ELSEVIER

Chemical Geology 234 (2006) 264–290

CHEMICAL GEOLOGY
INCLUDING
ISOTOPE GEOSCIENCE

www.elsevier.com/locate/chemgeo

Magma chamber processes in the Tellnes ilmenite deposit (Rogaland Anorthosite Province, SW Norway) and the formation of Fe–Ti ores in massif-type anorthosites

B. Charlier *, J.-C. Duchesne, J. Vander Auwera

Department of Geology, B20, University of Liège, B-4000 Sart Tilman, Belgium

Received 29 September 2005; received in revised form 5 May 2006; accepted 12 May 2006

Abstract

The origin of igneous Fe–Ti oxide ores associated with massif-type anorthosites is investigated through a detailed study of the world-class Tellnes ilmenite deposit, part of the late-Proterozoic (930–920 Ma) AMC series of the Rogaland Anorthosite Province (SW Norway). More than 100 samples from drill cores reveal significant petrographical and compositional variations within the ore body. Four zones are defined, based on variations in modal proportions and cumulus mineral assemblages: the Lower and Upper Central Zones and the Lower and Upper Marginal Zones. Plagioclase and whole-rock compositions discriminate the zones and display patterns interpreted as a result of mixing of either plagioclase–ilmenite or plagioclase–ilmenite–orthopyroxene–olivine cumulates with a melt of ferrodioritic (jotunitic) composition with a content decreasing from 80 to 20% from the margins to the central part of the ore body. Phase diagrams for a jotunitic parental magma reproduce the crystallization sequence at 5 kb. The orthopyroxene–olivine liquidus boundary is a peritectic in the Bjerkreim-Sokndal layered intrusion and a cotectic in Tellnes and this explains the differences in the sequence of crystallization of the two intrusions. The high concentration of ilmenite, well above cotectic proportions, resulted from gravity-sorting in the Tellnes ore body, which represents the lower part of a larger magma chamber. Uniform Sr isotope ratios do not support magma mixing. The cryptic layering of the ore body precludes injection as a crystal mush but favours in situ crystallization from an evolving magma in a sill-like magma chamber. The present trough-shape and mineral orientations result from deformation during gravity-induced subsidence and by up-doming of the anorthosite. Fractional crystallization of a TiO_2-rich magma with ilmenite as an early liquidus mineral and plagioclase buoyancy are the principal mechanisms responsible for the formation of Fe–Ti deposits in Proterozoic massif-type anorthosites.

Keywords: Anorthosite; Fe–Ti deposits; Tellnes; Magma chamber processes; Cumulate; Trapped liquid

1. Introduction

Economic igneous Fe–Ti oxide occurrences are commonly associated with massif-type anorthosites and two hard-rock deposits are currently being mined: the Tellnes ilmenite deposit (Rogaland Anorthosite Province, SW Norway) and the Lac Tio deposit (Allard Lake anorthosite, Quebec, Canada). The scarcity of Fe–Ti deposits has hampered research on the formation of such ore bodies and particularly on mechanisms responsible for ilmenite enrichment. There is no consensus as to whether accumulation processes, immiscibility, magma mixing, fractional crystallization, solid-state remobilisation, cotectic

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

0009-2541/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.chemgeo.2006.05.007

crystallization, or a combination of these processes or others, control the formation of Fe–Ti oxide ores. Nevertheless, the genesis of massif-type anorthosites and related rocks has been thoroughly debated (e.g. Ashwal, 1993; Longhi et al., 1999; Vander Auwera et al., 2000; Bédard, 2001; Longhi, 2005) and the Rogaland Anorthosite Province in particular has been the subject of numerous investigations (see Duchesne, 2001 for a review). In this province, the Bjerkreim-Sokndal layered intrusion, which contains all rock types belonging to the AMC series (Anorthosite–Mangerite–Charnockite), has been extensively studied (see Wilson et al., 1996 for a review). The petrogenesis of the Bjerkreim-Sokndal Intrusion has greatly improved our understanding of the origin of massif-type anorthosites and related rocks. An important feature of the AMC series in Rogaland is the inferred jotunitic (hypersthene monzodiorite) parental magma. These liquids, also called ferrodiorites (Ashwal, 1993; Emslie et al., 1994), are Fe-, Ti- and P-rich and, contrary to basaltic magmas, crystallize ilmenite as an early liquidus mineral. The liquid line of descent of jotunitic magma is well known due to the occurrence of fine-grained jotunitic dykes that represent liquid compositions (Duchesne et al., 1989) and as a result of experimental studies (Vander Auwera et al., 1998) performed on such compositions.

