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26. MAFIC INTRUSION-HOSTED TITANIUM-IRON

G.A. Gross

INTRODUCTION

Large ilmenite and titaniferous magnetite deposits are hosted in massive and layered intrusive complexes– dominantly ilmenite in Proterozoic anorthosite (subtype 26.1); and titaniferous magnetite in gabbro and leucogabbro (formerly termed gabbro-anorthosite; e.g. Wager and Brown, 1968) (subtype 26.2). Deposits of both subtypes include irregular discordant masses in layered or massive intrusions, and concordant oxide-rich layers produced during fractional crystallization. The principal ore minerals are oxides of iron and titanium: ilmenite ($FeTiO_3$), hemo-ilmenite (a solid solution of $FeTiO_3$-Fe_2O_3), magnetite (Fe_3O_4), and titaniferous magnetite. The term "titaniferous magnetite" refers to granular aggregates and exsolution intergrowths consisting of ilmenite, magnetite, hematite, and titanomagnetite (a solid solution of Fe_3O_4-Fe_2TiO_4).

Gross, G.A.
1996: Mafic intrusion-hosted titanium-iron; in Geology of Canadian Mineral Deposit Types, (ed.) O.R. Eckstrand, W.D. Sinclair, and R.I. Thorpe; Geological Survey of Canada, Geology of Canada, no. 8, p. 573-582 (also Geological Society of America, The Geology of North America, v. P-1).

The iron- and titanium-rich deposits are classified as two subtypes on the basis of the principal ore minerals and the petrology of the host intrusions. The proportions of the principal ore minerals vary from ilmenite-dominant in anorthosite host rocks to titaniferous magnetite-dominant in gabbro and leucogabbro host rocks. The dominant mineralogy determines whether deposits are of interest as resources of titanium and iron or mainly of iron (Gross, 1965, 1967a).

Subtype 26.1 deposits consist mainly of ilmenite and hemo-ilmenite with minor titaniferous magnetite, and form massive irregular discordant intrusions or layered bodies hosted in massif anorthosite. Important examples are Lac Tio (Lac Allard), Degrosbois, Lac des Pins Rouges, St. Urbain, and Ivry (Morin anorthosite) in Quebec, Canada; Tellnes and Egersund in Norway; and Ilmen Mountains in the former U.S.S.R.

Subtype 26.2 deposits consist mainly of titaniferous magnetite and minor ilmenite and complex Fe-Ti oxide mineral assemblages hosted in layered and/or massive intrusions of leucogabbro, gabbro, norite, and rocks of intermediate composition. Examples include Magpie Mountain, St. Charles, Lac Doré complex, Kiglapait, Newboro Lake, and Lodestone Mountain in Canada; Smaalands-Taberg in Sweden; Bushveld Igneous Complex in South Africa; Kachkanar and Kusinskoye in the former U.S.S.R.; Tahawus and Iron Mountain in the United States.

Deposits of both subtypes provide resources of titanium, vanadium, and iron. Some deposits contain important quantities of apatite (Gross, 1967a; von Gruenewaldt, 1993).

IMPORTANCE

The Lac Tio deposit near Lac Allard, Quebec (Bergeron, 1972) is the only titanium-iron deposit (subtype 26.1) being mined in Canada at present. Mining was started in this area in 1951, and currently about 800 000 t of TiO_2 and 600 000 t of iron are produced annually from the processing of approximately 2 million tonnes of ilmenite ore (Harben and Bates, 1990). Production from Lac Tio accounts for nearly 25% of the world production of titanium oxide (Adams, 1994). High quality iron metal and TiO_2 are coproducts recovered from titaniferous slag produced from the ilmenite ore of subtype 26.1 deposits. Iron ore concentrates in which the titanium content has been reduced to 1% or less have been produced from subtype 26.2 deposits. Other titanium-iron deposits hosted in mafic rocks are mined in Norway (subtype 26.1) and in Russia (subtype 26.2). Deposits of subtype 26.2 have been minor sources of iron ore in Canada in the past, and have been a substantial source of iron ore in the former U.S.S.R.

Titanium dioxide powder is a nontoxic, white pigment used in paint, plastics, rubber, and paper. Titanium metal, resistant to corrosion and with a high strength-to-weight ratio, is used in the manufacture of aerospace and marine components. Significant changes are taking place throughout the world with respect to the kinds and sources of raw materials used for the production of titanium oxide and metal. For example, environmental regulations in many countries make production of hard-rock-derived ilmenite impossible because of the large acid requirements. About 95% of the total titanium mineral production, from both primary magmatic deposits and heavy mineral placer deposits, is used in the production of titanium dioxide. About 20% of the world production of titanium oxide is recovered in the processing of rutile (TiO_2) derived from beach sands (see Adams, 1994).

SIZE AND GRADE OF DEPOSITS

Ilmenite deposits of subtype 26.1 rarely host more than 300 Mt of ore; they contain from 10 to 45% TiO_2, from 32 to 45% Fe, and less than 0.2% V. The ratios of Fe:Ti are usually about 2, and the contents of Cu, Cr, Mn, and Ni commonly range from 0.05 to 0.2% for each element. Sulphide minerals and apatite are present in low and variable amounts. Ore treatment processes currently in use for the production of titanium dioxide require ore concentrates that contain at least 45% TiO_2 (pure ilmenite contains 52.7% TiO_2).

