

A Deposit Model for Magmatic Iron-Titanium-Oxide Deposits Related to Proterozoic Massif Anorthosite Plutonic Suites



Scientific Investigations Report 2013–5091

COVER. McIntyre mine located in the Adirondack State Park, New York (photo taken by Laurel G. Woodruff, U.S. Geological Survey).

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By Laurel G. Woodruff, Suzanne W. Nicholson, and David L. Fey

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Contents

Abstract.....	1
Introduction.....	1
Purpose and Scope	3
Deposit Type and Related Commodities	4
Name.....	4
Synonyms	4
Brief Description.....	4
Associated and Transitional Deposit Types	7
Stratiform Mafic-Ultramafic Iron-Titanium-Vanadium Deposits.....	7
Nickel-Copper-Magmatic Sulfide Deposits.....	8
Contact Metasomatic Rutile with Alkalic Anorthosite	8
Heavy-Mineral Deposits	8
Primary Commodities	8
Byproduct Commodities	8
Example Deposits.....	9
Important Deposits	9
Historical Evolution of Descriptive and Genetic Knowledge and Concepts.....	9
Regional Environment.....	10
Geotectonic Environment and Magmatic Temporal Relations.....	10
Temporal (Secular) Relations of Oxides to Host Rocks	11
Relations to Structures	12
Relations to Igneous Rocks.....	12
Relations to Metamorphic Rocks	12
Relations to Sedimentary Rocks	12
Physical Description of Deposit	12
Dimensions in Plan View	12
Size of Hydrothermal System Relative to Extent of Economically Mineralized Rock.....	14
Vertical Extent	14
Form and Shape	14
Host Rocks	14
Structural Setting(s) and Control	15
Geophysical Characteristics.....	15
Magnetic Signatures.....	15
Gravity Signatures	16
Electrical Signatures.....	16
Hypogene Ore Characteristics	16
Mineralogy and Mineral Assemblages	16
Paragenesis	17
Zoning Patterns.....	19
Textures and Grain Size	20
Gangue Mineral Characteristics	20
Mineralogy and Mineral Assemblages	20
Paragenesis.....	21

Zoning Patterns	21
Textures and Grain Sizes	21
Hydrothermal Alteration	22
Supergene Ore and Gangue Characteristics	22
Weathering and Supergene Processes	22
Geochemical Characteristics	22
Trace Elements and Element Associations	22
Zoning Patterns	22
Isotope Geochemistry of Ores	23
Stable Isotope Geochemistry	23
Radiogenic Isotope Geochemistry	23
Petrology of Associated Igneous Rocks	23
Rock Names	24
Forms of Igneous Rocks and Rock Associations	24
Mineralogy	24
Textures, Structures, and Grain Size	24
Petrochemistry	25
Major-Element Geochemistry	25
Trace-Element Geochemistry	25
Isotope Geochemistry of Igneous Rocks	27
Stable Isotope Geochemistry	27
Radiogenic Isotope Geochemistry	29
Petrology of Associated Sedimentary Rocks	31
Petrology of Associated Metamorphic Rocks	31
Theory of Deposit Formation	31
Ore Deposit System Affiliation	31
Sources of Ti-Fe-P-Ore Components	31
Mechanisms that Concentrate Ore	31
Summary of the Origin of Magmatic Fe-Ti-Oxide Deposits	32
Geological Assessment Guides	34
Attributes Required for Inclusion in Permissive Tract at Various Scales	34
Geochemical Considerations	34
Geophysical Attributes	34
Geoenvironmental Features and Anthropogenic Mining Effects	34
Soil and Sediment Signatures Prior to Mining	34
Secondary Minerals	34
Drainage Signatures	34
Climate Effects on Geoenvironmental Signatures	35
Past and Future Mining Methods and Ore Treatment	35
Metal Mobility from Solid Mine Waste	35
Pit Lakes	36
Volume of Mine Waste and Tailings	36
Smelter Signatures	36
Human Health Issues	36
Acknowledgments	36

References Cited.....	37
Appendix.....	46

Figures

1. World map showing distribution of Proterozoic massif anorthosite.....	2
2. Simplified geologic map of part of the Grenville Province showing the distribution of Proterozoic massif anorthosite suites	3
3. Simplified geologic map of the Rogaland Anorthosite Province showing the distribution of the main geologic units, including the Egersund-Ogna, Håland-Helleren, Åna-Sira, Garsaknat, and Hidra massif anorthosites and the Bjerkreim-Sokndal layered intrusion.....	4
4. Simplified geologic map of the Duluth Complex, Minnesota.....	10
5. Classification of rock association and iron-titanium-oxide (Fe-Ti-oxide) mineralogy for massif anorthosite based on silica activity and oxygen fugacity for idealized lithologies.....	11
6. Surface outline of the three main orebodies at the Lac Tio deposit, Quebec, Canada, and a north-south cross section of the Main orebody showing the reconstructed exploited ore removed from the open pit and remaining ore	13
7. Simplified geologic map of the host Åna-Sira anorthosite, Norway, and location and three cross sections of the Tellnes ilmenite-norite orebody	13
8. Photograph showing deformed layers and remobilized veins of massive titaniferous magnetite and ilmenite and oxide-rich leucogabbro norite in labradorite-type anorthosite of the Rivière-au-Tonnerre Massif of the Havre-Saint-Pierre anorthosite suite, Quebec, Canada.....	14
9. Aeromagnetic profile of the Allard Lake anorthosite across the Lac Tio deposit, Quebec, Canada, displaying a contour line of equal magnetic-field intensity.....	15
10. The subsystem $\text{FeO-Fe}_2\text{O}_3\text{-TiO}_2$ showing major solid solution joins for the cubic (ulvöspinel-magnetite), rhombohedral (ilmenite-hematite), and orthorhombic (pseudobrookite) series	17
11. A. Reflective-light photograph of hemo-ilmenite from the Lac Tio deposit, Quebec, Canada. B. Reflective-light photograph of titanomagnetite (Ti-Mte) and ilmenite (Ilm) from the Hervieux East massive titaniferous lens in the La Blache anorthosite complex, Quebec, Canada	18
12. Cross sections of the Tellnes orebody, Norway	19
13. Photograph of massive hemo-ilmenite ore from the floor of the Main pit at the Lac Tio deposit, Quebec	20
14. $\text{Al}_2\text{O}_3\text{-FeO-MgO}$ triangular diagrams showing simplified compositional character of rocks related to Proterozoic massif anorthosite.....	26
15. All Adirondack massif anorthosite and related rocks plotted on a $\text{CaO-Na}_2\text{O+K}_2\text{O-Fe}_2\text{O}_3$ triangular diagram.....	27
16. Chondrite-normalized rare earth elements (REE) patterns for representative samples of the anorthosite suite from the Marcy massif anorthosite, Adirondacks, New York	28
17. Whole-rock δD (WR δD) versus $\delta^{18}\text{O}$ for the Åna-Sira anorthosite, the Tellnes orebody, and norite dike hosting the Tellnes orebody; the Bjerkreim-Sokndal layered intrusion (BKSK) and apophysis and the metamorphic envelope of gneiss in the Rogaland Anorthosite Province.....	29

18.	Compilation of $\delta^{18}\text{O}$ whole-rock and plagioclase values for Proterozoic anorthosites.....	30
19.	Hypothetical model for the magmatic evolution of Fe-Ti-oxide deposits.....	33
A1.	Varying rocks types related to Fe-Ti-oxide deposits hosted within Proterozoic anorthositic plutonic suites and related layered rocks are classified based on their proportional mineralogy	33

Table

1.	Selected Proterozoic massif anorthosite suites and contained magmatic iron-titanium-oxide deposits or districts with multiple deposits.....	5
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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m ²)	0.0002471	acre
square kilometer (km ²)	0.3861	square mile (mi ²)
Volume		
cubic meter (m ³)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
microgram (mg)	0.0000003527	ounce, avoirdupois (oz)
milligram (mg)	0.00003527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
tonnes (t)	2204.6226	pound avoirdupois (lb)
tonnes (t)	1.1023	ton (US, short)
million tonnes (Mt)	1.1023	million tons (US, short)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F} = (1.8 \times ^{\circ}\text{C}) + 32$$

An isogam is a line joining points on the Earth's surface having the same value of the acceleration of gravity.

A gal is a unit of acceleration equal to a centimeter per second per second; a milligal is one thousandth of a gal.

A Deposit Model for Magmatic Iron-Titanium-Oxide Deposits Related to Proterozoic Massif Anorthosite Plutonic Suites

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Abstract

This descriptive model for magmatic iron-titanium-oxide (Fe-Ti-oxide) deposits hosted by Proterozoic age massif-type anorthosite and related rock types presents their geological, mineralogical, geochemical, and geoenvironmental attributes. Although these Proterozoic rocks are found worldwide, the majority of known deposits are found within exposed rocks of the Grenville Province, stretching from southwestern United States through eastern Canada; its extension into Norway is termed the Rogaland Anorthosite Province. This type of Fe-Ti-oxide deposit dominated by ilmenite rarely contains more than 300 million tons of ore, with between 10- to 45-percent titanium dioxide (TiO_2), 32- to 45-percent iron oxide (FeO), and less than 0.2-percent vanadium (V).

The origin of these typically discordant ore deposits remains as enigmatic as the magmatic evolution of their host rocks. The deposits clearly have a magmatic origin, hosted by an age-constrained unique suite of rocks that likely are the consequence of a particular combination of tectonic circumstances, rather than any a priori temporal control. Principal ore minerals are ilmenite and hemo-ilmenite (ilmenite with extensive hematite exsolution lamellae); occurrences of titanomagnetite, magnetite, and apatite that are related to this deposit type are currently of less economic importance. Ore-mineral paragenesis is somewhat obscured by complicated solid solution and oxidation behavior within the Fe-Ti-oxide system. Anorthosite suites hosting these deposits require an extensive history of voluminous plagioclase crystallization to develop plagioclase-melt diapirs with entrained Fe-Ti-rich melt rising from the base of the lithosphere to mid- and upper-crustal levels. Timing and style of oxide mineralization are related to magmatic and dynamic evolution of these diapiric systems and to development and movement of oxide cumulates and related melts.

Active mines have developed large open pits with extensive waste-rock piles, but because of the nature of the ore and waste rock, the major environmental impacts documented at the mine sites are reported to be waste disposal issues and somewhat degraded water quality.

Introduction

Overviews of magmatic iron-titanium-oxide (Fe-Ti-oxide) deposits include Lister (1966), Rose (1969), Force (1991), Gross (1996), Korneliussen and others (2000), and Corriveau and others (2007). Economic magmatic ilmenite and titaniferous-magnetite (Fe-Ti-oxide) deposits have spatial and temporal connections with massif anorthosite suites found in Proterozoic rocks on all continents (Anderson, 1969; Ashwal, 1993) (fig. 1). Many deposits occur in rocks of the Proterozoic Grenville Province, which are exposed from the Adirondack Mountains (Adirondacks) in New York, through eastern Canada (fig. 2), and into the Rogaland Anorthosite Province, Norway (fig. 3). The Grenville Province is considered the largest titanium province in the world (Corriveau and others, 2007) (table 1).

Understanding the formation of magmatic Fe-Ti-oxide deposits relies on understanding the nature of anorthosite and related rocks hosting these deposits, the evolution of parent magma from which oxide and silicate minerals crystallized, and the tectonic setting of these rocks and ores (Weihed and others, 2005). Massif anorthosites are igneous bodies ranging in size from small individual plutons to large (15,000 to 20,000 km^2) intrusive complexes, typically composed of more than 90-percent plagioclase of fairly restricted composition, and mainly Proterozoic in age (Ashwal, 1993; Ashwal, 2010). Related rock types have a complex nomenclature that includes leucotroctolite, leuconorite, troctolite, norite, gabbro-norite, ferrogabbro, ferrodiorite, jotunite, mangerite, and charnockite (see appendix 1 for rock classification scheme used in this report). These related unusual rock types are commonly part of what is referred to as anorthosite-mangerite-charnockite-granite (AMCG) suites (Emslie, 1991). The structures of massifs range from composites of multiple diapiric intrusions (for example, Havre-Saint-Pierre anorthosite suite, Quebec; van Breemen and Higgins, 1993) to dozens of discrete layered troctolite, gabbro and anorthosite intrusions (for example, Duluth Complex, Minnesota; Miller and Ripley, 1996) to large, layered mafic intrusions (for example, Bjerkreim-Sokndal intrusion, Norway; Wilson and others, 1996; fig. 3), all of which can host significant concentrations of magmatic Fe-Ti oxides.

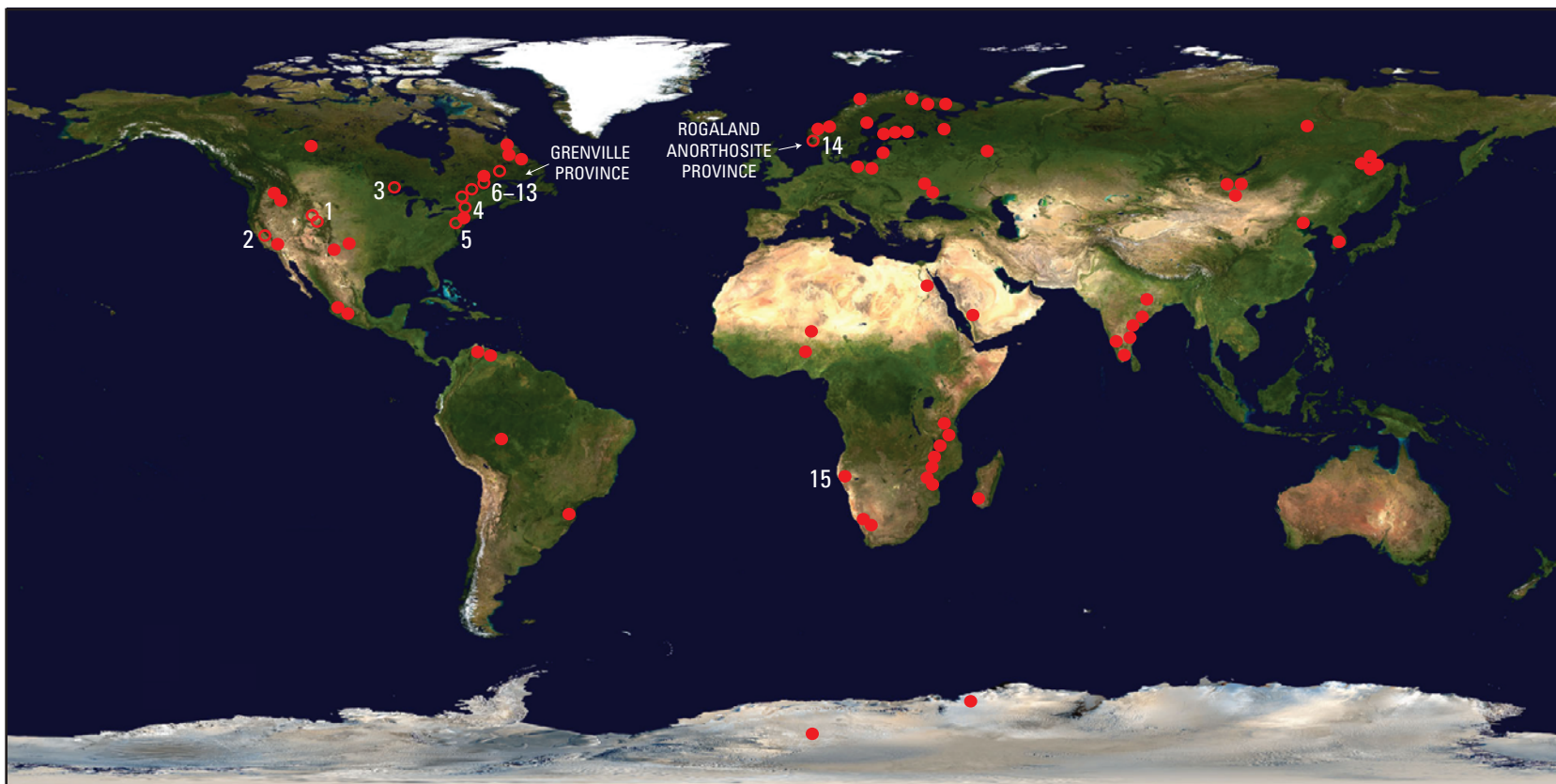


Figure 1. World map showing distribution of Proterozoic massif anorthosite (locations from Ashwal, 1993). Anorthosite suites that host significant iron-titanium-oxide deposits are denoted by open red circles. The numbers given for these anorthosite suites corresponds to the numbers in table 1.

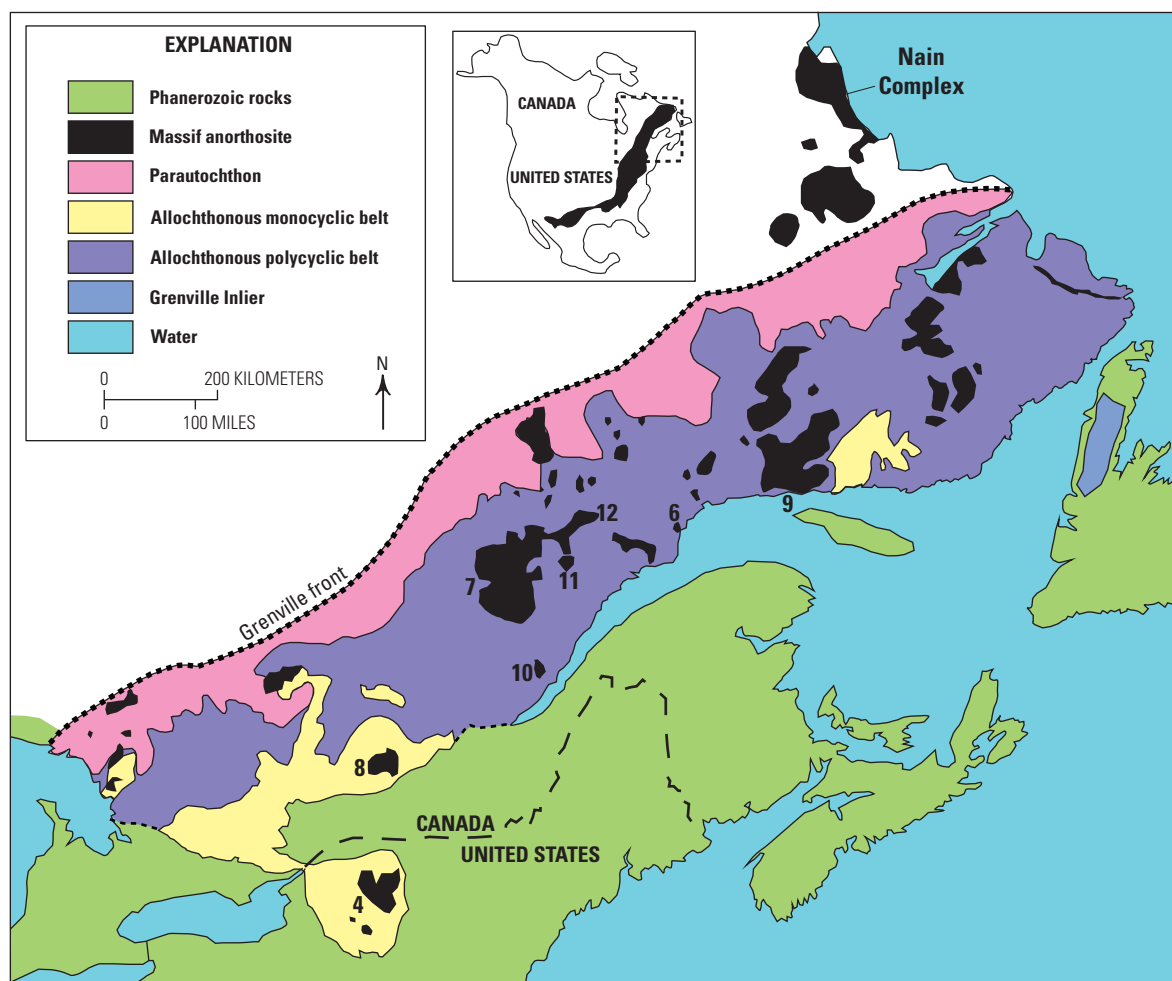


Figure 2. Simplified geologic map of part of the Grenville Province showing the distribution of Proterozoic massif anorthosite suites (modified from Davidson, 2008). Numbers correspond to numbers shown in figure 1 and table 1. Inset shows the extent of the Grenville Province (black) in North America.

The principal ore minerals are ilmenite (FeTiO_3), hemo-ilmenite (ilmenite with abundant hematite (Fe_2O_3) exsolution lamellae), and titanomagnetite (a solid solution of magnetite (Fe_3O_4) and ulvöspinel (Fe_2TiO_4)) (Gross, 1996). The presence or absence of discrete crystals of ilmenite is the key factor determining the economic value of these deposits (Force, 1991). Magmatic ilmenite deposits typically contain less than 300 million tons (Mt) of ore with 10- to 45-percent TiO_2 , 32- to 45-percent Fe, and less than 0.2-percent vanadium (V) (Gross, 1996). There are only two currently active magmatic Ti mines, Lac Tio in Quebec, Canada, and Tellnes in Norway. Other Fe-Ti-oxide deposits with past mining operations include deposits in numerous anorthosite suites of the Grenville Province in Quebec (see Hébert and others, 2005; Corriveau and others, 2007), the Storgangen and Blåfjell deposits, among others, in the Rogaland Province in Norway (Schiellerup and others, 2003), and four deposits (Sanford Hill/South Extension, Cheney Pond, Mt. Adams, and Upper Works) in the Sanford Lake district in the Adirondacks of New York (Gross, 1968). Additional potential Fe-Ti-oxide

resources in the United States include oxide-bearing ultramafic intrusions (OUIs) in the Duluth Complex, Minnesota (Severson, 1995; Hauck and others, 1997), ilmenite (with rutile) in the Roseland Anorthosite, Virginia (Herz and Force, 1987), Fe-Ti-oxide mineralization (dominantly titanomagnetite with ilmenite) in the Laramie Range, Wyoming (Diemer, 1941), and Fe-Ti-oxide mineralization (dominantly titanomagnetite with ilmenite) in the San Gabriel Range, California (Force 1991) (fig. 1 and table 1).

Purpose and Scope

This report is part of an effort by the U.S. Geological Survey's Mineral Resource Program to update existing mineral deposit models and develop new, more complete deposit models to be used for an upcoming U.S. Geological (USGS) national mineral resource assessment. The deposit model presented here replaces previously published USGS descriptive model 7b for anorthosite Ti (Force, 1992).

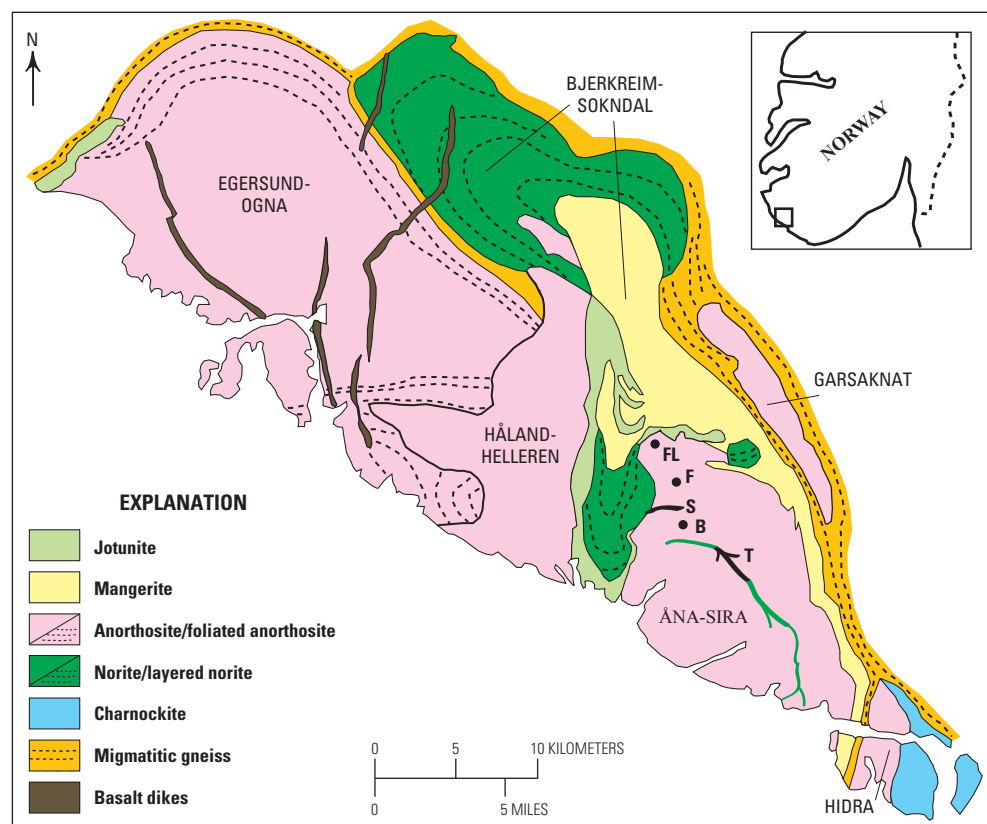


Figure 3. Simplified geologic map of the Rogaland Anorthosite Province showing the distribution of the main geologic units, including the Egersund-Ogna, Håland-Helleren, Åna-Sira, Garsaknat, and Hydra massif anorthosites and the Bjerkreim-Sokndal layered intrusion. Iron-titanium-oxide deposits: T=Tellnes, B=Blåfjell, S=Storgangen, F=Flordalen, and FL=Frøtlog (modified from Duchesne and Schiellerup, 2001).

