Original paper

# Perthite in nepheline syenite from the kakortokite unit in the Ilímaussaq Complex, South Greenland

Hans K. SCHØNWANDT[1], Gregory B. BARNES[1], Thomas ULRICH[2]*

[1] *G.B. Barnes & Associates, 47 Labouchere Road, South Perth, W.A. 6151, Australia*
[2] *Department of Geoscience, Aarhus University, Hoegh-Guldbergs Gade 2, 8000 Aarhus, Denmark; thomas.ulrich@geo.au.dk*
* *Corresponding author*

Petrographic investigations of white kakortokite (nepheline syenite) reveal two structurally different types of perthite grains, herein called type A and B. Type A is more common and consists of an intimate intergrowth of microcline and albite. Microcline in type A perthites consists of two irregular penetrative individuals which appear as elongated pointed bodies parallel to (010) intergrown with polysynthetic twinned albite, which occurs as serrated bodies elongated parallel to (010). In type B perthites, K-feldspar (microcline) shows tiled structure and albite appears as microcrystalline equigranular veinlets, penetrating the perthite grain often perpendicular to (010). A great compositional variation of the type A grains (from nearly 100% microcline to almost pure albite) excludes exsolution to be the main process responsible for the structure. On the other hand, a replacement process controlled by a simultaneous dissolution–precipitation can explain the structure of type A, which means that widespread Na-metasomatism (albitization) had to have taken place in the kakortokite. Due to the different twinning structure of K-feldspar (microcline) in type B, the albitization in these grains occurred by albite veining of the grains.

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## 1. Introduction

Perthite, an intimate intergrowth of Na- and K-feldspar, is widespread in felsic igneous rocks. The structure of the intergrowth is frequently interpreted as reflecting subsolidus exsolution, but in cases it can result from a replacement process (Lee and Parsons 1997). As has been pointed out in a series of papers (e.g., Alling 1938; Parsons 2010), detailed study of the perthite structure is essential for any convincing genetic interpretation.

Perthite from the lower layered kakortokite (eudialyte-bearing nepheline syenite) in the Ilímaussaq Complex, South Greenland has been considered as a result of an exsolution process (e.g., Ferguson 1964, 1970; Markl et al. 2001; Sørensen et al. 2006; Lindhuber 2011; Upton 2013; Borst et al. 2018). Ussing (1912) regarded the perthite structure as a primary intergrowth of microcline and albite. However, our petrographic study of the perthite in white kakortokite, the main perthite-bearing member of the kakortokite sequence, points to replacement as a key mechanism for the formation of the perthite in the lower layered kakortokite. This assigns the formation of that part of the kakortokite sequence to subsolvus conditions.

## 2. Geological setting

The Ilímaussaq Complex is an oval-shaped (17 km by 8 km) alkaline intrusive complex (Fig. 1), which is a part of the Mesoproterozoic Gardar Province in South Greenland. The Gardar Province is related to two rifting episodes between 1.3 and 1.1 Ga and consists of a volcanic-sedimentary sequence (Eriksfjord Formation), dyke swarms and several alkaline to peralkaline central intrusive complexes (Upton 2013). The Ilímaussaq Complex has been dated repeatedly by single-crystal $^{40}Ar/^{39}Ar$ step-heating of amphibole and yielded a plateau ages of 1160 ± 5 Ma (Krumrei et al. 2006) and 1156 ± 1.4 Ma (Borst et al. 2019) and is part of the younger Gardar rifting episode.

The development of the Ilímaussaq Complex has traditionally been described as a succession of three intrusive phases, but work by Sørensen et al. (2006) suggested that at least four phases have been involved. The alkaline to peralkaline melts parental to each of the four phases are inferred to having originated from the same deep-seated magma chamber. Phase 1 is a marginal outer augite syenite, which partly encloses and overlies the complex. Phase 2 is represented by a thin sheet of peralkaline granites and quartz syenite in the roof zone.

