrating from one source area to another, both within and across metallogenic provinces.

The interplay of geological, chemical, physical, and biological processes may produce a unique set of conditions resulting in the formation of a mineral deposit at a particular place and during a particular period of time. These conditions may be repeated more or less regularly or rarely during a particular epoch or throughout geological time, resulting in metallogenic epochs, periods, or eras. When conditions of time and environment are favourable, mineral deposits may result.

### Classification of Vanadium Occurrences

The known vanadium occurrences in Canada are classified in Table VII on the basis of their geological environment, type of host rocks, associations, and the dominant geological processes believed to have operated in their formation. The method of classification is intended to be objective. Important examples of each class of occurrence in Canada are mentioned.



## Chapter VII

### CANADA'S VANADIUM POTENTIAL

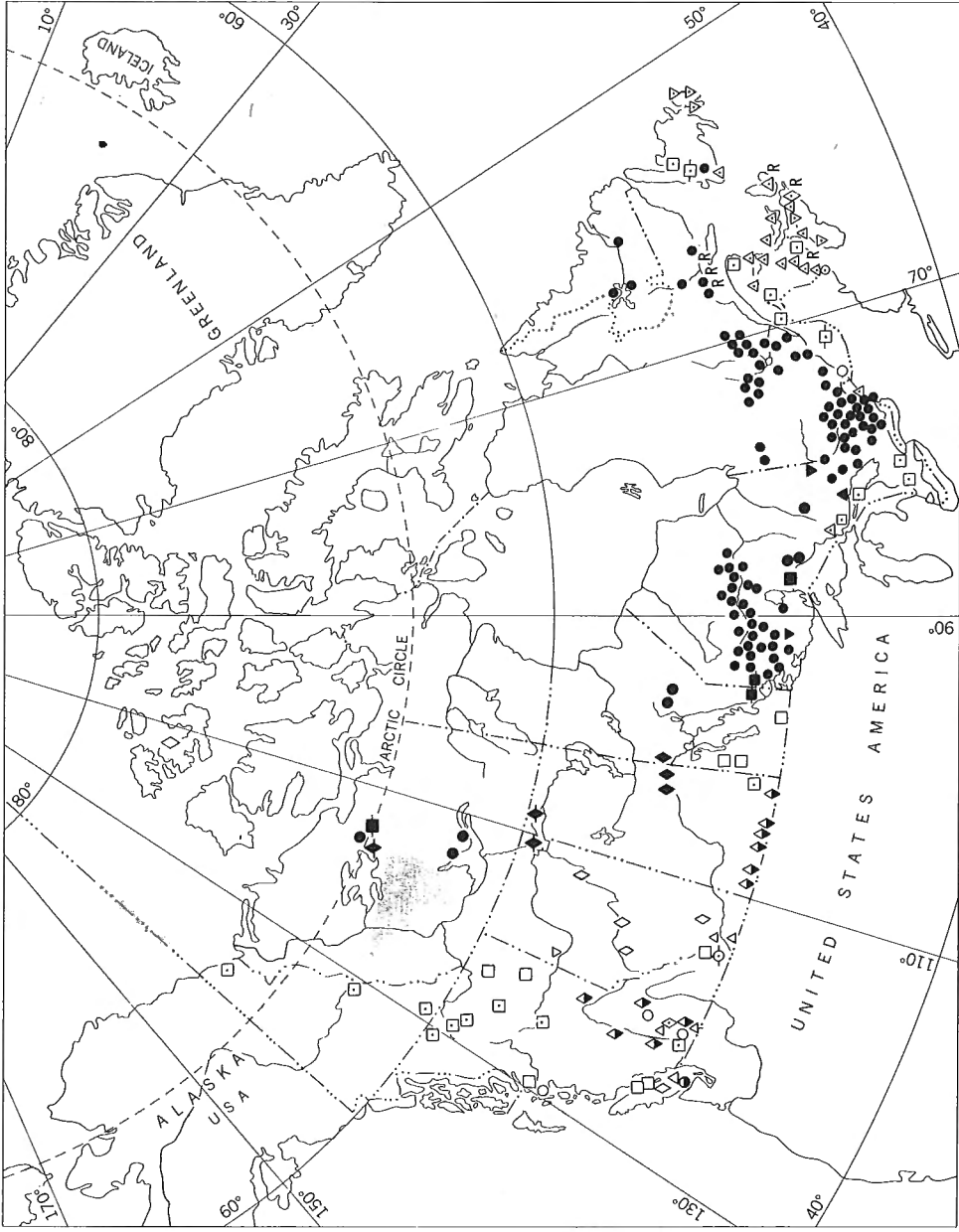
The abundance and variety of vanadium occurrences in Canada suggest that this country may possess mineable vanadium deposits, or deposits from which vanadium could be profitably recovered as a byproduct. A summary of information on vanadium occurrences in Canada is given in Table VIII (*in pocket*). Some of the known occurrences are sufficiently similar in size and grade to others being mined elsewhere, that in time, they undoubtedly could produce and perhaps become competitive. Moreover it is quite probable that higher grade deposits will be found in Canada if efforts to locate them are intensified. However, high-grade deposits of vanadium are rare, and the greatest potential of vanadium in Canada, as elsewhere, seems to lie in large-scale development of low-grade deposits, from which several metals or mineral products can be ultimately recovered, including vanadium or a vanadium compound. At the moment, sizable deposits of vanadium-bearing titaniferous magnetite at several localities across Canada and the vanadium potential of the Athabasca tar sands appear to hold the most promise.