The two largest iron-titanium deposits of subtype 26.1 which are hosted in anorthositic intrusive rocks are the Lac Tio deposit in Canada and the Tellnes deposit in

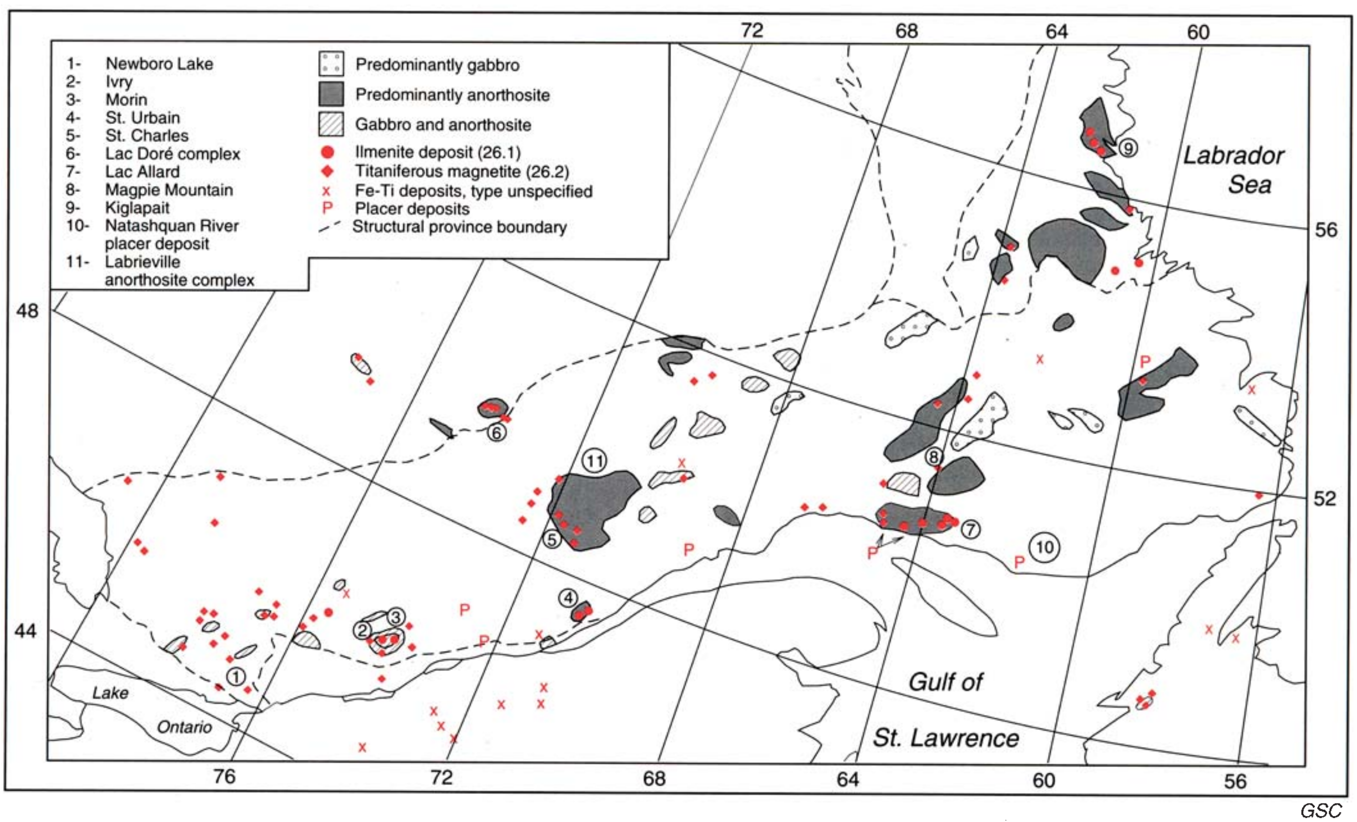

Figure 26-1. Titaniferous magnetite and ilmenite deposits hosted in mafic intrusive rocks in the Grenville Province and Eastern Canada. Important deposits mentioned in text are labelled.

southwestern Norway. Lac Tio is a flat-lying irregular tabular intrusive mass, 1100 m long and 1000 m wide, which is estimated to contain more than 125 million tonnes of ore averaging 32% TiO_2 as ilmenite and 36% FeO. The high-grade ore contains as much as 75% ilmenite and 20% hematite. The Tellnes deposit is about 2800 m long, 400 m wide, and at least 350 m deep. Estimated reserves are 300 million tonnes of ore averaging 18% TiO_2 as ilmenite, 2% magnetite, and 0.25% sulphides.

Titaniferous magnetite deposits of subtype 26.2 range in size from one million tonnes to more than 1000 million tonnes. They usually contain from 20 to 45% iron and from 2 to 20% TiO_2. Ratios of Fe:Ti range from 40:1 to 2:1 and are commonly about 5:1. The average content of V is about 0.25%, Cr is present in trace amounts, and the content of P_2O_5 is variable, but usually less than 7.1%.

GEOLOGICAL FEATURES

Despite the geological and economic importance of iron and titanium deposits hosted in mafic intrusions, few comprehensive reviews are available. Gross (1967a) and Rose (1969) provided geological descriptions and analytical data for deposits being mined and many of the deposits of possible economic importance known in Canada at the time. More recent reviews of the characteristics of titanium ores can be found in Korneliussen et al. (1985), and of anorthosite-hosted deposits in Ashwal (1993).

Geological setting

Ilmenite and titaniferous magnetite deposits associated with anorthosite and gabbro are widely distributed in the Grenville Province and in many other tectonic belts of North America and the world. Both types of intrusive complexes are typically associated with granitoid gneisses, granulites, schists, amphibolites, quartzites, and skarn rocks of deep crustal settings but some occur in greenschist-facies terranes.

Deposits of subtype 26.1 are hosted worldwide in anorthosite; intrusions of the Grenville Province are typical (Fig. 26-1). Most of the deposits form discordant dykes, sills, and stock-like masses in the host anorthositic rocks; others are layered concentrations of Fe-Ti oxides within anorthosite or gabbro, concordant to layering in the host and to the internal fabric of late stage intrusions.

Subtype 26.2 deposits are hosted worldwide in mafic layered and massive intrusions, and are also widely distributed in the Grenville Province (Fig. 26-1). The layered deposits generally form concordant, laterally continuous magnetite-rich layers measuring centimetres to metres thick. Deposits in massive intrusions usually consist of disseminated titaniferous magnetite. Deposits of subtype 26.2 also include massive discordant stock-like bodies of Fe-Ti oxide in layered deposits, as at Newboro Lake in Canada. The host intrusive complexes are typically differentiated and include gabbro, leucogabbro, diorite, diabase, gabbro-diorite, and quartz monzonite.

