Mineralogy
S.K.

GEOLOGICAL
SURVEY
OF
CANADA

DEPARTMENT OF ENERGY,
MINES AND RESOURCES

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GEOLOGY OF TITANIUM
AND TITANIFEROUS DEPOSITS
OF CANADA

E. R. Rose

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PLATE 1. Aerial view southeasterly showing the Lac Tio – Lac Allard open pit ilmenite mine of Quebec Iron and Titanium Corporation. The mine is 27 miles north of the village of Havre-St-Pierre.

Quebec Iron and Titanium Corporation.

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By
E. R. Rose

DEPARTMENT OF
ENERGY, MINES AND RESOURCES
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PREFACE

Titanium is a potential mineral resource that is plentiful but as yet almost undeveloped in Canada. This report provides abundant information on the ores of titanium, their distribution, and the environments in which they occur, based on the extensive geological, geochemical, and geophysical evidence collected by the author from his field work during recent years, and from an intensive study of the literature on titanium that covers the work of many individuals and organizations during the past century.

Chapters I to IV deal with the geology, mineralogy, and technology of titanium. Chapters V and VI contain descriptions of the many titanium occurrences throughout Canada and an account of the titanium resources in the rest of the world. Chapter VII presents generalizations on the Canadian titanium occurrences and a brief statement on the economic outlook of Canada's extensive low-grade deposits from which both titanium and iron may be recovered.

Y. O. FORTIER,
Director, Geological Survey of Canada

OTTAWA, May 31, 1965

WIRTSCHAFTSGEOLOGISCHER BERICHT Nr.
25 — Die Geologie des Titans und der titan-
haltigen Lagerstätten in Kanada

Von Edward R. Rose

Dieser Bericht gibt Auskunft über die Titanerze, ihre
Verbreitung und die Umwelt, in der sie vorkommen. Er
gründet sich auf umfangreiches geologisches, geochemisches
und geophysikalisches Material, das der Verfasser in den
letzten Jahren bei seiner Arbeit im Gelände gesammelt
hat, und auf ein gründliches Studium der vorhandenen
Literatur.

ДОКЛАД ОБ ЭКОНОМИЧЕСКОЙ ГЕОЛОГИИ
Ч. 25 — Геология титана и титаносодержа-
щих месторождений в Канаде.

Эдуард Р. Роз

В этом докладе даются сведения о рудах титана, их
распределении и об окружающих их среде на основании
численного материала по геологии, геохимии и геофизике,
собранного автором во время своих полевых работ за по-
следние годы, а также на основании изучения большого
количества работ других ученых.

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GEOLOGY OF TITANIUM AND TITANIFEROUS DEPOSITS OF CANADA

Abstract

This report describes the nature of occurrence of the titanium and titaniferous deposits of Canada in general and in detail, outlines their distribution, classification, origin, age, size, and grade, and points out the close genetic relationship existing between them and anorthositic rocks. Most of the titanium deposits occur in both massive and disseminated form throughout large, composite, multiple, intrusive anorthositic bodies in eastern Canada. Anorthosite and gabbroic anorthosite or gabbro (troctolitic and noritic) are the two most common and closely related phases of these intrusive bodies, but in places monzonite, syenite, granite, and pegmatite may also be distantly related.

The main ore minerals—ferrian ilmenite, titanomagnetite, and titanhematite—occur most abundantly in the gabbroic phases of the anorthosites, but they are also found in the anorthosites proper, and less commonly in the country rocks into which the anorthositic massifs are intruded. These minerals commonly show exsolution textures characteristic of deposits formed at magmatic temperatures, and they may possess self-reversing magnetic mechanisms and hard components of remanent magnetism capable of affecting the direction and intensity of the resulting magnetic fields. The report includes a discussion of the advantages and limitations of magnetic surveys in locating titanium deposits, and suggestions for applying the study of remanent magnetism of occurrences as an aid to geological interpretation.

Because of their heavy magnetic character, the iron–titanium ore minerals are readily separated magnetically from their host-rock silicates, and although many of the deposits are of low grade in both iron and titanium they may be readily concentrated. Furthermore, although many of the deposits are too high in titanium to be iron ores (or too high in iron to be titanium ores at present) and the iron and titanium minerals are practically inseparable, some of the deposits consist of iron–titanium mineral intergrowths of such nature that it is possible to separate them magnetically into high iron (titanomagnetite) and high titanium (ilmenite–hematite) concentrates, potential ores of iron and titanium, respectively.

Résumé

Dans le présent rapport, l'auteur décrit de façon générale et détaillée la nature des gisements de titane et titanifères au Canada; il en esquisse la répartition, la classification, l'origine, l'âge, les dimensions, et la teneur, et il souligne leur parenté étroite avec les roches anorthositiques. La plupart des gisements de titane se retrouvent à la fois sous forme massive et disséminée à

travers de vastes massifs anorthositiques intrusifs, complexes, multiples, dans l'Est du Canada. L'anorthosite et l'anorthosite à gabbro ou gabbro (troctolite et norite) sont les deux phases les plus communes et les plus étroitement apparentées dans ces massifs intrusifs, mais, par endroits, la monzonite, la syénite, le granite et la pegmatite peuvent aussi être apparentés de loin.

Les principaux minerais (ilménite ferrifère, titanomagnétite, et hématite titanifère) abondent plus particulièrement dans les phases à gabbro des anorthosites, mais ils se trouvent aussi dans les anorthosites mêmes, et moins souvent dans les roches encaissantes dans lesquelles les massifs d'anorthosite ont pénétré par intrusion. Ces minéraux sont assez souvent d'une texture propre aux solutions solides d'insertion caractéristique des gisements formés à des températures magmatiques. Ils peuvent mettre en jeu des mécanismes d'auto-inversion magnétique et des composantes dures de magnétisme rémanent capables d'influer sur la direction et l'intensité des champs magnétiques qui en résultent. L'auteur examine aussi les avantages et les limitations des levés magnétiques dans la prospection de gisements de titane, et fait des recommandations sur l'application de l'étude du magnétisme rémanent des massifs pour faciliter l'interprétation géologique.

À cause de leur forte densité et de leur caractère magnétique, les minerais de fer–titane sont facilement isolés par magnétisme des silicates encaissants, et bien que plusieurs de ces gisements soient à faible teneur à la fois de fer et de titane, les minerais peuvent être facilement concentrés. De plus, bien que de nombreux gisements soient trop riches en titane pour être du minerai de fer (ou trop riches en fer pour être considérés présentement comme du minerai de titane) et que les minéraux ferrifères et titanifères soient pratiquement inséparables, certains des gisements sont composés de tels enchevêtrements de minéraux de fer et de titane qu'il est possible de les séparer par magnétisme en des concentrés à forte teneur en fer (titanomagnétite) et en d'autres à forte teneur de titane (ilménite et hématite), respectivement minerais possibles de fer et de titane.

Chapter I

INTRODUCTION

Canada is abundantly supplied with titaniferous deposits, particularly in the provinces of Quebec, Newfoundland, and Ontario, but with a few exceptions little serious attempt has yet been made to extract titanium and iron from them on a commercial scale. Despite its considerable potential as a metal, titanium has no-where in the world been used on a scale commensurate with its abundance and out-standing properties. One of the greatest obstacles preventing widespread increase in titanium production arises from misunderstanding of the nature of titaniferous deposits. Another comes from conflicts with the iron and steel industry, which generally regards titanium as a deleterious ingredient in iron ores and effectively restricts the smelting of ores carrying more than a trace (0.1 per cent) of titanium.

Scope

This report describes the geology of the titaniferous deposits of Canada, outlines their distribution (*see* Map 1238A, *in pocket*), indicates areas and geological conditions favourable for additional occurrences, and stresses the close relationship between titaniferous deposits and anorthositic rocks. It reviews in detail the use of aeromagnetic data in interpreting structural relationships and evaluating the possibility of economic titanium deposits associated with anorthositic rocks. The author's studies have indicated that the determination of the direction and nature of the remanent magnetization of ore materials and host rocks may be of considerable assistance in the interpretation of the magnetic anomalies associated with them. Microscopic studies of thin and polished sections of the ore materials and host rocks are of fundamental importance in the study of these occurrences and are an effective means of anticipating the best methods of beneficiation and utilization of the ore materials.

Field Work

The project was begun in 1958 as a study of the nature of occurrence and distribution of iron and titanium in the Morin anorthosite north of Montreal (Rose, 1960). It was subsequently extended to include the St-Urbain anorthosite area north of Baie-St-Paul (Rose, 1961), and in 1960 and 1961 to various other areas of anorthosite in Ontario (Seine Bay – Bad Vermilion Lake), Quebec (Lac St-Jean, Sept-Îles, Lac Allard, Magpie Mountain), and Newfoundland (Steel

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Mountain, Indian Head). Field work was completed in 1961. The report was written during the winter of 1961–62. Because of the great extent of the anorthosite masses and the widespread distribution and large number of iron–titanium mineral occurrences found within them, the author's areal coverage was necessarily limited; without the use of geological and aeromagnetic maps the task could not have been accomplished. Detailed attention was given mainly to iron–titanium mineral and ore deposits where new information, fresh exposures, and drill-cores were available, as at Ivry and Lac du Pin-Rouge in the Morin anorthosite, the Bignell and other deposits at St-Urbain, and the Lac Tio and Magpie deposits northeast of Sept-Îles. The geology of outstanding aeromagnetic anomalies was checked where possible on the ground (Figs. 2, 4, and 7, *in pocket*), and detailed plane-table maps were prepared where warranted (Figs. 5 (*in pocket*), 3, 9, and 10). Representative samples were collected for laboratory tests, microscope study, analyses, age determinations, and for Geological Survey collections. Dip-needle readings were made over all areas to check against geological and aeromagnetic data, and suites of oriented specimens were taken for studies of remanent magnetism. Direct field observation was supplemented by interpretation of aeromagnetic maps and dip-needle readings.

Previous Work

So many studies of titanium-bearing anorthositic rocks in Canada have been made during the past century that it is not possible to give proper recognition to all previous workers in this field. The first scientific studies of anorthosites and titaniferous deposits in Canada were made by Logan and Hunt in the 1850's, later notably by F. D. Adams at the turn of the century, and by Dulieux in the 1910's. Adams' work has been augmented considerably by that of F. F. Osborne (1928) who contributed important theories on the origin of ilmenite deposits.

Many other scientists have added information from local areas, among whom must be mentioned: H. G. Vennor (1872), R. W. Ells (1889), M. J. Obalski (1890), E. D. Ingall (1899), B. F. Haanel (1909), Charles H. Warren (1912), A. H. A. Robinson (1922), J. B. Mawdsley (1927), Joseph L. Gillson (1932), E. P. Wheeler 2nd (1935), P. E. Bourret (1935), Joseph Retty (1942), Carl Faessler (1942), David M. Baird (1943), James M. Harrison (1944), G. W. Waddington (1944), Weston Bourret (1949), LeRoy Scharon (1950), Paul Hammond (1952), D. Karpoff (1953), Louis Moyd (1955), Marcel Morin (1956), E. O. Dearden (1958), René F. Jooste (1958), Robert B. Hargraves (1959), C. M. Carmichael (1959), J. R. Mowat (1960), R. A. Blais (1960), E. H. Kranck (1961), W. E. Hale (1962), C. K. Bell (1962), R. F. Emslie (1963) and I. M. Stevenson (1966). The work on titanium by personnel in the Canadian Mines Branch has been outstanding; it covers several decades and various aspects ranging through concentration and beneficiation of ore materials, mineralogical research, metallurgy, and fabrication. A number of publications dealing mainly with production of titanium have been issued during the past

decade by W. K. Buck, T. H. Janes, and V. B. Schneider, all of the Mineral Resources Branch, Department of Mines and Technical Surveys (now Department of Energy, Mines and Resources).

As early as 1874 a small batch of good quality iron had been produced at St-Urbain using ore from the Furnace deposit and wood charcoal as fuel. Titanium was lost in the slag, costs were high, and the operation soon closed. It was not until much later, however, that the deleterious effects of titanium in iron ore were recognized and discounts placed against titaniferous ores.

Canadian research on titanium was begun more than 40 years later. In 1921 W. M. Goodwin developed for the Research Council of Canada a process to smelt titaniferous ores and simultaneously recover most of the vanadium in the ore in the resulting pig iron. A pilot plant was built at Belleville and several titaniferous ores were successfully smelted there in an electric furnace, but although a good recovery of high-quality vanadium-bearing pig iron was produced, the process was never developed commercially. In 1955, however, Quebec Iron and Titanium Company Limited began the production of titanium oxide-rich slag and pig iron by-product by the electro-smelting of ilmenite–hematite ore from Lac Tio, Quebec, and a new era in the processing of Canadian titanium ores was begun.

Acknowledgments

and to Le Séminaire de Québec for general provision of their scientific reports and for data for use and publication by the Geological Survey of Canada.

Grateful acknowledgment is also made of the help of H. L. Lovell and the late George F. Rose who assisted the writer at various times during the summers of 1958 and 1959, and to many others whose assistance and kind help were so freely given from time to time in the field. On occasion the writer was given valuable assistance by Professor D. M. Baird of the University of Ottawa in locating the Hayes deposit in western Newfoundland, by R. F. Black and G. N. Freda of the Palaeomagnetic Section of the Geological Survey in reaching and sampling the Bishop North and Bishop South deposits also in western Newfoundland, by G. H. R. Gauthier and J. Turpin of the Mineralogy Section of the Geological Survey in reaching and sampling the Brazeau-Woods occurrence in Ontario, and by C. K. Bell in reaching and examining the Cross Lake (Pipestone Lake) occurrence in Manitoba. D. K. Norris provided samples of the Burmis and Dungarvan occurrences in southwestern Alberta, and G. A. Gross provided information on an occurrence near Roberval, Quebec.

Throughout the project the writer was generously supported by the efforts of colleagues in various laboratories of the Geological Survey, particularly in the fields of rock magnetism, X-ray diffraction, X-ray fluorescence, and spectrographic and chemical analyses.

Full recognition must be given to the work of the Quebec Department of Mines covering many years and many areas of investigation in this field. Through this work a broad and in many places detailed knowledge of the anorthositic rocks and titaniferous deposits in Quebec has been accumulated and published in numerous reports. J. I. McGerrigle, then assigned by the Quebec Department of Mines to survey titaniferous occurrences in Quebec, visited Ottawa in 1959 and very kindly supplied the writer with a copy of lists summarizing his available information on Quebec occurrences and on currently producing properties there. This was most thoughtful as well as very helpful and is accordingly gratefully acknowledged.

Finally, various sections of the report have had the benefit of critical scrutiny by several colleagues of the Geological Survey and by officers of various companies controlling the deposits described.

Terminology

Throughout this report the author has endeavoured to restrict the use of technical terms in order that it may not be unduly abstruse. Persons concerned with more precise scientific definition and classification are referred to the extensive bibliography.

The term *anorthosite,* as used in this report, is used to represent an igneous rock composed of 90 per cent or more of plagioclase feldspar. The plagioclase is commonly of labradorite or andesine composition, and pyroxene and ilmenite are common accessory minerals. In the occurrences in eastern Canada, in situ

anorthosite was commonly found to grade into gabbroic anorthosite by increasing content of dark minerals, pyroxene, hornblende, olivine, spinel, ilmenite, and titanomagnetite. Both ortho- and clino-pyroxenes, and more rarely also olivine, are commonly present in gabbroic anorthosite. When orthopyroxene is more abundant than clinopyroxene in a gabbroic rock the rock is called norite. Thus a gabbroic anorthosite may be called noritic anorthosite or norite depending upon the relative abundance of the two types of pyroxenes present, and may grade into anorthositic gabbro, gabbro, or diorite if the calcium content of the plagioclase falls below that of labradorite. For convenience of description and for the reasons given above, however, only the terms anorthosite and gabbroic anorthosite are frequently used in this report.

Similarly, the term *ilmenite* is used to refer both to the true mineral ilmenite composed essentially of iron, titanium, and oxygen as represented by the chemical formula $FeTiO_3$, and to a material that is actually a microscopic intergrowth of hematite (iron oxide or Fe_2O_3) lenticles in ilmenite (*see* Pl. VII A). In the environment of anorthositic and gabbroic rocks microscopic intergrowths of hematite are rarely absent from ilmenite, but they are commonly visible only under the microscope and may be of relatively small proportion. Thus the field term ilmenite is ordinarily applied to apparently homogeneous material in which hematite is, however, actually intergrown with ilmenite on a microscopic scale. In the intergrowths neither host nor guest are commonly pure species, but may be respectively iron-rich (ferrian) or titanium-rich (titanian) varieties of the two minerals.

Titaniferous magnetite is used as a general term referring to material carrying a high proportion of iron and titanium with iron predominating. It is commonly in the form of titanium-bearing magnetite, titanomagnetite (also called titanmagnetite), ilmenite, ilmenite–hematite, and other iron–titanium oxide minerals and intergrowths (*see* Pl. VIII A and B).

Ilmenite–hematite or hemo-ilmenite (or haemoilmenite) refers to an intergrowth of hematite in ilmenite (Pl. VII A). *Magnetite–ilmenite* refers to an intergrowth of ilmenite in magnetite (Pl. VIII B).

It appears possible that there may be a more or less complete iron–titanium oxide oxy-solid–solution mineral series between magnetite and ilmenite, of which ulvöspinel and pseudobrookite are intermediate members. Further research is required on this probable mineral series, but this is the meaning implied where the writer refers generally to members of an iron–titanium oxide series or other iron–titanium oxide minerals.

Chapter II

TITANIUM AND ITS ORES: TECHNOLOGY, PROBLEMS, AND POTENTIAL

History

The element titanium was discovered late in the eighteenth century, less than 200 years ago, as the result of independent investigations in England and in Germany. As reported by Robinson (1922) the Rev. Wm. Gregor (or McGregor), a Scottish scientist, investigating the occurrence of a black sand at Menachan in Cornwall about 1790 named it menachanite (menaccanite) and the new element it contained, menachite. In 1794 or 1795 Klaproth, a German chemist, while investigating the composition of a mineral from Boinik called "Hungarian red schorl" (now known as rutile) anticipated in it a new metal which he called "titanium" after the Titans of Greek mythology because of the great strength of the chemical combination in which it was held. Subsequently in 1797 Klaproth investigated the mineral ilmenite, named from the Ilmen Mountains of the Urals near Miask in Russia, and recognized that his titanium was the same as the menachite of Gregor.

Many attempts were made to isolate and describe the new metal, notably by Lampadius in 1797 and by Berzelius in 1825, but because of its high fusion point and its strong affinity for nitrogen, carbon, and oxygen the resulting products were far from pure titanium. In 1895 Moissan fused carbon with an excess of titanium dioxide in an electric furnace and obtained a product free of nitrogen and silicon but containing 2 per cent carbon and some oxygen, and it was not until later that pure metal seems to have been obtained by heating a tungsten filament in a vapour of titanium iodide. About 1910 Hunter succeeded in producing relatively pure titanium by an earlier method of Nilson and Peterson which consisted of reducing titanium tetrachloride ($TiCl_4$) by sodium in an airtight steel cylinder. This process, thereafter the standard laboratory method of producing metallic titanium, was modified by Kroll in 1946, using magnesium as the reducing agent, in United States Bureau of Mines pilot plant tests. This process was subsequently adapted for industrial production of sponge titanium in 1948 by E. I. du Pont de Nemours and Company. In 1957 Mallory-Sharon, Metals Corporation, announced a cost-lowering liquid sodium method of reducing and producing sponge titanium. The liquid sodium and magnesium reducing methods are now the leading commercial procedures used to produce sponge titanium in the United States.

Properties and Uses of Titanium[1]

Fused metallic titanium appears much like polished steel and is harder than quartz. It is slightly brittle when cold but is malleable at low red heat and may be readily forged like red-hot iron. It combines with oxygen with incandescence at a temperature of 610°C and burns brilliantly in air at a temperature of 1,200°C. On heating it combines with the halogens (chlorine, fluorine, bromine, and iodine) and with oxygen with incandescence to form halogen salts and oxides, and with sulphur and carbon to form sulphides and carbide. It combines with nitrogen avidly and is unique in that it also burns in nitrogen with incandescence at 800°C to form nitrates.

Titanium metal has a high resistance to salt water and other corrosive agencies comparable to or better than that of stainless steel. Its high strength, low weight, and excellent corrosion resistance appear to adapt it for major use in ship, aircraft, automobile, and bridge building, provided the price of production can be lowered sufficiently to allow it to compete economically with other metals and alloys now being used. Table I permits comparison of some of the physical properties of titanium, cast iron, steel, and aluminum. The contrasts in specific gravity, melting point, and tensile strength are illustrated.

TABLE I | *Table of Physical Properties*[1]

	Titanium	Cast iron	Steel	Aluminum
Atomic weight	47.90			26.97
Specific gravity (at 20°C)	4.54	7.87	7.7–7.9	2.72
(at 875°C)	4.31			
Melting point	1,668°–1,800°C	1,175.5°C	1,514°C	660°C
Boiling point	2,800°C	2,740°C		2,060°C
Hardness	Rockwell	Brinell	Brinell	Brinell
	60	180	130–205	23–44
Tensile strength (1,000 psi)	126	25	60–104	13–24

[1]From The General Engineering Co. (Canada) Limited, Facts and Figures (1947), Barksdale (1949), Kinsey (1953), and Hampel (1961).

Limited amounts of titanium are now being used by steel industries in the form of ferrotitanium or ferrocarbontitanium as efficient deoxidizers, grain refiners, and alloying elements in steel. It is used as an alloy in the manufacture of the austinitic 18-8 chromium-nickel stainless steels that are not heat treated after welding, and in the casting and conversion of certain pig iron to which a steely quality is imparted.

[1] Data in this section have been taken largely from Barksdale (1949), U.S. Bureau of Mines mineral reports on titanium (1956–1961), Canadian Mineral Resources Division Information Circulars, and from Engineering and Mining Journal Bulletins (1960–1963).

The ferrotitanium alloy industry was anticipated by Robert Mushet in England and was later developed largely by the efforts of Auguste J. Rossi, a French metallurgist who established the Titanium Alloy Manufacturing Company in Niagara Falls, New York, in the 1890's. In 1861 Mushet failed to convince the steelmakers of his day of the value of his titanic steel, but Rossi was more successful in America. The first extensive use of ferrotitanium by the Maryland Steel Works came in 1907. By 1918 its use by the steel industry mainly in the purifying of Bessemer steel had increased to the point where about 2,400,000 tons of steel was treated with ferrotitanium alloys that year in the United States. With the development of the open-hearth process this practice was dropped, but the number of applications and uses by the iron and steel industry have increased and a considerable tonnage of steel is still treated with titanium alloys each year in the United States.

Titanium may also be alloyed with aluminum or used directly or as the base alloy for rotors in jet turbines. Cuprotitanium salts are used as reducing agents and mordants in fabric and textile dyeing. There may be new uses for titanium in the petroleum industry for piping high-sulphur crudes, and elsewhere for a host of other products such as salt-water piping systems, pumps, propellers, autoclaves, anodizing racks, anode hooks, filter presses, heat exchanger tubes, lithographic plates, and rocket skins. In 1960 a major development in technique of welding titanium to steel was reported (Engineering and Mining Journal Bull., 1960). An announcement in 1961 suggested that titanium might find increasing military use in infantry weapons to greatly reduce their weight, thus increasing their manoeuvrability and scope. A new stainless steel containing 11 per cent chrome and a lesser amount of titanium is being tested by Ford Motor Company to increase muffler life on its automobiles. A new ferrotitanium alloy containing 70 per cent titanium and 30 per cent iron has been developed for melting high-temperature steel alloys. The addition of titanium, in the form of an alloy with aluminum and boron, to molten aluminum casting alloys is reported to result in refined grain structure and improved qualities (E. & M.J. Bull., 1962). A new alloy of nickel and titanium, named nitinol, is hard, non-magnetic, can be machined, and is reported to have other properties varying with composition that may be of use in missiles and space craft (E. & M.J. Bull., 1962). A new titanium–palladium alloy with as little as 0.1 per cent palladium is said to extend the corrosion resistance of titanium to reducing media (E. & M.J. Bull., 1961). A titanium–beryllium alloy has been singled out as a good material for brazing beryllium to itself for space program use (The Iron Age, 1963 *quoted in* The Northern Miner, Dec. 1963). In 1963 its use in commercial jet aircraft was increased, and in 1964 its importance in making the United States' new supersonic jet fighter plane A11 was announced by President L. B. Johnson.

Various compounds of titanium also have important commercial uses. The most important of these at present is titanium oxide produced mainly from ilmenite ore as a slag; it is used by the paint, rubber, rayon, plastics, paper, and cosmetic industries. Most of the titanium oxide slag is refined to produce titanium white, a non-toxic, sparkling white paint with very good covering qualities. Pure titanium

oxide is recrystallized under controlled conditions to produce an attractive artificial gem stone of very high dispersion called titania. Either rutile or manufactured TiO_2 is used in ceramics and in colouring pottery glazes, floor tiles, and dinnerware. Fiberglass is made by adding rutile to molten glass in the furnace. Titanium oxide in the form of mineral rutile is used in the manufacture of rods for electric welding and as a source of titanium for various chemical uses. More than 95 per cent of the titanium ore currently being mined goes into the production of TiO_2.

Titanium carbide is harder than carborundum and a new group of cemented carbides using titanium as a base appears to extend the range of usefulness of this group of materials for high temperature–pressure applications such as turbine impellers designed to function at 1,100°C, and pressure reaction vessels designed to withstand pressures of 15 tons per square inch at 1,200°C.

Titanium-bearing pig iron may be produced directly from titaniferous iron ore, but usually most of the titanium in such ores goes into the slag. It is interesting to note that titanium was found in samples of ancient cast iron from China, more than 1,000 years old.

Titanium Ores and Their Beneficiation

Although the main ore minerals of titanium at present are ilmenite and rutile, titanium may also be recovered from titaniferous magnetite, that is, from mixtures of titanomagnetite, ilmenite–hematite, and intermediate solid–solution series minerals. Rutile contains a higher proportion of titanium by weight than does ilmenite, but it is far less abundant than either ilmenite or titaniferous magnetite. Certain other titanium-rich minerals such as sphene (titanite), perovskite, leucoxene, columbite–tantalite (lyndochite), davidite, and brannerite might be considered as possible sources of titanium, but with the exception of perovskite and sphene these minerals do not compare favourably either in abundance or titanium content with ilmenite or rutile, and they are not as abundant as titaniferous magnetite. Certain bauxite and laterite deposits may contain as much as 8 per cent or more of titanium and this might possibly be recovered as a by-product of the aluminum industry of the future as has been done already in Germany (Planner, 1942).

Beach Sands

Heavy minerals may be recovered from beach sands, starting with gravity separation on Humphreys spirals, from which an 80 to 90 per cent heavy mineral concentrate is obtained. This concentrate is then dried and passed over electrostatic and magnetic separators in which magnetite, hematite, ilmenite, and rutile are concentrated electrostatically because of their good electrical conductivity, and then separated magnetically because of differences in magnetic susceptibility. The titanium oxide content of ilmenite in beach sands may be high because of leaching of iron during weathering, and the final products of beneficiation of beach sands are commonly unusually high in titanium. The ilmenite concentrate from a plant

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at Trail Ridge, Florida, operating on local beach sands, is reported to contain 63 per cent titanium oxide and a non-magnetic fraction consisting largely of leucoxene as much as 80 per cent TiO_2 (Elliot, 1959).

Ilmenite Ores

Many ilmenite ores are microintergrowths of hematite in ilmenite on such a fine scale that it is not possible to separate them mechanically. The intergrowth ore minerals, however, can be more or less separated from the gangue silicates by means of gravity and magnetic processes. Sulphur in the form of pyrite, chalcopyrite, pyrrhotite, and other sulphide minerals can be removed or reduced by magnetic separation, flotation, and sintering. Phosphorus in the form of apatite is also commonly reduced or eliminated by magnetic separation. Low-intensity followed by high-intensity magnetic separation appears to give the best results of any of these methods for most ilmenite-bearing ores.

Rutile Ores

As in beach sands, rutile can be separated from ilmenite in lode deposits (after crushing and grinding) by gravity methods followed by electrostatic and high-intensity magnetic methods, as rutile has a much lower magnetic susceptibility than ilmenite or ilmenite–hematite intergrowths.

Titaniferous Magnetite

Titanian magnetite, titanomagnetite, ilmenite, ilmenite–hematite, magnetite–ilmenite intergrowths, and intermediate members of a solid–solution series of iron–titanium oxide minerals form a group of ore materials known as titaniferous magnetite commonly disseminated through a gabbroic host rock. They may present difficulty in concentration or removal of titanium. They are generally recognized as being objectionably high in titanium for iron ores, and too low in titanium to be ores of that metal. Actually titaniferous magnetite is a potential ore of both iron and titanium and eventually will probably become an important producer. These ore materials cover a wide range of composition, but may be considered arbitrarily to range from 1 to 15 per cent titanium. They probably grade below this content of 1 per cent titanium into low titanium magnetites and above 15 per cent titanium into ilmenite–hematite deposits. But in this grade range they may be concentrated, after crushing and grinding, by gravity, electrostatic, and high-intensity magnetic processes in a manner similar to that described for beach sands. In this way concentrates of the various potential ore minerals present, such as titanian magnetite, ilmenite–hematite, and possibly rutile and apatite, may be recovered. The proportions of the various minerals will, of course, largely control the relative amounts recoverable and determine the best ore usage and beneficiation process. In many of these titaniferous magnetites, titanium averages about 6 to 8 per cent, and the titanium content of the magnetic concentrate from many of these materials may be reduced to less than 2 per cent, in a few instances to less than 0.2 per cent titanium. In some samples the intergrowth of ilmenite and magnetite

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is so fine grained and intimate that mechanical separation and concentration of the individual ore minerals is not possible. The use of iron ores containing more than 0.1 per cent titanium is restricted because of modern blast furnace practice in North America, and it appears that all types of titaniferous magnetites are now restricted from development as iron ores. One such North American deposit is, however, being mined by the National Lead Company at Tahawus in New York State's Adirondack Mountains and from it ilmenite is being recovered for pigment use, and magnetite as a by-product iron ore. Thus combined recovery of two or more elements from this type of ore material under certain circumstances does appear to be economically feasible, and this lends incentive to the testing of other deposits with multiple recovery in view. In this connection the common association of small amounts of other valuable elements such as vanadium, chromium, manganese, cobalt, and nickel should not be overlooked.

Metallurgical Problems and Practices[1]

In the modern blast furnace, as in the older type, most of the titanium in titaniferous ores should be removed in the slag, but if not treated properly may form corrosive compounds harmful to the furnace. Under certain conditions a small amount of titanium may be reduced in the blast furnace to alloy with the pig iron, and its presence there is said to improve the quality of the resulting titaniferous pig iron. When titaniferous pig iron is made into steel, however, any titanium present is oxidized and passes entirely into the slag. To effect the quality of finished steel, titanium must therefore be added to the molten steel in the form of an iron–titanium or iron–carbon–titanium alloy such as ferrotitanium or ferrocarbontitanium. Metallurgists generally agree that titanium may be used to advantage in the final purification of almost every form of steel, high-carbon, low-carbon, and special alloy steels. This is mainly because of the gas-seeking property of titanium—its avidity for oxygen and nitrogen, two of the most common and serious contaminants of good steel. Titanium thus combines with oxygen and nitrogen to remove the last traces of these elements from the final steel, and at the same time increases the fluidity of the resulting slag, thereby facilitating the separation of the slag from the metal. In this use titanium is known as a deoxidizer or scavenger. Despite its recognized merits titanium has not been used as extensively in treating open-hearth steel as it once was in Bessemer steel, partly because of expense. It is also because of its affinity for gases that difficulty is encountered in the production of pure titanium metal. At high temperatures and over long periods titanium metal absorbs gases from the air and becomes brittle. Air must therefore be excluded during the production of the metal and the production costs are thereby increased. To prevent molten titanium from dissolving the walls of its container the practice of pouring it into water-cooled copper crucibles has been developed; the chilled titanium prevents reaction at the margins, but also adds to the expense of production.

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[1] For more complete discussions on these topics the reader is referred to Robinson (1922), Barksdale (1949), Kinsey (1953), and Hampel (1961).

In the past titaniferous ores were smelted with reportedly good results in Sweden, England, and in the states of New York and New Jersey, and Rossi's experiments led him to believe that titaniferous ores could be successfully smelted. In this regard considerable work carried to the pilot plant stage by W. M. Goodwin indicated as early as 1921 that many of the harmful effects attributed to titanium in the blast furnace could be avoided by use of siliceous instead of calcareous flux, and that most of the vanadium in the ore could be recovered in the resulting p'g iron. Indeed, Goodwin reported that some of the natural ore materials are "self-fluxing", probably because of a high content of limesoda feldspar. In Russia, Lyuban and Basov (1934, 1935) came to similar conclusions after experiments with Jehol iron ore, and of recent years there have been favourable results handling slags containing 5 to 37 per cent TiO_2 using sodium chloride as flux. Rock salt is added to coal before coking to ensure better mixing and retention. J. A. Heskett (1920) reported that iron ores containing 9.31 per cent TiO_2 have been successfully smelted in New Zealand, and the German steel industry has developed effective emergency methods for smelting titaniferous ores without trouble (Tillmann, 1940; Planner, 1942).

From time to time within the past decade several processes have been advanced that claim the successful recovery of iron from titaniferous magnetite. Among these may be mentioned the following:

(1) the Halverson process, in the United States, in which rock salt (sodium chloride) is used as a flux. This practice has been used successfully in smelting titaniferous magnetite in Russia (Britzke, Shmanenko, and Tagirov, 1932);

(2) the Strategic–Udy process, in the United States, which involves direct smelting in a rotary kiln electrical furnace in which titanium and other undesirable elements are eliminated in the slag;

(3) the Widberg–Soderfors process, in Sweden, in which carbon monoxide and hydrogen from coal are passed through the bottom of a shaft furnace. Lump ore, pellets, or sinter are reduced for use in electric furnaces such as the Tysland-Hole furnace with the newly developed Soderberg continuous electrode;

(4) the Krupp–Renn process, in Germany, which involves the continuous reduction of iron ore in a long sloping rotary kiln fired by oil, gas, and powder coal. The discharge is in the form of $\frac{1}{16}$ to $1\frac{1}{2}$ inch metallic nodules called "luppen", which are dispersed in a pasty slag. Titanium is reduced and goes into the slag. Luppen are recovered from the slag by crushing followed by magnetic separation.

Only one company in Canada, Quebec Iron and Titanium Corporation, Limited, has as yet commercially recovered either iron or titanium from a titaniferous ore. Ilmenite ore from its Lac Tio mine is smelted in its plant at Sorel, and in addition to high-titanium oxide slag, pig iron (Sorelmetal) is recovered as a by-product. Titanium metal is not produced; the titanium oxide slag is absorbed mainly by the pigment industry and the Sorelmetal by local foundries.

Titanium alloy steels for special use are made in limited amounts at several points in Ontario, such as St. Catharines, Welland, Etobicoke, and London, and there has been some processing of titanium sponge to titanium metal for use in military aircraft. Pilot plants for titanium metal production research have also been operated by Dominion Magnesium Limited at Haley, Ontario, by The Shawinigan Water and Power Company at Shawinigan, Quebec, and by the Mines Branch in Ottawa.

Mines Branch research on titanium is a continuing project with financial assistance from the Defence Research Board. Much still remains to be learned about the metallurgy of the metal, the treatment of ores, extraction processes, and the fabrication of titanium and its alloys. Research has been done by the Mines Branch on pressure-leaching extraction of titanium from low-grade ores as well as on the electrolytic production of titanium. The soda-ash process of titanium recovery, developed by the United States Bureau of Mines, is suited to ores with high iron and relatively low titanium content. The ore is processed into sodium titanate, and then into titanium dioxide (of rutile grade) and sponge iron or iron powder. The pressure-leaching process tested by the Mines Branch of Canada permits the separation of titanium dioxide 94+ per cent pure and of relatively pure ferric oxide. The former is purer TiO_2 than that produced in the Quebec Iron and Titanium plant at Sorel; the ferric oxide may be made into pellets and sold as iron ore or processed into iron powder. Continental Iron and Titanium Company reported that they have experimented on their ilmenite ore with favourable results using both processes in their laboratory at L'Assomption, Quebec.

In the new plant of Canadian Titanium Pigments Limited at Varennes, Quebec, titanium oxide slag from the Sorel smelter of Quebec Iron and Titanium Corporation, Limited is now being chlorinated and reduced to produce anatase and rutile types of pigments for use in the manufacture of paint, paper, rubber, plastics, linoleum, and ink. The company is a subsidiary of National Lead Company of New York. In 1956 Canada imported 37,872 tons of titanium dioxide and pigments valued at more than 12.5 million dollars. During the same year the value of the TiO_2 slag produced and exported was about half this amount and has since increased. With the new plant at Varennes, Canada is expected to become an exporter of pigments.

Prior to 1962 production of commercially pure titanium metal, mainly as sponge, was continuing in only three countries—United States, Japan, and Britain, with only 2 per cent of the total world production of titanium minerals being used to produce titanium metal. Dominion Magnesium Limited at Haley, Ontario, now produces titanium, in the form of sintered pellets weighing from 5 to 7 grams each, from TiO_2 manufactured by Canadian Titanium Pigments Limited at Varennes, Quebec (Schneider, 1963), and Atlas Titanium Limited produces experimental titanium as well as commercial ferrotitanium in its plant at Welland, Ontario. Titanium carbide powders for use in cemented carbide alloys are being produced from rutile and refined TiO_2 by Kennametal Inc. at Port Coquitlam, British Columbia.

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Specifications and Prices[1]

The price of titanium ore concentrates and of the metal have declined substantially during the past 5 years. In 1955 ilmenite ore carrying 59.5 per cent TiO_2 was quoted by E. & M.J. Metal and Mineral Bulletin at $26.25 to $30.00 per ton, f.o.b. Atlantic seaboard; in 1960 by the same source at $23.00 to $26.00 per ton; and in 1965 at $23.26 per long ton. Similarly, the price of rutile concentrates 94 per cent pure was quoted from 10 to 15 cents a pound, or $200.00 to $300.00 per ton in 1955; at $80.00 per ton in 1960; and at $104.00 per short ton 96 per cent pure in 1965. During the same period the price of titanium sponge containing a maximum of 0.20 per cent iron was reduced from $3.45 per pound in 1955, to $1.55 per pound in 1960, and to $1.32 per pound in 1965. During 1956 prices on titanium mill products such as sheet, strip, plate, wire, billets, and hot-rolled bars were all lowered materially, in the case of sheet titanium from a high of $13.00 per pound, f.o.b. mill, to a low of $11.60 per pound. In 1960 and 1961 shipments of titanium mill products in the United States were 5,000 and 5,600 tons, respectively, and the price of sheet titanium had been reduced to $6.97 per pound with further reductions in 1962. Forging billets reached a low price quotation of $6.85 per pound in 1956. From 1956 to 1965 the price of low-carbon ferrotitanium remained unchanged at $1.35 per pound of contained titanium, but high-carbon and medium-carbon ferrotitanium were advanced in price from $200.00 to $310.00 and from $225.00 to $375.00 per ton, respectively.

Rutile concentrates, 96 per cent TiO_2, ranged from $120.00 per ton in Jacksonville, Florida, and $147.50 per ton in Niagara Falls, New York, in 1956, to $104.00 per ton in 1965; 54 per cent ilmenite ore was quoted at $21.00 per long ton in 1965 (E. & M.J. Bull., 1965). Refined titanium dioxide was quoted from $24\frac{1}{2}$ cents to $27\frac{1}{2}$ cents per pound in 1956, and from $25\frac{1}{2}$ cents to $27\frac{1}{2}$ cents per pound in 1959. In 1956 titanium pigment, bagged, in carload lots delivered, was quoted at $9\frac{1}{4}$ cents per pound, and titanium tetrachloride in drums at about 41 cents per pound.

Potential

An attempt has been made in the foregoing to indicate from its properties and uses the great developing potential of titanium, its compounds, and its ores. For further information on applications of the metal the reader is referred to Monoghan (1962), Bomberger (1962), and to numerous articles in the 1962–63 issues of "Materials in Design Engineering" and in 1963–64 issues of "Steel, the Metalworking Weekly". Titanium appears to be coming of age with the advent of supersonic flight and the space age.

As illustrated on Map 1238A, Canada has abundant deposits of ilmenite and titaniferous magnetite, many of which have been known for more than 50 years. Some of the largest of these have been discovered within the past 15 years,

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[1] Data mainly from E. & M. J. Bulletins and from Mineral Resources Division, Information Circulars and Yearbook.

and doubtless many more remain to be found. Canada's reserves of high-grade ilmenite and titaniferous magnetite are measurable in hundreds of millions of tons, while low-grade deposits are available in billions of tons. Together these deposits form an immeasurable source of iron and titanium that is of very great potential value to the economy and industrial importance of the country.

Chapter III

GEOLOGY OF TITANIUM

Types of Deposits

Only two kinds of titanium deposits are presently of economic importance: (1) the deep-seated primary magmatic deposits carrying mainly rutile, ilmenite, titaniferous magnetite, or sphene, and (2) the surficial mechanical sedimentary deposits of heavy dark sands, the placer or beach deposits, derived mainly by physical weathering and erosion of type (1). There are many other types and varieties of titaniferous deposits known, but they are commonly neither large nor abundant.

Titanium deposits can be classified by origin (a genetic classification), or by mineralogical or chemical composition (descriptive classifications). The purely genetic classification is perhaps the most desirable to attain from a geological point of view, but is not always practical, because the origins of too many deposits are simply not known with certainty owing to insufficient or questionable evidence. A chemical classification can neglect origin entirely, but may require large amounts of chemical data not readily obtainable. A mineralogical classification, like the chemical classification, is factual and may also be more practical, but if it neglects origin and texture it may be of limited geological application.

The writer has found the classification on the following page, which is based on a combination of origin, composition, geology, and mineralogy, most useful for titanium deposits and occurrences. Examples of important occurrences of each type in the classification are given from outstanding deposits throughout the world, and where possible from Canadian localities.

Most of the economically important ilmenite deposits of Canada fall in class AIb (late magmatic oxides) of this classification. Canada also has many important titaniferous magnetite deposits in the early magmatic class (AIa), as well as a number of representatives in class BIb, the transported mechanical sediments, both consolidated and unconsolidated.

Geochemistry

Abundance and Distribution

Titanium is the ninth most abundant element in rocks of the crust of the earth where it is estimated to average 0.4 to 0.6 per cent. It is the eighth most prevalent metallic element following silicon, aluminum, iron, calcium, sodium,

Classification and Occurrences of Titanium Deposits

A. IGNEOUS
I. Intrusive
    (a) Early magmatic
        Oxides   Ilmenite, Bushveld Complex, South Africa; titaniferous magnetite, gabbroic anorthosite, Lac du Pin-Rouge, Quebec
        Multiple oxides   Pyrochlore, alkaline complex, Oka, Quebec
        Silicates   Sphene, alkaline intrusion, Kola Peninsula, U.S.S.R.
    (b) Late magmatic
        Oxides   Ilmenite, anorthosite, Lac Tio, Quebec
        Multiple oxides   Lyndochite–fergusonite–columbite, in granite, Quadeville, Ontario
        Silicates   Sphene, aplite, Kragero, Norway
    (c) Pegmatitic
        Oxides   Rutile, nelsonite dykes, Virginia
        Multiple oxides   Euxenite, pegmatite dykes, Hybla, Ontario
        Silicates   Sphene, pegmatite dykes, Westport, Ontario
    (d) Pneumotectic–pyrometa-   Perovskite, carbonate rock, Oka, Quebec
        somatic–pneumatolytic
    (e) Hydrothermal   Davidite, alkaline complex veins, Olary, Australia

(*Aqueo-igneous* brace spanning sections (c), (d), and (e))

II. Extrusive
    (a)   Titaniferous magnetite, andesitic flows, Keweenawan Peninsula, Michigan

B. SEDIMENTARY
I. Mechanical
    (a) Residual (eluvial)   Rutile rubble, gneisses and schists, Nyasaland (Malawi), Africa
    (b) Transported (alluvial)   Titaniferous magnetite, sandstone, Burmis, Alberta
II. Chemical
    (a) Residual   Laterite, Hawaii; clay, Sierra Leone, Africa
    (b) Transported   Marine oölites, England
III. Biochemical   Bog iron ore, Finland
IV. Combinations   Bauxite, British Guiana (Guyana)

C. METAMORPHIC
I. High temperature–pressure   Rutile, gneisses and schists, Nyasaland (Malawi), Africa
II. Low temperature–pressure   No examples known

D. SECONDARY   Leucoxene-bearing beach sands, Florida

potassium, and magnesium; is the most common of the trace elements; and greatly exceeds the individual common base metals such as nickel, copper, lead, zinc, and the precious metals, gold, silver, and platinum in terrestrial abundance.

Titanium appears to be concentrated notably above the world crustal average in three main rock types: basic to intermediate igneous rocks, detrital sedimentary rocks, and lateritic deposits. The true home of titanium, however, is in the gabbroic rocks associated with anorthositic massifs.

Table II compares the titanium content of various types of rocks with that of the average igneous rock of the earth's crust. The sedimentary rocks included in the table, like all sedimentary rocks, were formed by chemical and physical weathering of older rocks that were ultimately derived from pre-existing igneous

rocks, and thus have received their titanium content originally from igneous rocks. The detrital sedimentary rocks and sediments are placer deposits formed by concentration of heavy mineral grains in beach sands; they are formed by mechanical action and separation of the products of weathering during transportation. Laterites, on the other hand, are the products of chemical weathering in tropical or sub-tropical climate in which alumina, iron, and titanium are selectively removed from the siliceous rock base. They may form in situ or be redeposited after transport in solution. Bauxite deposits are a special type of aluminum-rich laterite. Bauxite, the ore of aluminum, commonly contains iron and is said to contain as much as 4 to 8 per cent of titanium in places (Rankama and Sahama, 1950). Laterites in the Meyer Lake area of Hawaii reportedly contain 21 per cent TiO_2 (Lynd, 1960). Some shales, sandstones, laterites, bauxites, and bog ores locally carry iron and titanium in amounts comparable to those in gabbros.

Geochemical Character

Titanium may be grouped with zirconium and hafnium as being chemically related to silicon in the periodic system. All three elements are strongly concentrated in silicate meteorites as compared to the metallic meteorites. In silicate meteorites of gabbroic composition titanium is twice as abundant as in common stony meteorites. Thus this group of elements may be described as being lithophilic (silicon-seeking) and they are also strongly oxyphilic (oxygen-seeking) in the earth's crust. In fact, the oxyphilic character of titanium greatly governs its mode of occurrence in the crustal rocks of the earth, and it is estimated that more than 90 per cent of the titanium present there is carried in ilmenite, rutile, and related iron–titanium oxides. Ramdohr (1940) stated that ilmenite is almost as abundant as magnetite among the opaque iron oxide constituents of igneous rocks. Ramdohr also stated that the bulk of titanium in a slowly crystallizing magma rich in volatile constituents becomes incorporated mainly in ilmenite and magnetite and sometimes in rutile, whereas only a small amount goes into silicate minerals such as hypersthene and biotite. In quickly cooled volcanic rocks more titanium is incorporated in silicate structures than in slowly cooled plutonic rocks, but the amounts are still relatively small, in most cases much less than 10 per cent titanium.

Titanium also belongs to the iron family of elements, the ferrides—titanium (Ti), vanadium (V), chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), and nickel (Ni), atomic numbers 22 to 28, and is generally associated with them in nature. Of these elements, chromium, vanadium, ferric iron, and titanium have relatively small ionic radii, and nickel, cobalt, ferrous iron, and manganese are somewhat larger. In magmatic crystallization the former group of elements shows a marked preference to crystallize as structurally compact early oxide minerals, whereas the latter group shows a greater tendency to enter the less compact structures of silicate minerals, especially those of the ferromagnesian type such as olivines, pyroxenes, garnets, amphiboles, and micas. In these groups of silicate minerals titanium may replace aluminum, iron, and magnesium to some extent

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because of similarities in atomic size; in addition, because of its chemical relationship to silicon, small amounts of titanium may substitute to a limited extent for silicon in the silicon–oxygen tetrahedral structure.

Titanium in Igneous Rocks

Igneous rocks are the primary terrestrial source of titanium. Like iron, titanium commonly separates at an early stage from crystallizing magma, but may be held in solution by hyperfusibles such as water, phosphorus, chlorine, fluorine, and sulphur in the magma, and so may crystallize later than might ordinarily be expected. Because of its avidity for oxygen titanium combines with oxygen at an early magmatic stage, but probably because of the abundance of iron and its relationship to titanium the combination iron, titanium, and oxygen in the form of iron–titanium oxide minerals, ilmenite and titanomagnetite, are more common and abundant in igneous rocks than the structurally less compact titanium oxide mineral rutile. Rutile in igneous rocks is also commonly iron-bearing and may carry as much as 10 per cent iron. It is normally more abundant in gabbroic pegmatite than elsewhere, but it is also commonly found in granitic rocks. Because both are early to late magmatic differentiates the basic igneous rocks and iron–titanium oxide minerals are common associates. Basic varieties of alkalic rocks and their pegmatites are commonly rich in titanium. Basic alkalic rocks may contain perovskite, sphene, and the titanium garnet melanite, in addition to ilmenite and titanomagnetite. Their pegmatites may contain rare titano-silicates such as astrophyllite, lamprophyllite, and rinkite. Sphene is a common constituent of the calc-alkalic rocks and is more abundant in plutonic than in extrusive types. Complex multiple oxides of titanium, tantalum, niobium (columbium), calcium, rare earths, uranium, etc., occur in granite, alkaline rocks, pegmatites, and in vein and placer deposits, but they are not important geochemically.

