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Interactions between an agpaitic magma and syenite xenoliths in the Ilímaussaq intrusion, South Greenland

J. Schoenenberger, G. Markl

Eberhard-Karls-Universitaet Tuebingen, Institut fuer Geowissenschaften, AB Mineralogie und Geodynamik, Wilhelmstraße 56, 72074 Tuebingen, Germanymarkl@uni-tuebingen.de / Phone: +49-7071 2972390

The 1.16 Ga old Ilímaussaq intrusion is situated in the Gardar province of South Greenland which represents a failed rift between the Archean craton in the north and the Ketilidian mobile belt in the south. It consists of 10 major and several smaller intrusions which are of granitic to syenitic composition [1].

The evolution of Ilímaussaq involved three different magmatic batches ([2] & [3]). The first magmatic batch consists of augite syenite with hedenbergite, fayalite, Fe-Ti ores, alkali feldspar, little nepheline, apatite and zircon/baddeleyite as well as late-stage amphibole and biotite. The second batch is represented by a small volume of alkali granite. The third and main magmatic batch comprises different agpaitic nepheline syenites. They mainly contain arfvedsonite, aegirine, alkali feldspar, nepheline, eudialyte, sodalith and fluorite. Roof rocks (pulaskite, foyaite and naujaite) can be distinguished from floor rocks (kakortokite). The kakortokites exhibit spectacular magmatic layering in the form of 29 units. Each unit consists of a black (arfvedsonite-rich), a red (eudialyte-rich) and a white (alkali feldspar-rich) layer. The kakortokites are the lowermost exposed rocks of the intrusion, but it is assumed that beneath the exposed rocks dense cumulates exist as counterparts to the “light” agpaitic rocks.

During the crystallization of the kakortokitic magma, the roof of the magma chamber collapsed. Already crystallized rock fragments of augite syenite and naujaite fell into the still liquid kakortokitic magma. These xenoliths have a diameter up to 500 m and are concentrated in one distinct layer of the kakortokites. In this study, we investigated the interaction between the kakortokitc magma and the xenoliths. For this purpose, we sampled eight sections through the contact areas between the kakortokite and several xenoliths.

Principally, two types of xenoliths exist: one with a border pegmatite which is between 0.1 and 2 m thick and one without pegmatite, with razor-sharp contacts. We analyzed in detail one kakortokite-augite syenite profile with border pegmatite, one without pegmatite and one kakortokite-naujaite profile.

The formation of a border pegmatite between the xenoliths and the kakortokite resulted in the oxidation of primary arfvedsonite to aegirine in the kakortokites. During this reaction, the fluorine of the amphibole was released and lead to the formation of fluorite grains. They usually occur together with secondary aegirine. In the section with the sharp contact between the xenolith and the kakortokite, no changes of the primary kakortokitic mineralogy were observed. The only difference compared to a normal kakortokite without xenoliths is the occurrence of fluorite as interstitial grains and inclusions (e.g. in amphibole) close to the contact.

The augite syenite xenoliths show different reaction textures which can be divided in reactions which occurred up to several meters *inside the xenoliths* and those which took place *close to the contact* only.

The most common reaction *inside the xenolith* is the decomposition of hastingsitic amphibole to symplectites consisting of pyroxene, nepheline and in some samples aenigmatite. The schematic reaction

amphibole + fluid I = pyroxene + nepheline ± aenigmatite + fluid II

was quantified using the isocon method for metasomatic alteration [4]. The reaction textures are always in contact with the alkali feldspar matrix of the augite syenite and the quantified reactions indicate that Na, K, Si and Al were added. Therefore we propose a reaction including alkali feldspar as one of the reactant phases (**reaction a**). In this reaction, mainly Na but also Ca and Al were added with a fluid phase while mostly the volatiles were removed. The occurrence of analcime as a secondary product especially of nepheline suggests **reaction b**. Furthermore, fluorite was observed along grain boundaries of nepheline (**reaction c**). This indicates that the released volatile elements were conserved locally in the xenoliths.

Close to the contact, the primary augite syenitic texture is completely altered and augitic clinopyroxene broke down to secondary Na-rich amphibole according to the schematic reaction

pyroxene + fluid I = amphibole + fluid II.