Deposit Type and Related Commodities Brief Description

Name

Iron-titanium-oxide (Fe-Ti-oxide) deposits hosted by Proterozoic massif anorthosite plutonic suites and related mafic layered intrusions

Synonyms

These Fe-Ti-oxide deposits are referred to informally as anorthosite Ti deposits, hard-rock Fe-Ti-oxide deposits, or magmatic Fe-Ti-oxide deposits. However, the qualifier of “hosted by Proterozoic massif anorthosite plutonic suites and related layered mafic intrusions” is used here to distinguish these discordant massive oxide lenses, weakly discordant oxide layers, and more stratiform oxide layers of predominantly ilmenite and titaniferous magnetite in massive anorthosite and related rocks as well as layered mafic intrusions within anorthositic provinces from consistently stratiform mafic-ultramafic Fe-Ti-V-oxide deposits dominated by magnetite in the upper parts of large, layered intrusions, such as the Bushveld Complex in South Africa. This latter class of magmatic Fe-Ti-oxide deposits belongs in a separate, distinct deposit model (USGS descriptive model 3; Bushveld Fe-Ti-V; Page, 1992).

It is estimated that the two active magmatic Fe-Ti-oxide mines, Tellnes and Lac Tio, together produce about 32 percent of the world’s titanium dioxide (TiO_2) (Gross, 1996; Schiellerup and others, 2003). The remaining 68 percent comes from ilmenite and rutile in shoreline placer deposits (Force, 1991). About 95 percent of the world’s Ti is refined into TiO_2 , a pigment used to impart a durable white color to paints, paper, toothpaste, sunscreen, and plastics; the remaining 5 percent is used for production of corrosion-resistant Ti metal (Towner and others, 1988).

Magmatic Fe-Ti-oxide deposits occur as discordant lenses—dike-like or pipe-like bodies—and as layers or disseminations within Proterozoic plutonic suites dominated by anorthosite, norite, and gabbro; related rock types may include mangerite (hypersthene-bearing monzonite), jotunite (hypersthene-bearing monzodiorite), nelsonite (oxide-apatite rock with few or no silicates), oxide-apatite gabbro-norite (oxide- and apatite-rich rock with plagioclase and two pyroxenes), and minor ultramafic rocks, such as pyroxenite, peridotite, and dunite (Gross, 1996; Owens and Dymek, 1992; Hauck and others, 1997; Schiellerup and others, 2003; Hébert and others, 2005; Corriveau and others, 2007) (see appendix 1 for details on rock name classifications). Discordant relations between ore-bearing bodies and host rocks and incorporation of anorthositic xenoliths within some ore-bearing bodies

Table 1. Selected Proterozoic massif anorthosite suites and contained magmatic iron-titanium-oxide deposits or districts with multiple deposits.

[Numbers in parentheses given to the 15 listed anorthosite suites correspond to numbers applied to anorthosite suite locations in figure 1. The name of the anorthosite suite, deposit mineralogy, resource, and host rock information are compiled from Towner and others (1988), Force (1991), Ashwal (1993), Duchesne and Schiellerup (2001), Severson and others (2002), Hébert and others (2005), U.S. Geological Survey (2005), Gross (1996), Corriveau and others (2007), von Seckendorff and others (2000), and Arianne Resources (2012). Resources are in millions of tons (Mt) and TiO₂ and Fe grades are in weight percent]

Anorthosite suite	Oxide deposit or district name	Ore mineralogy	Resources Mt	Grade TiO ₂	Grade Fe	Host and related rocks
Laramie Range complex (1) Wyoming, U.S.A.	Iron Mountain	titanomagnetite-ilmenite-magnetite	134.0	9.69	20.2	troctolite/leucogabbro/anorthosite
	Shanton	titanomagnetite-ilmenite-magnetite	---	---	---	anorthosite
	Taylor	ilmenite-magnetite-apatite	---	---	---	anorthosite
San Gabriel Range (2) California, U.S.A.	unnamed oxide bodies	titanomagnetite-ilmenite	4.8	12	---	pyroxenite/ferrodiorite/anorthosite
Duluth Complex (3) Minnesota, U.S.A.	Section 17	ilmenite-titanomagnetite	---	---	---	pyroxenite/peridotite/troctolite
	Longear	ilmenite-titanomagnetite	---	---	---	pyroxenite /troctolite
	Longnose	ilmenite-titanomagnetite	50	21	---	pyroxenite/peridotite/dunite/troctolite
	Wyman Creek	ilmenite-titanomagnetite	---	---	---	pyroxenite/peridotite/troctolite
	Skibo	ilmenite (+ sulfides-graphite)	---	---	---	dunite/peridotite/troctolite
	Section 22	ilmenite-titanomagnetite	---	---	---	picrite/peridotite/troctolite
	Water Hen	ilmenite (+ sulfides-graphite)	62	14	---	picrite/peridotite/troctolite
	Section 34	titanomagnetite-ilmenite	---	---	---	peridotite/pyroxenite/anorthosite/troctolite
	Boulder Creek	titanomagnetite-ilmenite	---	---	---	peridotite/picrate/dunite/troctolite
	Boulder Lake North	ilmenite-magnetite-apatite	---	---	---	peridotite/pyroxenite/anorthosite/troctolite
	Boulder Lake South	ilmenite-apatite	---	---	---	peridotite/pyroxenite/troctolite
	Sanford Lake district (four deposits)	titanomagnetite-ilmenite (+ apatite)	8.6	35	---	gabbro/anorthosite
	Piney River district	ilmenite-apatite	---	---	---	ferrodiorite/nelsonite/anorthosite
	Rivière Pentecôte	titanomagnetite-ilmenite (+ sulfides)	---	---	---	anorthosite
Lac Saint-Jean (7) Quebec, Canada	Saint-Charles	titanomagnetite-ilmenite-apatite	5.4	10.1	29.5	anorthosite
	La Hache-Est	titanomagnetite-ilmenite-apatite	20.3	5.12	24.75	anorthosite
	Buttercup	titanomagnetite-ilmenite-apatite	3.5	19	49	leuconorite/leucogabbro/nelsonite
	Lac à Paul	ilmenite-apatite	348	8.4		anorthosite/leuconorite/nelsonite
Morin (8) Quebec, Canada	Desgrobois	titanomagnetite-ilmenite	5	11	40.8	anorthosite

6 A Deposit Model for Magmatic Iron-Titanium-Oxide Deposits Related to Proterozoic Massif Anorthosite Plutonic Suites

Table 1. Selected Proterozoic massif anorthosite suites and contained magmatic iron-titanium-oxide deposits or districts with multiple deposits.—Continued

[Numbers in parentheses given to the 15 listed anorthosite suites correspond to numbers applied to anorthosite suite locations in figure 1. The name of the anorthosite suite, deposit mineralogy, resource, and host rock information are compiled from Towner and others (1988), Force (1991), Ashwal (1993), Duchesne and Schiellerup (2001), Severson and others (2002), Hébert and others (2005), U.S. Geological Survey (2005), Gross (1996), Corriveau and others (2007), von Seckendorff and others (2000), and Arianne Resources (2012). Resources are in millions of tons (Mt) and TiO₂ and Fe grades are in weight percent]

Anorthosite suite	Oxide deposit or district name	Ore mineralogy	Resources Mt	Grade TiO ₂	Grade Fe	Host and related rocks
Morin (8) Quebec, Canada	Ivry	hemo-ilmenite	0.16	33.23	42.5	anorthosite
	Saint-Hippolyte	titanomagnetite-ilmenite	10	20	27	anorthosite
Havre-Saint-Pierre (9) Quebec, Canada	Grader	hemo-ilmenite-apatite	7.62	32	36.9	anorthosite
	Lac Tio (Allard Lake; Lac Allard)	hemo-ilmenite	125	34.2	38.8	anorthosite
	Everett (Puyjalon)	ilmenite-magnetite-apatite	294	9.75	16.2	anorthosite
	Big Island	hemo-ilmenite (+ rutile + sapphirine)	---	---	---	anorthosite
	Mills	hemo-ilmenite	---	---	---	anorthosite
	Magpie Mountain (four deposits)	ilmenite-magnetite-apatite	1,500	10.9	56	oxide gabbro/leuconorite
La Fournier (10) Quebec, Canada	Furnace	hemo-ilmenite	2	37	26	anorthosite
	Seminaire	hemo-ilmenite (+ rutile)	---	---	---	anorthosite
	Coulombe East & West	hemo-ilmenite (+ rutile + sapphirine)	6.71	39	36	anorthosite
	General Electric	hemo-ilmenite (+ rutile)	6.5	29.2	37.3	anorthosite
	Bignel	hemo-ilmenite-apatite (+ rutile)	2.5	36.4	35.7	anorthosite
	Glen	hemo-ilmenite	---	---	---	anorthosite
	Dupont	hemo-ilmenite	2.27	33.6	31.1	anorthosite
	Bouchard	hemo-ilmenite-apatite	---	---	---	anorthosite
	Lac Brûlé	hemo-ilmenite	5.8	35	43	anorthosite
Labrieville (12) Quebec, Canada						
La Blache (13) Quebec, Canada	Hervieux East	ilmenite-magnetite-ulvöspinel	---	---	---	anorthosite
	Hervieux West	ilmenite-magnetite-ulvöspinel	71.7	20.1	48	anorthosite
	Schmoo	ilmenite-magnetite-ulvöspinel	---	---	---	anorthosite
	Lac Dissimieu	ilmenite-apatite	235	45	---	anorthosite
Åna-Sira (14) Norway	Tellnes	hemo-ilmenite	380	18.4	1	norite/anorthosite
	Blåfjell	hemo-ilmenite (+ magnetite-apatite)	---	---	---	pegmatitic norite/anorthosite
	Storgangen	hemo-ilmenite (+ magnetite)	70	19.6	---	leuconortite/norite/anorthosite
	Flordalen	hemo-ilmenite	---	---	---	anorthosite
	Frøytlog	hemo-ilmenite (+ trace magnetite)	---	---	---	anorthosite
Kunene (15) Namibia	unnamed oxide bodies	titanomagneite-ilmenite	---	---	---	anorthosite

suggest intrusion of oxide-bearing units into older anorthosite host rocks. In contrast, conformable oxide concentrations in gabbro and layered rocks related to anorthosite indicate an origin by crystal settling and accumulation. Both discordant and conformable styles can be found together in composite anorthosite suites.

Principal ore minerals are ilmenite, hemo-ilmenite, and titanomagnetite; titaniferous magnetite is a general term applied to granule aggregations of ilmenite (typically formed by oxidation of ulvöspinel), magnetite, hematite, and titanomagnetite (Krause and others, 1985; Gross, 1996). Magmatic Fe-Ti-oxide deposits related to anorthosites are classified based upon orebody mineralogy (see for example, Duchesne, 1999; Hébert and others, 2005; Corriveau and others, 2007) and host rock composition (see for example, Force, 1991; Gross, 1996). The two currently economic deposits are Lac Tio in Quebec, Canada, and Tellnes in Norway. Lac Tio consists of massive hemo-ilmenite in anorthosite with andesine-type plagioclase; Tellnes is dominantly hemo-ilmenite hosted by a norite dike-shaped body cutting andesine-type anorthosite. Deposits with a mineral assemblage of titanomagnetite+ilmenite±apatite, more commonly hosted by anorthosite with labradorite-type plagioclase or in related gabbro and norite, are less economic for Ti, although deposits with abundant apatite may contain an economic phosphorus (P) or rare earth element (REE) resource (Hébert and others, 2005). Massive titanomagnetite+ilmenite-oxide deposits, thought to be derived from late-stage residual melts from anorthosite, occur in troctolite and olivine gabbro in the Laramie Range anorthosite complex (Mitchell and others, 1996). A recently recognized potentially important resource for Ti is ilmenite-dominated deposits in ultramafic plugs cutting troctolite in the Duluth Complex of northern Minnesota (Hauck and others, 1997).

A single complex anorthosite suite composed of multiple anorthosite lobes with varying ages and plagioclase compositions can host differing styles of Fe-Ti-oxide mineralization. For example, seven separate anorthosite lobes have been recognized in the Havre-Saint-Pierre anorthosite suite, Quebec (Gobeil and others, 2003). The 1139 to 1129 Ma (Wodicka and others, 2003) labradorite-type Rivière Sheldrake anorthosite lobe has non-economic concentrations of massive titaniferous magnetite. In contrast, the 1061 Ma (Morisset and others, 2009) andesine-type Allard Lake anorthosite lobe (also referred to as the Lac Allard anorthosite in the literature) hosts numerous hemo-ilmenite deposits (for example, Lac Tio) and ilmenite-magnetite-apatite deposits (for example, Everett) (Perreault, 2003). This contrast in both plagioclase composition and related Fe-Ti oxides over a time span of about 60 million years likely reflects the tectonic and magmatic evolution of the Grenville Province (Morisset and others, 2009).

It is generally accepted that Fe-Ti-oxide deposits are magmatic in origin, but questions remain about the magmatic processes creating Ti-enriched oxide accumulations in economic quantities. Current genetic models rely on combinations of fractional crystallization, mineral accumulation and density

separation processes, dynamic magma chamber replenishment and mixing mechanisms, multiple pulses of magma flowing through restricted conduit systems, and formation and mobilization of late-stage residual liquids (see for example, Duchesne and Schiellerup, 2001; Dymek and Owens, 2001; Charlier and others, 2006; Charlier and others, 2010; Morisset and others, 2010).

Deposits dominated by hemo-ilmenite may represent accumulations resulting from fractional crystallization of TiO₂-rich magma with ilmenite as an early liquidus mineral. Segregation and emplacement of these early ilmenite-laden liquids are likely related to dynamic crystallization and emplacement of massive anorthosite (Duchesne and Schiellerup, 2001; Charlier and others, 2006). An assemblage of titanomagnetite+ilmenite±apatite can form primary massive layers in labradorite-type anorthosite or weakly discordant magnetite- and oxide-rich leuconorite dikes emplaced roughly parallel to regional tectonic fabric in anorthosite (Dymek and Owens, 2001). These deposits may represent concentration of Fe, Ti, and P in residual magmas. In contrast, a nelsonite layer of primarily ilmenite and apatite (with minor plagioclase) in the Grader layered intrusion, Quebec, probably has a cumulate origin (Charlier and others, 2010). Thus, the timing and nature of oxide saturation in a crystallizing magma will determine the type and style of oxide mineralization.

Associated and Transitional Deposit Types

Stratiform Mafic-Ultramafic Iron-Titanium-Vanadium Deposits

Variants of magmatic Fe-Ti-oxide deposits are large stratiform Fe-Ti-V deposits that are hosted worldwide in the upper parts of large repetitively layered mafic-ultramafic intrusions. We define these as a distinct deposit type not included in this present deposit-model description. Examples include the Bushveld Complex, South Africa (McCarthy and Cawthorn, 1983) and the Sept-Îles layered intrusion, Quebec (Namur and others, 2010). These deposits typically comprise concordant, laterally continuous magnetite-rich layers ranging in thickness from centimeters to meters. The Sept-Îles layered intrusion also contains significant horizons of nelsonite (Namur and others, 2010). Major differences between magmatic Fe-Ti oxides related to (a) Proterozoic massif anorthosite plutonic suites, which may include layered intrusions and (b) stratiform Fe-Ti-V-oxide deposits include one or more of the following: (1) a more typical form of host plutonic rocks (for example (a) massive domical intrusions and related layered intrusions versus (b) large, repetitively layered intrusions); (2) major mineralogy of the deposits (for example, (a) ilmenite-dominated versus (b) magnetite-dominated); (3) plagioclase composition of related anorthosite (for example, (a) labradorite-andesine versus (b) bytownite-anorthite); (4) magmatic crystallization sequence (for example, (a) ilmenite as an early liquidus

mineral versus (b) magnetite as a late-stage residual mineral); and (5) age distribution (for example, (a) Proterozoic age versus (b) no apparent geologic age restrictions).

Nickel-Copper-Magmatic Sulfide Deposits

Nickel-copper (Ni-Cu) sulfides occur in small quantities in a number of magmatic Fe-Ti-oxide deposits and related gabbro-anorthosite rocks. Significant disseminated Ni-Cu mineralization occurs with OUIs in the Duluth Complex (Ripley, 1986), in several noritic intrusions in the Rogaland Province (Schiellerup and others, 2003), and in pyroxenite and melanorite of the Nord-Ouest anorthosite massif, Havre-Saint-Pierre anorthosite suite (Perreault, 2003). Discovery of Ni-Cu deposits at Voisey's Bay in a Proterozoic anorthosite suite within the Nain Complex of Labrador, and recognition that sulfides in that deposit were concentrated by dynamic fluid processes in magma conduits (see for example, Evans-Lamswood and others, 2000), suggests genetic parallels to proposed concentration of ilmenite in dynamic magma settings by similar processes (see for example, Charlier and others, 2010; Morisset and others, 2010). Based on observations from the Voisey's Bay deposits, Kerr and Ryan (2000) suggest that anorthosite-hosted massive Ni- and Cu-bearing sulfide mineralization can be viewed as part of a spectrum of magma processes in which metal-bearing liquids are introduced by mafic magmas but separated from host magmas to variable degrees. Factors that may drive magmatism toward sulfide mineralization rather than oxide mineralization may be related to parent magma compositions, depth of fractionation and subsequent separation of plagioclase and mafic minerals and residual melt, and possible magma contamination by sulfide-bearing country rock (Kerr and Ryan, 2000).

Contact Metasomatic Rutile with Alkalic Anorthosite

Iron-Ti-oxide mineralization can be present in skarn rock and alteration zones near the contact of ilmenite-bearing anorthosite and country rocks. The Roseland district, Virginia, contains magmatic ilmenite in dike-like bodies cutting anorthosite and contact metasomatic rutile developed in country rocks cut by swarms of anorthosite dikes (Herz and Force, 1987). The presence of rutile with ilmenite in highly metamorphosed rocks, including alkali anorthosite, near the town of Pluma Hidalgo, Mexico, is similar to the Roseland rutile occurrence suggesting a possible similar contact metasomatic origin (Paulson, 1964; Force, 1991).

Heavy-Mineral Deposits

Much of the high-grade ilmenite and rutile used today is extracted from heavy-mineral deposits in unconsolidated shoreline placers and dunes and older equivalents. Deposits develop when relatively resistant Ti-bearing and other heavy

minerals are eroded from oxide-bearing parent rocks, subsequently transported, sorted, and finally deposited in fluvial, alluvial, or eolian settings. Many productive heavy-mineral provinces, such as the east coast of the United States, the west coast of South Africa, and both the east and west coasts of Australia, are located on trailing continental margins usually backed by elevated, often highly weathered, high-grade metamorphic or mafic igneous hinterlands (Force, 1991). Terranes that have prominent anorthosite and gabbro intrusions hosting Fe-Ti-oxide deposits can be an important source for heavy-mineral placer systems (Gross, 1996). An example is a large heavy-mineral deposit in deltaic sands of the Natashquan River on the north shore of the Saint Lawrence River in Quebec (Gauthier, 2003).

Primary Commodities

Titanium is the primary economic commodity from hemo-ilmenite deposits, with Fe commonly occurring as a co-product, particularly from deposits that also contain titanomagnetite and magnetite. Ilmenite deposits typically have 10- to 75-percent TiO_2 , 41- to 58-percent FeO, and less than 0.2-percent vanadium (V) (Gross, 1996). Titaniferous magnetite at the Sanford Hill/South Extension deposit in New York, also referred to as the McIntyre mine, was an early Fe resource before the presence of Ti was recognized (Gross, 1968). In the mid-1880s, a number of small mines in the Rogaland Province shut down when the high Ti content of ore limited the value of extracted Fe (Schiellerup and others, 2003). Currently titaniferous magnetite is thought to be objectionably high in Ti for iron ore, yet too low in Ti for titanium ore; however, if metallurgical problems with extraction and separation could be resolved, then deposits containing very large reserves of titaniferous magnetite could become economically viable for both elements (Rose, 1969).

Some deposits also have significant phosphate (P_2O_5) potential from apatite-bearing oxide-rich rock related to anorthositic rocks. The Lac à Paul deposit, in the Lac Saint-Jean anorthosite complex, Quebec, contains numerous layers with abundant apatite-ilmenite (nelsonite), olivine, and magnetite in anorthosite, norite, and leuconorite. The deposit has indicated resources of 348 Mt with 6.5-percent P_2O_5 and 8.4-percent TiO_2 (Arianne Resources, 2012). Phosphate resources reported for other Fe-Ti-oxide deposits in the Lac Saint-Jean anorthosite complex are 5.4 Mt with 9.25-percent P_2O_5 for the Saint-Charles deposit and 20.3 Mt with 5.2-percent P_2O_5 for the La Hache-Est deposit; the Everett (Lac Puyjalon) deposit in the Havre-Saint-Pierre anorthosite suite has 294 Mt with 4.0-percent P_2O_5 (Corriveau and others, 2007).

Byproduct Commodities

Byproducts from the Tellnes deposit include Ni and Cu from trace amounts of sulfides and V from magnetite (Schiellerup and others, 2003). Vanadium (as V_2O_5) and chromium

(Cr) are reported as potential byproduct commodities for a number of deposits in the Grenville Province of Quebec, including 5.4 Mt with 0.1-percent V_2O_5 at the Saint-Charles deposit, 3.5 Mt with 0.67-percent V_2O_5 at the Buttercup deposit, and 810 Mt with 0.2-percent V_2O_5 and 1.55-percent Cr for the Magpie Mountain deposits (Corriveau and others, 2007).

Example Deposits

In general, Fe-Ti-oxide deposits occur as discordant tabular intrusions, lenses, sills, or dikes emplaced into anorthosite massifs. In layered segments of anorthosite massifs or in related layered mafic intrusions, oxide mineralization can be weakly concordant or stratiform. Hemo-ilmenite is the ore mineral at the two currently active mines, Lac Tio in Quebec, Canada, and Tellnes in Norway. The Lac Tio deposit, hosted within the Allard Lake anorthosite in the Havre-Saint-Pierre plutonic suite in the Grenville Province, is estimated to contain more than 52 Mt of proven and probable reserves of titanium dioxide (Rio Tinto, 2011). The ore averages 34.2-percent TiO_2 as ilmenite and 27.5-percent FeO, 25.2-percent Fe_2O_3 , and 3.1-percent magnesium oxide (MgO) (Gross, 1996). Tellnes, a hemo-ilmenite-bearing norite body cutting the Åna-Sira anorthosite in the Rogaland Province, has ore reserves estimated to be 380 Mt averaging about 18-percent TiO_2 as ilmenite and 2-percent FeO as magnetite (Gross, 1996; Schiellerup and others, 2003). Titanium deposits in the entire Duluth Complex may represent the largest known resource of Ti in North America (Ulland, 2000). Hauck and others (1997) estimate that the Duluth Complex may contain as much as 245 Mt of >10-percent TiO_2 in numerous deposits (fig. 4). The four mineralized deposits in the Sanford Lake district in western New York (Sanford Hill/South Extension, Cheney Pond, Mt. Adams, and Upper Works) are dominated by titaniferous magnetite in gabbro and anorthosite and contain between 9.5- to 30-percent TiO_2 (Gross, 1968; table 1). The Big Island massive hemo-ilmenite dike, cross-cutting the Allard Lake anorthosite body in the Havre-Saint-Pierre anorthosite suite, can contain as much as 15-modal-percent magmatic rutile; assays give values of 40.3-percent TiO_2 , 26-percent FeO, and 21.1-percent Fe_2O_3 (Perreault, 2003; Morisset and others, 2010). The Magpie Mountain deposits, consisting of massive titanomagnetite hosted in gabbro, is one of the largest titanomagnetite resources in the Grenville Province with resource estimates greater than 1,500 Mt with 56-percent FeO and 10.9-percent TiO_2 (Gross, 1996).