Clarke and Washington (1924) estimated the average titanium content of igneous rocks at 6,400 grams per ton, i.e., 0.64 per cent. Goldschmidt (1937) considered that this value was too high owing to the large amount of rare basic rock types rich in titanium included in the material analyzed. Goldschmidt found the glacial and post-glacial clays of Norway to average 0.47 per cent titanium, and the opdalite (an average igneous rock from Opdale-Indset) of southern Norway 0.58 per cent titanium. The estimates of Sederholm (1925) for Precambrian rocks of Finland, and of Vogt (1931) for igneous rocks were 0.25 and 0.33 per cent titanium, respectively. Grout (1938) estimated that the Canadian Shield averaged 0.49 per cent titanium, and Knopf (1916) estimated that Cordilleran and Appalachian rocks averaged 0.5 per cent titanium. If a crustal average of about 0.5 per cent titanium is assumed, then iron is roughly ten times more abundant than titanium in the earth's crust.

Table II illustrates that titanium is slightly more abundant in the igneous rocks than in sedimentary rocks, except in the case of some laterite and bauxite and some detrital deposits of black sands. It also shows that there is a gradual decline in titanium content progressing from gabbroic to granitic igneous rocks.

TABLE II | *Iron and Titanium Content of Average Rocks and Calculated Iron:Titanium and Ferric:Ferrous Ratios*

Rock[1] (average)	Fe, %	Ti, %	Fe:Ti (calculated)	Fe^{+3}:Fe^{+2} (calculated)
IGNEOUS				
Mica peridotite		2.97		
Dunite	6.3	0.01	63:1	2:1
Hornblendite	11.76	0.97	12:1	0.6:1
Olivine gabbro	7.5	0.70	11:1	0.5:1
Gabbro	8.84–6.8	0.58	15:1 to 12:1	0.5:1
Norite	6.70	0.68	10:1	0.6:1
Plateau basalts	10.34	1.31	8:1	0.3:1
Basalts	8.86	0.82	11:1	0.7:1
Diabase	8.91	0.87	10:1	0.4:1
Diorite	5.63	0.46	12:1	0.6:1
Granodiorite	3.28	0.34	10:1	0.6:1
Syenite	4.54	0.40	11:1	0.7:1
Nepheline syenite	4.12	0.52	8:1	1.3:1
Granite	2.48	0.23	11:1	0.8:1
Anorthosite[2]	1.64	0.09	18:1	0.8:1
Average igneous rock	5.1	0.64–0.44	8:1 to 11:1	
SEDIMENTARY				
Shale	4.71	0.43	11:1	1.5:1
Sandstone	0.99	0.44	2:1	3.2:1
Quartzite	1	0.10	10:1	
Limestone	0.38			
Marine oölitic, siliceous iron ores[3]	40	0.39	100:1	
Bog ores[3]	12–50	0.15	80:1 to 333:1	

[1]Analyses from Rankama and Sahama (1950, pp. 33, 159, 558, 564, 658, 668) unless otherwise noted.
[2]Analyses from Daly (1933).
[3]Analyses from Landergren (1948).

True anorthosites generally are even lower in iron and titanium than the average granite, according to Tables II and III, but nevertheless anorthosites are the most common host rocks of titanium-rich ilmenite deposits and such deposits are seldom found outside their borders. The gabbroic phases associated with them are usually much higher than the anorthosites, but all four—anorthosite, gabbroic anorthosite, titaniferous magnetite and ilmenite deposits—are spatially related in nature, as indicated on Map 1238A, and all four appear to be genetically related.

Gabbros are commonly much higher in iron and titanium than are anorthosites and granites, and thus iron:titanium ratios are also higher, as shown in Tables II and III. These ratios are in fact close to that of shale, but both the iron plus titanium content and iron:titanium ratio are generally lower in anorthosites than in either granite or shale.

TABLE III | *Iron and Titanium Content of Anorthosites*

Selected rock and locality	Fe, %	Ti, %	Fe+Ti	Fe:Ti (calculated)	Reference for analysis
White anorthosite, Rawdon, Quebec	0.3	—	0.3+		T. S. Hunt (1863)
Yellow anorthosite, New York State, U.S.A.	0.98	—	0.98+		T. S. Hunt (1863)
Grey anorthosite, Coast of Labrador, Nfld.	0.5	—	0.5+		F. D. Adams (1896)
Grey anorthosite, Wilkinson, Ontario	2.1	0.3	2.4	7.0	J. M. Harrison (1944)
Grey anorthosite, Degrosbois, Quebec	1.6	0.2	1.8	8.0	E. R. Rose (1960)
Brown anorthosite, Ste-Agathe-des-Monts, Quebec	3.1	0.7	3.8	4.4	E. R. Rose (1960)
Average anorthosite (range)	1.4 (0.3–3.1)	0.2 (— –0.7)	1.6+ (0.3–3.8)	7.1 (4.4–8.0)	from above
Average gabbro	6.8	0.58	7.4	11.7	Rankama and Sahama (1950)
Average granite	2.48	0.23	2.7	10.8	Rankama and Sahama (1950)

Table III contains precise data on the iron and titanium content of parts of some anorthosite bodies in eastern Canada. This gives some indication of the degree of variation in iron–titanium content and ratio in various coloured phases of anorthosite and shows calculated average values that might apply more closely to Canadian occurrences than the figures for anorthosite given in Table II which were compiled from world-wide occurrences (Daly, 1933).

Mineralogy

Titanium Minerals

Titanium is a major constituent of about twenty minerals; these are listed in Table IV along with their chemical composition and outstanding physical properties. The relationships of the iron–titanium oxide minerals are shown diagrammatically in Figure 1, and the nature of the main titanium minerals, all of which are potential ores, is described below.

Ilmenite—$FeO \cdot TiO_2$, hexagonal, rhombohedral, composition theoretically 36.8 per cent iron, 31.6 per cent titanium, 31.6 per cent oxygen; may carry small amounts of other metals such as magnesium, calcium, manganese, lead, and zinc substituting for iron, and aluminum, silicon, iron, chromium, and vanadium substituting for titanium; a hard, black mineral resembling magnetite

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TABLE IV | *The Main Titanium Minerals, their Composition, Properties, Nature of Occurrence, and Abundance*

Mineral	Chemical composition	Physical properties	Nature of occurrence	Abundance
RUTILE ilmeno–rutile strüverite	TiO_2; Ti 60%, Fe impurity as much as 10%, also V Ferriferous rutile with Nb, Ta	Hard, reddish brown crystals, tetragonal	In ilmenite, in veins, as accessory grains, and in placer deposits	Widespread but not abundant
Brookite	TiO_2 ($Fe_2O_3 \cdot TiO_2$); Ti 60%	Like rutile, but orthorhombic	Veins and placer deposits	Rare
Anatase (octahedrite)	TiO_2; Ti 60%	Like rutile but of secondary origin, tetragonal	In altered titanium-bearing rocks	Rare
Arizonite	$Fe_2O_3 \cdot 3TiO_2$; Ti 36%	Hard, dark steel grey, brown streaks	With gadolinite in pegmatite, Mohave County, Arizona	Rare
ILMENITE	$FeTiO_3$; Ti 31.6%, Fe 36.8%;	Hard, black, weakly magnetic, will cling to magnet when powdered, rhombohedral	In massive vein-dykes and disseminations in anorthosite and gabbroic anorthosite; also in placers	Abundant
ferrian ilmenite	6–13% Fe_2O_3 in solid solution			
magneto-ilmenite	Intergrowths of magnetite			
hemo-ilmenite	Ferrian ilmenite with inter-growths of titanhematite			
geikielite, högbomite, pyrophanite, senaite, silicoilmenite?	$(Mg,Fe) TiO_3$, with Al, Fe,Mn,Pb Si			
Perovskite niobian perovskite (Oka) and other multiple oxide minerals (brannerite, davidite, etc.)	$CaTiO_3$; Ti 35.3% 25–56.2% TiO_2; Ti 15–30%	Hard, cubic crystals, perfect cleavage, isometric	In chlorite, talc, and serpentine rocks, and in alkaline rocks	Not abundant

Sphene (titanite)	CaTiSiO$_5$; Ti 24.5%	Hard, brownish wedge-shaped crystals, good cleavage, monoclinic	Common accessory mineral, also in pegmatite, alkaline rocks, and contact deposits	Not abundant
Ulvöspinel mogensite	Fe$_2$TiO$_4$ (2FeO·TiO$_2$); Fe 44%, Ti 16.8% Intergrowth of ulvöspinel in magnetite	Hard, dark, magnetic, isometric	Intergrown with titano-magnetite, forms solid-solution series	Rare
Pseudobrookite	Fe$_2$TiO$_5$; Ti 12%	Dark brown tabular crystals, streak ochre yellow	In lavas of Europe, as at Vesuvius, and in artificial melts	Rare
Titanomagnetite ilmeno-magnetite	(FeTi$_3$O$_4$); Fe 40–71%, Ti 1–15%; Titanomagnetite with inter-growths of ilmenite or ferrian ilmenite	Hard, dark, strongly magnetic, isometric	Forms solid–solution series	Abundant
Titanhematite ilmeno-hematite	(FeTi)$_2$O$_3$; Ti 1–10%; Titanhematite with inter-growths of ferrian ilmenite or hemo-ilmenite	Hard, dark, weakly magnetic, rhombohedral	Forms solid–solution series with ilmenite	Widespread but not abundant
Leucoxene brown creamy white	A mixture of rutile, hema-tite and pseudobrookite, etc. A mixture of sphene (tita-nite) altered feldspar, etc.	Hard, dark films Soft, creamy films	Alteration products and coat-ings on titanium-bearing ores and sands Alteration products and coat-ings on titanium-bearing rocks	Widespread but not abundant
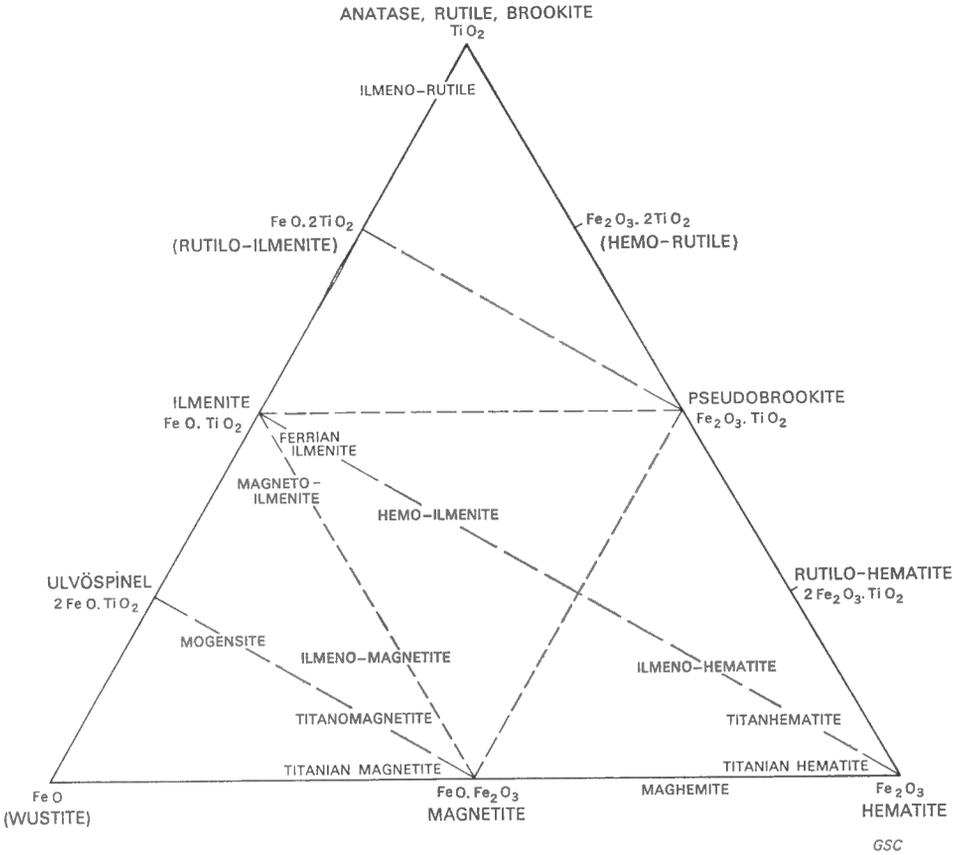
FIGURE 1. $FeO-Fe_2O_3-TiO_2$ system showing suggested mineral series names and their approximate chemical compositions (*derived from* Balsley and Buddington, 1955).

but distinguished from magnetite by its weak magnetism: powdered ilmenite will cling to a hand magnet but will rarely jump to the magnet as magnetite does; commonly intergrown with hematite, spinel, and magnetite.

Rutile—TiO_2, tetragonal, composition 60 per cent titanium, 40 per cent oxygen, may contain as much as 10 per cent iron in part substituting for titanium and in part as intergrown ilmenite or ilmeno-rutile; may contain tantalum as in strüverite; rutile is a hard, non-metallic mineral of high birefringence, commonly of deep reddish brown colour resembling garnet.

Titanomagnetite—(titanmagnetite) $(Fe,Ti)O \cdot Fe_2O_3$, isometric, octahedral, generally about 40–70 per cent iron, 20–30 per cent oxygen, and 1–15 per cent titanium; may also contain magnesium, calcium, manganese, cobalt, and nickel substituting for ferrous iron, and chromium, vanadium, silicon, and aluminum for titanium; a hard, black, strongly magnetic mineral which will jump to the hand magnet when crushed or powdered, and which in places may form a natural magnet or lodestone.

Ulvöspinel—$2FeO \cdot TiO_2$, a hard, black mineral intermediate in composition and physical properties between magnetite and ilmenite; possibly a member of a continuous solid–solution series of mix-crystals intermediate between magnetite and ilmenite.

Perovskite—$CaO \cdot TiO_2$, isometric, theoretically about 35 per cent titanium, a hard, brittle, non-metallic mineral; characteristically found in alkaline intrusions and their contact deposits.

Sphene—(titanite) $CaO \cdot TiO_2 \cdot SiO_2$, theoretically 30.6 per cent silica, 28.6 per cent lime, and 40.8 per cent titanium dioxide, i.e., 24.48 per cent titanium; a hard, dark brown non-metallic mineral showing distinct cleavage and parting, often in wedge-shaped crystals; characteristically found in pegmatite dykes, granitic intrusions, and contact deposits.

Leucoxene—a cloudy white opaque secondary product of weathering of ilmenite, similar in composition to sphene; and brown leucoxene, also a product of alteration of ilmenite, consisting of a mixture of hematite, pseudobrookite, and rutile; may carry about 35 per cent titanium, 30 per cent iron, and 35 per cent oxygen.

Bauxite—essentially $Al_2O_3 \cdot 2H_2O$, a soft oölitic, clay-like, light coloured mineral, the ore of aluminum, may be red with iron and may carry as much as 8 per cent titanium; bauxite and laterite are products of rock alteration in tropical and subtropical weathering during which iron, titanium, and aluminum hydroxides are more or less separated from silica; in an advanced stage of weathering further separation of silica is accomplished and also an effective separation of aluminum and titanium hydroxides from those of iron.

Heavy minerals—concentrated in dark beach sands commonly include ilmenite, hematite, magnetite, titanomagnetite, rutile, and leucoxene, forming deposits, which under favourable conditions have been used as sources of titanium.

Titanium is a minor constituent of many other minerals, notably phlogopite and biotite (wodanite), olivine, pyroxene, amphibole, garnet (melanite), spinel, astrophyllite, lamprophyllite, and rinkite.

Crystal Structure and Atomic Substitution

Crystals of iron–titanium oxide minerals are classed as ionic types, and are held together by electrostatic attraction of the positively charged metallic cations (Fe^{+2}, Fe^{+3}, Ti^{+3}) for negatively charged oxygen (O^{-2}) anions. The ions of these oxide minerals group together into ordered crystalline structures of two main types, the spinel structure and the hematite structure. The spinel structure is cubic, close packed, and characteristic of the smaller ions such as aluminum (Al^{+3}) 0.57 kx*, chromium (Cr^{+3}) 0.64 kx, vanadium (V^{+3}) 0.65 kx, and ferric iron (Fe^{+3}) 0.67 kx. The hematite structure is hexagonal, rhombohedral,

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* Ionic radius: 1 kx $= 1.00202$ Å
  1 Å $= 10^{-8}$ cm

and more characteristic of the slightly larger ions such as titanium (Ti^{+3}) 0.69 kx, magnesium (Mg^{+2}) 0.78 kx, nickel (Ni^{+2}) 0.78 kx, cobalt (Co^{+2}) 0.82 kx, manganese (Mn^{+2}) 0.83 kx, and ferrous iron (Fe^{+2}) 0.83 kx. Titanium ions are of intermediate size and may be found in both types. The available electrostatic charge of the ions concerned is probably equally as effective as the size factor in determining the chemical bonds formed and the structure assumed by the growing crystal. In its attempt to assume an ordered stable structure the growing crystal's ionic charges must be electrically balanced and the ions of favourable size range. The more compact spinel structure characteristic of magnetite, titanomagnetite, and ulvöspinel is generally stable at higher temperatures than is the less compact hematite structure of hematite and ilmenite, but because of substitution of one element for another each ideal type of structure may become less stable than it otherwise would be. Substitution of one or more elements for another is governed by availability, favourable size ratio, and electrostatic charge (valence). Generally Mg^{+2} may substitute for Fe^{+2} or Mn^{+2}, and Al^{+3}, Cr^{+3}, V^{+3}, and Fe^{+3} may substitute for Ti^{+3}, and vice versa to some extent. A combination of Fe^{+2} and Fe^{+3} may substitute for $2Ti^{+3}$ leaving a deficiency in charge and a more loosely bonded structure into which other cations may enter.

The ferride elements have a chemical resemblance because of their similarities in size and in electrostatic charges, and they may substitute for one another freely depending largely upon their availability at the time of crystallization. Thus many of the magmatic iron oxide minerals carry more of the ferride elements than do their hydrothermal and metamorphic counterparts. This is perhaps generally true also in the chemical sedimentary deposits, but reversals may be expected in these minerals because of selective concentration and precipitation of particular elements from solution. In other words, some of the ferride elements characteristic of magmas may become more or less concentrated in chemical sediments. For example, Fe, Mn, Ti, and V are commonly enriched in bog deposits, oölitic iron ores, laterites, and bauxite.

In oxide-rich crystallizing magmas at high temperatures the spinel structure is generally stable and early spinel crystals (spinel, chromite, magnetite, ulvöspinel) should be high in the smaller cations Al^{+3}, Cr^{+3}, and Mg^{+2}. As the temperature drops more of the larger ferride ions such as Fe^{+3} and Ti^{+3}, and Fe^{+2} and Mn^{+2} may enter the structure, and the hematite structure is formed at a higher temperature than it might have if the larger ions were not available for substitution. Thus the original composition of the magma or magmatic extract must have a strong controlling influence on the general course of crystallization and composition of the oxide minerals within it.

Intergrowths

A feature typical of many titanium-rich minerals, particularly of the ilmenite–hematite group and of the magnetite–ulvöspinel–ilmenite series, is the striking exsolution textures shown in polished sections of these minerals viewed under the reflecting microscope. Some of these textures are illustrated in Plates VI–VIII (cf. Singewald, 1913a, b).

Ilmenite–Hematite

The most common type of intergrowth is hematite (titanhematite) lamellae in an ilmenite (ferrian ilmenite) host (Pl. VII A). The entire grain, as a unit including both host and guest, might be called hemo-ilmenite. These lamellae are generally considered to represent exsolution from the solid as the crystals cooled from a temperature above 700°C. The same polished section under higher magnification reveals more clearly that there are smaller lenticles presumably of ferrian ilmenite within the primary lamellae of titanhematite. The smaller lenticles have been considered by Ramdohr and others to represent a second generation of exsolution that took place in the solid as the crystals cooled below 400°C. Greig (1932), however, pointed out that when two crystalline phases unmix the composition of one is modified by the other, and that unmixing takes place over a wide range of temperatures. It is not possible, therefore, to infer the temperature of formation of the exsolved phases. The extent of these microscopic intergrowths of minerals appears to be limited only by the resolving power of the microscope to the viewer's eye.

A reversed mineral texture to that in Plate VII A, with ferrian ilmenite lamellae as exsolved guests in a titanhematite host, appears in samples from the Cliff mine, Indian Head, Newfoundland; the unit grain in this case may be called ilmeno-hematite. In the types of intergrowths discussed above the lamellae and lenticles appear to be lenticular plates or platelets generally having their long dimensions parallel with the basal plane (0001) of the host mineral. In some places the plates are aligned in two preferred planes, controlled by the crystal structure of the host, one parallel to the base (0001) the other to the rhomb $(10\bar{1}1)$.

Ilmenite and hematite crystals have a similar atomic structure in which groups of iron, titanium, and oxygen atoms are arranged in rhombohedral lattice pattern. The structure of the minerals may be likened to that of a deformed cube; in hematite the rhombohedron differs only slightly from a cube, but in ilmenite the difference is more pronounced. In both structures the oxygen atoms are concentrated in the basal and rhombohedral planes, which thus become favoured crystallographic directions controlling the crystal habit, cleavage, twinning, and exsolution. It is believed that in these planes some of the oxygen atoms are shared by the intergrown ilmenite and hematite lenticles. This type of intergrowth is found in both massive and disseminated ilmenite and in coarse- and medium-grained phases of rocks that were apparently slowly cooled. It has also been reported in quickly cooled, fine-grained rocks such as the dacite pumice of Mount Haruna in Japan (Uyeda, 1958), and the somewhat coarser grained Keweenawan andesite lavas (Cornwall, 1951b).

Ilmenite–Magnetite

Intergrowths of magnetite in ilmenite and of ilmenite in magnetite have been described by a number of authors from various localities, and although they are abundant in titaniferous magnetite they are commonly found only in minute

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quantities in the ilmenite-rich segregations or in association with disseminated ilmenite–hematite. Plate VIII B shows magnetite grains carrying exsolved ilmenite accompanying separate ilmenite grains in a specimen from Magpie Mountain, Quebec. The intergrowths of titanomagnetite in ilmenite generally appear to be found in iron-rich and quickly cooled rocks where disordered structures prevail. It is also possible that the minerals reported as magnetite and ilmenite are impure titanium or iron-rich varieties. An irregular (or replacement) type of intergrowth of ilmenite in magnetite is occasionally found in which ilmenite appears to replace parts of the magnetite grains and also occurs interstitially with them. The writer has found this irregular, flame-type of intergrowth in an ilmenite-rich sample from Bad Vermilion Lake, Ontario.

In certain slowly cooled rocks of more ordered structures intergrowths of magnetite and ilmenite are less common, and the two minerals (or impure varieties of them) occur together in assemblages of separate grains which appear to have formed at the same time. In these assemblages the ilmenite commonly shows exsolution lamellae of hematite, and the magnetite appears to be homogeneous. This type of texture is exhibited in titaniferous magnetite from numerous localities in gabbroic anorthosite of the Grenville subprovince.

Titanomagnetite–Ulvöspinel

Detailed work by Akimoto and Katsura (1959) on titanomagnetite separated from ilmenite–hematite series minerals in volcanic rocks in Japan indicates that there is a grain by grain variation in the chemical composition of this mineral that may be related to the reduction–oxidation potential. This suggests that the formation of titanomagnetite in volcanic rocks is more complicated than expected. This may also be true in plutonic rocks, because titanomagnetite samples separated by the writer from titaniferous magnetite deposits in various anorthositic bodies in eastern Canada and some from within a single anorthositic massif in Quebec also showed certain variations in chemical composition. Such variations in deep-seated rocks theoretically should be less pronounced, however, and this appears to be the case.

A possible key to the observed variations in chemical composition of titano-magnetite may be found in its relationship to the mineral ulvöspinel. This mineral was first noted by Mogensen (1946) in an iron ore from the Ulvö Islands of northern Sweden. It was later described and named by Ramdohr (1953). Also, in 1953, ulvöspinel was reported from titanomagnetite at Lac de la Blache, Quebec, by J. P. Girault (1953); it has been described and discussed also in papers by Nicholls (1955) and by Vincent, et al. (1957). In 1957 E. H. Nickel of the Mines Branch detected ulvöspinel in a submicroscopic intergrowth with magnetite in titaniferous magnetite from Mount Yamaska, one of the Monteregian alkaline hypabyssal intrusions of essexite in Quebec. This texture, illustrated in Nickel (1958), shows the intimacy of the intergrowth revealed under very high magnification. The intergrowth, which is apparently homogeneous under low magnification, is much higher in titanium at 10.7 per cent than ordinary magnetite, or titano-

magnetite from the Morin anorthosite and many other plutonic rocks in the Grenville subprovince. It is close in titanium content, however, to that of magnetic concentrates made from titaniferous magnetite from the Magpie Mountain, Sept-Îles, St-Charles, Moquin, and Mine Centre deposits, in all of which ilmenite occurs both as discrete grains and as exsolved intergrowths. It is generally believed that magnetite and ulvöspinel form a solid–solution series of iron–titanium oxide minerals with characteristic spinel structure, and that variations in the proportions of the two may produce variations in the chemical composition of the resulting solid solution or exsolved mixtures of mineral components. If variations in the chemical composition of ilmenite and titanomagnetite are considered, a range of titanium from 0.2 to 12.6 per cent for titanian magnetites and titanomagnetites and from 18.7 to 44.4 per cent for ilmenites (ilmenite–hematites) is shown (Tables V–VII). The materials sampled are similar macroscopically and microscopically and it seems possible that they consist of members of an exsolved solid–solution series between ilmenite and magnetite of which ulvöspinel is an intermediate member, as suggested by the work of Vincent, et al. (1957). According to R. W. Taylor (1961) the observed intergrowths of ilmenite in magnetite probably result from the oxidation of members of the magnetite–ulvöspinel solid–solution series rather than by exsolution of ilmenite from solid solution in magnetite since, as he pointed out, the solubility of ilmenite in magnetite is limited below 1,000°C (cf. Buddington and Lindsley, 1964). As indicated by the detailed studies of Wright (1959), Vincent (1960), and Verhoogen (1962), however, the solid–solution oxidation relationships of the iron–titanium oxide minerals are very complex, although their mineralogy may appear to be deceptively simple.

Origin of Titaniferous Magnetite and Ilmenite

Titaniferous magnetite, consisting of titanomagnetite and ilmenite, may contain any of the intergrowths described above. The observed variations in chemical composition and magnetic properties of the titaniferous magnetites may be caused by subtle variations in the minerals present that are not readily detectable microscopically. The manner of formation and rate of cooling as well as the oxidation potential and chemical composition must all have a bearing on the properties of the resulting end products. It seems obvious that ilmenite, a high titanium oxide mineral, and magnetite, a low titanium oxide mineral, may crystallize together under the same conditions, but it is not clear what controls the partition of elements between them.

Some aspects of the interpretive problems pertaining to the origin and temperature of formation of magnetite and titaniferous magnetite have been presented in papers by Buddington, et al. (1955, 1963), Marmo (1959), and Whitten (1959) in addition to the one by Verhoogen (1962). All are in general agreement regarding the complexity of the problems and the importance of titanium content, i.e., chemical composition, in modifying the temperature and course of crystallization, but emphasis is variously laid by each author on particular factors.

Buddington, *et al.* concluded that in the $Fe_3O_4 - FeO \cdot TiO_2$ system the TiO_2 content of the magnetite is largely a function of the *temperature,* whereas Marmo stressed that bulk *composition* as well as temperature may determine the composition of the magnetite. Whitten indicated that composition (titanium content) was not always indicative of temperature of formation, and Verhoogen stressed the complicated effects of oxidation on the formation of magmatic iron–titanium oxides. The oxidation potential of the magma and that of its ore-forming fluids are probably important factors in determining the mineralogical nature of the deposits.

Despite this somewhat conflicting situation it is remarkable that although there are apparently certain variations in the composition of titanomagnetites from widespread localities within gabbroic anorthosites in eastern Canada, the variations for the most part are limited and show a general consistency within certain groups, as shown by the many analyses listed in Tables V to VIII. In fact, certain groups are notable for their uniformity rather than for variation in chemical composition. This uniformity is undoubtedly a reflection of the deep-seated magmatic origin of such deposits. Notable too is the remarkably low titanium content of some of the magnetites, many of which are associated with ilmenite, and all of which have come from terrains high in titanium (*see* Tables V and VI). For example, a sample of magnetite separated by the writer from gabbroic anorthosite of the Lac Allard area showed upon X-ray fluorescence analysis a content of 71.3 per cent iron and only 0.2 per cent titanium. The magnetite from other samples taken from this area, six by the Quebec Iron and Titanium Corporation (from 1.0 to 2.0 per cent TiO_2) and others by various workers (from 0.75 to 3.3 per cent TiO_2), has shown a range of 0.4 to 1.98 per cent of titanium. A suite of magnetites extracted by the writer from seven samples taken from oxide-rich gabbroic anorthosite of the Morin anorthosite in Wexford township showed a range of from 62.3 to 65.0 per cent iron, and from 0.96 to 2.42 per cent titanium. Another by the Mines Branch for the Laurentian Titanium Company showed 69.36 per cent iron and 0.24 per cent titanium. In some cases the titanium content of the magnetite is lower than that of the rock or ore in which it is found. The relative depletion of titanium in the magnetite in many of these rocks and ores may be accounted for by its selective incorporation in ilmenite there, and given conditions appropriate for slow cooling, the more effective the separation into ilmenite-rich and magnetite-rich materials tends to become.

Titaniferous magnetite is therefore regarded as an intermediate product of differentiation of iron–titanium rich mafic magma from which ilmenite and magnetite may be the final end products.

Geophysics

Magnetic Properties of Iron–Titanium Minerals

The magnetic properties of the iron–titanium minerals vary greatly with their composition, texture, temperature, and pressure, and although a great deal of work has been done on them by groups of scientists in many countries, partic-

ularly in England, France, Japan, and the United States, it is not yet possible to state the precise nature and cause of the magnetic effects of these minerals. It is beyond the scope of this report to deal adequately with the full extent of these investigations, and reference must be made to the literature for detailed information on these topics (*see* especially paper by Shull, *et al.*, 1951; Nagata, 1961).

One of the outstanding magnetic properties of these minerals is their ability to produce magnetic anomalies. Another related property is their varying capacity to retain a hard component of remanent magnetism; and a third related property is their inherent mechanism of reversing their magnetic fields. These properties are of importance in interpreting magnetic anomalies as well as in palaeomagnetic studies because of the widespread occurrence of iron–titanium minerals in rocks of many types throughout the earth's crust.

Remanent Magnetism

The writer's studies of the remanent magnetism in seventy oriented samples have resulted in the following conclusions.

(*a*) Remanent magnetism is characteristically strongly developed and retained in intergrowths of iron–titanium oxide minerals, especially in ilmenite–hematite intergrowths, but is also found in certain titaniferous magnetite (magnetite–ilmenite) deposits.

(*b*) Remanent magnetism is commonly subordinate to induced magnetism in most titaniferous magnetite; because of this, titaniferous magnetite is commonly unstable under magnetic washing, whereas ilmenite–hematite is commonly stable.

(*c*) Although ilmenite–hematite intergrowths are commonly reversely polarized and magnetite–ilmenite (titaniferous magnetite) intergrowths are commonly normally polarized, in certain places the reverse of both situations is found in which ilmenite–hematite is normally polarized and titaniferous magnetite is reversely polarized (*see* Rose, 1960, 1961).

Carmichael (1961) recently concluded that exsolution intergrowths of certain iron–titanium mineral series have an ionic or electronic mechanism capable of reversing their magnetic polarity. Many such titanium-rich intergrowths, particularly those of ilmenite–hematite, were found to be reversely polarized in the Adirondack region of New York State (Balsley and Buddington, 1958), and although this is also generally true in occurrences in Canada studied by the writer, exceptions were noted that have an important bearing on the interpretation of aeromagnetic anomalies. Discussion of several examples of such exceptions follow.

The writer's studies indicate that although the magnetic anomalies associated with titaniferous deposits are generally controlled either by titaniferous magnetite with a strong component of induced magnetism and high magnetic susceptibility, or by ilmenite–hematite with weak component of induced magnetism and low magnetic susceptibility, the hard component of remanent magnetism of both titaniferous magnetite and ilmenite–hematite may be inclined in any direction and may be either positive or negative. Thus it may be a very important factor affecting,

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and in places controlling, the resulting magnetic anomaly. In fact, the reversed (negative) remanence of ilmenite–hematite (much less commonly of titaniferous magnetite) commonly produces a reversed or true negative magnetic anomaly.

Use of Magnetic Surveys in Locating Titaniferous Deposits

Magnetic surveys include those made from the air by airborne magnetometer and those made on the ground by magnetometer or dip needle. Aeromagnetic surveys cover large areas, and in addition to outlining regional trends, may indicate zones favourable for the occurrence of magnetic minerals. Ground-magnetometer and dip-needle surveys may be used to fill in magnetic detail and to give resolution not supplied by aeromagnetic surveys. Both dip needle and ground magnetometer are much more influenced by near-surface magnetic bodies than is the airborne magnetometer and may be used to outline in detail the most magnetic zones near surface. Although the dip needle is much less sensitive than the ground magnetometer, it is an inexpensive instrument and may be used to good advantage in this manner in prospecting, particularly in conjunction with aeromagnetic maps.

The following discussion of the five titanium-bearing areas is based upon a comparison of aeromagnetic and dip-needle surveys with geological observations on iron–titanium deposits in associated anorthositic and gabbroic rocks. In many cases the results are supplemented by inferences drawn from studies of the direction and type of magnetization given by oriented specimens.

Morin Anorthosite Area

The Morin anorthosite is a large body of anorthosite and related mafic rocks with numerous titanium occurrences in the Grenville structural province about 60 miles north of Montreal (*see* Map 1238A; also Adams, 1896; Osborne, 1936; Rose, 1960). Figure 2 illustrates good correlation of mafic phases of the Morin anorthosite massif with strong, positive aeromagnetic anomalies. Many of the anomalies show an intensity of more than 8,000 gammas forming a magnetic plateau high above that of most of the rocks surrounding the anorthositic massif and of the anorthosite proper.

The writer's reconnaissance ground examination indicated that many of the strong anomalies are associated with iron–titanium oxide-bearing gabbroic anorthosite bodies, in some of which considerable concentrations of titaniferous magnetite are present. Many of the titaniferous magnetite occurrences gave positive dip-needle readings and were later found to consist mainly of disseminated discrete grains of titanomagnetite and of ilmenite–hematite (ilmenite with hematite or titanhematite exsolution lamellae) in gabbroic anorthosite host rock. In a few of the occurrences fine-grained pyrrhotite is another disseminated magnetic mineral. In places ilmenite and titaniferous magnetite form massive zones, but generally they range from 10 to 30 per cent of the rock. The ratio of titanomagnetite to ilmenite in these rocks also varies considerably from about 2:1 to 1:2, and commonly as the ilmenite–hematite content increases with respect to titanomagnet-

Overburden

×3 ×3 ×3
×3 ×3

×3

×2

2×

1×2

2×2
2×2

×2

Lac de la Roche

Overburden

To Mont-Rolland
3×

Base line

Laurentian Titanium Mines Ltd.

Private road

Overburden

3× ×3
×3
×3

3× ×3
×3
3× ×3
3× ×3

85

3×
80

3×

×3 75

Private road
Private road

Lac à l'Ours

×1

2×

Private road

Road

Lac du Pin-Rouge

Road

×1
60

Overburden

75

To Lac-en-Coeur

To Lac-en-Coeur

Overburden

80

MAG. NORTH
NORTH

Overburden

×1
×1

×2

2×

×3
3×

3× 3
×3
60
68
3×

×3
60
×3

×2

Overburden

×2

2×

×2

×1

×1
×3

Lots 5-12, Ranges I-III,
Wexford Tp.,
Terrebonne Co., Quebec

To St-Hippolyte-
de-Kilkenny

Feet
0   500
0   180
Metres

GSC

LEGEND

3	Disseminated titaniferous magnetite and ilmenite
2	Gabbroic anorthosite
1	Anorthosite

Rock outcrop . . . . ×

Area of rock outcrop . . . . ⬭

Area of low positive or negative dip-needle readings
(by Laurentian Titanium Mines Ltd.) . . . .

Foliation (inclined, vertical, dip unknown) . . . .

Glacial striae . . . .

FIGURE 3. Geology and dip-needle survey, Lac du Pin-Rouge area.

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ite the intensity of the magnetic anomaly decreases. In some places, generally where ilmenite–hematite greatly predominates over magnetite, the result is a negative anomaly.

Dip-needle and aeromagnetic readings are negative in the Lac du Pin-Rouge area of Wexford township, Quebec, over several such ilmenite-rich zones within broad belts of titaniferous magnetite, which themselves generally give strong positive dip-needle and aeromagnetic readings. Figure 3 shows a part of the ilmenite–magnetite deposit north of Lac du Pin-Rouge with areas of positive and negative dip-needle readings superimposed on the geological map. A Laurentian Titanium Company diamond-drill hole penetrated the relatively small, negatively polarized part of this deposit within the larger, positively polarized zone; the writer found that ilmenite-rich and titanomagnetite-rich zones intermingle gradationally there. A similar gradation was also found in the outcrops south of Lac du Pin-Rouge where gabbroic anorthosite rich in ilmenite passes into the magnetite-rich rock, and the corresponding dip-needle and aeromagnetic readings change from negative through zero to positive. An oriented specimen of ilmenite-rich gabbroic anorthosite from the main titaniferous outcrop near the south end of Lac du Pin-Rouge showed remanent magnetism inclined in a direction almost opposite to the earth's present magnetic field. Thus the negative anomaly at Lac du Pin-Rouge is undoubtedly the result of the strong reversely (upward) directed component of remanent magnetism in the ilmenite–hematite-rich material there.

St-Urbain Anorthosite Area

The St-Urbain anorthosite is an oval-shaped, well-differentiated body, about 75 miles northeast of Quebec city, composed largely of andesine and labradorite anorthosite and carrying local concentrations of ilmenite (*see* Mawdsley, 1927; Rose, 1961). The relationships between magnetic properties and geology in the St-Urbain area of Charlevoix East and Charlevoix West counties are somewhat different from those in the Morin anorthosite. The St-Urbain anorthosite massif (Fig. 4) underlies a magnetic depression in the surrounding rocks and is almost encircled by a belt of strongly positive magnetic hills corresponding to a belt of diorite, gabbroic anorthosite, syenite, granite, and mixed rocks which in places carry disseminations and pods of titanomagnetite and ilmenite.

The St-Urbain ilmenite–hematite deposits (Fig. 5; Pl. III A and B) are associated with a positive magnetic anomaly near the southwest margin of the anorthosite body. Massive ilmenite–hematite vein-dykes in this locality give positive dip-needle readings generally similar to but perhaps slightly lower than those of the enclosing anorthosite. The writer collected several oriented specimens of anorthosite host rock from both hanging-wall and foot-wall parts of these deposits and had them tested in the Geological Survey's geophysics laboratories. They were found to be magnetically stable and positively polarized, but with various inclinations and declinations. Four oriented specimens of massive ilmenite–hematite from these deposits were similarly tested, and like the anorthosite samples were found to be magnetically stable, but two were negatively polarized and two were posi-

tively polarized. This contrast in polarization of the ilmenite–hematite of St-Urbain was not found in samples of ilmenite–hematite from other localities and appears to be a unique phenomenon. All four ore specimens from St-Urbain had different magnetic inclinations and declinations and all possessed intense magnetic remanence. As with the Lac du Pin-Rouge deposit in the Morin anorthosite remanent magnetism in the titanium minerals is undoubtedly an important factor in producing the magnetic anomalies at the St-Urbain ilmenite–hematite deposits. Its main effect is probably to increase the intensity of the positive aeromagnetic anomaly there, but it is not clear how much of the anomaly is produced by the deposits as known or by associated occurrences. Part of the aeromagnetic anomaly in the area of the St-Urbain deposits is undoubtedly due to normal polarization of the ilmenite–hematite in this location; another part may be due to reverse polarization, and an unknown part may be due to the underlying rocks and ores, possibly titaniferous magnetite.

It seems possible that in other localities the component of remanent magnetization might be inclined in such a manner as to merely detract from the resulting magnetic anomaly, and in some cases might be directly opposed so that a reversed or negative anomaly is produced. This opposition of magnetic forces resulting in a negative magnetic anomaly appears to apply to some of the deposits in the Lac Allard area of Quebec including the main deposit at Lac Tio.

Lac Allard Anorthosite Area

The Lac Allard anorthosite is a large, incompletely mapped mass of anorthosite and associated gabbroic rocks in the Grenville province about 25 miles north of Havre-St-Pierre, Quebec (*see* Retty, 1944; Hammond, 1952; and Hargraves, 1959a). It carries abundant concentrations of titaniferous magnetite as well as ilmenite–hematite, including one of the largest such deposits in the world at Lac Tio (Fig. 6; Pls. I, II, and VII). Figure 6 shows the outlines of the great Lac Tio ilmenite–hematite orebody with the aeromagnetic contours superimposed on the geological map. The orebody is associated with an intensely negative aeromagnetic anomaly and with negative dip-needle readings. Oriented specimens taken from the deposit by Carmichael (1959) and by Hargraves (1959a, b) proved to be uniformly negatively (reversely) polarized with a strong remanence. Oriented specimens of the ore and hanging-wall capping gabbroic anorthosite host rock taken by the writer also proved to be reversely polarized; they were magnetically stable, but had different magnetic orientations, that of the ore being almost directly opposed to that of the earth's induced field. There is little doubt that reversed remanent magnetism is the cause of the negative magnetic anomaly associated with the ilmenite–hematite ore at Lac Tio as was concluded by Bourret (1949), since directly associated magnetite is negligible and the direction of remanence is opposed to the present induced field.

The negative anomaly and orebody at Lac Tio lie within a much larger belt of mainly strong positive aeromagnetic anomalies and other associated negative

FIGURE 6. Lac Tio ilmenite deposit (*from* E. O. Dearden, Quebec Iron and Titanium Corporation, 1962).

anomalies. An office analysis by Brubaker and DeVore (1955, unpbl.) of the available geological and aeromagnetic maps indicated that a number of other negative anomalies in the Lac Allard area are associated with ilmenite deposits, but in a few places massive ilmenite occurrences gave no anomaly. Negative anomalies exist at eight, and positive anomalies at four areas of disseminated ilmenite–hematite. From these observations they concluded that disseminated ore may cause either positive or negative anomalies, or that disseminated ore might be underlain by massive ore. Subsequent detailed ground surveys by Kennco indicated that in the Lac Allard area all massive ilmenite deposits produce negative anomalies and disseminated oxides produce positive anomalies (pers. com., C. H. Burgess, Vice-president, Kennecott Copper Corporation, 1962).

As it is probable, however, that many of the massive ilmenite–hematite occurrences in the Lac Allard area and elsewhere are directly or indirectly associated with large quantities of disseminated titanomagnetite, together forming what is known as titaniferous magnetite deposits, the material at depth may be considerably different from that at surface in some of the deposits. As the magnetic susceptibility of titanomagnetite is generally much higher than that of ilmenite–hematite the magnetic properties of the mixture are largely controlled by the titanomagnetite; the result is generally a strong positive magnetic anomaly. But when ilmenite–hematite predominates, its magnetic influence, in the form of a hard component of remanent magnetism, is more strongly felt and it may either decrease or increase the resultant magnetic anomaly. Generally its effect is to reduce the intensity of the anomaly since its polarity is commonly reversed and inclined in a direction different from that of the magnetic field being induced at present; but by the same token it is possible that the anomaly may be made either positive as at St-Urbain, or negative as at Lac Tio, by the opposition of remanent and induced magnetism where the former predominates and is either normally (positively) or reversely (negatively) polarized.

Sept-Îles Anorthosite

The Sept-Îles anorthosite body occupies a semicircular area around Baie des Sept-Îles (Seven Islands) about 300 miles northeast of Quebec city (Map 1238A). It was investigated by Dulieux (1912) and mapped by Faessler (1942) for the Quebec Department of Mines. Its exposures consist largely of gabbroic anorthosite carrying local disseminations and concentrations of ilmenite and titaniferous magnetite, with a marginal zone of less mafic anorthosite. Complex intrusive relationships are exhibited locally.

As outlined by Faessler the relationship of aeromagnetic data to the anorthosite around the bay is shown on Figure 7. This figure shows the same general type of magnetic pattern as is illustrated by the anorthosite massifs shown on Figures 2 and 4, with local variations caused by geological complexity. The zones most favourable for investigation are clearly indicated by the areas of magnetic anomaly.
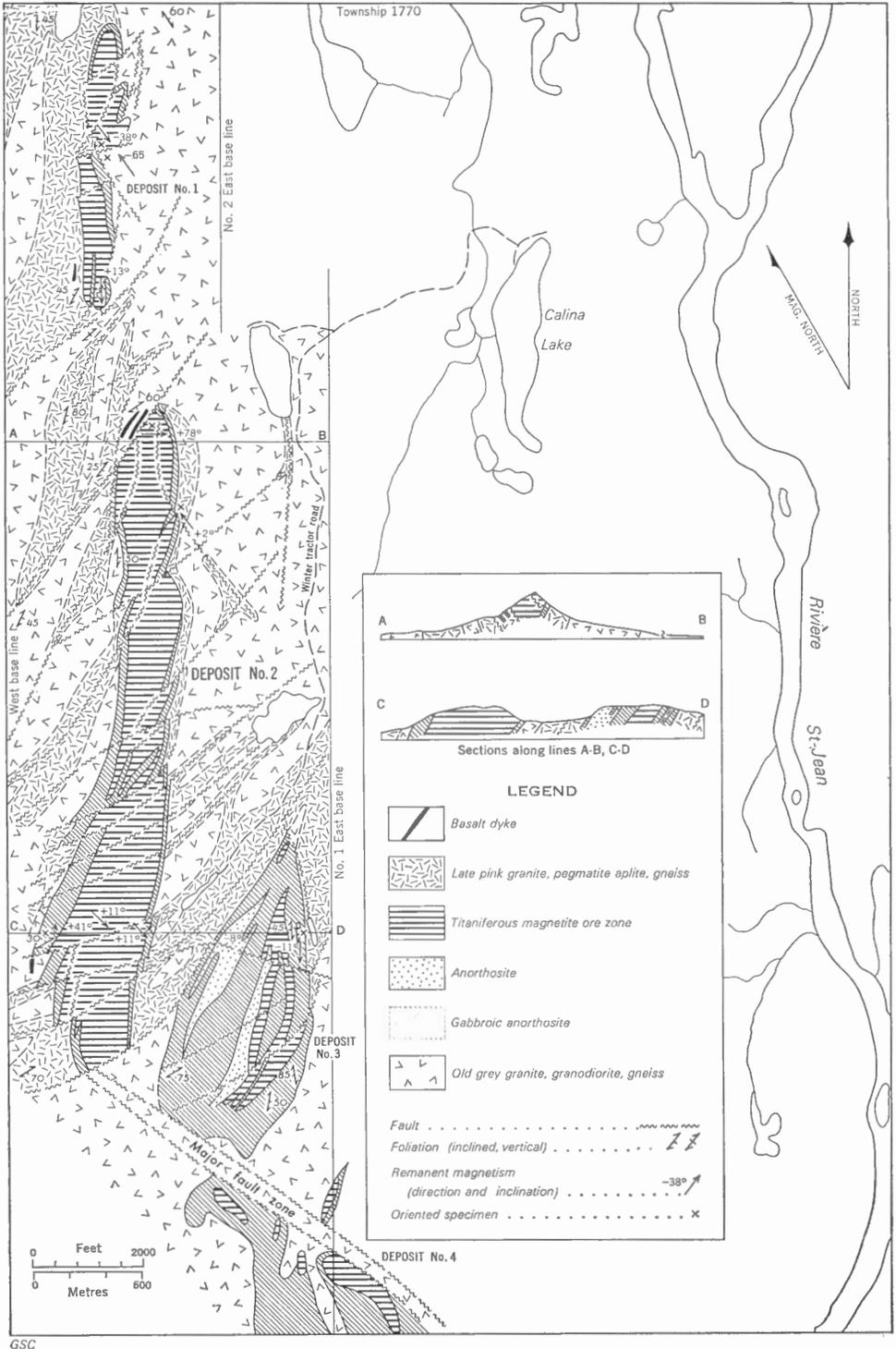
FIGURE 8. Magpie Mountain titaniferous magnetite deposits (*from* J. R. Mowat, Stratmat Ltd., 1962).

Magpie Mountain Deposits

The Magpie Mountain titaniferous magnetite deposits form a series of great dyke-like masses associated with gabbroic anorthosite that is intrusive into Grenville-type granitic gneisses about 78 miles north of Mingan, Quebec, and 50 miles northwest of the Lac Tio ilmenite deposit. The deposits have been investigated and mapped by J. R. Mowat for Stratmat Ltd., and were examined by the writer in 1961. They are shown in Figure 8, and Plate VI A.

