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Experimental constraints on the Skaergaard liquid line of descent

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Abstract

New experimental information permits a forward approach to modeling the liquid line of descent of the Skaergaard intrusion. A series of melting experiments on chilled margins of evolved tholeiitic and ferrobasaltic dikes associated with the intrusion is, in combination with existing data, used to develop quantitative crystallization models that allow liquid and solid compositions to be predicted for initial magma compositions and crystallization conditions open or closed with respect to oxygen. The new experimental results comprise 6 experiments with melts coexisting with plagioclase and olivine, 29 experiments in addition containing augite, 14 experiments in addition containing ilmenite and/or magnetite, and 6 experiments in addition containing pigeonite and sometimes lacking olivine. All melting experiments were done at atmospheric pressure and with a furnace gas mostly controlled to the fayalite-magnetite-quartz oxygen buffer (FMQ).

Using these experimental results, the melt evolution can be constrained for the layered series of the Skaergaard intrusion. Fractionation of a LZa troctolitic assemblage drives the residual liquid toward increasing iron with slight increase in silica. The appearance of augite as an abundant mineral phase in the LZb and the fractionation of a gabbroic assemblage adjust the liquid trend to one of slightly decreasing silica with continued strong increase in iron. Silica decline is principally dependent on the crystallization of augite and restricted to LZb. The appearance of Fe–Ti oxide minerals and the fractionation of Fe–Ti oxide gabbroic assemblages in LZc deflect the evolution trends of iron and silica. The modeling based on the experimental results suggests marked LZc–MZ silica enrichment concurrently with increasing iron content until upper MZ and thereafter relatively constant or slightly decreasing iron.

The iron concentration level at which the deflection in iron and silica contents occurs is dependent on several factors of which the oxygen fugacity (f_{O_2}) has the strongest effect. Because of the restricted variation in f_{O_2} modeled in LZ (~0.1 log unit above FMQ), the saturation of oxide minerals and the liquid line of descent are unlikely to deviate strongly from the predicted variation based on open system experimental conditions. For the same reason, there is no support for the suggestion that widely different LZc oxide mineral modes will result from crystallization conditions closed with respect to oxygen as opposed to the experimental conditions.

Modeling based on the new experimental result suggests that iron can continue to increase through LZc, past the appearance of Fe–Ti oxides, and supports the possibility that iron may have continued to increase well into MZ. However, the forward modeling supports only a modest MZ and UZ decrease in f_{O_2} (<1 log unit below FMQ). This result is supported by a good correspondence between the experimental modes and the actual observed gabbro modes. A marked UZ drop in f_{O_2} (~2–3 log units below FMQ), as has been suggested, requires relatively high total modal content of Fe–Ti oxides (>20 wt.%) and dominating magnetite over ilmenite not permitted based on the experimental observations. Such high oxide modes will always result in liquid lines of descent

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that are characterized by strong enrichment in silica with strong depletion in iron. The forward modeling illustrates that only for unrealistic small amounts of Fe–Ti oxide minerals will iron enrichment accompany silica depletion into UZ.

Keywords: Layered intrusions; Skaergaard intrusion; Experimental constraints; Closed system; Fractional crystallization; Gabbro; Liquid line of descent; Iron variation; Silica enrichment; Oxygen fugacity

1. Introduction

The Skaergaard intrusion represents an extreme example of fractional crystallization of a small basaltic magma chamber trapped in continental crust during Tertiary rifting of the North Atlantic (Wager and Deer, 1939). Today, more than half-a-century after Wager and Deer's discovery of the intrusion and their pioneering work, the nature of the fractionating processes and the evolution path of the Skaergaard magma are still controversial and subject for debate (Hunter and Sparks, 1987, 1990; McBirney and Naslund, 1990; McBirney, 1995; Tegner, 1997; Irvine et al., 1998; Jang et al., 2001; Ariskin, 2002).

The Skaergaard magma chamber crystallized slowly by the separation and accumulation of the solid fraction on the floor and margins. The marginal and upper border series (MBS and UBS) formed by crystallization along the walls and under the roof, respectively, while the layered series (LS) simultaneously accumulated upward from the floor of the chamber (Fig. 1). The base of the LS is not exposed and the unknown section is often referred to as the hidden zone (HZ). The crystallization fronts converged in the sandwich horizon (SH) and resulted in an extremely differentiated stratigraphic gabbro section. This gabbro section allows assessments of the melt evolution and modes of solidification. The principal manifestation of the evolving nature of the magma is a systematic enrichment in the contents, for example, of albite in plagioclase and fayalite in olivine. An equally important manifestation is a systematic appearance/disappearance of minerals with falling temperature. The latter observation allows the layered and border series to be divided into zones and subzones dependent on the principal constituent mineral assemblages that provide convenient reference points for the magmatic evolution (Fig. 1).

Despite the well-preserved gabbro sequences, no direct traces of liquid are preserved in the intrusion. Rare mineral aggregates contained in early formed minerals have been interpreted to represent melt inclusions (Hanghøj et al., 1995; Jakobsen et al., 2005). The liquid line of descent can thus best be inferred indirectly. Because Fe–Ti oxide minerals appear relatively early in the Skaergaard cumulates (LZc), a subsequent differentiation trend characterized by iron and titanium depletion and silica enrichments was predicted by Hunter and Sparks (1987, 1990). This prediction contrasts with the strong iron enrichment that has been suggested to continue well past the appearance of Fe–Ti oxides (Fig. 2; Wager and Deer, 1939; Wager, 1960; Wager and Brown, 1967; McBirney and Naslund, 1990; Morse, 1990; McBirney, 1995; Tegner, 1997; McBirney, 1998). Basaltic magma undergoing fractional crystallization typically shows, dependent on the availability of oxygen, an initial path of iron and titanium enrichment with moderate silica depletion, followed by late stage evolution towards strongly decreasing iron and increasing silica contents (Bowen, 1928; Fenner, 1929; Osborn, 1959; Presnall, 1966). This has been confirmed by experimental melting of ferrobasalts under conditions appropriate for oceanic magmas (Juster et al., 1989; Snyder et al., 1993; Thy and Lofgren, 1994; Toplis and Carroll, 1995). These

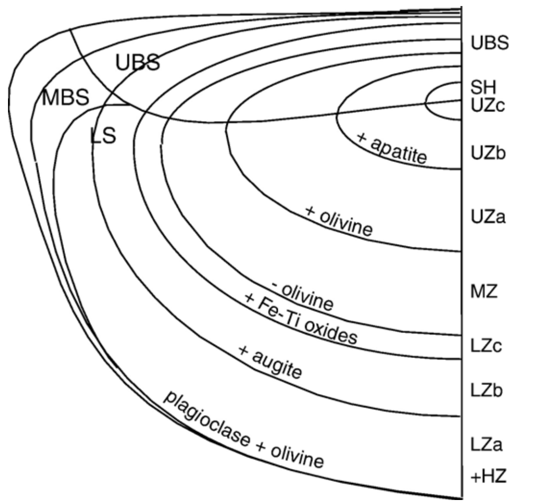

Fig. 1. Schematic representation of the margins and interior of the Skaergaard intrusion. Illustrated are the relative extent of the border series (Marginal Border Series, MBS, and Upper Border Series, UBS) and layered series (LS) with zone divisions and incoming/exit of mineral phases after Wager and Brown (1967), Naslund (1984), and Hoover (1989b). Additional abbreviations are Hidden Zone, HZ; Lower Zone, LZ; Middle Zone, MZ; Upper Zone, UZ, and Sandwich Horizon, SH.