#### Regional Assessment

The general distribution and relative size of known vanadium occurrences in Canada are indicated on Figures 3 and 12 in Table VIII. Occurrences have been found in each of the provinces and territories, but the most significant of the known deposits are those in Quebec, Alberta, and British Columbia. The greatest variety of occurrences is found in British Columbia, and the prospects for finding other significant deposits appears to be best there and in Yukon Territory. The Appalachian and Arctic regions of Canada also appear favourable for the occurrence of vanadium.

The association of vanadium with pitchblende-bearing uranium ores in the Beaverlodge area, northern Saskatchewan, and with the uranium-bearing sandstone ores of the western United States, suggests that other uranium and radioactive occurrences in Canada should be investigated for vanadium. Traces of vanadium have been noted by the writer in samples of uranium ore from Elliot Lake, Bancroft, Beaverlodge, and Great Bear Lake, as well as in an assortment of associated rocks. The amounts of vanadium and uranium are variable, and local concentrations of one or the other may occur.

Similarities in the geology and tectonic history of the western United States and western Canada suggest that uranium-vanadium sandstone ores might also be found in the sedimentary basins of the Great Plains and Cordillera of western Canada. Widespread occurrences of vanadium and uranium have been noted in the west, and the great thicknesses of uplifted sedimentary rock of Mesozoic and Cenozoic age



**LEGEND**

**VANADIUM OCCURRENCES (by age)**

- CENOZOIC**
- MESOZOIC**
- PALEOZOIC**
- PRECAMBRIAN**

**VANADIUM OCCURRENCES (by association)**

- Shale . . . . . □
- Titaniferous magnetite . . . . . ○
- Coal, bitumen, lignite, graphite . . . . . ◇
- Sandstone . . . . . △
- Iron ore . . . . . ▽
- Chromite . . . . . ◻
- Phosphate rock, apatite . . . . . ◊
- Uranium ore . . . . . ◊
- Copper ore . . . . . ◊
- Manganiferous shale . . . . . ▽
- Unconsolidated materials . . . . . R



**FIGURE 12. Types and range of ages of vanadium occurrences in Canada.**

exposed in western Canada should be expected to contain uranium-vanadium ores. To some extent this also applies to the Arctic Islands and the Appalachian region of eastern Canada. The phosphate rocks, organic shales, lignites, coal, asphaltite, and the bitumen of the vast Athabasca tar sand deposits in the west all carry persistent faint traces of vanadium. Not only does this suggest the possibility of the presence of vanadium ore material, but points up the probability of the concentration of vanadium by metamorphic and igneous processes where low-grade vanadiferous material may be involved in orogeny or subjected to igneous activity. The high-grade patronite deposit at Mina Ragra, in the South American cordillera, was probably formed in this manner.

In eastern and central Canada, numerous titaniferous magnetite deposits of Precambrian age (many of them large), have significant vanadium content in addition to iron and titanium. These deposits form a great untapped primary source of metals in Canada. They show a remarkable association with the gabbroic phases of the anorthositic intrusions of the Canadian Shield and elsewhere, as they invariably occur either within these intrusions or in the country rocks around their margins. The magnetism and high density of titaniferous magnetite occurrences make them readily detectable by magnetic and gravity methods of geophysical prospecting. Aeromagnetic and geological maps used in conjunction are particularly helpful in outlining favourable areas for investigation.

The marine oölitic hematite beds of Ordovician age at Wabana, Newfoundland, and of Silurian age at Torbrook, Nova Scotia; and the soft coal of Carboniferous age on Cape Breton, Nova Scotia; carry traces or faint traces of vanadium. The manganeseiferous, phosphatic shales of Cambrian age, the 'red bed' sequences, the organic shales and asphaltite (albertite) of Carboniferous age, all carry traces or faint traces of vanadium, and they provide good prospects to investigate for low-grade metal content, particularly in places where they are metamorphosed and involved in igneous activity. Former zones of secondary enrichment and concentrations of metals may reasonably be expected to occur within limited zones in these rocks, as they do elsewhere, although deep weathering and oxidation is not a characteristic of mineral deposits in Canada.