Although aeromagnetic maps and ground magnetic surveys of the Magpie Mountain deposits are not yet available for comparison, preliminary magnetic sampling by the writer suggests unusual characteristics. Scattered dip-needle readings indicate strong positive magnetic attraction in many places on the deposit, but in a few places weak readings indicating a balance of magnetic forces, or negative readings indicating a reversal of polarity, have been obtained. The writer's study of the magnetic properties and remanent magnetism of oriented specimens from the deposits and wall-rock has indicated that the deposits are positively polarized for the most part, but in places they are reversely polarized. Moreover, their component of remanent magnetism is very important; it is generally inclined gently towards the southeast almost opposite to the direction of the present induced field of the earth and to the stable component of remanent magnetism in the host rock granite. This Magpie Mountain titaniferous magnetite occurrence is most unusual in that it carries a strong and significant component of remanent magnetism. Also, this component of remanent magnetism conflicts with that of present induced magnetism in many places in the deposits nullifying the field, and in a few places the samples are also reversely polarized. There are several possible explanations that might account for the reversals in polarity, such as overturning of the deposit after magnetization, lightning strokes, reversals of the earth's field, and self-reversing mechanisms, but it is not possible to properly assess these possibilities at this time. The generally opposite inclination, stability, and intensity of the component of remanent magnetization however, are suggestive of an ancient field reversal in post-Grenville time, perhaps due to the reversal of the earth's field subject to the modifying influence of a large magnetic body in the area to the southeast. Although the deposits were formed about 930 million years ago according to K–Ar measurements made for the writer, it is not certain that this remanent magnetism was acquired at that time, and it is possible that the polarity and inclination are due to self-reversal.

Summary

The magnetic data associated with titaniferous minerals and rocks are difficult to interpret. In general, however, within the domain of anorthositic rocks, broad zones of magnetic highs are characteristically associated with gabbroic, oxide-rich phases of anorthosite in which the titaniferous magnetite deposits commonly occur. In contrast to this, zones of magnetic lows are characterized by the occurrence of true anorthosite in which concentrations of ilmenite are commonly indicated by negative anomalies. Ilmenite deposits may be represented by a null or

positive magnetic anomaly in some places; in others titaniferous magnetite occurrences may be associated with low or negative magnetic anomalies because of reverse remanence.

Gravity Surveys

The Dominion Observatory has made general gravimetric surveys over large areas of Canada including that part of the Canadian Shield in which some of the anorthosite bodies are located. Their gravity maps generally show areas of gravity lows, that is, negative gravity anomalies, over or near the anorthosite bodies. These results, somewhat similar to those obtained over large granitic batholiths, suggest a similarity in form and character between the two types of intrusions. Gravity lows associated with pure anorthosite are to be expected, but it would be surprising to find them associated with gabbroic and oxide-rich phases of the anorthosites which have a much higher specific gravity than the average igneous rock; this should give high gravity readings and positive gravity anomalies.

Specific gravity determinations made in the Geological Survey laboratories from samples of gabbroic anorthosite, some of which were rich in iron–titanium oxides, ranged from 2.7 to 4.5, the average being 3.5. Table VIII lists the specific gravity of various rocks and minerals tested. Indeed, because of its high specific gravity and resistance to corrosion, massive ilmenite–hematite from the St-Urbain and Ivry deposits has recently been used as a source of heavy aggregate in concrete for laying natural gas pipelines under rivers, lakes, and bogs in Canada.

Detailed gravimetric surveys should be useful in outlining areas of gabbroic rock as well as concentrations of heavy iron–titanium oxide minerals in anorthosite. They have been used to good advantage in conjunction with aeromagnetic and ground magnetic surveys by E. O. Dearden and others in the Lac Allard area. This suggests that detailed gravimetric surveys are helpful in outlining the relatively restricted areas of high-density gabbroic rocks and titaniferous deposits that may be associated with any particular anorthosite body. The main factor controlling the gravity anomaly is likely to be the predominating low density mass of the anorthosite body which has a tendency to override the localized positive influence of relatively small dense bodies, and also to some extent even in detailed surveys.

Chapter IV

GEOLOGICAL RELATIONSHIPS OF TITANIFEROUS
DEPOSITS AND ANORTHOSITES

Most of the titanium in the earth's crust is in gabbroic and anorthositic rocks in the ancient Precambrian Shield areas of the world. The 2½ million square miles of the Canadian Precambrian Shield is the largest of the earth's shield areas, and it is well supplied with rocks favourable for occurrence of titanium. The southeastern part of the Canadian Shield (known now as the Grenville structural province) and its northeastern extension into the coast of Labrador (the Nain structural province) and western Newfoundland are particularly well noted for their tremendous development of anorthositic and gabbroic rocks and their associated titanium-rich occurrences. Other regions of the Canadian Shield, notably the Superior, Churchill, and Slave structural provinces, also contain anorthositic rocks with associated titanium concentrations, but most of the anorthosites now known there appear to be of a layered, sill-like or dyke-like nature and of smaller dimensions than those of the Grenville and Nain provinces. The layered type of anorthosite commonly forms narrow bands in much larger differentiated layered lopolithic intrusive complexes, like those of the Bushveld complex in South Africa and the Stillwater complex in Montana. The Duluth gabbro in Minnesota, and the Sudbury irruptive, Nipissing diabase, and Logan sills in Ontario should also be noted as having minor differentiated anorthosite bands or segregations. Shield areas of Africa, Australia, Europe, and Asia also contain large bodies of anorthosite.

Anorthosites are not, however, entirely limited to Precambrian Shield areas, but have also been found in younger mountain belts. At least one such Canadian occurrence of Tertiary (post-Eocene–pre-Miocene) age is known at East Sooke on the southwest tip of Vancouver Island in British Columbia (Cooke, 1919), and certain anorthositic phases of the Quebec Monteregian intrusions, which are now indicated to be of Jurassic or Cretaceous age (i.e., about 125 million years old; Larochelle, 1962), are in places carriers of titaniferous magnetite. In western Newfoundland the Bay of Islands igneous complex of ultrabasic rocks of Palaeozoic age has minor layers of associated anorthosite, and some of the anorthosites and lode deposits in the U.S.S.R. are reported to be of Palaeozoic age. The diabase Palisade sills of the Hudson in New York State, of Triassic age, also carry some minor differentiated anorthosite phases. In Europe the ring-dyke complexes of the Isles of Skye and Rum of Tertiary age also contain minor anorthositic layers.

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As shown on Map 1238A, most of the occurrences and deposits of titaniferous minerals in Canada are associated with large bodies of anorthositic rocks. In detail, most of the occurrences are more directly related to gabbroic or noritic phases of the anorthositic bodies which are in turn closely related genetically to the true anorthosite phase. The striking spatial relationship exhibited by bedrock titaniferous deposits and anorthositic masses, not only in Canada but elsewhere throughout the world, is one of the most outstanding and convincing of geological relationships, and it forms a most solid foundation from which to speculate on the broader geological problems. Because of the close association of the titaniferous deposits and anorthositic rocks, a knowledge of the latter is necessary before details of the titaniferous occurrences in them can be properly understood. A discussion of anorthositic rocks follows.

The Anorthosite Problem

One of the larger geological problems, specifically in the field of petrology but with ramifications beyond the formation of magma into that of the origin of continents, the earth, and the universe itself, is the origin of anorthosite. This is of particular interest here because of the close association shown by anorthosites and titaniferous ores, and for that reason it is discussed at some length. Anorthosite is commonly regarded as a monomineralic rock consisting essentially of plagioclase feldspar which is generally of labradoritic (high lime) composition. Current Geological Survey usage defines anorthosite as an igneous rock consisting of 90 per cent or more of plagioclase feldspar. It commonly carries less than 10 per cent of extraneous minerals, and these minerals are normally one or more of the following: pyroxene, amphibole, biotite, apatite, ilmenite, titanomagnetite, garnet, rutile, pyrite, pyrrhotite, chalcopyrite, chlorite, and carbonates. The unusual composition of such a rock has created a special problem for petrologists. Intermediate to basic plagioclase feldspar (labradorite), and therefore anorthosite, has an unusually high content of alumina (Al_2O_3) and lime (CaO) (and a rather low silica content) when compared with most other igneous rocks. Similarly it should theoretically have a rather high melting point (above 1,400°F). It does not always show this high melting point, however, presumably because of the presence of other primary minerals, and in places, swarms of exsolved microantiperthitic feldspar intergrowths. Mainly because of this unusual composition and inferred high melting point anorthosites have generally been regarded as of unusual origin; this idea was given great emphasis as a result of the conclusions in 1928 of North America's then leading "magmatist", N. L. Bowen, that anorthosites could not have formed from igneous magma of the same composition. One of the most compelling arguments given by Bowen in support of this conclusion was that anorthosite dykes are rare, and flow rocks and natural glasses of the same composition are unknown. Despite the fact that numerous dykes and other evidence of the intrusive igneous origin of anorthosite have since been found by many geologists in widespread localities, the absence of reported anorthositic flow rocks remains a serious objection to the acceptance of anorthosite as the

product of primary magma. Are there explanations? Perhaps we may see that there are. It must be noted at once that almost all of the large anorthosite bodies are of great age; this plus extensive metamorphism has undoubtedly obscured many primary features and almost precluded the finding of glass.

Of the several theories that have been advanced by some of the most eminent petrologists to account for the origin of anorthosite the most credible is that of magmatic origin proposed by A. F. Buddington (1939b, 1957) as a result of many years of study. In this he is in general agreement with J. H. L. Vogt who first proposed magmatic origin for the rocks and ore at Taberg in Sweden, with R. A. Daly who compiled and collected world-wide information on the subject, and with many other geologists in various fields. Buddington pointed out (1939b, p. 208) that there are predominantly two types of relationships for anorthosite and associated gabbroic, noritic, and troctolitic anorthosite. In Buddington's words (1957, p. 422):

> One type exists as a major layered facies of great differentiated stratiform sheets or lopoliths such as the Bushveld complex of South Africa and the Stillwater complex of Montana, U.S.A., or as minor layered facies of small gabbroic bodies such as that of the Cuillin Hills, Scotland or Preston, Connecticut, U.S.A. The second, or Adirondack type, exists as masses of usually very large, but locally small, areal extent, commonly with a domical structure such as the Adirondack, New York; Morin, Quebec; and St. Paul, Labrador bodies. There may also be sheets with an average composition of gabbroic anorthosite . . . The first or stratiform type of anorthosite was interpreted as a crystal accumulate controlled by gravity from a normal gabbroic magma, the Adirondack type was explained as formed from an intrusive magma equivalent in composition to a gabbroic anorthosite . . . The domical anorthosite massifs usually have gabbroic anorthosite or anorthositic gabbro in the border facies which grade transitionally into the predominant anorthosite of the ore . . . One problem that has been much to the fore in the last score of years is as to whether anorthosites are a product of magma, metasomatism or metamorphic differentiation. Phase petrology can contribute to the solution of this problem.

According to the new evidence of phase petrology submitted by Buddington (1957, pp. 422–430) including plagioclase twinning, exsolved microintergrowths of clinopyroxene in orthopyroxene, and the composition of the titaniferous magnetites, in the rocks of the stratiform sheets, are all consistent with inferred high temperature essential for an origin of the anorthositic facies from a magma. Buddington adds (1957, p. 430):

> New experimental data on the role of water in lowering the melting interval of plagioclase and in radically shifting the cotectic ratio for calcic plagioclase and pyroxene towards the plagioclase component gives additional support to the reasonableness of a magma of gabbroic anorthositic composition from which relatively pure anorthosite could be differentiated.

In opposition to the magmatists Hans Ramberg (1948, pp. 553–570) proposed a theory according to which the anorthosites and their associated titanic ores were formed by metamorphic differentiation owing to recrystallization of rocks of charnockitic affinity—including anorthosites—under granulite facies conditions. According to Ramberg (1952, pp. 264–266) the gravitational field at deep levels in the earth's crust " . . . tends to squeeze out oxygen, silicon, potassium, and

some sodium from the solid rocks and minerals so that here only plagioclase of intermediate composition remains stable, together with pyroxenes, garnet, olivine and ore minerals". Neither the distribution of anorthosites nor their almost exclusive confinement to Precambrian time supports Ramberg's theory (1952) of the development of a more or less continuous anorthositic shell. Nor indeed do their general position and age show any positive correlation with Buddington's earlier concept (1943) of the development of differentiated layers, including some of bytownitic anorthosite, beneath the continents.

In a series of papers on certain anorthositic rocks in Norway, P. Michot (1955a, b, c; 1957) concluded that there part of the anorthosite is of magmatic origin derived from basaltic magma by the assimilation of large quantities of pelitic sedimentary rocks deep within an orogenic belt, and part is developed by metasomatic replacement (anorthositization) of norite. According to these opinions leuconoritic magma was developed by anatexis (melting), the purer anorthosite being inferred to be a post-anatexis residual material. The formation of bands of anorthosite within a norite–granite series of gneisses was related to introduction of K, Na, and Si into norite–anorthosite accompanied by migration of Mg and Fe, which went to form a basic front. Some of these views of the anatexis of sedimentary rocks in producing igneous rocks have long been held by T.F.W. Barth of Norway. He has elaborated on this in a recent paper (1961) in which he stated that the diversity of igneous rocks is caused by sedimentary processes, and that neither anorthosites nor pyroxenites are problems any more. The strong development of anorthositic rocks in ancient metasedimentary terrains known to hold argillaceous and calcareous metasediments, as exemplified by the Grenville structural province of eastern Canada, supports the concept of the development of anorthosite by anatexis or by magmatic assimilation of sedimentary rocks. The high alumina and lime content of each is consistent with these views, but the high iron and titanium content of the associated oxide-rich facies presents another problem not so readily explainable. The notable content and enrichment of aluminum, iron, and titanium in lateritic and bauxite deposits formed by tropical weathering of older rocks does, however, provide at least one possible sedimentary source of these elements and one unsupported answer to the question of source.

Studies of Canadian anorthosites may shed certain light on this controversy. In the writer's experience the Canadian anorthosites form part of composite, multiple, igneous intrusions produced by separation and repeated injection of magmatic differentiates at various stages in their development and including noritic, gabbroic, or troctolitic anorthosite, anorthosite, titaniferous magnetite and ilmenite–hematite lodes, and possibly also granitic rocks. This has resulted in complicated textural and intrusive relationships. Evidence of magmatic conditions is given by intrusive relationships of dyke-like bodies, contact breccias, inclusions of wall-rock, contact alteration coronas, microantiperthitic exsolution intergrowths in plagioclase, and exsolved microintergrowths in the associated iron–titanium oxide mineral series. Very fine grained phases of the Morin anorthosite and its eastern salient appear to be chilled equivalents of anorthosite, in places possibly of extrusive origin. It should be emphasized that the gabbroic phase of the

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anorthositic masses forms a very substantial part of many of these bodies. It is a phase that is intimately related to the anorthosite which grades into anorthosite in many places but generally forms a marginal zone about an anorthosite core, and which commonly also intrudes the anorthosite in the form of dykes and breccia cements. Although certain of the syenites are very similar in appearance to anorthosite, the relationship between granitic rocks and anorthosite is usually much less intimate in contrast with that of the gabbroic phase.

Many of the anorthositic massifs of eastern Canada are located within a terrain of highly metamorphosed crystalline rocks including partly engulfed, folded, and faulted remnants of metasedimentary formations (quartzite, crystalline limestone, etc.), various forms of gneiss and schist, metamorphic pyroxenite and amphibolite, others of igneous origin, but consisting predominantly of granitic gneiss and granite. Despite their obvious intrusive relationship into formations of the older gneissic terrain as revealed by broad structures and by detailed contact relations, the anorthosites are in many places intruded by younger granitic rocks. F. F. Osborne (1928) was strongly of the opinion that the younger granitic rocks, quartz monzonite, syenite, granite, and pegmatite, are genetically related to and comagmatic with the anorthosites as was suggested by Bowen (1917). Other workers are not so convinced (cf. Lodochnikow, 1925). At the present state of knowledge of the distribution of these rocks it is very difficult to add to this particular point of discussion regarding the granitic rocks. Hargraves (1959a) suggested that the pyroxene syenite gneiss at the border zone of the Lac Allard anorthosite was produced by metasomatism associated with intrusion of gabbroic anorthosite magma. It seems clear, however, that in places bodies of granitic rocks have intruded and metamorphosed the anorthositic masses (Jooste, 1958; Blais, 1960), but elsewhere syenite is also gradational into gabbroic anorthosite and probably comagmatic with it (Blais, 1960). Grout (1928) indicated that on Pigeon Point, Minnesota, anorthosite and syenite are minor differentiates of a diabase sill, and Blais (1960) has shown that minor anorthosite lenses have segregated along definite planes in layered norite constituting an original flow structure.

It is beyond the scope of this report to carry the discussion of the origin of anorthosites further, since the difficulties involved in attempting to distinguish differences in ultimate origin of rocks and ores of great age and complexity, which may have been re-melted, or re-mobilized, or re-constituted, or ultra-metamorphosed during one or more periods of geological time, may be insuperable. E. H. Kranck (1961) has recently presented an excellent review of anorthosites in eastern Canada. The writer echoes his remarks that anorthosites are developed fully as well as granite in eastern Canada, and that one must travel for days within anorthositic terrain without seeing other rocks to properly appreciate the immensity of the anorthosite problem. Kranck (1961, pp. 318–319) concluded that ". . . the formation of anorthosites took place in several stages, and most of them have been repeatedly recrystallized . . . ", and that " . . . the concentration of anorthosite in eastern Canada may depend on the length of time during which the Grenville geosyncline developed".

For all intents and purposes the anorthositic rocks of Canada appear to be mainly of magmatic igneous origin, and they may be regarded as such in the search for the iron–titanium oxide deposits associated with them.

Form, Size, and Grade of Deposits

The titaniferous deposits associated with the anorthositic rocks in Canada include some of the largest known mineral deposits in the world; they range from low-grade disseminations of accessory opaque minerals in rock to lodes of nearly massive ore. Low-grade occurrences are naturally much more abundant than high-grade deposits and most of the iron and titanium associated with these rocks is in the low-grade disseminations of titaniferous magnetite. The high-grade lenses are the plums which the mining companies naturally strive to locate, but more attention might well be diverted to the development of the low-grade deposits.

Billions of tons of low-grade titaniferous magnetite averaging more than 20 per cent iron and 5 per cent titanium are available at widespread localities in Quebec. The dyke-like Magpie Mountain titaniferous magnetite deposits (Fig. 8) are of medium grade, averaging about 43 per cent iron and 6 per cent titanium. They probably include more than 250 million tons, possibly more than a billion tons, of open-pit material. The sill-like Lac Tio ilmenite–hematite deposits (Fig. 6) are estimated to hold about 100 million tons of high-grade open-pit material, and many millions (perhaps billions) of tons of lower grade material is probably disseminated through the gabbroic anorthosite rock of the region. More than 20 million tons of high-grade ilmenite–hematite is estimated in the dyke-like deposits now established at St-Urbain (Fig. 5). In the Morin anorthosite mass (Fig. 2) several million tons of slightly lower grade ilmenite–hematite, including a high-grade segment in the main pit, is judged to be present in the deposit near Ivry (Fig. 9), and about 19 million tons of similar material has been indicated by diamond drilling in the Lac du Pin-Rouge area of Wexford township, near St-Hippolyte-de-Kilkenny (Fig. 3). In the latter area the ilmenite-rich deposit is gradational into a much larger belt of low-grade titaniferous magnetite through which several billion tons of material grading upwards of 25 per cent combined iron and titanium is disseminated. Substantial deposits of low-grade titaniferous magnetite and ilmenite occur at many other localities in the Morin anorthosite (as indicated on Figs. 2, 3, 10, 11) as well as in the St-Charles deposit and other occurrences in the Lac St-Jean anorthosite. Through the narrow elongated sill-like bands of titaniferous magnetite stretching 14 miles from Seine Bay to Bad Vermilion Lake a considerable tonnage of low-grade material is also represented, partly in the form of high-grade pods and lenses and partly as disseminations. Higher grade dyke-like deposits of smaller tonnage are known at Steel Mountain and Indian Head with disseminations near Labrador Pond, all in western Newfoundland, and at numerous other localities such as the Brazeau-Woods occurrence south of Mattawa in Ontario. Generally, all the anorthositic massifs of the Saguenay district, as well as those at Sept-Îles (Fig. 16), Lac Allard, St-Urbain, and the Morin areas, appear to be

LEGEND

Ilmenite-hematite

Anorthosite

Outcrop boundary . . . .

Foliation (inclined, vertical) . . . .

Joint (inclined, vertical) . . . .

Dip-needle reading . . . . +5°N

To Nantel

Ivry mine road

To Ivry-Nord

+5°N

+5°N

+5°N

Overburden

-5°S

+60°N

Dump

Pit

72

Overburden

MAG. NORTH

NORTH

+5°N

+15°N

-10°S

Edge of stripping

Overburden

+5°N

Overburden

+5°N

0°

0°

-20°S

30

60

+5°N

Overburden

-10°S

-10°S

Feet   200

0

0   60

Metres
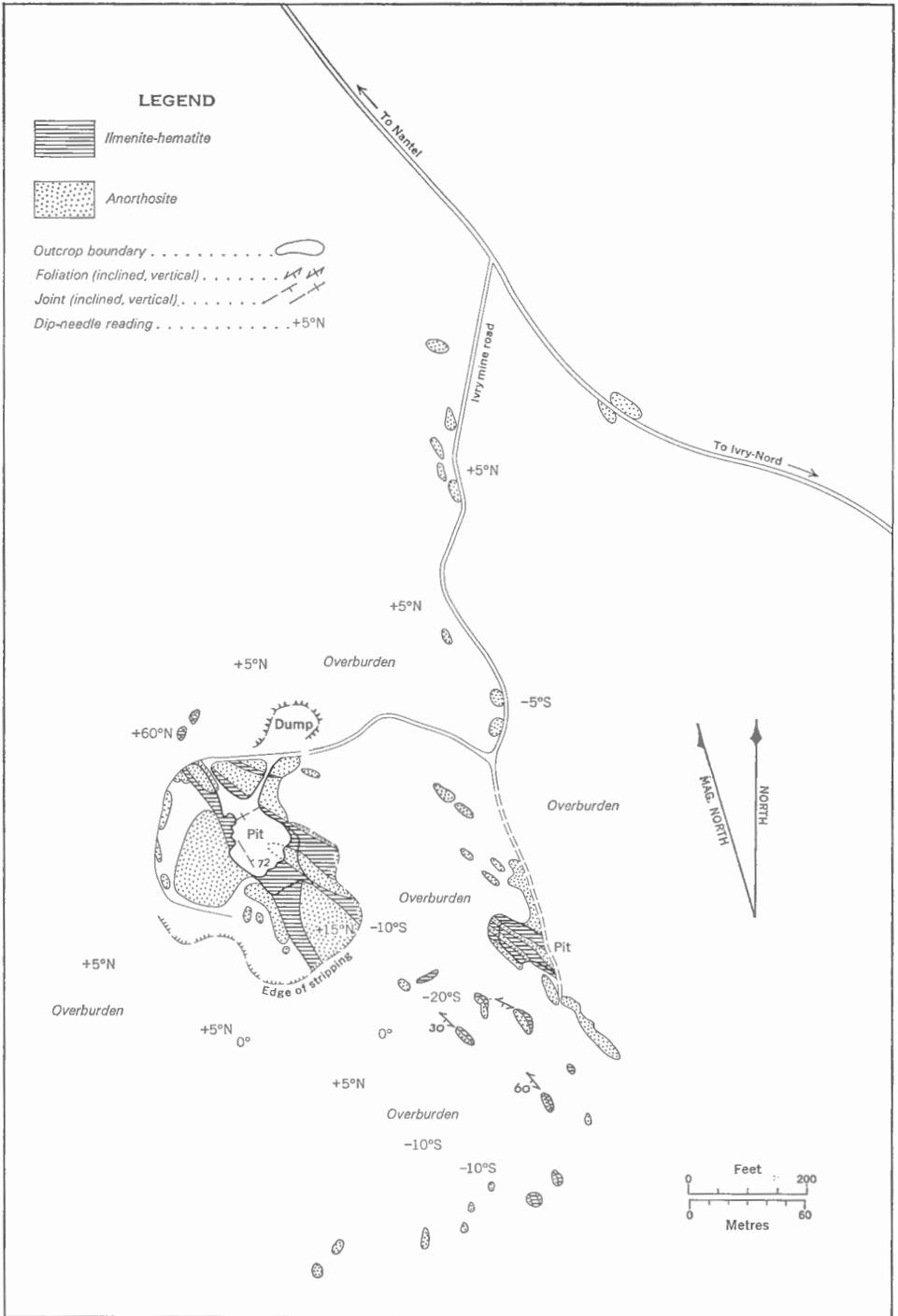
Lots 36, 37, 38, 39, Range V, Beresford Tp., Terrebonne Co., Quebec

GSC

FIGURE 9. Ivry mine ilmenite deposits.

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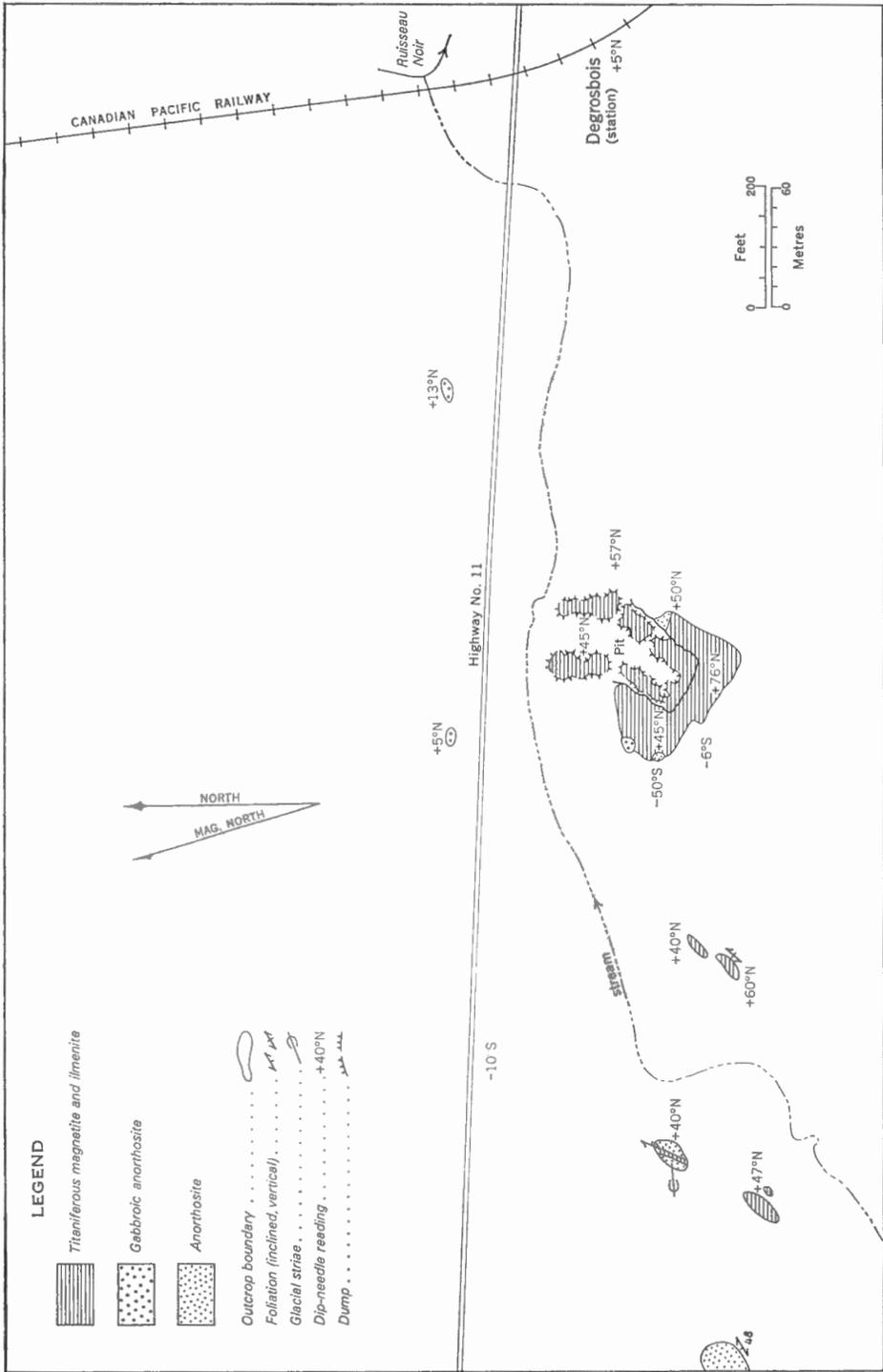
Lots 38, 39, 40, Range VI, Beresford Tp., Terrebonne Co., Quebec

FIGURE 10. Degrosbois titaniferous magnetite deposit.

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LEGEND

Disseminated ilmenite, titaniferous magnetite, and pyrrhotite

Gabbroic anorthosite

Outcrop boundary . . . .
Foliation (inclined, vertical) . . . .
Joint (inclined, vertical) . . . .
Dip-needle reading . . . . +5°N

Lots 26, 27, Range V, Wolfe Tp., Terrebonne Co., Quebec

FIGURE 11. Wolfe township ilmenite occurrence.

potential sources of large tonnages of low-grade titaniferous magnetite. Other possible large sources are the gabbroic and anorthositic rocks of the Chibougamau – Bell River areas in Quebec and those of eastern Ontario and northern Manitoba.

Analytical Results and their Interpretation

The Tables V–VIII and Figures 12–18 appearing in this section were prepared from chemical and spectrographic analyses made in the Geological Survey laboratories on several series of samples collected by the writer, mainly from within a number of the large anorthositic massifs of eastern Canada. They are intended to represent the two main rock phases of the massifs, anorthosite and gabbroic anorthosite as well as their associated mineral deposits, titaniferous magnetite and ilmenite. Direct comparison is made in the tables between analyses of naturally occurring material with those of magnetically concentrated material so that the economically important concentration possibilities of each occurrence is readily evident.

The tables and figures show the gradation in iron and titanium content through the series: anorthosite—gabbroic anorthosite—titaniferous magnetite—ilmenite, confirming the view that they form an interrelated group of rocks and minerals.

As shown graphically in Figure 12, the Fe:Ti ratio of anorthosite is usually lower than that of granite and other felsic and mafic igneous rocks, and this ratio declines as the total iron plus titanium content increases from oxide-rich gabbroic anorthosite, through the average titaniferous magnetite in Canada, to the average Canadian ilmenite. Figure 13 shows the relationships between the iron and titanium content of various rocks and the average Canadian titaniferous ores and indicates the gradational nature, with respect to iron and titanium, of these rocks, protores, and ores.
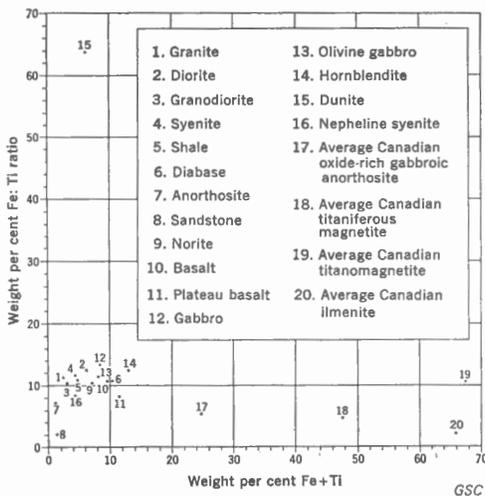
FIGURE 12

Fe and Ti plot against Fe:Ti showing relationships of average rocks, titaniferous magnetites, and ilmenites.
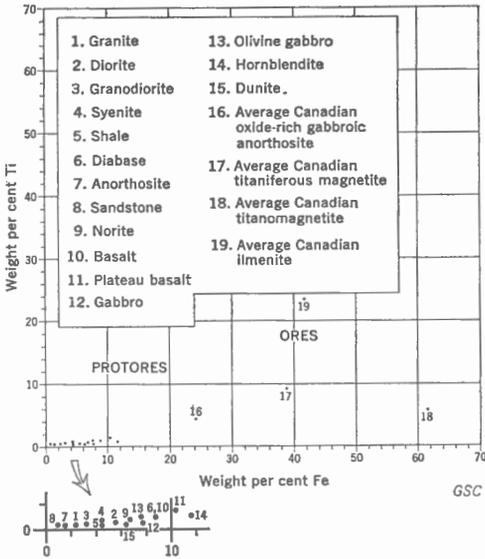
FIGURE 13

Fe plot against Ti showing relationship of average rocks, titaniferous magnetites, and ilmenite.

Tables V and VI are collections of analyses for iron and titanium of oxide-rich gabbroic anorthosite and titaniferous magnetite from many of the large anorthositic massifs in Canada; they represent selected mineralized areas within each massif as indicated. These tables show in detail how the iron and titanium content and the ratio of these elements varies in the gabbroic anorthosite and titaniferous magnetite, both within a single mineralized belt and from massif to massif. A considerable range in composition is shown by the analyses (Tables III, IV, VIII), but although the gabbroic phases are generally much higher in both iron and titanium than the anorthosite, their iron:titanium ratios are generally slightly lower than those of anorthosite. The ratio of ferric to ferrous iron, however, as shown in Figure 13, increases from gabbro, through anorthosite and granite, to a high in shale and sandstone.

Table V shows variations in the iron–titanium content and ratio in gabbroic phases of the anorthosite massifs in detail. In general it shows higher content of iron and titanium, and slightly lower iron:titanium ratios than the anorthosites proper.

Table VI examines titaniferous magnetite samples in the same manner as above, and compares their iron–titanium content and ratio with others from Norway as well as with theoretical values. Here again the iron and titanium content is higher, but the iron:titanium ratio averages close to that of anorthosite and gabbroic anorthosite. A further comparison is made in both Tables V and VI between the iron–titanium content and ratio as shown by the crude ore samples and the magnetic concentrates made from them. This comparison shows the relative ease and feasibility of concentrating these titaniferous ores magnetically, the average concentrate carrying 61.2 per cent iron and 6.0 per cent titanium. It becomes obvious that the iron and titanium content and ratio are largely controlled in these samples by the iron–titanium oxide mineral content.

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TABLE V	Iron–Titanium Content[1] of Gabbroic Anorthosite from Selected Localities in Eastern Canada

Description and location of samples		% Fe	% Ti	Fe:Ti ratio
MORIN ANORTHOSITE AREA	OXIDE-RICH GABBROIC ANORTHOSITE FROM ONE OCCURRENCE			
	Lac du Pin-Rouge, 0–5′	26.9	12.8	2.1:1
	Wexford tp., Quebec 5–10′	21.8	12.7	1.7:1
	45-ft channel sample 10–15′	26.3	10.8	2.4:1
	RG-58, B/49, B/57[2] 15–20′	28.3	11.8	2.4:1
	20–25′	27.0	12.5	2.1:1
	25–30′	24.6	8.9	2.8:1
	30–35′	26.7	8.0	3.3:1
	35–40′	20.4	5.7	3.6:1
	40–45′	22.2	13.5	1.6:1
	Range	20.4–28.3	5.7–13.5	1.6:1–3.6:1
	OXIDE-RICH GABBROIC ANORTHOSITE FROM SEVERAL OCCURRENCES WITHIN THE SAME BELT			
	Lac du Pin-Rouge south o	20.5	6.6	3.1:1
	RG-58[2] c	66.5	0.96	
	North of Lac Moulin o	18.7	3.4	5.5:1
	RG-58, B/42[2] c	65.0	1.03	
	Northeast of Lac de la Roche o	19.7	3.4	5.8:1
	RG-58, B/43[2] c	63.6	1.61	
	Northeast of Lac Adair o	23.9	5.2	4.6:1
	RG-58, B/44[2] c	64.0	2.1	
	South of Lac du Pin-Rouge o	20.4	4.0	5.1:1
	RG-58, B/45[2] c	63.1	1.6	
	Northeast of Lac Moulin o	17.7	4.1	4.3:1
	RG-58, B/46[2] c	64.0	0.96	
	East of Lac de la Roche o	19.3	3.2	6.0:1
	RG-58, B/47[2] c	63.0	1.83	
	Northwest of Lac du Pin-Rouge o	21.3	4.0	5.3:1
	RG-58, B/48[2] c	65.1	2.25	
	Range o	17.7–23.9	3.2–6.6	3.1:1–6.0:1
	c	63.0–66.5	0.9–2.2	

TABLE V (*cont'd*)

Description and location of samples		% Fe	% Ti	Fe:Ti ratio
OTHER OXIDE-RICH GABBROIC ANORTHOSITE OCCURRENCES WITHIN THE SAME MASSIF				
North of Ste-Marguerite Station ·	o	23.3	3.1	7.5:1
RG-60-1[2]	c	61.9	3.6	
Lac Brulé	o	15.7	2.2	7.1:1
RG-60-2[2]	c	60.6	1.2	
St-Faustin	o	11.1	1.7	6.5:1
RG-60-3[2]	c	64.9	2.0	
South of Lac Laurin	o	11.1	1.8	6.2:1
RG-60-4[2]	c	61.5	1.6	
North of Lac Laurin RG-60-5[2]	o	11.8	1.4	8.4:1
Val-David	o	15.1	2.2	6.9:1
RG-60-6[2]	c	61.8	1.9	
Range	o	11.1–23.3	1.4–3.1	6.2:1–8.4:1
	c	60.6–64.9	1.2–3.6	
ST-URBAIN ANORTHOSITE AREA — OXIDE-BEARING GABBROIC ANORTHOSITE				
West of St-Urbain	o	12.4	3.9	3.2:1
RG-60-13[2]	c	64.7	4.0	
East of St-Urbain	o	7.5	1.2	6.2:1
RG-60-14[2]	c	66.7	4.1	
SEPT-ÎLES ANORTHOSITE AREA — OXIDE-RICH GABBROIC ANORTHOSITE				
West of Rivière des Rapides	o	22.5	5.2	4.3:1
RG-60-15[2]	c	57.9	12.0	
East of Rivière des Rapides	o	31.1	3.5	8.9:1
RG-60-17[2]	c	54.6	11.0	
North of Clarke City	o	11.3	1.7	6.8:1
RG-60-18[2]	c	60.0	11.0	
Hall River	o	32.9	10.7	3.1:1
RG-60-16[2]	c	59.5	12.0	
Range	o	11.3–32.9	1.7–10.7	3.1:1–8.9:1
	c	54.6–60.0	11.0–12.0	

TABLE V (*cont'd*)

Description and location of samples			% Fe	% Ti	Fe:Ti ratio
LAC ST-JEAN ANORTHOSITE AREA	OXIDE-RICH GABBROIC ANORTHOSITE				
	Moquin, north of Kenogami RG-60-24[2]	o c	24.2 60.1	5.9 6.2	4.1:1
	Roberval, west of Chambord	o c	24.0 67.2	6.0 0.2	4.0:1
LAC ALLARD ANORTHOSITE AREA	OXIDE-RICH GABBROIC ANORTHOSITE				
	Lac Allard area	o c	14.9 71.3	2.7 0.2	5.5:1
	(Hargraves, 1959a)	o c	17.3 52.7	0.4 0.4	43:1
	(Hargraves, 1959a)	o c	23.6 65.3	0.6 0.2	40:1
	(Hargraves, 1959a)	o c	19.6 64.3	0.4 0.2	49:1
	Range	o c	14.9–23.6 52.7–71.3	0.4–2.7 0.2–0.4	5.5:1–49:1
EASTERN ONTARIO	OXIDE-BEARING GABBROIC ANORTHOSITE				
	Newboro	o c	25.7 62.7	3.2 4.5	8.0:1
	Wilkinson area (Harrison, 1944)	o	8.5	1.3	6.5:1
	Tichborne area (Harrison, 1944)	o	8.4	1.1	7.6:1
NORTH-WESTERN ONTARIO	OXIDE-RICH GABBROIC ANORTHOSITE				
	Bad Vermilion Lake area RG-60-21[2]	o c	27.1 61.7	3.5 10.0	7.7:1 6.2:1
NEWFOUND-LAND	OXIDE-RICH GABBROIC ANORTHOSITE				
	Indian Head RG-61-P-6[2]	o c	25.0 69.3	3.0 1.4	8.3:1 49:1

TABLE V (*conc'd*)

Description and location of samples			% Fe	% Ti	Fe:Ti ratio
GENERAL AVERAGES	OXIDE-RICH GABBROIC ANORTHOSITE EASTERN CANADA				
	Total Range	o	7.5–32.9	0.4–10.7	2.3:1– 19.0:1
		c	52.7–71.3	0.2–12.0	5.2:1–211.0:1

[1]All analyses by GSC chemical laboratory except where otherwise indicated
[2]GSC sample number, Table VIII
o = rock or ore material
c = magnetic concentrate therefrom (largely titanomagnetite)

TABLE VI | *Iron–Titanium Content[1] of Titaniferous Magnetite and Magnetic Concentrates (Titanomagnetite) from Selected Localities in Eastern Canada*

Description and location of samples			% Fe	% Ti	Fe:Ti ratio
MORIN ANORTHOSITE AREA	TITANIFEROUS MAGNETITE FROM A SINGLE DEPOSIT				
	Lac du Pin-Rouge RG-58, B/41[2]	o c	23.9 44.1	10.2 18.7	2.3:1
	(Mines Branch)	o c	24.2 69.4	5.5 0.2	4.4:1
	(Mines Branch)	o c	24.2 52.6	11.2 1.3	2.1:1
	Range	o c	23.9–24.2 44.1–69.4	5.5–11.2 0.2–18.7	2.1:1–4.4:1
	TITANIFEROUS MAGNETITE FROM OTHER DEPOSITS IN THE SAME BELT				
	Lac Adair RG-58, B/44[2]	o c	23.9 64.5	5.2 1.9	4.6:1
	Lac Moulin RG-58, B/42[2]	o c	18.7 62.8	3.4 1.1	5.5:1
	TITANIFEROUS MAGNETITE FROM OTHER DEPOSITS IN THE SAME MASS				
	Ste-Marguerite Station RG-60-1[2]	o c	23.3 61.9	3.1 3.6	7.5:1
	Degrosbois RG-60-9[2]	o c	41.4 62.9	6.1 4.2	6.8:1

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TABLE VI (*cont'd*)

Description and location of samples			% Fe	% Ti	Fe:Ti ratio
SEPT-ÎLES ANORTHOSITE AREA	TITANIFEROUS MAGNETITE				
	Road to Lac des Rapides	o	42.2	8.5	4.9:1
	RG-60-19[2]	c	61.5	10.0	
	Hall River	o	32.9	10.7	3.1:1
	RG-60-16[2]	c	59.5	12.0	
LAC ST-JEAN ANORTHOSITE AREA	TITANIFEROUS MAGNETITE FROM A SINGLE DEPOSIT				
	St-Charles	o	38.7	8.9	4.3:1
		c	60.8	10.0	
	(Robinson, 1922)	o	42.0	9.6	4.3:1
		c	52.1	12.6	
	TITANIFEROUS MAGNETITE FROM ANOTHER DEPOSIT IN THE SAME MASS				
	Kenogami tp.	o	41.75	10.3	4.1:1
	(Mines Branch)	c	59.7	6.0	10:1
RIVIÈRE ST-JEAN – MAGPIE LAKE AREA	TITANIFEROUS MAGNETITE FROM SEVERAL DEPOSITS IN SAME BELT				
	Magpie No. 1	o	43.7	6.0	7.3:1
		c	48.7	10.0	4.9:1
	No. 2 north	o	43.5	6.2	7:1
		c	48.3	9.0	5.4:1
	No. 2 south	o	42.7	6.4	6.7:1
		c	43.5	9.0	4.8:1
	No. 3 east	o	40.7	6.2	6.5:1
		c	45.8	9.5	4.8:1
	No. 3 west	o	40.6	6.0	6.7:1
		c	49.3	11.0	4.5:1
	Range	o	40.6–43.7	6.0– 6.4	6.5:1–7.3:1
		c	43.5–49.3	9.0–11.0	4.5:1–5.4:1
PONTIAC CO., WESTERN QUEBEC	TITANIFEROUS MAGNETITE FROM SEVERAL OCCURRENCES				
	Vinton	o	42.9	8.3	5.2:1
		c	71.9	0.2	
	Waltham	o	44.2	8.8	5:1
		c	68.4	1.1	

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TABLE VI (conc'd)

Description and location of samples			% Fe	% Ti	Fe:Ti ratio
EASTERN ONTARIO	TITANIFEROUS MAGNETITE				
	Mattawa	o	32.8	5.0	6.5:1
	(Mines Branch)	c	67.8	0.3	
		o	50.0	8.0	6.2:1
		c	71.1	1.4	
NORTH-WESTERN ONTARIO	TITANIFEROUS MAGNETITE				
	Bad Vermilion Lake	o	48.0	12.0	4:1
		c	61.7	10.0	6:1
NEWFOUND-LAND	TITANIFEROUS MAGNETITE				
	Bishop North	o	53.0	4.5	11.8:1
		c	64.5	6.6	9.7:1
	Bishop South	o	55.8	7.7	7.1:1
	Hayes	o	55.0	9.0	6.1:1
		c	70.5	3.5	20.1:1
	Brinco. 13 samples	o	47.3	11.0	4.3:1
	Range	o	47.3–55.8	4.5–11.0	
		c	64.5–70.5	3.5– 6.6	
GENERAL AVERAGES	TITANIFEROUS MAGNETITE FROM EASTERN CANADA				
	Total Range	o	18.7–55.8	3.1–12.0	2.1:1–11.8:1
		c	43.5–71.9	0.2–18.7	4.5:1–20.1:1
	TITANIFEROUS MAGNETITE FROM NORWAY				
	Storgangen	o	24.2	11.14	2:1
	(Dybdahl, 1960)	c	65.0		
	THEORETICAL MAGNETITE (Dana)		68.8–72.4	0–3.6	
	THEORETICAL ULVÖSPINEL		44.0	16.8	2.6:1

[1]All analyses by GSC chemical laboratory except where otherwise indicated
[2]GSC sample number, Table VIII
o = rock or ore material
c = magnetic concentrate therefrom (largely titanomagnetite)

Table VII, in a similar manner, permits comparison of the iron plus titanium content and ratios of ilmenite–hematite from several of the anorthosite bodies in eastern Canada with the theoretical values and data from foreign occurrences. The Canadian ilmenite occurrences show a range of values that suggests a slightly higher iron content and higher iron:titanium ratio than the theoretical and foreign occurrences. A comparison made between Tables VI and VII shows that while the total iron plus titanium content of the ilmenites is higher than that of the crude titaniferous magnetites, their iron:titanium ratios are lower. The total iron

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plus titanium in the magnetic concentrates made from titaniferous magnetites is generally close to that of the ilmenites, and the iron:titanium ratio of the former is higher and similar to that of the average gabbro. Table VII also indicates that whereas the total iron plus titanium content of the St-Urbain ilmenite is close to that from Lac Tio, it has a lower iron:titanium ratio, close to that of Norwegian ilmenite. The iron:titanium ratio of ilmenite is notably lower than that of

TABLE VII | *Iron–Titanium Content[1] of Ilmenite–Hematite of Eastern Canada and Elsewhere*

Description and location of sample		% Fe	% Ti	Fe:Ti ratio
MORIN ANORTHOSITE AREA	ILMENITE–HEMATITE			
	Ivry (Robinson, 1922)	42.9	19.8	2.1:1
	(Keys, 1936, average of 4)	45.4	19.3	2.3:1
	(Mines Branch)	38.2	19.7	1.9:1
	Lac du Pin-Rouge	44.1	18.7	2.4:1
	RG-58, B/41, C[2]			
	Range	38.2–45.4	18.7–19.8	1.9:1–2.4:1
ST-URBAIN ANORTHOSITE AREA	ILMENITE–HEMATITE			
	Furnace RG-60-12[2]	38.5	26.2	1.5:1
	(Dulieux, 1915)	36.6	24.2	
	(Leverin *in* Robinson, 1922)	45.5	24.3	
	General Electric	34.8	30.4	
	St-Urbain (C.I.T. concentrate)	39.3	44.4	0.9:1
	(Bourret, 1935)	38.3	24.7	
	(Dulieux, 1915)	41.4	24.7	
	Rivière du Gouffre RG-60-11[2]	35.3	23.0	1.5:1
	Range	34.8–45.5	23.0–44.4	0.9:1–1.5:1
LAC ALLARD ANORTHOSITE AREA	ILMENITE–HEMATITE			
	Lac Tio (Q.I.T. concentrate)	43.8	22.9	1.9:1
	(Hammond, 1952)	41.0	20.4	2.0:1
	(Hargraves, 1959a)	44.1	22.9	1.9:1
	(Hargraves, 1959a)	43.4	22.9	1.9:1
	(Carmichael, 1961a)	46.3	23.0	2.0:1
	Range	41.0–46.3	20.4–23.0	1.9:1–2.0:1
GENERAL AVERAGES	ILMENITE–HEMATITE OF EASTERN CANADA			
	Range	34.8–46.3	18.7–44.4	0.9:1–2.4:1
	THEORETICAL ILMENITE (Dana)	36.8	31.6	1.2:1
	NORWEGIAN ILMENITE–HEMATITE (av.)	38.8	25.2	1.5:1
	VIRGINIA ILMENITE–HEMATITE (av.)	32.8	31.6	1:1

[1]All analyses by GSC chemical laboratory except where otherwise indicated
[2]GSC sample number, Table VIII

anorthosite and it increases slightly through gabbroic anorthosite and titaniferous magnetite to gabbro (Fig. 12).