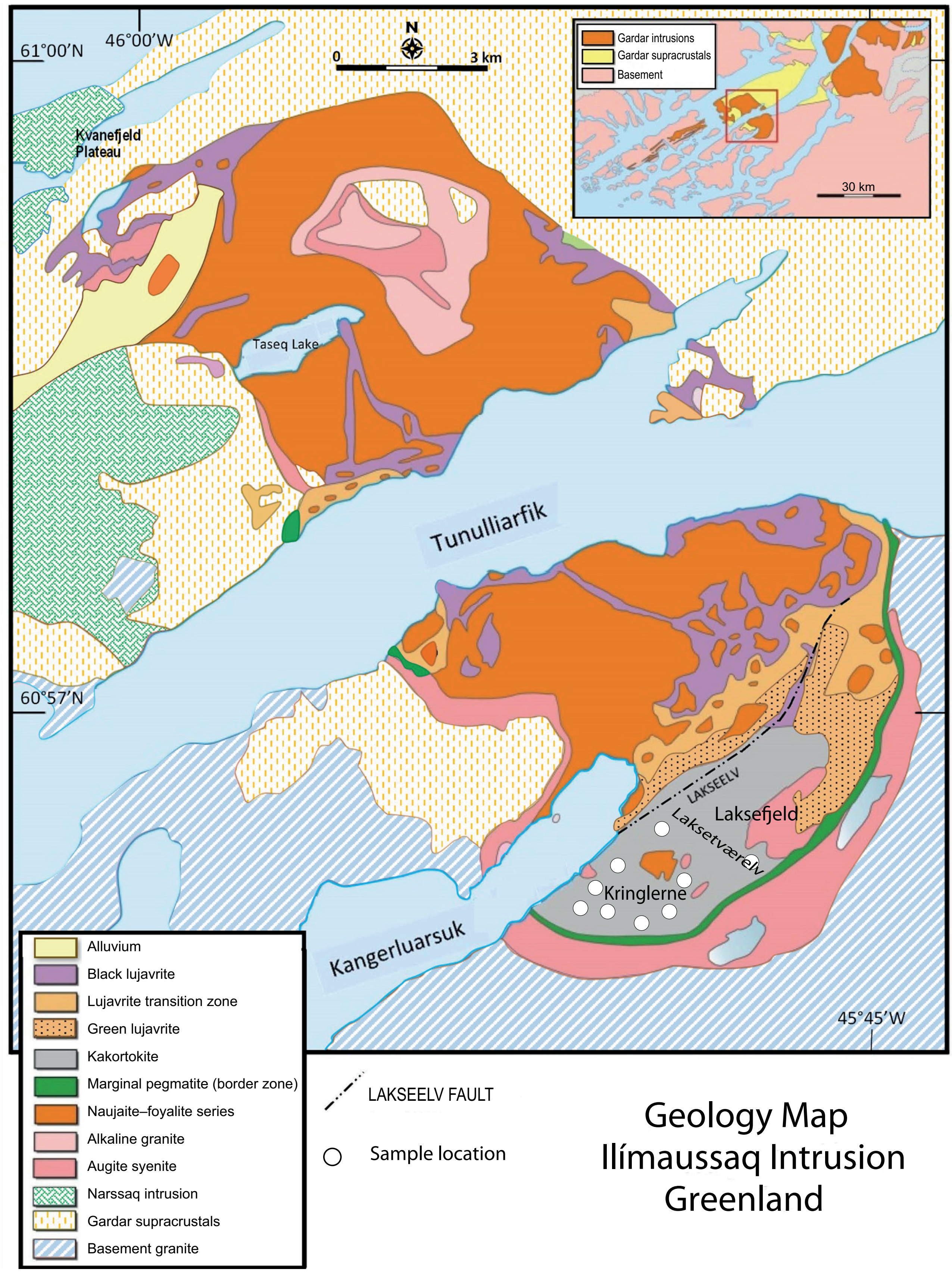



**Fig. 1** Geological map of the Ilímaussaq Complex (modified from Ferguson 1964 and Andersen et al. 1988).

Phase 3, forming the major part of the exposed layers of the complex, consists of peralkaline rocks, developing into dominant agpaitic nepheline syenites.

Phase 3 has been subdivided into a roof sequence, a floor sequence and a sandwich horizon between the roof and floor sequences. The Phase 3 produced the most evolved rocks of the complex (lujavrite, an agpaitic nepheline syenite: Larsen and Sørensen 1987; Bailey et al. 2001). The roof sequence crystallized from the apical part of the magma chamber downwards and resulted in the following nepheline syenitic rocks: pulaskite, foyaite, sodalite foyaite and naujaite (an eudialyte-bearing nepheline syenite) (Fig. 1). Naujaite is by far the most volumetric member of the roof sequence with a thickness 600–800 m (Andersen et al. 1981; Ferguson 1970).