Concentrations of metallic oxide minerals in both subtypes 26.1 and 26.2 are conspicuously developed in four styles:

1. disseminated syngenetic metal oxides in the host rocks;
2. irregular to conformable autointrusions which have sharp to indistinct or gradational borders with earlier phases of the host anorthosite and gabbro, and were emplaced during the lithification and cooling of the host intrusive rocks;
3. late stage dykes and intrusions transecting the lithified host anorthosite and gabbro complexes;
4. in the skarn rock and alteration zones at the contact of the host intrusions and wall rocks.

Ages of host rocks and ore

Anorthositic host rocks to deposits of subtype 26.1 that have been dated in Canada are Proterozoic in age. These anorthosite complexes range in age from 1.65 Ga (Mealy Mountains; Emslie and Hunt, 1990) to 1.01 Ga (Labrieville; Owens et al., 1994). Major anorthosite-hosted deposits such as Lac Tio and lesser deposits such as St. Urbain, and Ivry and Degrosbois in the Morin anorthosite complexes occur within a much more restricted period with ages ranging from the 1.16 Ga Morin anorthosite (Doig, 1991) through the 1.06 Ga Havre-Saint-Pierre intrusion (van Breemen and Higgins, 1993).

In most cases the precise timing of the Fe-Ti oxide mineralization relative to the crystallization ages of the host anorthosite and gabbro rocks is not known specifically because suitable data are not available. The crystallization age of the Tellnes deposit (southern Norway), 920 ± 2 Ma, is measurably younger than the crystallization age of the host anorthosite, 930 ± 4 Ma (Duchesne et al., 1993), whereas crystallization ages for the Sybille deposit and host anorthosite (Wyoming) are indistinguishable within error at 1434 ± 1 Ma by the uranium-lead method (Scoates and Chamberlain, 1993).

Host rocks to deposits of subtype 26.2 in Canada do not appear to be restricted in time. Ages of crystallization range from 2727 ± 1.3 Ma for the P3 ferric pyroxenite member of the Lac Doré complex (Mortensen, 1993; U-Pb zircon) through the 1305 Ma Kiglapait intrusion (DePaolo, 1985), which contains massive titanomagnetite layers, to the ~540 Ma Sept-Îles intrusion, which contains local concentrations of titaniferous magnetite and ilmenite (Higgins and Doig, 1981).

Form of deposits and relation to host rocks

Generalizations on the form and relationships of these deposits to host rocks are tenuous because of the many variations from deposit to deposit in the host rocks, mineralogy, and geological settings. Nevertheless the two groupings used herein may be of use for discussion, research, and exploration purposes. Both types of Fe-Ti oxide deposits occur in two general forms: massive lenses, dykes, sills, and irregular intrusions; and stratiform, layered, concordant, or irregular bodies. The Fe-Ti oxide minerals may be disseminated and interstitial to the silicate minerals or occur as massive aggregates separated from them. Deposits of subtype 26.1 of economic interest for the recovery of TiO_2 and iron metal are massive irregular intrusions. Deposits of subtype 26.2 are predominantly stratiform and layered. In some cases (e.g. Tahawus and Iron Mountain) attributes of both forms are combined in a single intrusive complex.

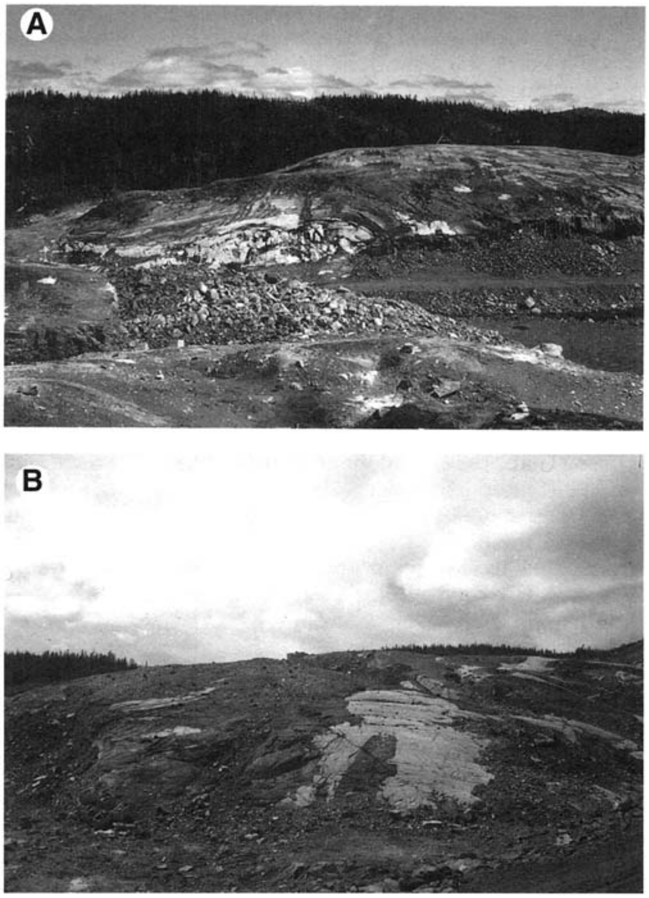

Figure 26-2. A) Irregular dyke (width approximately 5-10 m) of ilmenite (black) in anorthosite, northeast side of Lac Tio deposit, Lac Allard, Quebec. GSC 112341-A; **B)** Inclusions (width approximately 1-5 m) of anorthosite (light grey) in massive ilmenite (black) in Lac Tio deposit, Lac Allard, Quebec. GSC 152327

Ilmenite deposits of subtype 26.1, are typically massive discordant intrusive bodies in anorthositic host rocks (Fig. 26-2A), but some also occur as conformable layers within late stage gabbroic, troctolitic, and dioritic intrusions in anorthosite. Some of the Fe-Ti oxide masses, especially along their borders with the host rocks, have local fragmented or brecciated structures, show evidence of plucking and stoping of the enclosing rocks, and contain abundant xenoliths of anorthosite and xenocrysts of plagioclase derived from anorthosite (Fig. 26-2B). Both massive and disseminated ores are found within a single intrusion (Fig. 26-3A, 26-3B). The massive discordant intrusions of Fe-Ti oxide range in shape from sinuous dyke-like forms to irregular equidimensional masses.