### Prospecting for Vanadium in Canada

Because of the diversity of vanadium occurrences and the great diversity of geology in Canada, the prospects of finding new occurrences appear to be good. The growth of the vanadium industry around the world, and the present strong demand for the element, suggest that the time is appropriate for vanadium prospecting, but the difficulty of the task should not be minimized; high-grade vanadium deposits are rare, not only in Canada, but elsewhere.

Extensions of the vanadiferous Permian Phosphoria Formation from Montana and Idaho into Alberta and British Columbia, that have been found, have not yet been of economic importance; but prospecting for this type of phosphate rock in western Canada should be encouraged. The slightly younger basic volcanic rocks and interlava sediments of Triassic age on Quadra and northern Vancouver Islands are enriched in vanadium and copper in several places, and these types of rock merit careful attention. The younger sedimentary rocks of Cretaceous and younger ages that are derived from the former by weathering and erosion, should also be investigated. Other possible

sources of vanadium, such as lignite, coal, oil, bitumen, asphalt, dark shale and sandstone, mauve shale, graphite schist, 'red beds,' laterite, oölitic hematite, ferruginous rocks, manganiferous rocks, and chromite, should not be neglected; but particular attention should be given to the possible vanadium content of titaniferous magnetite occurrences of all forms and ages in both eastern and western Canada. Substantial occurrences of titaniferous magnetite have recently been noted in coastal islands south of Prince Rupert, British Columbia, in which the vanadium content of the magnetic concentrate is more than 1 per cent. Several such occurrences are known in eastern Canada.

### Prospecting Guides

In addition to the use of geological, geophysical, geochemical, and biogeochemical methods for locating vanadium already outlined, practical pointers to prospectors searching for occurrences are: (1) bright canary yellow, greenish yellow, and orange, secondary uranium–vanadium mineral powder films and stains are indicative, but they may or may not be present, even in small amounts; (2) the bulk of sandstone-type uranium–vanadium ores resemble light to dark sandstone or greywacke on the outcrop, and may easily be passed over if not checked for radioactivity or vanadium; (3) in advanced states of oxidation, sandstone-type uranium–vanadium ores, bearing several of the vanadium oxide and hydroxide minerals, may have either the appearance of earthy red hematite, or brownish limonite, or of black to blue-black pyrolusite, and may be easily passed over as iron- or manganese-stained rocks; (4) many of these sandstone-type ores are found in dark patches in bleached (reduced) zones within thick, reddish coloured (oxidized) variegated sandstone formations; (5) many vanadium ores are associated with one or more of the elements: uranium, iron, titanium, chromium, manganese, lead, zinc, copper, carbon, and phosphorus; (6) carbonaceous material is an effective reducing agent in precipitating vanadium from metal-bearing solutions migrating through permeable rocks—for this reason bits of carbonaceous trash and organic fossil remains that may be present in a rock should be carefully examined; (7) radioactivity is generally a good guide because of the common association of uranium and vanadium, but not all vanadium occurrences are radioactive; (8) some vanadium occurrences are magnetic, some are not; (9) some vanadium occurrences are both magnetic and radioactive; (10) chemical field tests for vanadium, as previously described, provide an excellent method of detecting the element in a variety of occurrences, many of which are of nondescript appearance, and otherwise indeterminable.

### Outlook

The future of vanadium in Canada appears promising. Prospects for the discovery of vanadium ore in Canada are good. The possibility of the development of low-grade occurrences from which vanadium may be produced as a byproduct of the recovery of other elements and materials has advanced. The future of vanadium appears to be bound with iron and titanium on the one hand, and with uranium and other elements on the other.

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PLATES II TO XIII

PLATE II A  
Adits of abandoned uranium-vanadium mine in sandstone-type ore of Entrada Formation near Rifle, Colorado.



*E.R.R. 1-1-65*

PLATE II B  
Open pit (flooded) of abandoned uranium-vanadium mine in sandstone-type ore of Dakota Formation near Edgemont, South Dakota.

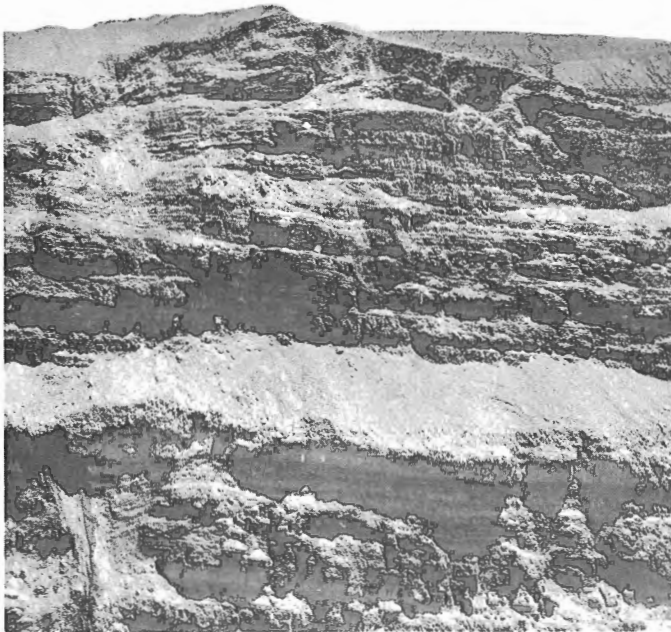


*E.R.R. 1-1-65*



*E.R.R. 1-2-65*

**PLATE III A**  
Open cut in sandstone-type uranium-  
vanadium ore near Edgemont, South  
Dakota, southwest of the Black Hills.