The mineralogical and chemical discontinuities between naujaite from the roof sequence and kakortokite from the floor sequence do not support a direct development of the kakortokite–lujavrite sequence from the residual melts of the roof sequence. It has therefore been suggested that the floor sequence (kakortokite) and the sandwich horizon (lujavrite) form a separate intrusive phase (Phase 4) (Sørensen et al. 2006).

## 3. Methods

### 3.1. Optical microscopy

A set of four new polished thin sections and 21 older thin sections from GEUS archives from white kakortokite form the basis for the textural description of feldspars in this study. The samples were taken from the outcropping part of the entire stratigraphic sequence of the lower layered kakortokite (sample locations indicated in Fig. 1). We used a Nikon Eclipse 600 polarization microscope with an attached camera to take photomicrographs.

### 3.2. Electron-microprobe analysis

Quantitative EDS chemical analysis of selected feldspar grains was carried out on two thin sections using a JEOL JXA-8600 Superprobe at the Department of Geoscience, Aarhus University. The aim was to determine the composition of grains that showed textural differences during the microscope investigation.

The acceleration voltage was set to 15 keV and a current of 10 nA. The beam diameter was 5 μm and the measuring time per point was 20 s. The calibration was done on natural and synthetic materials, including quartz, sanidine, jadeite, corundum, MgO, apatite, rutile, and hematite. The analysis quality was monitored with an in-house standard (labradorite plagioclase). The reproducibility of the standard values was 5 % and the detection limits are 0.02–0.05 wt. %. The concentrations of MgO, MnO, FeO, $TiO_2$, CaO and $P_2O_5$ were typically below respective detection limits.

## 4. Results

### 4.1. Petrography of kakortokite samples

#### 4.1.1. Macroscopic and microscopic description of kakortokite

The type locality for kakortokite is the Kringlerne area on the south side of Kangerluarsuk Fjord (Ussing 1912; Fig. 1). Bohse et al. (1971) mapped and established a terminology for the sequence, which consists of black, red and white layers due to modal enrichments of arfvedsonite, eudialyte, and K-feldspar–nepheline, respectively. This rhythmically layered kakortokite sequence is characteristic of the Kringlerne area (Bohse et al. 1971; Bohse and Andersen 1981). Each set of the three layers (black, red, white) has been termed a “unit”. In general, the thickness of the individual layers is 1.5, 1 and ~10 m for black (arfvedsonite-rich), red (eudialyte-rich) and white (feldspar–nepheline-rich) layers, respectively. A prominent unit along the Kringlerne cliff was chosen as a reference when the area was mapped, and is known as Unit 0 (Bohse et al. 1971). A total of 29 units have been distinguished, equivalent to a thickness of 212 m. Of these 17 occur above, and 11 below, the reference unit and are labelled +1 to +17 and –1 to –11, respectively (Bohse et al. 1971).

The texture of the white kakortokite is idiomorphic granular with euhedral alkali-feldspar laths (~1 cm in length), equant grains of eudialyte (~1 mm in diameter) and nepheline (~1 mm in diameter) (Fig. 2a). Alkali-feldspar constitutes between 30 and 50 vol. % of the rock. Nepheline is often square-shaped and generally rich in inclusions, especially of arfvedsonite. Arfvedsonite is the main interstitial mineral and can locally occur as oikocrysts enclosing eudialyte and nepheline chadacrysts (Fig. 2a). Sodalite is interstitial and constitutes a smaller part of the rock together with aegirine; the latter occurs as small laths and as fibrous alteration product of arfvedsonite. Alkali-feldspar shows perthite textures. Locally, analcime is replacing the K-feldspar part of the lath, without affecting the rest. Nepheline is replaced by analcime, which creates an embayed structure (Fig. 2b). Small albite laths (~0.5 mm) sometimes form clusters, in the interstitial spaces.

### 4.2. Petrographic investigation of perthite from the kakortokite

The alkali-feldspar is perthite, an intimate intergrowth of K-feldspar and albite. The average ratio of K-feldspar to

