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Chemical and physical evolution of the 'lower layered sequence' from the nepheline syenitic Ilímaussaq intrusion, South Greenland: Implications for the origin of magmatic layering in peralkaline felsic liquids

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ABSTRACT

The Mid-Proterozoic composite Ilímaussaq complex, South Greenland, is a classic locality to study magmatic layering in evolved peralkaline magmas. Most of the rock units show magmatic layering to differing extents, but 'kakortokites' – generally medium-grained agpaitic nepheline syenites – show a spectacular recurrence of black, red and white layers, which is due to regular changes in the modal contents of arfvedsonitic amphibole, eudialyte (sensu lato), alkali feldspar and nepheline, respectively. These three-layer units are found in the lower part of the intrusion and recur 29 times before grading into the overlying lujavrites (melanocratic agpaitic nepheline syenites), which are generally fine-grained and fissile with less-developed layering.

The compositional trends observed in amphibole and eudialyte throughout the stratigraphic sequence reflect various processes including the chemical evolution of the melt by crystal fractionation, changes in the crystallising mineral assemblage and sub-solidus alteration. Eudialyte is the first mineral to crystallise in the investigated sequence and is therefore appropriate for recording evolution trends within the melt. Amphibole, on the other hand, always crystallises later and is therefore affected by other crystallising minerals. A detailed microprobe study of both minerals through the whole kakortokite stratigraphy displays surprisingly little change in mineral compositions within the kakortokites, but strong fractionation trends in the overlying lujavrites.

Although various models have been proposed to explain the recurrence of the 29 rhythmic units, the origin of this prominent magmatic layering in the kakortokites and the lack of mineralogical and strong mineral chemical changes has not been quantitatively explained. We propose, that in the kakortokites, minerals were probably separated from each other as a result of their different densities. The interior cooled, resulting in crystallization but only a very small proportion of crystals (0.1–0.3% for each of the four minerals) could remain suspended in the melt before gravity forced them to settle down in a stagnant layer of reduced convection. A combination of volatile pressure variations caused by eruptive activity and repeated replenishment can explain the oscillating liquidus temperature, the small changes in mineral compositions and such a process would produce enough crystals to form the 29 layers.

1. Introduction

Magmatic layering is a common feature in large mafic intrusions (e.g., Wager and Brown, 1968; Campbell et al., 1983; Maaløe, 1987; Muerer and Boudreau, 1996; Wilson, 1996). In more evolved siliceous rocks like granites it occurs only rarely (e.g., Barrière, 1981; Pupier et al., 2008) but in highly evolved and silica-undersaturated intrusions, layering is more common (e.g., Wang and Merino, 1993; Féménias et al., 2005). The peralkaline Ilímaussaq complex, South Greenland is one of the chemically most evolved intrusive complexes in the world (Ferguson, 1964; Larsen and Sørensen, 1987; Bailey et al., 2001; Markl et al., 2001, Marks et al., 2004a) and its repetitive modal layering occurs in a regular way comparable to that seen in some mafic layered intrusions. In the southern part of the intrusion, so-called kakortokites (layered nepheline syenites) comprise twenty-nine three-layer units with a relatively uniform thickness of ~8 m (Bohse et al., 1971). Each unit is made up of a black, a (sometimes absent) red and a white layer, their colour reflecting the dominant mineral, i.e. arfvedsonitic amphibole, eudialyte, or alkali feldspar, respectively.

To explain the recurrence of magmatic layering in general, a wide variety of models have been proposed:

- Magma chamber recharge (e.g. Irvine and Smith, 1967).
- Continuous convection (e.g., Wager and Brown, 1968).
- Gravitational crystal settling (e.g., McBirney and Noyes. 1979).

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- Compositional layering in the crystallising melt (e.g., Wörner and Schmincke, 1984; Wilson and Larsen, 1985).
- Ostwald ripening, based on different surface energies of grains of different sizes (e.g., Boudreau, 1987; McBirney et al., 1990).
- Coats (1936) suggested that crystals of differing sizes and densities tend to sort themselves in crude layers as they consolidate under the force of gravity.
- Wang and Merino (1993) showed that the feedback between mineral growth rates and the concentrations of reactant species can also cause the repetition of layering.

For the Ilímaussaq complex, in particular, several models have been proposed to explain the repetitive layering: Sørensen (1968) invoked oscillatory changes of the liquidus temperature around the temperature of the magma that could have been caused by the migration of volatiles and thermal energy in an un-layered magma chamber. Later, Bohse et al. (1971) proposed periodic overturns of the magma by convection to be the cause of the recurrence of the three-layer units. Larsen and Sørensen (1987) explained the repetitive layering by a multiply layered magma chamber. In their model, crystallization started at the lowermost layer and proceeded successively upwards, and the resulting transfer of thermal energy and volatiles caused crystallisation in the overlying magma layer. This model was also supported by Bailey et al. (2006), who found changes of some geochemical parameters—e.g., silica, H_2O and NaCl activities, varied in a step-like pattern between different units.

In the present study, we examine the mineral chemical variations in amphibole and eudialyte throughout the kakortokites and parts of the overlying lujavrites in order to track evolutionary trends and relate them to the chemical evolution of the fractionating melt. In the light of these data, the various models proposed for the magmatic layering of the lower part of the Ilímaussaq intrusion are discussed.