*E.R.R. 2-3-65*

**PLATE III B**  
Open-pit face in vanadiferous black shale  
and phosphate rock of the Permian Phos-  
phoria Formation, as exposed in the Ballard  
Mine, near Soda Springs, Idaho.



PLATE IV A  
Orange-red gossan on shale on mountain slope overlooking the headwaters of the Gataga River, and Springiron Lake, north-eastern British Columbia.



*E.R.R. 4-4-65*

PLATE IV B  
Close-up view of the heavy gossan near the base of the ridge shown above.



*E.R.R. 4-3-65*



*E.R.R. 2-10-65*

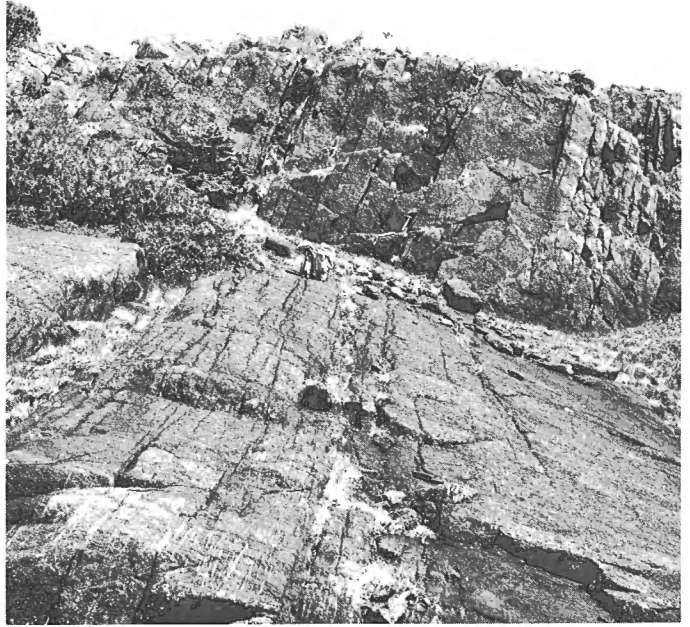
PLATE V A  
Vanadium-bearing volcanic rocks in a stripped area at the Menzies Bay, north location, being sampled by the writer (1965).



*E.R.R. 2-11-65*

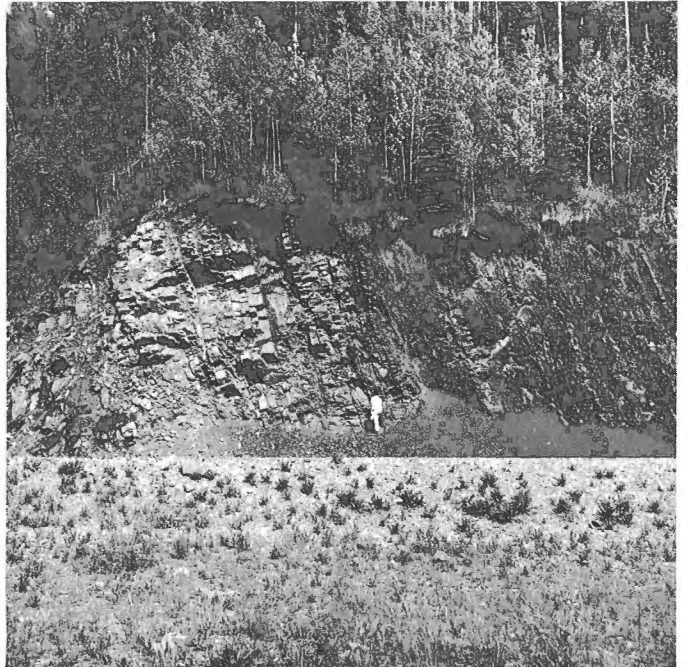
PLATE V B  
Vanadium and copper-bearing sedimentary lens, in dark shadow, intercalated between volcanic flows, at Menzies Bay, south location.

PLATE VI A  
Northerly view along strike of banded gabbro, rich in vanadium-bearing titaniferous magnetite, on Banks Island, south of Prince Rupert, British Columbia.



*E.R.R. 3-7-65*

PLATE VI B  
Northerly view of steeply dipping, vanadium-bearing, dark shale and sandstone of Cretaceous age, on Alaska Highway about 80 miles west of Fort Nelson, British Columbia.



