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Crustal assimilation in basalt and jotunite: Constraints from layered intrusions

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Abstract

To constrain the amount and rate of crustal contamination that is possible in basaltic and jotunitic magma, and to gain an insight into the physical and thermal processes of assimilation in crustal magma chambers, we have modelled published Sr and Nd isotopic data from three layered intrusions. Well-exposed sequences of cumulates with no evidence of magma recharge provide direct records of concurrent assimilation and fractional crystallization (AFC). The key to the modelling is that *F*, the mass fraction of magma remaining in the chamber, can be estimated from the thicknesses of the studied cumulate sequences. This allows AFC model curves to be fitted to the isotopic data by varying ***r***, the ratio of the rate of mass assimilated to the rate of mass crystallized. The results of modelling show that ***r*** is nearly constant in 800 to 2000 m thick sequences of cumulates displaying up-section decreases in anorthite content of plagioclase, increases in whole-rock Sr_0 (initial $^{87}Sr/^{86}Sr$) and decreases in whole-rock εNd_0 (initial εNd). The ***r***-values of the layered sequences range from ~0.12 in the Fongen–Hyllingen Intrusion, over 0.20 in the Bjerkreim–Sokndal Intrusion, to 0.27 in the Hasvik Intrusion. The total amount of assimilation, the *bulk crust/magma ratio*, reaches values of 0.08, 0.19 and 0.28 at the level of the most contaminated samples after 60% to 80% crystallisation, whereas the *instantaneous crust/magma ratio* of the most contaminated magmas were respectively 0.14, 0.46, and 0.70, for the three intrusions.

Innumerable country rock xenoliths occur in the three layered intrusions and played a crucial role in the assimilation process. The xenoliths spalled off the roofs of the magma chambers during magma emplacement and their initial temperature and composition relate to ***r*** in the intrusions. In the Hasvik Intrusion (***r***=0.27), the initial temperature of the country rocks was ~450 °C and the xenoliths were fusible metasediments and therefore produced a high fraction of partial melt that could be assimilated. In the Bjerkreim–Sokndal Intrusion (***r***=0.20), the country rocks were initially at temperatures of 640–880 °C but included both refractory massif-type anorthosite and fusible gneisses. In the Fongen–Hyllingen Intrusion (***r***=0.12), the country rocks were cooler (~300 °C) and the xenoliths include refractory metabasalt (dominant) and fusible metapelite. We argue that the refractory metabasalt and anorthosite xenoliths acted mainly as heat sinks, resulting in reduced ***r***-values in Fongen–Hyllingen and Bjerkreim–Sokndal Intrusions.

Heating of refractory and fusible xenoliths, and melting of fusible xenoliths absorbed sensible and latent heat of the magma. Energy-balanced modelling shows that up to 75% of the heat available was absorbed by xenoliths within the magma chambers, promoting higher rates of cooling and crystallisation than would have resulted from loss of heat to the envelope of country rocks

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alone. The high ***r***-values reflect the amount of heat absorbed by heating and melting country rock within the magma chambers themselves, and their constancy reflects the ready availability of fusible xenoliths.

Keywords: Layered mafic intrusion; Crustal assimilation; Xenoliths; Hasvik; Fongen–Hyllingen; Bjerkreim–Sokndal, Norway

1. Introduction

Concurrent crustal assimilation and fractional crystallization (AFC) is recognised in virtually all mantle-derived magmas emplaced into the Earth's crust. For example, in the Oman ophiolite, the mid-ocean ridges, and the Skaergaard Intrusion, all previously thought to have negligible crustal contamination, recent isotopic and trace element investigations have demonstrated some assimilation of the local country rocks (Stewart and DePaolo, 1990; Michael and Cornell, 1998; Coogan et al., 2003). Crustal assimilation may significantly alter the composition of magmas, including their water and chlorine contents, resulting in significant changes in liquidus relations, liquid lines of descent, and, perhaps most importantly, the proportions and compositional variety of the differentiation products (Bowen, 1928; Wilcox, 1954; Taylor et al., 1979; Reiners et al., 1995).

The physical processes by which assimilation takes place and the amounts and rates of assimilation, however, remain at best loosely constrained. In the AFC formulation of DePaolo (1981), the ratio of the rate of mass assimilated to the rate of mass crystallized, ***r***, can only be determined if the fraction of the mass of magma remaining (F) can be estimated. This is commonly impossible in volcanic systems. Hence, a shortcoming of AFC modelling is that ***r*** normally has to be assumed.

Contamination of mantle-derived magmas takes place mainly in large crustal magma chambers. It is a consequence of coupling between the concurrent release of latent heat of crystallization and heat consumed in heating and melting country rocks (Bowen, 1928; DePaolo, 1981). Layered intrusions, which represent solidified magma chambers, often provide secular records of concurrent assimilation and fractional crystallization, as demonstrated by the inverse correlation of plagioclase compositions [An%=Ca/(Na+Ca)] and Sr_0 (initial $^{87}Sr/^{86}Sr$) (Fig. 1). In layered sections, the upward decrease in An% and the successive appearance of cumulus phases correlate with F. This applies both when the up-section decrease in An% is continuous and step-like. Layered intrusions therefore provide direct insights into AFC processes.

In this presentation we first review published estimates of ***r*** from thermodynamic models such as MELTS (Reiners et al., 1995), energy-constrained assimilation and fractional crystallization (EC-AFC; Spera and Bohrson, 2001), and a kinetic model for rates of mineral dissolution (Edwards and Russell, 1998). We then discuss the maximum rates and amounts of country rock assimilation that are possible in crustal magma chambers. Thirdly, we review and model published Sr- and Nd-isotopic data from the Bjerkreim–Sokndal, Fongen–Hyllingen and Hasvik layered intrusions with the aim of constraining ***r*** and the amount of assimilation. Finally, we discuss the physical

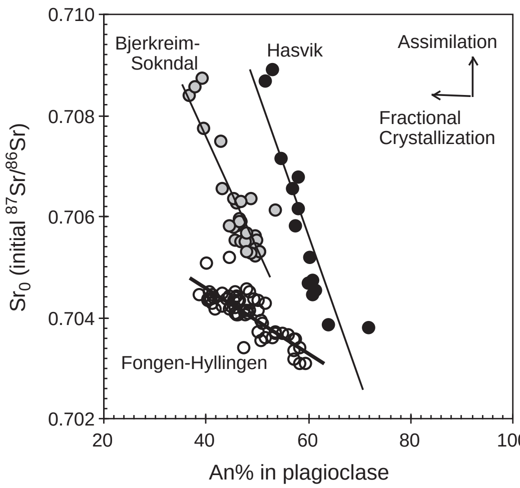

Fig. 1. Relationships between whole rock Sr_0 (initial $^{87}Sr/^{86}Sr$) and An% in plagioclase of sequences of cumulates formed by concurrent assimilation and fractional crystallization in large crustal magma chambers. The data shown are from the Bjerkreim–Sokndal (Nielsen et al., 1996), Fongen–Hyllingen (Sørensen and Wilson, 1995), and Hasvik layered intrusions, Norway. Modified from Tegner et al. (1999).