2. Geology

Magmatism in the Gardar Province, South Greenland, was closely related to continental rifting between 1350 and 1140 Ma (Upton et al., 2003). During this period, several alkaline to peralkaline plutonic complexes and a large number of compositionally highly variable dyke rocks intruded the Early Proterozoic (1.80–1.85 Ga) granitic basement rocks (Julianehåb batholith; Garde et al., 2002) and early-Gardar Eriksfjord basalts and clastic sediments (Poulsen, 1964). The Ilímaussaq complex has been dated at 1160±5 Ma (Krumrei et al., 2006) and consists of alkaline to peralkaline, mostly agpaitic rocks, for which eudialyte$_{s.l.}$ (Na–Ca–HFSE silicate) is an index mineral (Sørensen, 1997; Fig. 1a).

Four pulses of magma successively intruded to 3–4 km depth (Larsen, 1976; Sørensen, 2006). The first pulse produced a silica-saturated to slightly under-saturated augite syenite, which is now found as a marginal shell and as autoliths within the later agpaitic rocks. Subsequently, a sheet of peralkaline granite intruded the augite syenite. In the third and fourth stages, various peralkaline to agpaitic nepheline syenites were formed mostly by low-pressure in situ fractionation of a broadly phonolitic melt. They mainly consist of various proportions of nepheline, eudialyte, sodalite, alkali feldspar, aegirine and arfvedsonite. These units make up the major part of the complex and are subdivided into a roof series (pulaskite, foyaite, sodalite foyaite and naujaite, from the roof downwards) that was formed from the third melt batch, a bottom series (kakortokites) and the most evolved rocks (lujavrites) in between. The latter two crystallised from the fourth stage melt. The roof series formed by downward crystallisation and flotation of minerals less dense than the melt, the bottom series by gravitational separation after the solidification of the roof series. The residual melts (lujavrites) intruded the roof cumulates along fractures (Larsen and Sørensen, 1987). The thickness of the Ilímaussaq magma chamber is estimated to be less than 1 km, whereas the horizontal extent of the intrusion is 17×8 km (Andersen et al., 1981b).

The whole kakortokite–lujavrite sequence is exposed as an approx. 700 m thick body, with kakortokites in the lower part (about 300 m in thickness), and lujavrites nearer the top. Kakortokites are the lowermost exposed rocks of the Ilímaussaq intrusion, but more cumulates are suspected to be below, as indicated by gravitational and magnetic anomalies (Sass et al., 1972; Blundell, 1978; Forsberg and Rasmussen, 1978). Kakortokites are only exposed in the southern part of the complex, whereas lujavrites occur in the whole complex and cross-cut the other rock types (Fig. 1b). A proposed SW–NE trending major fault divides the unit into two blocks with an upthrusting of about 500 m vertical extent.

Mineralogically, kakortokites and lujavrites are very similar, but texturally, they show marked differences in grain size, the predominance of aegirine or arfvedsonite, or in their feldspar mineralogy. However, kakortokites grade successively into the lowermost of the overlying lujavrites. Kakortokites and lujavrites are further subdivided into several units (Fig. 2; Andersen et al., 1981b):

(i) Lower layered kakortokites (about 200 m thick) consist of twenty-nine units with each unit subdivided into a black, a (not always fully developed) red, and a white layer. The black layer is the lowermost of the three layers and is dominated by arfvedsonitic amphibole. The red layer is eudialyte-rich and the uppermost white layer consists mainly of alkali feldspar and nepheline. The transition from black to red and from red to white is gradual, whereas a sharp contact separates the white layer from the next overlying unit. On average, one three-layer unit is ~8 m (3.5 to 12.5 m) thick. Close to the margins of the intrusion the dip of the layers becomes steeper and is not longer as flat as in the centre. Also, the layering becomes more small-scale and enigmatic. Bohse et al. (1971) numbered the twenty-nine units from −11 to +17. In layer +3, large autoliths (up to several hundreds of meters) of augite syenite and naujaite are found, which were detached from the rocks above by a roof collapse (e.g. Larsen and Sørensen, 1987). The successive units envelop these autoliths and the roof collapse may have intensified movements in the magma chamber for a while (the same can be seen in Western Kungnat; Upton, 1960), because unit +4 contains again numerous features indicating magmatic flow (Bohse et al., 1971), whereas the units below show sagging and compaction features (see Fig. 2a in Schönenberger et al., 2006) demonstrating the sedimentary character of the kakortokites in general. Furthermore, sedimentary structures induced by flows (i.e. trough banding and current bedding) are visible close to the margins of the intrusion, around the above-mentioned autoliths in unit +3 and in the lowermost exposed units (Upton, 1961).

(ii) Slightly layered kakortokites (about 50 m thick) conformably overlie the lower layered kakortokites but show hardly any layering. Their outcrop is poor and no samples of this unit were investigated.

(iii) Transitional layered kakortokites (about 60 m thick) show again the prominent layering as the lower layered kakortokites. The units are named upwards from F to A (Bohse et al., 1971). Mineralogically, these units are very similar to the lower layered kakortokites. However, the modal abundance of aegirine compared to arfvedsonite increases upwards: the uppermost black layer A is aegirine-dominated and quite similar to the overlying aegirine lujavrite I. However, since this black layer A is again overlain by a red and a white layer, it is grouped with the transitional layered kakortokites.

(iv) Aegirine lujavrites are divided into two textural varieties (I and II; Fig. 2) with cumulate textures being less developed than in kakortokites. Major minerals in both varieties are aegirine,