Has immiscibility occurred in the Bjerkreim-Sokndal layered intrusion (S. Norway)?

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ABSTRACT

The Bjerkreim-Sokndal layered intrusion (Rogaland anorthosite province, South Norway) is made of a series of rocks of intermediate composition that result from fractional crystallization of a jotunite magma (Fe-Ti-rich diorite). The intermediate nature of the liquid line of descent makes possible the action of an immiscibility process that gives rise to conjugated Fe-rich and Si-rich melts. It is particularly plausible at the transition between gabbronorites and mangerite, where Fe-Ti-P-rich ultramafic layers are intercalated into norite and mangerite. The chemical compositions of a suite of rocks in a cross-section of the intrusion are here synthetized and compared to the recent experimental data of Charlier and Grove, 2012. It is shown that the ultramafic layers are do not derive from a Fe-rich immiscible melt. Moreover the reconstructed liquid line of descent of the intrusion by several methods does not enter into the two-immiscible melts domain. It is concluded that evidence of immiscibility in the evolution of the fractionation process is still lacking.

KEYWORDS: AMCG, Jotunite, liquid line of descent, Fe-diorite

INTRODUCTION

Silicate liquid immiscibility has long been invoked as an operating mechanism in the evolution of mafic magmas that differentiate to extreme degrees of Fe-enrichment (McBirney, 1975; Philpotts, 1976; Roedder, 1979). In the Skaergaard layered intrusion, the process, first proposed by McBirney (1975), has received further support by the identification of melt inclusions in apatite (Jakobsen et al., 2005, 2011), late magmatic microstructures (Holness et al., 2011), precious metal occurrence (Nielsen et al., 2015) and compositional evolution (Nielsen et al., in press). In other layered intrusions, the immiscibility process has been put forward with various successes. It is indeed particularly stealthy in cumulate rocks because, at equilibrium between the two liquids, the nature and compositions of the crystallizing minerals are identical, only their proportions are different. The latter differences can be blurred by density sorting of the cumulus minerals. Subtle differences in mineral proportions have however been demonstrated in the Sept-Iles layered intrusion, that, together with melt inclusions and reactive symplectites, strongly support immiscibility (Namur et al., 2012; Namur et al., 2010). In the Duluth intrusion, coexistence of a sulfur-rich and a Fe-Ti-P-rich liquids has been proposed by Ripley et al. (1998), although the same minerals in the two liquids have different compositions. In the upper part of the Bushveld intrusion, Van Tongeren and Mathez (2012) also suggest coexistence of two liquids but the latter crystallise different phases with different compositions. The Bjerkreim-Sokndal (BKSK) intrusion (S. Norway) (Fig. 1) is potentially an adequate case of differentiation producing immiscible liquids. It is made up of an extended series of mafic cumulates evolving towards Fe-enrichment and low Mg numbers, topped by Si-rich rocks (mangerite and quartz mangerite)(Wilson et al., 1996). A possible immiscibility origin of the Si-rich rocks was first mentioned by (Wiebe, 1984) on the basis of occurrence of microgranular mafic enclaves. The same origin for the Si-rich rocks was also proposed by Wilson and Overgaard (2005) but the

