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Dual origin of Fe–Ti–P gabbros by immiscibility and fractional crystallization of evolved tholeiitic basalts in the Sept Iles layered intrusion

Olivier Namur [a,*], Bernard Charlier [b], Marian B. Holness [a]

[a] Department of Earth Sciences, University of Cambridge, CB2 3EQ Cambridge, United Kingdom
[b] Massachusetts Institute of Technology, Department of Earth, Atmospheric, and Planetary Sciences, Cambridge, MA 02139-4307, USA

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ABSTRACT

We present a detailed study of two ca. 200 m-thick apatite-bearing ferrogabbro horizons of the Sept Iles layered intrusion (Canada). These rocks are the most evolved cumulates of the megacyclic units (MCU) I and II, and mark the transition between basaltic and silicic magmatism. They are made up of plagioclase (An_{55-34}), olivine (Fo_{66-21}), clinopyroxene (Mg#75–55), ilmenite, magnetite, apatite, ± pigeonite and are a significant source of Fe–Ti–P ore. Ferrogabbros have relatively uniform bulk-rock compositions in MCU I but are bimodal in MCU II. The liquid lines of descent for major elements in equilibrium with cumulates of MCU I and II have been calculated using a forward model formalism. Both trends evolve towards SiO_2-enrichment and FeO_t-depletion after saturation in Fe–Ti oxides. However, because of magma mixing in MCU II, they do not follow the same path. Evolved liquids from MCU II are shown to enter the experimentally-determined two liquid stability field, while MCU I liquids do not. Immiscibility in MCU II and its absence in MCU I are supported by the presence of contrasted reactive symplectites in cumulate rocks. Apatite-bearing ferrogabbros in MCU II have crystallized from distinct immiscible Fe-rich and Si-rich silicate melts which have physically segregated in the slow-cooling magma chamber. Two different types of cumulate rocks are thus produced: leucocratic and melanocratic gabbros. This is consistent with the presence of Si-rich and Fe-rich melt inclusions in apatite. In contrast, homogeneous ferrogabbros from MCU I were produced by simple fractional crystallization of a homogeneous liquid. Our data suggest that immiscibility could also explain the large geochemical variability of ferrogabbros in the Upper Zone of the Bushveld Complex (South Africa).

1. Introduction

Fe–Ti–P gabbros are common cumulate rocks crystallized from tholeiitic basalts. Thick horizons of gabbro dominated by Fe–Ti oxides and apatite are observed in various layered intrusions such as Bushveld, Skaergaard, Bjerkreim-Sokndal, Duluth and Panzhihua (Duchesne and Charlier, 2005; Eales and Cawthorn, 1996; Higgins, 2005; Miller and Ripley, 1996; Namur et al., 2010; Ripley et al., 1998; Tegner et al., 2006; Zhou et al., 2005). Ferrogabbros are also commonly associated with massif-type anorthosites (e.g. Duchesne et al., 2006; Dymek and Owens, 2001; Zhao et al., 2009). Occurrences in subvolcanic–volcanic environment (Kiruna-type deposits; Harlov et al., 2002) and in the lower oceanic crust have also been reported (Dick et al., 2000; Natland et al., 1991). The origin of these rocks has been variously suggested to result from crystal fractionation associated with density-driven mineral sorting (e.g. Charlier et al., 2008; Tegner et al., 2006; Tollari et al., 2008; Wager and Brown, 1968) or crystallization of an Fe–Ti–P-rich silicate melt segregated from its Si-rich immiscible conjugate (e.g. Bateman, 1951; Harlov et al., 2002; Naslund, 1983; Philpotts, 1967). However, Charlier et al. (2011) and Jakobsen et al. (2011) have shown that evolved Fe–Ti–P gabbros from the Skaergaard and Sept Iles layered intrusions have crystallized from a liquid emulsion. The question concerning the origin of these rocks is thus not whether they are cumulates or solidified immiscible liquids but if they are cumulates formed from a homogenous melt or from a mixture of immiscible liquids.

