Available online at www.sciencedirect.com
ScienceDirect
Lithos 101 (2008) 359–378
LITHOS
www.elsevier.com/locate/lithos

The Grader layered intrusion (Havre-Saint-Pierre Anorthosite, Quebec) and genesis of nelsonite and other Fe–Ti–P ores

Bernard Charlier [a,*], Emmanuel Sakoma [b], Martin Sauvé [b], Kerry Stanaway [b], Jacqueline Vander Auwera [a], Jean-Clair Duchesne [a]

[a] *Department of Geology, B20, University of Liège, 4000 Sart Tilman, Belgium*
[b] *Rio Tinto Iron & Titanium Inc., Canada*

Received 16 October 2006; accepted 6 August 2007
Available online 16 August 2007

Abstract

The Grader layered intrusion is part of the Havre-Saint-Pierre anorthosite in the Grenville Province (Quebec, Canada). This intrusion has a basin-like morphology and contains significant resources of Fe–Ti–P in ilmenite and apatite. Outcropping lithologies are massive oxide alternating with anorthosite layers, banded ilmenite–apatite–plagioclase rocks and layered oxide apatite (gabbro-)norites. Drill cores provide evidence for stratigraphic variations of mineral and whole rock compositions controlled by fractional crystallization with the successive appearance of liquidus phases: plagioclase and ilmenite followed by apatite, then orthopyroxene together with magnetite, and finally clinopyroxene. This atypical sequence of crystallization resulted in the formation of plagioclase–ilmenite–apatite cumulates or "nelsonites" in plagioclase-free layers. Fine-grained ferrodiorites that cross-cut the cumulates are shown to be in equilibrium with the noritic rocks. The high TiO_2 and P_2O_5 contents of these assumed liquids explains the early saturation of ilmenite and apatite before Fe–Mg silicates, thus the nelsonites represent cumulates rather than crystallized Fe–Ti–P-rich immiscible melts. The location of the most evolved mineral and whole rock compositions several tens of meters below the top of the intrusion, forming a sandwich horizon, is consistent with crystallization both from the base and top of the intrusion. The concentrations of V and Cr in ilmenite display a single fractionation path for the different cumulus assemblages and define the cotectic proportion of ilmenite to 21 wt.%. This corresponds to bulk cotectic cumulates with ca. 8 wt.% TiO_2, which is significantly lower than what is commonly observed in the explored portion of the Grader intrusion. The proposed mechanism of ilmenite-enrichment is the lateral removal of plagioclase due to its relative buoyancy in the dense ferrodiorite melt. This plagioclase has probably accumulated in other portions of the intrusion or has not been distinguished from the host anorthosite.

Keywords: Anorthosite; Grenville; Fe–Ti deposit; Ilmenite; Layered intrusion; Nelsonite

1. Introduction

Despite the discovery of the Voisey's Bay Ni–Cu deposits in Proterozoic Anorthosite–Mangerite–Charnockite–(rapakivi) Granite (AMCG) suites (e.g. Kerr and Ryan, 2000), Fe–Ti oxide deposits remain the major

* Corresponding author. Tel.: +32 4 3662250; fax: +32 4 3662921.
E-mail address: b.charlier@ulg.ac.be (B. Charlier).

0024-4937/$ - see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.lithos.2007.08.004

mineralization type in Proterozoic anorthosite. Two world-class Fe–Ti oxide deposits are currently being mined in massif-type anorthosites: the Tio Mine (Havre-Saint-Pierre anorthosite, Quebec) and the Tellnes deposit (Rogaland anorthosite Province, Norway). At the present time, exploration for ilmenite deposits is not only focused on the grade of the ore but also on finding minerals suitable for industrial processing (e.g. Cr- and Mg-poor ilmenite). A genetic model for the formation of Fe–Ti oxide deposits in massif-type anorthosites is thus crucial for the prediction of the chemical variability of different ore types. Immiscibility of a Fe–Ti–P-rich melt has been invoked for the formation of some ilmenite ore types (e.g. Kolker, 1982; Force, 1991), but more recent studies on the Tellnes ilmenite deposit (Charlier et al., 2006, 2007) have emphasized the role of fractional crystallization with ilmenite as an early liquidus phase.