Important Deposits

- Lac Tio, Quebec, Canada (Hammond, 1952; Charlier and others, 2010) (in production)
- Tellnes, Norway (Krause and others, 1985; Duchesne and Schiellerup, 2001) (in production)

- Sanford Hill/South Extension, New York, United States (Gross, 1968) (now closed)
- Longnose and Water Hen, Minnesota, United States (Severson, 1995; Hauck and others, 1997) (speculative)
- Lac à Paul, Quebec, Canada (Arianne Resources, 2012) (speculative)

Historical Evolution of Descriptive and Genetic Knowledge and Concepts

The origin of magmatic Fe-Ti-oxide deposits is obscured by their relative paucity and their problematic relation to their enigmatic anorthositic host rocks. It has long been recognized that these deposits had a magmatic origin, and originally it was hypothesized that they formed either from accumulation of oxide minerals in magma or by immiscibility between Fe-Ti±P liquids and silicate liquids (for example, Lister, 1966; Philpotts, 1967; Kolker, 1982; Force, 1991). However, experimental results have not successfully replicated any combination of possible Fe-Ti±P melts at reasonable magmatic temperatures, and it seems inescapable that liquid immiscibility as an explanation for the development of these deposits is not geologically viable (Lindsley, 2003; Tollari and others, 2006). More recent work, including detailed trace-element analyses, stable and radiogenic isotopic work, and precise geochronology, supports formation by physical and chemical magmatic processes (see for example, Duchesne, 1999; Dymek and Owens, 2001; Charlier and others 2006; Charlier and others, 2010; Morisset and others, 2010).

Petrologic questions regarding the origin of anorthosite massifs and related rocks, such as jotunite, charnockite, and oxide-rich rock, continue to be thoroughly debated (see for example, Ashwal, 1993; Vander Auwera and others, 2000; Seifert and others, 2010). The combination of accumulation processes, magma mixing, fractional crystallization, solid-state remobilization, and cotectic crystallization necessary to form the immense ilmenite-dominated deposits of Lac Tio and Tellnes remain to be resolved (Charlier and others, 2006). Dynamic emplacement mechanisms involving multiple pulses of crystal-laden magma flowing through restricted conduit systems, as suggested for major Ni-Cu deposits such as Voisey's Bay (see for example, Evans-Lamswood and others, 2000), have recently been invoked to explain the high hemo-ilmenite concentrations in the Tellnes and Lac Tio deposits (Wilmart and others, 1989; Charlier and others, 2010).

Interaction with crustal rocks also plays an important role in anorthosite development. Assimilation prior, during, and following differentiation and diapiric uprise of plagioclase-bearing magmatic mush will influence oxygen fugacity and silica activity of anorthosite parent magmas and thus play a critical role controlling oxide mineralogy (Morse, 2006; Frost

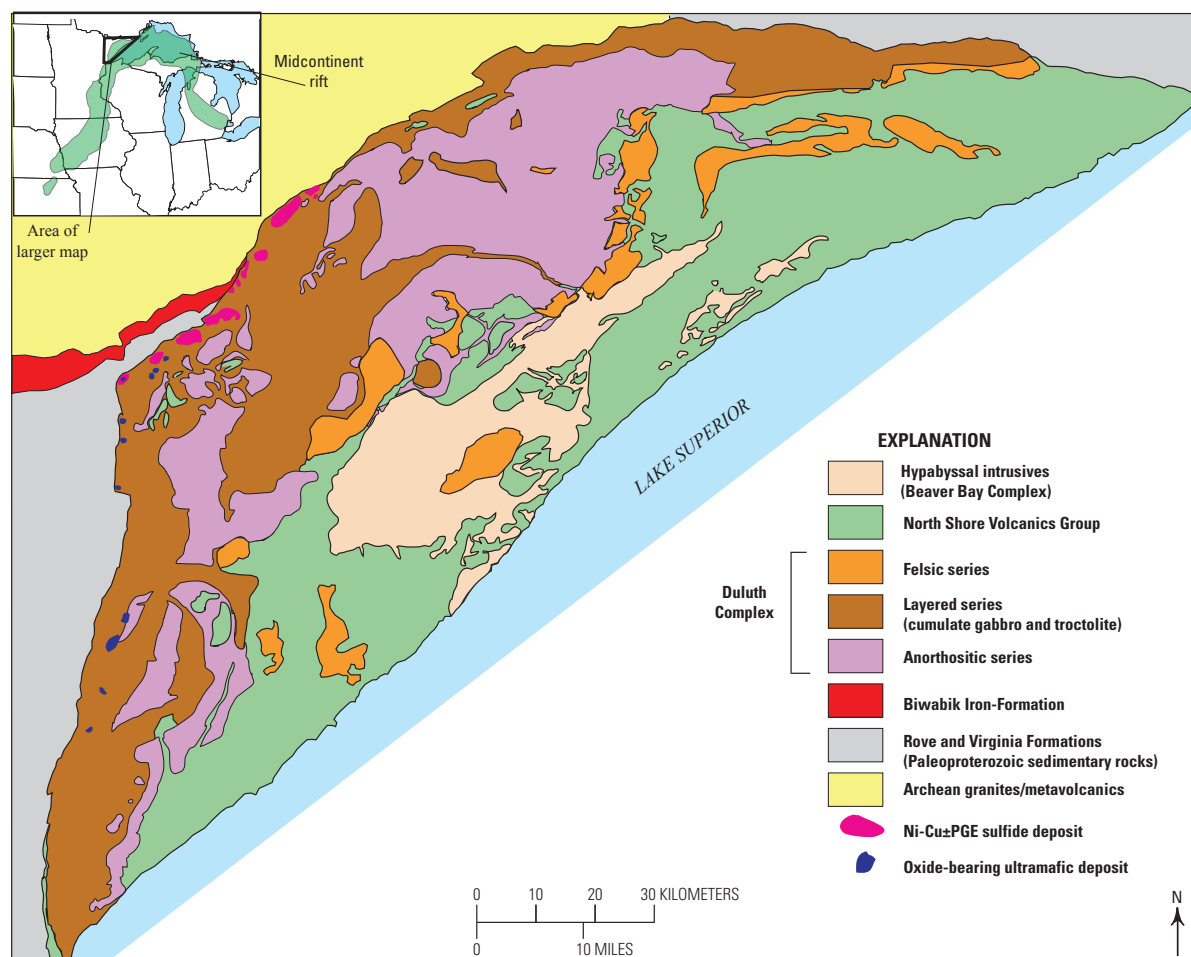


Figure 4. Simplified geologic map of the Duluth Complex, Minnesota (modified from Hauck and others, 1997). The basal part of the complex contains world-class nickel-copper±platinum group elements (Ni-Cu±PGE) deposits (shown in pink) and numerous Fe-Ti-oxide-bearing ultramafic deposits (shown in dark blue).

and others, 2010). Assimilation of silica-rich rocks by ascending and differentiating mafic magma can increase oxygen fugacity (fig. 5), consuming magnetite and making ilmenite more abundant as well as increasing the hematite component of ilmenite (Frost and others, 2010). The control exerted by redox conditions and silica activity corroborates observations by Anderson and Morin (1969) of the dominance of titaniferous magnetite in labradorite-type anorthosite plutons versus the dominance of hemo-ilmenite in andesine-type anorthosite plutons.

Regional Environment

Geotectonic Environment and Magmatic Temporal Relations

Economic magmatic Fe-Ti-oxide deposits have spatial and temporal associations with massif-type anorthosite suites, which are found in Proterozoic rocks on all continents

(Anderson, 1969; Ashwal, 1993). The time span during which massif-type anorthosite formed is largely restricted from about 930 Ma (Rogaland, Norway; Schärer and others, 1996) to about 2120 Ma (Labrador, Canada; Hamilton and others, 1998), but most anorthosite suites were emplaced between about 1800 and 1060 Ma (Ashwal, 2010). A long-lived, geologically active geotectonic setting operating over length scales of several thousand kilometers seems to be a critical favorable factor for development of massif-type anorthosite suites permissive for economic magmatic Fe-Ti-oxide deposits (Rivers, 1997; Morse, 2006; Ashwal, 2010).

There is now an apparent consensus on a general tectonic evolution of the Grenville Province that favors an accretionary model rather than a plume model (see for example, Rivers, 1997; Morse, 2006; Ashwal, 2010; McLelland and others, 2010; Hynes and Rivers, 2010). Main crustal build-up of the Grenville Province occurred through Andean-type continental arc and intercontinental back-arc magmatism with additional accretion of magmatic arcs followed by post-collisional replacement of mantle lithosphere by asthenosphere, perhaps by delamination or convective thinning.

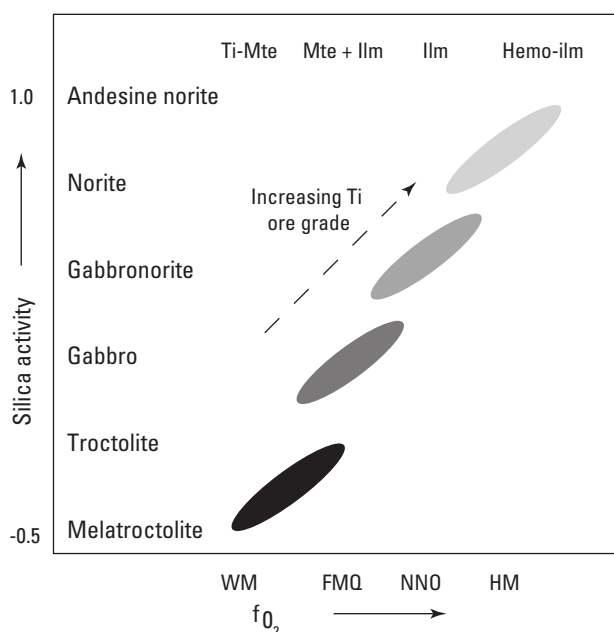


Figure 5. Classification of rock association and iron-titanium-oxide (Fe-Ti-oxide) mineralogy for massif anorthosite based on silica activity and oxygen fugacity for idealized lithologies (modified from Morse, 2006). The anticipated oxide mineralogy is given along the top: Ti-Mte = titanomagnetite; Ilm = ilmenite; Hemo-ilm = hemo-ilmenite. Oxygen fugacity (f_{O_2}) buffers are indicated semi-quantitatively along the bottom axis: WM = wüstite-magnetite; FMQ = fayalite-magnetite-quartz; NNO = nickel-nickel oxide; HM = magnetite-hematite. The dashed arrow indicates a trend of increasing titanium-ore grade for potential Fe-Ti-oxide deposits.

Rivers (1997) suggests that anorthosite complexes in the Grenville Province were emplaced in two contrasting extensional environments: (1) areas of backarc extension inboard from an active continental-margin magmatic arc and (2) within a collisional orogen during periods of tectonic collapse and rising isotherms. During such periods of extension, hot mantle lithosphere would have had access to the base of a previously thickened continental crust (Rivers, 1997). The ultimate source of anorthosite and related rock types is thought to be related to decompression melting of asthenospheric mantle (referred to as lithospheric delamination; Emslie, 1978; Corrigan and Hanmer, 1997; McLelland and others, 2010) or delamination-related melting of lower crustal material underthrust into the mantle at depths greater than 40 km (referred to as the crustal-tongue model; Duchesne and others, 1999; Longhi and others, 1999) producing mafic magmas that would pond at the base of the crust.

Morse (2006) suggests that restricted time constraints for anorthosite development were imposed by a continental lithosphere that was just thick enough to suppress volcanism and to permit failed rifting that trapped magma capable of generating anorthosite at depth. Vander Auwera and others (2011) propose a model for anorthosite generation requiring a balance between sufficiently high mantle temperatures and availability of subducted continental crust for partial melting. They hypothesized that an ideal combination of these two factors occurred only during the Proterozoic, thus restricting the anorthosite time window.

For Fe-Ti-oxide deposits in Proterozoic massif-type anorthosite in the Grenville Province, further age and mineralogical generalizations are given in Hébert and others (2005): (1) labradorite-type massif anorthosite is associated with gabbro and occurs only in plutons older than 1130 Ma, and Fe-Ti oxides in these rocks are dominantly titaniferous magnetite; (2) ages for andesine-type massif anorthosite are younger than

1160-Ma, although this generalization is complicated by the 1354-Ma Rivière-Pentecôte anorthosite, Quebec, that has both labradorite- and andesine-type anorthosite; and (3) no massive hemo-ilmenite deposits are known in anorthositic plutons older than 1160 Ma.

The Havre-Saint-Pierre anorthosite suite is a microcosm for these observations by Hébert and others (2005). In the Havre-Saint-Pierre anorthosite suite, older (about 1139 to 1129 Ma) labradorite-type anorthosite contains abundant titaniferous magnetite and younger (about 1056 to 1045 Ma) andesine-type anorthosite contains abundant hemo-ilmenite (Wodicka and others, 2003; Perreault, 2003; Morisset and others, 2009).

Temporal (Secular) Relations of Oxides to Host Rocks

Typically, massive Fe-Ti-oxide ore has sharp, cross-cutting contacts with its anorthositic host forming lenses tens to hundreds of meters wide and several hundred meters long. Massive ore also may have apophyses cutting host rock, be associated with intrusive breccias, and contain anorthositic xenoliths, all of which suggest that oxide deposits postdate host anorthosite intrusion. A zircon uranium-lead (U-Pb) age for the Åna-Sira anorthosite host to the Tellnes deposit is 931 ± 2 Ma, whereas a zircon age for the deposit itself is 920 ± 3 Ma, suggesting a 10 million-year gap between anorthosite intrusion and injection of the hemo-ilmenite-bearing norite dike (Schärer and others, 1996). However, based on more recent detailed petrologic and geochemical research on ilmenite-zircon relations at Tellnes, Charlier and others (2007) suggest the younger age may have been influenced by late-stage interstitial crystallization and exsolution of zircon from ilmenite rather than be indicative of the age of ore formation. They conclude that the hemo-ilmenite-bearing norite is only

marginally younger than enclosing host anorthosite. This relation would thus link massive oxide deposition more closely to the magmatic processes responsible for the anorthosite host. The Big Island massive Fe-Ti-oxide dike that cross-cuts the Allard Lake anorthosite has overlapping ages for oxide and host rock. The Big Island dike is dated at 1052.9 ± 6.5 Ma, and its anorthosite host has an age of 1057.4 ± 5.7 Ma (Morisset and others, 2009). This overlap in ages also suggests a close link between processes of ore formation and the dynamics of anorthosite intrusion.

In layered intrusions, including the Bjerkreim-Sokndal intrusion in the Rogaland Anorthosite Province (Wilson and others, 1996), the Sybille monzonite in the Laramie Range anorthosite complex (Scoates and others, 1996), and the Grader layered intrusion (Charlier and others, 2008), Fe-Ti oxides crystallized contemporaneously with host rock. In the Duluth Complex, the OUIs that intrude troctolite are interpreted to represent late-stage residual magmatic liquids (Hauck and others, 1997). Contact relations of the OUI body at Water Hen suggest emplacement of the main OUI body before its troctolite host had fully crystallized (Severson, 1995).

Relations to Structures

Emplacement of a number of anorthosite complexes may be related to large crustal zones of weakness and lithospheric-scale discontinuities (Emslie and others, 1994; Scoates and Chamberlain, 1997; Duchesne and others, 1999). In the Grenville Province, some ilmenite-rich deposits formed in anorthosite intrusions located along deep-seated fault zones at the margins of major tectonic provinces and belts (Gross, 1996).

Relations to Igneous Rocks

Magmatic Fe-Ti-oxide deposits are related to igneous rocks simply by definition of the ore type. The fundamental constraint on where these deposits occur is a specific association with Proterozoic massif anorthosite and related rock types. The geotectonic spatial and temporal setting favorable for formation of these rock types apparently resulted in formation of distinct magmas enriched in Ti and Fe, and subsequent magmatic processes controlled crystallization and concentration of ilmenite- or titanomagnetite-dominated orebodies.

Relations to Metamorphic Rocks

Massif anorthosites display a wide range of metamorphic grades, from strongly metamorphosed (for example, Marcy Anorthosite, Adirondacks, New York) to essentially unmetamorphosed (for example, Åna-Sira anorthosite, Norway). In the Adirondacks, anorthosite and related rocks were emplaced in mid- to upper-crustal levels between 1175–1155 Ma producing low-pressure contact metamorphism in country rocks

(Valley and Essene, 1980; Valley, 1985). In turn, contact metamorphism was overprinted by high-pressure, high-temperature granulite-grade regional metamorphism during the Grenville orogeny, which had its metamorphic peak at about 1050–1040 Ma (McLelland and others, 1996). Country rocks for the Morin and Lac Saint-Jean anorthosite suites, Quebec, were strongly metamorphosed prior to anorthosite emplacement; surrounding country rock and the Havre-Saint-Pierre suite were strongly metamorphosed after anorthosite emplacement (Corriveau and others, 2007). Thus, as supported by highly variable field relations to metamorphic rocks, metamorphism has no role in development of magmatic Fe-Ti-oxide deposits.

Relations to Sedimentary Rocks

Sedimentary rocks are not genetically related to Fe-Ti-oxide deposits hosted by rocks of Proterozoic massif anorthosite plutonic suites. Many Proterozoic sedimentary or metasedimentary rock lithologies can act as country rocks to ore-related plutonic suites.

Physical Description of Deposit

Dimensions in Plan View

Magmatic Fe-Ti-oxide bodies are highly variable in size and shape reflecting diverse magmatic and physical processes that lead to their development. The Lac Tio deposit is made up of three orebodies, the Main deposit, the Northwest deposit, and the Cliff deposit (fig. 6) (Perreault, 2003). The Main deposit is an equant tabular sheet, 1,097 m by 1,036 m with an estimated thickness of 110 m inclined about 10° to the east. The Northwest deposit, separated from the Main deposit by a late normal fault, forms a band of massive ilmenite alternating with anorthosite that varies from 7 to 60 m in thickness, inclined gently to the east. The Cliff orebody is roughly elliptical in plan, about 380 m by 230 m and 60 m thick (Hammond, 1952).

In the Rogaland Province, discordant Fe-Ti-oxide deposits occur as dikes, pods, veins, or stockworks in anorthosite (Krause and others, 1985) (fig. 3). The Tellnes orebody is within a sickle-shaped, hemo-ilmenite-bearing norite, dike-shaped intrusion more than 2.5 km long and 400 m thick, extending on both ends into a 5- to 10-m-thick jotunite dike (Wilmart and others, 1989) (fig. 7). The Blåfjell deposit is made up of several irregularly shaped bodies that are as much as 15 m thick and 55 m long (Krause and others, 1985). The Storgangen orebody is a dike with numerous offshoots extending about 4 km in a wide arch cutting the Åna-Sira anorthosite with thickness varying between several meters to about 50 m in the center (Krause and others, 1985).

Small OUIs within the Duluth Complex are irregular pipe-like bodies. Diamond drilling at the Longnose deposit indicates a roughly elliptical orebody, 700 m by 600 m and

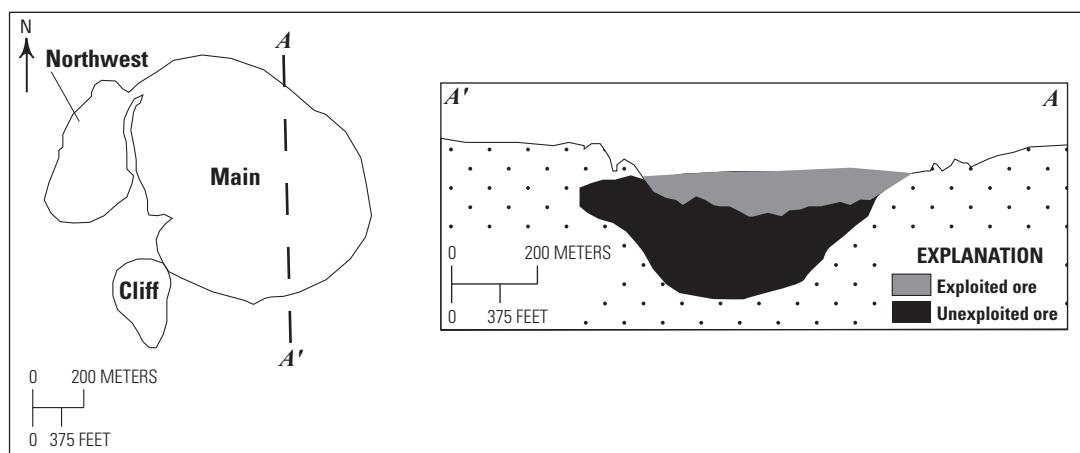


Figure 6. Surface outline of the three main orebodies at the Lac Tio deposit, Quebec, Canada, and a north-south cross section of the Main orebody showing the reconstructed exploited ore removed from the open pit and remaining ore (modified from Charlier and others, 2010).

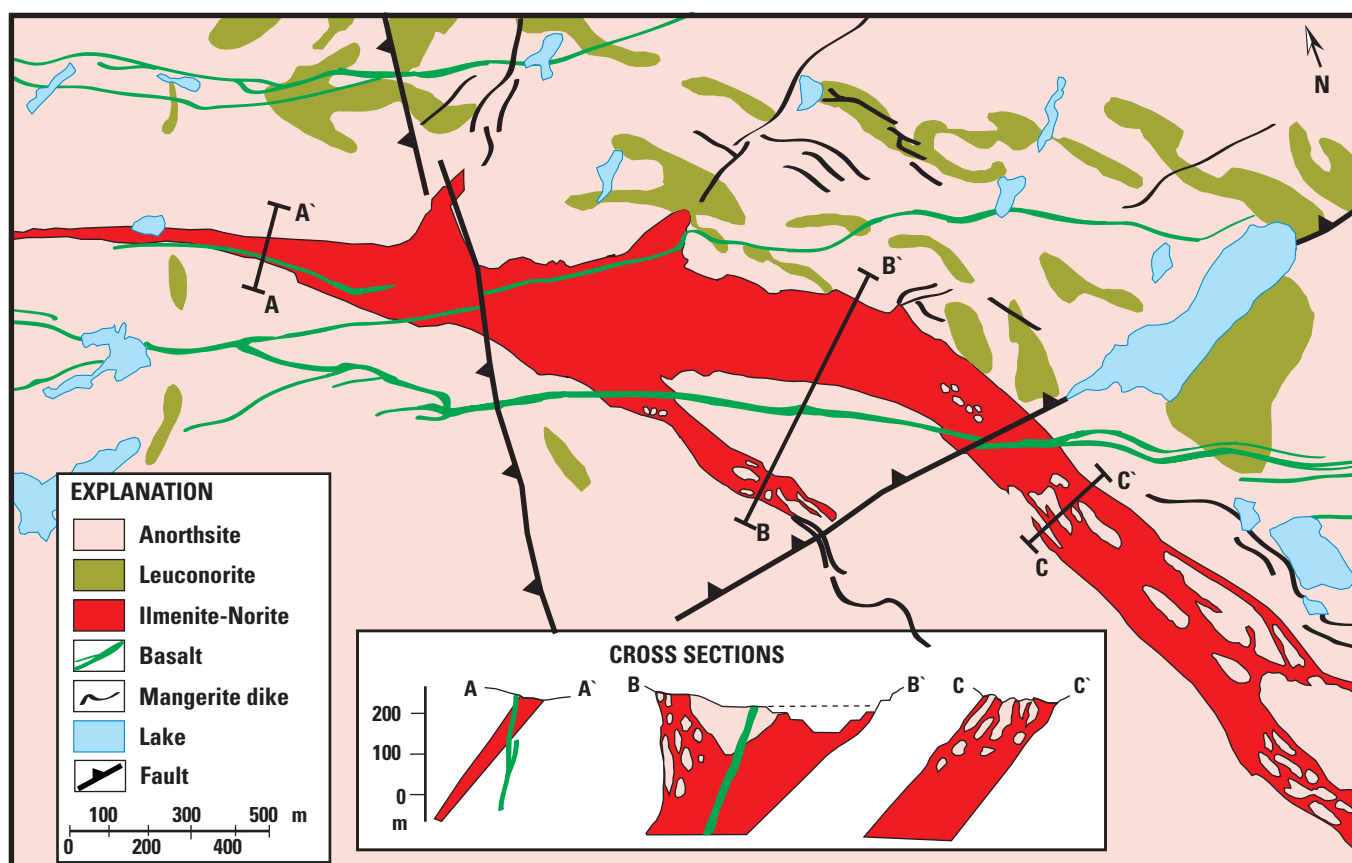


Figure 7. Simplified geologic map of the host Åna-Sira anorthosite, Norway, and location and three cross sections of the Tellnes ilmenite-norite orebody (modified from Krause and others, 1985).

about 150 m thick (Hauck and others, 1997). The Water Hen intrusion is about 490 m by 150 m by 210 m thick with ilmenite concentrations from 5 to 50 percent in various ultramafic lithologies (Strommer and others, 1990)

Size of Hydrothermal System Relative to Extent of Economically Mineralized Rock

Magmatic Fe-Ti-oxide deposits do not develop large hydrothermal systems; they are magmatic accumulations of ore minerals.