In Figure 14 the ratio of ferric to ferrous iron is plotted against the iron plus titanium content of various rock types. Rocks of low iron plus titanium content such as anorthosite and granite show slightly higher $Fe^{+3}:Fe^{+2}$ ratio than those of higher iron plus titanium content such as gabbro and basalt. Sandstone and shale show higher $Fe^{+3}:Fe^{+2}$ ratios than most of the igneous rocks, excepting dunite.

Figures 15 and 16 show that as iron plus titanium content increases from anorthosite through gabbroic anorthosite to titaniferous magnetite the calcium plus magnesium and sodium plus potassium contents show slight declines. Figures 17 and 18 and Table VIII show, however, that both the iron and titanium oxide contents of these materials increase considerably as the alkali content decreases.
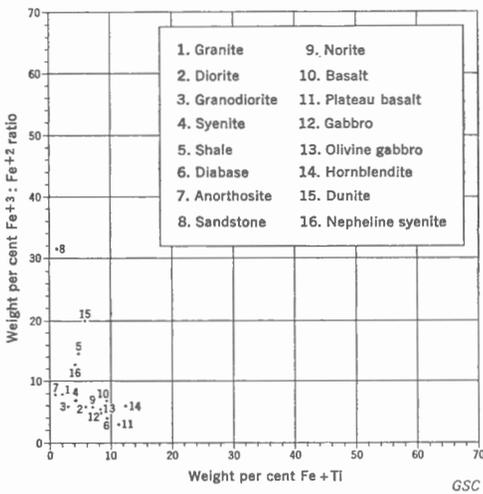
FIGURE 14

Fe and Ti plot against $Fe^{+3}:Fe^{+2}$ showing relationship of average crustal rocks.

FIGURE 15

Fe and Ti plot against Ca and Mg showing relationship of anorthosite, gabbroic anorthosite, and titaniferous magnetite.

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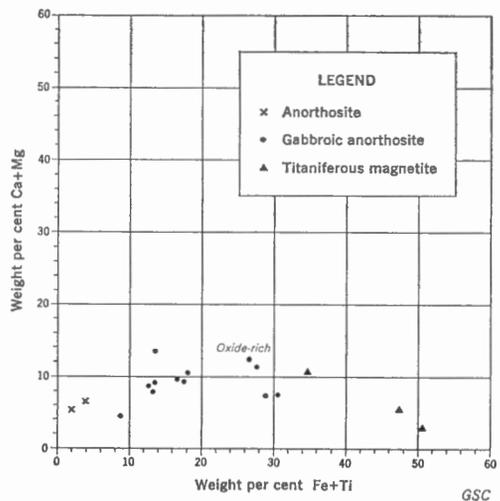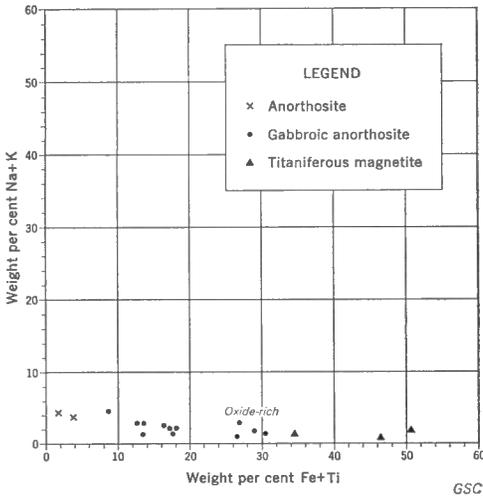
FIGURE 16

Fe and Ti plot against Na and K showing relationship of anorthosite, gabbroic anorthosite, and titaniferous magnetite.

Table VIII supplies a list of complete chemical analyses of anorthosites, gabbroic anorthosites, titaniferous magnetites, and ilmenites from selected areas in Canada. From these it is obvious that the anorthosites are much higher in silica and alumina, and slightly higher in the alkalis, than the gabbroic anorthosites. The latter are significantly higher in iron, titanium, calcium, magnesium, and phosphorus than the former, and perhaps also in traces of other members of the ferride group.

The anorthosites are notably lower in silica and higher in alumina than either the average igneous rock or granite. They come fairly close to phonolite in this regard, but are low in the alkalis. The composition of the gabbroic anorthosites corresponds best with that of diabase, basalt, and gabbro, but gabbroic anorthosites are generally lower in silica and richer in iron, titanium, and phosphorus.

The iron content of the titaniferous magnetites is generally higher and their titanium content lower than that of ilmenites, but the total iron plus titanium content of the titanomagnetite in them is commonly close to that of ilmenite. As shown in Table VI the magnetic concentrate from the average titaniferous magnetite of eastern Canada carries 67.2 per cent iron plus titanium, and the average ilmenite–hematite carries 65 per cent iron plus titanium. Their iron:titanium ratios average 4.3 and 1.8, respectively, as compared with 5.0 for oxide-rich gabbroic anorthosite and 7.1 for anorthosite.

Moreover, as indicated above, iron and titanium appear to increase along with calcium, and as indicated in Table VIII, as the ratio of lime to alkalis increases, so generally does the iron plus titanium content of the anorthositic rocks. The titanium content does not appear to increase at the same rate as the iron, however, and it seems possible that there is a relationship between iron–titanium and lime–alkali content and ratios in gabbroic anorthosites, as indicated in Figures 15, 16, 17, and 18.

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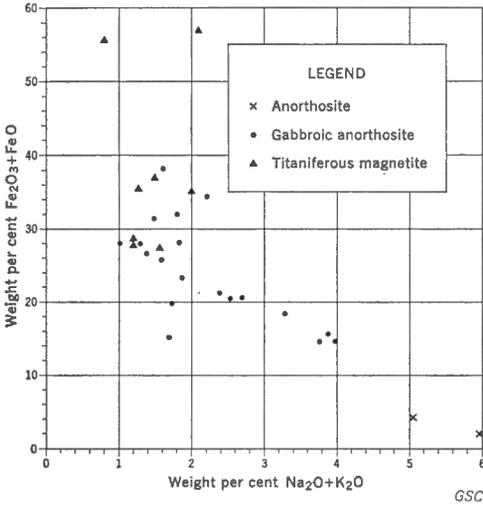
FIGURE 17

Alkali plot against iron oxide content showing relationship of anorthosite, gabbroic anorthosite, and titaniferous magnetite.
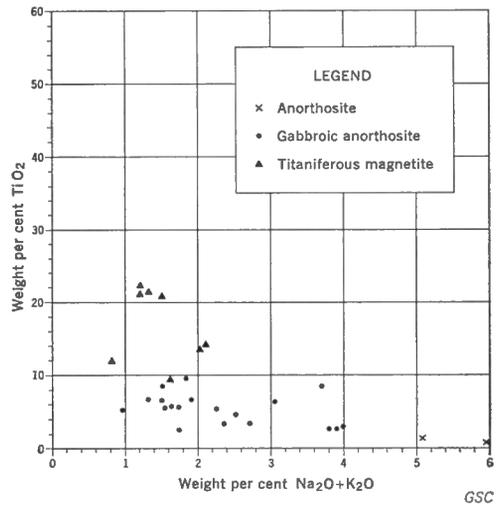
FIGURE 18

Alkali plot against titanium oxide content showing relationship of anorthosite, gabbroic anorthosite, and titaniferous magnetite.

TABLE VIII | *Chemical Analyses (Weight Per Cent) of Anorthosites, Gabbroic Anorthosites, Titaniferous Magnetites, and Ilmenites of Canada*

Constituent	ANORTHOSITE		GABBROIC ANORTHOSITE											
	RG-60-8	RG-60-10	RG-60-1	RG-60-2	RG-60-3	RG-60-4	RG-60-5	RG-60-6	RG-60-13	RG-60-14	RG-60-15	RG-60-17	RG-60-18	RG-60-22
	Ste-Agathe-des-Monts	De-gros-bois	Ste-Mar-guerite	Lac Brulé	N. Lac Laurin	S. Lac Laurin	St-Faustin	Val-David	W. St-Urbain	E. St-Urbain	Sept-Îles	Sept-Îles	Clarke City	New-boro
SiO_2	53.9	55.7	34.8	39.6	48.0	48.1	48.7	40.8	40.3	57.8	26.1	24.9	46.7	31.2
Al_2O_3	23.3	26.7	8.1	13.8	16.1	16.7	9.1	13.5	16.1	13.6	8.8	5.2	15.6	12.0
Fe_2O_3	1.2	0.56	8.7	9.5	6.6	7.7	3.9	9.5	6.8	4.7	10.8	10.6	5.5	19.4
FeO	3.0	1.52	19.6	11.64	8.32	7.32	11.68	10.96	10.68	5.4	19.12	28.36	9.68	15.52
CaO	6.7	7.1	9.2	10.2	8.7	8.5	8.8	9.1	6.6	4.5	13.1	8.9	7.8	6.3
MgO	3.7	0.73	9.9	5.5	4.5	3.6	12.0	5.8	6.1	2.3	3.8	6.8	6.3	4.9
Na_2O	4.5	4.7	0.8	2.1	3.1	3.2	1.5	2.3	2.8	3.1	2.0	1.5	3.3	1.7
K_2O	0.6	1.3	0.18	0.28	0.72	0.82	0.26	0.42	0.54	3.1	1.7	0.16	0.64	0.54
TiO_2	1.1	0.39	5.2	3.6	2.9	3.0	2.3	3.6	6.5	2.0	8.6	5.8	2.9	5.4
P_2O_5	0.09	0.10	2.9	3.0	1.1	1.6	0.07	2.9	1.2	1.0	5.8	5.9	0.42	0.11
MnO	0.01	0.02	0.46	0.26	0.22	0.21	0.26	0.29	0.12	0.11	0.37	0.7	0.24	0.16
V_2O_5														
S														
CO_2	0.54	0.03	0.34	0.07	0.38	0.01	0.13	0.00	0.00	0.13	0.01	0.00	0.3	0.6
H_2O	0.66	0.23	0.54	0.41	0.62	0.56	0.82	0.52	1.0	1.8	0.93	1.2	1.2	1.3
Total	99.3	99.1	100.7	99.9	101.3	101.3	99.5	99.7	98.7	99.5	101.1	100.0	100.6	99.1
Sp. Gr.	2.9	2.7	3.5	3.2	3.0	3.0	3.1	3.1	3.0	2.8	3.3	3.5	3.0	3.4

TABLE VIII (*cont'd*)

					Sample number, location, and description										
		GABBROIC ANORTHOSITE								TITANIFEROUS MAGNETITES					Constituent
RG-60-24	RG-60-25	B/41	B/42	B/43	B/44	B/45	B/46	B/47	B/48	B/53	B/49	B/56	B/57	B/51	
Moquin	Lac Allard	Lac du Pin-Rouge	Lac Moulin	Lac de la Roche	Lac Adair	Lac du Pin-Rouge	Lac Moulin	Lac de la Roche	Lac du Pin-Rouge	Lac du Pin-Rouge channel sample					
29.4	38.1	26.1	35.8	34.4	28.7	34.1	36.3	34.9	31.9	22.2	21.9	23.0	20.1	23.8	SiO_2
12.2	12.9	13.3	10.7	10.2	11.8	10.3	11.7	11.1	9.1	10.2	15.9			10.1	Al_2O_3
11.5	10.6	15.1	9.3	11.9	16.1	12.4	11.2	12.4	12.6	15.6	9.1	16.5	17.9	19.5	Fe_2O_3
20.64	9.88	16.6	15.27	14.21	15.78	14.64	12.34	13.28	15.58	20.02	19.24	18.5	19.8	16.72	FeO
4.7	9.8	5.2	10.6	11.1	8.3	10.0	9.0	9.4	11.4	4.0	4.5			2.9	CaO
7.4	5.2	2.7	5.4	6.0	4.5	6.1	6.4	7.5	7.7	3.1	3.8			1.9	MgO
1.6	2.2	1.5	1.5	1.4	1.3	1.2	1.6	1.5	1.1	1.0	1.0			1.2	Na_2O
0.22	0.3	0.3	0.2	0.2	0.2	0.2	0.3	0.2	0.2	0.3	0.2			0.3	K_2O
9.9	4.5	17.0	'5.6	5.7	8.7	6.6	6.8	5.4	6.7	21.4	21.1	18.0	19.7	20.9	TiO_2
0.11	4.1	0.2	2.6	2.6	1.9	2.1	1.6	2.4	2.8	0.1	0.1			0.1	P_2O_5
0.24	0.15	0.0	0.3	0.3	0.2	0.3	0.2	0.3	0.3	0.0	0.1			0.1	MnO
			<0.01	<0.01	<0.01										V_2O_5
		0.76	0.04	0.28	0.17	0.15									S
0.5	0.0	0.27	0.44	0.03	0.08	0.01	0.06	0.06	0.00	0.05	0.04			0.05	CO_2
0.83	1.0	1.11	0.35	0.96	1.37	0.95	0.74	0.91	0.87	0.48	1.23			1.98	H_2O
99.2	98.7	100.1	98.1	99.2	99.1	99.06	98.2	99.4	100.3	98.5	98.2			99.6	Total
3.3	3.0														Sp. Gr.

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TABLE VIII
(conc'd)

Chemical Analyses *(Weight Per Cent)* of Anorthosites, Gabbroic Anorthosites, Titaniferous Magnetites, and Ilmenites of Canada

				Sample number, location, and description									
		TITANIFEROUS MAGNETITES								ILMENITES			
Constituent	B/55	B/54	B/52	B/50	RG-60-16	RG-60-20	RG-60-21	RG-60-23	RG-60-9	RG-60-19	RG-60-7	RG-60-11	RG-60-12	B/41
	Lac du Pin-Rouge channel sample				Hall River	Vinton	Bad Vermilion	St-Charles	Degrosbois	Lac des Rapides	Ivry	Rivière du Gouffre	Furnace	Lac du Pin-Rouge
SiO^2	27.3	31.4	32.1	20.3	M	M	M	M	10.8	10.3	M	M	M	2.82
Al_2O_3		7.6	11.4	15.5					7.9	10.3				1.97
Fe_2O_3	17.3	15.6	15.6	15.4	15.98	34.91	13.23	25.19	31.4	37.0	23.64	22.35	18.94	26.65
FeO	15.6	19.72	11.82	14.22	27.87	26.81	22.90	27.02	24.85	20.87	27.81	25.24	32.41	33.10
CaO		5.3	8.9	5.2					5.1	2.7				0.54
MgO		2.5	4.9	3.2					3.1	1.8				1.75
Na_2O		1.6	1.3	1.0					0.6	2.0				
K_2O		0.4	0.3	0.2					0.2	0.12				
TiO_2	14.8	13.3	9.5	22.5	17.78	13.86	5.89	14.94	10.2	14.1	32.83	38.28	43.73	31.25
P_2O_5		0.1	1.5	0.1	3.38	0.02	0.02	7.08	3.8	0.15	0.69	<0.01	0.23	0.07
MnO		0.1	0.1	0.1					0.25	0.34				0.19
V_2O_5					0.11	0.28	0.13	0.05			0.20	1.84	0.17	0.4
S					0.25	1.47	0.91	0.04			1.05	0.82	0.06	2.27
CO_2		0.16	0.01	0.22					0.3	0.0				
H_2O		1.69	1.23	0.58					0.58	0.58				
Total		99.5	98.7	98.5	65.37	77.35	43.08	74.32	99.1	100.3	86.22	88.54	95.54	101.01
Sp. Gr.					4.3	4.2	5.9	4.0	4.1	3.6	4.3	4.4	4.5	

Chemical analyses by Geological Survey of Canada chemical laboratory. All determinations except those for FeO, V_2O_5, CO_2. S, and H$_2$O were done as "Rapid Methods" of analysis.
Sp. Gr. = specific gravity; determinations by K. R. Dawson, Geological Survey of Canada, petrographic laboratory.
M = Mines Branch chemical laboratory analysis.

Origin and Age of Deposits

The precise origin of many rocks and mineral occurrences, particularly those of great age and of extreme complexity, is commonly difficult to establish with certainty. There seems little doubt to the writer, however, that the ilmenite and titaniferous magnetite deposits which are so commonly found associated with the anorthosite and gabbroic anorthosite rocks in eastern Canada are genetically related to them. This relationship is apparently also true in the many other localities throughout the world in which these types of rocks and ores are found.

It is interesting to consider whether these rocks and ores are indeed truly igneous, or have passed through an igneous phase, or are merely of igneous aspect. The writer considers that these rocks and ores are of igneous origin because they intrude and metamorphose adjacent older rocks and minerals and to some extent engulf and replace them. The minerals of which the rocks and ores are composed consist mainly of high-temperature types and their textures are characteristic of high temperature–pressure conditions. Only in a few places do they carry low-temperature minerals and these are apparently associated with late-stage ore emplacement mineralization. If these rocks and ores are not of ultimate magmatic igneous origin they presumably must at least have gone through a magmatic phase at one stage in their development. Because of the close genetic relationship between the anorthositic rocks and the related titaniferous deposits their mode of origin is very similar. The titaniferous deposits consist for the most part of primary disseminations and high temperature fluid injections of iron–titanium oxide and gangue minerals which are genetically related to but slightly younger than their associated anorthositic rocks. For further discussion of these topics, the reader is referred to other parts of the report dealing with geochemistry, mineralogy, and particularly to the sections on interpretation of textures and on the anorthosite problem.

Many of the oxide-rich anorthositic rocks intruded Grenville-type rocks before the beginning of the Palaeozoic Era and are thus of late Precambrian (Proterozoic) age; a few are intrusive into Keewatin-type rocks and thus may be early Precambrian (Archaean), possibly associated with the Kenoran orogeny. Titaniferous magnetite occurrences in the Monteregian essexite of Montagne d'Yamaska in the Eastern Townships of Quebec are presumably of Cretaceous or Jurassic age (Larochelle, 1962). The placer deposits of titaniferous magnetite of southwestern Alberta are in sandstones of Late Cretaceous age, and may have been derived by weathering and erosion of the late Precambrian Purcell intrusions and flows. Bedrock occurrences of titaniferous magnetite in anorthosite gabbro of East Sooke on the southwest tip of Vancouver Island are of late Tertiary (Eocene) age and are the youngest known in Canada. Unconsolidated black titaniferous beach sands of Recent age are of widespread occurrence in many parts of Canada.

Absolute age determinations by the K–Ar method made by the Geological Survey of Canada on various samples of primary biotite mica collected by the writer and associated with the emplacement of the ores (Lowdon, 1960, 1961)

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indicate that the Indian Head deposits in western Newfoundland were formed about 900 ± 45 million years ago; those at St-Urbain, Quebec, 890 ± 44 million years ago; those at Lac Tio, Quebec, less than 1025 ± 60 million years ago; those at Magpie Mountain, 930 ± 46 million years ago; and those in Litchfield township, Quebec, 940 ± 47 million years ago. These titaniferous deposits measured from western Newfoundland to western Quebec thus fall within an age range, including experimental error, of about 840 to 1100 million years. A pegmatite dyke that intrudes the Lac St-Jean anorthosite, and is therefore younger, was similarly found to be 865 ± 43 million years old (822–910 m.y.), somewhat younger than the normally accepted value for Grenville-age pegmatites.

The absolute ages assigned depend on the measure of the ratio of the potassium isotope (K^{40}) and inert argon (Ar) in the ore and rock samples as well as the fairness of the samples selected. Their geological history is a most important consideration. The intensity, length of duration, and number of orogenies and metamorphism to which they have been subjected leave variable effects, and the dates presented must be regarded only as good attempts to establish the age of these rocks and ores as they are found today.

It is well known that at least one and probably several periods of orogeny have affected rocks within the Grenville structural province. This period or periods of Precambrian orogeny were accompanied both by high-grade metamorphism of the Grenville rocks and by widespread intrusion of igneous rocks that range from granite to gabbro in composition. The name Grenville has been applied to this period of orogeny and it has been assumed that it occurred over a 260-million-year period of time about a billion years ago. It is within this period that the anorthositic rocks and the titaniferous ores associated with them appear to have formed, but since both Grenville-type and anorthositic rocks have been intruded by younger granite of late Precambrian age, it is probable that both types of rocks may be older than the 840–1100 million years the K–Ar dates suggest.

Chapter V

DESCRIPTION OF AREAS OF OCCURRENCE AND DEPOSITS IN CANADA

Titaniferous deposits of both primary lode and sedimentary type are found in Canada, but the primary lode deposits undoubtedly form the greatest resource. The lode deposits comprise rutile, ilmenite, titaniferous magnetite, sphene, and perovskite occurrences; of these the ilmenite and titaniferous magnetites carry by far the greatest reserves of titanium in this country. Primary ilmenite and titaniferous magnetite deposits are most abundant in the provinces of Quebec and Ontario, and important titaniferous magnetite deposits are known in western Newfoundland and northern Manitoba. Other occurrences have also been reported from Alberta, British Columbia, and the Northwest Territories. Minor amounts of rutile of mineralogical interest have been reported in Templeton township, Beauce county, and Brome county in Quebec; from Algoma district and Hastings county in Ontario; from Halifax county and Kings county in Nova Scotia; and from Thistle Creek in the Yukon Territory (Robinson, 1922, pp. 44–45).

Dark sands carrying iron–titanium minerals are of widespread occurrence on modern and raised beaches along the north shore of the St. Lawrence River, on inland lakes in Quebec and Labrador, and along the Pacific coast of British Columbia on the Queen Charlotte and Vancouver Islands. Consolidated dark titaniferous sands form thin but extensive beds in sedimentary rocks of Cretaceous age in the Burmis and Dungarvan areas of Alberta.

Newfoundland

In the uplands of Newfoundland, not far from St. George Bay,
There shines a mountain made of steel,
Or so the stories say,
But, to reach it one must face the hidden perils of the trail,
That passes through Hells Gulch,
Beyond Skull Mountain's pale.

Substantial deposits of titaniferous magnetite occur in the Steel Mountain area of western Newfoundland. The deposits occur as segregations and injections in a body of anorthosite that is intruded into gneisses of the Long Range complex, and which on its west side is in fault contact with sedimentary rocks including coal and gypsum deposits of Carboniferous age. The main titaniferous magnetite deposits are the Bishop North, Bishop South, and Hayes prospects, but several others are known within the one anorthosite mass.

Poems by E. R. Rose.

About 10 miles to the northwest, separated by a lowland that is underlain (presumably entirely) by sedimentary rocks of Carboniferous age, a smaller body of anorthosite and gabbroic anorthosite is found in the Indian Head Peninsula. Granitic rocks intrude anorthosite and gabbroic anorthosite in places, and a number of small deposits of titaniferous (high titanium) and non-titaniferous (low titanium) magnetite and hematite occur in the rocks of the igneous complex and are presumably related to them.[1] The granitic rocks of this area have been dated at 830 ± 41 million years. A sample of biotite collected by the writer from a pegmatite dykelet that cuts the interbanded titaniferous magnetite and gabbroic anorthosite at the Indian Head mine was dated at 900 ± 45 million years by K–Ar measurements in the Geological Survey laboratories.

Steel Mountain – Flat Bay Brook Area

The geology and mineral deposits of this area were mentioned by Brunton (1913) and Singewald (1913b), discussed by Buddington (1939a), and described in detail by Baird in 1943 (1954). They have recently been investigated by the British Newfoundland Corporation Limited (Brinco) and were the subject of a report by George Rejhon (1957). A Geological Survey of Canada report and map by George Riley (1962) and aeromagnetic Map 251G have been published for this area. Dip-needle surveys of some of the deposits were made by Baird for the Geological Survey of Newfoundland in 1943 but no diamond drilling or further development has ensued. A K–Ar age determination on chlorite extracted from the gabbroic anorthosite of Flat Bay Brook indicates that the mineral is at least 451 million years old. The orientation of direction of remanent magnetism in the titaniferous deposits associated with the anorthosite mass is apparently random and subordinate to induced magnetism. This reflects the instability of the magnetization of the deposits.

Bishop North

The Bishop North prospect is the largest exposure of massive titaniferous magnetite in the area. Coarse-grained, blue-black titaniferous magnetite forms a dyke-like body about 50 feet wide that is exposed for a length of 300 feet on the crest of a rolling hill of grey anorthosite (see Pl. VI B). The vein-dyke cuts abruptly through the anorthosite, trends north-northeasterly, and apparently dips steeply to the west. The deposit consists almost entirely of coarse-grained inter-locking crystals of titanomagnetite as much as three-quarters of an inch long, with a few included grains of plagioclase, pyroxene, and green spinel. There is little evidence of metamorphism along the contacts, and the host anorthosite

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[1] Small outcrops of anorthosite and granitic gneiss on Journois Brook, reported by Baird in 1958, are associated with a gravity high and an extensive aeromagnetic high (Riley, 1962) that suggests a large, partly exposed inlier of gabbroic rocks within the Carboniferous lowland west of Steel Mountain. Anorthosite is reported to underlie the gypsum deposits south of Journois Brook at a shallow depth (pers. com., Dr. L. M. Cumming).

consists almost entirely of plagioclase. The south end of the deposit is slightly sheared parallel to the westerly trending draw which truncates it. About 500 feet to the north a westerly trending diabase dyke also cuts through the ore zone.

As a result of detailed mapping Baird estimated the deposit to be 650 feet long, averaging 30 feet in width, and carrying 800,000 tons of high-grade ore, specific gravity 4.54, to an assumed depth of 325 feet. There is no direct evidence of the actual depth extent of the deposit.

Under the microscope the ore material is shown as an interlocking mosaic of grains of creamy brown coloured isotropic titanomagnetite. Most of these grains show well-developed octahedral cleavage and an almost submicroscopic intergrowth of an anisotropic mineral, presumably ilmenite, which forms a rectangular or octa-hedral pattern following octahedral parting planes in the magnetite. This pattern is emphasized by elongated spindles of a gangue mineral, probably spinel, that are also oriented parallel to the cleavage directions. In some of the grains the inter-growths are more abundantly developed in the cores than on the margins. Relict, circular, and spindle-shaped grains of spinel are almost completely replaced by magnetite which contains tiny patches of other included gangue minerals. A con-siderable amount of anisotropic ilmenite is developed between magnetite grains, and in places ilmenite projects into magnetite. The ilmenite is generally clear, but sometimes shows a few narrow anisotropic blades, or sets of blades, presumably of hematite, which form a rhombohedral pattern following the rhombic structural planes of the host ilmenite.

Although some reduction of titanium might be obtained by separation of the free ilmenite grains, the intimacy and fine-grained character of the other ilmenitic intergrowths in the magnetite preclude a complete separation of titanium from the magnetite by mechanical processes. Samples of the deposit taken by the Geological Survey of Newfoundland (G.S.N.) (Baird, 1943) and by Brinco (Rejhon, 1957) showed upon analysis:

	G.S.N. %	Brinco %
Fe	52.63	55.06
Ti	7.43	8.13
V	0.47	nil
S	0.008	—
P	nil	—
SiO_2	0.13	—

A magnetic concentrate made from a sample of the deposit taken by the writer and analyzed in Geological Survey laboratories by X-ray fluorescence methods still showed 6.6 per cent titanium as well as 65.5 per cent Fe, 0.13 per cent Mn, 0.1 per cent Cr, 0.25 per cent V, and 0.01 per cent Ni. The Fe:Ti ratio of the magnetic concentrate is 9.7, and that of the ore is 7.1.

The deposit is located on the flank of an extensive positive aeromagnetic anomaly. Dip-needle readings over the deposit varied from strongly positive to negative. An oriented specimen of the titanomagnetite proved to be magnetically

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unstable and positively polarized, and when washed magnetically it became negatively polarized in a plane near that of the earth's present induced field, but inclined in a direction almost at right angles to it and oblique to the strike and dip of the deposit. The reversed remanence thus detracts from the intensity of the anomaly, and the deposit may be larger than suggested by the anomaly on GSC Map 251G.

Bishop South

This deposit of titaniferous magnetite is exposed on the north end of a rounded hill overlooking a small pond about 2,000 feet south-southeast of the Bishop North prospect. Both Bishop North and Bishop South deposits are similar in nature and appear to be located along a minor shear zone which transects the anorthosite host rock and which is itself broken by other cross faults. Exposures are poor at the Bishop South prospect and much of the surface magnetite is a loose rubble of cleavage fragments. The deposit appears to strike northeasterly and to dip steeply northwesterly. It is partly exposed over a length of about 200 feet and a width of at least 40 feet. As a result of detailed mapping and dip-needle survey Baird (1943) estimated reserves of 350,000 tons of ore over a length of 400 feet, an average width of 41 feet, and an assumed depth of 200 feet. A sample taken by Baird in 1943, and another by Rejhon in 1957, showed:

	G.S.N. %	Brinco %
Fe	53.50	55.80
Ti	5.69	7.76
V	0.50	none
S	0.006	—
P	nil	—
SiO_2	0.16	—

The deposit is on the west flank of an aeromagnetic anomaly near a sharp westerly deflection in the isograds. Dip-needle readings vary from strongly positive to negative, and an oriented specimen from the deposit was magnetically unstable, but remained normally polarized under "magnetic washing"; the total magnetic anomaly of the specimen is augmented because its direction of remanent magnetism is in the same plane as that of the earth's present induced field but oppositely directed and inclined nearly at right angles to it. The directions of the stable component of remanent magnetism in the closely related Bishop North and Bishop South deposits thus seem to be almost diametrically opposed, suggesting a spontaneous reversal of magnetization (self-reversing mechanism) rather than a reversal of the earth's field.

A polished surface examined under the microscope showed that the ore consists essentially of cleaved grains of isotropic creamy brown titanomagnetite, many of which are replete with very fine grained intergrowths of an anisotropic mineral, presumably ilmenite or hematite, which are arranged in sets parallel to the octahedral cleavage directions in the magnetite. There are, in addition, elongated spindles of a grey gangue mineral, probably spinel, arranged in a similar manner.

Many of the grains have more abundant intergrowths in the cores than on the margins. Besides titanomagnetite, a number of clear grains and lamellae of anisotropic ilmenite were observed in the section, as well as several large grains of gangue minerals showing alteration and corona structures. Some of the ilmenite grains showed narrow lamellae of another anisotropic mineral, presumably hematite, arranged in rhombohedral pattern. Four or five broad lamellae of strongly anisotropic ilmenite with parallel oriented spinel spindles follow rectangular cleavage pattern in the magnetite. Gangue grains contain fine-grained stringers and blebs of magnetite and ilmenite, and both ore minerals and gangue minerals are fractured and penetrated by veinlets carrying ilmenite or hematite and gangue in places. The foregoing textural aspects revealed by the polished section suggest that mechanical separation of ilmenite from magnetite in this deposit would be impractical.

Bishop III

A massive magnetite outcrop, about 20 feet long by 10 feet wide, occurs in a mound on the western side of a swampy area about 1,700 feet south and 35 degrees west from the Bishop South prospect. The magnetite is bounded on the west by 100 feet of light coloured anorthosite and elsewhere by swamp. Irregular dip-needle readings in a zone about 500 feet long and 30 feet wide suggest that the deposit is pockety and rather small. This occurrence appears to be on a magnetic ridge sloping off the aeromagnetic anomaly with which the Bishop North and Bishop South deposits are associated and is presumably an extension of the Bishop South deposit, all of which may be larger than indicated.

Hayes Prospect

The Hayes prospect is a narrow vein-dyke of titaniferous magnetite that cuts through grey anorthosite on the crest of a ridge overlooking the valley of Flat Bay Brook and Skull Mountain. The writer was guided to the prospect in 1961 by D. M. Baird, who had last visited it some 18 years before. The deposit is intermittently exposed for a length of about 400 feet, and averages 6 feet in width. The contacts are sharply defined, and in places along the vein there is evidence of contact metamorphism in the development of brown garnet and bleached rock which under the microscope appears to be highly saussuritized anorthosite, consisting now largely of garnet, epidote, zoisite, clinozoisite, chlorite, white mica, magnetite, and plagioclase. In places the host rock is rich in amphibolitized pyroxene, and the vein contains inclusions of both types of rock.

The vein strikes northeastward towards the Bishop occurrences, and the ore resembles that of those occurrences. It is coarse grained and jointed, and subtly shows two types of ore minerals on the weathered surface, both dark and magnetic, but one with a light blue sheen, the other dull with a brownish tinge. The differences in colour appear to be due to differences in content of intergrowths and thus to differences in bulk composition. The ore material carries remnants of altered pyroxene and feldspar crystals and has a few vuggy cavities, some of which

are partly filled with a soft creamy kaolinitic (?) aggregate. A few hair-like veinlets of a soft white non-effervescing mineral, possibly a zeolite, cut through the magnetite.

A sample from the vein collected by the writer showed about 54 per cent iron and 9 per cent titanium, and a magnetic concentrate from it analyzed 68.5 per cent Fe, 3.5 per cent Ti, 0.05 per cent Mn, 0.15 per cent Cr, 0.28 per cent V, and 0.01 per cent Ni. The Fe:Ti ratio of the raw ore material is about 6:1, that of the concentrate 20:1. Baird (1943) estimated the deposit conservatively at 10,000 tons on the basis of detailed mapping and a dip-needle survey. It is located near the peak of a broad, circular, positive aeromagnetic anomaly with an intensity of 4,500 gammas. Dip-needle readings in the area were mainly positive, and were fairly strong and positive on the magnetite outcrop. Two oriented samples taken from subjacent positions in the vein were found to be moderately unstable in both declination and inclination under magnetic washing, changing from positive to negative polarity and showing reasonable agreement in results. The declination of the two changed from north-northeasterly to northerly (parallel to the strike of the vein) and the inclination changed from gently positive to very gently negative, thus being obliquely inclined to that of the earth's present field and in the plane of the vein. This conflict in magnetic vectors must detract from the intensity of the magnetic anomaly. In its reversed character its remanence agrees with that of the Bishop North specimens, and the deposit is probably larger than indicated by the magnetic anomaly and surface exposure.

Hudson Prospect

The Hudson prospect on a heavily wooded hillside south of Flat Bay Brook and east of Mendwagi Brook is a 100-square-foot exposure of magnetite in 400 square feet of anorthosite (Baird, 1954). The magnetite appears dark and rusty and in sharp contact with fine-grained grey anorthosite. Small clots of biotite occur in places along the contact. According to Baird the deposit contains as much as 20 per cent of bright pyrite and a small amount of chalcopyrite.

Other Occurrences

A 1957 helicopter survey by British Newfoundland Corporation Limited (Brinco) of the Steel Mountain anorthosite mass located a dozen other occurrences; samples taken by Brinco showed from 44 to 55 per cent iron and from 7 to 20 per cent titanium. Judging from the aeromagnetic anomalies on GSC Map 251G it appears possible that considerable tonnages of titaniferous magnetite may be present at some of the sites, and it is probable that more readily separable material may be found, particularly within mafic phases of the anorthosite probably associated with the strong magnetic anomalies lying to the north and east of the main anorthosite body.

Indian Head Area

The principal titaniferous deposits of the Indian Head area include titaniferous magnetite, magnetite–ilmenite, and magnetite–ilmenite–hematite deposits. They are located in the eastern part of the Ernest Harmon Base of the United States Army

Air Force at Stephenville. The Indian Head deposits were discovered prior to 1920, and were prospected by the Reid Newfoundland Company Limited in 1923. A. F. Buddington (1939a) studied the area briefly, and in 1941 Dominion Steel and Coal Corporation, Limited began a prospecting program. The deposits were mapped in 1942 by Allen V. Heyl and John J. Ronan for the Geological Survey of Newfoundland, and their report was published in 1954 by the Geological Survey of Canada. Several of the deposits were worked for iron for a short time from 1941 until 1943 by the Dominion Steel and Coal Corporation, Limited, and some diamond drilling was done by the Geological Survey of Newfoundland.

Heyl and Ronan (1954) described the iron deposits of this area as mainly flat-lying thin lenses rich in magnetite and hematite, which generally are found parallel to the banding in two types of rocks, norite–gneiss and pink soda granite – gneiss. They further added that practically all the deposits are at or near the contacts of the norite–gneiss and the pink soda granite – gneiss, where the norite–gneiss has been partly replaced by granite–gneiss, or where inclusions of norite–gneiss exist in the granite–gneiss. According to Heyl and Ronan (1954, pp. 60–61) two deposits of low-grade disseminated magnetite occur in the area south of Labrador Pond, one associated with pyroxenite, the other with norite–gneiss. Chemical analyses of two samples of the ore material collected from the shore of the pond analyzed 24.25 and 25.70 per cent iron, and 0.48 and 3.21 per cent titanium (Heyl and Ronan, 1954). This material might be concentrated magnetically; the occurrences merit further investigation to determine their full extent and grade.

Aeromagnetic Map 268G of the Indian Head area was issued by the Geological Survey of Canada in 1956. No conspicuous magnetic anomalies are shown on the map. Remanent magnetism is usually not strongly retained in the titaniferous magnetite and gabbroic anorthosite of this area except in hematite-rich parts. It shows a wide spread in orientation but is generally similar to that of the Bishop North and Hayes deposits; this supports the suggestion that the anorthositic rocks and titaniferous deposits of the two areas are genetically related.

Indian Head Mine

This deposit of titaniferous magnetite is located about a quarter mile east of the eastern corner of Stephenville Pond. It was opened in 1941 by the Dominion Steel and Coal Corporation, Limited, and after a few hundred tons of ore were mined operations were transferred to the Cliff deposit. In 1942 the Indian Head mine was a pit about 150 feet long and 25 feet wide; it was later re-opened by the United States Army Air Force to provide rock for construction on Harmon Base. It now consists of three quarry benches, the lowest 300 feet long and 18 feet high, the middle 250 feet long and 20 feet high, and the upper 180 feet long and 40 feet high.

The rock in all three benches is grey-green gneissic gabbroic (noritic) anorthosite (norite–gneiss), with a number of disseminations and conformable bands of black titaniferous magnetite that range from $\frac{1}{4}$ inch to $1\frac{1}{2}$ feet in thickness. The banding in these rocks strikes generally eastward and dips 25° southward, but in

places the dip flattens and rolls gently to the north. Rock and ore have many joints coated with black chloritic films. Irregular granite pegmatite stringers cut both rock and ore in places. A sample of biotite collected by the writer from one of these pegmatites was dated at 900 ± 45 million years, thus placing the age of the magnetite deposit as Precambrian.

In the hand specimen the ore appears as medium-grained, dull, chloritic, greenish black magnetite, with prominent joints coated with glistening black chlorite. Under the microscope it appears to be an interlocking mosaic of creamy, isotropic, magnetite grains with a considerable amount of disseminated gangue. Many of the magnetite grains show a faint rectangular cleavage pattern and almost submicroscopic intergrowth. In addition, fine-grained, patchy, anisotropic ilmenite or hematite is developed along some of the fractures in the magnetite.

Adjacent oriented samples of ore and rock material from the pit were unstable to magnetic washing, both becoming positively polarized but showing considerable spread in declination and inclination of the remanent component. The declination and inclination of the Indian Head titaniferous magnetite were similar, however, to those of the Bishop North titaniferous magnetite, and the magnetic orientation of the Indian Head magnetite-bearing rock was similar to that of Hayes prospect massive magnetite.

Cliff Mine

The Cliff mine is a narrow open pit with a short adit on the south-facing brow of a granite hill overlooking the north side of Gull Pond. The pit, about 400 feet long and 60 feet wide, was opened by Dominion Steel and Coal Corporation, Limited in 1941 and 1942. It exposed two narrow parallel lenticular bands of iron ore in pink and grey granitic gneiss that is cut by pegmatite and granite and is impregnated and seamed with epidote. Foliation in the granite and gneiss strikes 130° and dips from 5° to 20° northeasterly. The rock is intersected by sets of nearly vertical joints, one set striking parallel to the gneissosity the other crossing it obliquely at about 255°.

The upper ore band runs easterly along the cliff face, pinching and swelling from 2 inches to 2½ feet in thickness in a distance of 400 feet and dipping gently from 15° to 20° northerly. According to Heyl and Ronan (1954) the lower ore band is 8 feet thick at the adit portal (which in 1961 was water filled) and extends in the adit about 10 feet to a zone of mixed rock and ore in which a band of norite–gneiss occurs between two ore bands. The ore bands are reported by Heyl and Ronan to be cut off on the west by a north-trending fault, and the lower ore band is said to pinch out to the east within 30 feet of the fault.

The ore is a mixture of dark dull magnetite and friable blue-black to silvery grey hematite; it varies from strongly magnetic to weakly magnetic along the strike. Under the microscope the strongly magnetic ore appears to consist essentially of brownish, isotropic grains of magnetite, with a considerable amount of interstitial, slightly younger intruding grains of strongly anisotropic greyish hematite. The magnetite carries some fine-grained gangue, and the hematite shows a distinct rhombohedral cleavage pattern which is emphasized by tiny,

exsolution blades of another anisotropic mineral, presumably ilmenite. A polished section of the weakly magnetic, hematite-rich ore shows under the microscope a clean cut, coarse-grained, interlocking mosaic of hematite grains, each grain having a well-developed rhombohedral pattern of anisotropic ilmenite intergrowth blades. Some gangue minerals are also included in the hematite grains and these are in part embayed and replaced by hematite.

Dip-needle readings in the vicinity of the Cliff mine were generally weakly positive. Near the adit the reading was $+25°$ north. An oriented sample of the ore material there, carrying much hematite as well as magnetite and minor ilmenite, also showed positive polarity and considerable stability under magnetic washing, its remanent component of magnetization being strong and inclined gently in a westerly direction, i.e., in the plane of the ore band. Its magnetic stability seems to be due to the presence of abundant hematite in the sample and deposit.

Upper and Lower Drill Brook Mines

Dominion Steel and Coal Corporation opened two small elongate pits about 300 feet apart, one 50 feet above and 100 feet north of the northwest corner of Oxback Pond, the other along strike to the west. Heyl and Ronan (1954) described the country rocks as fine-grained norite–gneiss with numerous small injections of granite–pegmatite.

In the Upper Drill Brook mine the ore occurs in a series of three lenses that range in thickness from 6 inches to 3 feet. Smaller lenses and crosscutting veins follow small faults or joints from the main lenses. The general strike of the lenses is parallel to the foliation in the gabbroic anorthosite (norite–gneiss) which strikes about 80° and dips 20° to 40° to the north. A small area of fine-grained, pink, gneissic granite is exposed on the south wall of the pit. It appears to grade into darker gneiss which is impregnated with magnetite stringers and dark mica.

The ore material consists mainly of magnetite which in places contains large crystals of plagioclase and small amounts of chlorite and garnet. In the Lower Drill Brook mine the ore is a mixture of mainly magnetite and hematite, but pyrite, chalcopyrite, and molybdenite are also present (Heyl and Ronan, 1954). Groundwater has caused extensive oxidation and leaching of the sulphides to form limonite with stains of cuprite (CuO) and malachite ($CuCO_3$).

In polished section the ore appears as a very irregular aggregate of brownish, cream-coloured, weakly anisotropic grains that show a faint rectangular pattern in places outlined by tiny exsolution spindles of ilmenite and spinel. The weakly anisotropic grains are strongly magnetic and presumably are titanomagnetite. Other grains in this aggregate are distinctly anisotropic and appear to be ilmenite. Intergrown with this magnetite and ilmenite is an amazing stockade or spear-type intergrowth of two other lighter coloured minerals, presumably varieties of hematite and ilmenite. Most of these grains have a patchy light coloured core of hematite that is surrounded by creamy brown ilmenite and titanomagnetite. Conspicuous in the sheaf-like hematite–ilmenite intergrowth are long grey spindles

of spinel which project from the cores into the margins of the grains. Some gangue minerals are present that appear highly altered and corroded. A few sporadic grains of pyrite, and more rarely chalcopyrite, were noted. The sulphides appear to be slightly later than the oxide minerals. One tongue of pyrite contains a little chalcopyrite and gangue minerals of two kinds, and a few specks of chalcopyrite appear to be isolated within magnetite adjacent to the tongue of sulphides and gangue.

Diamond drilling by the Geological Survey of Newfoundland in 1942–43 to the north and east of the Upper Drill Brook mine outlined an estimated 57,000 tons of titaniferous iron ore with an average grade of 54.8 per cent iron. It indicated also that soda granite–gneiss underlies this cap of norite–gneiss and that pegmatites from it intruded upward into the norite. The metamorphic effect of these granitic intrusions into the titaniferous magnetite-bearing noritic anorthosite is revealed in the development of hematite and the peculiar inter-growths of magnetite, hematite, ilmenite, and spinel described above.

Dip-needle readings in the vicinity of the workings vary from positive to weakly negative. An oriented sample of titaniferous magnetite from the noritic gneiss showing a positive dip-needle reading proved to be reversely polarized, but it was magnetically unstable and when washed magnetically became normally polarized, inclined very gently towards the west-southwest, i.e., parallel to the strike of the deposit. The conflict of magnetic vectors detracts from the intensity of the resulting weak magnetic anomaly.

Coast of Labrador

Large areas of anorthositic rocks with associated occurrences of "titanic iron" have been known for many years in parts of the coastal and interior areas of Labrador. These include bodies in the Nain–Hopedale–Kiglapait Mountains, Michikamau Lake – Lake Ossokmanuan, Lake Melville – Mealy Mountains, and Sandwich Bay – Square Lake areas. Our knowledge of the geology of Labrador dates back to the early coastal studies of Packard (1891) made in 1860 and 1864, and to the exploratory inland treks of Hind (1863), Robert Bell, and Low (1895). Later contributions were made by R. A. Daly, A. P. Coleman, E. M. Kindle, E. P. Wheeler, 2nd., N. E. Odell, E. H. Kranck, G. V. Douglas, A. M. Christie, W. R. Baragar, W. F. Fahrig, K. E. Eade, R. F. Emslie, I. M. Stevenson, and others.

This is the type locality of the feldspar mineral, labradorite, which is found in places such as Paul Island and Napoktulagatsuk (Tabor) Island in the Nain area, in semiprecious form showing an iridescent play of colours. The anorthositic rocks of this area have been the subject of an intensive study over a period of many years by E. P. Wheeler, 2nd. S. A. Morse has recently given a paper (C.I.M. Ottawa, 1962) describing an alkalic layered intrusion of the Skaergaard type, the Kiglapait intrusion, at the outer contact of the Nain anorthosite mass and related to it. Black ore, presumably titaniferous magnetite, is said to be related there to an upper zone of olivine gabbro in the Kiglapait intrusion. The intrusion has

been dated at 1,480 ± 50 million years at M.I.T., and the crosscutting granites at 1,140 ± 40 million years. R. F. Emslie reported recently (pers. com., 1964) that similar dates of 1,400 ± 80 million years for the Michikamau anorthositic intrusion and 1,360 ± 80 million years for crosscutting granite had been obtained by K–Ar measurements at the Geological Survey of Canada. Titaniferous occurrences are also reported in the anorthosite.

Since Low (1895) first recorded the occurrence of ilmenite in anorthosite in Labrador, many titaniferous occurrences have been noted in various private reports. Occurrences of ilmenite and titaniferous magnetite are known at Hillsbury Island near Nain, Flowers (Jem Lane) Bay, Tessisoak Lake, Wilson Lake, and in the Mealy Mountains, and it is to be expected that large titanium deposits may eventually be found in these incompletely explored areas. What may be significant occurrences of ilmenite are reported in the western part of the Michikamau anorthositic intrusion (pers. com., R. F. Emslie, 1964).

Quebec

The known ilmenite and titaniferous magnetite deposits in the province of Quebec are numerous and among the world's largest; doubtless many remain to be discovered and developed but currently ilmenite is being produced by only two companies in Quebec: Quebec Iron and Titanium Corporation from the Lac Tio deposit, and Continental Titanium Corp. from the St-Urbain deposits. Heavy-Rock Mines Ltd. also produced several thousand tons of ilmenite from the old pit of the Ivry mine in 1958–1959.

Unconsolidated deposits of dark magnetic beach sands are abundant along the north shore of the St. Lawrence River, and numerous attempts to sample and use them have been made. The chief deposits are at Bersimis, Moisie, Mingan, and Natashkwan. G. C. Mackenzie (1912) estimated that the Natashkwan sands held 5,800,000 gross tons containing 500,000 tons of magnetic concentrates of 67 per cent iron. The average iron content of the sand is reported to be 8 to 9 per cent, and the average depth of the sand 15 feet. Recent tests by the Mines Branch on Natashkwan sands held by Aconic Mining Corporation indicate that about 4 per cent by weight of the crude sand could be recovered as a magnetic concentrate analyzing 67–69 per cent iron and 2–3.5 per cent titanium oxide. An additional 6 per cent of the sand can be recovered as an ilmenite–hematite concentrate carrying 48 per cent iron and 29 per cent titanium oxide.

St-Urbain Area

In the early days, long before, discovery of iron in Labrador,
Titanic ore with its 'titane', was smelted by fire, at St-Urbain.