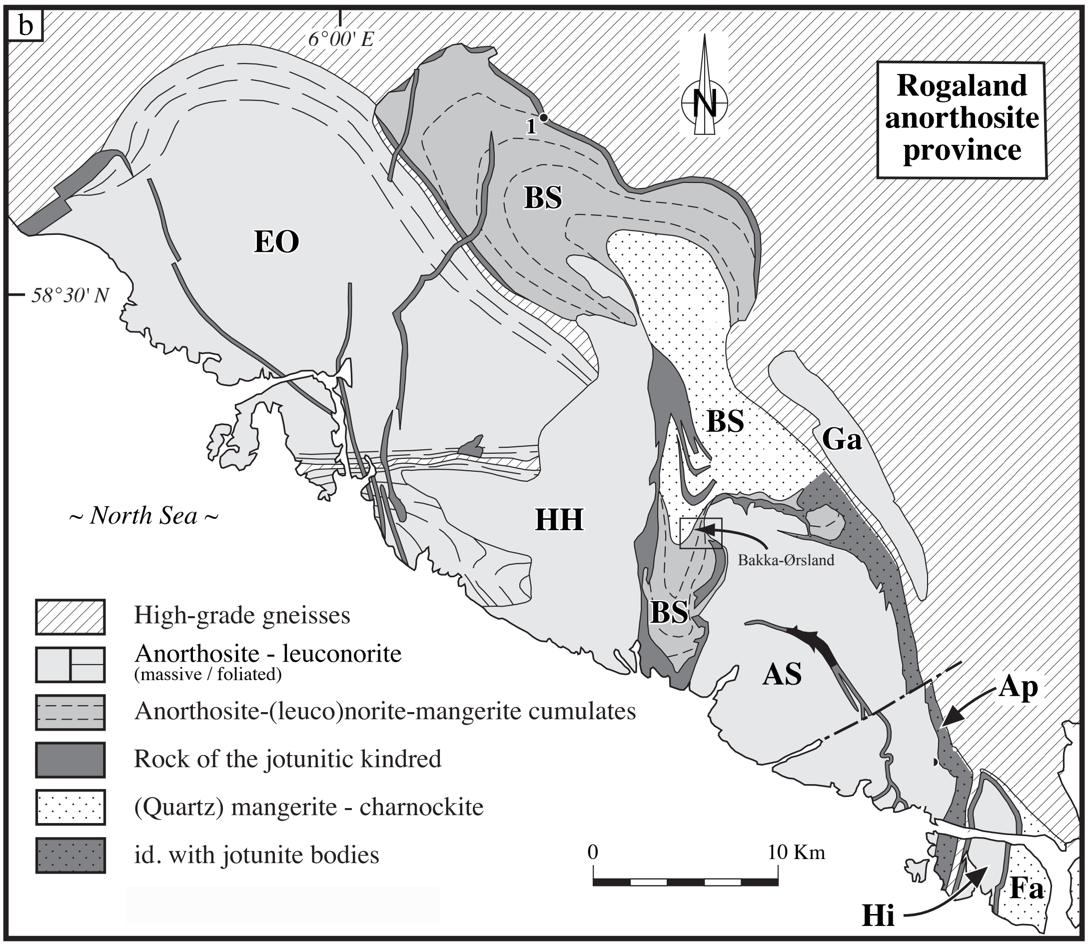

Fig. 1. Geological map of the Rogaland anorthosite province (compiled and modified from various references listed in Duchesne (2001b) and Bolle et al. (2003). EO, HH and ÅS: Egersund-Ogna, Håland-Helleren and Åna-Sira anorthosites, respectively; BS: Bjerkreim-Sokndal layered intrusion; Ap: Apophysis; Ga and Hi: Garsaknatt and Hidra leuconorite outliers, respectively. The Bakka-Ørsland area is indicated. Detailed maps are available in Duchesne (2001a).

fate of the conjugated Fe-rich melt was not envisaged. Duchesne et al. (1987) discussed the evolution of Fe-rich olivine bearing lithologies in the transition zone at the top of the layered series and below the mangerite but concluded that immiscibility was not operating at this stage of evolution. Recent developments in the study of immiscibility have provided new experimental constraints on the composition of the coexisting liquids pairs (Charlier and Grove, 2012; Charlier et al., 2013). On the other hand, the liquid line of descent in the BKSK intrusion has been better documented on the basis of peculiar properties of the cumulate rocks (Duchesne and Charlier, 2005) and on experimental work (Vander Auwera and Longhi, 1994; Vander Auwera et al., 1998). The purpose of the present report is to synthetize the available data of the transition zone (TZ) and on mangeritic rocks in the Bakka-Ørsland area and to explore the possibility of finding relationships between residual melts and the two-liquid immiscibility field. It will be concluded that the strong evidence in favour of coexistence of two immiscible melts are still lacking.

THE TRANSITION ZONE IN BJERKREIM-SOKNDAL INTRUSION

The Bjerkreim-Sokndal layered intrusion (Rogaland, S. Norway) is made up of rocks of the AMCG series (anorthosite, mangerite, charnockite, granite) (Michot and Michot, 1969; Michot, 1960; Michot, 1965; Wilson et al., 1996). The lower part of the massif is divided in five macrocyclic units (MCU) starting with anorthosite grading into leuconorite and into norite or gabbronorite. On top of the layered series the relatively thin transition zone (TZ) comprises ferrous olivine gabbronorites grading into mangerites on top of which quartz mangerite and charnockite form the upper part of the massif. The roof is nowhere exposed but large enclaves of leucocharnokites, likely coming from the roof, occur in amphibole charnockites on top of the intrusion (Duchesne and Wilmart, 1997). The quartz mangerites comprise olivine bearing and two-pyroxene varieties. U-Pb geochronology shows that the olivine quartz mangerites have zircon cores of the age of the layered series (and of the main anorthosites) (931 Ma, (Schärer et al., 1996) and rims of the age of a later episode of magmatism (920 Ma). This suggests that the olivine quartz mangerites are residual liquids from the layered series mixed with a slightly later input of two-pyroxene mangeritic melt (Vander Auwera et al., 2011), possibly coming from the western margin of the intrusion (Bolle and Duchesne, 2007). This an important consideration because it implies that any border facies that could have crystallized at the roof of the intrusion has been removed or at least separated from the already crystallized layered series and mangeritic unit by this new input of magma.