Vertical Extent

The vertical extent of Fe-Ti-ore deposits is as variable as their dimensions in plan view ranging in thickness from centimeters to hundreds of meters.

Form and Shape

Iron-Ti-oxide deposits are commonly discordant or weakly concordant within their host rocks and less commonly occur as conformable layers. Most deposits can be generally classified by form and shape into six groups: (1) flat-lying tabular bodies of large areal extent (for example, Lac Tio deposit), (2) steeply to shallowly dipping dike-like bodies

(for example, Tellnes deposit in a norite dike), (3) irregular lenticular masses and pods (for example, Furnace deposit), (4) elliptical plug-like pipes and bodies (for example, Longnose and Water Hen deposits), (5) oxide concentrations in cross-cutting pegmatitic dikes (for example, Blåfjell deposit), and (6) layered, stratiform, and concordant bodies (for example, the Grader deposit (a massive ilmenite deposit in the Grader layered intrusion that was mined in the late 1940s). Numerous Fe-Ti-oxide deposits in the Allard Lake anorthosite of the Havre-Saint-Pierre anorthosite suite display at least three of the form-shape groups listed above (Hammond, 1952). Deposits also can be deformed and remobilized by tectonic and metamorphic events (fig. 8). Deposits in the Sanford Lake district have multiple examples of varying forms and shapes (Gross, 1968). Deposits in the Duluth Complex are all plug-like in form with the exception of the Boulder Creek deposit that is stratabound (Hauck and others, 1997).

Host Rocks

Massif anorthosite and related rocks are the most important hosts for economic magmatic Fe-Ti-oxide deposits. In general, deposits dominated by hemo-ilmenite are hosted by andesine-type anorthosite and deposits dominated by titanomagnetite with ilmenite are hosted by labradorite-type anorthosite. Deposits with significant apatite can be hosted by a variety of rock types from oxide gabbro to nelsonite.



Figure 8. Deformed layers and remobilized veins of massive titaniferous magnetite and ilmenite and oxide-rich leucogabbro norite in labradorite-type anorthosite of the Rivière-au-Tonnerre Massif of the Havre-Saint-Pierre anorthosite suite, Quebec, Canada. Photograph provided by Serge Perreault, used with permission.

Structural Setting(s) and Control

The shape and orientation of some Fe-Ti-oxide deposits suggest mobilization of oxide minerals through magmatic conduits or zones of weakness within anorthosite host rocks. The Tellnes body is an ilmenite-bearing norite dike extending on both ends into a 15-km-long jotunite dike (Wilmart and others, 1989). Parallelism of magnetic foliation trajectories with the contacts of the Tellnes orebody and homogeneity of magnetic lineation pattern over the entire body strongly point to a fabric acquired during magma flow along a feeder zone from southwest to northwest (Diot and others, 2003). Diot and others (2003) suggest that magma injection at Tellnes was favored by a transcurrent, dextral opening of a west-northwest to east-southeast striking zone of weakness across the host Åna-Sira anorthosite when the host rock was somewhat brittle. However, this interpretation is disputed by Charlier and others (2006) who suggest that the Tellnes norite dike actually represents remnants of a sill deformed by ductile subsidence of the host Åna-Sira anorthosite.

Most OUIs in the Duluth Complex are spatially arranged along linear trends and are generally related to faults or are positioned in the immediate vicinity of fault zones. This suggests that structural control was important to their genesis (Hauck and others, 1997).

Geophysical Characteristics

Fe-Ti-oxide deposits have been exploited for a long time. Mining in the Rogaland Province began in 1785 (Duchesne and Schiellerup, 2001). Whereas many of these deposits were initially discovered through geological field mapping and

related exploration activities, geophysical methods are now widely applied to regional exploration in permissive terranes. The Tellnes deposit was discovered in 1954 by an aeromagnetic survey (Krause and others, 1985) as were extensions of known orebodies in the Grader layered intrusion (Charlier and others, 2008).

Magnetic Signatures

Aeromagnetic surveys have long been used in ilmenite exploration, although distinctive patterns for anomalies vary greatly. An underlying concept in aeromagnetic exploration rests on an assumption of a direct correlation between strong magnetic conductors and mineralization. However, most valuable Fe-Ti-oxide deposits contain ilmenite intergrown with hematite or ilmenite of a stoichiometric composition. Magnetite may be absent (for example, Blåfjell), occur only as a minor phase (for example, Tellnes), or be somewhat abundant in less economically attractive deposits (for example, Sanford Lake district). A scarcity of magnetite in the largest hemo-ilmenite deposits means that the magnetic signature of these deposits can be quite subdued (McEnroe, 1996; McEnroe and others, 2001; Brown and others, 2011). For Lac Tio and similar orebodies containing ilmenite with very fine exsolution lamellae of hematite, remanent magnetization commonly acquired in an ancient magnetic field with an orientation different from the present Earth's field can contribute to or even dominate the current magnetic response of the host-rock body (McEnroe and others, 2001). Many hemo-ilmenite orebodies have a large negative aeromagnetic anomaly dominated by reversed natural remanent magnetization (NRM) and exhibit very high coercivity and low susceptibility (Bourret, 1949; Hargraves, 1959; McEnroe and others, 2001; McEnroe and others, 2007) (fig. 9). This high coercivity is attributed to a

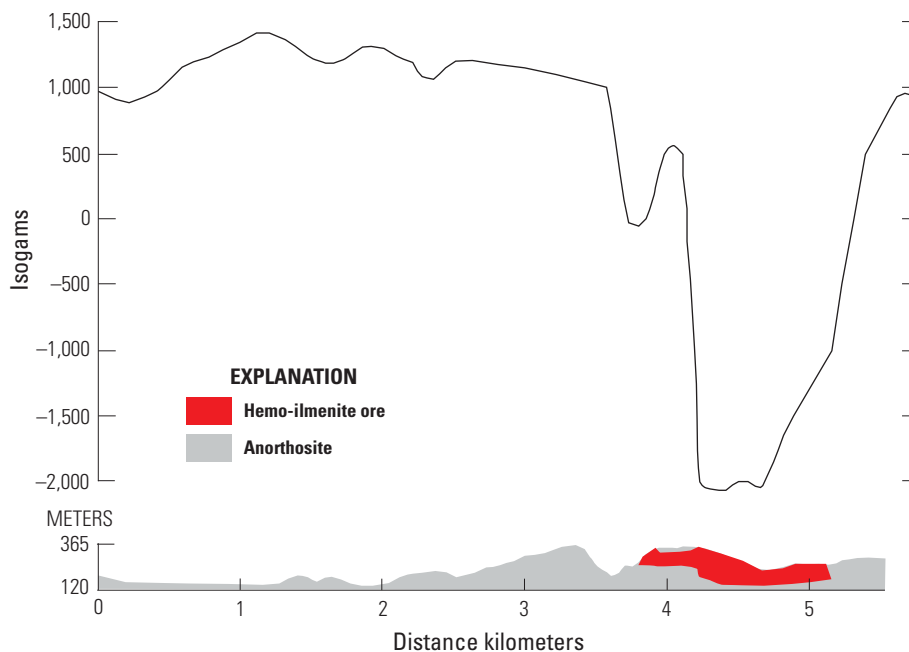


Figure 9. Aeromagnetic profile of the Allard Lake anorthosite across the Lac Tio deposit (in red), Quebec, Canada, displaying a contour line of equal magnetic-field intensity. The datum or zero anomaly isogam was selected arbitrarily by inspection (modified from Bourret, 1949).

very fine scale micro-texture of exsolution lamellae in hemo-ilmenite and ilmenite (that is, lamellar magnetism) resulting from a prolonged cooling history (McEnroe and others, 2002). The ratio of NRM to induced magnetism (susceptibility multiplied by the ambient field) is the Koenigsberger ratio (Q). When Q values are greater than 10, NRM will overwhelmingly dominate a rock's magnetic response (McEnroe and others, 2001).

Brown and others (2011) examined magnetic anomalies over seven different anorthositic bodies. Different bodies had a large range of magnetic susceptibility values and NRM intensities, which depended on the mineral phase, composition, concentration, and grain size of oxides in anorthosite. Samples with high susceptibility all contained magnetite; samples with low susceptibility contained only hemo-ilmenite. Samples dominated by magnetite had moderate NRM values; samples with the strongest NRM had mixed hemo-ilmenite+magnetite or just hemo-ilmenite. Thus, ilmenite-dominated deposits may exhibit either a subdued or a strong negative magnetic anomaly; commonly a subdued response displays characteristic irregular patterns of negative and positive anomalies that can show broad, smooth profiles (Gross, 1996).

In the Duluth Complex, Q is commonly greater than 1 indicating that NRM for these rocks dominates the magnetic anomaly signature (Chandler, 1990). The OUIs bodies themselves are commonly expressed as small, circular magnetic highs, which may be related to magnetite developed by alteration of olivine in host ultramafic rocks (Severson, 1995).

Gravity Signatures

Gravity surveys in Canada show areas of gravity lows (negative gravity anomalies) over or near anorthosite bodies (Rose, 1969). Zones of Fe-Ti oxides typically provide a density contrast to anorthositic or gabbroic host rock and thus have a positive gravity anomaly. Both the Longnose and Longear OUI bodies have surprisingly strong gravity anomalies (amplitudes of 2 to 3 milligals), reflecting the high density of the bodies (Chandler, 2002). Geophysical exploration targets for OUIs in the Duluth Complex are thus marked by small dot-like gravity and magnetic anomalies that stand out from surrounding rocks.

Electrical Signatures

The OUIs in the Duluth Complex also can produce detectable electromagnetic and induced polarization anomalies, provided the deposits are fairly close to the surface. Airborne electromagnetic surveying detected anomalies over both the Longnose and Longear deposits with Fe-Ti oxide and perhaps graphite the likely conductors (Chandler, 2002).

Hypogene Ore Characteristics

Mineralogy and Mineral Assemblages

Most Fe-Ti oxides in igneous rocks are members of two solid solution series—the hematite-ilmenite rhombohedral series (Fe_2O_3 – FeTiO_3) and the magnetite-ulvöspinel spinel series (Fe_3O_4 – Fe_2TiO_4) (fig. 10). Above about 800 °C, the ilmenite-hematite series forms an extensive solid solution; the magnetite-ulvöspinel series has complete solid solution above about 600 °C (Haggerty, 1976). In slowly cooling plutonic rocks, hematite will exsolve from ilmenite forming hemo-ilmenite (Lindsley, 1981; fig. 11A). Titanium in titanomagnetite exsolves to form either lamellae of ilmenite in magnetite or granular, interlocking discrete grains of ilmenite and magnetite (Buddington and Lindsley, 1964; fig. 11B). Observed mineralogy in Fe-Ti-oxide deposits has typically undergone exsolution, oxidation, diffusion, and other subsolidus effects such as Ostwald ripening. In many deposits, metamorphism has further altered oxide mineralogy. Detailed modal studies and careful textural examinations are required to distinguish between primary precipitated oxides and oxides grown from late-stage interstitial liquids.

Magmatic rutile is found at several deposits in the Saint-Urbain anorthosite in the Grenville Province (Charlier and others, 2008; Morisset and others, 2010). Rutile in the Roseland anorthosite may be metasomatic (Herz and Force, 1987). Rutile, along with magnetite and anatase, at Lac Tio results from late-stage alteration of hemo-ilmenite (Charlier and others, 2010). Geikielite (MgTiO_3) can occur as lamellae in hemo-ilmenite, although with slow cooling, Mg in oxide can exchange with Fe in surrounding silicates.

The presence or absence of discrete crystals of ilmenite is a key factor that determines the economic value of an oxide deposit (Force, 1991). Titanium in solid solution in magnetite or as exsolution lamellae in magnetite is considered uneconomic (Force, 1991). Coarser grain sizes are more desirable than finer grain sizes. Economic ore minerals in oxide deposits are ilmenite and hemo-ilmenite (ilmenite with less than 50-percent exsolved hematite). Less economic titanomagnetite is typically a mixture of Ti-poor magnetite, ilmenite, and ulvöspinel. Proportions of these ore minerals vary from deposit to deposit, but mineral assemblages can be classified into four groups (see for example, Duchesne and Schiellerup, 2001; Hébert and others, 2005; Corriveau and others, 2007; Hauck and others, 1997): (1) hemo-ilmenite (\pm magnetite \pm rutile) that cross-cuts or is concordant in anorthosite and related rocks (for example, Tellnes, Lac Tio, Big Island), (2) titaniferous magnetite+ilmenite disseminated or as layers in anorthosite and related intrusions (for example, Sanford Lake district, Magpie Mountain, Buttercup), (3) titaniferous magnetite with ilmenite and apatite cross-cutting anorthosite or concordant in oxide-apatite gabbro (for example, Everett, La Hache-Est, Lac à Paul), and (4) ilmenite+magnetite in ultramafic rocks cross-cutting (rarely stratabound) layered

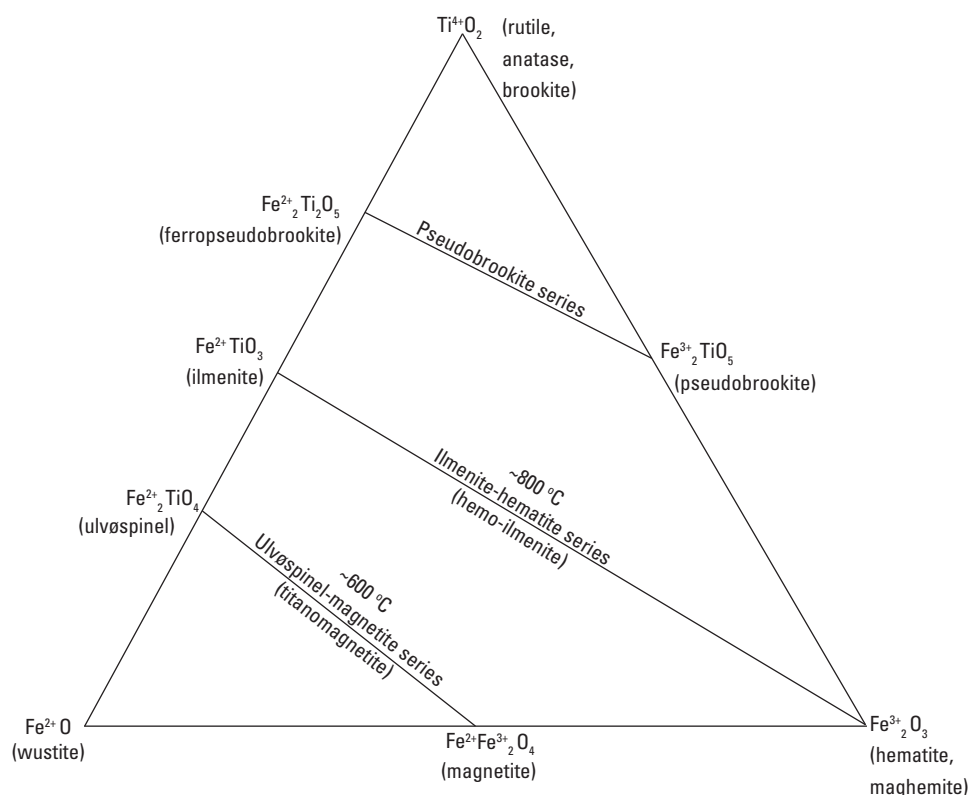


Figure 10. The subsystem $\text{FeO}-\text{Fe}_2\text{O}_3-\text{TiO}_2$ showing major solid solution joins for the cubic (ulvöspinel-magnetite), rhombohedral (ilmenite-hematite), and orthorhombic (pseudobrookite) series. Temperatures along the cubic and rhombohedral joins are consolute temperatures (critical points for the solvi).

troctolite (for example, Longnose, Water Hen). Combinations of these mineral assemblages can be found in various deposits within the same anorthosite suites (see for example, Perreault, 2003; Hébert and others, 2005; Corriveau and others, 2007).

Paragenesis

Paragenetic sequences of Fe-Ti-oxide deposits are typically complex due to widely varying proportions of ilmenite, hemo-ilmenite, titanomagnetite, and magnetite among deposits. Postcumulus high-temperature re-equilibration, complex exsolution textures, secondary mineral reactions, and possible metamorphic overprinting further complicate mineral relations. Thus, the sequence of mineralization of ore minerals may be unique for individual deposits (Gross, 1996). The primary oxide paragenetic sequence depends on original TiO_2 content, silica activity, and the oxygen fugacity path of parent magma (see fig. 5). These parameters will determine whether ilmenite is an early liquidus mineral, potentially leading to concentrations of massive ilmenite or hemo-ilmenite with little or no magnetite, or whether silicate crystallization alone will drive fractionated liquids toward Fe-Ti-P enrichment, potentially resulting in late-stage concentrations of ilmenite, titanomagnetite, and apatite crystallizing from residual liquids.

For massive hemo-ilmenite deposits, ilmenite along with plagioclase is an early liquidus mineral, controlled primarily by the TiO_2 content of the parent magma and the oxygen fugacity of the silicate magma from which oxides crystallize (Haggerty, 1976; Wilson and others, 1996; Duchesne, 1999; Charlier and others, 2008). In a magmatic system closed to oxygen, the $\text{Fe}^{2+}/\text{Fe}^{3+}$ ratio of the system is fixed, and crystallization of Fe^{3+} -bearing minerals (such as ilmenite) increases this ratio in the melt, thereby lowering the melt oxygen fugacity and driving the system toward crystallization of magnetite. In an open system, ilmenite crystallization will have little effect on oxygen fugacity because a melt can readjust and keep oxygen fugacity relatively constant. Iron-Ti-oxide deposits in the Rogaland Province fit an evolutionary trend exemplified by Fe-Ti oxides in the Bjerkreim-Sokndal layered intrusion. The Bjerkreim-Sokndal trend has early precipitation of hemo-ilmenite with minor Ti-poor magnetite followed by a gradual decrease in the hematite component in ilmenite, matched with increasing Ti content of magnetite and an appearance of apatite (Wilson and others, 1996). In the Adirondacks, there is a perceptible compositional trend among the Fe-Ti oxides. In anorthosite and other early cumulates, ilmenite tends to be richer in hematite, and coexisting spinels are richer in magnetite compared to later cumulates and mafic rocks (Ashwal, 1982).

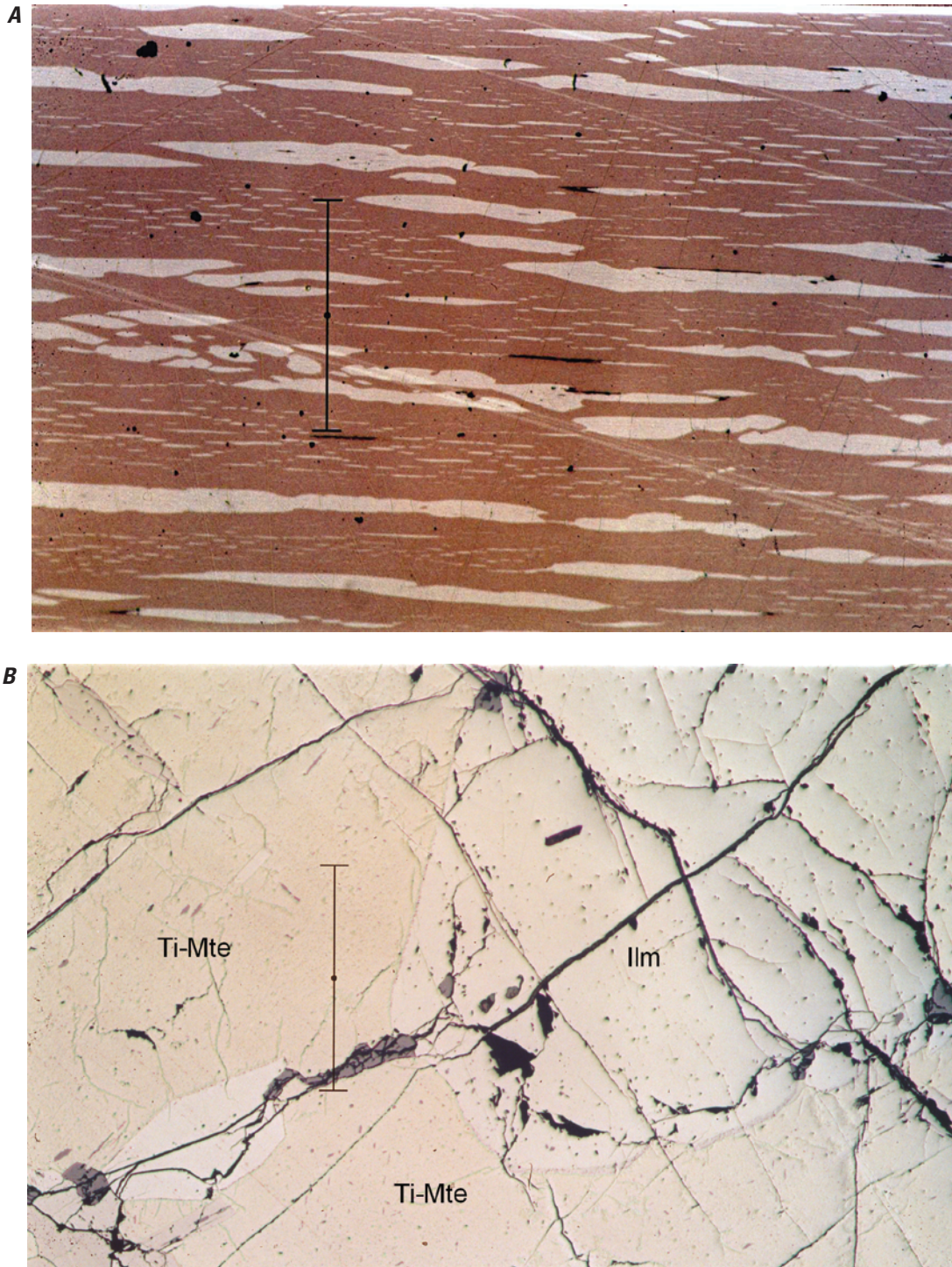


Figure 11. A. Reflective-light photograph of hemo-ilmenite from the Lac Tio deposit, Quebec, Canada. Light-colored lamellae are hematite exsolving from the brown-pink ilmenite. Scale bar is 0.5 mm. B. Reflective-light photograph of titanomagnetite (Ti-Mte) and ilmenite (Ilm) from the Hervieux East massive titaniferous lens in the La Blache anorthosite complex, Quebec, Canada. Scale bar is 0.5 mm. Photographs provided by Serge Perreault, used with permission.

At the Longnose OUI deposit, ilmenite and titanomagnetite are cumulus minerals, titanomagnetite is also intercumulus, magnetite occurs as an alteration product of olivine and rutile, and hematite rims ilmenite (Cardero Resource Corporation, 2012).

Zoning Patterns

Physical and chemical conditions in the magmatic environment where Fe-Ti-oxide minerals are crystallizing control the physical distribution and chemical composition of oxides. Charlier and others (2006) document variations in modal proportions of both silicates and oxides in a large-scale zonation of the Tellnes orebody reflecting in-place crystallization history and development of varying proportions of residual liquid. The deepest parts of the Tellnes orebody contain mainly plagioclase and ilmenite, with little magnetite or sulfide, suggesting that plagioclase and ilmenite were early liquidus minerals. In the upper part of the orebody, olivine and orthopyroxene appear as cumulus phases, with magnetite,

clinopyroxene, biotite, apatite, and hornblende present as intercumulus phases. Based on modal contents of ore-forming minerals, the Tellnes orebody has been divided into four zones (fig. 12): (1) an upper marginal zone with high modal contents of plagioclase and Fe-Mg silicates (orthopyroxene and clinopyroxene) and low contents of ilmenite; (2) an upper central zone with low plagioclase contents but high Fe-Mg silicate and ilmenite contents; (3) a lower central zone with low Fe-Mg silicate contents, plagioclase contents intermediate between the upper central zone and upper marginal zone, and the highest ilmenite contents; and (4) a lower marginal zone with decreasing ilmenite contents and increasing silicate contents (Kullerud, 2003).