As early as 1666 and perhaps before[1] the first occurrence of "titanic iron" was reported from the St-Urbain area of New France, but it was not until 1872

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[1] An occurrence of iron ore of the very best quality is said to have been mentioned in accounts of the north shore of the St. Lawrence by Jacques Cartier in the 1500s.

that the Furnace deposit was opened and an attempt was made to smelt its ore. The project, undertaken on the hillside below the site, was short-lived and financially unsuccessful, and was abandoned within 2 years. The first published geological descriptions of the area and its ilmenite–rutile occurrences are by Logan (1850, 1863) and Hunt (1853, 1863). Subsequently several other deposits were discovered in the same area, and other occurrences were noted by Low (1895) in the anorthositic rocks of the upper Romaine River, the headwaters of the Rivière St-Jean, the west side of Michikamau Lake, and near Lake Ossokmanuan. In 1900, 1908, and 1909 test shipments of ore from the mine dumps at St-Urbain were made to the Titanium Alloy Company in Niagara Falls, New York, for testing in the electric furnace. Subsequently in 1910 the General Electric Company of the United States became interested in the deposits and during the First World War years mined considerable ilmenite for use in the manufacture of ferro-titanium alloys. In 1928 Dupont Chemical Company became interested in the deposits as a source of titania and some ore was shipped until 1932. The outbreak of the Second World War renewed interest in the deposits and from 1940 to 1946 about 200,000 tons of ore was shipped. Ten years later, after intermittent production by the American Titanic Iron Company and St. Lawrence Iron & Titanium Mines Ltd., Continental Iron & Titanium Mining Limited acquired mining rights on the Bignell occurrence and subsequently on the Furnace, Coulombe, and General Electric deposits. In 1957 the company had proved 3 million tons of high grade ilmenite in the Bignell deposit, and began production of massive ilmenite from the Furnace and Bignell deposits (Pl. IV A). In 1959 the General Electric deposit was also reopened (Pl. IV B), and in the 1957–1959 period about 100,000 tons of ilmenite was mined, crushed, and shipped from the three deposits, mainly for use as heavy aggregate in concrete. In 1959 the company estimated their ore reserves at 22 million tons in 4 deposits. To date these four deposits have yielded about half a million tons of ilmenite ore. In 1960 the company was re-named Continental Titanium Corp. In addition to field exploration, mining, and development the company has set up a pilot-plant laboratory to test and evaluate methods of ore treatment designed for the efficient recovery of titanium oxide from ilmenite. The company has announced plans to enter the field of titanium oxide production.

The known deposits are clustered on the hillside in a square-mile area west of St-Urbain as shown on Figure 4. They are all lode deposits, entirely within anorthosite and coinciding with an aeromagnetic anomaly of positive magnetic intensity. This anomaly in itself is apparently unusual for ilmenite deposits (cf. Bourret, 1949; Balsley and Buddington, 1958). Moreover, part of the ilmenite–hematite ore material is normally polarized and part is reversely polarized. The host rocks are apparently all normally polarized, and the directions of magnetization in the ore materials is generally considerably different from that in the adjacent host rock. The magnetic anomalies produced are the result of the interplay of these variously oriented magnetic vectors, leading in places to a reduction in the intensity of the magnetic anomaly because of reversed remanent magnetism.

The emplacement of ilmenite of the Bignell deposit was dated by the writer at 890 ± 45 million years by K–Ar absolute age measurements on associated biotite (Lowdon, 1961). This is at least a hundred million years younger than the age recorded for the nearby Lac Pied des Monts pegmatite dyke (Lowdon, 1960), and also about a hundred million years younger than the age of 1,015 million years measured from biotite flakes in the gabbroic anorthosite marginal to the St-Urbain anorthosite body.

Furnace Deposit

The Furnace deposit, lowest on the side hill and nearest St-Urbain, is small and erratic, consisting of irregular branching lodes of dark lustrous ilmenite in light grey and greenish grey anorthosite. It has been the source of some of the highest density aggregate recovered, but requires selective mining and cobbing to separate the ilmenite from waste rock.

The original pit has been extended and deepened in an irregular manner as shown in Figure 5. The irregular, pockety nature of the ore is well shown in the present pit. Bands and pockets of ore are measurable in tens of feet and appear to trend northwestward and to dip steeply towards the southwest. The ore lenses cut through the anorthosite with sharp contacts and little evidence of contact metamorphism beyond possibly a general bleaching of the anorthosite and chloritization along joints in the rock. The ore consists of a coarsely crystalline aggregate of ilmenite carrying exsolved hematite lenticles, plagioclase, pyroxene, and spinel. Soft green cellular aggregates of chlorite are also found in the ore. In places the ore is cut by narrow white veins of calcite and laumontite, and in a few places these soft, crystalline, pink and white minerals also fill fissures and line cavities in the ore.

The deposit is located on the site of a small positive aeromagnetic anomaly, a satellite of the main anomaly in which the other deposits are grouped. The writer's dip-needle readings on the ore and host rock were entirely positive, and oriented specimens taken from both hanging-wall and foot-wall anorthosite showed a strong, positive component of remanent magnetism that was stable under magnetic washing. In the ore specimen this remanent component was negatively inclined. All specimens showed different declinations and inclinations, but although the declination of the ore specimen was close to that of the earth's present field, it was reversely inclined. On the other hand, the remanent component of magnetization in the anorthosite wall rock was directed to the south and southeast. Both were inclined positively but moderately in those directions. In this case the polarization attitude in the rocks is almost at a right angle to the presumed general attitude of the deposit and is obliquely opposed to the polarization attitude of the ore sample. The conflict of magnetic vectors detracts from the intensity of the magnetic anomaly.

Coulombe East and Coulombe West Deposits

The Coulombe workings located in lot 319, St-Jérôme parish, on the flat-topped summit of the hill west of St-Urbain, comprise a large pit and two smaller pits on the west and east outcroppings, respectively, of an ilmenite-rich zone in

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anorthosite. The two main pits are partly filled with water and are separated by a knoll of intermixed anorthosite and ilmenite. The pit and ore outlines and probable extensions of ore are shown on Figure 7. Dyke-like and vein-like bodies of massive ilmenite appear to transect anorthosite host rock that varies in colour from grey to green to pink. Large inclusions of anorthosite appear to be engulfed by ilmenite and some anorthosite is impregnated by stringers and disseminations of ilmenite. The ore lenses and bands are irregular, pinching and swelling, but they appear generally to strike in an east-west direction and to dip steeply southward. The ore extends along strike in places between the pits and beyond. On the east face of pit 1 a cross-section of the deposit is exposed showing large "horses" or inclusions of anorthosite incorporated in the ilmenite deposits; on the west face of pit 2 a sharp tongue of ilmenite projects from the upper side of the main orebody about 10 feet upwards into the hanging-wall anorthosite. These features clearly indicate that the ilmenite lode was emplaced from below. On the foot-wall side of pit 2 there are a number of narrow bands and areas of ilmenite (disseminated) in anorthosite, and a few stringers leading from the larger ore bands into the host rock. Such stringers and disseminations of ilmenite suggest a relatively high mobility and fluidity of the ore material.

The deposits lie within a positive aeromagnetic anomaly, and dip-needle readings taken on and around it were consistently positive. An oriented specimen of the ore was found to have a strong stable component of positively polarized and moderately inclined remanent magnetism directed southeastward. A specimen of anorthosite from a large included "horse" was also found to have a positive stable component of remanent magnetism, but it was directed east-northeasterly and gently inclined. These polarization directions of ore and included rock are both obliquely inclined to the strike of the deposit. The remanent magnetism of both ilmenite ore and anorthosite host rocks contributes to the intensity of the magnetic anomaly.

General Electric Deposit

The General Electric pit is located in lot 321 about 700 feet north of the Coulombe deposits. It is a deep, water-filled pit in which ramifying bands of ilmenite are exposed in dark grey and grey-green anorthosite that in places is gabbroic and carries disseminated ilmenite. The ore bands strike in an east-west direction but appear to curve gently to the southwest and southeast at the west and east ends of the pit, respectively. The hanging-wall contact of the main lode is sharp and dips steeply southward, almost vertically. Several ore bands on the foot-wall side, some of which are associated with disseminated ilmenite, dip more gently southward and branch from the main lode below (Pl. IV B). In places the deposit is rich in orange to reddish brown rutile that occurs as disseminated grains and as small stringers in the ilmenite; an area near the east end of the pit appears to be unusually rich in rutile. A late lenticular vein of coarse-grained white calcite occurs in the ilmenite nearby. Some of the rutile grains are also incorporated in a matrix of calcite, and a few are also found sporadically distributed through the anorthosite.

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In polished section under the microscope the ore appears as a coarse-grained, interlocking mosaic of ilmenite and rutile. Exsolution blebs of hematite are found in many of the ilmenite grains, but rutile grains appear uniformly uncontaminated. A few grains of gangue and sulphide minerals, pyrite, pyrrhotite, and chalcopyrite, make up a small part of the ore specimens.

The deposit lies within the same positive aeromagnetic anomaly as the Coulombe, Bignell, Glen, and Bouchard deposits, and dip-needle readings about it are consistently positive as they are for the other four deposits. An oriented specimen from a band of ore on the foot-wall side of the deposit was found to be positively polarized and magnetically stable. Its remanent magnetism was directed towards the west and inclined steeply and positively downwards in that direction (i.e., nearly parallel to the strike and dip of the deposit). An oriented specimen of grey anorthosite host rock immediately above this ore band was also found to be magnetically stable and positively polarized, but in an east-north-easterly direction and with moderate inclination similar to that of the anorthosite inclusion in the Coulombe deposits. As in the Coulombe deposits, the orientation of remanent magnetism in the ore is obliquely opposed to that in the rock, but both contribute to the total intensity of the magnetic anomaly.

The curvature of the deposit suggests that its extensions may link with those of the Coulombe East deposit to the southeast and possibly with that of the Bignell deposit to the northwest.

Bouchard Deposit

Two small pits on lot 319 of the Seminary area are located about 700 feet west of the Coulombe West pit. Ilmenite in both pits strikes in a direction slightly north of west cutting through dark grey anorthosite, but in the southern-most pit the vein splits, one branch diverging towards the northwest the other to the northeast. The occurrences appear to be pockets of ilmenite and direct extensions along the strike of the Coulombe deposit. Dip-needle readings in and around the pits are consistently positive.

Glen Deposit

Another small pit on a lens of ilmenite known as the Glen deposit is located in bush on the top of the ridge overlooking the Gouffre valley half a mile south-east of the Coulombe East deposit. A body of ilmenite about 130 feet long and 15 to 20 feet wide is exposed cutting anorthosite in the pit. The ilmenite appears to strike westward, tapering to the east, widening slightly to the west, and dipping steeply towards the south. The deposit is located on the southeast extension of the main aeromagnetic anomaly on which the Coulombe and General Electric deposits are found. Dip-needle readings in the area are positive.

Bignell Deposit

The Bignell deposit located in lots 607, 608, and 609, St-Jérôme Range, half a mile northwest of the General Electric deposit, was developed by Continental Titanium Corp. from an unimpressive prospect to a producing deposit holding

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more than 3 million tons of high-grade ilmenite reserves. Most of the ore was covered by overburden, but it has been removed from an oval-shaped pit area about 300 feet long by 175 feet wide. In 1959 the pit had been opened to a depth of about 30 feet; later some parts were deepened to about 60 feet. In it the massive ilmenite was seen in sharp contact with light coloured anorthosite along the length of the pit, striking northwestward and dipping gently under the anorthosite to the southwest (Pl. IV A). The ore appears to terminate rather abruptly at the northwest end of the pit, but probably extends for some distance to the south and west.

Within the pit the ore varies from massive to strongly disseminated. At the northwest end it shows traces of banding formed by intermittent layers of more or less barren anorthosite and anorthosite carrying disseminated ilmenite, all within the main lode of massive ilmenite, striking northwesterly and dipping about 40° southwesterly. Both ore and rock are jointed, but the pattern is much better developed in the massive ore. One set of joints parallels the banding described above. Two other prominent joint sets intersect the ore, one striking northwesterly and dipping 80° northeasterly, the other striking southwesterly and dipping 80° southeasterly. Numerous other joint sets are superimposed on this pattern, and some of the joints form a fan about a large anorthosite inclusion in the ore.

For the most part the ore is massive and cuts with sharp contact through hard, fresh looking, light-coloured anorthosite, which varies in colour through light shades of grey, green, and pink; but in places on the hanging-wall side the anorthosite is softer and bleached and is more or less extensively altered to zeolites and carbonates. In some places on both the hanging-wall and foot-wall contacts, however, the ore is vuggy and some biotite is developed in both the ore and in the anorthosite at the immediate contact of ore and rock. The crystallization of this biotite was dated at 890 ± 45 million years by K–Ar measurements in the mass spectrometry laboratories of the Geological Survey's Petrological Sciences Division. In addition, a considerable amount of pyrite is found in vuggy, sheared zones near the contacts. Pyrite forms veins that cut vertically through the ilmenite in places; it also lines and fills vugs in the ore along with brown limonite and some films of red hematite. Both massive pyrite and a cellular type of pyrite occur as a cementing matrix for rounded crystals and grains of ilmenite–hematite. Near the contacts the ratio of hematite to ilmenite is about 1:1, but in the interior of the deposit it is about 1:3. Narrow white veins and veinlets composed mainly of carbonates and zeolites cut through the ore and through some of the late pyrite seams in the pit. Most of the carbonate–zeolite veins are nearly vertical. Also, a few of the anorthosite inclusions in the ore at the west end of the pit near the hanging-wall side are altered to zeolites and carbonates in the same manner as the hanging-wall anorthosite mentioned above, which strongly suggests that the zeolitic alteration is post-ore since zeolites are not stable at the high temperatures required for emplacement of the ilmenite–hematite lode.

In polished and thin sections under the microscope the ore appears as a mosaic of interlocking grains of ilmenite in which blades, lenticles, and blebs of hematite are exsolved. The hematite is of at least two generations, one of which is extremely fine grained. Both host and guest minerals are probably impure varieties

as each contains submicroscopic inclusions of the other. Grains of gangue, mainly plagioclase, are commonly rounded and penetrated by tongues of ilmenite–hematite, and some corona structures are developed about the ilmenite–hematite grains in contact with plagioclase and pyroxene. The contact alteration products include biotite, chamosite, chlorite, and minor sapphirine; these rim some of the ilmenite–hematite grains and also penetrate plagioclase along fractures and cleavages.

Two types of pyrite, massive and cellular, intersect the ore and cement ilmenite–hematite grains; the cellular type also intersects the massive type of pyrite. Many of the ilmenite–hematite grains are rimmed with the cellular type, and some of them are rounded and polished as if by the emplacement of the pyrite. Cells in the pyrite are lined with tiny cubes of pyrite and sometimes with calcite. Rare crystals of pyroxene caught up in pyrite are intensely altered to an aggregate of chlorite and serpentine and are rimmed with a selvedge of biotite flakes as are crystals of plagioclase enclosed in pyrite. Both types of pyrite are higher in cobalt and nickel than ordinary pyrite, but the cellular type is much richer in nickel than in cobalt, and richer in nickel than ordinary pyrite, according to analyses made in the Spectrographic Laboratory of the Geological Survey of Canada (Rose, 1958, 1961).

The Bignell deposit is situated on the northwest end of the main aeromagnetic anomaly in which the St-Urbain ilmenite deposits are included. Dip-needle readings are moderate to strong over both the host rock anorthosite and massive ore; they are consistently positive and slightly higher over rock than over ore. An oriented specimen of the massive ilmenite–hematite ore from the northwestern end of the Bignell pit was tested in the Geological Survey's rock magnetism laboratory and found to be magnetically stable and negatively polarized in an easterly direction with a relatively high angle of inclination. Thus the strong component of remanent magnetism in the ore sample is directed almost parallel to the structural attitude of the deposit, but it is reversely inclined in that plane. This orientation is almost parallel to that in the General Electric deposit, but it is reversely inclined. It also lies in almost the same plane as that of the Furnace and Coulombe ore samples, but all are inclined in different manner. Its reverse remanence detracts from the intensity of the magnetic anomaly.

Séminaire de Québec Deposits

A number of ilmenite–hematite occurrences have been described by Mawdsley (1927) on the property of the Quebec Seminary in the east-central part of the anorthosite massif between the southwest branch of the Rivière du Gouffre and Lac Ontario in the interior part of the anorthosite. The writer was guided to one of these occurrences by Mr. Saul Gagnon of St-Urbain. It is located in thick bush about 1½ miles northeast of Lac à l'Empêche. Rock exposures are generally poor in this area because of heavy overburden, but a low outcrop has now been uncovered for an east-west length and north-south width of about 43 feet and 33 feet, respectively. This outcrop consists entirely of very coarse grained dark blue-black ilmenite–hematite in crystals averaging almost ½ inch in diameter (Pl. III B), except for two inclusions of pink anorthosite the largest of which measures about

9 feet in diameter. Strong joint systems intersect the ilmenite–hematite outcrop, one striking north-northwest (350°) and dipping 60° westerly, the other striking west-northwest (285°) and dipping steeply to vertically northward. Near the west end of the outcrop the ilmenite–hematite is lightly sheared, striking at 355° and dipping at 60° to the west.

A small outcrop of anorthosite only a few feet square was found about 20 feet northwest of the ilmenite exposure and also a small pit about 30 feet to the south, but there are no other rock exposures around the stripping. Rusty stand-pipes of two diamond-drill holes are located in the centre of the ilmenite mass; one is vertical and the other is inclined at 50° towards the east. No information is available on the drilling reported by Mr. Gagnon to have been done in 1947.

The occurrence is in an area of no magnetic anomaly, near the 1,500 gamma aeromagnetic contour line. Dip-needle readings ranged from +67°N in the centre of the exposure to +66°N at the east and west ends, +67°N at the north end, +64°N at the south end; and from +62°N to 67°N in the area of overburden for a distance of 200 feet around the outcrop. Thus there are apparently no significant differences in dip-needle readings in this area to indicate the extent of the deposit.

Under the direction of LeRoy Scharon (1950) ground geological and magnetometer surveys were made for the National Lead Company in several areas on Quebec Seminary property in the summer of 1949. In October and November of the same year diamond drilling was carried out in selected areas of seven holes totalling 2,718 feet. Some disseminated ilmenite and areas of gabbroic anorthosite as well as altered anorthosite were found in these drill cores, but only in drill-hole number 5 were bands of massive ilmenite encountered. This is also in the area east of Lac Ontario.

Rivière du Gouffre Occurrences

Two or more lenticular vein-like bodies of ilmenite–hematite occur in sheared and altered fragmental rocks in a fault zone just east of the Rivière du Gouffre and south of St-Urbain. One of these occurrences, on the land of Mr. Oscar Bouchard about 1½ miles south of St-Urbain, is at least 30 feet long and 7 feet thick; it strikes N35°E and apparently dips southeasterly. Another, about ½ mile south of the bridge over the Rivière du Gouffre at St-Urbain, is at least 25 feet long and ranges in thickness from 6 inches to 5 feet; it strikes N65°E and dips from 65° southeasterly to nearly vertical.

Both deposits are composed of granular aggregates of subangular to rounded grains of ilmenite–hematite with subordinate grains of plagioclase, spinel, rutile, pyrite, biotite, pyroxene, and magnetite. Ilmenite–hematite grains exhibit striking exsolution textures of hematite lenticles in ilmenite. Many of the ilmenite–hematite grains show a marginal zone of alteration to brown leucoxene, which affects the ilmenite and hematite differentially, penetrating the ilmenite selectively and more deeply. Ilmenite-rich bands grade into light coloured feldspar-rich bands of en-closing arkose and thence into coarser conglomerate–breccia or in places into black shale. Some ilmenite–hematite and feldspar grains are fractured, brecciated,

and penetrated by very narrow cross-cutting veinlets carrying ilmenite, hematite, pyrite, and a gangue mineral. The northern seam is intersected sharply by a fault which strikes at 158° and dips 61° southwesterly. Slickensides on this smooth fault surface on the ilmenite seam rake obliquely at 73° to the southeast and suggest a late (post-ilmenite) oblique slip movement.

The fragmental altered conglomerate–breccia, arkose, and ilmenite–hematite lenses are all derived from altered anorthosite that forms most of the surrounding terrain. They might be considered to be of the same age, formed by crushing and brecciation of an altered ilmenite-bearing anorthosite, but there are also remnants of undoubted sedimentary beds of Ordovician limestone and of black shale that are apparently associated with the ilmenite–hematite, the arkose, and the conglomerate breccia. All of these rocks are much disturbed and infaulted into the surrounding anorthosite. The writer suspects that these fragmental rocks are remnants of clastic beds of Cambro-Ordovician age derived by the erosion of the surrounding ilmenite–hematite-bearing anorthosite, and that they were subsequently infaulted into their present position in post-Ordovician time.

Other Occurrences

Ilmenite–hematite associated with anorthosite is reported to occur in discontinuous lenses or exposures on lots 132, 133, 136, 137, 169, and 172 of range Cran Blanc, Parish of St-Urbain, Seigneurie du Gouffre, Charlevoix East and Charlevoix West counties (Henri Girard, unpubl. rept., Kelley Mining Corporation, 1961). The occurrences lie in an area of no magnetic anomaly in a zone about a mile long near the road on the valley wall east of Rivière du Gouffre and northeast of St-Urbain (Pl. III A).

Morin Anorthosite Area

Laurentian playground, verdant, white
Rocky hills of anorthosite,
A heritage of pleasant dreams,
Minerals, forests, sparkling streams.

The Morin area north of Montreal embraces one of the first anorthosite bodies studied by geologists in Canada. It was described in petrological detail by F. D. Adams in 1896, and much of it was later mapped by F. F. Osborne (1936, 1938) and others for the Quebec Department of Mines (*see* Côté, 1948; Klugman, 1957; and McGerrigle, 1959). Numerous occurrences of ilmenite and titaniferous magnetite were noted by Adams prior to 1896 and they were considered by him to be of potential economic importance, but it was not until 1910 that the Ivry ilmenite deposit north of Ste-Agathe-des-Monts was opened. Shortly after the titaniferous magnetite deposit at Degrosbois was also opened, but both ventures were short-lived.

In the period 1951 to 1954, the Crane Company of Chicago conducted a program of prospecting for ilmenite in the Morin area. An aeromagnetic survey of the anorthosite area was made, and the anomalies were investigated by sampling

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and drilling (Moyd, 1955a). No new large deposits of titanium ore were located, but the results of the survey were made available to the Geological Survey soon thereafter.

On Figure 2 the aeromagnetic contours are superimposed on a sketch-map of the area, the geology of which is taken largely from the maps of Adams (1896) and Osborne (1936, 1938). This figure also shows the distribution and abundance of the gabbroic anorthosite phase of the intrusion as well as the titaniferous occurrences now known (Rose, 1960). It is apparent from the spatial relationships shown on Figure 2 that the gabbroic phase of the anorthosite, with its associated titaniferous magnetite and ilmenite, is the cause of or contributes to many of the anomalies. Field observations by the writer indicate that large volumes of the iron–titanium oxide minerals are disseminated through the gabbroic anorthosite phase, and in several localities, because of its availability and amenability to magnetic concentration and separation, this material constitutes possible low-grade ore of iron and titanium. The Morin anorthosite area thus has considerable potential as a source of these elements.

Beresford Township

Two iron–titanium deposits are known in the central part of the Morin anorthosite, one near Ivry, the other near Degrosbois station. Fine-grained disseminations of titanomagnetite and ilmenite occur in the gabbroic anorthosite west of Lac Brulé.

Ivry. The ilmenite deposit near Ivry, in Terrebonne county about 65 miles north of Montreal, was opened in 1910. From 1912 to 1918, when production terminated, a total of about 16,000 tons of ilmenite ore was reportedly shipped from the Ivry Mine to the Titanium Alloy Company of Niagara Falls, New York, for use in the manufacture of ferrotitanium, a deoxidizer of steel (Robinson, 1922). In 1958–59 Heavy-Rock Mines Ltd. reopened the deposit and was said by Mr. Emile Latremouille (the owner of the pit) to have shipped about 36,000 tons of ilmenite to Montreal for use as heavy aggregate. The deposit is largely covered by overburden and bush, but it is at least 1,000 feet long and 130 feet wide in places. It is located on the crest of a high hill of anorthosite that extends northeasterly from the northeast tip of Lac Manitou (Pl. V A). The main pit is on lot 38, but the deposit extends in a northwesterly direction into lot 39 and in a southeasterly direction through lots 37 and 36, all in range V, Beresford township, Terrebonne county.

In the main pit on lot 38 a body of massive ilmenite about 60 feet wide cuts with sharp contact through dark anorthosite and contains large inclusions or horses of the anorthosite. The main lode strikes northwesterly, dips steeply towards the southwest, but tapers towards the northwest and splits at the southeast end of the pit into two or more bands that may be traced intermittently along strike into lots 37 and 36 (Fig. 9). The relationships are obscured by overburden to the northwest, but the location of a few loose pieces of ilmenite in the drift along the northwesterly extension of the strike suggests that the deposit may also extend into lot 39.

The deposit was examined by F. F. Osborne and was magnetically surveyed by D. A. Keys in 1935 (1936). Osborne (1936) described the deposit as dyke-like injections of a high-titanium magma into the anorthosite, and Keys concluded that it consisted of a patchwork of ore pods because of the erratic nature of his magnetometer readings. He calculated that the deposit was at least 186 feet deep at the main pit.

The ilmenite of the Ivry deposit is characteristically coarse grained and has a well-developed exsolution texture of aligned hematite blades and lenses. The ilmenite–hematite grains form an interlocking mosaic in which crystals of dark green spinel, dark plagioclase feldspar, pyroxene, amphibole, mica, apatite, magnetite, and sulphides (mainly pyrite) are incorporated. A carbonate mineral, possibly siderite, is finely dispersed through some of the feldspar grains. In places irregular veinlets of pyrite carrying some pyrrhotite and a little chalcopyrite intersect the ore.

Ore samples analyzed by the Mines Branch gave the following results:

	Robinson, 1922 %	Robinson, 1922 %	Rose, 1962 (unpubl.) %
Ti	19.92	19.84	19.7
Fe	42.75	42.98	38.2
SiO_2	7.54		
P	0.036	0.076	0.03
S	1.010	0.144	1.05
V_2O_3		0.04	0.164
Cr_2O_3		0.08	0.023

Recalculation of these results in terms of mineral constituents indicates that the ore contains about 59 per cent ilmenite, 27 per cent hematite, and 2 per cent pyrite.

The anorthosite around the deposit varies in colour from dark grey to chocolate brown and brownish red, and in texture from coarse grained to very coarse grained. It is generally very fresh and composed almost entirely of plagioclase of labradorite composition, but also carries limited amounts of hypersthene, augite, magnetite, and ilmenite–hematite. On the hanging-wall side of the deposit the anorthosite is slightly altered and has weathered to a light pink colour on the surface exposed from under the protective covering of the glacial till.

Both rock and ore are jointed, but joints are particularly well developed in the ore in the main pit where one set of joints strikes northwesterly parallel to the deposit and dips 72° to the east, and another set strikes easterly at right angles to the strike of the ore and dips vertically. Foliation and banding in interbanded ore and rock on lots 38 and 37 strike northwesterly and dip from 30° to 60° southwesterly.

The deposit is located on an aeromagnetic low and gives erratic magnetometer and dip-needle readings. It is inconspicuous when tested with a dip needle as it gives both low positive and low negative readings from spot to spot even on massive

ilmenite. An oriented specimen of ore from the pit was found to be stable under magnetic washing and reversely polarized, with its component of remanent magnetism directed towards the southwest and inclined gently upwards, i.e., almost at a right angle to the attitude of the deposit at that locality. Thus the low angle of inclination of the remanent magnetization and its reverse orientation, as compared with that of present induced magnetism, may be the cause of the inconspicuous and erratic magnetic readings over the deposit.

Degrosbois. In lots 38–41, range VI at Degrosbois station on the Canadian Pacific railway and about a mile north of the Ivry mine, an irregular titaniferous magnetite deposit occurs in dark, rusty weathered, medium-grained gabbroic anorthosite, and coarse-grained grey anorthosite. Part of the deposit is exposed in pits and outcrop a few feet south of highway 11 near the railway crossing about 6 miles north from Ste-Agathe-des-Monts. The deposit was opened in 1911 and was visited and described by Dulieux at that time (1913, pp. 72–78). It is now controlled by Pershing Amalgamated Mines Limited, Montreal. Several thousand tons of ore has been blasted from the main pit on lot 40 over an area of about 10,000 square feet, but little more than half of this material has been removed.

The general geology of the occurrence is shown in Figure 10. The titaniferous magnetite occurs in a breccia zone in and near the contact of gabbroic anorthosite and anorthosite. The gabbroic anorthosite is foliated in part and is crushed and brecciated together with the anorthosite, but in places it cuts and reticulates through coarse-grained anorthosite. Titanomagnetite and ilmenite–hematite replace the crushed groundmass anorthosite and include unreplaced remnants of anorthosite, crystals, and crystal fragments of plagioclase, pyroxene, and apatite. Fine-grained pyrrhotite is disseminated through much of the titaniferous magnetite, and corona zones of altered material occur about many of the feldspar grains in the titaniferous magnetite. Here and there titanomagnetite appears to invade and cement ilmenite–hematite grains. Because of the preponderance of titanomagnetite over ilmenite, the deposit has a higher iron:titanium ratio than the Ivry deposit. Four samples from the deposit taken by Dulieux ranged from 52 to 60 per cent iron and from 4.49 to 18.09 per cent titatinum. Early attempts to concentrate the ore magnetically were not successful in lowering the titanium content materially (Dulieux, 1913), but recent Mines Branch tests have been more successful in recovering iron, titanium, and phosphate concentrates. A magnetic concentrate made by the writer showed a content of 62.9 per cent iron, 4.2 per cent titanium, 0.07 per cent phosphoric acid (P_2O_5), and 1.73 per cent sulphur.

The ore material is strongly magnetic, and dip-needle readings are strongly positive but erratic at the occurrence. The aeromagnetic anomaly associated with the deposit is positive but only moderately strong. An oriented specimen from the deposit was found to be positively polarized but very unstable, with only a weak component of remanent magnetism inclined gently in a westerly direction, i.e., oblique to the earth's field and almost parallel to the trend of the deposit and of the associated aeromagnetic anomaly.

Wexford Township

St-Hippolyte-de-Kilkenny. An occurrence of titaniferous magnetite in lot 7, range I, mentioned by Adams (1896), and a dip-needle survey led to the discovery of a titanium deposit at Lac du Pin-Rouge nearby, and to the formation of Laurentian Titanium Mines Ltd. in 1952. Following their magnetic survey the Laurentian Titanium Company diamond drilled the deposit and reported that it contained 15 million tons of ilmenite-bearing material averaging 19.9 per cent TiO_2 and 27.6 per cent iron to a depth of 225 feet. The deposit is situated in lots 6–9, ranges II and III, extending past Lac du Pin-Rouge and Lac de la Roche.

The detailed geology of the deposit is shown on Figure 3 (*see* also McGerrigle, 1959). The ilmenite deposit forms only part of a series of larger, low-grade, titaniferous magnetite in gabbroic anorthosite that extends for 6 to 8 miles from St-Hippolyte-de-Kilkenny to near Lac Masson, and which is roughly outlined by aeromagnetic anomalies. The anomalous area consists of a belt of dark, medium-grained, foliated, gabbroic anorthosite that carries disseminated ilmenite, ilmenite–hematite, titanomagnetite, and intermediate minerals. Some of these iron–titanium oxide minerals are concentrated in irregular clots, veins, and massive bands (Pl. V B), and may contain associated pyrite, pyrrhotite, and chalcopyrite, generally in small amounts.

The belt of partly banded, iron–titanium-bearing gabbroic anorthosite, about 1,000 feet wide, trends northerly and is flanked by grey anorthosite that is poor in iron–titanium oxide minerals. It probably extends to considerable depth. Eight bulk surface samples taken by the writer from exposures along this belt were found to range in composition from 23.5 to 31.9 per cent iron oxide, and from 5.4 to 17.0 per cent titanium oxide. Large tonnages of this type of low-grade material are undoubtedly present in this belt.

Titanomagnetite, ilmenite, ilmenite–hematite, in places showing good exsolution textures, commonly form as much as 30 per cent of the host rock, but range from 5 to 50 per cent or more. Plagioclase feldspar, pyroxene, garnet, and apatite are the main gangue minerals and all are intimately associated with the opaque oxides in normal, interlocking, igneous texture. Because of this and the generally medium–coarse grain size (about 1 cm in diameter), a good separation of the ore and gangue minerals may be anticipated. Surface exposures and Laurentian Titanium Mines diamond-drill core indicate that the ilmenite-rich and titanomagnetite-rich ore materials are gradational one to the other.

Magnetic concentrates made by the writer from seven of eight bulk samples collected from along the titaniferous magnetite belt ranged in composition from 62 to 65 per cent iron, 0.9 to 2.4 per cent titanium, 0.15 to 0.22 per cent vanadium, 0.25 to 0.56 per cent P_2O_5, and 0.11 to 0.3 per cent sulphur. Mines Branch tests in concentrating the material from Laurentian Titanium Mines property ground to −200 mesh ranged from 62.5 per cent iron and 1.0 per cent titanium to 69.4 per cent iron and 0.3 per cent titanium, with 0.037 per cent phosphorus, 0.056 per cent sulphur, and 0.88 per cent SiO_2. Thus it is indicated

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that a good magnetic separation of much of this low-grade material may be made, together with a satisfactory reduction in the titanium content of the magnetite concentrate.

The magnetic concentrate from the eighth sample, however, that of ilmenite-rich material from the Laurentian Titanium Mines main showing south of Lac du Pin-Rouge, proved to be high in titanium and was determined by X-ray diffraction to be ilmenite. Although normal ilmenite is only weakly magnetic, this black mineral, when powdered, will jump to a hand magnet, thus behaving as normal magnetite. In addition, an oriented specimen of this material proved to be stable under magnetic washing and reversely polarized with a strong component of remanent magnetism. A chemical analysis of this material showed it to carry 44.14 per cent iron and 18.75 per cent titanium, having an Fe:Ti ratio of 2.4 and an $Fe^{+3}:Fe^{+2}$ ratio of 0.7. This is unusually high in iron (*see* Table VI) when compared with other ilmenite, and although some of the excess iron is undoubtedly due to exsolved hematite (titanhematite) and some to included titanomagnetite, it appears that the ilmenite itself is a ferrian variety. This probably accounts for its unusual magnetic properties.

Tamara Mining Ltd. and Drummond Copper Corporation Ltd. jointly hold claims on the northern part of the gabbroic anorthosite belt in which they are reported to have outlined a large occurrence of titaniferous magnetite. An estimated combined potential of 230 million tons averaging 20 to 23 per cent iron and 6 per cent TiO_2 is reported by the company in this northern part of the belt (Janes and Elver, 1959).

Other occurrences of low-grade titaniferous magnetite were noted by the writer south of Lac Castor, on the railway about a mile north of Ste-Marguerite Station, and near the road south of Wexford Lake (Lac des Îles). A sample from the occurrence north of Ste-Marguerite Station showed 23.3 per cent Fe, 21 per cent Ti, and 1.2 per cent P. A magnetic concentrate of this material carried 61.9 per cent Fe, 3.6 per cent Ti, 0.24 per cent P, and 0.24 per cent S.

Wolfe Township

An occurrence of ilmenite was noted on the road about a mile south of St-Faustin, in an area of low magnetic intensity. The geology of the occurrence is shown on Figure 11. A narrow band of dark gabbroic anorthosite, carrying sporadically disseminated ilmenite, magnetite, and pyrrhotite, was traced for a length of 1,200 feet and a width of 200 feet; it was flanked by grey anorthosite containing bands of grey anorthosite. In polished sections the ilmenite shows exsolution blades of hematite, a few grains of magnetite, and a little pyrite and pyrrhotite. In thin sections blades of ilmenite are seen to penetrate deeply along the cleavage of feldspar crystals. A sample of the rock showed only 11.8 per cent iron and 1.4 per cent titanium. Negative dip-needle readings were obtained in several parts of this area, much of which is covered by overburden.

Farther south along the road near Lac Laurin, rusty boulders and outcrops of gabbroic anorthosite carry considerable fine-grained titanomagnetite and ilmenite. Two samples from north and south of the lake each showed 11.1 per cent iron

and 1.7 per cent titanium. From these, magnetic concentrates made by the writer averaged 63 per cent iron, 1.8 per cent titanium, 0.24 per cent P_2O_5, and 0.22 per cent sulphur. Dip-needle readings vary from positive to negative, and strongly positive aeromagnetic anomalies occur near the lake.

Other Occurrences

Chertsey township. Titaniferous occurrences mentioned by Adams (1896) in lots 5 and 6, range VIII, and in lot 9, range I, were investigated by Laurentian Titanium Mines Ltd. Forty-four holes were drilled in ilmenite-bearing gabbroic anorthosite on lots 5–7, range VIII of Chertsey, from which reserves of 626,400 tons of ore containing 19.9 per cent TiO_2 and 27.3 per cent Fe were estimated by the company.

Chilton township. Occurrences of ilmenite–hematite, and of nickeliferous pyrrhotite with titaniferous magnetite in lots 8–12, range III, and in lots 5–8, range III, respectively, have been investigated by Laurentian Titanium Mines Ltd.

Rawdon. A deposit of titaniferous magnetite in foliated white anorthosite near the edge of the outlying arm east of the main anorthosite mass was reported by Adams (1896). The deposit is located in lot 2, range II, near the village of Ste-Julienne.

St-Jérôme. An occurrence of non-titaniferous magnetite was reported by Adams (1896) in the gneiss near the satellite anorthosite body of St-Jérôme.

Lac St-Jean – Saguenay Area

Dark hills and rushing rivers,
From a frigid inland bay,
Pour power down the clefted gorge,
Of mighty Saguenay.
And through the hills prospectors forge,
For treasures cached away,
Among the rocks and in the folds
Of mighty Saguenay.

Rocks assigned to the anorthosite series occupy part of the Lac St-Jean depression extending northeasterly for a distance of at least 200 miles and covering an area of more than 20,000 square miles. This is the largest known anorthositic body in Canada, if not in the world, but it may be rivalled by others to the northeast that are as yet incompletely known. The typical anorthosite is a coarse-grained dark grey rock composed largely of labradorite that weathers to a lighter shade. It shows great variation in grain size, colour, and texture, however, and grades in many places into large masses of more basic rock including gabbroic anorthosite, gabbro, norite, troctolite, and diorite.

In Bourget township, as shown by Jooste (1958), great dykes of pyroxene diorite and of ophitic troctolitic anorthosite and troctolite cut through the anorthosite. A few small dykes of black diorite porphyry, most of which are less than a foot thick, cut both anorthosite and diorite just west of the St-Charles titaniferous magnetite deposits (Jooste, 1958). Jooste regarded the former dykes

as being older than the titaniferous deposits, whereas the latter might be younger. He also found dykes of quartz syenite, granite, and pegmatite cutting the anorthosite group rocks, and he concluded that the acidic rocks of Bourget area formed two distinct groups, the earlier being syenitic in composition, the later granite. He found no further evidence beyond spatial relationship in support of Osborne's general contention that the acidic rocks were comagmatic with the anorthosite, and concluded that in this area they were distinctly younger and separate intrusions, possibly unrelated to the anorthosite group[1].

The titaniferous magnetite deposits near St-Charles, described by Osborne (1944) and others, were known before 1884, and a number of other occurrences have been located within the anorthositic mass. Recent aeromagnetic surveys by the Crane Company in the southeastern part of the massif have revealed many strong magnetic anomalies, both positive and negative. Many of these anomalies have been investigated by Louis Moyd and W. B. Agocs for the Crane Company. Moyd (1955b) 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. Although no new deposits of economic value were discovered, many concentrations of titaniferous magnetite and ilmenite were reported and much scientific information and data were collected. Anorthositic rocks were found to extend beyond Rivière Portneuf, and some of the negative anomalies (pole inversions) there were found to be associated with ilmenite–magnetite intergrowths as well as with ilmenite–hematite intergrowths. Strong negative anomalies were found to be associated in places with relatively sparse disseminations of opaque minerals. At Lac Pauline an anomaly of −11,000 gammas is associated with a zone of noritic anorthosite containing 16 per cent opaques (ilmenite grains with exsolution lamellae of hematite). In the Rivière Portneuf area an anomaly of −9,000 gammas is associated with a zone of basic diorite containing 17 per cent opaques (intergrown ilmenite and magnetite in a ratio of about 2 to 1) according to Moyd (1957).

St-Charles Deposits

The St-Charles titaniferous magnetite deposits lie north of the Saguenay River on lots 44 and 48, range I, Bourget township, about 3 miles upstream from the settlement of St-Charles. The general geology of the area was described by Dresser (1916), and a complete description of the deposits with an account of their history until 1950 was given by Jooste (1958). The possibility of utilizing the deposits by electric smelting was discussed by Stansfield (1916), and some good quality steel has been produced in pilot plant tests. No further development has ensued, however, despite the harnessing of the Saguenay River for hydro-electric power at Shipshaw nearby. Several companies have been interested in the deposits as a source of both iron and phosphorus, and recently some drilling was

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[1] K–Ar measurements made on a sample of biotite taken by the writer from a pegmatite dyke that intrudes the anorthosite in this area showed an age of 865 ± 43 million years, about 25 million years younger than that determined for emplacement of the Bignell ilmenite deposit of St-Urbain.

done by Canadian Javelin Limited. The ownership of the deposits is now divided among the J. F. Gauthier family of Jonquière, Canadian Javelin Limited, and others.

The deposits are irregular, lenticular bodies within a large mass of anorthosite and gabbroic anorthosite. The deposits are not completely exposed, but outcrop sporadically, trending northward through a zone about 2 miles long and a quarter mile wide flanking a dyke of gabbroic or troctolitic anorthosite. The ore material is mainly titanomagnetite with exsolved ilmenite and spinel. Ilmenite and spinel occur also as discrete grains along with the magnetite. Accessory olivine and pyroxene are common, and apatite is abundant in some of the ore lenses. Minor amounts of hornblende, biotite, and plagioclase are also found in the ore material. The largest of the exposed ore outcrops is on a hill about 60 to 75 feet high, 300 feet long, and 100 feet wide; it forms part of an ore mass that is at least 2,000 feet long and 300 feet wide at one location.

A ledge of massive and strongly disseminated titaniferous magnetite about 100 feet long and 15 feet high is found 300 feet south of the Saguenay River along the strike from the St-Charles deposits and in lot 44, range A, north of Kenogami township. The ore material exposed is similar to that of the St-Charles deposits; banding in it strikes at 20° and dips generally westerly. Judging from the position and structure of this outcrop and from the aeromagnetic anomaly associated with the deposits, it seems probable that the St-Charles ore zone extends southward across the Saguenay River for several hundred feet. Because of the irregularity of the occurrence it is difficult to estimate the total tonnage of titaniferous magnetite in the deposits, but it seems clear from the outcrops that at least several million tons of open-pit material is available throughout the ore zone.

The phosphorus-poor occurrences are mainly in the southern part of the zone. They average about 46 per cent Fe, 19 per cent TiO_2, and carry less than 0.13 per cent phosphorus. The phosphatic deposits, which occur mainly in the northern part of the zone, carry about 35 per cent Fe, 15 per cent TiO_2, and 3 to 5 per cent phosphorus. A selected sample analyzed for the writer by the Mines Branch showed 38.7 per cent Fe, 14.94 per cent TiO_2 (8.96 per cent Ti), 0.04 per cent S, 3.08 per cent P, 0.007 per cent Cr, and 0.03 per cent V. After grinding to -100 mesh and magnetic separation the magnetic concentrate (titanomagnetite carrying exsolved ilmenite) showed 60.8 per cent Fe, 10 per cent Ti, 0.22 per cent Mn, less than 0.05 per cent Cr, and about 0.05 per cent V. The Fe:Ti ratio of the raw ore material is 4.3; that of the magnetic concentrate 6.1. Thus difficulty is to be expected in attempting to reduce the titanium content of this ore material by mechanical methods.

Other Occurrences

Several other occurrences of titaniferous magnetite are known in parts of this district in Kenogami township near Moquin, in Alma Island township on lot 36, range II; and in Taché township, in lots 13–14, range V near Mine Lake. A strong magnetic disturbance was also reported by field men of Price Brothers & Company, Limited near Lac au Poivre east of Shipshaw River (Moyd, 1955b).

In 1957–58 a titaniferous magnetite deposit about 42 miles west of Roberval and 16 miles south of St-Félicien was being investigated by Roberval Mining Corporation. The property in Lyonne township, Roberval county, was not visited by the writer, but was examined in 1958 by G. A. Gross, who advised that the occurrence appeared to be similar in nature to the Matthews and Chaffey deposits at Newboro, Ontario. A magnetic survey is reported to indicate several magnetic anomalies which are to be tested by diamond drilling. Initial sampling indicated a grade of 24 per cent iron and 6.5 per cent titania. It is reported (Janes and Elver, 1959) that a concentrate grading 68 per cent iron and 0.5 per cent titania can be obtained with a grind to 100 mesh. Over 100 million tons of open-pit reserves is said to have been outlined. Early in 1959 it was announced that Oglebay, Norton and Company of Cleveland had obtained a 5-year lease on the property (Janes and Elver, 1959).

Other important titaniferous magnetite and ilmenite occurrences are reported in anorthositic rocks in both Chicoutimi and Saguenay counties, and on the Bersimis River (Morin, 1956). A deposit carrying more than 100 million tons of titaniferous magnetite is also said to have been outlined near Lac de la Blache about 50 miles northeast of Lake Pipmaukan (Janes and Elver, 1959).

Baie des Sept-Îles Area

The sombre hills that circle round, the busy port of Sept-Îles town,
Hold tons of titanmagnetite, cemented in anorthosite,
Formed in eons long ago, of molten magma from below,
Where once perhaps a crater's play, shaped the landscape of today!

Baie des Sept-Îles is a nearly circular indentation about 8 miles in diameter on the north shore of the St. Lawrence River, sheltered by a group of off-shore islands, and formed largely on anorthosite and gabbroic anorthosite. The anorthosite is typically grey-green to black and varies in texture from fine grained to very coarse grained. Much of the anorthosite is dark and heavy with pyroxenes, titanomagnetite, and ilmenite, and it becomes gabbroic anorthosite, norite, or gabbro. This rock type also carries olivine and becomes a troctolitic anorthosite or troctolitic gabbro. In several places dykes of similar variable composition and texture intrude these rocks from below, plainly indicating that all of these rocks form components of a composite multiple intrusion—some parts consolidated quickly, others crystallized more slowly. The rocks are commonly brecciated and cemented by masses of consanguineous anorthositic rock. Some rounded blocks of altered white anorthosite are included in the dark gabbroic anorthosite, and in a few instances pink granitic dykes intrude the anorthositic complex.

As early as 1866 titaniferous magnetite occurrences were known and later mined on a small scale at three localities on Rivière des Rapides: the Cran de Fer Falls (W. M. Molson mine), the Outarde Falls and the Gagnon deposit; and at two localities on the Rivière Ste-Marguerite, one a half mile below Clarke City, the other a mile above the falls of Clarke City. The Baie des Sept-Îles deposits were first mentioned by T. Sterry Hunt in the report of the Geological Survey

of 1866–69. They were mentioned by R. W. Ells in the report for 1888–89, and by J. Obalski in the Mines and Minerals of Quebec in 1889 and in the report of Mining Operations in the Province of Quebec in 1901. Other titaniferous magnetite occurrences were known at Cap Rond near the mouth of the Rivière-à-la-Chaloupe, and at Thunder River about 75 miles east of Sept-Îles.

The occurrences were examined by Prof. E. Dulieux for the Quebec Mines Branch in 1910, and his descriptions (1912, 1913, 1915) are among the best available. Dulieux recognized that the titanomagnetite occurrences graded transitionally into the dark gabbro and cut sharply across the light coloured phase of the anorthosite. The deposits at Sept-Îles were further studied by Faessler and Schwartz (1941) whose report made particular reference to the peculiar microtexture noted in the magnetite–ilmenite intergrowths. The area was one of several along the north shore of the St. Lawrence that were mapped geologically by Carl Faessler for the Quebec Department of Mines (1942). Faessler (1942) pointed out that the occurrences were but small parts of much larger ferriferous gabbros associated with the anorthosite, and that they had great potential as sources of low-grade iron ore. Judging by these reports, by the numerous occurrences of both massive and disseminated titaniferous magnetite and ilmenite in the gabbroic anorthosite of this area, and by the strong anomalies shown on the Crane Company aeromagnetic map of the area (*see* Fig. 7), this may indeed be true. It must be noted, however, that difficulty may be encountered in satisfactorily lowering the titanium content of part of this material because of the intimacy of the magnetite–ilmenite–spinel intergrowth. A magnetic concentrate made by the writer still held as much as 12 per cent titanium.