The TZ is particularly well exposed in the Bakka-Ørsland region where it contains ultramafic layers (UML) made up of Ti-magnetite, ilmenite, ferrous olivine, Ca-rich pyroxene and apatite (Duchesne, 1972; Duchesne et al., 1987) that are intercalated with norites at the basis of the TZ and with mangeromonzonites higher in the stratigraphy. In this area, the mangeritic unit above the TZ has been studied in detail by Duchesne and Wilmart (1997). We have compiled a stratigraphic log of all studied samples from the lowest gabbronoritic rocks to the highest quartz mangerites (Duchesne et al., 1987; Duchesne and Wilmart, 1997). It should be noted that the distance between samples is empirical and does not correspond to the real thickness. Possible lateral variations in thickness, petrographic type and chemical composition are thus ignored. The TZ and its relationships with mangerite and quartz mangerite have also been studied in the northern lobe of the intrusion by Wilson and Overgaard (2005) who confirmed the overall interpretation of Duchesne and Wilmart (1997). No ultramafic layers were mentioned elsewhere than in the Bakka-Ørsland area, which makes this region very tantalizing.

BULK ROCK COMPOSITION

The bulk composition of samples from the TZ up to quartz mangerite are reported in Table 1 (supplementary file) that are taken from Duchesne et al. (1987) and Duchesne and Wilmart (1997). The stratigraphic evolution of the bulk rock major and trace element composition and the mineral composition are illustrated in Figs. 2, 3 and 4.

Several points are worth being mentioned: 1. The noritic and mangeritic UMLs are quite peculiar: compared to their associated norites and mangeromonzonites, they are enriched in Fe, Mg, Ti and P and depleted in Si, Al, K and Na. In the ternary diagram of Charlier and Grove (2012), the UML project close to the immiscibility field curve (Fig. 5). 2. The Mg# in olivine, clinopyroxene and bulk rock steadily decrease upwards with a small reversal on top of the mangeromonzonite unit. 3. Some mangeritic rocks are enriched in Zr pointing to high values in the quartz mangerites. 4. Both K_2O and Ba show high values in mangeromonzonites (with the appearance of perthitic to mesoperthitic K-feldspar) but Ba steadily decreases upwards while K_2O tends to slightly increase. 5. Positive Eu anomalies (Eu/Eu*> 1.5) characterize the mangeromonzonites and mangerites. 6. The highest Sr content occurs at the base of the mangeritic unit.