Layered stratiform deposits of subtype 26.2 hosted in gabbro and leucogabbro usually contain layers of disseminated titaniferous magnetite which alternate with layers of feldspar and mafic silicate minerals (Fig. 26-4). Individual layers range in thickness from centimetres to metres. Lateral continuity of oxide-rich layers in large intrusions may be in the order of several thousand metres.

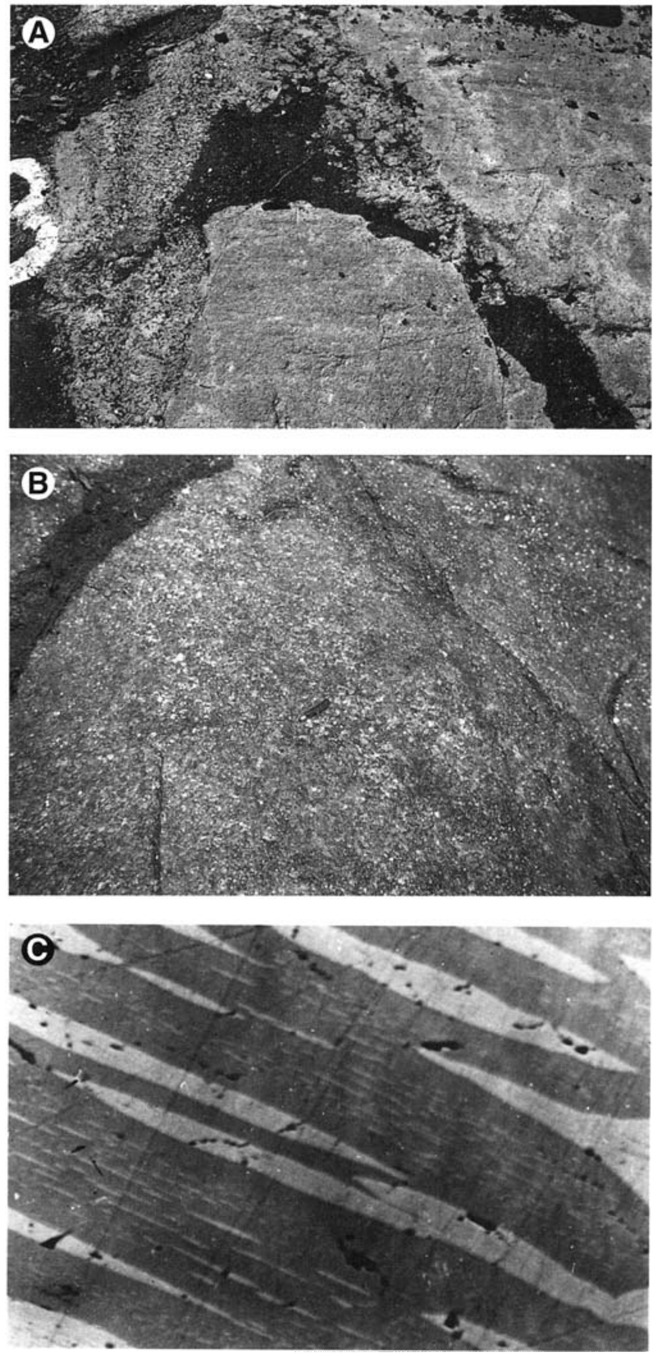

Figure 26-3. A) Massive and disseminated ilmenite (black) in anorthosite. Width of field of view approximately 1 m. GSC 112341-U; **B)** Coarse grained ilmenite, Lac Tio deposit, Lac Allard, Quebec. Width of field of view approximately 1 m. GSC 152330; **C)** Photomicrograph showing hematite (light grey) exsolved from ilmenite (dark grey) Lac Tio deposit, Lac Allard, Quebec. (Width of field of view ~2 mm). GSC 1995-020

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Figure 26-4. Layered anorthositic gabbro with disseminated magnetite near Newboro Lake, Ontario. GSC 152354

Ore mineralogy, composition, and texture

The proportions of the common ore minerals, ilmenite, hemo-ilmenite, titaniferous magnetite, titanomagnetite, and magnetite vary greatly from one deposit or deposit type to another. The complex exsolution textures and mineral relationships that indicate mineral paragenesis and sequence of crystallization vary greatly and appear to be distinctive for individual deposits.

The principal ore minerals in deposits of subtype 26.1 are ilmenite, hemo-ilmenite and their exsolution intergrowths, and titanomagnetite. They are associated with plagioclase, pyroxene, olivine, garnet, biotite, apatite, ulvöspinel, quartz, hornblende, rutile, and pyrrhotite which are present in varying proportions. Hemo-ilmenite, the principal ore mineral at the Lac Tio and Tellnes deposits (subtype 26.1) hosted in anorthosites, is typically equigranular with coarse exsolution lamellae of hematite that constitute as much as 30 mole per cent of the grains (Fig. 26-3C). A second set of very fine exsolution lamellae of ilmenite is commonly developed within the broad hematite lamellae. The forms of earlier titanomagnetite grains can be recognized where the diagnostic trellis lamellae of ilmenite are still preserved along the {111} planes of the host magnetite.

Some parts of the Lac Allard ilmenite deposits contain 8 to 10% fluorapatite (Gross, 1967a). Ilmenite-apatite occurrences (nelsonites) have been reported in many anorthosites (Kolker, 1982). Some of the anorthosite-hosted Fe-Ti oxide deposits contain minor rutile, sapphirine, corundum, sillimanite, and graphite (Ashwal, 1993).

The principal ore minerals in deposits of subtype 26.2 are titanomagnetite, and other varieties of titaniferous magnetite and ilmenite which occur as discrete grains and as exsolution intergrowths in various proportions in magnetite. They are associated with plagioclase (commonly labradorite), olivine, pyroxene, and small amounts of apatite, titanite (sphene), rutile, spinel, biotite, pyrite, chalcopyrite, and pyrrhotite.

Table 26-1. Partial compositions of: I) typical ilmenite-hematite ore at Lac Allard (subtype 26.1), II) average of three titaniferous magnetite deposits at Magpie Mountain (subtype 26.2), and III) Massive titaniferous magnetite at Chaffey mine (subtype 26.2) (in weight per cent).