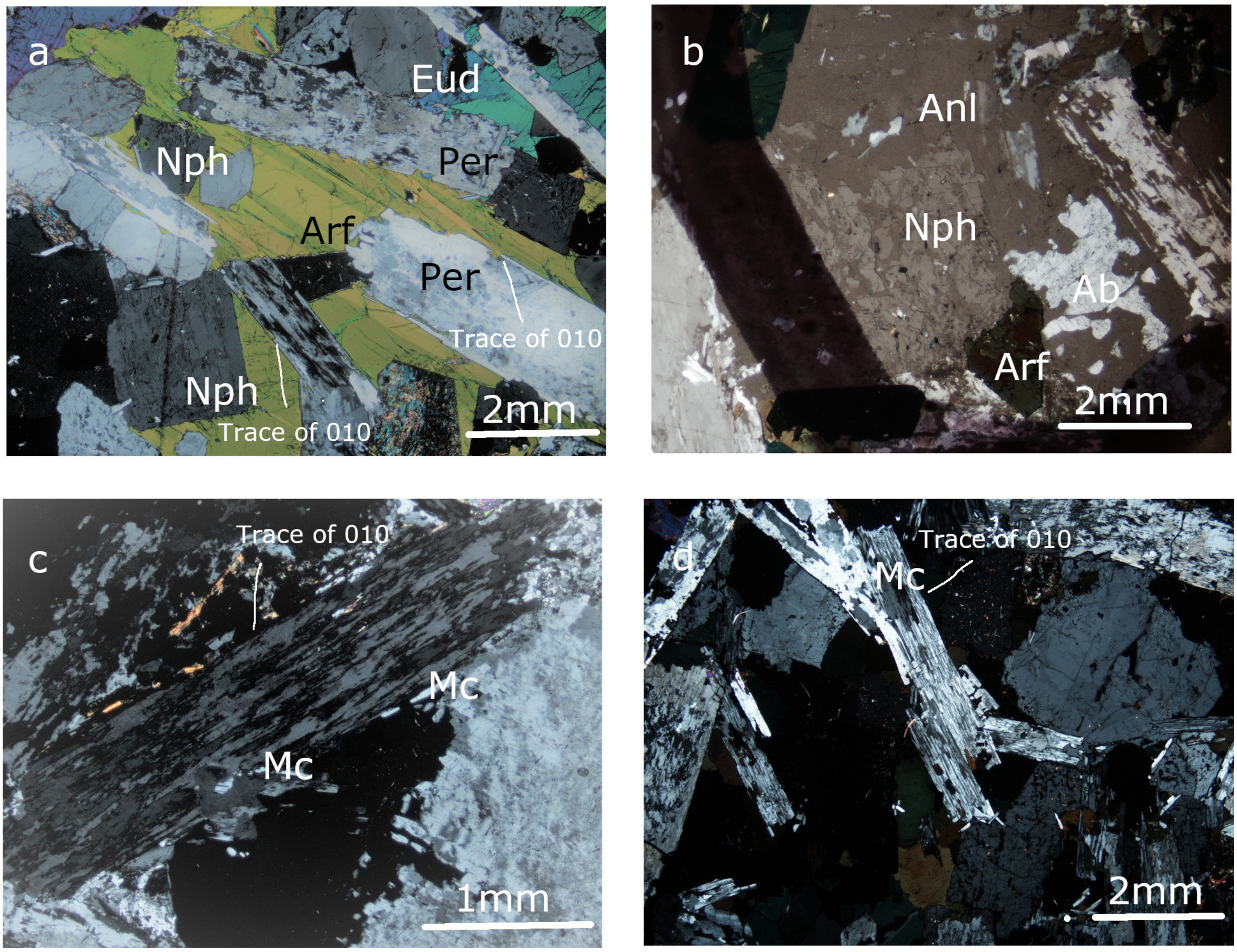



**Fig. 2a** – Texture of white kakortokite from lower layered kakortokite. Euhedral perthite (Per), eudialyte (Eud) and nepheline (Nph). Interstitial poikilitic arfvedsonite (Arf). Crossed nicols (+N). **b** – Analcime (Anl) replaces nepheline (Nph) forming embayment texture. Albite (Ab) and arfvedsonite (Arf) remain untouched. +N. **c** – Central part of photo showing a nearly pure microcline lath (Mc) with irregular penetrative twins elongated parallel to (010) of perthite. +N. Black; individual in extinction position, grey; individual in non-extinction position. **d** – Perthite lath dominated by polysynthetically twinned albite with a minor amount of microcline (Mc). +N. Mineral abbreviations according to Warr et al. (2021).

albite is 75 : 25 according to Ussing (1894) and Ferguson (1964). In contrast to these earlier studies, we have found a large modal variation from nearly pure K-feldspar to almost pure albite (Fig. 2c–d). Consequently, some of these crystals should be referred to as mesoperthite or antiperthite. The rim of the lath often consists of pure albite, normally without twinning. An average composition of the perthite does not appear to be informative because of the large variation. The modal proportion between K-feldspar and albite varies from sample to sample.