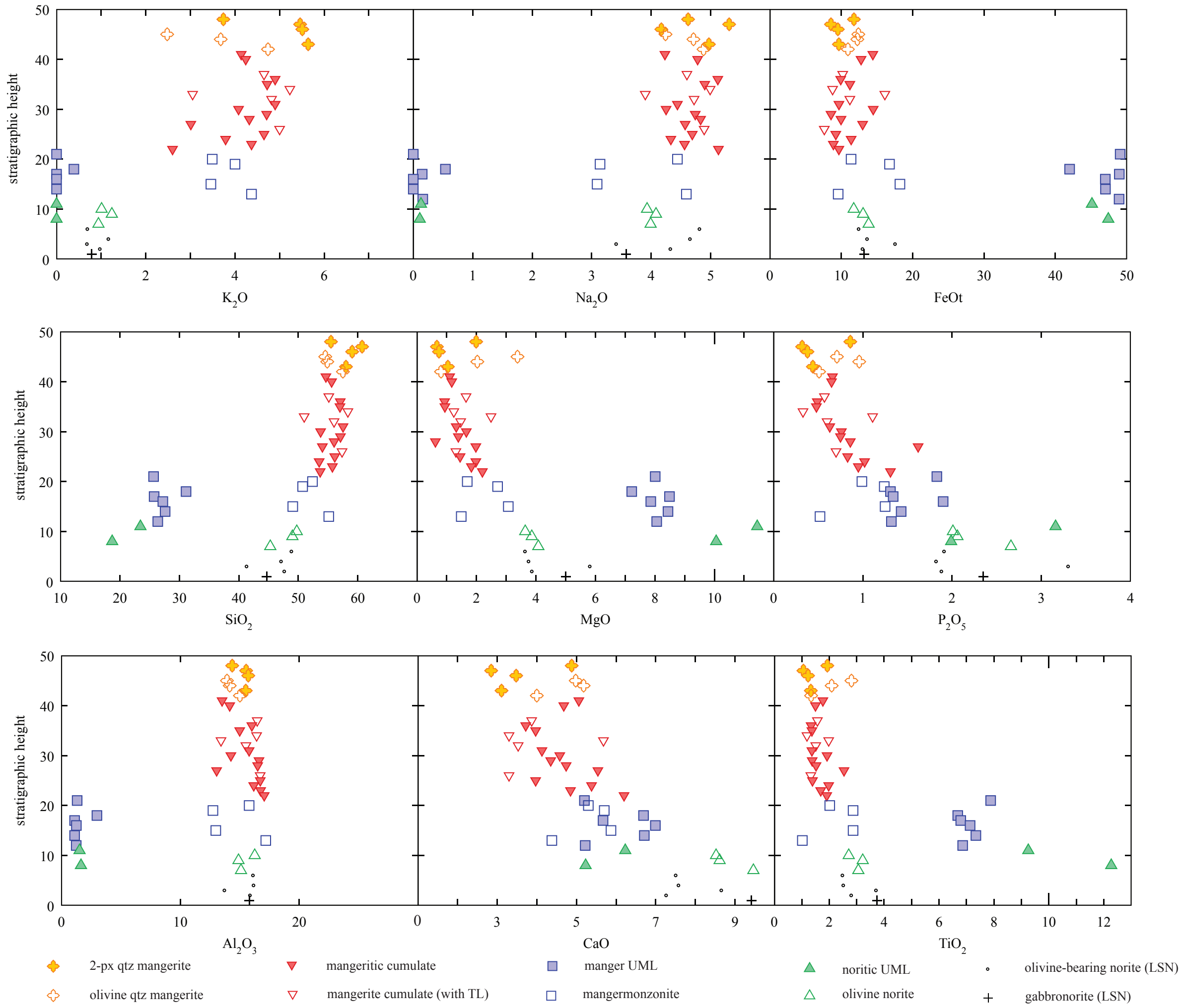

Fig. 2. Major element evolution with stratigraphic height in the TZ lithologies in the Bakka-Ørsland area. Data in Table 1.

Discussion

There is no reversal in the decreasing trend of the Mg# evolution on top of the stratigraphic sequence that could have resulted from the crystallization of a border facies at the roof of the intrusion. The olivine quartz mangerites on top of the sequence have olivines with the same Mg# as in the uppermost mangerite and thus can be a melt in equilibrium with them. A model for the evolution of the magma chamber has been proposed by Duchesne et al. (1987). The model remains grossly valid except for the interpretation of the mangeritic cumulates. In the model, when the mesoperthitic K-feldspar appears on the liquidus, it starts floating and accumulates on top of the magma chamber. The detailed evolution within this unit (Duchesne and Wilmart, 1997) does not show any reversal in the mineral composition as should be expected in a border facies at the roof. When mesoperthite appears on the liquidus, the magma has overstepped the maximum in Fe composition and its density decreases due to subtraction of Fe-Ti-rich mafic minerals. This gives rise to a stable situation with the possibility of developing a stratified column of magma (Campbell, 1996). The trapped residual melt in mesoperthite cumulate can escape upwards by convection and/or compaction. This interpretation does not require floatation of K-feldspar.