	I) Lac Allard	II) Magpie Mountain	III) Chaffey mine
Fe	40.2	43.69	50.23
TiO_2	35.0	10.9	9.8
V_2O_5	0.3	0.17	NA
MgO	3.2	5.78	NA
FeO	28.3	NA	NA
Fe_2O_3	26.2	NA	NA
P_2O_5	0.015	0.085	NA
Al_2O_3	3.1	11.57	5.65
SiO_2	3.7	5.9	7.1

After: I) Hatch and Cuke, 1956;
II) Rose, 1969;
III) Unpublished analyzes, GSC
NA = not analysed.

Mineralogy and texture are important factors to be considered in assessing potential resources that might be recovered from Fe-Ti oxide deposits. Massive ilmenite deposits of subtype 26.1, mined for the production of titanium oxide and iron metal, are usually coarse (<1 cm) equigranular aggregates of ilmenite with minor titaniferous magnetite. The large titaniferous magnetite deposits of greatest interest as potential sources of iron ore consist of titaniferous magnetite, magnetite, and minor ilmenite in coarse, discrete grains that have a minimum of exsolution textures and intergrowths of Fe-Ti minerals. Material of this kind is amenable to processing and can provide concentrates of relatively pure magnetite that contain less than one per cent titanium.

Partial data on the composition of the Lac Allard (subtype 26.1), Magpie Mountain (subtype 26.2), and Chaffey mine (subtype 26.2) Fe-Ti oxide deposits are shown in Table 26-1, for the purpose of illustrating the concentrations of the main ore elements for mineral processing.

Alteration

Some aspects of mineral alteration are considered in the section on genetic models.

CANADIAN EXAMPLES

Subtype 26.1

Lac Allard deposits

The ilmenite deposits of the Lac Allard area, located 40 km north of Havre-Saint-Pierre on the north shore of the Gulf of St. Lawrence, are described briefly to illustrate some of the typical geological features of subtype 26.1 deposits. Six deposits ranging in size from one million to several hundred million tonnes are located near the east border of a large oval-shaped anorthosite intrusion that extends west from the Romaine River for more than about 150 km (Fig. 26-1). Uranium-lead zircon dating of the southwest lobe of the Havre-Saint-Pierre anorthosite intrusion indicates that it is 1062 ± 4 Ma old and the parallelism of magmatic and solid-state foliation with the adjacent Abbe-Huard lineament suggest that anorthosite parental magmas rose along this shear zone. The anorthosite complex of this area formed as part of a widespread magmatic event between 1.09-1.05 Ga that included extensive intrusion of anorthosite in the Grenville Province. This magmatic event was a manifestation of deeper mantle processes that probably were not coupled to, but coincided with, the tectonic regime of the overlying crust and the late stage convergent tectonics in the southwestern Grenville Province (van Breemen and Higgins, 1993).

The host intrusion at Lac Allard is composed of almost pure plagioclase anorthosite, associated with leucogabbro, norite, ilmenite-rich anorthosite, and gabbro. The most abundant variety of anorthosite has less than 5% mafic minerals. It is medium- to coarse-grained, porphyritic in places, and varies from light to dark grey pinkish to greenish brown. Most of it is massive, but some parts are distinctly layered and foliated. Protoclastic textures are present throughout most of the intrusion. The composition of the plagioclase ranges from An_{40} to An_{52}. The mafic minerals consist mainly of hypersthene with minor clinopyroxene, ilmenite, amphibole, and biotite.

Noritic and other mafic phases commonly are layered and foliated. Some form dykes and sills that have intruded the anorthosite. Gabbro and diorite dykes cut gneiss and granitic rocks adjacent to anorthosite. The border zones between anorthosite and the host gneissic rocks consist of a group of hypersthene-bearing hybrid rocks with altered phases of anorthosite, and dykes of syenite, granite, and pegmatite that cut the anorthosite and gabbro. Some of the pegmatite dykes are zoned and cut granite, massive ilmenite, and anorthosite; these may be the youngest intrusions of the region.

The ilmenite-magnetite norite phases of the Lac Allard anorthosite complex were intruded during late stages of consolidation of the anorthosite and consist of elongated lenticular sheets that are several kilometres long, a kilometre or less in width, and dip steeply east. They are composed of plagioclase and 50 to 60% mafic minerals including hypersthene, apatite, ilmenite, and magnetite, and 30% or less of iron and titanium oxide minerals that are interstitial to the other minerals. Most of the norite is banded or gneissic and the oxide minerals are most abundant in the lower parts of the bands. Grain size varies from 1 to 20 mm. Ilmenite and magnetite occur as discrete grains and ilmenite is usually the most abundant. The ilmenite grains contain exsolved lamellae of hematite but magnetite grains appear to be homogeneous and contain from 0.75 to 3.3% TiO_2 in solid solution. The content of fluorapatite associated with the oxides ranges from 8 to 10%.

The Lac Allard ilmenite deposits, clustered in the eastern part of the anorthosite intrusive complex, are massive, medium- to coarse-grained dykes, sills, lenses, and irregular bodies. The Lac Tio ilmenite deposit, a good example of subtype 26.1 deposits, is the largest and best known in the area, and is an irregular tabular mass, about 1100 m long and 1000 m wide, with a maximum thickness of 100 m and surface relief of about 130 m. It forms a basin-like or open synformal body of ilmenite in anorthosite. Typical ore structures, textures, xenoliths of anorthosite, and typical dykes and intrusions of ilmenite and hematite in anorthosite are illustrated in Figures 26-2 and 26-3.

Lac Tio orebody is composed of a complex interconnected maze of sills and dykes of hemo-ilmenite. Inclusions and xenoliths of anorthosite range from single feldspar crystals to angular and irregular masses several metres in size. Vertical boundaries of the ore mass are usually sharp and well defined, but horizontal boundaries are irregular and indistinct. Massive ore grades to crudely banded disseminated ore and anorthosite along many margins of the ilmenite mass. Small stringers and dykes of massive ilmenite extend from the main ilmenite mass through the marginal zones into the anorthosite.