Layered intrusions are commonly present in anorthositic provinces and several have been studied in detail, including the Kiglapait intrusion of the Nain Plutonic suite (Canada) (e.g. Morse, 1996) and the Bjerkreim–Sokndal layered intrusion in the Rogaland Anorthosite Province (SW Norway; e.g. Wilson et al., 1996). Other intrusions of note include the Newark Island layered intrusion in Labrador (Wiebe and Snyder, 1993) and the Fedorivka layered intrusion in Ukraine (Duchesne et al., 2006). Many other less-studied small intrusions have also intruded anorthosite plutons (e.g. Vander Auwera et al., 2006). These intrusions are commonly interpreted as resulting from the fractional crystallization of anorthosite residual magma to produce a series of cumulate rocks.

The Grader layered intrusion is part of the large Havre-Saint-Pierre anorthosite complex in Quebec, Canada (Hargraves, 1962). The abundance of ilmenite in the Grader intrusion is high, well over 10 vol.%, and much of it has less Cr and Mg than ilmenite that is being mined from the Tio Mine (Bergeron, 1986) and the Tellnes ilmenite deposit (Charlier et al., 2007). The base of the intrusion however contains ilmenite with Cr and Mg contents similar to those of the Tio Mine oxide ore. An exploration campaign on the Grader intrusion yielded complete cores from 10 diamond drill holes. Information from these cores is used to define the structure and to examine the genetic link between the different rock types. Economic resources start at the base with massive ilmenite, then layers of ilmenite alternating with anorthositic layers followed upward by ilmenite–apatite ore (nelsonites) with variable proportions of plagioclase, culminating with oxide apatite (gabbro-)norites. In this paper, the proposed mechanism of ilmenite enrichment in the Grader layered intrusion and the relation between the ore and fine-grained ferrodiorites is considered to be applicable to the formation of Fe–Ti oxide ores in massif-types anorthosites in general, and specifically to the origin of nelsonites.

2. Geological setting

The Grader layered intrusion outcrops in the Allard lobe of the Havre-Saint-Pierre anorthosite complex (Quebec, Canada), which is part of the allochthonous polycyclic belt of the Grenville Province (Rivers et al., 1989). This anorthosite complex is composed of several anorthositic lobes separated by monzonitic, mangeritic to charnockitic envelopes (Fig. 1). The small Rivière au Tonnerre anorthosite was dated at 1062±4 Ma (U–Pb zircon; van Breemen and Higgins, 1993) and a monzonite from the Magpie river area gives an age of 1126^{+7}_{-6} Ma (U–Pb zircon; Emslie and Hunt, 1990; see approximate sample locations on Fig. 1).

The Grader intrusion is located about 4 km southwest of the Tio Mine and contains the Grader mine which was exploited in the late 1940s. A simplified geological map of the intrusion (Fig. 2) shows that the Grader mine was excavated in massive ilmenite containing minor anorthosite. In 2002, ten holes ranging from 75 to 274 m deep were drilled by Rio Tinto Iron & Titanium west of the Grader mine (Fig. 2). These vertical drill holes show that rock contacts (i.e. layers) dips from 0 to 45°. This, combined with surface sampling, ground gravity data and an electro-magnetic survey, allow for a description of the morphology of the Grader intrusion. All results indicate a basin-like structure, with outcropping oxide apatite (gabbro-)norite, banded nelsonite and massive oxide in the north and east that dip southward in the north, westward in the east and steeply north-eastward in the southwest (Fig. 2). This structure is interrupted by faults with NNE–SSW or NE–SW trends. The location of these faults is inferred from drill hole correlations, coupled with the outcrop pattern and orientation of the norite and banded layers; it is also corroborated by gravity interpretation and topographic breaks. These faults displace the east-side blocks upward, except for the NE–SW fault that displaces the east-side downward. The exact location and displacement along these faults are problematic because none were intersected in the drill cores or observed on the limited outcrops. Local variations in dip and strike may be explained by *m*-scale slump-style folds that are prominent in large outcrops of alternating anorthosite and ilmenitite or nelsonite immediately west of the Grader mine. Thin, fine-grained, ferrodiorites dykes with thickness ranging