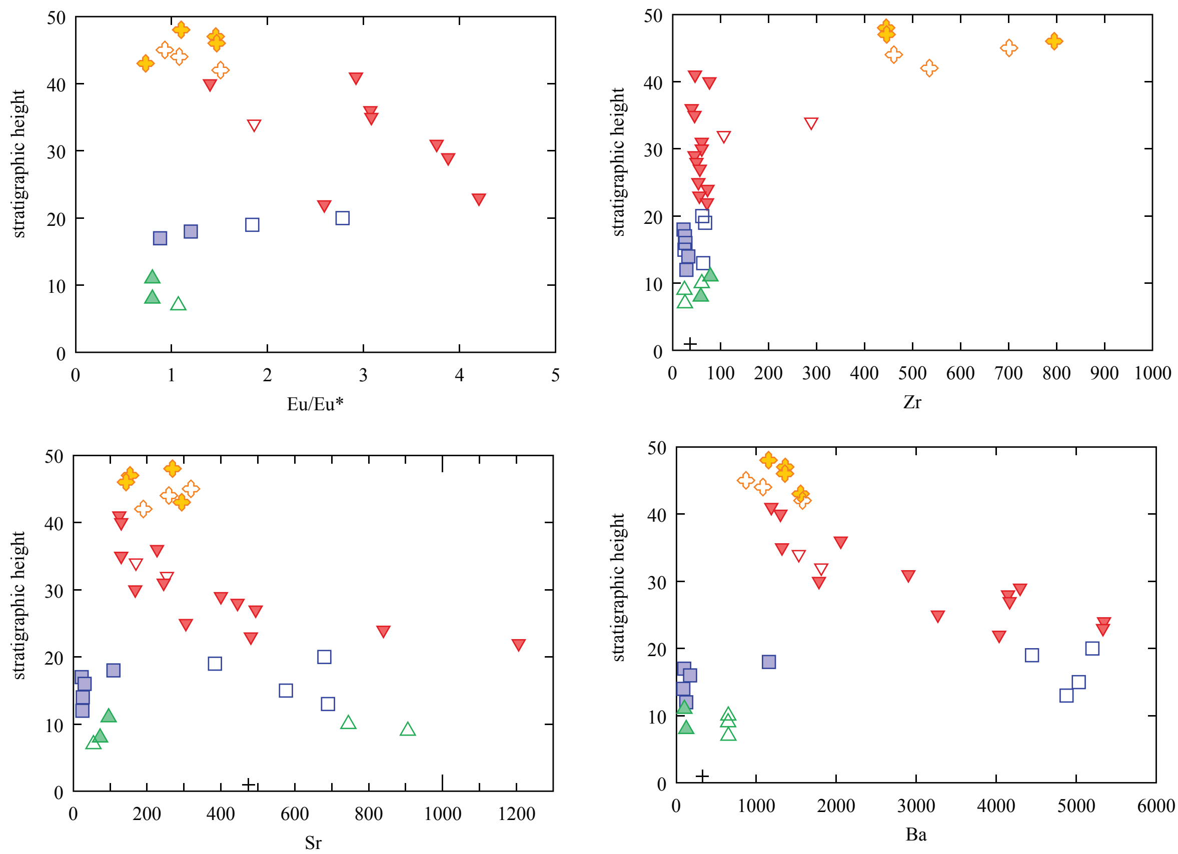

Fig. 3. Minor element evolution with stratigraphic height in the TZ lithologies in the Bakka-Ørsland area. Data in Table 1.

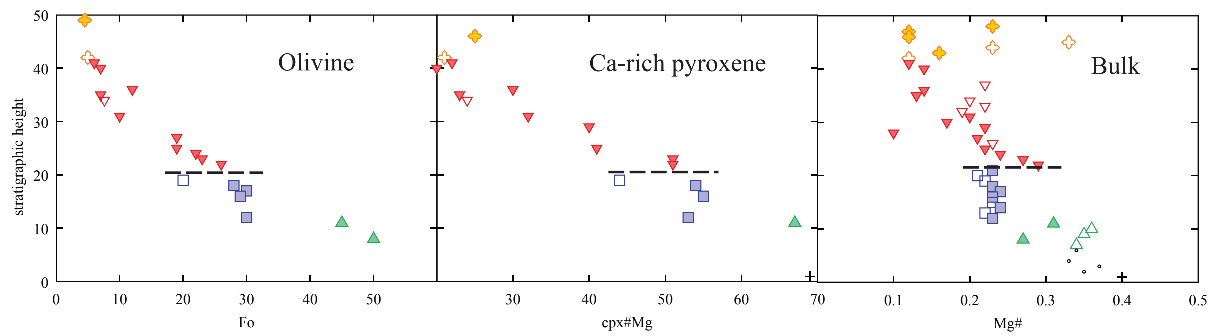

Fig. 4. Mg# evolution with stratigraphic height in olivine, Ca-rich pyroxene and bulk composition. Data in Duchesne et al. (1987) and Duchesne and Wilmart (1997).

An intriguing high Sr value (Fig. 3) together with a small reversal in Mg# (Fig. 4) occur at the base of the mangeritic unit (rock sample BA1). The sample is richer in Ca and Na and lower in K, suggesting a higher plagioclase content than the overlying samples. We propose that a magma movement in the chamber has brought a less evolved melt on top of the mangeromonzonitic transition cumulates that contains plagioclase xenocrysts formed in another part of the intrusion. It has indeed been shown in the northern lobe of the intrusion that plagioclase in olivine gabbronorite on top of the layered series can reach 1500 ppm Sr (Duchesne, 1971, 1978). Some of the plagioclase crystals could have been entrained in the magma movement and mixed with the mesoperthite cumulate.

The UML are very rare rocks. They occur specifically in the Bakka-Ørsland area and have not been found elsewhere in the intrusion despite good outcrops of the TZ in the northern lobe of the intrusion (Wilson and Overgaard, 2005). They are not known in other intrusions even in the highly evolved Fedorivka massif (Ukraine) (Duchesne et al., 2006).

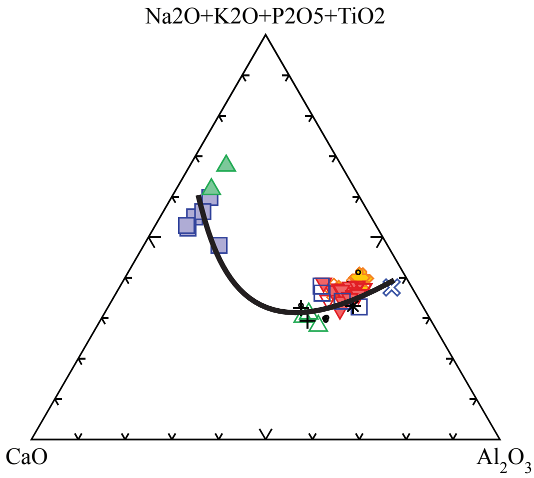

Fig. 5. Bulk rock composition projected in ternary diagram CaO, $Na_2O+K_2O+TiO_2+P_2O_5$, Al_2O_3. The 2-liquid field limit after Charlier and Grove (2012). Data in Table 1.