The massive ilmenite ore at Lac Tio consists of 88 to 97% combined Fe and Ti oxides (Fig. 26-3A). It is equigranular, coarse grained, dull black to brownish black, and has a glistening jet black surface where freshly broken. Ilmenite grain size ranges overall from 5 to 15 mm, but crystals are fairly uniform in size in local patches several metres in diameter (Fig. 26-3B). The ilmenite that is located close to fault zones is, in most cases, much finer grained, dense, and extremely hard. Ilmenite grains are uniform in composition; they contain microscopic blades and lenses of exsolved hematite which constitute about 15% of the ore (Fig. 26-3C). A small amount of magnetite is present in the ore. Pyrite, pyrrhotite, and chalcopyrite form veins or interstitial fillings around iron-titanium oxide mineral grains.

The ratios of iron to titanium throughout the orebody are remarkably uniform. The ore contains an average of 32% TiO_2 and 36% iron. The grade of the ore can be estimated to within 2% from its specific gravity, which varies from 4.46 to 4.9. The composition of typical ilmenite-hematite ore reported by Hatch and Cuke (1956) is given in Table 26-1.

Subtype 26.2

Magpie Mountain deposit

One of the largest massive titaniferous magnetite deposits known is located 3 km west of the St. Jean River and 200 km northeast of Sept-Îles, Quebec. The steeply dipping tabular masses of magnetite form the crests of ridges that rise 180 m to 300 m above the surrounding terrane. The magnetite bodies are surrounded by anorthosite zones up to 30 m thick and the composite mass has been intruded into granite and granite gneiss.

Four separate deposits are intersected by two major steeply dipping reverse faults (see also description in Rose, 1969, p. 103, 104). The magnetite is medium- to coarse-grained and contains ilmenite in very fine, exsolved blades. The tabular masses consist mainly of magnetite and 15% plagioclase and pyroxene. The largest of the four deposits is 3500 m long, 300 m wide, and is reported to contain 737 Mt of material that contains 45.7% iron, 10.8% TiO_2, and 7.45% silica. Resources of potential ore suitable for open-pit mining in the four deposits are estimated to be greater than 1500 Mt. The average composition for three deposits of titaniferous magnetite reported by Rose (1969) is given in Table 26-1.

Newboro Lake deposit

This deposit is typical of many banded and layered leucogabbro intrusions in the Grenville Province that contain sufficient magnetite and titaniferous magnetite to be of interest as possible sources of iron ore, and that have granular textures which make them amenable to concentration of the iron and separation of the titanium. The leucogabbro that hosts the Newboro Lake deposit is part of a differentiated intrusive complex of layered gabbro, leucogabbro, monzonite, and migmatite, and layered titaniferous magnetite-bearing gabbro. The Newboro Lake iron deposit as now defined consists of magnetite-rich zones in dark grey to green, ophitic-textured, layered leucogabbro in which distinct banding is developed by the separation of variable proportions of andesine and labradorite feldspar, augite, ferroaugite, hornblende, biotite, titaniferous magnetite, ilmenite, and accessory apatite (Fig. 26-4).

The massive titaniferous magnetite intrusions in which the previous Chaffey and Matthews mines were located are enclosed in a layered magnetite-rich zone in the leucogabbro host rock which is about 100 m wide and 1000 m long and forms the Newboro Lake deposit. It contains at least 50 million tonnes of potential ore within the possible limits of an open pit mine. It has an average grade of 26.7% iron and about 6% titanium dioxide. A magnetite concentrate containing 51% iron, was produced by grinding the crude ore to 28 mesh, and 80% of the iron was recovered with a crude ore:concentrate ratio of 2.4:1.

Some layers of magnetite are essentially free of inclusions, but in others ilmenite has exsolved along the octahedral planes of the magnetite and Mg-Fe spinel has exsolved along the cubic planes. Ilmenite with exsolved lamellae of hematite (Fig. 26-3C) forms discrete grains intermixed with magnetite. Titanite (sphene) associated with calcite is present in some parts of the magnetite-rich zones, and in fractures in the gabbro. Small amounts of pyrite are disseminated in some of the magnetite-rich layers. Analyses of higher grade material from the Chaffey mine are shown in Table 26-1.

DEFINITIVE CHARACTERISTICS OF ORE

1. Massive and layered ilmenite and hemo-ilmenite deposits (subtype 26.1) are hosted in anorthosites. Layered and massive concentrations of titanomagnetite, titaniferous magnetite, magnetite, and ilmenite (subtype 26.2) are hosted in differentiated mafic layered and massive intrusions.
2. Subtype 26.1 deposits are massive irregular to tabular bodies and disseminated masses of coarse grained ilmenite containing blades of exsolved hematite, pure ilmenite, and titaniferous magnetite hosted in massive or layered anorthosite and leucogabbro intrusive complexes, stocks, and sills.
3. Typical subtype 26.1 deposits contain from 20 to 40% titanium and 25 to 45% iron with Fe/Ti ratios of about 2:1, and 100 million tonnes or less mineable ore.
4. Subtype 26.2 deposits consist of layered disseminated concentrations and massive irregular to tabular intrusions of titaniferous magnetite, titanomagnetite, magnetite, and ilmenite. These minerals are distributed as discrete grains, and as granular and exsolution intergrowths. The host silicate phases include gabbro, gabbroic anorthosite, and other differentiated intrusive complexes ranging in composition from gabbro, through norite, quartz monzonite, to syenite.
5. The iron content in subtype 26.2 deposits ranges from 20 to 45%; TiO_2 from 2 to 20%; Fe:Ti ratios vary from 40:1 to 2:1 and are commonly about 5:1; the content of P_2O_5 varies to a maximum of about 8% and the content of V, Cu, Ni, Cr, and Mn may vary greatly, but the average for each element is about 0.25% or less.
6. As a group, subtype 26.2 deposits vary greatly in composition, mineralogy, and physical characteristics, but individual deposits are fairly uniform.
7. The mafic-hosted titanium-iron deposits of both subtypes vary greatly in character and composition depending on the kinds of associated host intrusions, the stage of differentiation and oxygen potential in the magma from which they were derived, tectonic setting, and mobilization of elements during metamorphism (cf. Yoder, 1968).
8. They are important as sources of titanium oxide and high quality iron metal that are recovered as coproducts, and as resources of iron ore concentrate in which the titanium content can be reduced to one per cent or less.