In this contribution, we present a detailed study of two ca. 200 m-thick horizons of magnetite, ilmenite and apatite-rich gabbros in the Sept Iles layered intrusion (Canada). One occurs in the lower part of the intrusion and the other one in the middle part. Both horizons are the most evolved cumulates of their respective megacyclic unit (MCU). The lowermost gabbro horizon is very homogeneous, comprising moderately leucocratic (plagioclase-rich) rocks with ca. 5 wt.% of apatite (av. 2.5 wt.% P_2O_5; Namur et al., 2010). The uppermost gabbro horizon is more heterogeneous and contains layers of gabbro dominated by Fe–Ti oxides, ferromagnesian minerals and apatite (ca. 20 wt.% of apatite) that alternate with very plagioclase-rich gabbros depleted in mafic minerals and apatite (ca. 2 wt.% of apatite)

* Corresponding author. Tel.: +44 1223 333434; fax: +44 1223 333450.
E-mail address: obn21@cam.ac.uk (O. Namur).

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on a scale of 5 to 20 m (Charlier et al., 2011). Using new mineral and whole-rock data of these rocks together with those presented in Charlier et al. (2011) and Namur et al. (2010), and modeling of the liquid line of descent, we show that the fractionation path followed, and the processes that occur, during differentiation are critical in determining the extent of Fe–Ti–P enrichment. The compositional evolution of the melt controls whether the Fe–Ti–P gabbros form by fractional crystallization of a homogeneous melt or of a mixture of immiscible liquids. Late-stage microstructures in cumulate rocks from the Skaergaard intrusion have recently been studied by Holness et al. (2011). Various types have been described among which oxy-symplectites (comprising orthopyroxene and magnetite) and Type 2 symplectites (comprising orthopyroxene and plagioclase) were attributed to reaction between a homogeneous melt and cumulus phases, while Type 1 symplectites (Fe–Ti oxide-rooted symplectites dominated by clinopyroxene, olivine and plagioclase) were attributed to reaction between cumulus primocrysts and an Fe-rich immiscible liquid (Holness et al., 2011). We use the stratigraphic distribution of similar microstructures in the Sept Iles intrusion to determine when immiscibility occurred during progressive crystallization.

2. The Sept Iles layered intrusion

The Sept Iles layered intrusion is located on the north shore of the St Lawrence River, about 500 km to the north-east of Quebec City. It is an unmetamorphosed and undeformed magmatic body, emplaced at 564 ± 4 Ma (U–Pb on zircon; Higgins and van Breemen, 1998) into high-grade gneisses of the Grenville Province. The intrusion has a dinner-plate shape with a diameter of ca. 80 km, a maximum thickness of ca. 5.5 km and an estimated magma volume of ca. 20,000 km³ (Loncarevic et al., 1990). The north-western part of the intrusion crops out around the Sept Iles peninsula and on islands of the Sept Iles archipelago, where three different series have been described: the Layered Series, the Upper Border Series and the Upper Series (Fig. 1A; Higgins, 2005).