The ovate structure of the Sept-Îles anorthosite body is well illustrated by the curvature of the magnetic anomalies shown on Figure 7. The zones of high magnetic intensity outline zones of iron–titanium oxide-rich gabbroic anorthosite in which some potential titaniferous magnetite and ilmenite deposits are suggested. On the north side of the bay the gabbroic anorthosite is composed essentially of twinned plagioclase, pyroxene, olivine, titanomagnetite, and ilmenite. The rock varies considerably in grain size and in places grades into less mafic anorthosite on the one hand and into darker titaniferous magnetite on the other. 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 grained and finer grained dyke-like phases of the same rock, and by a few dykes of granitic composition. In addition to these veins and dykes, very fine grained branching black veinlets composed mainly of dark green chlorite, which seems to be a form of partly devitrified glass, and also a few white calcite veins penetrate the rock. In the quarry near the power dam on the Rivière Ste-Marguerite north of Clarke City, the gabbroic anorthosite is less mafic than that near Rivière des Rapides. In the former locality extreme variation in grain size is shown as well as complex intrusive relationships between the coarse-grained phases. There the coarse-grained anorthosite in the lower benches of the quarry grade upwards through medium- to fine-grained greenish phases that are in-

truded by dykes and branching dykelets of medium-grained anorthosite of precisely the same type as that in the intermediate zone. Evidently the consolidating anorthosite was more quickly cooled in the upper levels and was fractured and penetrated by fluid magma from below. Dark gabbroic anorthositic rock in quarries near Rivière des Rapides has a slight foliation produced by semi-parallel arrangement of elongated plagioclase plates, which strikes west-northwesterly and dips gently south-southwesterly. This slight layering, coupled with the chilled effects, suggests that the dark gabbroic anorthosite may form a layer or zone within the anorthositic body, and that this layer or zone may dip gently inward towards the centre of Baie des Sept-Îles forming part of a complex oval-shaped crater-like intrusion.

The occurrences near Rivière des Rapides are associated with a positive aeromagnetic anomaly (Fig. 7) and generally give positive but variable dip-needle readings. Two oriented samples of oxide-rich gabbroic anorthosite and one of titaniferous magnetite and ilmenite were taken by the writer from quarries near Rivière des Rapides for magnetic measurements. After magnetic washing they showed a fairly close grouping on the stereographic net, the general declination being to the northwest and the inclination very gentle; the two rock samples were positively polarized whereas the ore specimen was negative, that is, the direction of remanent magnetism in the three samples is roughly parallel with the strike of the foliation, and is also near the plane of the earth's present field. The gentle inclinations of $+$ or -14 degrees appear to be a reflection of the proportions of mixture of titanomagnetite and ilmenite in the rock. This conflict of magnetic vectors detracts from the intensity of the resulting magnetic anomaly.

Lac Allard — Romaine River Area

A sea of hills in a land rock-bound,
Clothed in fir and spruce,
How can your mineral wealth be found,
And then be put to use?

The occurrence of ilmenite in anorthositic rocks in this area was first recorded on the upper Romaine River by A. P. Low (1895). In 1942 and 1944 the Quebec Department of Mines published the results of J. A. Retty's geological work of 1941 in the Romaine River area in which he described finding outcrops of ilmenite within anorthosite on the shores of lakes Bat-le-Diable, Puyjalon, Allard, and Petit Pas, north of the fishing village of Havre-St-Pierre on the north shore of the St. Lawrence River. Late in 1942 some claims were staked that were subsequently optioned by Kennco Explorations, (Canada) Limited and by The New Jersey Zinc Company. In 1946 Kennco geologists located eight ilmenite deposits in the area, among which was the main deposit south of Lac Petit Pas, near the small lake now called Lac Tio (Pls. I, II). In the same year Quebec Iron and Titanium Corporation was formed to develop the new property, owned two-thirds by Kennecott Copper Corporation and one-third by The New Jersey

Zinc Company. A loading dock was built at Havre-St-Pierre, and a railroad was built 27 miles north to the Lac Tio deposit and completed in 1950. At Sorel, 550 miles up-river from Havre-St-Pierre, an electrical smelting plant was constructed to process the ore. An open pit with crushing plant was established on the Lac Tio deposit, ore was shipped from Havre-St-Pierre, and at Sorel in 1951 production began of a slag rich in TiO_2 suitable for the pigment industry and a high purity iron by-product known as Sorelmetal. Ten years later the 1961 production at the mine was 1,032,122 tons of ilmenite, and at the plant 413,715 tons of TiO_2 slag and 277,107 tons of Sorelmetal (pers. com., C. H. Burgess, Vice-president, Kennecott Copper Corporation). In 1964 the Sorel smelter produced 470,000 tons of 70–72 per cent TiO_2 slag and 330,000 tons of premium pig iron (Guimond, 1964).

In 1949 the Quebec Department of Mines published an account of Jacques Claveau's work in the upper Romaine River area in which he reported several occurrences of ilmenite in anorthosite; large deposits may occur in that area.

In 1947, the summer following the discovery of the main Lac Tio deposit, Quebec Iron and Titanium Corporation conducted an aeromagnetic survey over a large area and found that the main deposit was associated with a strong negative aeromagnetic anomaly (Fig. 6); this survey was extended in 1951. Results of these surveys were interpreted and published by Weston Bourret in 1949, Paul Hammond (1952), and R. J. Uffen (1955). No new orebodies were located by the aeromagnetic surveys, but they served as a means of screening large areas of inaccessible country. Bourret (1949) recognized that the strong negative anomalies in the area were the result of negative polarization of the massive orebodies, and Hammond (1952) further pointed out that strong negative anomalies were obtained from deposits of massive ilmenite although in most cases positive anomalies were registered over areas of "disseminated ilmenite". A study of the aeromagnetic data by D. G. Brubaker and J. R. DeVore (1955) of The New Jersey Zinc Company showed, however, that not all of the known areas of massive or disseminated ilmenite gave negative anomalies; some gave no anomalies or weak anomalies and some areas of disseminated ore gave positive anomalies. They concluded from this that either disseminated ore can cause anomalies of either sign or the negative anomalies associated with disseminated ore are probably underlain by undisclosed massive ore.

Description of Lac Allard Deposits

Since 1956 E. O. Dearden, geologist for Kennco Explorations, (Canada) Limited, has been responsible for the development and exploration of the Lac Allard area. He has made extensive use of both geological and geophysical methods (aeromagnetic, ground magnetometer, and gravimeter surveys) and in 1958 compiled a report on Lac Tio geological data for his company. The following description of the Lac Tio deposit is taken from his report, and is reproduced with the kind permission of Quebec Iron and Titanium Corporation.

> The Lac Tio deposit is roughly triangular in plan, with apex to the south. Its dimensions are 3,600 feet north–south and 3,400 east–west. Its surface area is 140

acres. A north–south valley cuts through the centre of the deposit forming Lac Grondin to the north and Lac Tio to the south. Approaching from the north, ilmenite is first exposed on the south shore of Lac Grondin and continues from this point southward to the north end of Lac Ano.

The section west of Lac Tio is called the Cliff orebody. It outcrops on a cliff rising 350 feet from the west shore of Lac Tio. It is elliptical in plan and is 1,240 feet north–south by 740 feet east–west. The Cliff orebody is a 200-foot thick tabular mass of ilmenite–hematite ore striking north–south and dipping ten degrees to the east. It is separated on the north from the Main orebody by a large tongue of barren anorthosite.

The Main orebody is north and east of Lac Tio. It is roughly rectangular in plan. It occupies the valley floor and extends up the valley sides for a maximum vertical distance of 400 feet. A lobe of the Main orebody extends southward along the east side of Lac Tio opposite the Cliff orebody.

A north–south fault zone cuts through the Main orebody west of the central valley and follows the west side of Lac Tio forming the scarp face of the Cliff orebody. The fault dips 70° to the east, but has an unknown displacement due to lack of horizon markers.

West of the fault, the Main orebody is 25 to 200 feet thick with a gentle dip to the west not exceeding five degrees. The ore east of the fault is the most important and extensive part of the deposit as now known. Diamond drilling in this area disclosed ore to a depth of 300 feet and many of the holes were bottomed in ore. The much greater thickness of the ore east of the fault is probably due to the downward displacement of this section of the orebody.

Inclusions of anorthosite, as well as horizons of ilmenite-rich anorthosite, are found throughout the orebody on surface and in the diamond drill cores. These waste blocks have no consistency in size, shape or orientation. They are presumed to represent blocks of country rock engulfed by the ilmenite during emplacement.

East of the valley (from co-ordinate 10,500-E), the Main orebody is covered by a low-grade capping composed of alternating bands of ilmenite and anorthosite. These bands dip 10° to the east and appear to reflect the general flat-lying attitude of the deposit as a whole. The thickness of massive ore beneath this capping has not been determined. At the eastern extremity of the orebody the overlying low-grade material reaches a vertical thickness of as much as 280 feet, (D.D.H. 90–12), averaging less than 40% ilmenite . . .

Megascopically, Lac Tio ore consists of crystal aggregates of thick, tabular ilmenite grains, up to 10 mm. across and 2 mm. thick, in parallel orientation, which produce a rough grain to the rock. Gangue minerals occur interstitially and include feldspar, pyroxene, biotite, pyrite, pyrrhotite and chalcopyrite. Although most of the ore is quite dense, near the fault zone it has a coarse, granular texture. The ore is strongly magnetic.

Microscopically, the ilmenite grains are seen to contain discontinuous blades of hematite oriented parallel to the basal pinacoid of ilmenite. The hematite lamellae are all elongated parallel to one another in the same crystallographic orientation. Between rows of coarse hematite blades are rows of much finer lamellae.

The Lac Tio mineral mixture consists of 75% ilmenite and 25% hematite. The intergrowth is so intimate and microscopic that mechanical separation is impossible, regardless of fineness of grind.

Ore Composition

According to Bourret (1949) and Hammond (1952) the ore averages from 32 to 36 per cent TiO_2 and from 39 to 43 per cent Fe, with a specific gravity of 4.46 to 4.9, and constant Fe:TiO_2 ratio. The iron:titanium ratio of the ore estimated by the writer from available analysis of ore and concentrates is close to 2, i.e., 2 to 1. In addition to major iron, titanium, and oxygen, minor amounts of silicon, aluminum, and magnesium, and traces of calcium, manganese, sulphur,

phosphorus, vanadium, chromium, sodium, and potassium have been reported in analyses of the ore; faint traces of copper, nickel, cobalt, tungsten, molybdenum, and tin have also been detected in the pig iron produced from the ore (Guimond, 1964). Ore shipments from the mine have been maintained at a grade of 87 to 90 per cent combined oxides. Dearden (unpubl. rept., 1958) estimated that more than 58 million tons of such high-grade material was recoverable in the main Lac Tio pit along with about half as much slightly lower grade and a considerable amount of much lower grade material. Plates VII A and B illustrate the nature of the ore.

Petrology and Palaeomagnetism

Hargraves (1959a, b) found that sheets of gabbroic anorthosite, or oxide-rich norite, are concentrated near the marginal area of the anorthosite and are intruded into the anorthosite. He also found that ilmeno-hematite is the character-istic oxide accessory in the anorthosite and consists of nearly equal amounts of ilmenite and hematite, whereas in the ore ilmenite predominates over hematite (*see* Pl. VII A). In the norite, however, magnetite may be present in amounts almost equal to that of the hemo-ilmenite. Hargraves found that the hemo-ilmenite forms interstitial grains or a matrix of equant anhedral grains with or without magnetite, and further, that in samples containing considerable magnetite there is distinctly less hematite in the ilmenite than in samples containing less or no magnetite. He concluded that this reciprocal relationship between hematite in ilmenite and free magnetite testifies to local variation in oxygen pressure, and that the similarity in bulk composition of ore oxides and norite oxides suggests an apparent genetic relationship between the ore deposits and the oxide-rich norite.

Hargraves measured the remanent magnetism of 47 samples of hemo-ilmenite ore by spinner magnetometer and found them all to be reversely polarized with the exception of one specimen from near the contact with an intrusive basic dyke. Although the declinations and inclinations of the remanent magnetism showed a broad spread, Hargraves concluded that this was due to the tendency for the remanent magnetism vectors to lie in the plane of maximum magnetic sus-ceptibility of hemo-ilmenite, i.e., the basal plane.

In 1961 Carmichael published a complete account of his investigations into the magnetic properties of the Lac Tio ore. In this account he described in detail the exsolution intergrowths of the hemo-ilmenite crystals from the Lac Allard area and illustrated the two stages of exsolution that are represented in the ores. He found that the main magnetic component of these crystals is an ilmeno-hematite phase having a composition of about 10 mole per cent of ilmenite in hematite and present in the form of tiny exsolution lamellae that are roughly 5 microns (0.005 mm) long, 1 micron wide, and 0.2 micron thick. These are the second-stage exsolution lamellae that occur within the first-stage intergrowths, generally parallel to the basal plane of the host hemo-ilmenite. Carmichael also found that the crystals have a very strong magnetic anisotropy causing strong magnetization in the basal plane, and further, that spontaneous reversals of magnetic polarity

take place with slight changes in temperature on heating and cooling these crystals in a range of temperatures from 200° to —200°C. He thus concluded that the reversed natural remanence of these hemo-ilmenite crystals seems to be connected with their exsolution structure, and that this phenomenon is not limited to a fixed range of composition as suggested by Seiya Uyeda (1958). Carmichael also found that the very small, second-stage, exsolved lamellae are richer in hematite than the larger, first-stage lamellae. From analysis of the exsolved phases he concluded that the large lamellae separated at a temperature between 575° and 600°C and the small lamellae at a lower temperature, probably between 150° and 0°C. Thus according to Carmichael, the large lamellae of hemo-ilmenite formed at a temperature slightly above their Curie point and were magnetized parallel to the earth's field at that time, but the small lamellae of ilmeno-hematite, formed later when the temperature had dropped below their Curie point, were reversely polarized in a process of exsolution magnetization accomplished by a negative exchange interaction between the existing hemo-ilmenite and the second-stage ilmeno-hematite lamellae.

Both Carmichael and Hargraves agreed that while the hemo-ilmenite crystals are reversely polarized, magnetite crystals in the associated norite or gabbroic anorthosite are normally polarized. Hargraves pointed out that when the ratio of magnetite to hemo-ilmenite exceeds 0.7 then the polarity of the magnetite becomes dominant over that of the associated hemo-ilmenite. He accepted the possibility of the reversed earth field theory of magnetism. Carmichael, on the other hand, suggested that since the magnetite associated with reversely polarized exsolved hemo-ilmenite is normally magnetized, this is further evidence favouring a self-reversing mechanism in hemo-ilmenite as opposed to a reversed earth field hypothesis. Regardless of the mechanism, the reversed polarization of the ilmenite–hematite results in an intense negative aeromagnetic anomaly.

Field and Laboratory Observations

The writer's field work in the area was confined to a brief examination of the rocks and ores in the open pit with the expert guidance of E. O. Dearden and Mine Captain H. Duggan, and during which representative and oriented specimens of ore and rock were taken for laboratory study. One of the outstanding features of the geology of the pit, apart from the massive ilmenite–hematite deposit, is its capping of low-grade oxide-bearing anorthosite and gabbroic anorthosite, which contains both ilmenite–hematite and magnetite in disseminated form, the former predominating at the mine. If this cap rock had not been removed by erosion from a large part of the underlying ilmenite it is possible that the deposit might not have been discovered.

From what has been learned in the Lac Allard area and elsewhere in eastern Canada, the association of titaniferous deposits (both ilmenite-rich and titanomagnetite-rich) with gabbroic anorthosite is firmly established. Zones of oxide-bearing gabbroic anorthosite commonly form parts of large anorthositic massifs, and in them low-grade disseminations are of much more common occurrence than high-grade deposits. They appear to be true source rocks of ilmenite

and titaniferous magnetite deposits, and it seems reasonable to surmise that many more ilmenite deposits will be found in association with low-grade disseminations of ilmenite and of titaniferous magnetite.

At the main pit the writer found both the hemo-ilmenite ore and the oxide-bearing (hemo-ilmenite rich) anorthosite cap rock to be reversely polarized, the former being inclined gently upwards in a northwesterly direction, and the latter inclined steeply upwards in a southeasterly direction—that is, in the same plane but inclined nearly at right angles to the former. The orientation, strength, and stability of the remanent magnetism of the ore and cap rock at the pit are thus apparently largely responsible for the intense negative aeromagnetic anomaly. In the district about the pit the same general pattern of strongly positive aeromagnetic anomalies associated with oxide-rich gabbroic anorthosite and of negative anomalies associated with ilmenite deposits seems, to the writer, to prevail, as it does elsewhere in the anorthositic massifs of eastern Canada and also in the Adirondack Mountains of New York State (Balsley and Buddington, 1958). There are, however, exceptions to this generalization in the St-Urbain area where the main ilmenite lodes give a positive aeromagnetic anomaly and where remanent magnetism studies by the writer indicate that the host rock anorthosite and part of the ilmenite in the deposits are polarized normally (Rose, 1961). Also at Lac du Pin-Rouge in Wexford township in the Morin anorthosite massif north of Montreal (Rose, 1960) a belt of gabbroic anorthosite carrying disseminations and bands of titanomagnetite passes gradationally across the strike into an ilmenite-rich zone, and the magnetic anomaly associated with it passes from strongly positive over the titanomagnetite-rich zone to negative over the ilmenite-rich zone. It is thus clear that both massive and disseminated titaniferous deposits may be associated with positive, negative, or weak anomalies. Nevertheless it is also clear that because of the close geological relationship between titaniferous deposits and gabbroic anorthosite, some of the low-grade magnetically anomalous areas of gabbroic anorthosite may conceal or contain richer deposits than are now exposed to view and should be carefully investigated.

A sample of oxide-bearing gabbroic anorthosite that is associated with a strong positive aeromagnetic anomaly south of the Lac Tio deposit (submitted to the writer by E. O. Dearden) was found to have a specific gravity of 3. The sample was crushed, ground to -100 mesh powder, weighed, and separated mechanically first by low-intensity hand magnet and then by high-intensity Frantz isodynamic separator. The sample was found to carry about 22 per cent of magnetically recoverable, heavy, dark, magnetic iron–titanium oxides, about 10 per cent of which was highly magnetic magnetite (the hand-magnet concentrate) and 12 per cent weakly magnetic ilmenite (the high-intensity separate). An X-ray fluorescence analysis showed the magnetite concentrate to be quite pure, carrying 71.8 per cent iron and only 0.2 per cent titanium along with 0.02 per cent manganese, less than 0.05 per cent chromium, 0.2 per cent vanadium, and less than 0.01 per cent each of cobalt and nickel. According to Hargraves (1959a) X-ray fluorescence analyses showed that the TiO_2 content of magnetites separated from numerous samples of oxide-rich norite and syenite

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of the Lac Allard area ranged from 0.75 to 33 per cent. The TiO_2 content of magnetic concentrates made by Quebec Iron and Titanium Company from samples from six different noritic disseminated oxide areas ranges from 1 to 2 per cent TiO_2, i.e., 0.6 to 1.2 per cent titanium (pers. com., C. H. Burgess). Although more extensive sampling and testing is required, these results suggest that it may be possible both to find extensive deposits of low-grade titaniferous magnetite in the Lac Allard area, and to separate them by magnetic methods into high-iron and high-titanium concentrates, the former for use as iron ore, the latter as a source of titanium (cf. Rose, 1960). The possible economic significance of this statement should be readily apparent and requires no further elaboration here.

A K–Ar determination on biotite collected by the writer from a pegmatite dyke that intrudes gabbroic anorthosite on the east margin of the main ilmenite deposit showed an age of 1,025 ± 60 million years (pers. com., R. K. Wanless). As ilmenite penetrates both rock types at this locality this age is apparently a maximum for the emplacement of the ore.

Magpie Mountain Deposits

The ore strikes north; high, wide and true!
But does the massive stuff go through?
Or, by some curious diversion ...

The main Magpie Mountain deposits, formerly known as the Awater-Lapointe, outcrop in a massive, serrated, hog-back ridge that strikes north and towers above the surrounding hills of township 1770, county of Duplessis, district of Saguenay, Quebec (Pl. VI A). They are located at lat. 51°25'N, long. 64°05'W, about 2 miles west of Rivière St-Jean near its headwaters south of the Labrador–Quebec boundary. This is about 78 miles north of Mingan on the north shore of the St. Lawrence River.

In 1910 Prof. E. Dulieux and his assistant Eugène Poitevin sampled the magnetic sands at the mouth of Rivière St-Jean. They went up the river for 13 miles in search of reported iron mines but found only pockets of "titanic iron" in anorthosite. The deposits 60 miles farther north were first claimed by Messrs. Awater and Lapointe who had noted magnetic disturbances when flying over the conspicuous ridge en route from Sept-Îles to Goose Bay in 1953. Hollinger (Quebec) Exploration Company Limited, who were then engaged in the exploration and development of the great hematite iron deposits of the "Labrador Trough" area, later optioned and examined the Awater-Lapointe deposits. The deposits were found to be titaniferous magnetite, from which the titanium could not be satisfactorily removed magnetically, and no further work was done. In 1957 Canus Iron Company Limited made a ground magnetometer survey of an area to the south and west of the main occurrences (pers. com., J. R. Mowat). The property was optioned jointly by Stratmat Ltd., a Canadian subsidiary of Strategic Materials Corporation of New York, controllers of the Strategic–Udy process of smelting, and by Halmon Mining & Processing Limited, controllers of the Halver-

son process of smelting titaniferous ores. In 1958 the Stratmat and Halmon companies began reconnaissance work on the deposits and a representative 3-ton sample was taken for smelting tests by Strategic–Udy process in Niagara Falls, New York. The results of the tests were considered satisfactory, and in 1959–60 Stratmat began a more intensive program of exploration and development under the direction of Dr. G. C. Monture, Company Vice-president. The deposits were carefully surveyed, mapped, and sampled by J. R. Mowat, Stratmat geologist. To accomplish this some thirty-five lines were surveyed by transit and chain and cut directly east–west across the strike of the deposits from two north–south baselines on opposite sides of the Magpie ridge, a monumental task! In 1961 the property was fully owned and controlled by Stratmat Ltd.

In 1961 the writer visited the property in company with J. R. Mowat to collect samples for mineralographic, petrographic, and magnetic studies. With the kind permission of Stratmat Ltd., Strategic Materials Corporation, and J. R. Mowat a reduced copy of Mowat's geological map and two cross-sections are reproduced here (Fig. 8) to illustrate the nature of the deposits.

General Geology

As shown in Figure 8, there are four more or less separate deposits. Deposits 1 and 2 are relatively massive, homogeneous titaniferous magnetite, whereas deposits 3 and 4 are composed of interbanded titaniferous magnetite, gabbroic anorthosite, and anorthosite. With the exception of number 3 deposit, which lies a few hundred feet east of the south end of number 2 deposit, all the deposits occur in a linear zone at least 4½ miles long and about 2,000 feet wide. Deposits 3 and 4 occur within small areas of gabbroic anorthosite and anorthosite, and deposits 1 and 2 are mainly within granitic gneiss and granite, although both are partly enveloped in dark gabbroic anorthosite also. The deposits are more or less foliated, or even banded, and are intersected by numerous, well-developed joint systems and faults. Deposits 1 and 2 carry inclusions of rock, most of which are anorthosite and gabbroic anorthosite, and in a few places bands of rock or low-grade ore are found. The deposits are separated by small, irregular areas of granitic rocks.

The oldest rocks in the area are grey granitic gneisses; the gneissosity generally trends north-northeasterly but is complexly folded and faulted. Owing to recrystallization and deformation the origin of these rocks is obscure, but presumably they are the equivalents of the gneissic granitic terrane of much of the Precambrian Grenville structural province. Intrusive into these rocks are faulted segments of anorthosite and gabbroic (troctolitic) anorthosite, that in places carry abundant titanomagnetite and are transitional into the titaniferous magnetite deposits. The old grey granitic gneiss is invaded and permeated in places by younger pink granite, which shows both coarse-grained, pegmatitic, augen, myrmekitic phases, and fine-grained aplitic phases. The relationship of anorthosite, gabbroic anorthosite, and titaniferous magnetite to the late pink granite is not certain, but the granite appears to be younger, as the anorthosite, although fresh elsewhere, is sometimes highly altered to masses of zoisite and epidote near the granite boundaries. All

these rocks and the ore are intruded by a few small dark dykes of fine-grained altered basalt, which appear to be the youngest igneous rock in the area, but nonetheless are rather highly altered and have been subjected to both dynamic and thermal metamorphism. Titanomagnetite also is found in the basalt dykes, and they may be genetically related to the ore and its accompanying gabbroic anorthosite, representing a late stage, chilled differentiate. All these rocks are believed to be of Precambrian age. They were obviously much affected by folding and faulting, the ore in particular being displaced abruptly along faults in several directions and disrupted in places by segments of granitic rock.

Mineralogy and Petrography

The Magpie ore material is hard, fine-grained, dark titaniferous magnetite with hardness value of between 5 and 7 and specific gravity of 4. It shows some variations in mineral content, chemical composition, grain size, and texture, but is more noteworthy for its uniformity in these qualities than for its variability. By variations in its opaque iron–titanium ore mineral content, however, it does pass in places into low-grade ore material and rock of gabbroic (troctolitic) anorthosite classification.

Typical ore is composed essentially of titanomagnetite in subhedral crystals that average $\frac{1}{2}$ mm in diameter, intergrown intimately with variable but subordinate amounts of twinned plagioclase, forsteritic olivine, green picotite spinel, grey apatite, red-brown biotite, complexly twinned feldspar, and ilmenite. Each titanomagnetite grain shows well-developed octahedral parting planes along which microscopic intergrowths of a spinel and possibly of ilmenite are arranged in typical, high temperature exsolution texture (Pl. VIII B). Ilmenite, generally free of exsolved lamellae, occupies interstices between titanomagnetite grains, and sometimes partly invades and replaces them, indicating its slightly later development.

In parts of number 3 deposit the titanomagnetite grains are more irregular in shape and slightly larger than elsewhere in the Magpie deposits, forming narrow bands, stringers, and clots in which the grains are more than 1 mm in diameter. Some coarser grains are found in the altered part of the anorthosite, and are, in part, fractured and penetrated by zoisite–epidote stringers that are associated with extreme alteration of the anorthosite.

Near faulted contacts with granite in deposits 1 and 2 foliation has been imposed on the ore material by shearing and stretching of the titanomagnetite grains accompanied by alignment of the interstitial ilmenite and gangue minerals along the foliation planes. As a result the ore material in this condition is more easily weathered and becomes more friable.

Remnants of dark green, subrounded, blocky grains of picotite spinel may be seen in thin sections of the ore material. The spinel occurs in grains of size and texture similar to the accompanying titanomagnetite grains. Many of the spinel grains are almost completely replaced by titanomagnetite in such a way that only narrow rims of translucent spinel are left on the outside or in a zone inside the

opaque magnetite. In some grains replacement is less complete and the titano-magnetite is shown as opaque dendritic intergrowths in the interior of the spinel. Because of their magnetite content such grains are strongly magnetic and may be distinguished and separated from magnetite only with difficulty. As a result the extraneous ingredients of the spinel are carried into the magnetic concentrates that are made from this material.

Olivine and plagioclase in the ore are of much the same composition and texture as in the gabbroic anorthosite. The olivine is a forsterite-rich variety and occurs in clear, unaltered, anhedral forms, mainly in the interstices between plagioclase crystals in the rock and between titanomagnetite crystals in the ore (Pl. VIII A). In places olivine includes small euhedral crystals of both plagioclase and titanomagnetite, showing a poikilitic or diabasic texture, in which plagioclase and titanomagnetite have presumably crystallized slightly before olivine. Similarly, polysynthetically twinned plagioclase in the ore and rock include small euhedral crystals of titanomagnetite and apatite, suggesting that the latter were formed before but almost at the same time as the formation of the plagioclase. Other crystals of feldspar in the ore showing complex Carlsbad, albite, and pericline twinning also include titanomagnetite crystals and appear to have formed slightly after the magnetite. Red-brown biotite (Pl. VIII A) is found in relatively coarse flakes in parts of the low-grade ore where it includes small crystals and grains of titanomagnetite and apatite. In addition to its characteristic occurrence in blocky, equidimensional crystals titanomagnetite and/or ilmenite also penetrate tiny fractures in olivine and feldspar, fractures that were probably formed shortly after crystallization of these minerals. Thus, although an overlapping paragenesis is shown between ore and gangue, the close primary genetic relationship among all these minerals is firmly established, and a complete gradation is shown from ore through oxide-rich to oxide-poor gabbroic anorthosite.

Geochemistry

Analyses of the deposits are as follows (J. R. Mowat, unpubl. rept., 1960):

Average of 3 deposits (expressed as percentage)

	From 21 chemical analyses	From 701 spectrographic analyses
Total Fe	43.69	42.7
TiO_2	10.91	10.5
SiO_2	5.95	6.7
CaO	0.60	
MgO	5.78	
V_2O_5	0.17	
Al_2O_3	11.57	
Cr	1.45	1.66
S	0.027	
P	0.078	

Averages of numbers 1, 2, and 3 deposits (expressed as percentage)

	Number 1	Number 2	Number 3
Total Fe	43.7	43.7	40.7
TiO_2	10.0	10.6	10.3
Cr	0.87	1.55	2.48
SiO_2	9.9	6.6	5.7

In these averages there appears a notable uniformity in iron and titanium content in the three deposits, but a marked increase in silica and decrease in chromium in passing from number 3 across to number 2 and north to number 1 deposit. There are also local fluctuations and variations in chemical composition in both longitudinal sections and cross-sections of the deposits. These variations are due in part to contamination by rock material at the contacts and to bands and irregular bodies of rock or low-grade ore within the deposits, but they may also be due in part to variations in composition within the original intrusion or to subsequent modification of the original deposits.

The results of Mowat's study of the analytical results may be summarized as follows: (1) the iron, titanium, and chromium profiles show consistent decreases towards the contacts; (2) silica shows a corresponding increase; (3) titanium generally shows a migration toward the foot-wall; (4) the chromium content is generally proportional to the iron, but in a few places varies without corresponding change in iron content. The relatively high chromium content of number 3 deposit as compared with that of deposits 1 and 2 seems particularly significant in this regard. This analysis led Mowat to suggest that chromium had been differentially concentrated in the deposits, presumably near active channelways and injection vents, and further that the chromium-rich number 3 deposit was probably the latest of such injections.

Variations in the chromium content, however, are small, ranging from about 0.5 per cent in number 1 deposit, to 0.7 per cent in number 3 deposit, to 1.5 per cent in number 2 deposit; the total range in all three deposits is less than 2.5 per cent. Comparisons of analyses of raw ore material with those of magnetic extracts made from it indicate that chromium tends to concentrate with the magnetite. Some of the chromium is undoubtedly carried in solid solution in the titanomagnetite, but in the writer's opinion most of the chromium is carried in the picotite spinel grains and intergrowths that are intimately associated with the magnetite and concentrate with it. Thus the writer regards the number 3 deposit as the early formed, coarser grained, chromium-rich, deeper seated representative of the deposits, genetically closer to the parent rock.

Cell-edge measurements on five samples of titanomagnetite from chromium-rich and chromium-poor parts of the deposits varied from 8.388 A to 8.395 A, falling within the general range found by the writer for titanomagnetites from deposits elsewhere in Canada, and being greater than that of pure magnetite. No clear-cut relationship between cell-edge measurements and chromium content of

the Magpie titanomagnetite was found, but the small variation in cell-edge measurements suggests that the titanomagnetite is of rather uniform chemical composition throughout the deposits.

Structure

The ore bands of deposit 3 show clear and consistent evidence of a dip of about 45 degrees to the west, but in deposits 1 and 2 the evidence is rather obscure. Most of the ore–rock contacts and the faint foliation in parts of the ore suggest a moderate dip to the west between low walls of granitic gneiss and granite. The ore–rock contacts are typically higher topographically on the east side of the deposits than on the west and there is a more gentle slope to the west, but nowhere is there a marked difference in elevation of contact areas from one side to the other. Mowat (unpubl. rept., 1960) found the north end of number 2 deposit to be a flat shallow basin structure in which the ore is abruptly terminated by the underlying granite; this is strong evidence of the shallow depth of that part of the deposit, probably also of other parts, and possibly of much of deposits 1 and 2. The deposits are also truncated and displaced by numerous faults. Because of this structure Mowat is justifiably skeptical of the extension to depth of large areas of deposits 1 and 2.

Remanent Magnetism

Eleven oriented specimens from the deposits and their wall rocks were taken by the writer from deposits 1, 2, and 3 for magnetic measurements in the rock magnetism laboratory of the Geological Survey. The locations of specimens and their declinations and inclinations are shown on Figure 8. The specimens were measured magnetically in a magnetometer before and after magnetic washing in an alternating current demagnetizing field. In contrast to many titaniferous magnetites elsewhere, the Magpie ores were found to be moderately stable before and after magnetic washing, a condition which may be due to their uniformly fine grain size. The directions of remanent magnetization in nine ore specimens, including high grade and low grade, and one of anorthosite are all towards the south and east quadrants, i.e., generally southeast, whereas those of two granite specimens are towards the northwest in the general direction of the earth's present field. The angle of inclination is low in many of the ore samples and is reversed or negative in a few. The general uniformity in orientation of the remanent magnetism in these ore materials and the anorthosite supports the suggestion that they are all closely related in time, and of a different age than the late pink granite.

In addition, if one may ignore a number of complicated factors which might have materially affected the magnetic orientation of the samples and assume that the samples are magnetically stable and that they were magnetized together in the period of consolidation and cooling, then the direction of remanent magnetization should be similar in various parts of the same deposit, providing they have not been subsequently distorted by folding and faulting. As the prevalent direction of remanent magnetism in number 3 deposit and in the south part of number 2 deposit

seems to be gently inclined towards the south-southeast at a high angle to the ore bands and foliation, and is steeply inclined but still at a high angle to the foliation and flat basal contact at the north end of number 2 deposit, it seems possible that parts of the deposit have been differentially rotated since they were magnetized. If this is so, it is further suggested that the south part of number 2 deposit and parts of number 1 deposit may go to greater depths than that suggested by the structure at the north end of number 2 deposit. This suggestion remains to be tested by diamond drilling.

Summary

In broad terms the Magpie deposits appear to be magmatic injections of differentiated ore and rock material that were emplaced far from the parent body into the older gneissic terrane. Further separation has since been produced by post-ore faulting and erosion. At the south end of the ore zone deposits 3 and 4 appear to be directly associated with fine-grained gabbroic anorthosite, but the association is not as evident in deposits 1 and 2 and becomes less evident from the south to the north where the deposit reaches its greatest penetration into the gneisses although there is still a definite association with gabbroic anorthosite in some of the low-grade areas. The anorthosite and gabbroic anorthosite bodies with which deposits 3 and 4 are associated probably represent only small segments off the shoulder of a much larger anorthositic mass that presumably lies to the south. The Magpie titaniferous magnetite deposits thus all appear to be of the same high-temperature magmatic injection origin. Millions of tons of ore material are in sight, and great reserves, measurable in billions of tons, are probable.

Chibougamau Area

The quiet tread of moccasined feet,
Towards the post before,
Now replaced by a dusty street,
And headframes on the shore.

An interesting belt of anorthositic rocks is found on the north side of Lake Chibougamau extending for a length of 20 miles and width of about 2 miles. The geology of the area around Lake Chibougamau, first reported on extensively by Barlow, *et al.* (1911) and Retty (1929), has been mapped and described by Mawdsley and Norman (1935), Graham (1956), and more recently by Smith and Allard (1960). The anorthosite there is associated with gabbro, pyroxenite, and serpentine. A smaller body, separated from the larger one by a band of granite, occurs southeast of Lake Chibougamau. Similar bodies of anorthosite also are reported on Bell River and near Lake Opémisca.

The Chibougamau anorthosite appears to form part of a layered sill-like mass with more basic differentiates both within it and at its base. The anorthositic mass is intruded into the enclosing schists of the Superior structural province at the northeasterly trending boundary with the Grenville province. Both the anorthositic rocks and the enclosing Temiscamian-type schists trend northeasterly parallel to the "Grenville front" and to the general trends of the Grenville gneiss. The geologi-

cal evidence at this locality for separating these two provinces of the Canadian Shield is not strong, but it is supported by available K–Ar dates (*see* Lowdon, 1961). It is possible that the parallel trends in the rocks of these two provinces have been produced by folding, faulting, and intrusion along the Grenville front. Late olivine diabase dykes striking west-northwesterly across this trend intersect rocks of both provinces and are presumably younger than the Grenville front faulting, whereas northeasterly striking diabase dykes have been dated at about 1,240 million years and are presumably pre-Grenville orogeny (pers. com., W. F. Fahrig).

Although the presence of titaniferous magnetite and ilmenite in the anorthositic rocks of this area has been known for some time no attempt has yet been made to develop any of the occurrences. An aeromagnetic survey made in 1957 by the Dominion Gulf Company as part of Operation Overthrust revealed many strong anomalies in the Chibougamau area, mainly in association with the basic rocks of the anorthositic suite. Following this survey some claims in Lemoine and Rinfret townships southeast of the lake were optioned in 1958 by Jones & Laughlin Steel Corporation, and during the summer of 1958 a program of diamond drilling, sampling, geological mapping, and dip-needle traversing was reported to have been carried out on the property. The occurrence is said to be titaniferous magnetite[1] in which the magnetite–ilmenite mineralization occurs in banded form as segregations in the enclosing anorthosite–gabbro complex.

The rocks of the Chibougamau anorthositic complex are generally much altered (saussuritized) and in places are completely serpentinized. A late stage of serpentinization is the development of fibrous chrysotile asbestos. Serpentinization and the formation of chrysotile asbestos were later than the anorthositic suite, and were perhaps caused by solutions from slightly younger intrusions of troctolitic anorthosite (gabbro) and/or granite. Nevertheless the development of chrysotile is post-magnetite, as a vein-like body of fine-grained dense magnetite in serpentinized gabbro southwest of Lac Bourbeau is intersected by well-defined seams and veinlets of fibrous white asbestos. Magnetite in the vein is associated with minor pyrrhotite and chalcopyrite and also occurs as small pods scattered through the serpentinized gabbro, parts of which are unaltered and carry fresh olivine and magnetite interstitial to clear plagioclase laths. Although the magnetite is possibly of two or more closely-linked generations, one exsolved from pyroxene, another as disseminated crystals and segregated pods and veins, all are clearly pre-serpentinization. It is equally clear that the bulk of the magnetite in vein form is post-gabbro. Thus the formation of asbestos, and possibly the complete serpentinization process, is separated from emplacement of the mafic rocks by a presumably brief period of segregation and emplacement of magnetite and sulphides. Although the sulphide minerals (pyrrhotite, pyrite, chalcopyrite, galena, and sphalerite) are paragenetically later than the magnetite, they all appear to be related and not far separated one from the other.

The emplacement of the Chibougamau gabbro–anorthosite–granite complex appears to have been controlled by northeasterly trending structures in the rocks

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[1] A significant vanadium content was reported in this titaniferous magnetite by G. O. Allard, *in* Quebec Dept. Nat. Resources, Prelim. Rept. No. 567, 1967.

of both structural provinces along the Grenville front, and is therefore at least slightly younger than the youngest of these rocks and structures, probably of late Precambrian (Proterozoic) age. Although the late olivine diabase dykes intrude the granitic rocks of the area they are petrographically similar to the gabbroic rocks and may indeed be related to them, all being post-Grenville faulting. This is consistent with the negative magnetic expression of at least one such prominent west-northwesterly trending diabase dyke south of Chibougamau that may be traced on the aeromagnetic map into but not across the anorthositic rocks that occupy the Grenville front around Lake Opémisca.

Aeromagnetic anomalies in the district generally reflect the northeasterly trending structure of the gabbroic rocks associated with the anorthosite body. The anomalies are strongly positive and appear to indicate large areas of disseminated magnetic minerals, mainly magnetite, ilmenite, and pyrrhotite, some of which may be of possible economic significance. On the other hand the directions of magnetization of a number of oriented specimens of the rocks and ore minerals show a broad spread in declination and inclination, both before and after magnetic washing, but all vectors appear to augment the total magnetic anomaly.

Bell River (Opaoka River Basic Igneous Complex)

In 1939 Freeman and Black collected samples from magnetite-rich bands, four from Channel Rapids on Bell River and four from localities 2 miles east of Shallow Lake. These were analyzed by the Quebec Department of Mines with a view to testing the economic possibilities of the complex. The magnetite was found to be titaniferous and it was reported (Freeman and Black, 1940) that chromium was found in all the samples, the highest being 0.44 per cent, along with traces of nickel, copper, and a range in titanium from 'trace' to 8.92 per cent.

Eastern Townships

A number of occurrences of iron ores, hematite, magnetite, and titaniferous magnetite, have been reported from the Eastern Townships since the 1870s. Although variously described and interpreted by a number of experts during the course of nearly a century, none has yet been developed. The presence of strong aeromagnetic anomalies discussed by MacLaren and Larochelle (1958) lends some incentive to their further investigation. The representatives of the titaniferous deposits appear to fall into two categories: (1) titaniferous magnetite deposits within phases of the gabbroic anorthositic Monteregian intrusions of Cretaceous age, which have only recently been given attention; and (2) mixed titaniferous and chromiferous magnetite deposits associated with serpentinized rocks of the serpentine belt, which are of probable Palaeozoic (Ordovician?) age. Deposits of type (2) occur in pockets within and grading into serpentinite. Some of the pockets are chromium-rich and others are titanium-rich. Deposits of type (1) occur as disseminations within the Monteregian intrusions, and in places carry submicroscopic intergrowths of ulvöspinel as demonstrated by E. H. Nickel of the Mines Branch (1958).

Beauce County

The occurrence of titaniferous magnetite in the seigniory St-François-de-Beauce was reported in 1863 by Hunt as "a bed of granular iron ore, forty-five feet wide in serpentine", and consisting of about two-thirds magnetic oxide of iron to one-third ilmenite. In 1889 Ells referred to "a great bed of magnetic iron ore or more properly ilmenite"; and in 1907 Obalski described a mass of ore 100 feet long and as much as 35 feet wide. In 1912 Dulieux described occurrences between two tributaries of the Chaudière from 1 mile to 3 miles apart and about 6 miles from Beauceville: Rivière des Plantes in the St-Charles range, and Caldwell (Colway, Callway) River in the Bloc range. A description of these deposits was also given by MacKay (1921, pp. 85–86) who concluded that "the limited dimensions of these lenses, their irregular occurrence, and the high percentage of titanium generally present make them of little commercial importance".

St-Charles range. On lot 301, the only showings reported by Dulieux (1912) are some small pockets of magnetite a few feet in diameter enclosed in highly ferruginous greenstone (serpentine). Analysis of a sample from one of these pockets yielded 54.77 per cent iron and 7.49 per cent titanium (Dulieux, 1912). On lot 300 a lens of magnetite 10 or 12 feet wide, showing no definite walls but passing by transition into country rock of decomposed pyroxenite or peridotite, was exposed in a pit 15 feet wide and 65 feet long according to Dulieux (1912). An analysis of material from the pit recorded by Dulieux showed 34.70 per cent iron and 12.36 per cent titanium.

Bloc range. The workings in the Bloc range are a series of shallow pits and trenches over a distance of 200 feet. According to Dulieux the ore occurs in irregular pockets in a serpentine rock. In one of the excavations the ore is chromiferous magnetite and contains only small quantities of titanium (sample 115, Dulieux), but in a trench less than 100 feet away the titaniferous magnetite showed no chromium (sample 116, Dulieux). His analyses follow.

	Sample 115 %	Sample 116 %
FeO	55.36	61.36
(Fe)	43.06	47.73
TiO_2	0.16	16.28
(Ti)	0.09	9.78
Cr_2O_3	9.86	none
Cr	6.80	none
S	0.075	not ascertained
P	0.045	not ascertained

Brome Township

According to McGerrigle and Girard (1950) analysis of a sample from a hematite band in range III, lot 1, showed 41.46 per cent iron and 24.16 per cent titanic acid. Extensions of the deposits are also reported to occur discontinuously in lots 2 to 6, ranges III to V, and it was believed that these veins extended from occurrences in Sutton township (*see* below) (Obalski, 1889–90).

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Sutton Township

Numerous occurrences of hematite in bands or veins from 2 to 8 feet thick are reported in lots 6 to 9, range IX; in lot 7, range X; and in lots 7 and 9, range XI. Most of these occurrences appear to be low in titanium, but according to analyses reported by Obalski (1889–90), two of them show considerable TiO_2. According to Obalski one on lot 8, range IX, showed 39.14 per cent metallic iron and 29.86 per cent titanic acid; another, on lot 9, range XI, gave 40.87 per cent iron and 27.2 per cent titanic acid.

The analysis of more than 20 per cent TiO_2 in these hematite ore materials suggests the presence of ilmenite, the two minerals being difficult to distinguish from each other in certain forms.

South Ham Township

According to Ells (1888–89, p. 19K), "a large and apparently excellent vein of magnetic ore is found on lots 19 and 20 of the Gore, west side of Nicolet Lake. The vein occurs in serpentine with a width of six feet at the surface, increasing to eleven feet in a shaft twelve feet deep. It was opened by Mr. Colombe in 1881, by whom about one hundred tons were extracted." According to McGerrigle and Girard (1950) the range and lot numbers given by Ells are in error, and he suggests that what appears to be the same deposit is described by Obalski (1889–90, p. 22) as being in lot 21, range I, on the north side of Nicolet Lake. The ore is said to be "imbedded in the fissures of a green carbonate of copper . . . " Haanel (1909, pp. 109–110) described the ore as a pocket of titaniferous magnetite of no economic value. A magnetometric survey indicated no extension of the ore away from the workings. Analysis gave 46.5 per cent metallic iron and 26.5 per cent TiO_2.

B. T. Denis (1931, pp. 93–94) reported a small pit about 90 yards from the shore and 2 miles from the northeast end of the lake. He reported, "The ore is solid magnetite, and although insufficient work has been done to permit estimation of the extent of the deposit, it seems probable that the body of ore is large." An analysis gave:

	%
SiO_2	0.98
TiO_2	19.85
Al_2O_3	8.42
Cr_2O_3	10.81
Fe_2O_3	24.83
FeO	28.22
MgO	2.31
CaO	1.20
	96.60

Other Occurrences

Grondin Mine

The "Grondin" or "Shawinigan" mine is a small pit or trench on lot 22, range VII, Shawinigan township, St-Maurice county, about 4 miles northwest of

the village of St-Boniface-de-Shawinigan, which in turn is about 6 miles west of Shawinigan. In 1878 an attempt was made by Mr. Grondin to smelt the titaniferous magnetite in a small furnace that he built near the Yamachiche River on lot 17. The pit, measuring about 22 feet long, 10 feet wide, and 6 feet deep, is in a dark gabbroic anorthosite carrying strongly disseminated titanomagnetite that forms a low-grade ore material. Strong dip-needle readings are shown in the vicinity of the pit. Exposures are poor, but a number of small occurrences of titaniferous magnetite are reported from lots 22 and 23, all in dark gabbroic rock. The deposits occur as small lenses in a mass of gabbroic anorthosite about 7 miles long and 2 miles wide. An analysis of the crude ore given by Dulieux (1913) showed 41.55 per cent iron and 5.44 per cent titanium. A magnetic concentrate made from this material at −80 mesh gave 53.4 per cent iron and 2.33 per cent titanium.

Haycock Mine

The main pits of the old Haycock mine opened in 1873–74, now water-filled and overgrown, are located in the northeast corner of the south half of lot 28, range VI, Templeton township, about one-third mile west of the township road. Analyses of 15 samples of the ore from various lenses reported by Cirkel (1909), showed

	%
Metallic iron	47.23–68.49
"Titanic acid" (TiO_2)	0.9 –18.8
"Phosphoric acid" (P_2O_5)	trace – 0.409
Sulphur	trace – 0.07

Examination of the ore material by the writer showed that it is composed mainly of dark, glistening admixed magnetite and hematite. A polished section of this material under the microscope showed further that hematite forms a network of delicate veins that surround, cement, and replace a mosaic of brownish magnetite grains. A few coarse grains of ilmenite or hematite were also noted in the magnetite.

A number of other small occurrences of titaniferous magnetite and titaniferous hematite have been reported from localities in Hull and Templeton townships north of Ottawa, but for the most part they appear to be of mineralogical interest only (Cirkel, 1909).

Pontiac County

A number of small titaniferous iron occurrences have been found in Bristol, Clarendon, Litchfield, Leslie, Calumet, and Sheen townships of Pontiac county. From information available none of the known deposits appears to be of commercial importance, but it is possible that further work may disclose larger and more consistent deposits within the area.

Bristol township. An outcrop about 2 feet square of a coarse-grained rusty hornblende rock carrying titaniferous magnetite is reported from lot 22, range I, of Bristol township. Cirkel (1909) reported a sample from this outcrop to contain 34.25 per cent iron and 11.78 per cent TiO_2.

Clarendon township. Titaniferous magnetite occurs in small veins and pockets in a coarse, dark hornblendic-looking rock on lot 27, range VII (Cirkel, 1909). An analysis of a specimen gave:

	%
Fe	54.94
TiO_2	7.23
S	0.001
P_2O_5	7.84

The country rock is dark grey contorted gneiss interbanded with amphibolite and with dykes and sills of medium-grained gabbro-diorite, all of which are intruded by pink granite and pegmatite dykes. Dip-needle readings in the area are for the most part very weak. No large deposits appear to be indicated.

Litchfield township.

Vinton:—About a mile south of Vinton station on lot 12, range V, a shaft about 12 feet square and 20 feet deep was sunk many years ago on land now owned by Mr. William Flynn. A sample from the shaft was reported by Cirkel (1909) to contain 55.98 per cent iron and 13.3 per cent TiO_2.