On a larger scale, hemo-ilmenite deposits are typically contained within anorthosite hosts, whereas rocks carrying ilmenite+magnetite+apatite (oxide-apatite gabbro-norite) typically occur as discordant to concordant sill-like bodies within anorthosite, as layers along or near the outer limits of anorthosite massifs, or as layers within related jotunite (Dymek and Owens, 2001). Nelsonite can occur as dike-like

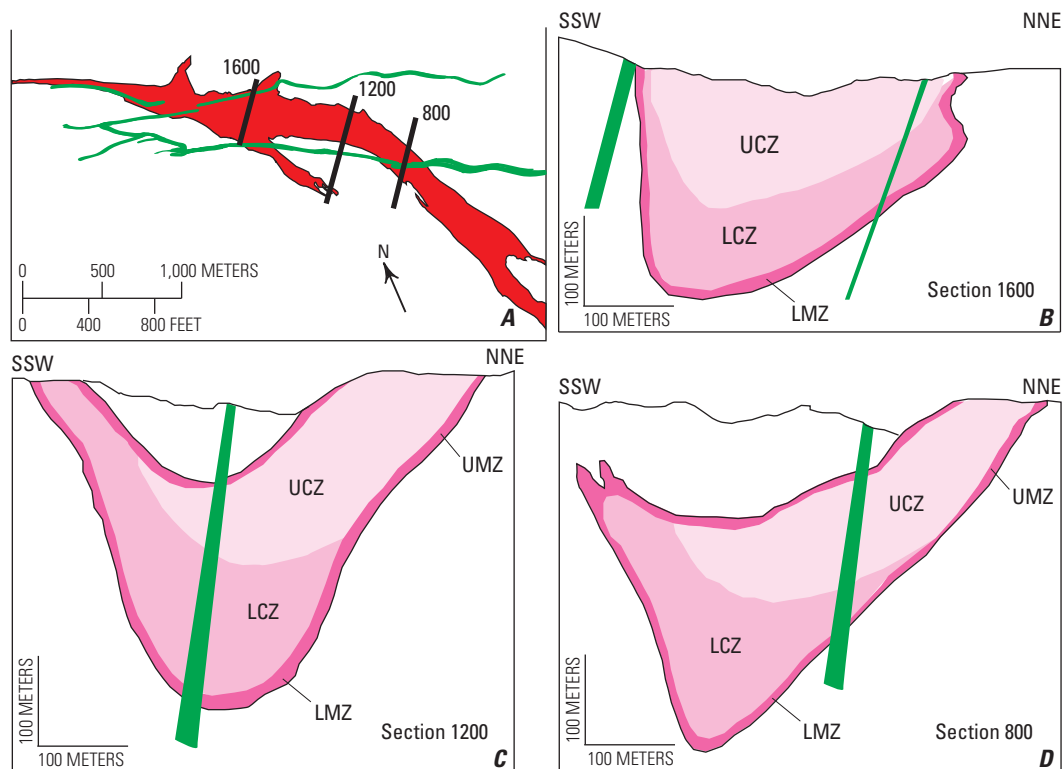


Figure 12. A. Location of three selected cross sections on the geological map of the Tellnes orebody, Norway (in red; cut by basalt dikes, in green; see fig. 7 for details); B. cross section 1600; C. cross section 1200; and D. cross section 800; cross sections are showing spatial distribution of the four different orebody zones, based on silicate and oxide mineralogy and concentration (modified from Charlier and others, 2006). UCZ = Upper central zone, with low plagioclase contents and high Fe-Mg-silicate and ilmenite contents; UMZ = Upper marginal zone with high plagioclase and Fe-Mg-silicate contents and low ilmenite contents; LCZ = Lower central zone with low Fe-Mg-silicate contents, plagioclase contents intermediate between the UCZ and UMZ, and the highest ilmenite contents; and LMZ = Lower marginal zone with decreasing ilmenite and increasing silicate contents.

bodies in anorthosite and as layers or segregations within massive deposits of ilmenite or magnetite (Dymek and Owens, 2001). The Grader layered intrusion in the Havre-Saint-Pierre anorthosite suite has massive ilmenite at its base, then layers of ilmenite alternating with anorthosite layers grading upward into ilmenite-apatite ore with variable proportions of plagioclase, and oxide-apatite gabbro at the top (Charlier and others, 2008). This sequence for the Grader intrusion is interpreted as evidence of successive appearances of liquidus minerals in a continually fractionating magma.

Textures and Grain Size

Textures and compositions of oxides indicate post-crystallization modification by re-equilibration and consolidation of loose grains into polycrystalline materials at subsolidus temperatures (annealing). Ore at Tellnes is medium-grained. Oxides are about 0.5 to 2 mm in diameter, with cumulate, equigranular, and massive textures. Discrete hemo-ilmenite grains are typically greater than 1 mm, commonly forming coarse-grained polygonal aggregates with interstitial green spinel and locally subsidiary amounts of magnetite (Schierlerup and others, 2003). Where hemo-ilmenite and magnetite are in contact, a symplectite of magnetite, ilmenite, and spinel can form by re-equilibration during cooling in which Fe^{3+} in ilmenite is exchanged for Fe^{2+} in magnetite (Schierlerup and others, 2003). Zones of clear ilmenite free of hematite lamellae also can develop where hemo-ilmenite is adjacent to magnetite because of subsolidus Fe migration; this texture does not appear at contacts with silicates or between two ilmenite grains (Duchesne, 1972). Two types of magnetite are recognized at Tellnes. These are small magnetite grains associated with sulfides and larger magnetite grains, about 0.5 mm in diameter, with exsolution lamellae of pleonaste that occur with olivine and prismatic orthopyroxene (Charlier and others, 2007).

At the Lac Tio mine, hemo-ilmenite is dense, black, and mostly present as coarse-grained, thick, tabular crystals, about 5 to 20 mm in length (Hammond, 1952; Charlier and others, 2010) (fig. 13). In the Sanford Lake district, Gross (1968) described titaniferous magnetite deposits as having anorthositic ore and a lean gabbro ore. Anorthositic ore consists of massive lenses of titaniferous magnetite (Fe:Ti ratio greater than 2:1) that are phaneritic ranging from equigranular to porphyritic to reticulated with coarse-grained subhedral to euhedral magnetite in a mesh of fine-grained anhedral ilmenite with no flow structures. Gabbro ore is oxide-enriched conformable bands in gabbro (Fe:Ti ratio less than 2:1) that are typically more fine-grained with porphyritic or reticulated textures. Both types of ore are present in the Sanford Hill/South Extension deposit with anorthositic ore forming a foot-wall orebody and gabbro ore forming a hanging-wall orebody (McLelland and others, 1993). Titanomagnetite, the dominant oxide in the Section 34 OUI in the Duluth Complex, occurs as round grains, coalesced rounded grains with or without



Figure 13. Massive hemo-ilmenite ore from the floor of the Main pit at the Lac Tio deposit, Quebec. Coin used for scale is about 26 mm in diameter. Photograph provided by Serge Perreault, used with permission.

embayed edges, subhedral grains, and skeletal blades (Severson, 1995). In the Skibo OUI, ilmenite is more abundant than magnetite; both oxides can be interstitial to major cumulate silicate phases and occur as rounded lobate grains (Severson and Hauck, 1990).

Gangue Mineral Characteristics

Mineralogy and Mineral Assemblages

The principal gangue minerals with magmatic Fe-Ti-oxide deposits are the silicates of the host rocks. Gangue minerals in the Tellnes norite are plagioclase (An_{45-42}), bronzite, augite, Ti-biotite, olivine, hornblende, magnetite, sulfides (bravortite, chalcopyrite, covellite, marcasite, millerite, pentlandite, pyrite, pyrrhotite, and violarite), and apatite (Krause and others, 1985; Wilmart and others, 1989). Bronzite and primary augite typically contain fine Schiller-type exsolution of ilmenite and hemo-ilmenite and rarely magnetite (Diot and others, 2003). At Lac Tio, hemo-ilmenite is hosted by anorthosite; accessory minerals include aluminous spinel, orthopyroxene, and Ti-phlogopite with minor amounts of sulfide (pyrite, pyrrhotite, chalcopyrite, and millerite) (Charlier and others, 2010). In the Duluth Complex, OUIs are hosted in ultramafic rocks—typically dunite, pyroxenite, and peridotite—intruding troctolite. Gangue mineralogy is dominated by olivine, plagioclase, augite, hornblende, biotite, and minor amounts of Ni-Cu sulfides (chalcopyrite, pyrrhotite, cubanite, and pentlandite) (Strommer and others, 1990; Severson, 1995). Graphite is also found in a number of OUIs (Severson, 1995). Gangue minerals in the Sanford Lake district are both igneous

and metamorphic and include feldspar, garnet, orthopyroxene, clinopyroxene, hornblende, and sulfides (chalcopyrite, sphalerite, molybdenite, pyrrhotite, and pyrite) with minor apatite, prehnite, barite, orthoclase, leucosene, scapolite, epidote, and quartz (McLelland and others, 1993).

Trace zircon and baddeleyite are common in many oxide deposits, typically occurring as rims surrounding ilmenite (Charlier and others, 2008; Morisset and others, 2010). Sapphirine (Mg-Fe-Al silicate) is unique to Fe-Ti-oxide deposits in the Saint-Urbain anorthosite suite and the Big Island deposit in the Havre-Saint-Pierre anorthosite suite and is interpreted as a subsolidus reaction of spinel and orthopyroxene in the presence of magmatic rutile (Morisset and others, 2010). Apatite can be a prominent mineral in some magmatic Fe-Ti-oxide deposits. Apatite+oxide (mainly ilmenite) rocks with few silicates occur most commonly with massif anorthosite as a nelsonite (Kolker, 1982). The assemblage apatite+ilmenite+magnetite is typical of many anorthosite suites, with the rock referred to as an oxide-apatite gabbronorite (OAGN) (Owens and Dymek, 1992). An abundance of apatite with Fe-Ti oxides, such as at the Lac à Paul deposit, can result in a phosphate resource. Some ilmenite deposits in the Allard Lake anorthosite locally contain as much as 8- to 10-percent fluorapatite (Gross, 1996). The concentration of rare earth elements (REE) in apatite could make some apatite-rich Fe-Ti-oxide deposits a speculative REE resource.

Paragenesis

The paragenetic sequence for gangue minerals in host rocks generally follows predicted silicate crystallization sequences for mafic intrusive rocks. Gangue mineral paragenesis at Tellnes is intimately linked to oxide mineral paragenesis. Plagioclase is an early liquidus mineral with ilmenite followed by crystallization of orthopyroxene, clinopyroxene, hornblende, biotite, and magnetite (Krause and others, 1985). Olivine is present only in the upper part of the body and is typically interstitial to other minerals or occurs as small inclusions in orthopyroxene (Charlier and others, 2006). Plagioclase, orthopyroxene, and olivine are considered cumulus minerals; magnetite, clinopyroxene, biotite, apatite, and hornblende are considered intercumulus minerals (Charlier and others, 2006). In the Adirondacks, large, euhedral plagioclase was the first phase to crystallize followed by augite and pigeonite and Fe-Ti oxide; apatite is cumulus only in very late stage low-Ca pyroxene-deficient or olivine-bearing cumulates (Ashwal, 1982). Primary mineralogies and textures of anorthosite in the Adirondacks have been affected to varying degrees by subsolidus recrystallization, which has resulted in the production of metamorphic garnet and hornblende (Ashwal, 1982).

The cumulate sequence for the Bjerkreim-Sokndal intrusion is plagioclase cumulates in the lower section, plagioclase-hypersthene-ilmenite cumulates in the middle section, and plagioclase-hypersthene/pigeonite-augite-ilmenite-magnetite-apatite cumulates in the upper section (Wilson and others,

1996). This sequence is interpreted as crystallization of a continuously fractionating, periodically replenished magma chamber (Wilson and others, 1996) and represents a progressive appearance of liquidus minerals. The sequence of cumulate minerals in the Grader layered intrusion in the Havre-Saint-Pierre suite is somewhat similar with ilmenite and plagioclase as the early liquidus minerals (Charlier and others, 2008). However, in the Grader intrusion, apatite joins the cumulate assemblage of plagioclase+ilmenite prior to crystallization of Fe-Mg silicates and magnetite, and, in some layers, plagioclase is very low or absent, producing nelsonite (Charlier and others, 2008).

Hydrous minerals, including biotite and hornblende, occur in many deposits and are typically late and volumetrically insignificant.

Zoning Patterns

The zoning pattern for gangue minerals is tied to ore mineral zonation as described above for a number of deposits, including the Tellnes deposit (Charlier and others, 2006) and the Grader deposit (Charlier and others, 2008), as well as the Bjerkreim-Sokndal layered intrusion (Wilson and others, 1996). Some OUIs in the Duluth Complex have a crude zonation from an olivine-rich core of dunite, peridotite, and melatroctolite, to an outer clinopyroxenite margin (Severson and others, 2002).

Textures and Grain Sizes

Gangue minerals in the Tellnes norite have a subophitic texture with euhedral plagioclase and bronzite and subordinate olivine; plagioclase laths are commonly slightly bent and locally granulated (Wilmart and others, 1989). Symplectic intergrowths of bronzite with magnetite or with oxide and sulfide found in the upper part of the orebody are considered to be products of the breakdown of primary olivine (Krause and others, 1985). Prismatic plagioclase and bronzite have features such as bending, undulatory extinction, deformation twins in plagioclase, kinking in bronzite, and local dynamic recrystallization into aggregates of small grains. Diot and others (2003) suggest that these textures were acquired during magma injection through the Tellnes dike and are indications of solid-state deformation in the presence of interstitial liquid. Charlier and others (2006) suggest that these textures were acquired by dynamic subsidence of underlying anorthosite during crystallization of the Tellnes oxide-bearing norite.

In the Poe Mountain anorthosite, one of three large composite anorthosite intrusions in the Laramie Range anorthosite complex, Wyoming, deformation and recrystallization of plagioclase were apparently continuous from subliquidus to subsolidus temperature conditions during emplacement of the intrusion (Lafrance and others, 1996). In addition, anorthosite with the highest degree of recrystallization has the lowest modal percentages of Fe-Mg silicates and Fe-Ti oxides

suggesting plagioclase separation from more mafic constituents during deformation and recrystallization (Lafrance and others, 1996). Tabular plagioclase in anorthosite in the Sanford Lake district can be 10 cm or more in length with subparallel alignment of the longest plagioclase dimensions forming a planar fabric generated by flow (Ashwal, 1982).

Hydrothermal Alteration

Hydrothermal alteration does not play a role in development or enrichment of Fe-Ti-oxide deposits related to Proterozoic massif anorthosite suites.

Supergene Ore and Gangue Characteristics

Supergene enrichment is not important for Fe-Ti-oxide deposits related to Proterozoic massif anorthosite suites.

Weathering and Supergene Processes

Weathering and supergene processes have no role in the formation of magmatic Fe-Ti-oxide deposits related to Proterozoic massif anorthosite suites. However, weathering can play an important role in secondary enrichment and concentration of magmatic Fe-Ti-oxides. For example, ilmenite and rutile were mined from saprolite developed over the Roseland anorthosite and adjacent rocks (Herz and others, 1970), and weathering of ilmenite to form secondary leucoxene or rutile is important for the value of heavy mineral deposits (Force, 1991).

Geochemical Characteristics

Trace Elements and Element Associations

Trace-element contents of ilmenite are critical because they can impact the economic value of an Fe-Ti-oxide deposit by complicating the pigment production process (Chernet, 1999). For example, Cr and V can affect pigment color (Chernet, 1999). Trace-element abundances and element associations in ore minerals reflect magmatic evolution and subsolidus re-equilibration, complicated by varying Fe-redox states. In Fe-Ti oxides, elements that preferentially substitute for trivalent Fe^{3+} are Cr^{3+} , V^{3+} , and Al^{3+} . Elements that preferentially substitute for divalent Fe^{2+} are Mg^{2+} , Mn^{2+} , and Zn^{2+} . Finally, Zr^{4+} can substitute for Ti^{4+} in ilmenite. Vanadium, Cr, and Al thus show a preference for a magnetite phase, whereas Mg, Mn, and Zn have a preference for an ilmenite phase, although these generalizations are complicated by the presence/absence

of exsolution lamellae (McEnroe and others, 2000). Typically the fine size of exsolution lamellae in oxide minerals makes it impossible to resolve trace-element distributions in the different phases.

Trace-element concentrations in oxide phases depend on the original element concentration in the parent magma, the sequence of mineralization for both silicates and oxides, the oxygen fugacity of magma during crystallization, and subsolidus re-equilibration among oxide minerals (Duchesne, 1999; Vander Auwera and others, 2003; Charlier and others, 2007). For example, Mg is concentrated in the ilmenite phase, so the presence of hematite lamellae in ilmenite will reduce the overall Mg content of ilmenite. Magnesium will also decrease in ilmenite during cooling by re-equilibration with surrounding silicates with Mg moving out of oxide and into silicate. Thus, ilmenite in massive ore will retain relatively high concentrations of Mg compared to isolated ilmenite surrounded by silicate minerals (McEnroe and others, 2000). Vanadium and Cr are concentrated in hematite-rich exsolution lamellae in ilmenite, but appearance of magnetite as a liquidus mineral will quickly deplete magma in these elements.

Thin zircon rims surrounding ilmenite at a number of deposits in the Grenville Province (Morisset and Scoates, 2008) and at Tellnes (Charlier and others, 2007) formed by migration of Zr^{4+} out of the ilmenite structure. Magnetite at Tellnes can contain coarse lamellae of zinciferous-aluminous spinel (Wilmart and others, 1989). Aluminous spinel also commonly occurs as granules external to ilmenite from exsolution and migration of Al^{3+} out of oxide at a number of deposits (McEnroe and others, 2000; Charlier and others, 2010). Concentrations of P and REE in parent magmas are mainly controlled by apatite crystallization.

Zoning Patterns

Zoning patterns of trace elements in Fe-Ti-oxide deposits are the product of magmatic evolution and subsolidus re-equilibration. The percentage of cumulus minerals to intercumulus trapped liquid exerts an important control on zoning patterns in layered deposits. From the lower to the upper part of the Tellnes orebody, the Mg content of cumulus ilmenite increases when plagioclase and ilmenite are cumulus minerals and then begins to decrease with the advent of orthopyroxene and olivine crystallization (Charlier and others, 2007). Ilmenite with a high hematitic component near the margins of the deposit has lower Mg contents. Chromium and V decrease continuously from the lower to the upper part of the orebody, consistent with their compatible behavior in the ilmenite structure (Charlier and others, 2007). An overall magmatic trend for oxides in the Bjerkreim-Sokndal intrusion from hemo-ilmenite with minor magnetite to hematite-poor ilmenite with titanomagnetite is accompanied by decreasing Mg and Cr and increasing V until magnetite is a primary mineral, after which V decreases (McEnroe and others, 2000).

Isotope Geochemistry of Ores

Stable Isotope Geochemistry

Ilmenite and titanomagnetite separates from oxide-rich ultramafic intrusions in the Duluth Complex have $\delta^{18}\text{O}$ values of 4.5 to 5.6 per mil (‰) (Ripley and others, 1998). Whole-rock and mineral separates including plagioclase, pyroxene, olivine, and, to a lesser extent, oxides from OUIs have higher $\delta^{18}\text{O}$ values than similar minerals in other troctolites in the Duluth Complex. Based on observed whole-rock δD values (−70 to −87 ‰) as well as plagioclase ($\delta^{18}\text{O}$ up to 13.2 ‰) and pyroxene ($\delta^{18}\text{O}$ up to 10.1 ‰) separates, Ripley and others (1998) suggested that the OUI rocks may reflect isotopic exchange with a $\delta^{18}\text{O}$ -rich fluid at about 500 °C. Such a fluid could arise from dehydration reactions of shale and greywacke in adjacent country rock (Virginia Formation) driven by the thermal pulse of Duluth Complex intrusion events (Ripley and others, 1998). Whole-rock $\delta^{18}\text{O}$ values of ilmenite norite from the Tellnes orebody range from 5.1 to 5.4 ‰ (Wilmart and others, 1994). Leuconorite and ilmenite norite whole-rock samples from the orebody yield δD values of −66.9 and −76.6 ‰, respectively. Wilmart and others (1994) concluded that these values were consistent with a mantle origin and did not suggest evidence of significant hydrothermal exchange, in contrast to the OUIs in the Duluth Complex.

In the Kunene anorthosite complex in Namibia, Gleissner and others (2010) analyzed mineral separates from major rock units including ilmenite and magnetite from an older white andesine-type anorthosite and a younger dark labradorite-type anorthosite. Ilmenite and magnetite from white anorthosite have $\delta^{18}\text{O}$ values of 1.3 and 1.2 ‰, respectively, whereas ilmenite and magnetite from dark anorthosite have $\delta^{18}\text{O}$ values of 2.3 to 4.0 and 0.8 ‰, respectively.

Radiogenic Isotope Geochemistry

Strontium (Sr) analyses of plagioclase separates from the Tellnes orebody gangue assemblage show remarkably homogeneous initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios ranging from 0.704368 to 0.704533 (Charlier and others, 2006). Such consistent ratios suggest that mixing of magmas was not likely, nor was there significant contamination from crustal rocks. Based in part on these data, the authors conclude that Tellnes hemo-ilmenite was likely derived through fractional crystallization of jotunitic magma.

At the Grader deposit, initial Sr isotopic compositions for plagioclase in host anorthosite (average = 0.703995) are slightly different from plagioclase in norite of the Grader deposit itself (average = 0.704319) (Charlier and others, 2008). Charlier and others (2008) concluded that this minor difference arose from slightly different magma sources for the two rock types, although overall both rocks developed by continuous fractional crystallization with small geochemical variations controlled by successive appearance of various liquidus phases.

Rhenium (Re) content in Fe-Ti-oxide deposits is a function of the proportion of Fe-Ti oxide in ore as Re is preferentially incorporated into titanomagnetite. Analyses of rhenium-osmium (Re-Os) isotopic compositions of Fe-Ti-oxide ores from the Kunene anorthosite complex indicate that initial $^{187}\text{Os}/^{186}\text{Os}$ ratios range from 10.7 to −4.9, with the negative values suggesting disturbance of the Re-Os isotope system by post-magma processes and therefore yielding unreliable initial compositions (Gleissner and others, 2012).

Petrology of Associated Igneous Rocks

Petrologic questions surrounding the origin of anorthosite massifs and related rocks continue to be thoroughly debated (see for example, Ashwal, 1993; Vander Auwera and others, 2000; Seifert and others, 2010). A generic two-stage model for massif anorthosite is generally accepted. First, there is stagnation of magma at the crust-mantle interface with crystallization of plagioclase and mafic silicates. Density separation of plagioclase from mafic minerals occurs by diapiric upwelling of a plagioclase-melt mush and sinking of mafic silicate minerals back into the mantle. This is followed by a stage of emplacement of a plagioclase-melt mush into the upper to middle crust where a complex magma chamber forms. Further fractional crystallization is dominated by plagioclase, Fe-Ti oxides, and Fe-Mg silicates (Ashwal, 2010).

Duchesne and Schiellerup (2001) attribute the complex evolution of massive anorthosite compared to layered mafic intrusions to explain differing deposit styles between ilmenite-rich deposits discordant to host anorthosite (for example, Lac Tio and Tellnes) and ilmenite-rich cumulates in layered intrusions (for example, Bjerkreim-Sokndal and Grader layered intrusions). Layered intrusions represent crystallization within relatively static magma chambers at near constant pressures. In contrast, development of massive anorthosite results from synchronous crystallization and deformation over a range of pressures, which would potentially mobilize magmatic liquids, crystal-magma liquids, or crystal mushes (Duchesne and Schiellerup, 2001). Within this dynamic environment, oxide-laden liquids (1) could be injected into extensional openings in cooling and contracting host rocks along zones of weakness (see for example, Vander Auwera and others, 2006), (2) could become concentrated in physical traps in magma-conduit systems (see for example, Charlier and others, 2010), or (3) could form irregular pod- to dike-like oxide concentrations that cross-cut host anorthosite representing keels to larger intrusions in which Fe-Ti-oxide minerals accumulated near the base of an intrusion separated from plagioclase within an ascending and crystallizing magma (see for example, Morisset and others, 2010). In all scenarios, density contrasts among oxide, silicate, and liquid are critical.