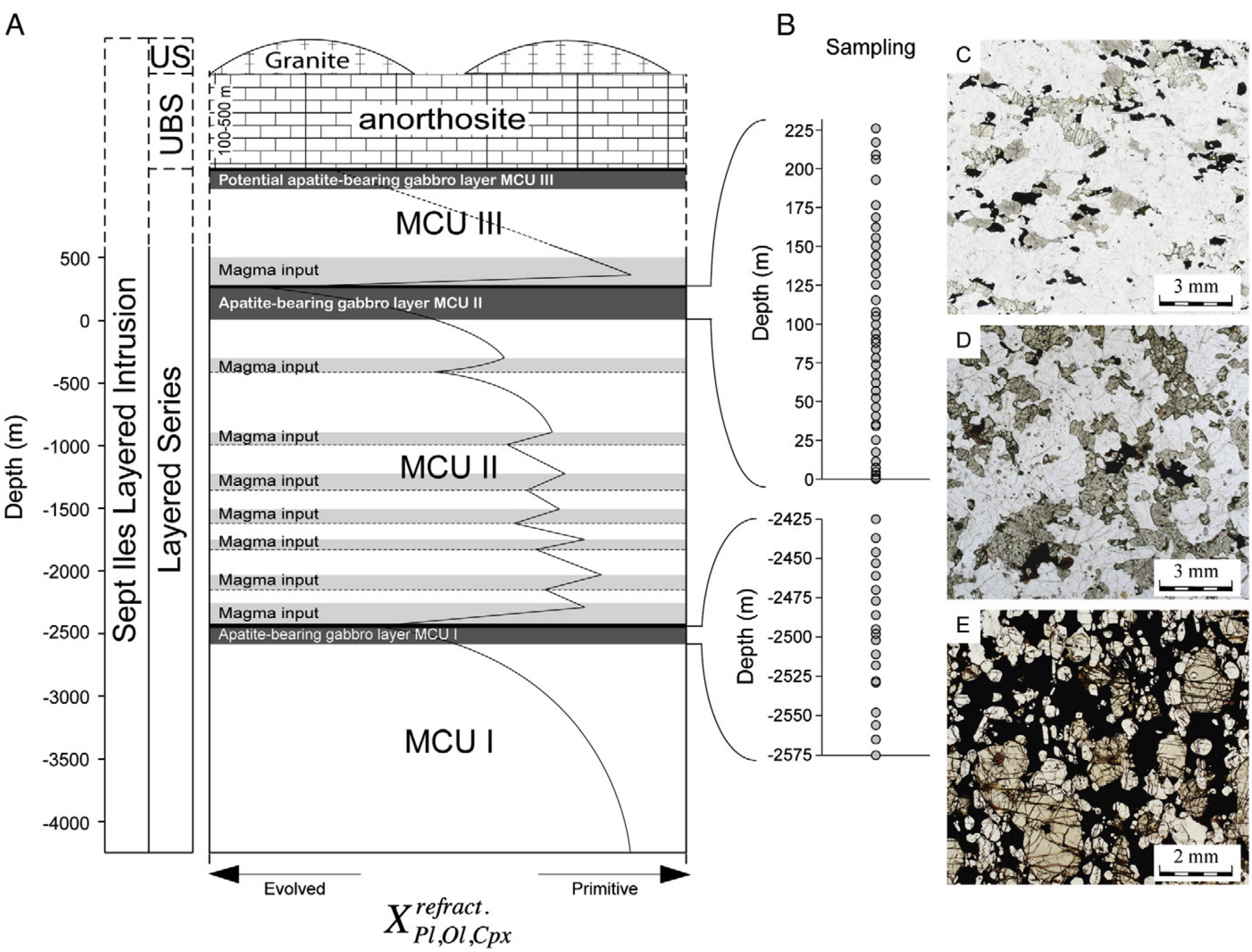

Fig. 1. Schematic stratigraphy of the Sept Iles layered intrusion, stratigraphic position of the samples and petrography of the Fe–Ti–P gabbro horizons. A. Stratigraphic subdivision of the intrusion (after Namur et al., 2010). The "0-meter" reference level corresponds to the appearance of cumulus apatite in Megacyclic Unit 2 (MCU II). Curves display schematically the evolution of mineral compositions (Pl: Plagioclase An-content; Ol: Olivine Fo-content, Cpx: Clinopyroxene Mg#; Mt: Magnetite Cr-content). Light grey bands in MCU II and at the base of MCU III represent mixing zones between residual liquid and new magma inputs. UBS: Upper Border Series; US: Upper Series. B. Stratigraphic intervals of the Fe–Ti–P gabbro horizons (MCU I and MCU II) investigated in this study. Stratigraphic positions of the samples from drill cores (DC9; s9) and surface samples are indicated. C. Photomicrograph of a representative Fe–Ti–P gabbro from the apatite-bearing horizon of MCU I. Sample DC9-419; transmitted light. D. Photomicrograph of a representative Fe–Ti–P-poor gabbro from the apatite-bearing horizon of MCU II. Sample s9-88.1; transmitted light. E. Photomicrograph of a representative Fe–Ti–P-rich gabbro from the apatite-bearing horizon of MCU II. Sample s9-148; transmitted light.