*E.R.R. 3-9-65*



*E.R.R. 4-7-65*

**PLATE VII A**

Grey bituminous sandstone of Cretaceous age overlying chert, conglomerate, and white limestone of the Clearwater Formation of Devonian age, as exposed on the south bank of Athabasca River west of McMurray. In the middle ground the new bridge to the Great Canadian Oil Sands development 30 miles to the north; and in the background, extensive exposures of the tar sands on the east bank of the Athabasca.



*E.R.R. 3-4-63*

**PLATE VII B**

Steeply dipping, dark phosphatic shale and nodular, phosphatic limestone, in Crowsnest Pass, on the highway near Crowsnest Lake.

PLATE VIII A

Heavy, dark, vanadium-bearing iron sands of the Belly River Formation of Cretaceous age, exposed in the Bull Creek area in the foothills of the Rocky Mountains, north of Burmis, Alberta.



E.R.R. 3-2-63

PLATE VIII B

Dark lignite seam in buff-coloured siltstone, shale, and sandstone of Tertiary age, exposed in strip-mining operation at Bienfait, near Estevan, Saskatchewan.



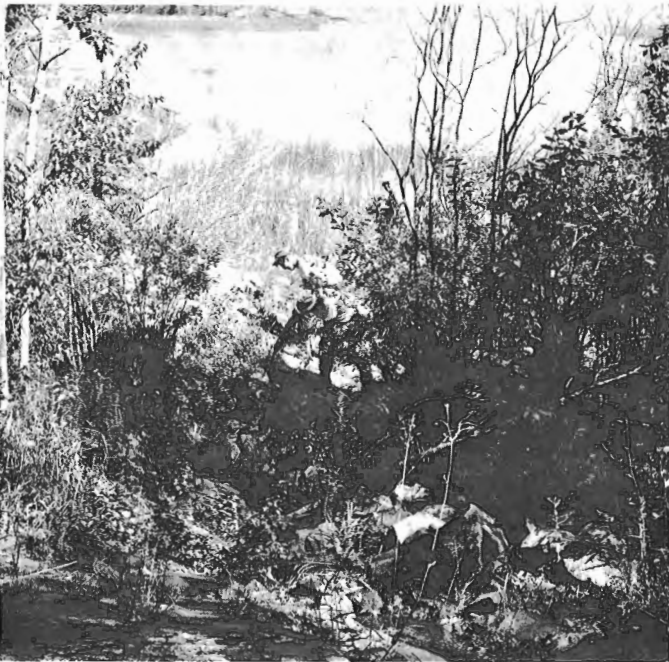
E.R.R. 2-4-63



*E.R.R. 4-4-63*

**PLATE IX A**

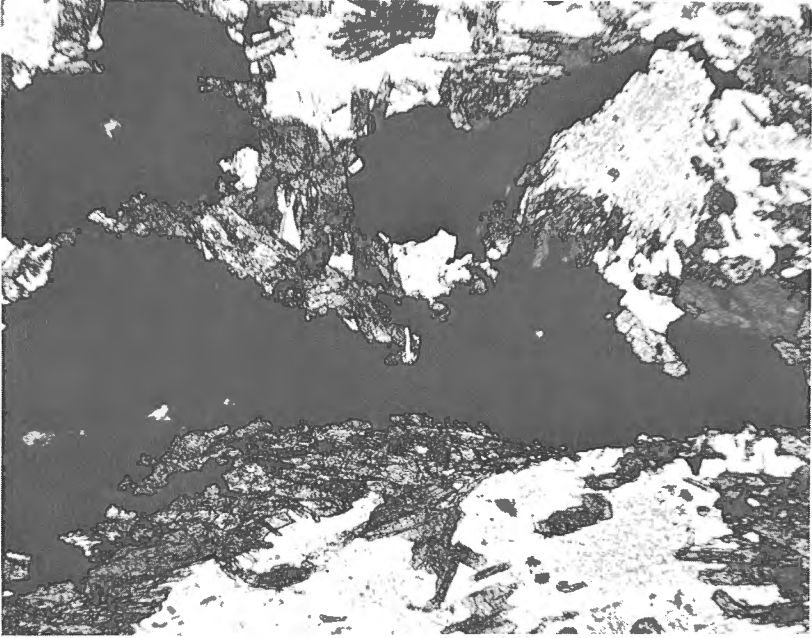
Westerly view of glaciated surface of banded gabbro, anorthosite, and gabbroic anorthosite, on the south shore of Cross (Pipestone) Lake, Nelson River, Manitoba.