More recently a ground magnetic survey was made which indicates a magnetic zone extending in an east–west direction into lots 13 and 11. A diamond-drill hole directed northward at an angle of 45 degrees at the edge of the road in lot 13B is said by Mr. Mark McGuire to have penetrated a magnetite-bearing zone for about 50 feet. Farther east on lot 13C a 30-foot drill-hole ending in granite is said by the owner to have cut a 15-foot zone in which bands of magnetite from 1 inch to 16 inches wide occur. Dip-needle readings in the area of the shaft are either weak or negative. At the shaft titaniferous magnetite occurs as disseminations and bands in a dark, micaceous, banded, or gneissic gabbroic rock that forms a lenticular, concordant, sill-like body in granitic gneiss and schist. The bands strike north-westerly and dip 65 degrees southwesterly. The gneissic magnetite-bearing gabbro band may be traced northwesterly for about 500 feet and appears to be only about 30 feet wide. Both gabbro and granitic gneiss are cut by pink granite and by pegmatite dykes which in places carry small grains of radioactive minerals. Pink granite appears to be the predominant rock in the area around Vinton. A selected sample of the ore material of specific gravity 4.2, taken from the shaft by the writer, was analyzed in the Mines Branch chemical laboratory as follows:

	%
TiO_2	13.86
FeO	26.81
Fe_2O_3	34.91
S	1.47
P	<0.01
Cr	0.018
V	0.154

which recalculates to the following:

	%
Fe	42.89
Ti	8.32
Fe + Ti	51.21 and Fe:Ti = 6.2:1

A magnetic concentrate of this material gave 71.9 per cent Fe, 0.2 per cent Ti, 0.05 per cent Cr, and 0.25 per cent V. The total ferride element content of the magnetic concentrate was 72.47 per cent and its Fe:Ti ratio was very high. The cell edge of this magnetite was found to be 8.394 ± 0.005 A. It was also possible to separate ilmenite magnetically from the ground ore material in amounts only slightly smaller than those of the magnetite.

Lot 10, range VIII:—Loose blocks of titaniferous magnetite and one small outcrop of magnetite in place along a rocky ridge in lot 10 were reported by Cirkel (1909) who also recorded magnetite occurrences in lots 11 and 14, range VIII of Litchfield township. An analysis of the magnetic material reported by Cirkel (1909) showed 53.68 per cent metallic iron, 15.75 per cent titanic acid, 0.005 per cent phosphorus, and 0.078 per cent sulphur.

Lots 4 and 5, range X:—Titaniferous magnetite was also reported by Cirkel (1909) on the line between the two lots. Large blocks of clean ore were supposedly available, but the extent of the deposits is not known. A sample analysis reported by Cirkel showed:

	%
Metallic iron	47.92
Titanic acid	15.44
Phosphorus	0.004
Sulphur	0.084

In the granitic hills of lot 5, range X, on the property of Moses Pitt, considerable work has been done to expose an occurrence of titaniferous magnetite and of radioactive pegmatite. A magnetometer survey was made in 1959, numerous pits and trenches were dug, and two diamond-drill holes were put down, one of which according to Mr. Pitt cut 40 feet of magnetite.

A concordant sill-like band of coarse-grained coronitic dark gabbroic rock intrudes the gneisses, trending northwesterly and dipping near vertically. It carries disseminations and segregations of titaniferous magnetite. Pink granite and pegmatite penetrate both rock and ore material in places.

The best magnetite showing is in two small pits each 2–3 feet in diameter and in which nearly massive magnetite is exposed in dark gabbro, both being intersected by feldspathic veinlets. Dip-needle readings are strongly positive near these pits. Twenty-five feet north of these pits an area about 50 feet by 25 feet has been stripped revealing irregular disseminations and clots of magnetite in coarse-grained gabbro. About 100 feet farther to the northwest stripping has exposed a black mass of radioactive minerals about 3 by 8 by 6 feet at or near the contact of a zone of pegmatite that intrudes the gabbroic rock. Biotite flakes are developed at the immediate contact of the two rocks, and tiny hair-like veinlets of feldspar carrying a little purplish fluorite penetrate both the radioactive minerals and the gabbro.

X-ray fluorescence analysis of the dark radioactive materials showed a strong concentration of rare earths (Ce, La, Nd, Gd) with major iron and considerable thorium and strontium. Titanium and traces of uranium were also detected. The

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major part of the dark radioactive material is believed to be formed of allanite and keilhauite, the variety of sphene rich in rare earths. The presence of the rare titano-silicate of the rare earths, chevkinite, and possibly other rare minerals is suspected.

An absolute age determination made by the K–Ar method on samples of biotite from the contact of this dyke gave an age of 940 ± 47 million years. The titaniferous magnetite, the gabbro, and the granitic gneiss are, of course, all older than this.

The magnetite-rich zone in the gabbro appears to be at least 15, possibly 20 feet or more wide, and it has been traced intermittently for a length of about 700 feet. The most intense dip-needle readings in this zone are over the two small pits in magnetite, where readings of $+75°$N and $+80°$W were obtained. Two oriented specimens from these pits were found to be positively polarized and relatively stable under magnetic washing. Both specimens were polarized and inclined from 17 to 48 degrees in a westerly direction. This is oblique to the earth's present induced field at that locality and more gently inclined. Remanent magnetism augments the intensity of the magnetic anomaly here. The deposit appears to lie on the flank of a broad weak aeromagnetic anomaly extending to the north-northwest for almost a mile.

As seen in polished section the "ore material" consists of a mosaic of inter-locking grains of magnetite and ilmenite with minor blocky grains of gangue and a rare pyrite grain. In detail the magnetite grains contain very minute spindles and rods of a grey mineral, presumably spinel, and although most of the ilmenite grains appear free of intergrowths a few of them showed an extremely fine grained and irregular, two-stage intergrowth of exsolved hematite. The nature of the polished section of this ore prompts the suggestion that it should be practical to make a good magnetite separation of both magnetite and ilmenite from this type of material, and although insufficient iron ore material appears in situ, the presence of radioactive minerals in addition to those of iron and titanium renders the prospect worthy of investigation.

Waltham township. A small outcrop of titaniferous magnetite was uncovered by the Perry Brothers in 1958 during wood cutting operations west of the Rivière Noire about 2½ miles north of Waltham Station. The occurrence may be reached by following the road along the west bank of the Rivière Noire 3 miles to its end and thence on foot 2 miles northwesterly up the beaver-dammed valley of Schmitt Brook. The writer was guided to the occurrence by Mieley Perry of Waltham Station. It is a small exposure in 3 shallow pits less than 10 feet square in the bush about 200 feet up the north-facing side of the ridge south of Schmitt Brook in lot 27, range V of Waltham.

Titaniferous magnetite intermixed with dark, coarse-grained gabbroic anorthosite and grey anorthosite are exposed in the pits. Dark green crystals of amphibole, pyroxene, and biotite are developed at the contact of titaniferous magnetite and anorthosite in the pit. In outcrops nearby grey anorthosite carrying dark pyroxene,

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amphibole, and clots of ilmenite appears to be the main rock, but it is flanked on the south by granite and pegmatite that penetrate the gabbroic anorthosite in a draw about 20 feet south of the pits. The anorthosite and gabbroic anorthosite with associated titanomagnetite and ilmenite appear to form a northwesterly trending band of limited but unknown extent in the gneisses of the area.

A 210-pound sample from the pits was submitted in 1959 by Mr. Charles I. Lynch to the Mines Branch for analysis. Both magnetite and ilmenite were detected in the sample, which when analyzed gave 44.25 per cent iron and 14.6 per cent titanium dioxide. A magnetic concentrate from this sample at −200 mesh showed 68.42 per cent iron, 1.85 per cent titanium dioxide (1.1 per cent Ti), and 1.06 per cent silica. The recovery of iron was 62.8 per cent and the ratio of concentration 2.5:1.

At the pits the dip-needle readings were +47°N and +75°E. An oriented sample of the titaniferous magnetite was found to be moderately stable under magnetic washing and positively polarized in a direction of 217 degrees and inclination of +30 degrees; the adjacent coarse-grained gabbroic anorthosite was also found to be relatively stable under magnetic washing, being polarized positively in a direction of 190 degrees with inclination of +21 degrees. The general direction of polarization of both rock and ore material is thus gently inclined and directed slightly west of south. This is of course greatly oblique (almost at right angles) to the present induced field of the earth in that area, but augments the total magnetic anomaly.

No prominent magnetic anomaly appears on the aeromagnetic map covering the area, but a broad though weak positive anomaly appears to centre about 2 miles to the north of the occurrence. This would lie in the wooded hills on the north side of Schmitt Brook, and may be the magnetic expression of gabbroic anorthosite with associated dissemination of titaniferous magnetite. This anomaly forms part of a more extensive belt of magnetic highs that extend north-north-westerly along the Rivière Noire.

Ontario

A number of titaniferous magnetite deposits are associated with gabbroic and anorthositic rocks in eastern Ontario, many of which have been described by Rose (1958). Recently some old surface pits on a newly mapped body of gabbroic anorthosite north of Westport were investigated by Mr. William Strong and associates of Perth, and the old Matthew (Yankee) mine property southwest of Westport has been acquired and tested by New Mylamaque Explorations Limited. In northwestern Ontario Stratmat Ltd. investigated the Bad Vermilion Lake – Seine Bay titaniferous magnetite deposit south of Mine Centre. Interest has been maintained from time to time in the vanadium-bearing titaniferous magnetite of the old Brazeau-Woods property south of Mattawa, and some diamond drilling has been carried out there. In general the Ontario deposits appear to be geologically similar but smaller than many of those in Quebec.

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Leeds County – Westport Area

Matthews (Yankee) and Chaffey Deposits

The old Matthews workings consist of an abandoned, water-filled pit about 300 feet long by 100 feet wide and reported to be 40 feet deep. The pit is located in lot 1, concession VI, North Crosby township, about a mile west of Newboro and near the west shore of Newboro (Mud) Lake. The Chaffey pit is nearby on a small island in Newboro Lake, in lot 27, concession VI of South Crosby township. After a long period of idleness both properties were optioned in 1958 by New Mylama-que Explorations Limited, who are reported to have conducted an exploration program including magnetic surveying, diamond drilling, sampling, beneficiation and smelting tests (Janes and Elver, 1959).

Titaniferous magnetite occurs in seams and disseminations throughout a body of banded gabbroic anorthosite and appears to be concentrated in two main masses about 2,000 feet apart near the old pits. Company engineers estimated 45 million tons averaging 27 per cent soluble iron to a depth of 350 feet, of which 32 million tons of 25.2 per cent iron grade are estimated in the Matthews and 12 million tons of 32.5 per cent iron in the Chaffey. The estimate has since been raised to 53 million tons averaging 26.73 per cent iron, 6 per cent titania, and 1 per cent sulphur to an open-pit depth of 350 feet (Janes and Elver, 1959).

The ore material is coarse grained and is composed essentially of intermixed grains of titanomagnetite, ilmenite, plagioclase, pyroxene, and minor pyrite and biotite. Both ore and rock material have an interlocking igneous texture, and the "ore" grades imperceptibly into rock by diminishing opaque mineral and increasing feldspar content. In polished surfaces some of the magnetite grains showed micro-scopic exsolved blades of ilmenite. The oxides are readily concentrated by magnetic methods at a relatively coarse grind. The texture and mineral content suggest that it should be possible to make both magnetite-rich and ilmenite-rich concentrates from this material; this was confirmed in part by a hand-magnetic separate made by the writer in 1953 in which the titanium content was reduced to less than 1 per cent. Concentration tests by the company are reported to have indicated that a magnetic concentrate grading 60–64 per cent iron, 4–5 per cent TiO_2, 1.3–3.5 per cent SiO_2, and 0.5–1.4 per cent sulphur may be made at a relatively coarse grind of −20 mesh.

A representative sample of dark, oxide-rich banded gabbroic anorthosite from a fresh pit about 100 feet north of the old Matthew pit, was taken for chemical analysis. Its analysis (A, below) is compared with two samples of ore from the dump (B and C) and to a magnetic concentrate made by the writer (D). Values are expressed as percentages.

	A	B	C	D
SiO_2	38.1	—	6.84	
Al_2O_3	12.9			
Fe_2O_3	10.6			
FeO	9.88			
Fe (calculated)	25.7	55.06	48.32	62.7

	A	B	C	D
CaO	9.8			
MgO	5.2			
Na$_2$O	2.2			
K$_2$O	0.30			
H$_2$O+, H$_2$O−	1.0			
TiO$_2$	4.5	11.15	16.40	
Ti (calculated)	2.7	6.7	9.8	4.5
P$_2$O$_5$	4.1			
P (calculated)	0.04	0.05	0.048	
MnO	0.15			0.09
Mn (calculated)				
CO$_2$	0.0			
S	—	0.66	0.159	
V$_2$O$_5$	—	0.10	—	
V (calculated)				0.19
Cr$_2$O$_3$	—	trace	—	
Cr (calculated)				<0.05
Ni	—	nil	—	n.d.
Fe + Ti	28.9	61.7	58.2	65.4
Fe:Ti ratio	8.0:1	8.2:1	4.9:1	13.9:1

It appears possible to raise the iron content from 25 to 62 per cent by magnetic concentration, but at the same time the titanium content is also slightly increased from 2.7 to 4.5 per cent. Thus difficulties are to be expected in attempting to lower the titanium content satisfactorily by magnetic separation (*see* also description of North Crosby township occurrence on following pages). Small-scale and large-scale metallurgical electric furnace tests have been carried out by Strategic–Udy Processes, Incorporated, at its Niagara Falls, New York plant. Strategic–Udy reported (Udy and Udy, 1958) that semi-steel or pig iron can be produced from these ores with a low power consumption, and that the sulphur, phosphorus, and titanium in the product can be held to within specifications.

The gabbroic anorthosite host rock of the deposits is intruded by a body of pink syenite on the south and by small fine-grained dykes of gabbroic anorthosite composition. These dykes are intruded parallel to the anorthosite–syenite contact and both syenite and dykes crosscut banding and foliation in the anorthosite. Both appear to have been intruded after the formation of the titaniferous magnetite seams in the anorthosite.

The direction of the stable component of remanent magnetism in these rocks and ores appears to be variable but generally inclined gently northwestward, i.e., parallel to the trend of the dykes and the anorthosite–granite contact and across the banding in the anorthosite. The magnetism is rather unstable; it is normal in the dykes (two specimens) but reversely polarized in the oxide-rich gabbroic anorthosite (two specimens). This supports the geological evidence of a slight difference in age between the dykes and the oxide-rich anorthosite.

The negative remanence over concentrations of intergrown ilmenite and magnetite must also be considered in the interpretation of magnetic anomalies in this area. This effect would generally tend to decrease the positive intensity of the resulting magnetic anomalies there, and perhaps produce negative anomalies in places where ilmenite, ilmenite–hematite, and other intergrowths are abundant.

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North Crosby Township

A number of iron occurrences have been found in the past in North Crosby township, but there is little or no information recorded about them. Reference was made by Ingall (1899) to Allans mine, a titaniferous magnetite occurrence in basic rock on lot 27, concession IV, where some test pitting had been done; his map also showed reported occurrences near Spectacle Lake about 3 miles northwest of Westport. In 1961 the writer was guided by Mr. William Strong of Perth to a number of titaniferous magnetite occurrences on or near lot 24, concession VI, and to another about a quarter mile north of Spectacle Lake on lot 20, concession VIII. The general geology of the area has been mapped by Wynne-Edwards (1959).

The titaniferous occurrences lie about 2½ miles apart and near the extremities of a pear-shaped body of gabbro and gabbroic anorthosite which is almost completely surrounded by granitic rocks. The occurrences consist of disseminations and seams of titaniferous magnetite in banded gabbroic anorthosite and thus appear to be geologically similar to those of the Matthews and Chaffey deposits in North Crosby township. Only a small amount of massive ore material is visible in the badly weathered test pits and trenches on the northern occurrences, but some fresh massive titaniferous magnetite is exposed in the small pits north of Spectacle Lake.

A ground magnetic survey conducted by Mr. Strong in 1960 outlined several magnetic anomalies in the areas about the pits. The anomalies appear to be associated with disseminations and concentrations of titaniferous magnetite in the gabbroic anorthosite. The area between the occurrences is incompletely explored.

In both north and south areas it is clear that the pink granite and pegmatite intrude the gabbroic anorthosite. A pegmatite dyke on the Cook farm penetrates gabbroic anorthosite a short distance east of the northern occurrences and is rich in sphene (titanite), the titanium content of which may have been derived in part from the gabbroic anorthosite.

Thin sections of the gabbroic anorthosite host rock of the northern occurrences show that magnetite and ilmenite occur mainly interstitially in a mosaic of interlocking plagioclase crystals with irregular boundaries. Some altered pyriboles, with rims of mica and zonally altered interiors, and a few grains of tourmaline and apatite were noted. Some of the plagioclase is warped, fractured, and penetrated by seams of chloritic material. Some of the grains, both of plagioclase and altered pyribole, are peppered with fine blebs and blades of magnetite. A polished section of the oxide material showed it to be essentially a coarse-grained mosaic of ilmenite, ilmenite–hematite, and magnetite, with minor included crystal remnants of plagioclase and pyribole. Pyrite is abundant—it occurs in both ore and gangue minerals and generally carries a little associated chalcopyrite. In many of the ilmenite grains, an almost submicroscopic two-stage intergrowth of exsolved hematite blebs and blades may be detected by close scrutiny. The ore minerals appear to be mainly interstitial to and marginally replacing the gangue minerals.

Thin sections from the host rocks at the Spectacle Lake occurrence show fresher, coarse-grained gabbroic anorthosite composed essentially of twinned

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plagioclase, intergrown ilmenite, magnetite, brown biotite, and green spinel. The ore minerals also occur in an included remnant of biotite schist and in minor amounts in the paragneiss wall-rock. A polished surface of the oxide material from Spectacle Lake, although strongly magnetic, consists mainly of a mosaic of interlocking subhedral ilmenite crystals that contain considerable gangue material including crystal fragments and irregular grains of plagioclase, pyriboles, and micas. A few magnetite grains are present, and some of the ilmenite grains show a very faint exsolution of hematite. Pyrite and chalcopyrite are less abundant than in the northern occurrence, and the ore minerals are of finer grain size. A few irregular areas of a greenish anisotropic mineral, possibly goethite or hematite, were noted within the ilmenite.

Mines Branch attempts to concentrate material submitted by Tib Exploration Limited in 1959 from North Crosby township showed an anomalous titanium distribution. In studying this E. H. Nickel found that the range of TiO_2 distribution in the magnetic concentrates of various sizes ranged from 1.04 per cent at 100 mesh, through 28.5 per cent at —200 mesh, to 1.67 per cent at —14 mesh, and 2.41 per cent at —10 mesh. He concluded that this must be due to the magnetic characteristics of the ilmenite–hematite grains themselves. Because of this complication some difficulty may be experienced in attempts to completely separate the magnetite and ilmenite of the North Crosby occurrences. This appears to apply also to the Matthews and Chaffey deposits.

Oriented specimens of the ore materials and rocks in these occurrences showed considerable magnetic instability and great spread in both declination and inclination of remanent magnetism. A sample of the Spectacle Lake ore material was reversely polarized, and one of the northern occurrences was positively polarized. A late trap dyke at the northern occurrence was reversely polarized. Dip-needle readings in the northern area were generally positive, varying from moderate to fairly strong ($+50°N$ to $+75°N$), and were very strong at the Spectacle Lake occurrence, varying from $+90$ to $—49$ degrees, showing a reversed polarity at the main pit.

Further geological development work and testing are required to determine whether an economic mineral deposit is present in this area.

Rainy Lake Area

Seine Bay and Bad Vermilion Lake

Titaniferous deposits are known south of Mine Centre, in the Rainy Lake region of northwestern Ontario about 20 miles east of the Minnesota boundary at International Falls. They extend for 14 miles in a linear belt from the shore of Bad Vermilion Lake from a point 3 miles south of Mine Centre southwesterly to Seine Bay on Rainy Lake. The northeast end of the belt may be reached from Mine Centre, on the Canadian National Railways, or by the highway between Fort Frances and Atikokan.

The Seine Bay titaniferous magnetite occurrences have been known for many years, and have been staked, abandoned, and re-staked several times. Some diamond drilling is reported to have been done for a Mr. Hunter of Duluth, Minnesota, in 1911 on the southwest part of the range (Robinson, 1922). In 1917 the Mines Branch made a magnetometric 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 a number of chemical analyses and of the diamond drilling and subsequent concentrating tests are given by Robinson (1922). The material was found to be a phosphatic, vanadium-bearing, titaniferous magnetite with siliceous gangue and not amenable to separation of iron and titanium by mechanical means (Robinson, 1922). By 1919, however, W. M. Goodwin and A. F. G. Cadenhead had developed, at Queen's University, a process for smelting titaniferous ores using silica or sand as a flux and recovering vanadium in the resulting pig iron. In some cases the ores proved to be self-fluxing. The process was applied on pilot plant scale to the Bad Vermilion Lake titaniferous magnetite and to similar materials from other localities with satisfactory results as indicated in Mr. Goodwin's report to the Canada Research Council in 1921. The deposits were never developed beyond this stage, however, and the process was never applied on a commercial scale. More recently in 1956–58 the deposits were again investigated and partly abandoned by Stratmat Ltd.

The general geology of the area is shown on maps by A. C. Lawson (1913) and T. L. Tanton (1936). It is clear from these maps that the titaniferous magnetite is associated with a sill-like or tongue-like body of gabbroic and anorthositic rocks that is intrusive into the older Keewatin-type greenstones, schists, and metasediments. The gabbro–anorthosite is in turn intruded by younger granitic rocks that may also be related in part to the anorthositic body or co-magmatic with it.

Drill-core and outcrop evidence indicate that the titaniferous magnetite occurs in a series of nearly vertical, elongated lenses or intermittent bands of both high- and low-grade material mainly within the western part of the gabbroic member of the intrusive body. For many years this was believed to be the largest titaniferous deposit in Canada, and although it is no longer thought to be so, considerable tonnages are undoubtedly present in the 14-mile stretch of this narrow but deep-seated zone. Indeed, aeromagnetic maps of the area published by the Geological Survey suggest that other zones may be present in the immediate area associated with gabbroic rocks or greenstones at Grassy portage to the west, along Grassy Lake, and south of Shoal Bay to the east.

Although a knowledge of the general geology of the area has a distinct value in the search for ore deposits, it is beyond the scope of this report to deal adequately with the complicated geology and conflicting geological reports that have been written on various parts of this region, which contains the type locality of the Coutchiching Series and the Keewatin volcanic rocks, as well as the site of two ages of Precambrian granite (Laurentian and Algoman) as described by A. C. Lawson (1913). The main problems confronting the development of the

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Seine Bay – Bad Vermilion Lake titaniferous magnetite deposits appear to be: (1) the difficulty of satisfactorily reducing the titanium content of the ore material by mechanical (magnetic) methods, and (2) the lack of any obvious, large-scale concentration of high-grade titaniferous magnetite suitable for most efficient open-pit operation. The first problem may be overcome by employing a suitable method of smelting such as the Goodwin–Cadenhead or the Strategic–Udy process in which titanium is removed and lost in the slag. The resolution of the second problem requires detailed surveys, drilling, and estimation of reserves in areas along the favourable belt. The severity of this problem is tempered by the relative ease of concentrating the ore material by magnetic methods to a relatively high Fe–Ti–V product. This enables larger tonnages of lower grade material to be utilized, and as has been indicated in unpublished reports by W. M. Goodwin and W. C. Ringsleben, at least two million tons of high-grade and a larger amount of low-grade titaniferous magnetite have been proven by the drilling in 1920. Diamond drilling by Stratmat in 1957 has added to the proven tonnage estimates.

Analyses of thirteen outcrop samples reported in Robinson (1922) range from 32 to 50 per cent Fe and from 6 to 16 per cent Ti. Eight drill-core analyses (op. cit.) showed a range of from 25 to 47 per cent Fe and from 4 to 14 per cent Ti. Impurities included SiO_2, P, and S; traces of V and Cr were also detected. The Fe:Ti ratios of these samples varied from 2.8:1 to 8.1:1.

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 TiO_2 (16.8 per cent Ti) according to Mines Branch analysis in 1918. The Fe:Ti ratio in this sample was about 2.7:1. Attempts to eliminate the titanium from this high-grade material by magnetic concentration tests in Mines Branch laboratories were unsuccessful; the best separation was at 20-mesh grind when a concentrate of 50 per cent Fe and 14.7 per cent Ti was obtained having an Fe:Ti ratio of 3.4:1.

A lower grade sample taken by the writer from an outcrop on the Seine Bay portage was analyzed at the Mines Branch as follows:

TiO_2	5.89
FeO	22.9
Fe_2O_3	13.23
S	0.91
P	<0.01
Cr	n.d.
V	0.072

This sample, carrying both ilmenite and magnetite, showed 27.1 per cent Fe, 3.5 per cent Ti, 30.65 per cent combined Fe and Ti, and gave an Fe:Ti ratio of about 8.7:1. A magnetic concentrate of this material made by the writer and analyzed by the Geological Survey X-ray fluorescence laboratory showed 61.7 per cent Fe, 10 per cent Ti, 0.25 per cent V, 0.05 per cent Cr, and 0.18 per cent Mn, thus showing an Fe+Ti content of 71.7 per cent and an Fe:Ti ratio of 6.2:1. This illustrates the facility of increasing the iron content,

and the difficulty of reducing the titanium content. It indicates also that vanadium, as well as titanium, has been concentrated in the magnetic extract, and that presumably most of the vanadium is carried in the magnetite and ilmenite.

Four other samples were analyzed in the Mines Branch laboratory (1922) as follows, with calculated titanium, iron plus titanium content, and iron:titanium ratios added:

	Fe	TiO_2	P	S	V_2O_5	Cr_2O_3	Ni	Fe+Ti	Ti	Fe:Ti
Diamond-drill core from claim A.L. 26	48.00	19.87	0.054	0.106	trace	0.07	nil	59.9	11.9	4.0:1
Outcrop sample from claim A.L. 26	52.21	27.38	0.032	0.014	nil	nil	nil	68.61	16.4	3.2:1
Outcrop sample from claim A.L. 27	37.51	11.86	2.608	trace	trace	trace	nil	44.61	7.1	5.3:1
Outcrop sample from claim H.P. 96	57.67	20.28	0.058	0.007	0.20	nil	trace	69.87	12.2	4.7:1

Examination of thin sections and polished surfaces under the microscope showed that the opaque minerals consist mainly of ilmenite and some magnetite with a few grains of pyrite and pyrrhotite. Ilmenite appears to be twinned and shows both cross-hatched and flame-type intergrowths. The associated magnetite is commonly intergrown with a patchwork of ilmenite and as a result appears anisotropic in spots. Both magnetite and ilmenite occur in irregular grains and masses that penetrate the associated grains of altered pyroxenes and plagioclase. The proportions of the iron–titanium oxide minerals to one another and to the gangue minerals show considerable variation, resulting in variations in grade. Here and there the pyroxenes and occasionally the feldspars are peppered with fine blebs and blades or needles of the magnetite and ilmenite usually arranged in parallel fashion along the cleavage planes of the gangue minerals. The ore minerals are commonly rimmed with chlorite and mica where they penetrate the silicates, and some pyroxene is almost completely chloritized. Plagioclase of the host rock is highly saussuritized, generally consisting of a mass of fine-grained clinozoisite, epidote, chlorite, and carbonates. In places the chlorite is in very coarse green pleochroic flakes that show deep anomalous "ultraviolet" interference colours. Some ore minerals carry considerable amounts of unreplaced gangue minerals and are themselves invaded and penetrated in irregular fashion by later generation gangue minerals. Both ore and host rock have been broken and

altered as a result of both dynamic and hydrothermal metamorphism that have been applied since their consolidation. The intrusive pink granite on the west flank of the deposits may have been the causative agent of the metamorphism, or at least of part of it, as the anorthosite adjacent to the granite contact is penetrated by quartz and feldspar veins and veinlets evidently derived from the granite.

Two main factors appear to preclude the satisfactory magnetic separation of this type of ore material into low-titanium and high-titanium concentrates: one is the intimacy of the intergrowth of magnetite and ilmenite, and the other is the anomalously magnetic character of the ilmenite. Ilmenite from this occurrence is quite strongly magnetic and will jump to a hand magnet when powdered. Small polished ore specimens, which appear to consist mainly of ilmenite, will jump and cling to a hand magnet in the natural state. Dip-needle readings above the outcrops of this material vary from strongly positive to weakly negative, generally being moderately strong and positive. Two oriented specimens, one from the portage and one from the lake-shore outcrops, proved to be magnetically unstable under magnetic washing and showed wide spread in declination and inclination, but both appeared to be positively polarized. The declination of one specimen is oriented parallel to the strike of the ore zone and the other is directed across it; this is different to that of the earth's present induced field, but both contribute to the intensity of the magnetic anomaly. Data on the Geological Survey's aeromagnetic map 1150G and ground magnetic surveys indicate a belt of strongly positive anomalies over this zone, although the ground magnetic data indicate the existence of sporadic isolated areas of negative anomaly interspersed among the positive ones.

The twinned character of the ilmenite, its probable ferrian composition, and the intimate intergrowth with magnetite appear to be reasons for the unusual magnetism of this material. The interplay of induced and remanent magnetic forces in this complex mixture of ilmenite and magnetite generally tends to decrease the magnetic anomaly and dip-needle readings at the site. Variations in the mineralogical composition of the ore material and of the minerals within it, particularly the ilmenite and titanomagnetite may, however, cause magnetic variations and reversals in places within a given ore lens. The overall magnetic pattern shown by the aeromagnetic map (1150G) suggests that remnants of a faulted southern limb of a large fold in the ore-bearing structure may extend along Bleak Bay, Little Grassy Bay, the Seine River, and south of Shoal Lake. A small Fe and Ti occurrence northwest of Mud Lake is also indicated by the northwesterly extension of the main anomaly there.

Other Occurrences

For the sake of completeness a number of other titaniferous occurrences in Ontario are mentioned here; more detailed descriptions of them can be found in Rose (1958) and elsewhere as noted in the following descriptions.

Frontenac County

Blessington (Eagle Lake). Titaniferous magnetite occurs in apatite–pyroxene deposits associated with gabbro near the south end of Eagle Lake. About 700 tons of titaniferous magnetite have been mined from pits east of the lake on lots 29 and 30, concession I, Hinchinbrooke township (Ingall, 1899). The geology of the area was described by Harrison (1944).

Clarendon township. Titaniferous magnetite is mixed with rock in small veins and pockets in coarse, dark hornblendic-looking rock on lot 27, concession VII of Clarendon township (Robinson, 1922). On analysis a specimen yielded 54.94 per cent Fe and 7.23 per cent TiO_2.

Haliburton County

Pine Lake or Pusey deposit. A titaniferous magnetite occurrence in gabbro of Glamorgan township has been known since 1885 (Robinson, 1922).

Township of Minden, lot 11, concession I. Rusty gneissic rock containing narrow stringers and disseminated grains of titaniferous magnetite is exposed over an area 4 feet wide and 40 or 50 feet long. The country rock of the district is crystalline limestone interstratified with well-banded gneiss and associated with coarse pegmatite. A sample of the magnetite from these stringers analyzed in the Mines Branch laboratory (Robinson, 1922) yielded:

	%
Fe	42.75
TiO_2	9.33
SiO_2	14.46
P	0.034
S	0.103

Hastings County

Green Island. Rutile has been reported in distinct crystals on Green Island in Moira Lake, Madoc township, and in veins with chlorite in adjoining Marmora township (Hoffman, 1889).

Orton and Ricketts, and Hastings road. A number of occurrences of titaniferous magnetite in lots 56, 57, 41, 42, 54, and 55, west of the Hastings road, in Tudor township, and in lots 16 and 17, concession XII, Lake township, all associated with the Millbridge gabbro, have been known for many years (Lindeman, 1913; Lindeman and Bolton, 1917). A definite trace of vanadium (1 to 0.1%) was shown in spectrographic analysis of a sample from the Orton occurrence (Rose, 1958).

Nipissing District

Angus township. Titaniferous magnetite has been known for many years in Angus township. A. E. Barlow (1898) reported a body of diabase lying within granite gneiss in the southern part of the district of Nipissing. Later surveys placed this body in the townships of Flett and Angus. Titaniferous magnetite outcrops

within the tip of a tongue of the diabase that extends northeasterly into Angus township. The main exposures are on location W.D. 403 about 5 miles northeast of Kenney siding on the Temiskaming and Northern Ontario railway.

The deposit was investigated by M. E. Hurst (1931) who found that the magnetite appeared to be genetically related to the diabase, but that although the diabase seemed to be younger than the granite, the magnetite deposits appeared to be truncated by the granite. Hurst observed that the principal titaniferous magnetite showings occur near the outlet of a small lake on location W.D. 403. Seven exposures, which appear to form parts of two roughly parallel, northwesterly-trending, magnetite-bearing zones, each about 400 feet long and 400 feet apart, were mapped, all within the diabase. A grab sample of the best-looking material from the B zone, taken by Hurst, was found to contain:

	%
Fe	43.62
TiO_2	21.96
P_2O_5	0.05
V_2O_5	0.18
S	0.03

According to Hurst the mineralized zones consist chiefly of a schistose mixture of titaniferous magnetite and altered diabase. In places there are streaks, patches, and veinlets of solid magnetite, but as a rule the magnetite and gangue are intimately intermingled. The gangue is reported to be mainly pale green talc, actinolite, and green spinel (ceylonite). Grains of spinel are commonly finely disseminated through the massive magnetite, and the mineralized zones contain remnants of greenstones or diabase that have been partly recrystallized into garnet, hornblende, and magnetite. The diabase carries disseminated titaniferous magnetite and has a content of 2.13 per cent TiO_2.

Ottertail Brook. Titaniferous magnetite was reported many years ago about 5 miles east of Bushnell station on the Temiskaming and Northern Ontario railway (Robinson, 1922).

Mountain Lake. Robinson (1922) reported titaniferous magnetite about 6 miles south of Latchford.

Parry Sound District

Bethune township. The Tiffany Mining Syndicate Limited, Welland, Ontario, in 1941 had the mineral rights on lots 12–15, concession VIII, and lots 14, 15, and the north half of 16, concession VII. Occurrences southeast and south of Little Peters Lake on lot 15, concession VII, carry titanium, tantalum, niobium (columbium), and certain rare earths (Satterly, 1943) but apparently nothing of economic significance.

Township of Lount. Small occurrences of titaniferous magnetite are reported from lots 132, 136, and 144 of Rousseau and Nipissing Road, and elsewhere in this township (Robinson, 1922).

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Renfrew County

Blithfield. A small lens of titaniferous magnetite is exposed in dark horn-blende gneiss in a rock cut on the Kingston–Pembroke branch of the Canadian Pacific Railway on lot 13, concession I, Blithfield township. The occurrence was diamond drilled by Algoma Ore Properties, Limited in 1951 and found to be of limited extent.

Sudbury District

McVittie locations (Multi-Minerals Ltd., Nemegos). Titaniferous magnetite occurs with apatite and pyrochlore in niobium-enriched zones in crystalline lime-stone and gneiss near the contacts of a cone-shaped alkaline intrusive complex in McNaught township close to Nemegosenda Lake, 5 miles northeast of Nemegos (Hodder, 1961).

Wallace mine. Rutile in the form of delicate acicular crystals lining drusy quartz cavities has been found in the Wallace mine, Bay of Islands, on the north shore of Lake Huron (Hunt, *in* Logan, 1863, p. 502; Robinson, 1922, p. 45).

Thunder Bay District

Haystack Mountain. Small patches of titaniferous magnetite are reported as segregations in coarser parts of the diabase forming a high hill surrounded by a swamp about 2 miles west of Willet station on the Canadian National Railways (Robinson, 1922).

Bamoose Lake. An occurrence of titaniferous magnetite associated with anorthosite and nepheline syenite is reported on an island in Bamoose Lake near Marathon (pers. com., Donald Hogarth).

Manitoba
Cross Lake (Pipestone Lake)

Significant occurrences of vanadium-bearing titaniferous magnetite and anorthositic rocks have been reported by C. K. Bell (1962) on the southwest shore of Pipestone Lake, a widening of the Nelson River, in the Superior struc-tural province of northern Manitoba. The deposits, which are poorly exposed, are being investigated by Noranda Exploration Company, Limited; they occur as disseminations and lenses in a linear zone several thousand feet long.

Alberta
Burmis and Dungarvan Deposits

More than twenty-five occurrences of titaniferous magnetite beds of detrital (placer) origin have been found in the Rocky Mountain Foothills area of southwestern Alberta (Allan, 1931). The occurrences near Burmis and in the Dungarvan Creek area are the best known. The deposits in the Dungarvan Creek

area are in township 3, range 30, W4; those at Burmis are in townships 7 and 8, range 3, W5 (on the Canadian Pacific railway 9 miles east of Blairmore). The Burmis deposits have been known for many years and are controlled by West Canadian Collieries, Limited, of Blairmore. All the occurrences are of sedimentary origin, and are found in the Belly River Formation of Upper Cretaceous age. The occurrences consist of folded and faulted beds of indurated dark magnetic 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 volcanic member.

In 1913 beds of consolidated titaniferous magnetite sands of similar nature and origin were also reported (Stebinger, 1913) 80 miles to the southwest on the Blackfeet Indian Reservation near Dillon in the state of Montana; similar occurrences in Wyoming were described by Houston and Murphy (1962). These black sandstones consist mainly of subangular grains of magnetite, ilmenite, quartz, monazite, rutile, garnet, epidote, zircon, spinel, sphene, radioactive opaques, zircon, biotite, and pyroxene, with secondary calcite, chlorite, anatase, leucoxene, and iron oxides. In addition to these minerals, rock fragments, feldspars, chert, biotite, zircon, and other accessory minerals are found in the associated grey sandstone.

Only one magnetite-bearing horizon has been found in southwestern Alberta and it is repeated by thrust faulting. The magnetite-bearing beds in Montana are at slightly different stratigraphic positions (Mellon, 1961) equivalent to the Virgelle and Fox Hills sandstones in southern Alberta. In places the magnetite-bearing horizon in Alberta is as much as 20 feet thick, but is generally only 3 to 5 feet thick and several hundred feet long. The black sand horizons are evidently shoreline deposits, and although they are of widespread occurrence and great areal extent, they probably vary in thickness and grade both along strike and down dip. Widespread analyses show an iron content of from 15 to 59 per cent, with 4 to 45 per cent silica, and 3 to 12 per cent titanium oxide.

The results of twenty-one chemical analyses of the Burmis deposit (Allan, 1931) showed a mean iron oxide content of 56 per cent, each sample containing a small percentage of TiO_2. An average of four chemical analyses of the Dungarvan deposit showed 52.68 per cent iron oxides, 19.5 per cent silica, and 8.51 per cent TiO_2 (Allan, 1931). Estimates based on limited drilling indicate 6–7 million tons in the Burmis deposit, and about 4 million tons in the Dungarvan deposit, each grading from 42 to 47 per cent iron.

In 1959 West Canadian Magnetic Ores Ltd., a subsidiary of West Canadian Collieries, Limited, estimated the average thickness of their Burmis ore horizon at 8 feet, and upwards of 35 million tons of reserves averaging 41 per cent iron and 4–12 per cent TiO_2 (Janes and Elver, 1959). More recently Mellon (1961) indicated that not only are the recoverable iron content and grade of the zones low and contaminated with titanium, but that reserves are less than 2 million tons at Burmis and 6 million tons at Dungarvan, grading between 25 and 30 per cent iron.

A magnetic concentrate made by the writer from a sample taken by D. K. Norris from the Burmis deposit was analyzed by X-ray fluorescence methods in the laboratories of the Geological Survey in 1962 and was found to contain 59.5 per cent iron, 9.0 per cent titanium, 0.24 per cent manganese, less than 0.05 per cent chromium, and less than 0.05 per cent vanadium. Nickel and cobalt were not detected. The sample showed an Fe:Ti ratio of 6.5:1, and a total ferride element content of 67.84 per cent. The results indicate the ease of making a high-iron magnetic concentrate and a probable difficulty in making a good magnetic separation of titanium from the iron by mechanical methods. Comparison of the above analysis with analyses of magnetite from the basic intrusive and volcanic rocks of the Proterozoic Purcell Series and from the alkaline flows of the Crowsnest Formation may indicate that these probably were the main source rocks of the ferruginous sands.

Although hope has been held for many years that the magnetite deposits of southwestern Alberta might provide the basis for an iron and steel industry there, Mellon (1961) recently discredited this possibility, mainly because of the low-grade nature of the deposits and the lack of sizable reserves. The titaniferous nature and the fine-grained character of the materials are also deterrents against development of the deposits.

British Columbia

Lode Deposits

Few titaniferous occurrences are recorded in British Columbia, but it is possible that more exist. C. H. Clapp (1912) described bodies of gabbro and anorthosite that contain titaniferous magnetite at East Sooke near Rocky Point on the southeast end of Vancouver Island. H. C. Cooke (1919) also mentioned the occurrence of titaniferous magnetite in magnetite–pyrrhotite deposits in the East Sooke gabbro–anorthosite on Iron Mountain. Titanium has also been reported in the magnetite of Lodestone Mountain in southern British Columbia (Bacon, 1956), and titaniferous magnetite is of common occurrence in many of the amphibolitic rocks in the Coast Range of western British Columbia (pers. com., J. J. McDougall, 1965).

Lodestone Mountain

Bedrock magnetites have been known for many years in the Lodestone Mountain area in the Tulameen district about 7 miles southwest of Tulameen. Charles Camsell (1913) described the occurrence as primary magnetite in the pyroxenitic rock of Jurassic age that occupies a belt from a mile to 2 miles wide extending from Olivine Mountain southward for 8 miles to Lodestone Mountain and beyond that for an unknown distance. The geology of the area was mapped and described by H. M. A. Rice (1947).

W. R. Bacon of the British Columbia Department of Mines reported (1956) that nine samples from various outcrops around Lodestone Mountain and on the

ridge south of Olivine Mountain assayed from 16.4 to 20.5 per cent iron. Bacon (1956) gave the average iron and titania contents as 18.5 and 1.5 per cent respectively (i.e., 0.9 per cent titanium).

Unconsolidated Deposits

Magnetite- and gold-bearing beach sands were known for many years at Florencia (Wreck) Bay at Cape Caution on the west coast of Vancouver Island about 4 miles north of Ucluelet, and on Graham Island of the Queen Charlotte group. These sands were investigated by Holland and Nasmith of the British Columbia Department of Mines in 1957. The magnetite content of the samples taken ranged from 7.04 to 0.3 per cent, and the titanium content was about 10 per cent that of the iron in the Florencia (Wreck) Bay beach. Some of the black sand beach deposits of the Queen Charlotte Islands also are titaniferous. Preliminary tests in 1957 by Utah Co. of the Americas on dark sands along the northeast coast of Graham Island near Rose Spit indicate, however, that recoverable magnetite constitutes only about 2 per cent of the raw sand to a depth of 12 feet. Janes and Elver (1959, p. 146) reported a strongly magnetic concentrate grading 68 per cent iron and 2 to 4 per cent titania and a weakly magnetic by-product carrying 18–20 per cent titania and 50 to 60 per cent iron could be made by wet magnetic separation. A selected sample of the beach sand from the Blue Jacket area was determined by the Federal Mines Branch to carry: magnetite, 23.9 per cent; hematite and ilmenite, 38.8 per cent; garnet, 15.0 per cent; quartz and feldspar, 11.2 per cent; altered silicates, 3.6 per cent; hornblende, 3.0 per cent; epidote, 2.0 per cent; zircon, 1.2 per cent; staurolite, 0.9 per cent; titanite, 0.3 per cent; and rutile 0.1 per cent.

Along the north coast twenty-six churn-drill holes and forty-five auger holes provided samples the heavy mineral content of which ranged from 2 to 35 per cent, averaging 6.6 per cent in the churn-drill holes, and less than 10 per cent in the hand-auger holes. Mineralogical study of the heavy mineral content of the sands indicated that the rutile and free ilmenite content is very low, and that the titanium occurs mainly in ferriferous ilmenite (ilmenite with exsolved hematite) and titanhematite (hematite with exsolved ilmenite).

Among private companies interest in the occurrences as sources of iron and titanium has again waned, partly because of the low tenor of both iron and titanium, and because of the difficulty in making a good magnetic separation of the two. The presence of such sands, however, does suggest that bedrock occurrences of titaniferous magnetite may also be found in western British Columbia.

Northwest Territories

François River

In 1936 F. Jolliffe reported a basic intrusive body of gabbro–anorthosite near the north shore of Great Slave Lake and southeast of François River. The body appears on Jolliffe's preliminary map of the Yellowknife River area as a pear-

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shaped mass about 7 miles long and 3 miles wide elongated in a northerly direction and surrounded by granitic rocks. He considered that it showed some similarities to the Bushveld Complex of South Africa which contains copper–nickel sulphides as magmatic segregations around the borders and platinum–chromite horizons in the central banded parts. In the François River intrusive body numerous zones consisting of a black magnetic mineral with some sulphides were found within the interbanded gabbro and anorthosite. One such zone about 5 feet thick was found 3½ miles southwest of the west end of Lake Y. The zone was channel sampled by Jolliffe and a 6-pound sample was found to assay 11.0 per cent TiO_2 and 0.02 ounce Troy of gold per short ton. The basic intrusion is intruded by granite, and both are cut by younger niccolite-bearing deposits according to Jolliffe.

Chapter VI

WORLD REVIEW[1]

Summary of Producers and Consumers

Titanium occurrences have been reported from most of the continents, mainly from the shield areas, but mining production has come chiefly from recent unconsolidated beach sand deposits in India, Australia, Malaya, Senegal, South Africa, and the United States. Production from bedrock deposits has been most important in Norway, the United States, Finland, recently Canada, and probably also the U.S.S.R. Production from bedrock is becoming increasingly important, particularly in Canada, Norway, and Russia. Total world production (exclusive of the Soviet countries) of the two main ore minerals, ilmenite and rutile, is still relatively small, but has increased from 10,000 tons per year in 1920 to more than 2 million tons per year in 1964 largely because of increasing demand for titanium pigments. By virtue of the opening of the high-grade ilmenite lode deposit at Lac Tio and the smelter at Sorel, Quebec, in 1951, Canada soon became a leading producer of ilmenite and of titania slag, contributing more than half a million tons of ilmenite per year to world production from a single deposit, and displacing the United States, India, and Norway among the top ilmenite producers in 1957. In 1964 ilmenite production in Canada climbed to almost a million tons. Australia and the United States continue to supply most of the world's rutile, mainly from placer deposits, but the total yearly production is small, amounting to only 75,500 tons of rutile concentrates in 1955 and about 100,000 tons in 1960. The distribution of the world's titanium resources is shown on Figure 19.

Although it is not certain how much titanium the U.S.S.R. is producing, the United States is probably still the leading producer and consumer of titanium metal with annual shipments of 5,600 tons reported in 1961. Growing titanium industries are established in Japan and Britain and are being developed in France and Germany; Canada has recently produced some titanium metal in the form of sintered pellets for export. A small tonnage of the metal is imported annually into Canada for processing into special forms and alloys.

Only a small proportion (about 2 per cent) of world production of titanium minerals is actually made into metal; about 98 per cent is presently being converted, first to slag rich in titanium dioxide (TiO_2), then to purified synthetic forms of anatase and rutile-type TiO_2 used mainly by the pigment industries of the United States, Europe, and recently Canada.