Perthite is flattened parallel to (010) and may be elongated parallel to the a-axis (Sørensen 1962). Perthite occurs as lath-shaped grains with the pinacoid (010) surface oriented along the lath (Fig. 2a) (Ussing 1894). The K-feldspar part of perthite does not show the cross-hatched twinning, but instead a penetration twinning (Fig. 2c). It is found to follow the albite law with (010) as twinning plane (Ussing 1894; Sørensen 1962). Monoclinic feldspars cannot show albite twinning (Deer et al. 2001), therefore, the K-feldspar must be triclinic, and hence, microcline. The penetration twins of microcline (K-feldspar part of perthite) show a strongly meandering course of the boundary between the two individuals (Fig. 2c), however with a distinct tendency to follow the trace of pinacoid lateral (010) (Ussing 1894). This characteristic twinning is best observed in (001) sections, but can be seen in random sections (Ussing 1894).

The albite part of the perthite lath shows thin polysynthetic twins, which are short and interrupted lamellar parallel to (010) and have a thickness of 0.05 mm or less. The albite part of the lath is elongated parallel to (010) of the perthite and exhibits a close intergrowth with the microcline part (Fig. 3).

In addition to the above-mentioned perthite, which originally was described by Ussing (1894, 1912), Ferguson (1964) mentioned that microcline from the perthite

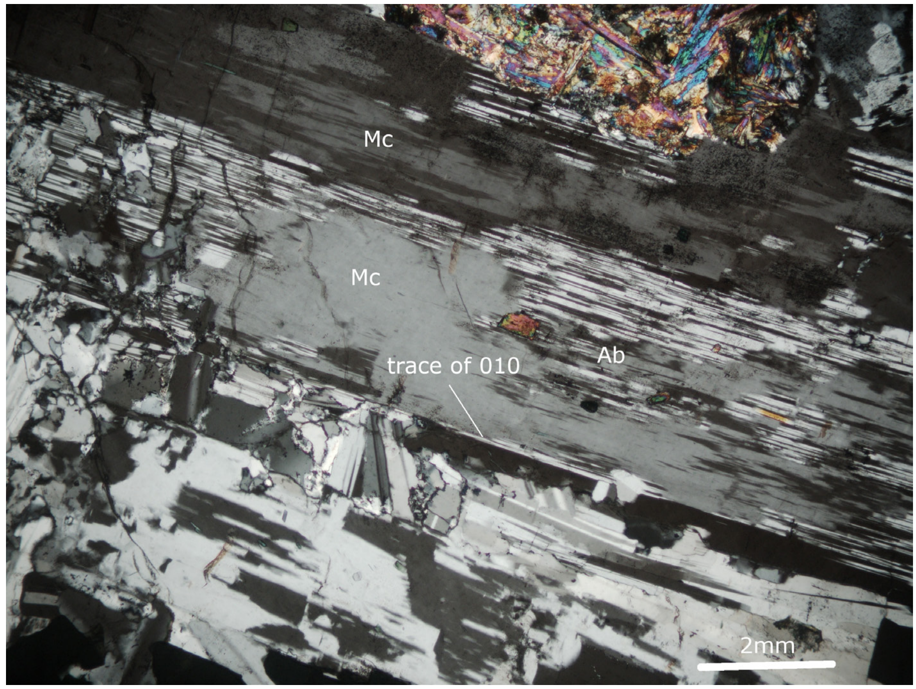



**Fig. 3** Polysynthetically twinned albite (Ab) in perthite lath with domains of microcline (Mc). +N. The microcline part in the center is between extinction positions where the two twin individuals appear as an optical homogeneous grain. Similar observations and descriptions have been made by Ussing (1894).

has developed albite "chess board" twinning. Smith and McLaren (1983) studied microcline from a nepheline-bearing syenite from Ilímaussaq, Greenland and suggested to replace the term "chess board" with "tiled", to avoid confusion, because the structure occurring in kakortokite is different from the standard cross-hatched twinning. The individual tiles are elongated and occur roughly parallel to (010) of the hosting microcline crystal. Under the polarization microscope, adjoining tiles throughout the lath extinguish symmetric about (010) indicating a twin-structure of two individuals. The TEM investigation by Smith and McLaren (1983) showed a mosaic of slightly misoriented domains, which had no obvious relationship to the optical microstructure. Some of the submicroscopic domains are twinned by albite or pericline law, others occur in a diagonal association. The above observations indicate the presence of two structurally different types of perthite lath in kakortokite. For the lack of a better terminology, we call the two types A and B. They are schematically shown in Fig. 4.