RELATED DEPOSIT TYPES

The iron-titanium oxide deposits described here as subtypes 26.1 and 26.2 are the largest and most common type of metallic oxide occurrences hosted in mafic intrusive rocks. They occur in layered intrusions (e.g. Bushveld Complex; Cameron, 1970; Naldrett and Cabri, 1976) that may also host deposits which contain chromium (see Type 28, "Mafic/ultramafic-hosted chromite") and platinum group elements (see subtype 27.2, "Magmatic platinum group elements") (Wardle, 1987). Significant concentrations of vanadium (Rose, 1973), chromium, apatite, nickel and copper sulphides, and platinum group elements occur in or are associated with the Fe-Ti oxide deposits and their host rocks.

Concentrations of magnetite in zoned ultramafic complexes of southeastern Alaska and in the gabbro-ultramafic belt of the Ural Mountains of Russia have been compared by Taylor and Noble (1969). The large Kachkanar and Kusinskoye Fe-Ti deposits on the east slope of the Urals, classified in this paper with other deposits hosted in gabbro and gabbro-anorthosite rocks as subtype 26.2 deposits, were reported to be hosted mainly in the marginal zones of a complex of gabbroic intrusions (see Gross, 1967b; Sokolov, 1970) which is intruded by numerous ultramafic bodies.

The anorthosites themselves are potential sources of alumina. Many of the anorthosite and gabbro intrusions provide decorative and building stone products of high quality and beauty.

Large placer deposits of economic significance that contain ilmenite, magnetite, rutile, and zircon are developed in drainage systems and on beaches in terranes that have prominent anorthosite and gabbro intrusions, with iron and titanium oxide deposits. The concentrations of black sand in the delta area of the Natashquan River on the north shore of the St. Lawrence River (Fig. 26-1) are typical examples of heavy mineral placer deposits derived from a gabbro-anorthosite terrane.

EXPLORATION GUIDELINES

1. Both layered and massive ilmenite deposits, subtype 26.1, are commonly hosted in anorthosite*. Titaniferous magnetite deposits, subtype 26.2, are commonly hosted in gabbroic intrusive complexes.
2. Massive ilmenite and hemo-ilmenite deposits, subtype 26.1, commonly have a distinctive negative magnetic anomaly, or irregular patterns of negative and positive anomalies that mark erratic polarization in segments of the deposits.
3. Intrusive rocks bearing significant concentrations of Fe-Ti oxide are characterized by high positive magnetic anomalies that show broad, smooth profiles or patterns.
4. Iron and titanium oxide deposits and the mafic intrusive rocks which host them have higher gravity anomalies than the surrounding granitic and gneissic rocks.
5. Iron-titanium oxide minerals in stream sediments can be used as effective markers or tracers in exploration for ilmenite and magnetite deposits.
6. Ilmenite deposits of subtype 26.1 appear to be best developed in anorthosite intrusions located along deep-seated fault zones and fracture systems as developed at the margins of major tectonic provinces and belts. In Canada, for example, the best deposits are associated with intrusive complexes along the St. Lawrence River lineament near the southeast margin of the Grenville Province (Gross, 1977).
7. The host intrusive complexes commonly consist of a number of differentiated phases of mafic rock that range in composition from anorthosite, through gabbro and norite to diorite and syenite.*
8. Ilmenite deposits (subtype 26.1) are associated with anorthosite intrusions in which the Fe:Ti ratios in the disseminated metal oxides are less than 3, usually about 2.
9. Titaniferous magnetite deposits (subtype 26.2) are commonly associated with the magnesian, labradorite phases of mafic intrusions, or igneous phases related to them. The Fe:Ti ratios in their metallic oxide minerals vary from 40:1 to 2:1 and are commonly about 5:1.
10. Titaniferous magnetite deposits of subtype 26.2 are most commonly developed in:
    a) the gabbroic phases near the margins of gabbro intrusive stocks;
    b) in the upper stratigraphic parts of mafic layered intrusions; and
    c) in the gabbro-diorite stocks, dykes, and sills which are associated with major gabbro intrusions.

* *Editorial note*, from T. Birkett, pers. comm., 1994: Massif anorthosites, at least those of the Grenville Province (see also Hill, 1988 for Nain area), are enveloped in jotunite. As well, jotunites form septa within many anorthosites, possibly defining "cells" within the larger complexes. Anorthosite-hosted Fe-Ti ores are invariably associated with jotunite. In the past, jotunites have been called gabbro-anorthosite, ferrodiorite, monzodiorite, gabbroic anorthosites, and oxide-apatite-gabbronorites. Jotunites are orthopyronene-bearing rocks of mainly monzodioritic composition, commonly containing appreciable Fe-Ti oxide and apatite. Jotunites are distinguished from minor products of crystallization of anorthosite by their higher concentrations of Ti, Fe, and especially P.

GENETIC MODELS FOR MAFIC INTRUSION-HOSTED TITANIUM-IRON DEPOSITS

J.S. Scoates

The titanium-iron deposits that are associated with Proterozoic anorthosites and layered mafic intrusions are clearly late products of the crystallization history of individual intrusions. Brecciation of ore-hosting anorthosite and truncation of structural elements in anorthosite are clear evidence for late intrusion of the ore-forming magmas in many subtype 26.1 deposits. Conformable layers in small intrusions in anorthosite and in large, mafic layered intrusions throughout the world indicate an origin by crystal settling and accumulation on the floors of magma chambers for subtype 26.2 deposits and parts of subtype 26.1 deposits.

Both subtypes of deposits require extensive periods of prior plagioclase crystallization to concentrate Fe and Ti in residual magmas, and variations in the oxidation state of the magmas (monitored by the intensive parameter - oxygen fugacity) to promote the formation of the titanium-iron deposits. Hemo-ilmenite deposits (subtype 26.1) require relatively more oxidizing conditions of formation compared to the more reduced titanomagnetite deposits (subtype 26.2).