They have been interpreted by Duchesne et al. (1987) as cumulates and their formation as Fe-rich immiscible melts conjugated with the Si-rick mangeromonzonites and mangerites was rejected because they plot far from the immiscibility field define by Philpotts (1981). Could the recent work of Charlier and Grove (2012) and Charlier et al. (2013) on immiscibility in Fe-rich tholeiitic gabbro modify this hypothesis as suggested in Fig. 5? In Harker diagrams (Fig. 6), the UML compositions are quite different from the experimental Fe-rich melts. They are lower in SiO_2, CaO and P_2O_5 and higher in FeOt and MgO. The Harker diagrams also preclude the following hypothesis: the olivine norites and the noritic UML would be cumulates that crystalized from an immiscible melt C3 the subtraction of which could give rise to the quartz mangeritic rocks (see below). C3 is indeed lower in P_2O_5 and CaO, and higher in MgO and Al_2O_3 than any Fe-rich experimental melts. Although there is no evidence that the UML are or result from the crystallization of immiscible melts, we have to admit that a weakness of the approach is that we are dealing with cumulates and not with true melts. What can teach us what we know about the liquid line of descent (LLD) of the intrusion?

THE LIQUID LINE OF DESCENT OF THE BJERKREIM-SOKNDAL INTRUSION

The absence of ultramafic rocks at the base of the intrusion led Michot (1965) to reject a basaltic composition for the parental magma of the intrusion and he suggested an intermediate composition. This hypothesis was also supported by quantitative modelling of trace elements in plagioclase and apatite (Duchesne, 1978; Roelandts and Duchesne, 1979). At Tjörn, a locality close to the northern margin of the intrusion (Maijer et al., 1987), a chilled facies of hypersthene monzodiorite (monzonorite or jotunite) locally loaded with plagioclase phenocryst displayed many similarities with the border facies of the Hidra anorthosite (Demaiffe et al., 1973; Demaiffe and Hertogen, 1981). The Tjörn jotunite was thus considered as the parental magma of the BKSK intrusion (Duchesne and Hertogen, 1988). Similar jotunites were also described at the contact of the intrusion with the enclosing rocks (Robins et al., 1997). Experimental data on the Tjörn composition, considered as a primitive jotunite, confirmed it could crystallize the BKSK cumulates at pressure around 5 kbar and 1150°C (Vander Auwera and Longhi, 1994) and provided an evolved composition at 1100°C (sample

TJ-45). Relationship with evolved jotunites occurring in a dyke system cutting across the whole anorthosite province led to the definition of the jotunite liquid line of descent (Vander Auwera et al., 1998). The Tellnes dyke in which displayed a continuous series of melts grading from evolved jotunite to charnockite played a crucial role in the definition of that LLD (Wilmart, 1988; Wilmart et al., 1989; Wilmart et al., 1987). Average compositions of the main types of melts along the LLD are given in Table 2 (supplementary data).

