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Discussion

On the Skaergaard intrusion and forward modeling of its liquid line of descent: A reply to "Principles of applied experimental igneous petrology" by Morse, 2008, Lithos 105, pp. 395–399

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ABSTRACT

Forward modeling based on an experimental investigation successfully duplicated main features of the gabbros in the Skaergaard layered series [Thy, P., Lesher, C.E., Nielsen, T.F.D., and Brooks, C.K. 2006. Experimental constraints on the Skaergaard liquid line of descent. Lithos 92, 154–180.]. The foundation for the modeling was equilibrium melting experiments that were controlled by temperature and oxygen fugacity at low-pressure conditions. The experimental techniques and methods were chosen to represent a reasonable approximation to the inferred emplacement and crystallization conditions of the Skaergaard intrusion. The dike rocks used as starting materials define a strong differentiation trend that represents the Skaergaard liquid line of descent. This suite of dikes allowed liquidus conditions to be defined for a range of composition and temperature. The initial redox conditions were chosen based on measured and calculated estimates for the gabbros of interest. The melting experiments defined liquidus and subliquidus conditions that were used to understand crystallization of the lower and middle zones of the Skaergaard layered series, and can be extrapolated to the upper zone gabbros assuming perfect fractional crystallization. The forward modeling reproduces the cryptic variation seen in the main gabbro minerals (olivine, augite, plagioclase) well into the upper zone and provides reasonable liquidus temperatures and compositions. It can be shown that based on the assumption of Fe–Ti oxide modes in the middle and upper zones, a range of oxygen fugacity trends can be obtained. We repeat our previous conclusion that iron depletion and strong reduction in oxygen fugacity in the upper zone are only feasible for very high Fe–Ti oxide modes that exceed the experimental evidence as well as the observations from the gabbros. A strong drop in oxygen fugacity in the upper zone requires a significant sink for Fe–Ti oxides that so far has not been identified. We thus reject Morse's [Morse, S.A., 2008. Principles of applied experimental igneous petrology: a comment on "Experimental Constraints on the Skaergaard liquid line of descent" by Thy, Lesher, Nielsen, and Brooks, 2006, Lithos 92: 154–180. Lithos 105, pp. 395–399.] contention that we violated in our original study established principles of applied experimental igneous petrology. Such principles dictate that experimental and forward models are carefully tested against field observations before petrologic processes can be verified.

"I would rather be attacked than unnoticed. For the worst thing you can do to an author is to be silent as to his works."– Samuel Johnson (1709–1784)[1]

1. Introduction

It is not surprising that issues concerning the liquid line of descent of the Skaergaard intrusion still command the acute attention of the igneous petrology community almost eighty years after the intrusion was first discovered by L. R. Wager during a brief visit in 1930 to the Kangerdlugssuaq area of East Greenland (Chapman, 1932; Deer, 1967; Brooks, 1985; Hargreaves, 1991). Wager and Deer (1939) argued convincingly from field observations, petrography, and mass balance considerations that fractional crystallization was responsible for producing the differentiated gabbros of the intrusion and that the progressive enrichment of iron in these rocks reflected a complementary enrichment of iron in the magmatic liquids from which they crystallized. This latter conclusion was supported at the time by the field and geochemical work of Fenner (1929) on differentiated basaltic suites. However, the notion that crystal fractionation could lead to strong iron

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[1] Quoted by Bloom (1979).

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enrichment in magmas ran counter to the experimental results of Bowen (1915, 1928) showing that derivative liquids from basaltic parents should become depleted in iron and enriched in silica by crystal fractionation.

Subsequent experimental works by Osborn (1959) and Presnall (1966), among others, have in part reconciled these early opposing views of fractional crystallization by showing that variations in oxygen fugacity ($f_{O2}f_{O2}$) and the appearance of Fe–Ti oxide minerals have strong effects on iron versus silica enrichment trends in residual liquids. High or increasing f_{O2} favors earlier crystallization of Fe–Ti oxide minerals, restricting iron enrichment and enhancing silica enrichment (calc-alkalic evolution), while low or decreasing $f_{O2}f_{O2}$ can delay Fe–Ti oxide saturation permitting continued iron enrichment (tholeiitic evolution) (Osborn, 1962). During the following decades, a consensus emerged that Skaergaard differentiation indeed followed a tholeiitic evolution trend in a closed system with iron enrichment associated with low or decreasing $f_{O2}f_{O2}$ (Presnall, 1966). While this latter condition would delay the appearance of Fe–Ti oxide minerals, it is well-established that magnetite appeared on the liquidus during formation of lower zone c (LZc), after approximately 40% of the magma had crystallized. Despite the inevitability of magnetite (and ilmenite) crystallization, investigations of Skaergaard and penecontemporaneous dikes during the 1970–80s (McBirney, 1975, Brooks and Nielsen, 1978; Hoover, 1989) and subsequent work (Tegner, 1997; McBirney, 1998) have amassed ample support for strong iron enrichments until the end stages of crystallization. This view was challenged by Hunter and Sparks (1987) and lead to a vigorous exchange (McBirney and Naslund, 1990; Brooks and Nielsen, 1990; Morse, 1990; Hunter and Sparks, 1990) highlighting the importance of the parental Skaergaard magma composition, field relations, and processes of differentiation. Of particular relevance to the present discussion are the gabbro melting experiments of McBirney and Naslund (1990) showing that interstitial Skaergaard liquids systematically increased in total Fe from 14 wt.% in lower zone a (LZa) to 31 wt.% in upper zone c (UZc). Nevertheless, experimental studies and modeling exercises that followed (Toplis and Carroll, 1995, 1996; Ariskin, 2003; Ariskin and Barmina, 2004) show that differentiation of Skaergaard-like liquids result in iron depletion and silica enrichments once or shortly after Fe–Ti oxide minerals appeared on the liquidus. We embarked on our experimental effort (Thy et al., 2006) aware of these unrelenting issues, cognizant of the limitations of modeling, and recognizing the important constraints provided by field relations.