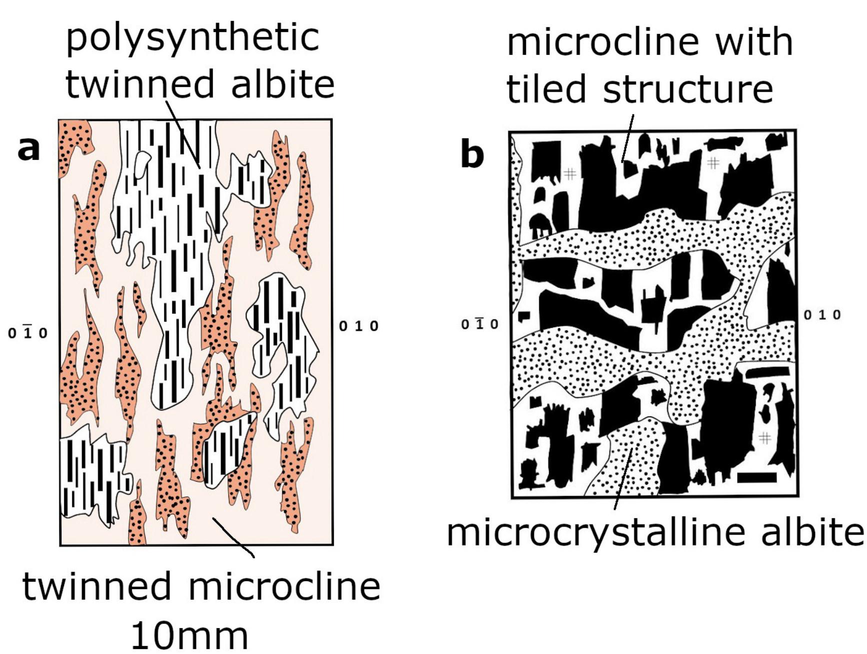
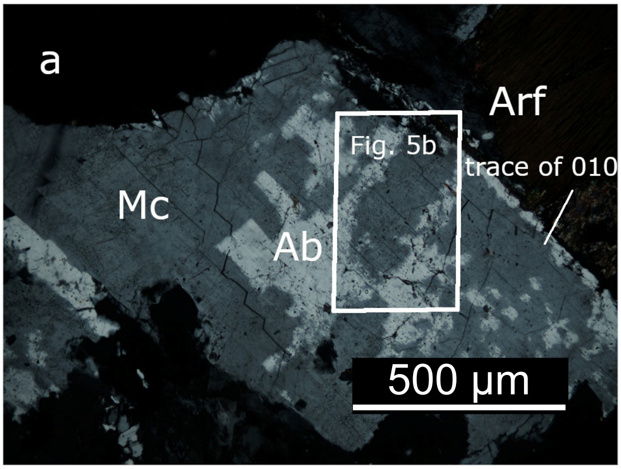



**Fig. 4** Schematic drawing of the two perthite types under crossed nicols. The drawing is in its simplified form shown with a coarser structure than in reality. **a** – Irregular, penetrative twins with a strongly meandering boundary between the two individuals, which follows (010) of the perthite. The twinning of the two individuals (one shown in dark red and dotted, while the other is red with no dots) follows the albite law. The microcline is intergrown with polysynthetically twinned albite, which is elongated parallel to (010) of the perthite. **b** – Microcline lath showing tiled structure locally associated with cross-hatched-like structure. Black: Tile in extinction position. The lath has been replaced by microcrystalline albite veinlets.



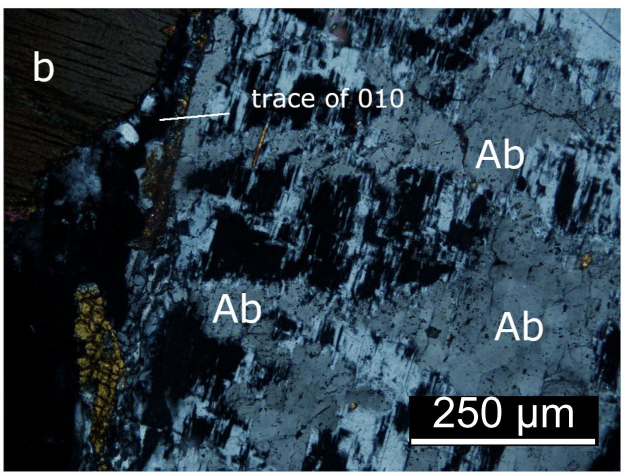




**Fig. 5a** – Microcrystalline albite (Ab) veining and partly rimming microcline (Mc) lath. +N. Framed area shown in Fig. 5b. Microcline is in a position where the two individuals appear with the same intensity and therefore resemble an optical homogenous grain. **b** – The same microcline lath as in Fig 5a, but in extinction position, showing tiled structure, which is locally associated with a cross-hatched-like structure between the tiles. Lamellae of the cross-hatched-like structure are parallel to (010) of the K-feldspar lath and point into the microcrystalline albite (Ab).