Evidence is lacking for the presence of hydrous fluids during formation of the Ti-Fe deposits, although CO_2-dominant fluids were likely present. The preserved primary mineral assemblages are typified by anhydrous mineralogies. Hydrous minerals are always late and volumetrically minor (<<1%) or definitely related to crosscutting monzonitic or granitic intrusions. The presence of grain-boundary graphite and CO_2-rich inclusions in apatite from anorthosites indicates that the very small amounts of fluids associated with anorthosites were probably CO_2-dominated.

The genesis of the discordant, massive Fe-Ti oxide deposits associated with Proterozoic anorthosites is the least understood of the deposit types. Two end-member genetic models are currently under consideration: (1) remobilization of Fe-Ti oxide-rich cumulates, and (2) formation of an Fe-Ti-oxide-rich, silica-poor immiscible melt. The remobilization mechanism involves the intrusion of dense, solidified Fe-Ti-oxide-rich cumulates into cracks or fractures within the host anorthosite (Bateman, 1951; Hammond, 1952; Ashwal, 1982, 1993). A similar remobilization mechanism, but also involving magma mixing, has been proposed for the Tellnes deposit of Norway (Wilmart et al., 1989). In this scenario, a noritic magma crystallized Fe-Ti oxides which concentrated at the bottom of the chamber, and plagioclase which concentrated at the top of the chamber. Before complete solidification, the chamber was tapped and Fe-Ti oxide cumulates were injected into a dyke that already contained a fractionated monzonitic melt.

A liquid immiscibility origin for the massive ores has been proposed for most of the large deposits in Quebec for many years (Hargraves, 1962; Anderson, 1966; Lister, 1966; Philpotts, 1966, 1967). Liquid immiscibility, the separation of a single magma into two distinctive liquid phases, is most likely to occur in systems with bulk compositions high in total iron, TiO_2, P_2O_5, and high ratios of Fe^{3+}/Fe^{2+} (oxidized conditions) (Naslund, 1983). Rocks of these compositions are found throughout Proterozoic anorthosite complexes and are referred to as ferrodiorites, monzonorites, jotunites, and oxide-apatite-rich gabbronorites. These Fe-Ti-P-enriched rocks are considered to have formed as residual liquids following extensive crystallization of plagioclase to produce the associated anorthosites.

Experimental support for the liquid immiscibility mechanism is derived from the observation in the system magnetite-fluorapatite that an immiscible eutectic melt with a composition of approximately two-thirds by volume magnetite and one-third apatite can separate from a silicate melt (Philpotts, 1967), although the temperatures of the experiments were geologically unreasonable (1420°C). Liquid immiscibility may be appropriate for the production of small apatite-rich oxide deposits, referred to as nelsonites (Kolker, 1982), but the majority of the major deposits are apatite-poor. If liquid immiscibility is to remain a reasonable option in the formation of titanium-iron deposits, then an additional suitable flux must be found associated with the massive ores, because the melting temperatures of pure Fe-Ti oxides are unrealistically high.

Titanium-free oxide liquids do exist, as exemplified by the magnetite lava flows of El Laco, Chile (Park, 1961; Henriquez and Martin, 1978), and by the experiments of Weidner (1982), which show that graphite and C-O fluids flux oxide liquids to temperatures below 1000°C. However, there is limited evidence for the existence of Fe-Ti oxide melts. Recent experimental work shows that graphite does not stabilize Ti in oxide liquids (Lindsley and Philipp, 1993), and thus the mechanism required for the generation of apatite-poor, Ti-bearing immiscible melts remains elusive.

The origin of conformable Fe-Ti oxide-rich layers in layered intrusions is more straightforward than that for the discordant massive intrusions. The conformable layers represent the overproduction of Fe-Ti oxides in a progressively crystallizing magma, mainly in response to local variations in oxygen fugacity (Morse, 1980). Prior to the cumulus arrival of magnetite and/or ilmenite in a magma, protracted crystallization of plagioclase will enrich the residual magma in Fe, Ti, (and V), and increase the density of this residual melt. The prominent titanomagnetite layers in the Kiglapait intrusion of Labrador (Morse, 1969, 1980) and the Bushveld Igneous Complex of South Africa (Willemse, 1970; Reynolds, 1985) occur relatively high in the stratigraphic sections of these intrusions, and require crystallization from magnetite-supersaturated liquids.

The compositions of Fe-Ti oxides in both hemo-ilmenite-rich and titanomagnetite-rich ores can undergo substantial modification during cooling by both intra- and intercrystalline reaction and exchange. During slow cooling, the titanium component in titanomagnetite may be exsolved by oxidation to form either discrete lamellae of ilmenite in magnetite, or granular exsolutions of ilmenite around magnetite grains, a process called oxy-exsolution (Buddington and Lindsley, 1964):

$$\underset{\text{in magnetite}}{6Fe_2TiO_4} + O_2 = \underset{\text{ilmenite}}{6FeTiO_3} + \underset{\text{magnetite}}{2Fe_3O_4}$$

This reaction may be facilitated by the presence of a CO_2-rich fluid, and can occur to very low temperatures (400-500°C). As a result, titanomagnetite grains can purge themselves entirely of the original titanium component, and the resultant ore mineralogy and texture is one of interlocking discrete grains of magnetite and ilmenite. In addition, at relatively high temperatures, exchange of titanium and iron between individual grains of magnetite and ilmenite can occur according to the following equilibrium reaction, which proceeds to the right with decreasing temperature:

$$\underset{\text{in magnetite}}{Fe_2TiO_4} + \underset{\text{in ilmenite}}{Fe_2O_3} = \underset{\text{ilmenite}}{FeTiO_3} + \underset{\text{magnetite}}{Fe_3O_4}$$

This produces magnetite and ilmenite grains that will approach their end-member compositions as cooling proceeds.

Oxidation of ilmenite-rich deposits can result in the alteration of ilmenite to rutile. Associated alteration of silicate and Fe-Ti oxide minerals always postdates the formation of the deposits.

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