Rock Names

Anorthosite complexes are complicated and exhibit a wide range of rock types, not all of which are present in every complex (Emslie and others, 1994). Typical rock types include anorthosite, leucotroctolite, leuconorite, troctolite, norite, gabbro, ferrogabbro, ferrodiorite, jotunite, mangerite, and charnockite. Collectively, plutonic suites containing these rocks are commonly referred to as anorthosite-mangerite-charnockite-granite (AMCG) suites. Local terminology and imprecise usage of rock names over time have complicated descriptions of anorthosite complexes in the literature, particularly with respect to the terms “charnockite” (Frost and Frost, 2008), “nelsonite” (Dymek and Owens, 2001), “jotunite” (Vander Auwera and others, 1998), and “ferrodiorite” (Force, 1991). To bring a sense of order to the confusion, a classification scheme that includes the common rock associations for massif-type anorthosite and related rocks using consistent terminology has been constructed and is given in figure A1 in appendix 1.

Forms of Igneous Rocks and Rock Associations

A number of Proterozoic terranes host large composite anorthosite massifs commonly made up of multiple diapiric intrusions or well-layered leucocratic troctolite, leuconorite, and leucogabbro overlain by thick anorthosite units (Longhi and others, 1999). Mafic rocks associated with anorthosite massifs include large layered intrusions and smaller ferrodiorite intrusions and dikes; commonly, granitic intrusions of various compositions (for example, mangerite and charnockite) are also present. Careful mapping in areas of well-exposed and undeformed anorthosite massifs typically reveals several dozen multiple intrusions of variable composition, as in the Rogaland Province (Michot and Michot, 1969), the Havre-Saint-Pierre suite (Gobeil and others, 2003), and the Nain Complex (Labrador) (Emslie and others, 1994; Ashwal, 1993, and references therein). For example, the Havre-Saint-Pierre anorthosite complex covers an area of 20,000 km² with as many as seven individual anorthosite lobes of varying ages within this complex separated by monzonitic, mangeritic, or granitic envelopes (Gobeil and others, 2003; Charlier and others, 2010).

In eastern Canada, geophysical studies were used to distinguish large, flat tabular anorthosite bodies 2 to 4 km thick, either with or without accompanying feeder pipes (for example, Marcy, Morin, and Harp Lake anorthosites), from anorthosite bodies with smaller related gabbro or troctolite intrusions (for example, Nain Complex and Lac Saint-Jean anorthosite suite). Layered intrusions related to anorthosite complexes may exhibit well-defined cumulate layering in broadly basinal structures (Ashwal, 1993).

In the Grenville Province, anorthosite bodies have undergone substantial regional deformation (see for example, McLelland and others, 2010). Original intrusion shapes may

now be elongated by ductile deformation and drawn out in shear zones (Ashwal, 1993; McLelland and others, 2010). Some metamorphosed anorthosite bodies exhibit domical structures locally related to the deformation (Ashwal, 1993). Likewise, earlier intrusions may be structurally altered and deformed by emplacement of later intrusions.

Mineralogy

Anorthosite is typically composed of greater than 95 percent plagioclase with rare orthopyroxene megacrysts (Charlier and others, 2006). Anorthositic rocks are often classified by the overall anorthite content of contained plagioclase (that is, percent An, equivalent to the percent of the CaAl₂Si₂O₈ end member; appendix 1). Anorthosites can be divided into andesine-type anorthosites with plagioclase compositions of An_{23–48} accompanied by orthopyroxene and ilmenite and labradorite-type anorthosite with plagioclase compositions of An_{45–63} accompanied by olivine or orthopyroxene and low-Fe₂O₃ ilmenite (Anderson and Morin, 1969). In the Åna-Sira andesine-type anorthosite, host to the Tellnes deposit, plagioclase is the predominant cumulus phase with ilmenite, orthopyroxene, and lesser olivine occurring as both cumulus and interstitial phases. Minor phases include intercumulus magnetite, clinopyroxene, biotite, apatite, and hornblende, and accessory phases include sulfides, spinel, baddeleyite, and zircon (Charlier and others, 2006). The Allard Lake andesine-type anorthosite, host to the Lac Tio deposit, comprises plagioclase (An_{37–49}) and less than 5-percent orthopyroxene, ilmenite, and, locally, clinopyroxene (Charlier and others, 2010).

The OUI host rocks in the Duluth Complex are rich in olivine and clinopyroxene, and their oxide content ranges from 15 to 20 percent to locally massive zones (Severson, 1995). The OUIs in the southern part of the complex typically intrude rocks that include anorthosite, troctolite, gabbro, pyroxenite, and basalt (Severson, 1995).

More acidic rocks related to anorthosite, such as jotunite, mangerite, quartz mangerite, and charnockite, are noncumulus and composed of plagioclase (typically antiperthitic), orthopyroxene, clinopyroxene, ilmenite, magnetite, and apatite. Potassium feldspar (typically perthitic), zircon, and quartz occur in the most differentiated units (Owens and others, 1993; Vander Auwera and others, 2011). Amphibole may occur locally in quartz mangerite and charnockite; biotite may also occur as a trace phase (Owens and others, 1993).

Textures, Structures, and Grain Size

Anorthosite complexes have a broad spectrum of cumulate textures ranging from orthocumulate (cumulates composed chiefly of one or more cumulus minerals plus the crystallization products of intercumulus liquid) to heterad-cumulate (cumulates in which cumulus crystals and unzoned poikilitic crystals have the same compositions) with ophitic to subophitic textures. Anorthosite textures may be massive (with

no preferred crystal orientation or stratification) or have igneous layering, including modal layers (defined by variations in percentage of mafic phases), as well as size-graded layering (defined by variations in plagioclase grain size) (Ashwal, 1993). Rhythmic layering is common, although layers may not be laterally persistent. Syndepositional cumulus features, such as cross-bedding, scour features, and slump structures, are well-developed in many intrusive complexes, including parts of the Nain Complex, the Laramie Range anorthosite complex, and the Kunene anorthosite complex (Ashwal, 1993 and references therein). Anorthosites may include xenoliths and roof pendants of country rocks, ranging in diameter from centimeters to kilometers, respectively.

Plagioclase crystals are typically coarse, 1 to 10 cm in length, tabular crystals; megacrysts as much as 1 m long are known (Ashwal, 1993). Pyroxene is present typically as a subophitic or ophitic phase; it may appear as a late fractionate cumulus phase typically ranging in diameter from 10 to 50 cm and commonly related to Fe-Ti-oxide rocks (Ashwal, 1993). Low-Al orthopyroxene megacrysts can also be as long as 1 m. Orthopyroxene is the typical pyroxene present in anorthosite massifs; inverted pigeonite and augite are less common. Olivine is a common cumulus phase in troctolite and leucotroctolite. Iron-Ti oxides are common accessory phases and can be either primary, early liquidus minerals, or late-stage concentrations.

Some massif anorthosite bodies have been variably affected by regional metamorphism ranging from greenschist to granulite facies commonly resulting in a metamorphic overprint of original igneous textures. Such metamorphic overprinting includes mineral replacement (for example, plagioclase replacement by sericite, epidote, or scapolite; pyroxene alteration to amphibole or chlorite), deformation (plagioclase lineations), and development of coronas surrounding crystals (for example, growth of orthopyroxene, clinopyroxene, amphibole, and garnet at the boundaries between plagioclase and olivine) (Ashwal, 1993).

Petrochemistry

Major-Element Geochemistry

During the last century, numerous studies have described the geochemistry and petrogenesis of Proterozoic massif anorthosite (see for example, Ashwal, 1993 and references therein; Buddington, 1972; Emslie, 1978, 1991; Morse, 2006; Seifert and others, 2010; McLelland and others, 2010). Anorthosite, reflecting its plagioclase-rich mineralogy, is characterized by enrichments of SiO_2 , Al_2O_3 , CaO , and Na_2O . With increasing differentiation in a suite of rocks ranging from anorthosite to leuconorite to norite to ferrogabbro, Fe, Mn, Mg, Ti, and P tend to increase, whereas Si, Al, and Ca decrease, in contrast to more typical fractionation trends (see for example, Emslie, 1991; Ashwal, 1993).

Seifert and others (2010) reviewed several hundred major-element analyses of massif anorthosite and associated rocks from the Adirondacks. The authors summarized the major-element content of anorthosite and related rocks (fig. 14). Anorthosite (greater than 90-percent plagioclase) compositions have high SiO_2 (about 53 to 56 weight percent), high Al_2O_3 (about 24 to 27 weight percent), and high CaO (about 9 to 11 weight percent). Leucogabbro compositions (70- to 90-percent plagioclase) have similar SiO_2 (50 to 56 weight percent) but lower Al_2O_3 and CaO than anorthosite because of lower plagioclase content. Gabbro and norite are characterized by widely variable compositions ranging from gabbro to oxide-rich gabbro-norite (OGN) or oxide-apatite gabbro-norite (OAGN). For Adirondack gabbro, SiO_2 ranges from about 46 to 52 weight percent, TiO_2 is typically high (greater than 2 weight percent) for gabbro to very high (4 to 12 weight percent) for OGN and OAGN. Two groups of gabbro can be broken out by MgO content: low MgO (2.45 to 3.06 weight percent) and high MgO (4.3 to 7.34 weight percent). Low MgO gabbro and some high MgO gabbro fall in the tholeiitic field, whereas remaining high MgO gabbro falls in the calc-alkaline field (fig. 14A).

Oxide-gabbro-norite and OAGN have widely varying compositions due to variable mineralogies. These rocks typically have SiO_2 less than 45 weight percent; high Fe_2O_3 , about 16 to 41 weight percent; TiO_2 , about 3.5 to 12.7 weight percent; and P_2O_5 , from about 1.3 to 3.7 weight percent. Noncumulus rocks have increasing average SiO_2 and K_2O with differentiation. For example, jotunite is characterized by 46- to 53-weight percent SiO_2 , 2- to 8-weight percent MgO , and 1- to 3-weight percent K_2O ; monzodiorite is characterized by 54-weight percent SiO_2 and 3.3-weight percent K_2O ; mangerite is characterized by 59-weight percent SiO_2 and 4.8-weight percent K_2O ; and charnockite is characterized by 66- to 71-weight percent SiO_2 and 5.4-weight percent K_2O . Anorthosite suites have strong Fe-enrichment compared with mangerite suites. Anorthosite-leucogabbro-gabbro-OGN+OAGN create one geochemical trend; monzodiorite-mangerite-charnockite create a second geochemical trend; and jotunite overlaps with gabbro where the trends meet (fig. 15).

Trace-Element Geochemistry

Anorthosites, dominated by plagioclase, are enriched in trace elements substituting for Ca^{2+} in plagioclase (for example, strontium (Sr) and europium (Eu)) and are depleted in other trace elements (Ashwal, 1993). Compared to layered intrusions, massif anorthosites have generally high Sr concentrations in the range of 600 to 1,000 parts per million (ppm); some massif andesine anorthosites have Sr concentrations as high as 1,400 ppm (Saint-Urbain) to 2,600 ppm (Labrieville, Quebec) (Ashwal, 1993, and references cited therein). Another distinction between layered intrusions and massif anorthosite is an inverse correlation between Sr concentration and the anorthite content of plagioclase that is common in layered

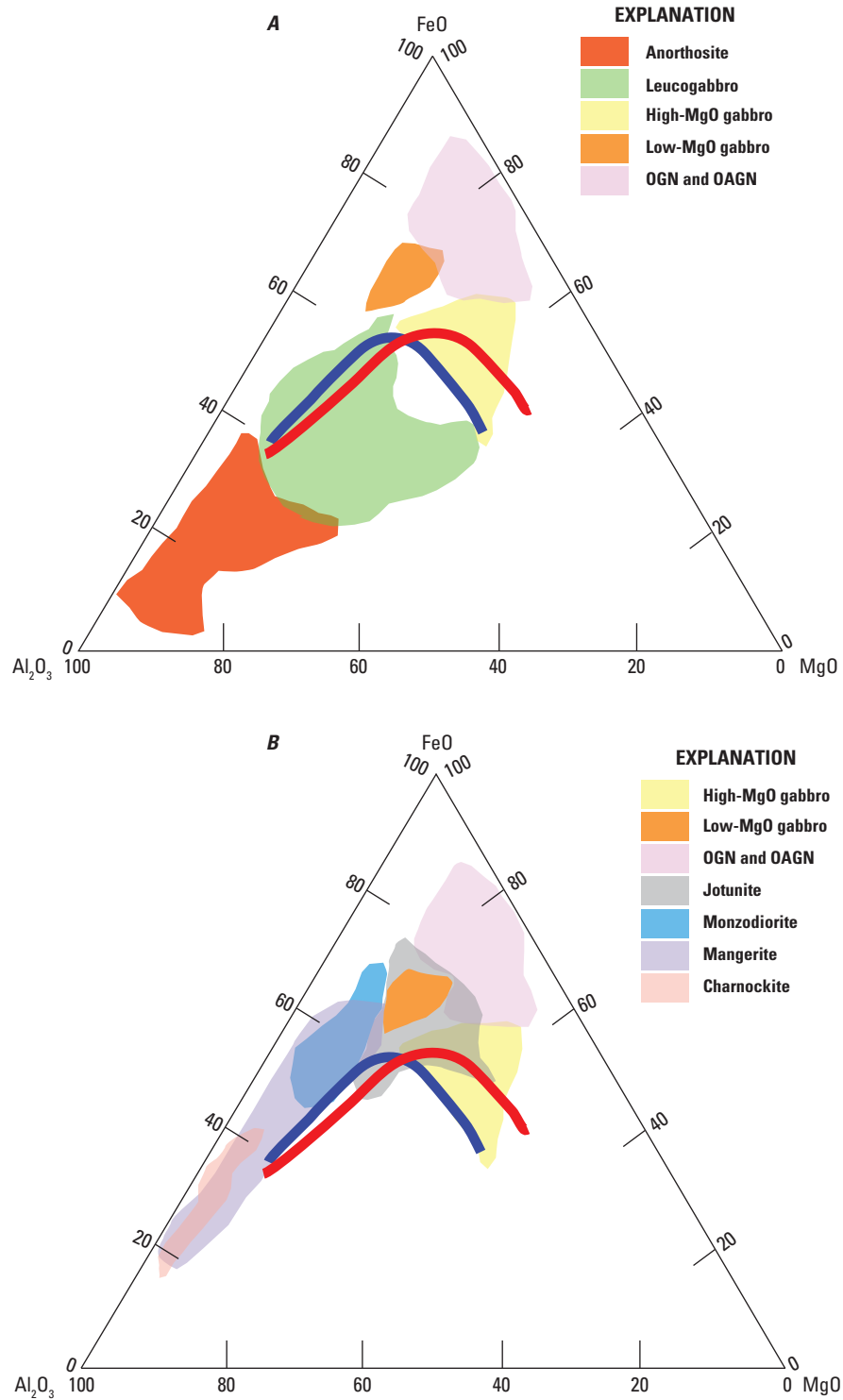


Figure 14. Al_2O_3 –FeO–MgO triangular diagrams showing simplified compositional character of rocks related to Proterozoic massif anorthosite (modified from Seifert and others, 2010). **A.** Anorthosite containing little potash feldspar plots on both sides of the tholeiitic/calc-alkaline boundary (heavy red line) as defined by Irvine and Baragar (1971). Assuming all gabbro follows a tholeiitic trend, then for the Adirondacks, shifting the field boundary (heavy blue line) to include all gabbro on the tholeiitic side may better account for the iron-rich nature of gabbro. Plagioclase-rich anorthosite and leucogabbro trend toward the Al_2O_3 corner, whereas the iron-rich oxide-gabbro (OGN) and oxide-apatite-gabbro (OAGN) trend toward the FeO corner of the diagram. **B.** Mangerite, monzodiorite, and charnockite trend toward the Al_2O_3 corner with increasing potash feldspar contents. Most jotunites plot with the low-MgO gabbros.

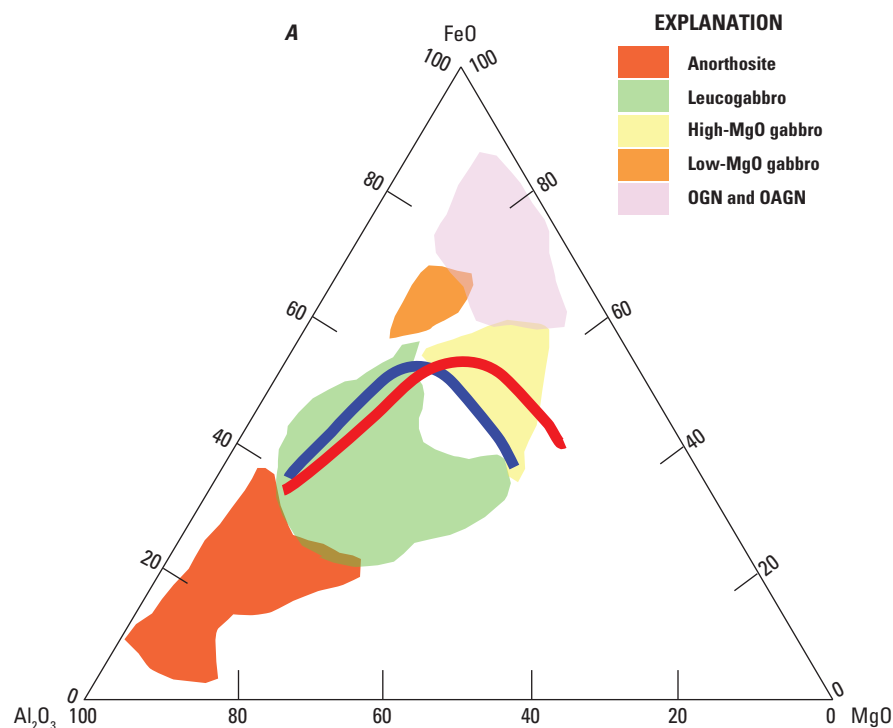


Figure 15. All Adirondack massif anorthosite and related rocks plotted on a $\text{CaO-Na}_2\text{O}+\text{K}_2\text{O-Fe}_2\text{O}_3$ triangular diagram (modified from Seifert and others, 2010). Two distinct trends are apparent. One trend is produced by anorthosite-leucogabbro-gabbro-OGN+OAGN, whereas a separate trend is produced by monzodiorite-mangerite-charnockite. Jotunite overlaps with gabbro. OGN, oxide-gabbro-norite; OAGN, oxide-apatite-gabbro-norite.

intrusions but may or may not be present in massif anorthosite. This suggests a complicated fractionation process for massif anorthosite with mixtures of plagioclase crystals formed under a variety of conditions (Ashwal, 1993).

Plagioclase has an affinity for Eu^{2+} creating plagioclase crystals with strong positive Eu anomalies and residual liquids with significant Eu depletions following plagioclase fractionation. Anorthosite is commonly light REE-enriched with REE concentrations in massif anorthosite generally an order of magnitude higher than concentrations in Archean anorthosite (Ashwal, 1993). When late-stage rocks, such as ferrodiorite, have high overall REE concentrations, negative Eu anomalies, and flat or depleted light REE concentrations, as noted for the Marcy Anorthosite (Ashwal and Seifert, 1980) and in the Laramie Range anorthosite complex (Goldberg, 1984), the rocks developed from fractionated liquids after anorthosite generation and extraction of significant plagioclase (fig. 16). However, in the Rogaland Province, ferrodiorite and related rocks have smooth REE patterns with no Eu anomaly suggesting that these rocks were not derived by the same fractionation process that produced anorthosite (Duchesne and others, 1974).

Isotope Geochemistry of Igneous Rocks

Stable Isotope Geochemistry

Stable isotopes have been used to assess the importance of crustal contamination in establishing the origin for Fe-Ti-oxide deposits related to Proterozoic massif anorthosite, study possible fluid-rock exchange, and evaluate depth of emplacement of host massif anorthosite intrusions.

In the Rogaland Province, Wilmar and others (1994) analyzed carbon (C), hydrogen (D), and oxygen (O) isotopic compositions in whole-rock and plagioclase samples from the Åna-Sira anorthosite, the Tellnes orebody, and surrounding granulite-facies gneisses. Whole-rock and plagioclase $\delta^{18}\text{O}$ values from anorthosite have strong homogeneity with an average $\delta^{18}\text{O}$ value of 6.1 ± 0.3 ‰, suggesting a mantle origin for anorthosite with little to no crustal contamination. Whole-rock $\delta^{18}\text{O}$ values of norite from the Tellnes dike have a similar narrow range ($\delta^{18}\text{O} = 4.9$ to 6.0 ‰). Surrounding gneisses have a much broader variation ($\delta^{18}\text{O} = 2$ to 9 ‰) considered to reflect the original compositions of the gneisses. Low-water

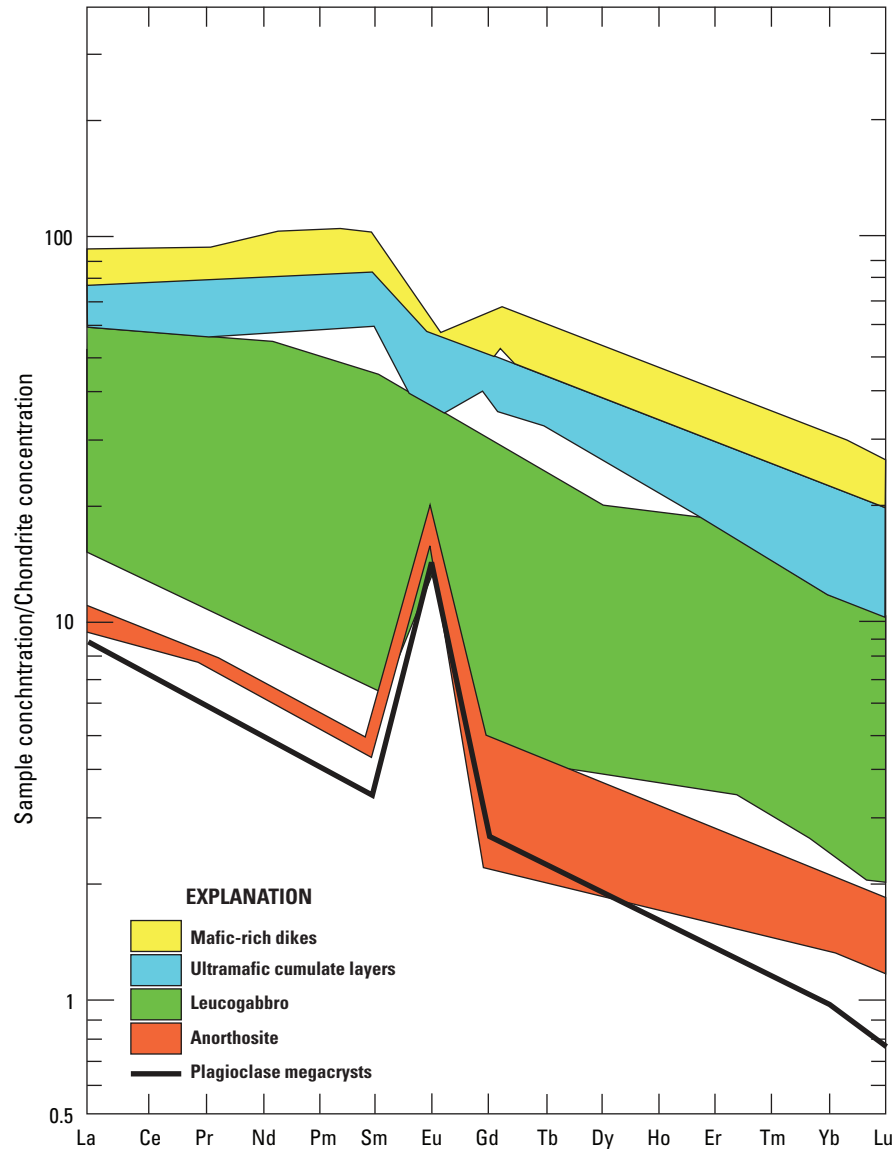


Figure 16. Chondrite-normalized rare earth element (REE) patterns for representative samples of the anorthosite suite from the Marcy massif anorthosite, Adirondacks, New York (modified from Ashwal and Seifert, 1980).

content of all analyzed igneous and metamorphic rocks suggests little modification of granulite-facies rocks after intrusion emplacement. Whole-rock δD (about -82 to -63 ‰) and $\delta^{18}O$ (about 6.1 ‰) values suggest a dominantly magmatic signature in intrusions and orebody (fig. 17). As a cumulate rock, anorthosite is low in carbon content. Interstitial carbonate is present within a few hundred meters of the margin of the anorthosite; however, carbonate appears to have precipitated from magmatic fluids with an estimated $\delta^{13}C$ value of -5.3 ‰ and related to late intrusions, rather than being derived from the surrounding metamorphic gneisses (Wilmart and others, 1994).