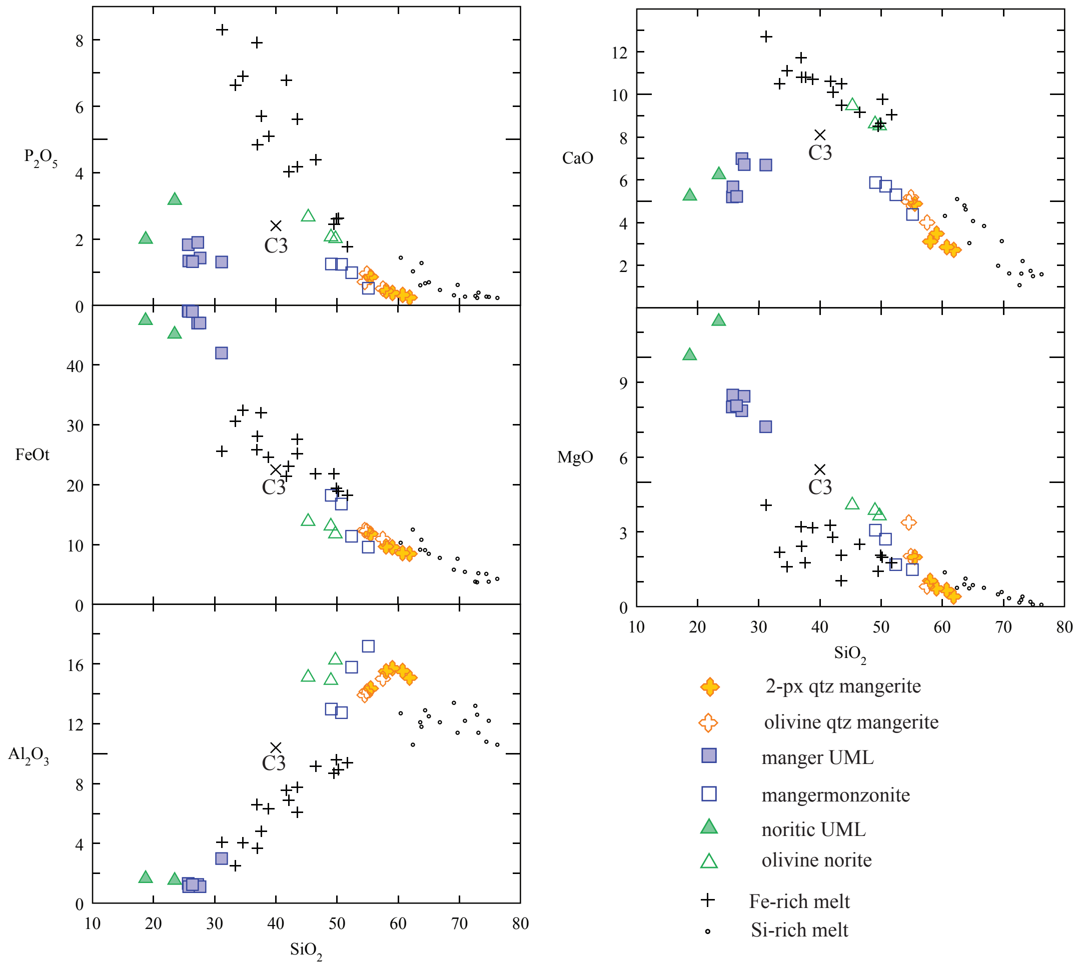

Fig. 6. Harker diagrams comparing the TZ lithologies to experimental immiscible melts of (Charlier and Grove, 2012). Date in Table 1 and in Charlier and Grove, 2012.

Another approach to define the LLD uses a peculiar property of the BKSK cumulates in the layered series (Charlier et al., 2005; Duchesne and Charlier, 2005). It has been shown that any cumulate can be described as a two pole mixture, one pole being a plagioclase and the other one all mafic minerals. Three mafic poles correspond to the three main types of cumulate: 1. ilmenite leuconorite with ilmenite and Ca-poor pyroxene; 2. magnetite leuconorite with magnetite, ilmenite and Ca-poor pyroxene; 3. gabbronorite with magnetite, ilmenite, apatite, Ca-rich pyroxene and Ca-poor pyroxene. In a type of cumulate, the mafic mineral content can vary from <10% (anorthosite) to >65% (melanorite/melagabbronorite). This observation implies that the average cumulate compositions have to lie on the straight lines between the poles. Two cumulate compositions (C1 and C2) corresponding to the main stages of the evolution (leuconoritic and gabbronoritic stages) were defined on the straight lines at the average values of the compositions. The LLD was divided in two stages: the parent magma L1 (TJ) evolves to L2 by subtraction of C1, and L2 to L3 by subtraction of C2. The transition zone cumulates (unfortunately) do not follow the 2 pole rule and an *ad hoc* cumulate C3 was defined to move L3 towards acidic rocks defined by the Tellnes LLD. It must be noted that if the composition C3 was a Fe-rich melt conjugated with Si-rich acidic melts its subtraction and further evolution on the two-liquid field curve would lead to the same result. It is thus necessary to test whether the reconstructed LLD effectively enters the two-liquid field.

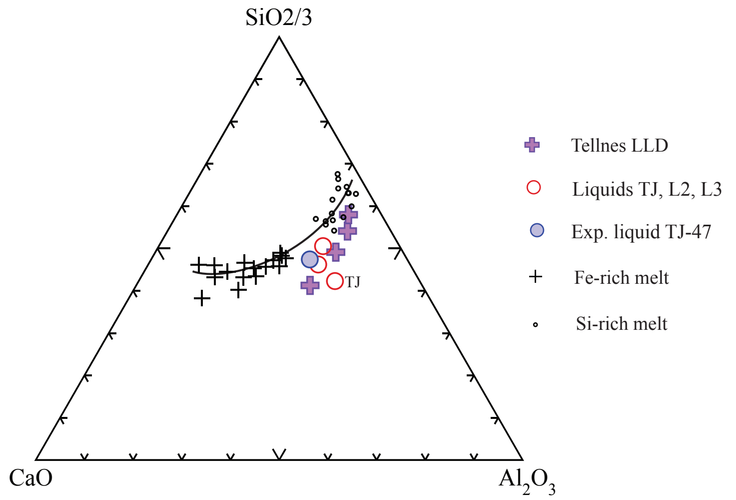

Fig. 7. Ternary diagram CaO, SiO2/3, Al_2O_3 comparing the experimental immiscible melts with the BKSK reconstructed LLD and the Tellnes LLD. The most evolved experimental glass TJ-47 of (Vander Auwera and Longhi, 1994) is also shown. Data in Table 2.