*Type A* is significantly more common than B and consists of two irregular penetrative individuals, which appear as elongated, pointed domains parallel to 010 (Fig. 2c). Albite occurs in type A as bodies elongated parallel to (010) and shows the characteristic polysynthetic twining parallel to (010) (Fig. 2c–d). The amount of albite varies considerably, and some of the type A grains should be classified as mesoperthite or alternatively antiperthite. It should be pointed out that regardless of the amount of albite, the shape of the perthite lath seems unaffected.

*Type B* is similar to the so-called tiled structure, which represents another type of K-feldspars twinning. They occur as individuals with a symmetric extinction pattern around (010) of neighboring tiles. Albite associated with type B appears as veinlets, penetrating the type B grains roughly perpendicular to (010) (Fig. 5a). This albite is microcrystalline, equigranular, and in some cases it occurs with a tiny netting of polysynthetic twins parallel to (010) of the feldspar lath.

Locally, a structure with resemblance to cross-hatched twinning (M twinning) occurs between the tiles. The prominent lamellar structure is parallel to (010) (Fig. 5b). The tiled and the cross-hatched like structure behave differently towards the microcrystalline albite. The tiles show concave or resending boundaries towards albite, whereas the K-feldspar lamellae often occur as small laths pointing into albite (Fig. 5b).

### 4.2.1. Chemical analyses of perthite

Electron-microprobe analyses of the structurally different types of perthite (A and B) are shown in Tab. 1. The chemical compositions of type A and B are similar within the uncertainty to the analyses for both albite and microcline. Apart from K, Na, Al, and Si, all other elements (i.e., Ca, Fe, Ba, Ti) were below the detection limit.

The microcline from kakortokite is Na-poor and compositionally similar to microcline from peralkaline rocks elsewhere (Deer et al. 2001). Low contents of Na and Ca will allow Na to be present in solid solution as indicated by the solubility field in the ternary system Ab–An–Or (Parsons 2010). This is in agreement with the lack of film-perthite and similar structures in the perthite.

## 5. Discussion

Given the large variation of the albite: microcline ratio of individual perthite grains and the irregular interface between albite and microcline, albite exsolution can be ruled out as a main mechanism responsible for the microstructure of the perthite. This suggests that replacement was more likely the key process.

Distinguishing a replacive metasomatic structure from epitaxial overgrowth in cases where parent and product phases have similar structure is difficult, because they occur with the same crystallographic orientation (Rong and Wang 2016). The morphology and distribution patterns characteristic of epitaxial growth of albite on microcline are expected to be evenly distributed in the rock mass, whereas the albite replacive structure (albitization) will be patchy (Rong and Wang 2016). The latter is in line with our observations of perthite crystals in the studied kakortokite, and therefore, supports a replacive process.

A model for such a replacement has been presented by Putnis and Putnis (2007), invoking an interface-connected dissolution–reprecipitation process. In case of structural similarities between parent (microcline) and product (albite), an epitaxial precipitation will occur of the product (albite). This increases dissolution of the parent (microcline) which again intensifies the precipitation of the product (albite) (Putnis and Putnis 2007). Such an autocatalytic reaction would lead to a balance between dissolution and precipitation and should preserve the integrity of the interface between parent (microcline) and product (albite) (Putnis 2002). A prerequisite for such a process is to keep pathways for fluid transport open, which can be accomplished if porosity is generated in the product phase (albite). The general presence of turbidity, which occurs in the albite part of the perthite lath, indicates the existence of micropores. As the lath shape of the perthite is preserved regardless of the amount of albite, porosity must be generated because the molar volume of albite (product) is smaller than that of microcline (parent). In the case of albite and microcline, the difference is 7.85 vol. %.