*E.R.R. 4-8-63*

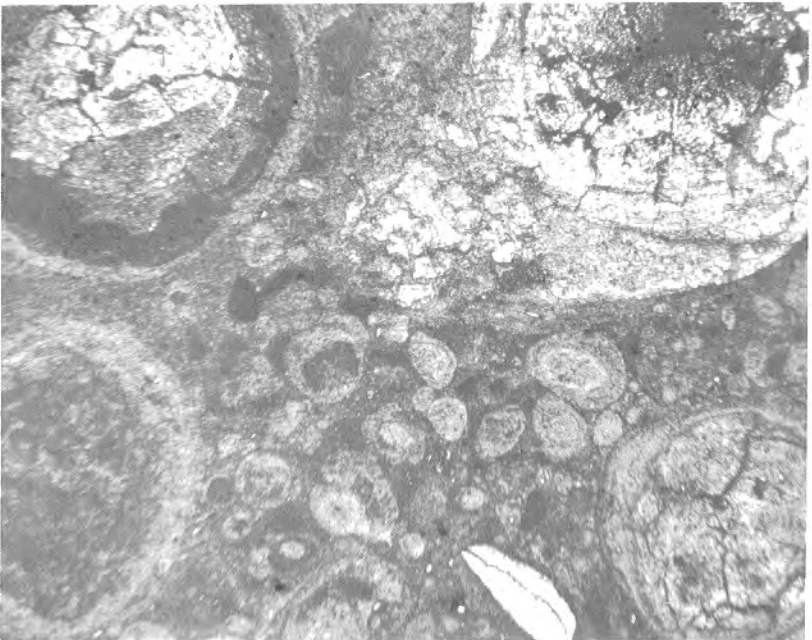
**PLATE IX B**

Northerly view of 50-foot trench in vanadium-bearing magnetite in gabbroic anorthosite of Archean age on south shore of Cross (Pipestone) Lake, across the bay from the exposure shown in Plate IX A.



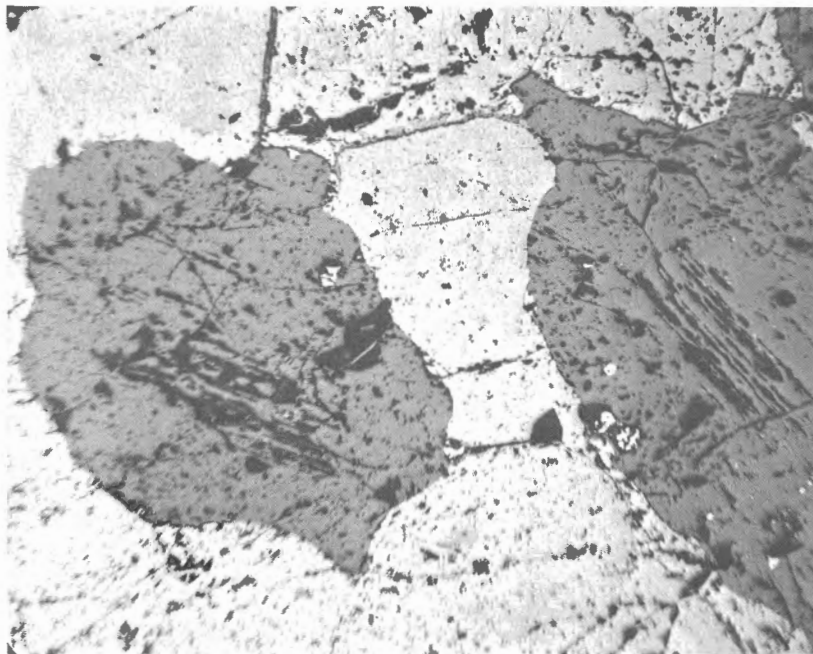
*RG-63-PIL-13 E.R.R. 201526-F*

PLATE X A. Thin-section photomicrograph of vanadium-bearing titaniferous magnetite (black) in gabbroic anorthosite from Cross (Pipestone) Lake, Manitoba, shows amphiboles (dark grey) and plagioclase (grey-white); 11 nicols, transmitted light, low power, x40.