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[1] Statistical information mainly from U.S. Bureau of Mines, bulletins of the Mineral Resources Division, Canada, and from E. & M.J. bulletins.
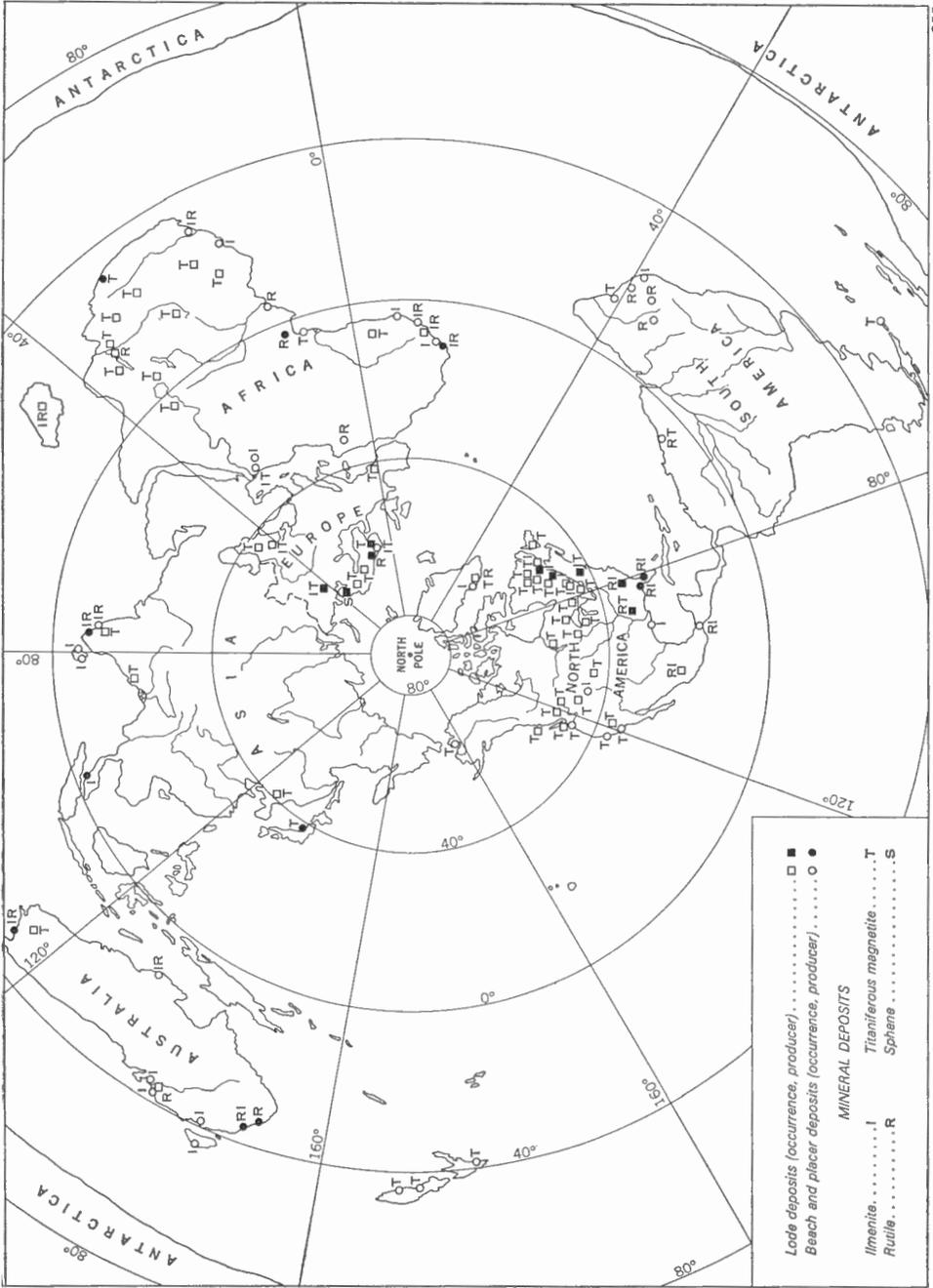
FIGURE 19. World titanium resources.

MINERAL DEPOSITS

Lode deposits (occurrence, producer) .... ■ □
Beach and placer deposits (occurrence, producer) ..... ● ○

Ilmenite I   Titaniferous magnetite ...... T
Rutile .... R   Sphene .... S

World Resources

Africa

The African continent seems to hold a great potential in both placers and bedrock titanium deposits. The most important of these appear to be in the Transvaal province of the Republic of South Africa, Nyasaland (Malawi), and Tanganyika (Tanzania), but others are known in Gambia, Senegal, Ghana, Sierra Leone, other parts of South Africa, South-West Africa, Uganda, and on the island of Madagascar (Malagasy Republic).

At present all the production, which has been of a limited nature, has come from unconsolidated beach sands. The dark bands in these sands represent the washed and concentrated detritus from the weathering and erosion of rocks and mineral deposits carrying the heavy dark resistant minerals such as magnetite, hematite, ilmenite, rutile, zircon, monazite, and uraninite. No production has yet come from consolidated deposits.

A summary review of known occurrences follows.

Algeria

Rutile is found in abundance in the sands of Souf, south of Constantine.

Belgian Congo (Republic of the Congo)

Rutile occurs in the sands, and primary titaniferous magnetite deposits have also been reported.

Cameroun

The sands of Yaoundé River contain commercial quantities of rutile and a small production has been reported from them.

Egypt (United Arab Republic)

The black sands of Egypt are amenable to selective flotation. Ilmenite and magnetite were removed by sodium sulphoricinate with oleic acid in an alkaline solution. A high-grade ilmenite deposit in the eastern desert is being prepared for production of 100,000 tons per year.

French Congo (Congo)

Rutile sands are known in the Congo.

Gambia

Small deposits of ilmenite-bearing sands in the coastal area northwest of Bathurst are being worked on a small scale. Reserves are not thought to be large.

Ghana

A number of titaniferous magnetite deposits in gabbroic rocks have been found in northern Ghana, and numerous occurrences of ilmenite and rutile have

been noted in Precambrian gneisses and in the surficial deposits throughout the country. There have been no major discoveries and no production. Concentrations of heavy black sands are also found along the coast.

Ivory Coast

Ilmenite sands containing 37 per cent TiO_2 occur along the Gulf of Guinea. Shaking screens yielded a concentrate containing 44.3 per cent TiO_2, 14.2 per cent SiO_2, and 12.4 per cent ZrO_2; further magnetic treatment raised the TiO_2 to 52 per cent and eliminated most of the other constituents.

Mozambique

A large deposit occurs of somewhat magnetic material, mainly titaniferous magnetite and ilmenite with a TiO_2 content of 10–13 per cent. An ilmenite–magnetite mixture derived from gabbro occurs in the valley of the Vongoabe River, a tributary of the Mahajlo.

Nyasaland (Malawi)

Small ilmenite–magnetite veins with some rutile occur in quartzitic bands in the regional (Precambrian?) gneisses of the Port Herald hills area. Weathering of these has given rise to ilmenite–magnetite rich rubble over large areas. Richer deposits in which monazite also is found have recently been investigated in the beaches around Lake Nyasa.

Sierra Leone

Rutile-bearing quartzite and lenticular bands of ilmenite and titaniferous magnetite in the basic igneous complex of the Colony Peninsula are the source of small beach deposits of rutile and ilmenite. More than 1½ million tons of rutile have been proved in the Lanti valley sandy grey clay derived by weathering of gneiss. There has been no production. Ilmenite and rutile are associated with the diamond deposits of Sierra Leone.

South Africa

Numerous beach sand deposits of ilmenite, rutile, and zircon are known south of Durban, and large-scale production from this area was begun in 1958 by Umgababa Minerals Limited. Low-grade ilmenite-bearing beach sands have also been found on the west coast in the Vanrhynsdorp district. Ilmenite in place is found east of Garies, ilmenite and sphene in pegmatite in Namaqualand, and titaniferous (ilmenite-bearing) magnetite occurs in basic and ultrabasic intrusions of the Bushveld Complex in Transvaal. Some of the large reserves of this type of ore are being exploited for their vanadium, but as yet not for their titanium content. Wagner estimated (1928) that 2 billion tons of 8–15 per cent titanium is in the Bushveld Complex. Ilmenite of 44–50 per cent TiO_2 also occurs in kimberlite of the diamond-pipes and could possibly be recovered as a by-product of diamond mining.

South-West Africa

Rutile, ilmenite, and magnetite have been found in beach sands in a number of places, but the occurrences do not appear to be large.

Tanganyika (Tanzania)

Large bodies of titaniferous magnetite are known to occur in anorthosite and gabbro in the Liganga area about 30 miles east of Lake Nyasa in southern Tanganyika. Workable deposits of many millions of tons are believed to be present. Small deposits of titaniferous iron are indicated in the Uluguru Mountains, and small deposits are found in the coastal beaches of the Indian Ocean.

Uganda

Magnetite with a variable titanium content, and with associated perovskite (knopite) and leucoxene (anatase), occurs in association with a ring complex near Tororo in the Eastern Province. One deposit near Namekara is estimated to hold 18 million tons of ore of 13 per cent TiO_2.

Madagascar (Malagasy Republic)

A deposit of ilmenite estimated to contain 3,500,000 tons of ore was discovered in Madagascar in 1912. Some samples from the deposit indicated a tenor of about 40 per cent titanium dioxide. Rutile is found in large crystals in mica schists to the west of Ambstrofinandrahana and north of the Matsiatra River. Small quantities of the loose material have accumulated in placer deposits, one of which was mined during the first World War.

Asia

Little is known regarding the titanium deposits of Asia, particularly those of the U.S.S.R. and of China. Ilmenite and titaniferous magnetite occur in the Ural Mountains of Russia, and Russia is reportedly recovering titanium from sphene (titanite), a mineral which is of rather common but of non-commercial occurrence in Canada. Titaniferous sands are found in Ceylon, India, Japan, and Malaya, and presumably important bedrock deposits are also present. No important lode occurrences are producing, however. The known occurrences are listed below.

Ceylon

Ilmenite, rutile, zircon, and monazite are chief constituents of the black beach sands of Ceylon. The most important of these deposits is at Pullmoddai on the east coast of the island. None of the primary ilmenite deposits seem to be of economic importance. The Pullmoddai sands are said to contain about 75 per cent ilmenite, the remaining 25 per cent consisting chiefly of rutile and zircon with minor amounts of garnet, spinel, magnetite, and quartz. At least 4,000,000 tons of this concentrated type of material is present in the Pullmoddai beach down to low watermark. In the sand in the dunes behind the beach ilmenite ranges from 10 to 60 per cent. The ilmenite from the beach assays 52–52.8 per cent TiO_2.

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Smaller deposits of black sand also occur on the west coast, at Dondra on the south coast, and at Beruwala and Induruwa on the southwest coast. The Induruwa sands contain appreciable amounts of monazite which is recovered in a small pilot plant. The monazite carries about 65 per cent of rare-earth oxides including 8 to 9 per cent thoria. Production of ilmenite at the rate of about 50,000 tons a year, with zircon and rutile as by-products, was planned in 1960 for the Pullmoddai beach.

India

India has important beach sand and bedrock titanium deposits associated with charnockites. At least 300 million tons of black sand are estimated of which ilmenite is the main constituent, but monazite and rutile are also present. Ilmenite was first recovered in India in 1924 from the black sands of Travancore which had previously been worked for monazite only. Until 1950 the beaches of Travancore and Quilon supplied over half of the world production of ilmenite. In 1957 the ilmenite production of India was surpassed for the first time by that of Canada, and although India's production has increased since then, it has fallen behind that of Canada, the United States, and Norway. Some rutile is also produced.

Many of the beaches of the east and west coasts are composed of black sands derived by weathering of the gneisses and pegmatites of the southern part of the state of Travancore, now known as the state of Kerala. At Travancore beach the sands contain 50 to 70 per cent ilmenite, which averages 55 per cent titanium. Monazite, zircon, garnet, rutile, and sillimanite are by-products. About 1 to 4 per cent of rutile is present. The south beach is 6,000 feet long, the north 15 miles. Rutile is plentiful in the kyanite-bearing rocks of Lapsa Buru in Singhbhum, and titaniferous magnetites occur in Singhbhum, Mayurbhanj, and the Channapatna area of Mysore.

A potential large-scale source of titanium lies in the laterite and bauxite deposits of India. These contain as much as 8 per cent titanium in places, and this may form a useful by-product of the aluminum industry of the future.

Japan

Beaches in Hondu (Honshu), Japan, contain 10 billion tons of black sand carrying 20–30 per cent Fe, 8–12 per cent TiO_2, and 0.6 per cent V_2O_5. The sand forms raw material for the Japanese titanium industry. It is concentrated and smelted to produce TiO_2 slag, which is chlorinated to produce $TiCl_4$, and then further reduced by molten magnesium to titanium sponge, most of which is exported.

Malaya

Ilmenite is associated with cassiterite in parts of the placer tin deposits of Malaya. Some of this is recovered from the tin-bearing gravels in the states of Perak and Selangor. In 1956 a record amount of 122,000 tons of ilmenite concentrates were exported. Production has since declined and estimates of titanium reserves in Malaya are not available.

Manchuria

Important titaniferous deposits are believed to occur in Manchuria (Hampel, 1961).

Australasia

Australia

Beach sands containing ilmenite, zircon, and large amounts of rutile occur on the east coast of Australia, whereas those of the west coast carry less rutile. Most of the production has come from beaches in southern Queensland and northern New South Wales, and recently from southwest Western Australia. Little is known regarding primary deposits.

In 1934 a successful attempt was made to recover zircon from the beach sands of the east coast. Since then these sands have been worked for rutile alone, and Australia has become the world's leading rutile producer. The ilmenite of the east coast sands is not recovered as it does not meet specifications for pigment production. Since 1956, however, ilmenite has been recovered, along with some rutile as well, from beaches on the southwest coast. In 1957, a record 128,903 tons of rutile and 71,155 tons of ilmenite were produced from Australian beach sands. In 1960, 88,630 tons of rutile and 106,015 tons of ilmenite were produced.

New South Wales. Beach sands on the east coast of New South Wales carry disseminated rutile and ilmenite which in places have been concentrated into flat seams along the present beaches. The best deposits are in the northern part, from Port Kembla northward to the Queensland border, where proven reserves totalled over $1\frac{1}{2}$ million tons containing 506,750 tons of rutile and 321,000 tons of ilmenite. In 1957 output was 86,155 tons of rutile concentrates.

Northern Territory. Two areas of black sands have been located, one near Port Essington and another on Bathurst Island 70 miles northwest of Darwin. The sample from the latter location contained 31 per cent rutile and 40 per cent ilmenite. The area is almost inaccessible and reserves appear to be limited.

Queensland. The most important deposits are in the beaches near the New South Wales border and between North Stradbroke Island and Tugun beach; many other beach sand occurrences are recognized. A total of 862,950 tons of high-grade beach sand containing 246,900 tons of rutile and 340,550 tons of ilmenite is known. Rutile concentrates amounting to 42,748 tons were produced in 1957.

South Australia. At Williamstown, 25 miles northeast of Adelaide, some rutile has been mined from a china clay deposit in which rutile occurs as veinlets and disseminated grains. Rutile is also found as lenses in mica schist at Yankalilla 40 miles south of Adelaide. Deposits of beach sands have recently been reported from near Port Lincoln on the western shores of Spencer Gulf and on Kangaroo Island south of Adelaide. Certain titaniferous magnetite and ilmenite–rutile shoots carrying as much as 51.8 per cent TiO_2 occur at Radium Hill near Olary, in association with the uraniferous davidite ore there. A pegmatite dyke at Mount Crawford contains titanium-bearing minerals.

Tasmania. Ilmenite-bearing sand is found in a raised beach at Naracoopa on the east coast of King Island, about 60 miles northwest of Tasmania. Known reserves amount to 45,000 tons of ilmenite. Titanium pigments are produced by Australian Titan Products at Burnic.

Western Australia. Ilmenite predominates in the beach sands in southwest Western Australia, with rutile and zircon content generally less than 5 and 10 per cent, respectively. The most important deposits are in the Bunbury–Capel district about 100 miles south of Perth. Several companies are operating in this area, and other occurrences are likely to be found as at Wonnerup and Yoganup. The ilmenite is low in chromium and is acceptable for the manufacture of titanium pigment; production began in 1956 and in 1957 was about 300,000 tons. In 1958 some rutile, leucoxene, monazite, and zircon were also recovered from the sands as by-products of the ilmenite operations. Reserves of 800,000 tons of heavy minerals are estimated by the Australian Bureau of Mineral Resources. A primary titaniferous iron deposit occurs near Gabanintha, which is 400 miles north-northeast of Perth.

Victoria. In the valley of the Acheron River about 12 miles northeast of Healesville boring has indicated about 9 million cubic yards of dredging ground from which a concentrate of 84.5 per cent ilmenite may be made. A low-grade, inaccessible beach sand deposit is at Cape Everard on the coast about 20 miles southeast of the Cann River in eastern Victoria.

New Zealand

Beach deposits of titaniferous sands occur on the west coasts of both the North and South Islands. It has been estimated that there are more than $1\frac{1}{2}$ billion tons of titanomagnetite and ilmenite in the beach sands of the two islands, but there has been no production to date.

North Island. On the west coast of the North Island the Taranaki iron sands are widely distributed for a distance of 290 miles about 15 miles west-northwest of Auckland. The deposits are accessible by road or water, and are partly covered by good farming country and partly by wasteland. Both recent beach and dune sands, and Pleistocene-raised beach and dune sands contain disseminations and concentrations of dark minerals which are probably derived from andesitic and basaltic flows and ash deposits that range in age from Miocene to Pleistocene. Titanomagnetite, containing about 55 per cent iron, 9 per cent TiO_2, and 0.4 per cent V_2O_3, is the main mineral in these sands; ilmenite is also present in some of the sands. It may be possible to recover a total of about 780 million tons of titanomagnetite and more than 8 million tons of ilmenite from these sands.

South Island. The black beach sands of the west coast of the South Island carry ilmenite and a little gold. They occur along a 250-mile stretch of coast, about 50 miles north of Westport, in the form of recent and raised beach deposits in marginal land. The ilmenite in these sands may have been derived from rocks of the Southern Alps. It contains 32.5 per cent iron, 44.5 per cent TiO_2, 2.5 per cent

MnO, and slight traces of V_2O_5 and Cr_2O_3. Deposits at Cape Foulwind average 5.5 per cent ilmenite. About 43 million tons of ilmenite may be recoverable from these sands to a depth of 40 feet.

Europe

With the exception of the Scandinavian Peninsula and the U.S.S.R. Europe is not rich in titanium deposits. The main Russian resources are in the titaniferous magnetites in the Ilmen Mountains, a branch of the Urals, the Kussinsk area, the Khibine area of the Kola Peninsula, and the Gatskavo region of the Ukraine. Large deposits of massive ilmenite, hematite, and titaniferous magnetite are found in the southwest part of Norway in the Egersund–Sogndal district. One of the largest of these is the Blaafjeld deposit in Sogndal, south of Egersund. Other deposits of titaniferous magnetite occur in the gabbroic rocks of the area. The deposit at Rodsand on the southeastern shore of Tingvoldfjord has been worked for iron. Titaniferous iron ore is mined at Taberg in Sweden and other occurrences are known there as well as in Finland, and in the Carpathian Mountains of Transylvania and Carinthia.

Rutile is mined at Kragero in southern Norway, where it occurs associated with plagioclase and quartz in white veins, streaks, and bands in foliated granite. Sphene is mined in the Kola Peninsula of Russia.

A deposit of ilmenite sands located in the Castelo Branco district of Portugal has produced a few hundred tons of concentrates a year. Other occurrences have been reported in Italy, Spain, Sweden, Switzerland, Yugoslavia, and Czechoslovakia.

Finland

The titanium ores of Finland have been described by Geiler (1940).

Norway

Vogt and Kolderup and more recently Carstens (1957) have described the Norwegian occurrences in norite and anorthosite in the great intrusive region in Egersund where the mining of ilmenite ore for iron dates back to the eighteenth century. One of the largest deposits known is almost 2 miles long and from 90 to 230 feet thick. It consists of about 38 per cent ilmenite, 21 per cent plagioclase, and 41 per cent hypersthene, and shows a well-defined crystallographic intergrowth of ilmenite and hematite. The high-grade Blaafjeld-type ore as formerly known contained from 40 to 45 per cent TiO_2, and reserves of this type were not large; available reserves have now been raised from 3 million to more than 300 million tons, however, by the development of the deposit at Tellnes. For some years ore from the Blaafjeld region was shipped to England and smelted for iron, but since 1918 ilmenite has been the product sought, and it was here that the titanium pigment industry was started about 50 years ago.

Also in this area are the Kohldahl, Kyland, Storgangen, and Lakesdal deposits. These are long dykes of ilmenite–magnetite from 50 to 300 feet wide in gabbro. The Lakesdal deposit averages about 35 per cent TiO_2. Titaniferous

magnetite at Rodsand containing from 6.0 to 7.5 per cent TiO_2, which may be reduced to 1.1 to 1.35 per cent in the magnetic concentrate, has been used as iron ore.

In 1957 the National Lead Company opened a large new deposit at Tellnes in the Egersund–Storgangen region from which it plans to recover a million tons of ore a year which is expected to yield about 300,000 tons of ilmenite and 20,000 tons of magnetite concentrate. The occurrence is reported to have been detected by an aeromagnetic survey in 1954 according to Dybdahl (1960) who described the ore body as a large intrusion in the anorthosite with an outcrop length of 2,700 metres (about 1¾ miles) and an estimated reserve of 200 to 300 million tons of ore. According to Dybdahl (1960): "The magmatic character of the ore is proved by the texture, by apophyses of ilmenonorite into the surrounding rocks, xenoliths of anorthosite in the ore itself and eruptive breccia." He also reported that the ore carries 39 per cent ilmenite, which contains about 12 per cent hematite exsolution lamellae, and about 2 per cent magnetite.

Aplite veins in deposits at Kragero carry 10 to 15 per cent rutile from which a black concentrate containing 97 per cent TiO_2 and unusually high proportions of chromium and vanadium are obtained. The productive rock occurs as streaks or stripes in foliated granite that is flanked by an enormous granite–pegmatite dyke on one side and by an olivine–hyperite dyke in amphibolite on the other.

Sweden

Taberg in southern Sweden is one of the first places in which the existence of magmatic ore deposits was demonstrated by Sjögren, Törnebohm, and Igelström, according to Lindgren (1933). Taberg is a norite hill 400 feet high; towards the centre ilmenite and magnetite are concentrated, forming a mass of ore with some olivine, biotite, and plagioclase. This material contains about 6 per cent TiO_2 and has been used as iron ore (*see* Hjelmquist, 1950).

At Sodra-Ulvon a deposit containing considerable ferro-orthotitanate, (Fe_2TiO_4), a mineral not previously known in nature, was discovered by Mogensen (1946). It was subsequently described and named "ulvöspinel" by Ramdohr (1953).

The great magnetite deposits, such as those at Kiirunavaara, Tuollavaara, Gellivara, and Luossavaara in the Precambrian gneisses of the extreme northern part of Sweden, are generally low in titanium (about 0.3 per cent TiO_2), but nearby at Routivare a huge body of titanic ore with some associated pyrrhotite occurs in highly altered gabbro. The gabbro is reported by Lindgren (1933) to have intruded strata of Cambro-Silurian age. H. Lundbohm published the first monograph on the Kiruna deposit in 1898. A little later Högbom proved the magmatic origin of the deposit. The investigations of Stutzer (1907) and the later works by Geijer (1910, 1931) showed that the ore was differentiated from magma at depth and was brought to its present position in a molten condition. These ores are similar in many respects to the lode deposits of ilmenite and titaniferous magnetite.

Union of Soviet Socialist Republics

Russian production of titanium ore is perhaps 2 to 3 million tons per year. There are apparently extensive low-grade titaniferous ores in the U.S.S.R., namely in the Ilmen Mountains from which ilmenite got its name. The Ural deposits reportedly carry 400 million tons of ore which contain about 14 per cent TiO_2, 54 per cent iron, and 0.6 per cent V_2O_5 and which is amenable to magnetic separation. Ore from the Kussinsk area ground to pass a 65-mesh screen and subjected to wet-magnetic separation gave an ilmenite concentrate representing 19.5 per cent of the original weight. The concentrate contained 45.3 per cent TiO_2, 35.8 per cent iron, and 0.34 per cent V_2O_5 (Barksdale, 1949).

Other important occurrences are known near Khibine, on the Kola Peninsula, and near Gatskavo in the Ukraine, and occurrences have been reported in the Carpathian Mountains of Carinthia and Transylvania. Rutile occurs in the central Kyzyl-Kum. In 1937 and 1938 the Soviet Government was reported to be mining sphene from a large deposit on the Kola Peninsula.

North America

North America is abundantly supplied with titaniferous deposits. Many extensive deposits are known in Canada and in the United States, and several of the latter are being mined. In Canada large-scale production has come from only one of its deposits since 1951 and some smaller scale production from two other deposits. Occurrences of titaniferous materials have also been reported from Greenland, Mexico, and Guatemala.

North American titanium ore production has come from a variety of sources including both lode and placer deposits. Lode deposits of rutile, titaniferous magnetite, and ilmenite, and placer deposits of ilmenite and rutile have been worked in the United States. Some ore has been imported.

Canada

The best known titaniferous occurrences in Canada are lode deposits at St-Urbain, Ivry, Lac Tio, and St-Charles all in Quebec; between Seine Bay and Bad Vermilion Lake near Mine Centre in Ontario; and on Steel Mountain and at Indian Head in western Newfoundland. The recently discovered Magpie (Awater-Lapointe-Melihersik) titaniferous magnetite deposit near the Labrador border in Quebec may be the largest of its kind yet discovered. Numerous other occurrences are known in these three provinces and other parts of Canada; in the Burmis area of southwestern Alberta consolidated placer deposits are found in sandstone of Cretaceous age. These various deposits are described at length in Chapter V of this report.

Greenland

Rutile and titanite (sphene) occur in the sands of east Greenland. Titaniferous magnetite and ilmenite occur in abundance in the anorthositic–charnockitic rocks of west Greenland (Ramberg, 1948).

Mexico and Guatemala

Dark sands occur in a few places in these two countries. Extensive, low-grade, rutile–ilmenite–apatite bearing deposits in gneissic anorthositic rock near Pluma Hidalgo, south of Oaxaca, Mexico, were investigated by the Republic Steel Corporation in 1953 and were described recently by Paulson (1964).

United States

The largest deposits of titaniferous ores in the United States are in the Adirondack Mountains of New York State where they have been developed at Sanford Hill (Tahawus) by the National Lead Company. The occurrences are large bodies of ilmenite–magnetite in dark anorthosite and gabbro or norite. Generally where there is ore there is also some gabbro. The ore is a titaniferous magnetite and ilmenite intergrowth that has the textural relationships of an igneous rock. In detail it is a granular mixture of magnetite, ilmenite, plagioclase, and pyroxene, and also carries "coulsonite", hornblende, garnet, pyrite, apatite, spinel, and quartz. At Sanford Hill two types of ore occur in more or less parallel lenticular bodies that are separated by a 200-foot-wide central waste zone composed of anorthosite and gabbroic anorthosite. The foot-wall orebody is 250 feet thick and averages about 45 per cent iron and 18 per cent titanium; it is low in sulphur and phosphorus. This anorthositic-type ore is massive, with a coarse-grained, even texture. The gangue within the ore consists of inclusions ("pheno-crysts") of green feldspar (labradorite) surrounded by reaction rims of garnet, hornblende, and biotite. The hanging-wall orebody is about 400 feet thick and averages 32 per cent iron and 18 per cent TiO_2. This gabbroic-type ore is fine grained and even textured, with gangue minerals, pyroxene, hornblende, garnet, and labradorite about the same size as the ore minerals. It is banded and lenticular and grades from 30 to 6 per cent TiO_2.

Grinding to 20-mesh is required for effective separation of the ore minerals. A magnetic concentrate averaging 5.6 per cent iron, rich in vanadium, and low in sulphur and phosphorus is obtained by low-intensity, wet-magnetic separation, and an ilmenite concentrate is obtained from the tailings by hydraulic classifiers and tables. The ilmenite product, containing 38 per cent TiO_2, is upgraded to 45 per cent on high-intensity, dry-magnetic separators.

The titaniferous ores and geology of the Adirondack area have been the subject of geological investigations by Kemp (1898), Singewald (1913b), Miller (1919), Alling (1925, 1932, 1939), Osborne (1928), Buddington (1939b), and others, and the Sanford Hill extension was mapped and studied in detail by M. M. Heyburn (1960) for the National Lead Company.

Extensive deposits of titaniferous magnetite are located in Lake and Cook counties, Minnesota, in which the titanium content ranges from 3 to 20 per cent or more. The deposits are associated with the Duluth gabbro, a large differentiated igneous mass of Precambrian age which intrudes the basement complex at the western end of Lake Superior. The occurrences have been described by Grout (1925, 1950) and by Youngman (1930).

A deposit of titaniferous ore 600 feet wide and 1,500 feet long outcrops at Cumberland in Rhode Island. A concentrate containing 22 per cent TiO_2 and 54 per cent Fe has been made by magnetic separation (Barksdale, 1949, p. 19).

In Wyoming, dykes of solid titaniferous magnetite or ilmenite outcrop on Chugwater Creek, 8 miles west of Iron Mountain Station on the Colorado and Southern Railroad. The dykes break through anorthosite that contains but little pyroxene and ilmenite. One of the dykes is more than a mile long and averages 175 feet in width. It is composed of almost solid ilmenite with some magnetite, olivine, and spinel included, and carries about 45 per cent iron, 22 to 23 per cent TiO_2, 4 per cent Al_2O_3, 2.45 per cent Cr_2O_3, 1.44 per cent sulphur, 1.38 per cent MnO, and a trace of phosphorus (Lindgren, 1933, p. 789). Satisfactory concentration of the ore required several steps.

Titaniferous magnetite is associated with the Stillwater Complex in Montana. Composite drill cores from the Choteau occurrence in Teton county analyzed 43.7 per cent iron and 7.2 per cent TiO_2 (Wimmler, 1946). Magnetic concentration of the 100-mesh material increased the percentage of iron to 60.6, but lowered the TiO_2 content to only 6.6 per cent.

Large deposits of titaniferous magnetite occur in gabbro and anorthosite of the San Gabriel Mountains, Los Angeles county, California (Moorhouse, 1938). In places the ores consist almost entirely of magnetite and ilmenite with little visible gangue. The TiO_2 content is said to range from 11 to 25 per cent (Moorhouse, 1938).

Titaniferous iron ores are also found in Colorado at Caribou Hill, Iron Mountain, and Cebolla Creek. Numerous smaller deposits believed to be magmatic segregations associated with anorthosite occur in the Wichita Mountains of Oklahoma. Other bedrock titaniferous magnetite occurrences have been reported in New Mexico, North and South Carolina, Tennessee, and New Jersey. Black sandstone carrying ilmenite, titaniferous magnetite, rutile, monazite, zircon, etc., form extensive placer deposits of Jurassic age in Wyoming and Montana.

Dark sands are abundant along the east coast of Florida from the mouth of the St. Johns River to the town of St. Augustine. The sands carry ilmenite, rutile, monazite, and zircon, all of which were recovered from a strip of beach at Mineral City, south of Jacksonville, from 1918 to 1929. Extensive deposits of heavy mineral sands in the Trail Ridge area of the north-central part of Florida contain ilmenite, rutile, and zircon. The ilmenite in this deposit, which has been classed as leucoxene, contains extremely fine grained rutile. The original source area is thought to have been the Piedmont area of Georgia and the Carolinas. Low-grade ilmenite-bearing sands are also found in the southern part of Howard county, Arkansas, and on Ship Island, Mississippi.

On the Pacific coast ilmenite, magnetite, gold, and other heavy resistant minerals are concentrated in the beach sands at Aptos, Santa Cruz county, and south of Redondo, Los Angeles county, California; at Grays Harbour, Washington; and at Nome, Alaska. The sands of Los Angeles county, as worked, contain 20 per

cent titaniferous iron oxide and magnetite, along with zircon, olivine, epidote, garnet, and quartz. Olivine, ilmenite, and titaniferous magnetite bearing black sands are of widespread occurrence on the Hawaiian Islands.

Large primary rutile and ilmenite deposits occur at Roseland in Nelson County, Virginia, in a rock called nelsonite. In it ilmenite and apatite or rutile and apatite are the essential minerals. Phlogopite, quartz, pyrite, pyroxene, and hornblende are accessories. The nelsonite dykes are enclosed in a biotite schist of the Lovington granite gneiss. In another type of deposit in the same area titanium minerals occur as disseminations in anorthosite. According to Hess and Gillson (1937) the deposit is a broad pegmatite replacement of a peculiar aplite that was intruded into granite gneiss. Small grains of rutile and ilmenite follow cracks in the pegmatite. Considerable proportions of white apatite are also present. Both the dyke and the adjacent syenite, which is impregnated with 3 to 6 per cent each of rutile and ilmenite, are mined. The nelsonite dyke rock, which averages 4 to 5 per cent each of rutile and ilmenite, has been mined since the turn of the century. It yields a rutile concentrate containing 92.5 to 98 per cent TiO_2 that has been one of the main sources in the United States from which titanium metal has been derived.

At Magnet Cove, Arkansas, rutile, octahedrite, and brookite occur as primary or secondary minerals in nepheline syenite. The heavy minerals are concentrated by gravity method and this concentrate is floated and jigged. After magnetic separation a product containing 95 per cent TiO_2 is obtained.

South America

The main titaniferous deposits of South America are dark sand beach deposits of ilmenite and rutile in Brazil and Argentina. Similar deposits are reported in British Guiana (Guyana) and in Guatemala and Mexico. The bauxite ores of the Guianas and Brazil also carry considerable titanium, which at present is lost in the tailing of bauxite processing for aluminum production.

Argentina

Considerable quantities of beach sands are found in Argentina containing 24.7 per cent ilmenite, 29.2 per cent magnetic iron sand, and 27.9 per cent ferruginous black sand (not magnetic). The principal deposits extend southward from Meconchea through the Straits of Magellan.

Brazil

Large beach deposits of ilmenite, mixed with monazite, zircon, garnet, and quartz sand occur along the southeast coast of Brazil. The principal beaches are located at Guarapary and Boa Vista in the state of Espirito Santo, near Pronto in the state of Bahia, and south of Barrodo Itabapoana in the state of Rio de Janeiro. In places the sands carry as much as 43.6 per cent TiO_2 which may be concentrated to 50 per cent TiO_2. A concentrate containing 71.6 per cent ilmenite, 6.0 per cent monazite, and 12.9 per cent zircon may be obtained by water tables and

magnetic separation (Barksdale, 1949). There has been some production from the deposits at Espirito Santo. The deposits are extensive, reserves are large, and the heavy minerals are thought to have been derived from erosion of Archaean granites, gneisses, and charnockites. Brazil's rutile resources are in the states of Goyaz and Minas Geraes. Production from the latter state ordinarily contains ilmenite, and the ore contains only 70 to 85 per cent TiO_2; production from Goyaz averages 95 per cent. At Bon Jardin rutile and ilmenite are intermixed but a magnetic separation gives a high-grade rutile concentrate.

British Guiana (Guyana)

Samples of rutile-bearing sands have shown as much as 95 per cent TiO_2.

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Chapter VII

CONCLUSION

Summary of Observations

The writer's study of the geology of titanium and titaniferous deposits in Canada has resulted in a number of observations that are summarized below. Several of the observations have both economic and academic significance, and because of the close relationship between anorthositic rocks and titaniferous deposits some of the statements may be applied equally to both. This is especially true of the low-grade disseminated titaniferous occurrences, many of which pass transitionally from rock to what may be termed "ore material". Whether such material ever becomes ore seems to depend more upon world economics, markets, general demands, and other factors, rather than upon the actual grade of the material.

The two most important observations on Canadian titanium occurrences are as follows.

(1) There is an unmistakable genetic relationship between anorthositic rocks, especially their gabbroic phases, and their commonly related titaniferous magnetite and ilmenite deposits. They were formed in eastern Canada by magmatic differentiation and injection mainly in Precambrian time, presumably from 850 million to 1,500 million years ago.

(2) Many of the iron and titanium oxides can be readily concentrated by magnetic methods, and some of these may be further separated into high-iron and high-titanium concentrates; these concentrates are potential ores of iron and titanium, respectively. Magnetite carrying as little as 0.2 per cent titanium can be extracted magnetically from some of these anorthositic rocks.

Five additional observations arise from this study of titaniferous deposits and their host rocks in eastern Canada.

(1) Anorthositic massifs commonly consist of two main closely related phases, anorthosite and gabbroic anorthosite, formed by deep-seated magmatic differentiation and repeated intrusion into higher levels of the earth's crust.

(2) Fine-grained dykes and chilled phases of the anorthositic rocks in places suggest near-surface intrusion and perhaps local extrusion.

(3) A compositional range in titanium from 0.2 to 12 per cent for titanomagnetites and 12.5 to 31 per cent for ilmenites suggests that a solid–solution series between magnetite and ilmenite is the cause.

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(4) Positive aeromagnetic anomalies are generally indicative of magnetite concentrations, and negative anomalies of ilmenite and hematite, but because of reversed remanence and variations in orientation the opposite may be true.

(5) In places the opposition of remanent and induced magnetism, particularly in a mixture of magnetite and ilmenite, may largely nullify the resulting magnetic anomaly.

Most of Canada's titaniferous deposits lie in the immense anorthositic massifs of the Grenville structural province in Quebec and Ontario. The nature and extent of these huge anorthosite bodies is not completely known, but to the writer they appear in general to be composite, multiple intrusions composed mainly of anorthositic and gabbroic (noritic) rock as exemplified by the Morin, St-Urbain, Lac St-Jean, Sept-Îles, and Lac Allard anorthosites. Anorthosite and gabbroic anorthosite are sometimes closely related and transitional. Gabbroic phases of the anorthosite commonly occupy a marginal belt around the anorthosite proper, but in some places they occur in interior parts of the anorthosite masses in the form of dykes, breccia cements, and irregular intrusions. In other places reversals of this sequence of intrusion are seen. Much variation in texture is also found, with fine-grained and coarse-grained phases of both rock types interpenetrating one another. Many suites of more femic olivine-bearing rocks (troctolites) and of salic quartz-bearing rocks (syenite, monzonite, and granite) seem to be associated with these anorthositic intrusions, and they generally appear to intrude the anorthosite; usually where this is so the salic rocks are the youngest intrusions in the sequence.

Many of the anorthositic massifs contain known occurrences of iron and titanium oxides, and each massif must be considered favourable for potentially economic deposits of these minerals. True anorthosite characteristically is host to the massive ilmenite–hematite lodes, whereas gabbroic anorthosite characteristically is host to the extensive deposits of low-grade, disseminated, titaniferous magnetite containing mixtures of titanomagnetite, ilmenite, ilmenite–hematite, and other intermediate members that possibly form a solid–solution series of iron–titanium oxide minerals. Although generally separate, in places the two types of deposits, as well as the host rocks, appear to be transitional.

Although a few ilmenite and titaniferous magnetite occurrences have been found in rocks that were invaded by anorthositic magma, the major deposits are almost always within the intrusion itself. Low-titanium magnetite deposits are commonly found in Grenville-type rocks outside the anorthosite massifs. In many places it is difficult to prove whether the low-titanium magnetite deposits in the rocks surrounding some of the anorthosite bodies have any genetic relation to them. Some of them may well be so related.

Economic Outlook

Little serious difficulty is foreseen in locating sources of titanium in Canada, especially of titaniferous magnetite deposits from which both iron and titanium may be recovered. Aeromagnetic surveys are of great assistance in outlining

favourable zones especially when used in conjunction with geological maps. Studies of remanent magnetism may be most helpful in interpreting the magnetic information.

Although most of the large, known titaniferous magnetite deposits are of low grade when compared with direct-shipping premium ores of titanium and iron, the large tonnages available in them constitute a raw material supply at present capable of sustaining large-scale mining and smelting operations. Undoubtedly many titaniferous deposits remain to be discovered; prospecting for titanium in Canada has been directed almost entirely in a search for high-grade, massive ilmenite.

The future of the so-called "wonder metal", titanium, still remains speculative, but demand for titanium oxide pigments has increased the market for ilmenite from deposits in Canada. In both ilmenite and titaniferous magnetite titanium is geologically and chemically combined with iron and its future appears to be bound with that of iron and steel, particularly because of certain similarities in physical properties between titanium and stainless steel. Anomalously this situation seems to have had a depressing effect to date upon the development of a titanium industry. Nevertheless, the future use of titanium metal and alloys in the age of supersonic flight and in the exploration of space seems assured.

The development of low-grade deposits of useful materials must always be a question of basic concern, and this is certainly true of Canada's titaniferous deposits. Continued research on inherent problems in the development and use of Canada's titaniferous deposits as well as on the nature of their occurrence is of importance, especially since these topics might prove to be of considerable significance to the nation—economically, industrially, and strategically.

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PLATES II TO VIII

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PLATE II A. View north from the ilmenite–hematite deposit at Lac Tio towards the anorthosite hills north of Lac Petit Pas, Lac Allard district, Quebec.

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PLATE II B. View westerly of northwestern part of the main Lac Tio ilmenite–hematite deposit now stripped and prepared for mining, showing light coloured anorthosite underlying ilmenite at the top and indicating the sill-like form of the deposit within the anorthosite host rock.

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PLATE III A. View northerly of Rivière du Gouffre valley from Baie-St-Paul towards St-Urbain and anorthosite hills in background. The valley is underlain by Ordovician lime-stone and shale that outcrop in disturbed zones along the sides of the valley graben.

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PLATE III B. View southerly of massive ilmenite outcrop in the bush on the Quebec Seminary property north of St-Urbain, Quebec, showing rhombohedral joint pattern in the ilmenite–hematite.

PLATE IV A. View westerly of blocky, jointed, limonite-coated ilmenite–hematite in the Bignell deposit at St-Urbain, Quebec, showing traces of internal banding dipping gently to the south (at right of man).

PLATE IV B. View northerly of two dark ilmenite dykes that penetrate grey anorthosite with sharp contacts on the foot-wall of the General Electric deposit, St-Urbain, Quebec. The dykes appear to be offshoots of the main ilmenite deposit, part of which shows in the distance on the left.

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PLATE V A. View downwards and northerly across the Ivry mine ilmenite pit north of Ste-Agathe-des-Monts, Quebec, showing light-coloured anorthosite on the lower left, darker ilmenite–hematite and anorthosite centre and right. Rolling hills of rocky farm land and bush stretch to the north towards the Degrosbois titaniferous magnetite deposit.

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PLATE V B. Close-up view downwards on outcrop of titaniferous magnetite south of Wexford Lake in the Morin anorthosite, Quebec. The prospector's pick rests on rusty, banded titaniferous magnetite in a gabbroic phase of the Morin anorthosite, and its head marks the contact of an anorthosite dyke cutting the titaniferous magnetite.

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PLATE VI A. View southerly of the south-trending ridge of the Magpie titaniferous magnetite deposits, taken from the No. 1 deposit near the headwaters of Rivière St-Jean, Saguenay district, Quebec.

113242-B

PLATE VI B. View westerly of coarse-grained, sparkling black, cleaved crystals of titanomagnetite of the Bishop North deposit, Steel Mountain area, Newfoundland. Anorthosite hills in distance extend to the Carboniferous lowland around St. George's Bay.

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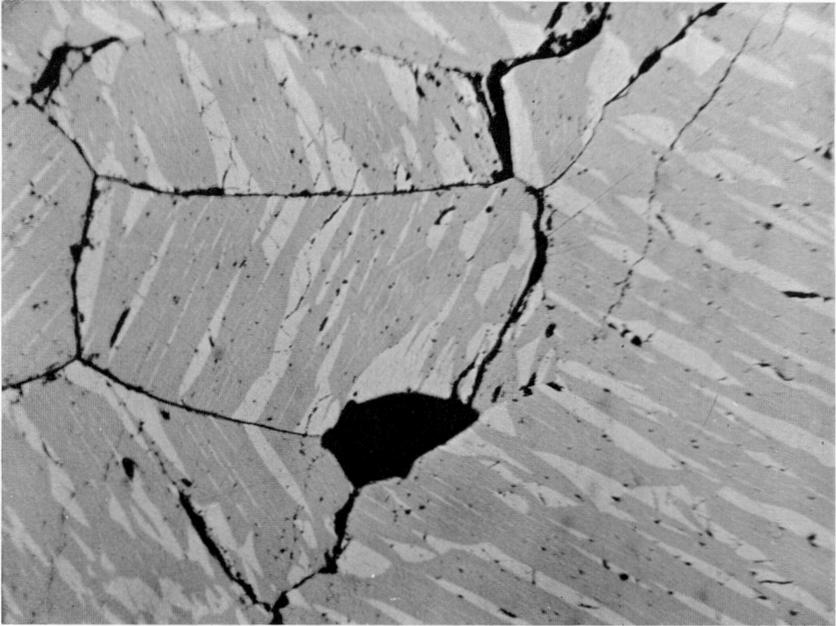
PLATE VII A. Polished surface photomicrograph of coarse-grained massive ilmenite–hematite ore from the main Lac Tio deposit, Lac Allard district, Quebec, showing hematite lamellae (light grey) variously oriented in grains of ilmenite (dark grey), and representing exsolution of hematite from ilmenite. Plain light, $\times$ 55.
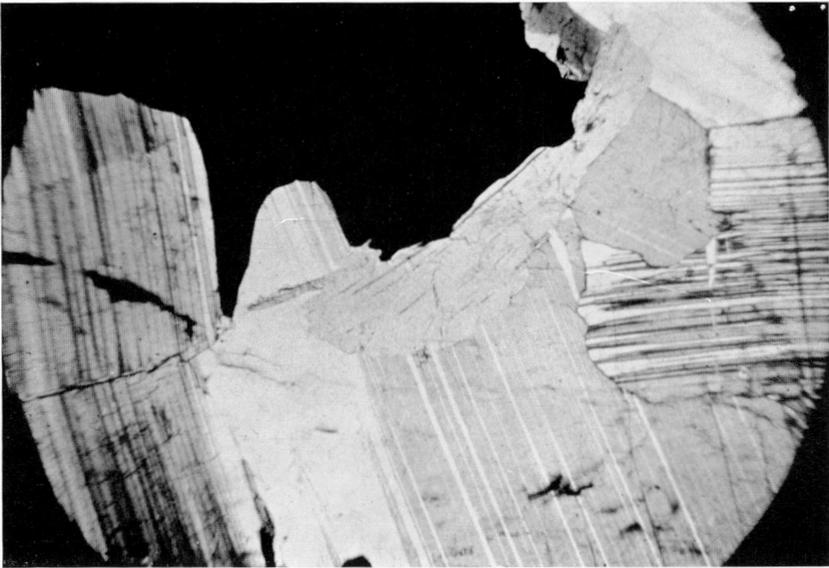
PLATE VII B. Thin-section photomicrograph of ilmenite in anorthosite, Lac Tio, Quebec, showing biotite at contact of ilmenite (black) and twinned plagioclase crystals. Crossed nicols, $\times$ 40.
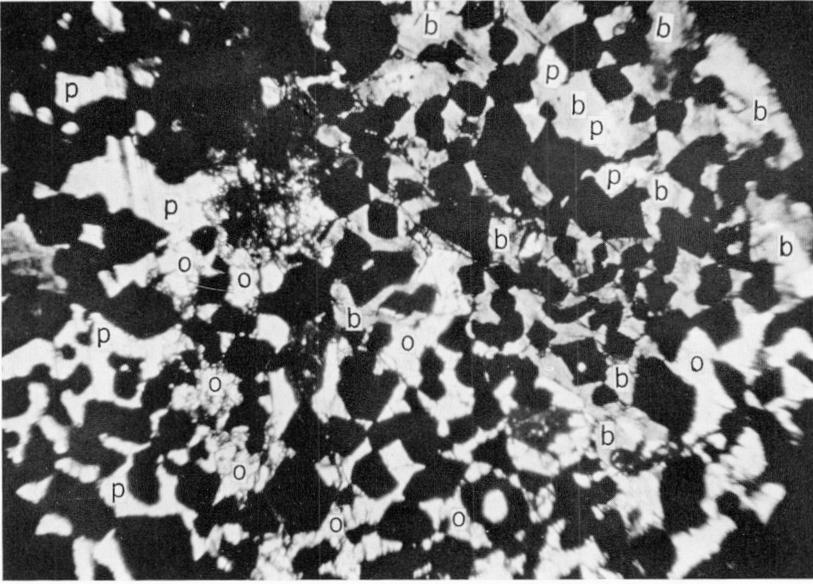
113242-F

PLATE VIII A. Thin-section photomicrograph of low-grade Magpie Mountain titaniferous magnetite-bearing gabbroic anorthosite, showing fine-grained, blocky, black titanomagnetite crystals intergrown with biotite (b), forsteritic olivine (o), and labradorite plagioclase (p). Crossed nicols, × 40.
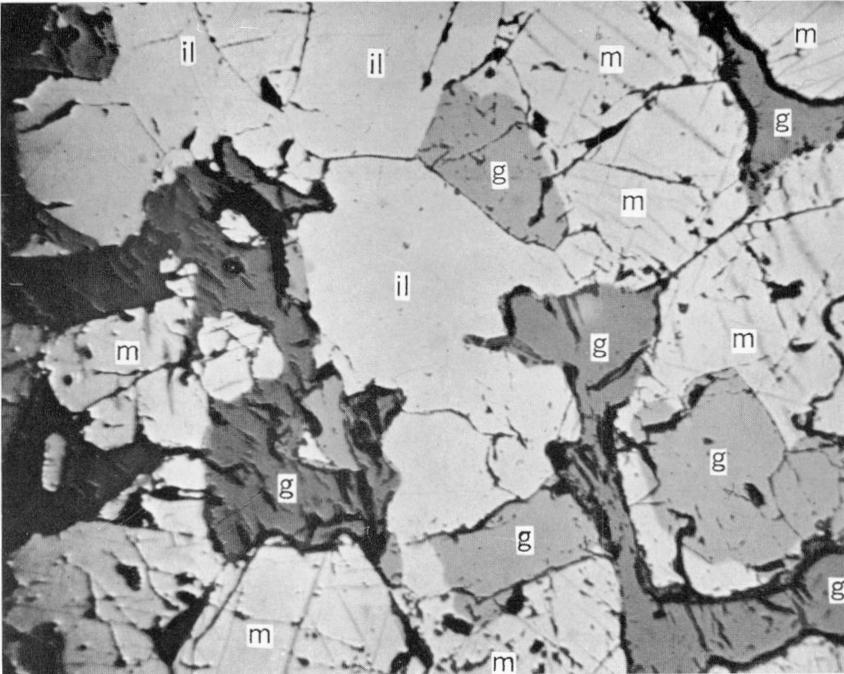
113242-A

PLATE VIII B. Polished surface photomicrograph of Magpie Mountain titaniferous magnetite (m), showing mosaic of titanomagnetite grains carrying exsolved blades of ilmenite and spinel intermixed with dark grey gangue grains (g), and three large discrete grains of ilmenite (i). Nicols partly crossed, × 70.

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