What appears at the root of Morse's (2008) challenge to our 2006 Lithos contribution is his certainty that the $f_{O2}f_{O2}$ for the Skaergaard magma markedly decreased during the course of Skaergaard evolution. Morse also finds fault with our experimental methods (techniques widely used to determine the phase relations for magmas at atmospheric pressure), with our choice of starting compositions, and, apparently, also with constraints provided by the rocks themselves bearing on the liquid line of descent. We greatly appreciate this invitation to return to the topic and to elaborate on our methods, results and their implications.

Our rebuttal focuses on several key issues raised in Morse's discussion bearing directly on the Skaergaard intrusion. We leave consideration of the digressions and philosophical views regarding petrologic principles to the concerned reader to ponder. Herein, we will discuss our choice of experimental procedures, starting compositions, initial redox conditions, interpretations of phase relations for modeling equilibrium and fractional crystallization, liquidus phase assemblages, and the strength and limitations of forward modeling. We further provide a more complete catalog of primitive gabbros of the Skaergaard intrusion and show once again the good correspondence between our model results and the zone divisions, cryptic variations, and modal compositions of the Skaergaard gabbros. We discuss intensive variables and illuminate the variations of model temperature and oxygen fugacity in the layered series of Skaergaard and close our response by offering our own opinion of what constitutes applied experimental petrology as it pertains to the Skaergaard intrusion.

2. Starting compositions

The choice of starting materials is obviously critical for experimental modeling of layered intrusions often left without direct traces of unambiguous melt compositions. Early experimental Skaergaard studies (Tilley et al., 1963; Biggar, 1974) utilized a chilled margin gabbro identified by Wager (1961) as representing the initial melt composition. A better-suited chilled margin gabbro was identified by Hoover (1989) and was used in experimental work by Hoover (1978, 1989) and Snyder et al. (1993). Several lines of evidence have subsequently questioned the availability of melt-representative gabbros in the chilled margins of the Skaergaard intrusion (McBirney, 1975; Hoover, 1989; Holness et al., 2007) and have redirected the search for the parental Skaergaard magma to the associated dike swarms. Brooks and Nielsen (1978, 1990) argued that a radial tholeiitic dike swarm related to the coastal flexure and penecontemporaneous with the Skaergaard and associate macrodike intrusions represented a close approximation to the Skaergaard liquid line of descent. This dike swarm does not cut the Skaergaard intrusion and defines a strong differentiation trend in many binary variation diagrams, such as the TiO_2–FeO variation shown in Fig. 1, with distinct iron enrichment correlated with modest silica depletion (Brooks and Nielsen, 1978, 1990). These well-characterized dikes were utilized as starting materials for our Skaergaard study. We selected a suite of dikes encompassing the observed differentiation (Fig. 1) to allow us to explore the effects of bulk composition on liquidus assemblage and element partitioning. Toplis and Carroll (1995) focused their study on a specific Skaergaard dike that they prepared directly from the simple oxide and carbonate reagents allowing them to simplify the compositional variance (by excluding MnO and P_2O_5). McBirney (1975) and McBirney and Naslund (1990) took a different approach by selecting gabbro cumulates for direct experimental melting with the purpose of determining compositions of trapped melt in equilibrium with the cumulus phases throughout the layered series. Although the results of this latter study are known, the detailed experimental procedures and analytical results still remain to be published.

3. Initial redox conditions

Oxygen activity is an important intensive variable that affects Fe^{3+}/Fe^{2+} ratios and phase equilibria (Kennedy, 1955; Fudali, 1965; Kilinc et al., 1983). It is generally accepted that the initial redox condition of the Skaergaard magma was near the fayalite–magnetite–quartz oxygen buffer (FMQ) (Fig. 2). This conclusion is based on several lines of evidence. Intrinsic measurements on bulk gabbro and mineral separates using solid-electrolyte, oxygen-cell methods have suggested highly variable oxygen fugacity (Sato and Valenza, 1980; Kersting et al., 1989). This high variability (Fig. 2) has been related to late magmatic carbonic fluids that could have resulted in precipitation of carbon along grain boundaries dropping the measured oxygen fugacity to just above the iron–wüstite (IW) oxygen buffer (Sato and Valenza, 1980; Frost and Lindsley, 1992). The result is that the intrinsic measurements slightly above the FMQ oxygen buffer on mineral separates by Kersting et al. (1989) is often accepted as best defining the magmatic conditions of the initial Skaergaard magma (Fig. 2). Since our 2006 study was only intended and expected to be able to constrain the Skaergaard evolution until into the lower part of the