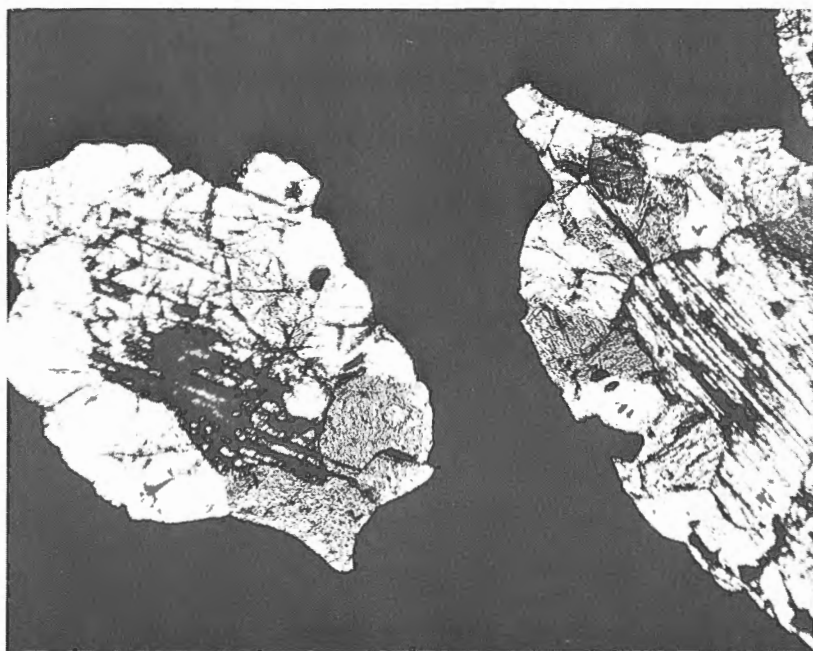
*RG-65-T27-SR E.R.R. 201526-L*

PLATE X B. Polished thin-section photomicrograph of vanadium-bearing, pisolitic, 'buckshot' iron ore from Steeprock Lake, Ontario, shows oölitic texture in hematite-goethite, and micro-oölitites within oölitites; 11 nicols, reflected light, low power, x40.



*RG-65-T23-MAT E.R.R. 201526-B*

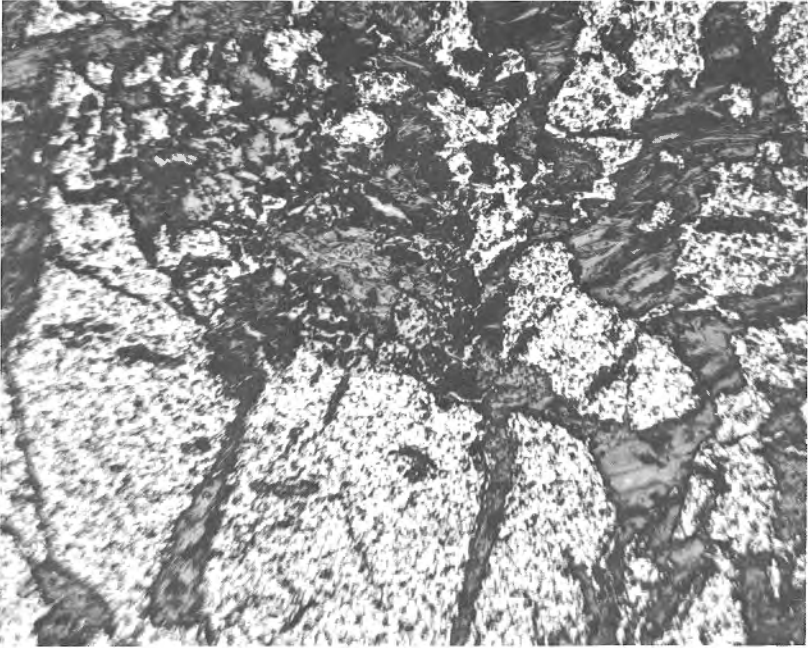
PLATE XI A. Polished thin-section photomicrograph of vanadium-bearing titaniferous magnetite (light grey) enclosing silicate gangue minerals (dark grey) from Papineau Township, south of Mattawa, Ontario; 11 nicols, reflected light, low power, x40.



*RG-65-T23-MAT E.R.R. 201526-C*

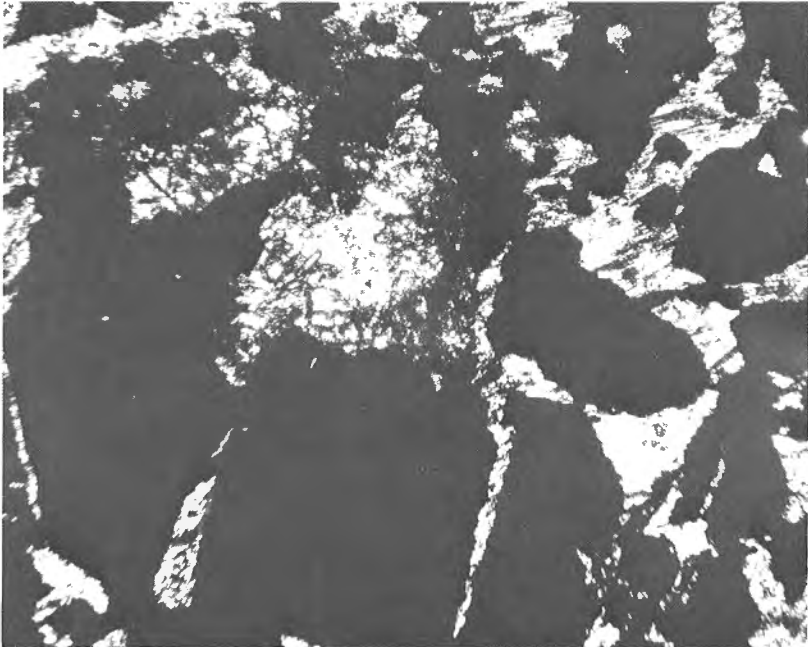
PLATE XI B. The same section as above viewed in transmitted light, shows titaniferous magnetite (black), enclosing plagioclase crystal grains (striated, grey) each with a corona of amphibole (grey-white); 11 nicols, transmitted light, low power, x40.