Valley and O'Neil (1982) analyzed wollastonite from skarns surrounding Adirondack anorthosite bodies. Plagioclase

phenocrysts in anorthosite have $\delta^{18}O$ values ranging from 7.8 to 9.3 ‰. Amphibolite into which anorthosite was emplaced has $\delta^{18}O$ values from 6.3 to 9.3 ‰. In contrast, wollastonite in skarn within 130 m of anorthosite is strongly depleted, with $\delta^{18}O$ values from 2.9 to -1.3 ‰. This zone of strong $\delta^{18}O$ depletion suggests interaction with hot meteoric water, which can only occur at shallow levels of less than 10 km. This observation led Valley and O'Neil (1982) to conclude that Adirondack anorthosites may have intruded at a wide range of depths, not necessarily just under granulite-facies conditions at depths of 20 – 30 km.

Taylor (1969) determined a range of $\delta^{18}O$ values from 5.8 to 7.6 ‰ for "normal" unmetamorphosed massif-type Adirondack anorthosite. This range is similar to $\delta^{18}O$ values for

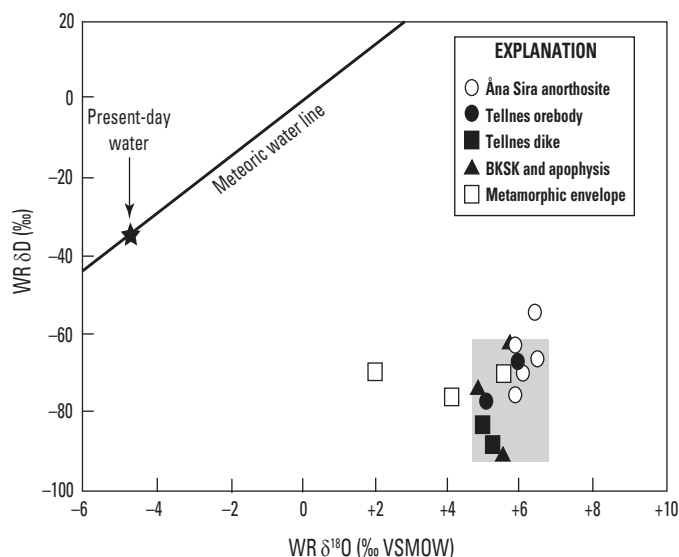


Figure 17. Whole-rock δD (WR δD) versus $\delta^{18}O$ for the Åna-Sira anorthosite, the Tellnes orebody, and norite dike hosting the Tellnes orebody; the Bjerkreim-Sokndal layered intrusion (BKS) and apophysis, and the metamorphic envelope of gneiss in the Rogaland Anorthosite Province (modified from Wilmarth and others, 1994). Also shown are the fields for present-day water and magmatic hydroxyl (magmatic “water” fixed as hydroxyl radicals in silicates under magmatic pressure-temperature conditions; gray box on graph). Abbreviations include ‰, per mil; VSMOW, Vienna Standard Mean Ocean Water, a primary reference water standard for relative oxygen and hydrogen isotopic measurements).

mantle-derived basalt and gabbro ($\delta^{18}O = 5.4$ to 7.4 ‰; Kyser and others, 1982). Morrison and Valley (1988) examined the unusual Marcy Anorthosite and reported significantly different values: most whole-rock anorthosite analyses had an average $\delta^{18}O$ value of about 9.5 ‰. Although a few rocks had depleted values ($\delta^{18}O = 3.0$ to 5.8 ‰), from a total of 93 analyses, only two values plotted in the range of expected magmatic values. After ruling out $\delta^{18}O$ enrichment caused by regional metamorphism, Morrison and Valley (1988) concluded that the probable cause of observed oxygen isotopic enrichment was crustal contamination of Marcy parental magma near the base of the crust.

Peck and others (2010) compiled $\delta^{18}O$ whole-rock and plagioclase values for many Proterozoic anorthosites (fig. 18). The $\delta^{18}O$ isotopic compositions of Nain Complex anorthosites are consistent with derivation from a mantle source contaminated by either lower crustal rocks of the Churchill Province ($\delta^{18}O = 6.5$ to 8.2 ‰) or the Nain Province ($\delta^{18}O = 4$ to 7 ‰) prior to emplacement (Peck and others, 2010). Many anorthosites from the Grenville allochthonous polycyclic belt, including Havre-Saint-Pierre anorthosite with $\delta^{18}O$ of about 9.5 ‰ and Allard Lake anorthosite with $\delta^{18}O$ of about 7.9 ‰, have a narrow range of $\delta^{18}O$ values averaging about 7 ‰ suggesting mantle derivation with some crustal contamination. Anorthosites in the Grenville allochthonous monocyclic belt, including

the Marcy Anorthosite, have a higher and broader range ($\delta^{18}O = 8$ to 11 ‰). Peck and Valley (2000) attributed these higher $\delta^{18}O$ values to low-temperature hydrothermally altered crust, perhaps old ocean crust, emplaced into the lower crust and subsequently melted and mixed with the parental source of these anorthosites.

Radiogenic Isotope Geochemistry

Radiogenic isotopic characteristics of anorthosite and related rocks have been used to determine emplacement age—although improved U-Pb dating of zircon and baddeleyite now provides precise ages for most rocks—and to assess relative contributions of mantle and crustal derived components in anorthosite sources. Schiellerup and others (2000) summarized Proterozoic massif-type anorthosite radiogenic isotopic signatures. They showed that if olivine-bearing anorthosite and leucotroctolite are present in an unmetamorphosed massif anorthosite suite, those rock types will be characterized by the most primitive neodymium (Nd) isotopic compositions, thereby providing the closest estimates of parental melt compositions. A wide range of isotopic compositions is thought to reflect heterogeneities in the upper mantle. Gleissner and others (2011) also pointed out that Sr isotopic compositions of individual plagioclase megacrysts are commonly less radiogenic than whole-rock analyses of the same rock. This suggests that for some anorthosite complexes, secondary (that is, metamorphic) processes can affect observed Sr isotopic compositions.

In the Kunene anorthosite complex in Namibia, anorthositic rocks range in initial ϵ_{Nd} values from $+1.1$ to $+3.0$. The ϵ_{Nd} notation represents the deviation of the $^{143}Nd/^{144}Nd$ ratio in the rock sample compared to an evolution line determined by the $^{143}Nd/^{144}Nd$ ratio calculated for a chondritic uniform reservoir (CHUR) over time (DePaolo and Wasserburg, 1976). An initial ϵ_{Nd} value compares the sample’s $^{143}Nd/^{144}Nd$ deviation from the CHUR evolution line at the time that the parent magma of that rock sample separated from the uniform reservoir, in the case for the Kunene anorthosite complex, at around 1371 ± 2.5 Ma (Mayer and others, 2004). The Kunene anorthositic rocks also have initial $^{87}Sr/^{86}Sr$ ratios of 0.7028 to 0.7041 . Unaltered related felsic rocks have initial ϵ_{Nd} values from $+0.4$ to $+2.2$ and initial $^{87}Sr/^{86}Sr$ ratios of 0.7025 to 0.7043 , calculated for a rock age of 1371 Ma. Unaltered related felsic rocks have initial ϵ_{Nd} values and initial $^{87}Sr/^{86}Sr$ ratios of 0.7025 to 0.7043 , whereas altered felsic rocks have initial ϵ_{Nd} values from -0.4 to 2.5 and initial $^{87}Sr/^{86}Sr$ ratios of 0.7063 to 0.7076 (Drüppel and others, 2007). The Sr isotopic compositions appear to have been more significantly affected by alteration than the Nd isotopic compositions.

Anorthositic and noritic samples from three Norwegian massif anorthosites (Egersund-Ogna, Håland-Helleren, and Åna-Sira; fig. 3) were analyzed for Sr, Nd, and Pb isotopic compositions (Demaiffe and others, 1986). Initial $^{87}Sr/^{86}Sr$ ratios vary widely among the three intrusions from 0.7030 for plagioclase and orthopyroxene megacrysts in the

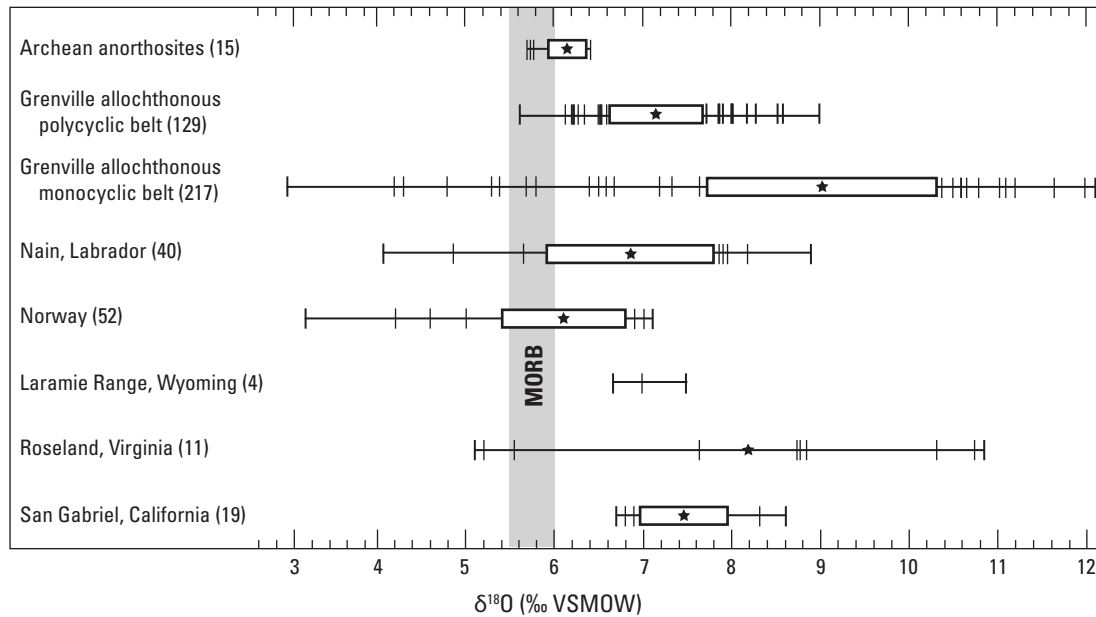


Figure 18. Compilation of $\delta^{18}\text{O}$ whole-rock and plagioclase values for Proterozoic anorthosites (omitting bodies partially converted to scapolite) (modified from Peck and others, 2010). The gray band represents $\delta^{18}\text{O}$ whole-rock values for modern ocean ridge basalts (MORB). Values in parentheses are the number of analyses (n); stars are the average value. In datasets with n larger than 7, the rectangle encloses ± 1 standard deviation. Archean anorthosites, which as a group have uniform $\delta^{18}\text{O}$ values close to MORB, are shown for reference.

Egersund-Ogna intrusion to 0.7077 for a jotunitic dike. The lower part of the Bjerkreim-Sokndal intrusion has an average initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of about 0.7055, somewhat above a typical mantle value of about 0.7030. More acidic rocks have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios as high as 0.7080 suggesting derivation either from somewhat contaminated upper mantle magma or from partial melting of the lower crust. In contrast, initial ϵ_{Nd} values for both anorthosite and jotunitic rocks range from about +1.8 to +5.5 (Demaiffe and others, 1986) suggesting likely derivation from a mantle source. Locally, more acidic rocks have less positive to slightly negative initial ϵ_{Nd} values suggesting progressive contamination of a mantle-derived magma with lower crustal melts.

Lead (Pb) isotopic compositions of various massif anorthositic complexes are internally consistent but vary among intrusions (see for example, Weis, 1986). Most Pb isotopic linear arrays do not represent isochrons, but rather mixing lines. In the Bjerkreim-Sokndal layered intrusion, for example, anorthosite and leuconorite have $^{206}\text{Pb}/^{204}\text{Pb}$ ratios from 17.718 to 17.879, $^{207}\text{Pb}/^{204}\text{Pb}$ ratios from 15.518 to 15.540, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios from 37.156 to 37.202 (Weis, 1986; Demaiffe and others, 1986). Mangerite and jotunitic rocks from the same intrusion have $^{206}\text{Pb}/^{204}\text{Pb}$ ratios from 18.001 to 19.033, $^{207}\text{Pb}/^{204}\text{Pb}$ ratios from 15.548 to 15.642, and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios from 37.240 to 38.097 (Weis, 1986). Based on these three radiogenic isotopic systems, Demaiffe and others (1986) concluded that these anorthositic intrusions were derived from depleted upper mantle or, possibly, by melting of mafic rocks in the

lower crust. Progressive contamination of primary magmas may have given rise to more acidic rocks in the suites.

Bolle and others (2003) summarized available Sr and Nd isotopic data for the Rogaland Province, including data for anorthosite, jotunitic, and charnockite. More than 200 initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have a range of 0.7033 to 0.7227, with an average of 0.7066. Anorthosite from the Egersund-Ogna, Håland-Helleren, and Åna-Sira massifs have initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of 0.7033 to 0.7063, with an average of 0.7047. Strontium and Nd isotopic compositions in three Norwegian layered mafic intrusions, including the Bjerkreim-Sokndal intrusion, were used to model the amount of possible crustal contamination that may occur in basaltic and jotunitic magmas. Tegner and others (2005) determined that the ratio of mass assimilated to mass crystallized for layered mafic intrusions ranges from about 0.1 to about 0.3 in basaltic and jotunitic magmas emplaced into the middle crust. Relatively constant Sr and Nd isotopic ratios suggested a steady assimilation-fractional crystallization process for these intrusions, and modeling suggested that assimilation was not a selective process but one of incorporation of large-fraction partial melts.

Osmium (Os) isotopes have been used to establish ages for Fe-Ti-oxide deposits and to evaluate the role of the crust, particularly the lower crust, in anorthosite magma sources (Schiellerup and others, 2000; Hannah and Stein, 2002; Gleissner and others, 2012). Rhenium (Re) is fractionated very efficiently from Os during mantle melting, resulting in significant concentration of Os in the upper mantle compared

to lower crust (Schiellerup and others, 2000). Thus, the Re-Os isotopic system is an excellent discriminator between mantle and crustal components. In the Rogaland Province, Schiellerup and others (2000) analyzed unmineralized anorthosite, anorthosite-hosted sulfide deposits, cumulate rocks from the Bjerkreim-Sokndal layered intrusion, and two ilmenite-rich cumulate dikes. All samples yield well-defined Re-Os and Sm-Nd isochrons of 917 ± 22 Ma and 914 ± 35 Ma, respectively, which in turn agree well with U-Pb zircon ages of 930–920 Ma (Schärer and others, 1996). Initial $^{187}\text{Os}/^{186}\text{Os}$ of the isochron is 0.63 ± 0.25 , with an initial $\gamma_{\text{Os}} = +419$, compared to an upper mantle γ_{Os} of about 0 ± 15 (γ_{Os} is the percent deviation of sample $^{187}\text{Os}/^{186}\text{Os}$ from average chondritic $^{187}\text{Os}/^{186}\text{Os}$). These data suggest that Rogaland anorthosites and related deposits were derived from melting of mafic source rocks in the lower crust with an age of 1,400 to 1,550 Ma. Based on Re-Os isotope characteristics, Gleissner and others (2012) determined that two phases of the anorthosite suite in the Kunene anorthosite complex, dark anorthosite and white anorthosite, had different (though related) origins. Dark anorthosite yielded initial $^{187}\text{Os}/^{186}\text{Os}$ ratios from 0.2 to 1.14, with initial γ_{Os} ranging from 48 to 872, whereas white anorthosite yielded initial $^{187}\text{Os}/^{186}\text{Os}$ ratios as high as 5, with an initial γ_{Os} of 3,982. Gleissner and others (2012) concluded that dark anorthosite was mainly mantle-derived with crustal contamination of less than 10 percent, whereas white anorthosite likely was derived from mantle melts with crustal contamination of about 30 percent.

Radiogenic Nd, Pb, and Sr isotopic compositions of unmetamorphosed massif anorthosite complexes commonly suggest that these bodies are derived from partial melts of the upper mantle (mantle plume model of Ashwal, 1993) and (or) partial melting of lower crustal material that has been thrust into the mantle (crustal-tongue delamination model of Longhi and others, 1999; Gauthier and Chartrand, 2005). The Nd and Pb isotopic signatures of the more felsic portions of these complexes suggest progressive contamination of mantle magmas by lower crustal melts (for example, the Rogaland Province). Strontium isotopic compositions are commonly affected by secondary metamorphic processes and thus may show a broad isotopic variation. In contrast to other isotopic systems, Re-Os isotopic determinations of anorthosites and associated sulfide fractions typically suggest very significant crustal contributions. However, fractionation of Re and Os during partial melting of the upper mantle leads to strong partitioning of Re into the crust. Selective assimilation of crustal sulfide through partial melting or devolatilization will result in high initial γ_{Os} values in the anorthositic magma and associated sulfides (Hannah and Stein, 2002). Thus, the variation of radiogenic isotopic values among anorthositic complexes reflects a wide range of possible processes that contribute to the isotopic characteristics of any given anorthosite complex and related mineral deposits (Hannah and Stein, 2002; Gauthier and Chartrand, 2005).

Petrology of Associated Sedimentary Rocks

Sedimentary rocks are not genetically related to magmatic Fe-Ti-oxide deposits related to Proterozoic massif anorthosite suites.

Petrology of Associated Metamorphic Rocks

Metamorphic rocks are not genetically related to magmatic Fe-Ti-oxide deposits related to Proterozoic massif anorthosite suites.

Theory of Deposit Formation

Ore Deposit System Affiliation

Magmatic Fe-Ti-oxide deposits that are economic for Ti are produced by complex magmatic processes from Ti-enriched parental magma in geologic terranes containing Proterozoic massif anorthositic plutonic suites and related rocks.

Sources of Ti-Fe-P-Ore Components

Residual magmas derived from andesine-type anorthosite parental magmas can become enriched in Fe, Ti and P, potentially forming economic Fe-Ti-oxide deposits. In the underplating mantle-plume model of Ashwal (1993), crystallization of olivine and high-Al orthopyroxene megacrysts in a deep magma chamber would enrich residual melts in Fe, Ti, and P, producing a composition close to ferrodiortite. In the crustal-tongue delamination model (Longhi and others, 1999; Duchesne and others, 1999), Fe-Ti-P-enriched magmas are produced by direct melting of subducted gabbro-norite crustal rocks. In either case, Ti-enriched magma will then rise to the middle to upper crustal levels entrained in diapiric plagioclase-rich mushes.

Mechanisms that Concentrate Ore

Existence of a primary Fe-Ti-P-rich magma alone is insufficient to produce an economic Fe-Ti-oxide deposit, as attested by numerous common occurrences of noneconomic Fe-Ti-oxide deposits in anorthositic suites (see for example, Hébert and others, 2005; Corriveau and others, 2007). Ilmenite, the most important ore mineral, has to crystallize as discrete grains and be concentrated by physical magmatic processes to create an economic Ti orebody. For hemo-ilmenite deposits, a critical first step is crystallization

of ilmenite, with plagioclase, as an early liquidus mineral, as postulated at Tellnes (Wilmart and others, 1989), Lac Tio (Charlier and others, 2010), the Bjerkreim-Sokndal layered intrusion (Wilson and others, 1996), and the Grader layered intrusion (Charlier and others, 2008). A second critical step is separation of ilmenite from plagioclase but through a process more efficient than cumulate behavior in a static magma chamber, such as the Bjerkreim-Sokndal intrusion, where the quantity of plagioclase+ilmenite cumulates is much less than the quantity of other cumulates (Wilson and others, 1996). One plausible model suggests flushing of oxide-laden magma through magma conduits or dike-like systems where dense oxide phases are segregated from plagioclase by flow and concentrated in traps created by wall-rock/conduit irregularities (for example, Tellnes, Wilmart and others, 1989; Big Island dike, Morisset and others, 2010; Lac Tio, Charlier and others, 2010). Eight discrete pod and dike-like Fe-Ti-oxide deposits in the Saint-Urbain anorthosite may represent keels to a large evolving system in which ilmenite collected in cracks and fractures in older anorthosite along the base of a chamber, whereas plagioclase was transported away by a moving and crystallizing magma (Morisset and others, 2010). Charlier and others (2006) present a similar argument for Tellnes by which the sickle-shape orebody represents the lower part of a larger sill deformed into its current shape by gravity-induced subsidence and anorthosite diapirism of the underlying host Åna-Sira anorthosite; the upper, more evolved parts of the hypothetical sill are not exposed or have been removed.

Summary of the Origin of Magmatic Fe-Ti-Oxide Deposits

Magmatic Fe-Ti-oxide deposits that are an economic resource for Ti are restricted by both host rock and age constraints; these constraints are likely the consequence of a particular combination of tectonic circumstances rather than any a priori temporal control. The arguments for immiscible Fe-Ti-P-rich liquids co-existing with complementary silicate liquids (see for example, Philpotts, 1967; Kolker, 1982) have been refuted by experimental studies (Lindsley, 2003) and field evidence supporting early magmatic crystallization of ilmenite (see for example, Duchesne, 1999). The tectonic controls required to create abundant free ilmenite, rather than titaniferous magnetite from which it is metallurgically difficult to separate Ti, include (1) favorable source rocks for melting, which are either those related to decompression melting of asthenospheric mantle (see for example, Morse, 1981; Corrigan and Hanmer, 1997; Scoates and Mitchell, 2000; Regan and others, 2011) or delamination-related melting of lower crust underthrust into the mantle (see for example, Longhi and others 1999; Duchesne and others, 1999) to create Ti-endowed parent magmas; (2) an environment favorable to development of andesine-type massif anorthosite rather than labradorite-type anorthosite (see for example, Anderson and Morin, 1969; Ashwal, 1993; Hébert and others, 2005); and (3) magmatic

conditions in the middle to upper crust that would lead to crystallization of ilmenite as one of the first liquidus minerals and subsequent concentration of that ilmenite into massive orebodies. A generalized diagram of possible magmatic evolution paths that could lead to differing oxide concentrations is given in figure 19.

The magmatic evolution presented in figure 19 is divided into four stages. The first two stages are common for all Fe-Ti-oxide deposits, whereas the latter stages result in unique mineral assemblages. Stage 1 consists of magma chambers developed at the base of the lithosphere that undergo plagioclase and Fe-Mg silicate fractionation, leading to stage 2, which is density separation and diapiric upward migration of a plagioclase + Fe- and Ti-enriched crystal-liquid mush. Crustal assimilation and further crystallization during ascent can influence both oxygen fugacity and silica activity within the diapiric mush, driving the system toward two possible outcomes. One outcome (stage 3) follows the paths depicted on the left part of figure 19, which leads to crystallization of ilmenite as an early liquidus phase. A trend of silicate crystallization along the right side of figure 19 (stage 4) concentrates Ti-Fe±P into residual melts. Outcomes along stage 3 are represented by massive hemo-ilmenite bodies in host andesine-type anorthosite and cumulate plagioclase+ilmenite in layered intrusions. Outcomes along stage 4 result in the occurrence of assemblages such as titanomagnetite+ilmenite±apatite, in labradorite-type host anorthosite and related mafic rocks or as concentrations in layered intrusions typically with olivine as an early liquidus mineral.