In this well-documented geological context, a comprehensive genetic model for the Tellnes ilmenite deposit remains to be established. This deposit, which has been mined since 1960 by TITANIA A/S, was previously described as a rather homogeneous ore body with plagioclase, ilmenite, and orthopyroxene as the major minerals (Gierth and Krause, 1973). However, an extensive database of whole-rock compositions built up by TITANIA A/S over the last twenty years indicates that compositional variations are larger than previously believed. A detailed petrographical and geochemical investigation of more than 100 samples from the deposit has thus been undertaken in order to constrain a genetic model for the ore body and Fe–Ti ore-forming processes in massif-type anorthosites in general.

2. Geological setting

2.1. The Rogaland Anorthosite Province

The Tellnes ilmenite deposit belongs to the late-Proterozoic Rogaland Anorthosite Province (see Duchesne, 2001 for a review), emplaced in the south-western part of the Sveconorwegian orogenic belt (SW Norway) (Fig. 1). The Province comprises different units of the AMC series: four large massif-type anorthosite plutons (Egersund-Ogna, Håland, Helleren and Åna-Sira), the Bjerkreim-Sokndal layered intrusion (Wilson et al., 1996), two smaller leuconoritic bodies (Hidra and Garsaknatt) (Demaiffe, 1977; Demaiffe and Hertogen, 1981), minor intrusions (Vander Auwera et al., in press) and dykes of the jotunitic (hypersthene monzodiorite) kindred (Duchesne et al., 1989). Another characteristic is the presence of numerous Fe–Ti deposits of subeconomic to economic grade (e.g. Tellnes), occurring in the Åna-Sira, Håland and Helleren anorthosites (Duchesne, 1999).

These magmatic rocks were emplaced between 930 and 920 Ma (Schärer et al., 1996) in granulite facies ortho- and paragneisses, generating a wide, high-temperature contact metamorphic aureole (Maijer, 1987; Möller et al., 2002). Intrusion of the Rogaland Anorthosite Province took place some 40 Ma after the Sveconorwegian orogeny (Bingen and van Breemen, 1998; Bingen and Stein, 2003) in a post-collisional regime (Duchesne et al., 1999). No subsequent metamorphism has overprinted this magmatic event. The anorthosite plutons crystallized over a large range of pressures, starting at about 11 to 13 kb in large magma chambers in the lower part of a thickened crust (Longhi et al., 1993, 1999; Longhi, 2005). The low density of a plagioclase crystal mush induced diapiric uprise of the anorthositic massifs, possibly through zones of weakness (Scoates and Chamberlain, 1997), to their final intrusion at a pressure of around 5 kb (Ashwal, 1993; Duchesne et al., 1999). Deformation observed in the Province can be accounted for by anorthosite emplacement (Barnichon et al., 1999) and gravity instabilities (Bolle et al., 2002). Late doleritic dykes cross-cut the Province and are related to the opening of the Iapetus Ocean at 616±3 Ma (Bingen et al., 1998).

2.2. The Tellnes ilmenite ore body

The ore body, an ilmenite-rich norite averaging slightly more than 18% TiO_2, was discovered in 1954 during an aeromagnetic survey, and production started 6 years later by TITANIA A/S as an open-pit mine. Reserves are estimated to be 57 Mt TiO_2, representing 14% of the world reserves of ilmenite and 12% of the total (ilmenite+rutile) world reserves of titanium minerals. By-products are magnetite and Ni–Cu sulphide concentrates.

The Tellnes ore body is intruded into the central part of the Åna-Sira anorthosite (Gierth and Krause, 1973; Krause et al., 1985) (Fig. 1). This anorthosite body is essentially made up of granulated plagioclase with rare isolated Al-rich orthopyroxene megacrysts. Some parts are leuconoritic, containing plagioclase, orthopyroxene and ilmenite. The massif contains numerous Fe–Ti deposits which have been mined in the past. The most important of these occurrences are Storgangen, Bøstølen, and Blåfjell (Fig. 1) (Krause and