Fig. 7 definitely shows that the LLD does not enter into the immiscibility lacune. A more detailed approach is suggested in Fig. 8 where the LLD of the intrusion has been plotted together with the experimental glass compositions in equilibrium with all liquidus minerals at temperature just above the appearance of two liquids in cooling experiments (Charlier and Grove, 2012). These glasses are less than 20°C higher than the beginning of immiscibility. We can thus consider that these compositions are close to the solvus (two-liquid field) crest. It comes from Fig. 8 that the BKSK liquid trend, at least to L3, remains far from the 2-liquid field particularly for P_2O_5, CaO and TiO_2. Moreover, the C3 cumulate that subtracted from liquid L3 permits to reach the Si-rich members of the jotunite (Tellnes) LLD. This strongly confirms that immiscibility is not taking place.

CONCLUSIONS

This compilation of the available data on the TZ, mangeritic unit and quartz mangerites confirms the lack of border facies in the upper part of the intrusion. The succession of cumulates is mostly continuous throughout the three units with a small regression at the basis of the mangerite unit that is possibly due to a movement of magma in the chamber.

We do not find evidence that an immiscibility process has taken place in the BKSK layered intrusion. The UML lithologies in the TZ are not comparable to experimental Fe-rich melts and, associated with their adjacent noritic rocks, they do not derive from Fe-rich melts. The BKSK liquid line of descent up to L3 compositions does not enter the 2-liquid field for the critical elements P_2O_5, CaO and TiO_2. The hypothesis suggested by Duchesne et al. (1987) that the UML are adcumulates in an evolved jotunitic liquid is thus still valid. Melt inclusions in apatite and reactive symplectites have not be mentioned, but at the layered series cumulates have been recrystallized due to syn-emplacement deformation (Bolle et al., 2000; Bolle et al., 2002; Paludan et al., 1994) and this might have blurred these structures. However further studies on the less deformed lithologies in the TZ might throw more light on the question.

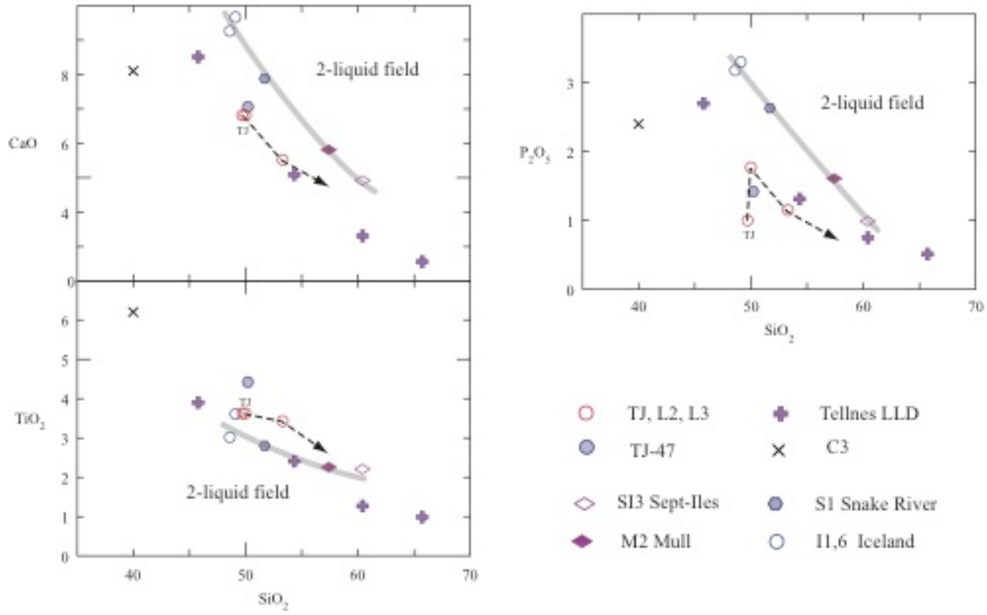

Fig. 8. Harker diagrams comparing the BKSK and Tellnes reconstructed LLDs and glass TJ-47 to the experimental melt compositions from various tholeiitic layered intrusions. The compositions are those of the last experiment with one glass in equilibrium with all minerals at 1047°C (and 1023°C for Iceland I-6). In the cooling experiments 2 melts appeared at a slightly lower temperature and the melts Si-rich melts were located in the 2-liquid field. Data in Table 2 and in Charlier and Grove (2012).

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Supplementary material in Table.xlsx