Early crystallization of ilmenite in stage 3 is a critical factor for development of a potentially economic hemo-ilmenite deposit versus a probably subeconomic titanomagnetite-ilmenite±apatite deposit. When ilmenite is an early liquidus mineral, it invariably has a high hematitic component suggesting that oxygen fugacity is a critical parameter controlling oxide-mineral assemblage. Both silica activity and oxygen fugacity are controlled by assimilation of continental crust, and this control carries through to the oxide-mineral assemblage and plagioclase composition (Morse, 2006; Frost and others, 2010). A great variety of rock types in the crust, from Archean rocks to more juvenile crust related to subduction events, creates a wide range of possible mineral and rock assemblages that could contaminate uprising anorthositic magmas. Crustal assimilation of materials that results in higher oxygen fugacity and silica activity favors early saturation of ilmenite. The dynamic environment of anorthosite emplacement, the persistence of ductile behavior in slowly cooled anorthositic plutons (for example, cooling rates of 3–4 °C per million years estimated by Morisset and others (2009) for the Saint-Urbain anorthosite), and the density contrast between plagioclase (≈ 2.67 grams per cubic centimeter (g/cm^3)) and ilmenite (≈ 4.72 g/cm^3) will facilitate hydrodynamic sorting of dense oxides from plagioclase-rich mushes, concentrating oxides into layers and traps.

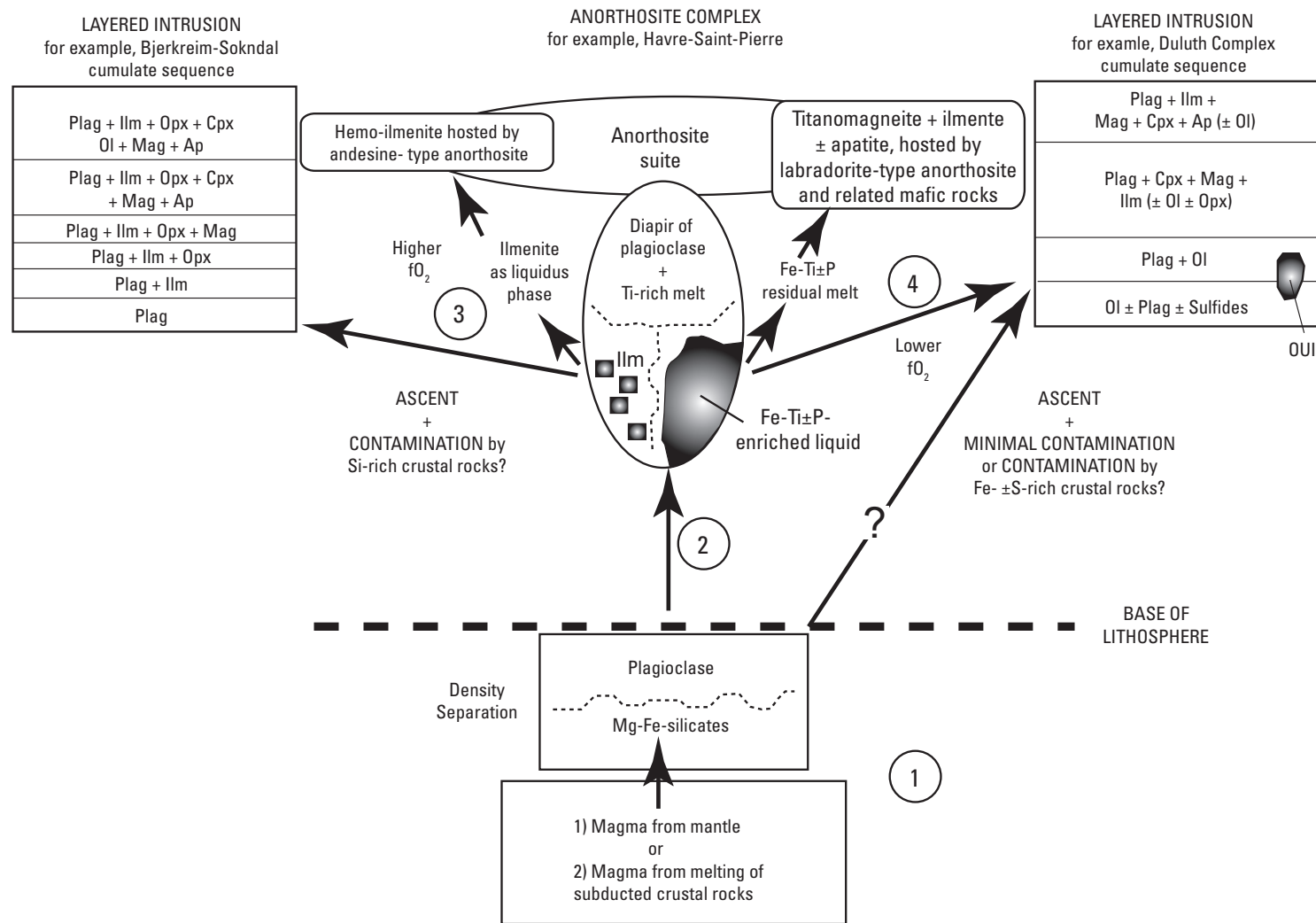


Figure 19. Hypothetical model for the magmatic evolution of Fe-Ti-oxide deposits, which is described in detail in the text. The cumulate sequence for the Bjerkreim-Sokndal layered intrusion is adapted from Wilson and others (1996), and the cumulate sequence for the Duluth Complex is adapted from Miller and Ripley (1996). Mineral abbreviations: Plag = plagioclase, Ilm = ilmenite, Mag = magnetite, Ol = olivine, Opx = orthopyroxene, Cpx = clinopyroxene, Ap = apatite. fO_2 , oxygen fugacity; OUI, oxide-bearing ultramafic intrusions.

The OUIs in the Duluth Complex are late-stage plugs and vertical lenses of oxide-bearing ultramafic rocks intruding troctolitic rocks. Severson and Hauck (1990) and Severson (1994) speculated that OUIs may have formed from assimilation of the underlying Biwabik Iron-Formation, or by possible infiltration metasomatism by late-stage Fe- and Ti-, and volatile-rich, intercumulus fluids expelled from crystallizing magma chambers. However, the generally low Ti content of the Biwabik Iron-Formation and existence of a number of oxide bodies where iron-formation is not in the Duluth Complex footwall preclude assimilation as an origin for all bodies, and the magma dynamics required to intrude dense, iron-rich partial melt high into the Duluth Complex remain speculative (Hauck and others, 1997). An origin for OUIs in the Duluth Complex continues to be somewhat enigmatic.

Geological Assessment Guides

Attributes Required for Inclusion in Permissive Tract at Various Scales

At a regional scale, Proterozoic massif anorthosite plutonic suites and related rocks represent a permissive tract. Within these regional tracts, ilmenite deposits may be best developed in anorthosite bodies intruded along deep-seated fracture systems developed at the margins of major tectonic provinces and belts. Locally, andesine-type anorthosite plutonic suites less than 1060 Ma are the more favorable rock type for the occurrence of deposits with desirable discrete, individual ilmenite grains.

Geochemical Considerations

Most Fe-Ti-oxide deposits were discovered by physical exploration and geophysical methods. The occurrence of ilmenite in fluvial heavy-mineral deposits may be an efficient method for backtracking to source areas prospective for Fe-Ti-oxide deposits in anorthosite and gabbro (Force, 1991; Gauthier, 2003).

Geophysical Attributes

At this time, exploration for ilmenite deposits is not only focused on grade and tonnage but also on finding ilmenite suitable for pigment processing (for example, Cr- and Mg-poor ilmenite). These criteria depend on relations among magmatic evolution, major- and trace-element chemistry, and subsolidus re-equilibration. One of the better guides for future prospecting for workable and chemically suitable ilmenite resources may rely in part on aeromagnetic signatures of the Fe-Ti oxides that record ore microtextures, which can be related back to ore chemistry (McEnroe and others, 2000).

Aeromagnetic maps over favorable terranes may have a spectacular range of positive and negative anomalies because of highly contrasting rocks and possible deposit types (McEnroe and others, 2001). Concentrations of hemo-ilmenite commonly have distinctive negative magnetic anomalies or mixed patterns of positive and negative anomalies. Strong positive anomalies related to magnetite content may point toward less economically favorable titanomagnetite concentrations. Iron-Ti oxides and their host rocks commonly have higher gravity anomalies than surrounding anorthositic, granitic, or gneissic country rock, and oxides produce a strong contrast to silicates (Gross, 1996). The shape and physical characteristics of OUIs in the Duluth Complex create small, round, intense spots of gravity and aeromagnetic highs in regional geophysical maps that represent obvious exploration targets (Chandler, 2002).

Geoenvironmental Features and Anthropogenic Mining Effects

Soil and Sediment Signatures Prior to Mining

Baseline characterization studies surrounding magmatic Fe-Ti-oxide deposits hosted by anorthosite complexes are absent in the literature. Trace elements in soil and sediment would be related to those elements incorporated into Fe-Ti-oxide structures (for example, Co, Cr, Ni, V, and Zn) or contained in sparse sulfide minerals (for example, Co, Cu, Ni, and Zn) (Duchesne and Bologne, 2009). Titanium ore from Tellnes has concentrations of about 110-ppm Co, 250-ppm Cr, 430-ppm Ni, 795-ppm V, and 128-ppm Zn (Wilmart and others, 1989). Thus, pre-mining sediment and soil signatures could include slightly elevated concentrations of Co, Cu, Cr, Fe, Ni, Ti, V, or Zn. Because magmatic Fe-Ti-oxide deposits do not have related hydrothermal systems, trace-element mobility is limited, and thus patterns of anomalously high metal concentrations would be restricted to short distances from oxide mineralization.

Secondary Minerals

Alteration and weathering play little role in the development of magmatic Fe-Ti-oxide deposits; thus environmental concerns related to secondary minerals are not an issue.

Drainage Signatures

Acid-mine drainage related to mineralization and mining can be a serious concern. The reaction of sulfides, mainly pyrite and pyrrhotite, in an aqueous environment with oxygen, mediated by bacteria, generates sulfuric acid (Plumlee, 1999; Nordstrom and Alpers, 1999). Acid then attacks other metal-containing minerals, often sulfides, and can release additional metals into the environment through aqueous transport.

At near-neutral pH, many metals either precipitate out of solution or are adsorbed to amorphous iron hydroxides thus becoming relatively immobile (Smith, 1999). However, some metals, such as Co, Ni, and Zn, will remain in solution even at neutral pH. Drainage water with near-neutral pH and elevated concentrations of dissolved metals is termed contaminated neutral drainage (CND). Plante and others (2008) addressed CND from the Lac Tio mine, Quebec, which sporadically contains Ni at levels slightly higher than local regulations allow. The source of the Ni was from the weathering of Ni-bearing sulfides found in small quantities in the ilmenite ore. Their research assessed sorption capacities of ore and waste rock and indicated that Ni sorption by residual ilmenite and plagioclase in waste rock played a significant role in the Ni geochemical behavior. Plagioclase is an effective acid neutralizer (Gunsinger and others, 2006; Cook, 1988), and Plante and others (2008) determined that any acid generated by sulfides in mine waste from Lac Tio was neutralized by silicates.

The abandoned Storgangen mine in the Rogaland Province produced 8 Mt of tailings. Annual precipitation in the area is about 194 cm, and 750,000 m³ of water drains from the impoundment annually. This runoff subsequently reaches the North Sea, a distance of about 5 km and has a neutral pH but a median Ni concentration of 3.2 milligrams per liter (mg/L) (n=24) (Ettner, 1999). A passive treatment system was designed and tested to remove Ni with variable efficacy over time (Ettner, 1999, 2007).

Climate Effects on Geoenvironmental Signatures

Three climate factors have the most effect on the environmental geology and geochemistry of mineral deposits: temperature, humidity, and precipitation. A cold climate tends to inhibit weathering, as does a dry climate and low precipitation, whereas a wet climate leads to a shallow water table, which tends to preclude deep weathering (Plumlee, 1999). However, differences in geologic characteristics have a greater effect on pH and metal content in deposit-related waters than do differences in climate for a given deposit type (Plumlee, 1999).

Past and Future Mining Methods and Ore Treatment

Many Fe-Ti-oxide deposits were mined for their Fe content before the value of the contained Ti was known (for example, the Sanford Hill/South Extension deposit). Early exploitation of magmatic Fe-Ti-oxide deposits was often by underground mining methods, whereas present-day operations at both Tellnes and Lac Tio employ open-pit operations.

There are two main industrial processes used to convert ilmenite into TiO₂: the sulfate process and the chloride process (Mackey, 1994). The sulfate process is the older of the two, perfected in 1916 by two Norwegian chemists (Korneliusson and others, 2000). In the sulfate process, finely ground

ilmenite, or high-TiO₂ slag, derived by smelting low-TiO₂ hemo-ilmenite feedstock with anthracite coal in an electric-arc furnace (Guéguin and Cardarelli, 2007), is digested with concentrated sulfuric acid. After initial heating, an exothermic reaction results in formation of a porous cake, which is then dissolved in dilute acid and water to yield titanyl sulfate (TiOSO₄) and iron sulfates (Chernet, 1999). Iron sulfate is removed as crystallized ferrous heptahydrate (FeSO₄·7H₂O), also known as copperas. Environmental concerns with the sulfate process include neutralization or regeneration of large amounts of sulfuric acid and disposition of large quantities of copperas. According to Mackey (1994), 3.5 tonnes of waste are produced for 1.0 tonne of TiO₂ product using the sulfate process. Copperas may be used in water-treatment operations, for soil enhancement, in animal feed, and for reduction of hexavalent chromium (Cr VI) in cement, but production far outstrips demand and large quantities of copperas are either stockpiled or disposed of as landfill (Filippou and Hudon, 2009). Accessory Cr in waste material can also be an environmental concern (Korneliusson and others, 2000).

The chloride process was developed in the 1950s (Mackey, 1994). This process requires higher grade TiO₂ feedstock, such as rutile from beach sands, Ti-rich slag derived from ilmenite, or synthetic rutile derived from leached ilmenite. Feed material is calcined with coke and chlorine to form gaseous titanium tetrachloride, which is then condensed and impurities separated as solids. The liquid is reheated to a gaseous state and mixed with hot oxygen to form fine high-purity rutile (white TiO₂ pigment) (Sahu and others, 2006). Displaced chlorine gas can be recycled and reused. This process produces only 0.2 tonnes of waste per tonne of TiO₂ product (Mackey, 1994). As of 1992, the sulfate and chloride processes produced about equal amounts of product. However, because of a superior TiO₂ pigment product and fewer waste products, the chloride process has mainly supplanted the sulfate process (Joseph Gambogi, USGS, oral commun., 2012). This shift from the sulfate route for TiO₂ pigment production to the chloride route has increased demand for high-grade TiO₂ feedstock. For ilmenite from magmatic deposits to be viable for the chloride process, it has to be upgraded to Ti-rich slag. A process developed by BHP Billiton, and purchased by Altair in 1999, dispenses with the filtration step and utilizes a spray hydrolyzer to produce nanoparticles of TiO₂ (Verhulst and others, 2003).

Metal Mobility from Solid Mine Waste

Placement of mine waste under low-oxygenated water is a suggested waste management practice (Plumlee and Logsdon, 1999). Mine waste rock from the Tellnes deposit was placed in a deep fjord until 1994. Environmental pressures forced the discontinuation of that practice, although no deleterious effects had been determined (Olsgard and Hasle, 1993). Benthic fauna have successfully recolonized the fjord

bottom sediment where the tailings had been placed. Waste rock is now placed in an open-land deposit where dust and metal release due to oxidation of tailings is a concern (Thornhill, 2007).

Some of the waste rock at the Lac Tio mine is adjacent to a lake called Lac Petit Pas. A study conducted by Rio Tinto Fer et Titane, the company that operates the Lac Tio mine, placed waste material in the lake. It was determined that elevated concentrations of some metals are in the first several centimeters of sediment within the lake, but that the sediment acts as a retention medium (Rio Tinto, 2009).

Pit Lakes

There is sparse reference to pit-lake chemistry related to magmatic Fe-Ti-oxide deposits. The McIntyre mine in the Sanford Lake district closed in 1982 and is now within Adirondack State Park. Country rock is anorthosite and olivine metagabbro. One measurement of pit-lake water at the McIntyre mine had a pH of 8, and the only trace element above the detection limit of an inductively coupled plasma–atomic emission spectroscopy (ICP–AES) analytical method was Zn, at 0.049 mg/L (S. Hollmeyer, University of Vermont, unpub. data, 2003). It is possible that pit-lake water from magmatic Fe-Ti-oxide mines could contain slightly elevated concentrations of Co, Cr, Ni, V, and Zn.

Volume of Mine Waste and Tailings

The open-pit methods used for Lac Tio and Tellnes produce large volumes of waste rock and tailings. The Storganen mine operated from 1917 to 1965, producing more than 10 million tonnes of ore (Schiellerup and others, 2003) and more than 8 million tonnes of tailings (Ettner, 1999). Production from the Tellnes open pit is 2 million tonnes of ore and 1.6 million tonnes of waste rock, yielding 580,000 tonnes of ilmenite concentrate (production data current to 1999; data after 1999 are withheld) (NGU, 2012). The ratio derived from these figures of total rock mined to ore is about 1.8:1. Tellnes ore is milled and partially processed near the mine site, then shipped to Tyssedal, Norway, where it is processed into titanium slag (and iron) and sent on to Fredrikstad where the titanium slag is processed into titanium pigment. Nilsen and Ballou (2006) report that in recent years total mined material

has been about 8 million tonnes per year yielding about 3 million tonnes per year of ilmenite (rock to ore ratio of 2.6:1).

Mining of the Lac Tio deposit began in the early 1950s; ore is shipped by rail to Sorel-Tracy, Quebec, where it is processed. Waste-rock piles at Lac Tio are estimated at more than 70 Mt, cover approximately 92 hectares, and are between 20 and 80 m in height (Plante and others, 2008).

Smelter Signatures

Information regarding smelter signatures from facilities processing magmatic Fe-Ti-oxide ore is limited. Chromium, Co, Ni, V, and Zn can occur in some ores at low concentrations; ore beneficiated by roasting before being processed may release these metals during that process. Metals contained in anthracite coal used in the smelting step of the sulfate process may also be released. Leaching of smelter slag can be a concern for some types of deposits (see for example, Plumlee and Nash, 1995), but for ilmenite smelting, smelter slag contains the TiO_2 product and thus is the feedstock used for further processing.

Human Health Issues

Exposure to dust created during mining, transport, and processing operations, and to acids and other chemicals used in ore beneficiation certainly constitutes some human health risk (Kabata-Pendias and Mukherjee, 2007), but human health concerns related to titanium mining are minimal.

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Appendix

Appendix

The wide variety of rock types related to Fe-Ti-oxide deposits and their host rocks includes many unusual characteristic rock compositions. These rocks are referred to in the literature by a number of names including, among many others, ferrodiorite, jotunite, monzonorite, nelsonite, or oxide-apatite gabbonorite, which can lead to confusion when comparing and contrasting compositions across regions (see for example, Owens and Dymek, 1992; Vander Auwera and others, 2001). The cumulate nature of many of the rock types as well as the possibility of highly fractionated rock compositions results in excessive labeling of rock types in an attempt to capture the specific mineralogical nature of each rock type. Rock names used in this report have been fit into a general rock classification scheme (fig. A1) that draws on the International Union

of Geological Sciences (IUGS) systematics for plutonic rocks (Le Bas and Streckeisen, 1991; Streckeisen, 1976), the nomenclature developed by Phinney (1972) for the Duluth Complex, and a recent treatment of the problematic nomenclature of the charnockite series (Frost and Frost, 2008).

Proterozoic massif anorthosites rarely contain anorthite-type plagioclase (Ashwal, 1993). The plagioclase series $(\text{Ca,Na})(\text{Al,Si})\text{AlSi}_2\text{O}_8$ is arbitrarily divided into six subspecies based on the proportion of Na to Ca and related Al-Si ordering in the plagioclase mineral structure. Six divisions given here are based on the anorthite (An) proportion.

Albite	An ₀ to An ₁₀
Oligoclase	An ₁₀ to An ₃₀
Andesine	An ₃₀ to An ₅₀
Labradorite	An ₅₀ to An ₇₀
Bytownite	An ₇₀ to An ₉₀
Anorthite	An ₉₀ to An ₁₀₀

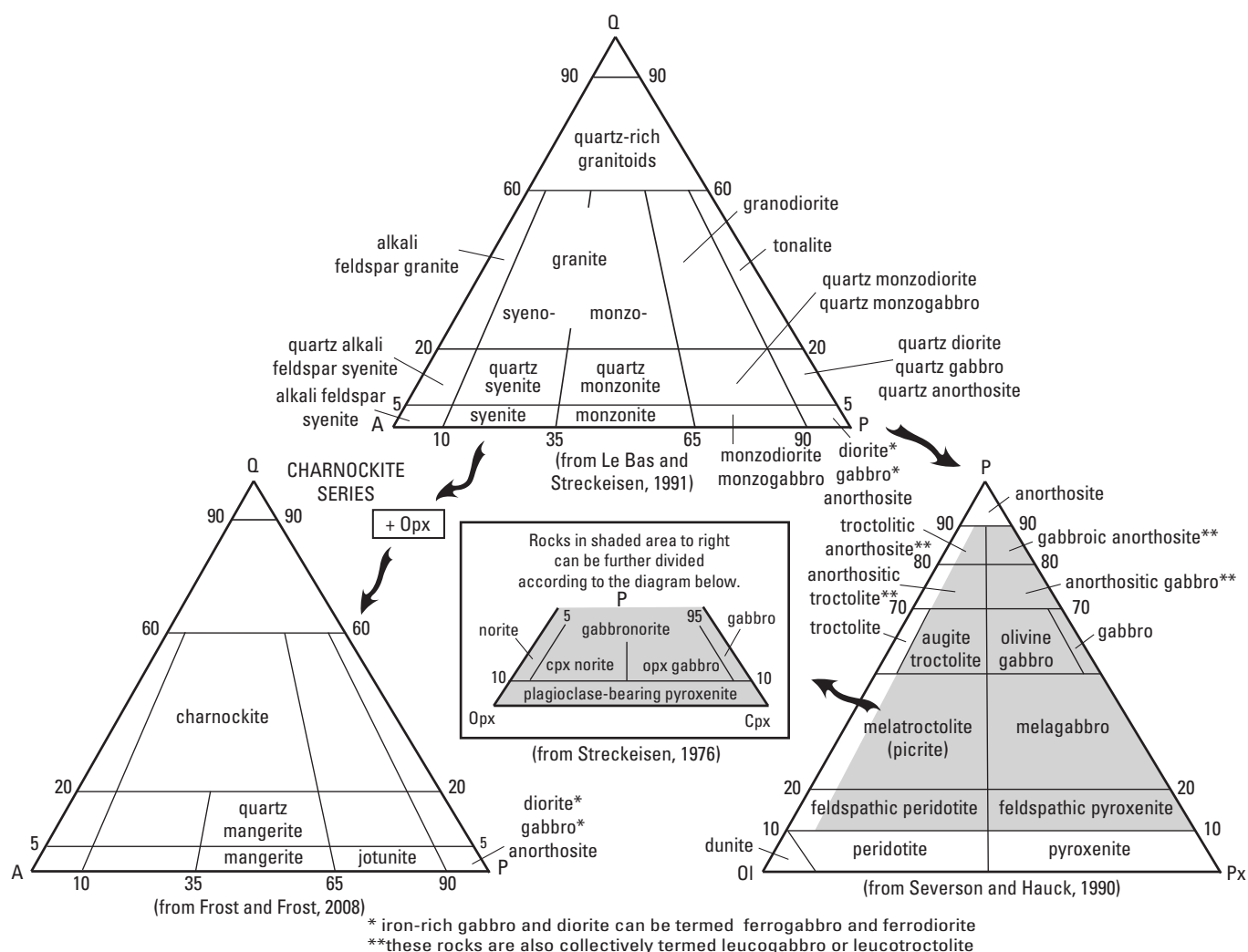


Figure A1. Varying rocks types related to Fe-Ti-oxide deposits hosted within Proterozoic anorthositic plutonic suites and related layered rocks are classified based on their proportional mineralogy. The traditional Q-A-P (quartz-alkali feldspar-plagioclase) diagram is adapted from the International Union of Geological Sciences classification of plutonic rocks of Le Bas and Streckeisen (1991). The P-Ol-Px (plagioclase-olivine-pyroxene) triangle is based on rocks from the Duluth Complex (modified from Severson and Hauck, 1990); development of the classification for the Duluth Complex is discussed in detail in Miller and others (2002). A subset of the P-Ol-Px triangle distinguishing between mafic rocks with clinopyroxene (Cpx) and orthopyroxene (Opx) is modified from Streckeisen(1976). Addition of orthopyroxene to rocks in the Q-A-P triangle results in the charnockite series as defined by Frost and Frost (2008). In all cases, numbers are percent of each mineral phase.

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