This reaction was also quantified using the isocon method (**reaction d**). The amphibole contains many fluorite grains which were formed from the Ca released from the pyroxene and fluorine from the fluid. Another type of fluorite grains are concentrated at nepheline or alkali feldspar grain boundaries indicating a similar fluorite forming reaction as **reaction c**. Primary Fe-Ti-minerals were replaced by aenigmatite (**reaction e**) and primary olivine was probably replaced by biotite (**reaction f**). In addition, secondary arfvedsonite reacted to aegirine.

2 amphibole + 4.84 alkali feldspar + 4.20 Na^{+} + 0.93 Al^{3+} + 1.59 Ca^{2+} + 0.11 K^{-} + 0.04 Mn^{2+} + 1.74 O_2 = 6.58 pyroxene + 10.38 nepheline + 0.45 aenigmatite + 0.11 Ti^{4+} + 0.19 Fe^{2+} + 0.02 Mg^{2+} + 0.02 Zr^{4+} + 0.04 Cl^{-} + 0.25 F^{-} + 3.68 H^{+} **[reaction a]**

nepheline + $SiO_2^{(fluid)}$ + H_2O = analcime **[reaction b]**

$Ca_{0,5}AlSiO_4$ + F^{-} + Na^{+} = 0,5 CaF_2 + nepheline **[reaction c]**

4 pyroxene + 2.08 Na^{+} + 1.08 Fe^{2+} + 0.46 K^{+} + 0.28 F^{-} + 1.73 H^{+} + 0.05 Si^{4+} + 0.02 Ti^{4+} + 0.01 Al^{3+} = 1,01 amphibole + 3.20 Ca^{2+} + 0.29 Mg^{2+} + 0.01 Mn^{2+} **[reaction d]**

Fe-Ti-Oxide + 2 albite + 3 $FeO^{(fluid)}$ = aenigmatite + $Al_2O_3^{(fluid)}$ **[reaction e]**

2 K-feldspar + 3 fayalite + 2 H_2O = 2 annite + 3 $SiO_2^{(fluid)}$ **[reaction f]**

The naujaite xenoliths also show different reaction textures. The poikilitic primary arfvedsonite is altered to pyroxene and biotite. With the help of the isocon method we were able to quantify the reaction:

$$\text{2 arfvedsonite + fluid}^{(added)} = \text{6.46 aegirine + 1.20 biotite + fluid}^{(lost)}$$

During this reaction, mainly K is added whereas F and H_2O are set free. Again, fluorite grains close to this reaction texture suggest the local conservation of the released fluorine.

The occurrence of secondary aenigmatite leads to the conclusion that arfvedsonite also reacted to aenigmatite although reaction textures were not observed. However, this type of reaction is described in the literature (e.g. [3]). Textural evidence was found for the aenigmatite breakdown according to the following reaction:

$$\text{aenigmatite} + Na_2Si_2O_5^{(fluid)} + O_2 = 4\ \text{aegirine} + FeTiO_3.$$

This reaction defines the stability of aenigmatite at low temperatures and high f_{O2} [5].

Due to a higher Fe^{3+}/Fe^{2+} ratio in the reaction product, each reaction involving mafic minerals can be described as an oxidation. Beyond that, the reactions also prove an enrichment in Na. There is an almost continuous evolution of the composition of pyroxenes from primary augite in the augite-syenite via aegirine-augites of the symplectites and acmite next to the contact to primary kakortokitic acmites. The aenigmatites represent a similar development and exhibit an exchange of Na+Si against Ca+Al.

The T-f_{O2} conditions of the reactions could be defined by qualitative comparison of hastingsite and aenigmatite stability in combination with the T-f_{O2} curve for the cooling of the Ilímaussaq rocks [3]. These considerations suggest that the reactions took place at temperatures between 570 and 630°C and f_{O2} values between 1 to 3 log units above the FMQ-buffer.

In summary, the reactions in the xenoliths were mainly driven by increasing oxygen fugacity and temperature decrease (after the heating due to the entrainment of the "cold" xenoliths into the hot magma). This led to the oxidation of the mafic reactants. In addition, it is supposed that the element exchange occurred in only one direction, i.e. from the kakortokite magma into the xenoliths and that the released ions (especially the anions like F) were preserved in the xenoliths. The penetration of the xenoliths by a Na-rich and oxidising fluid seems to be more intensive where a border pegmatite is developed.

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