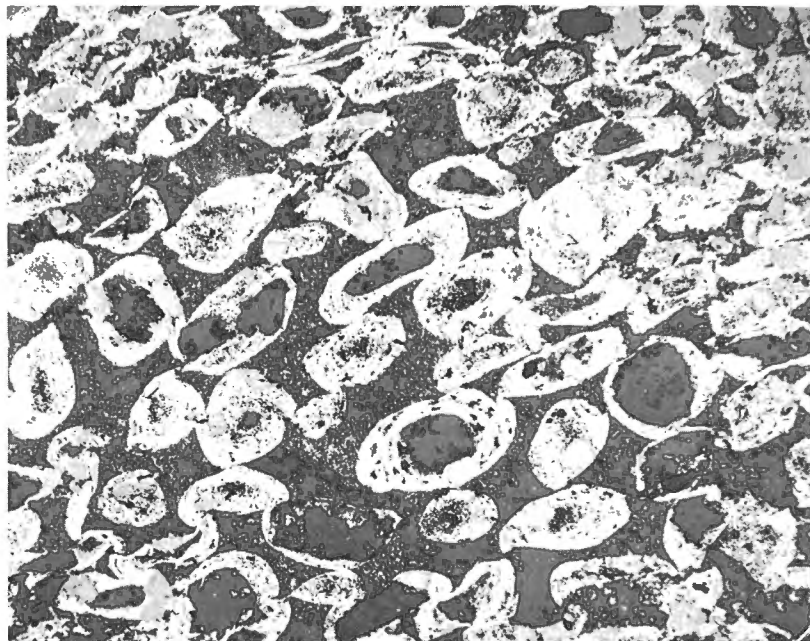
*RG-69-CH-P-1 TOP E.R.R. 201526-V*

PLATE XII A. Polished thin-section photomicrograph of vanadium-bearing titaniferous magnetite (light grey) with interstitial silicate gangue minerals (dark grey) from the Lac Doré Complex in Rinfret Township south of Chibougamau, Quebec; 11 nicols, reflected light, low power, x40.



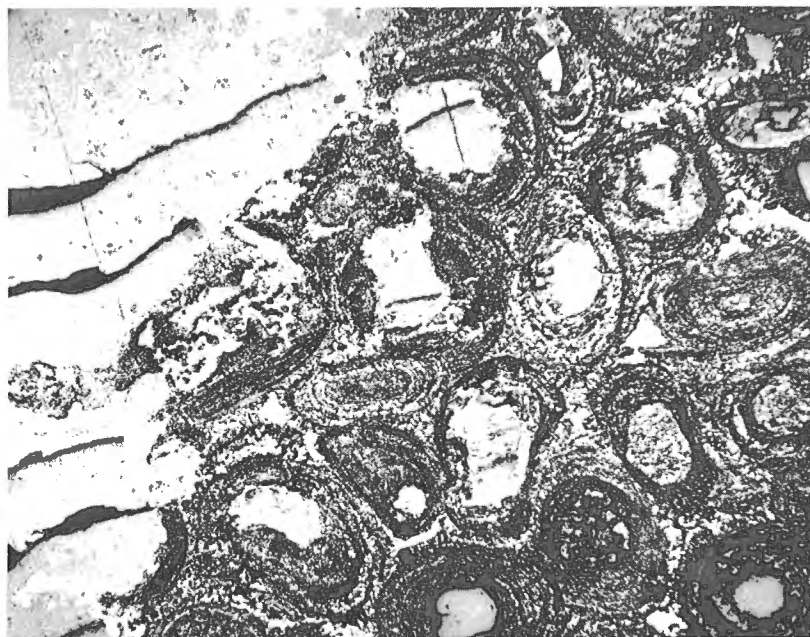
*RG-69-CH-P-1 TOP E.R.R. 201526-K*

PLATE XII B. The same section as above viewed in transmitted light shows titaniferous magnetite (black) with interstitial plagioclase (grey-white, twinned) and amphibole (grey crystals with moderate relief) in selvages; 11 nicols, transmitted light, low power, x40.



*E.R.R. RG-65-P11*

PLATE XIII A. Photomicrograph of polished surface of oölitic hematite of Silurian age from Torbrook, Nova Scotia.



*E.R.R. RG-64-3*

PLATE XIII B. Photomicrograph of polished surface of oölitic hematite of Ordovician age from Wabana Iron Mines, Bell Island, Newfoundland.



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