**Tab. 1** Microprobe analyses showing average composition of the two types of perthite lath feldspar (in wt. %)

| | Microcline | | | Albite | |
|---|---|---|---|---|---|
| | Type A penetrative twinning | | Type B tiled structure | Type A | Type B |
| n | 7 | 3 | 3 | 4 | 3 |
| Remarks | § | §§ | | | |
| $SiO_2$ | 64.54 | 63.79 | 64.32 | 67.89 | 69.38 |
| $Al_2O_3$ | 18.92 | 18.69 | 18.96 | 19.92 | 20.09 |
| CaO | bdl | bdl | bdl | bdl | 0.02 |
| $Na_2O$ | 0.39 | 0.33 | 0.52 | 11.27 | 11.52 |
| $K_2O$ | 16.88 | 16.94 | 16.93 | 0.11 | 0.05 |
| Total | 100.73 | 99.75 | 100.73 | 99.19 | 101.06 |
| (mol. %) | | | | | |
| Or | 97.94 | 98.28 | 97.38 | 1.14 | 0.50 |
| Ab | 1.96 | 1.72 | 2.62 | 98.86 | 99.30 |
| An | 0.00 | 0.00 | 0.00 | 0.00 | 0.20 |
| (*apfu*) | | | | | |
| Si | 2.96 | 2.95 | 2.94 | 2.99 | 3.00 |
| Al | 1.02 | 1.02 | 1.02 | 1.04 | 1.03 |
| Ca | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Na | 0.04 | 0.03 | 0.05 | 0.96 | 0.97 |
| K | 0.99 | 1.00 | 0.99 | 0.01 | 0.00 |

n: number of grains analyzed
§: Perthite lath with *c.* 20 % albite
§§: Perthite lath with less than 1 % albite
bdl: below detection limit

The above-mentioned model of interface-connected dissolution–reprecipitation in the presence of a fluid phase would preserve the morphology of the crystal and transfer structural properties from parent to product by epitaxial nucleation (Putnis and Putnis 2007). This provides a sensible explanation for the intergrowth of albite and microcline in the studied perthite laths, which would be otherwise difficult to explain.

The formation of porosity can be affected by the relative solubility of the two phases involved. This can lead to differences in porosity, which in turn can cause a different extent of albite replacement (Kaur et al. 2012). This is consistent with our observations of the variable modal composition of the perthite grains. The relative solubility of the two phases can clarify, or at least partly explain, the variable modal composition.

In addition to a slight gain in Si and a major gain in Na as well as a significant loss in K due to albitization, a change in a number of elements including those typical of mafic minerals can be expected (Kaur et al. 2012). Our samples show minor signs of alteration, only local alteration of eudialyte of the catapleiite type (Karup-Møller et al. 2010) and appearance of secondary aegirine associated with arfvedsonite.

The “cross-hatched” twinning (M-twinning) in K-feldspar in the type B perthite could be a result of inversion from monoclinic to triclinic structure. The TEM investigation by Smith and McLaren (1983) was inconclusive regarding the origin of the tiled structure, which either relates to an original (triclinic crystallized) microcline or an optical-scale manifestation of a diagonal association. Nevertheless, type B could also represent an intermediate structural state (Mackenzie and Smith 1962), with K-feldspar crystallized at a slightly higher temperature and therefore featuring domains of monoclinic structure. This could have resulted in the M-twinning-like structure observed between the tiles.

In contrast, the irregular, penetrative albite twinning of K-feldspar in type A is controlled by the original triclinic symmetry. There is no petrographic indication that type A and B represent different stages in the development of kakortokite, and therefore, it is possible that both types of K-feldspar originally crystallized with a triclinic symmetry.

According to Ussing (1912) the perthite structure (type A) also occurs in the rocks of the roof sequence e.g., naujaite and sodalite foyaite. However, the younger lujavrite shows separate microcline and albite grains without signs of perthitic intergrowth between the two. This indicates that the roof and the floor sequences have been exposed to widespread albitization. It presumably took place prior to, or simultaneously with, the emplacement of lujavrite since the microcline of lujavrite is not affected.

## 6. Conclusions

Two structurally different types of perthite grains occur in kakortokite. Their variable K-feldspar : albite ratios indicate a replacement process controlled by a coupled dissolution–precipitation. This would preserve the morphology of the crystal and transfer structural properties by epitaxial nucleation (see also Putnis 2002).

The albitization occurs in the central part of the intrusive complex and appears in the whole agpaitic sequence. It took place prior to, or simultaneously with, the lujavrite intrusion since no albitization appears in microcline from lujavrite. This attributes the formation of kakortokite to subsolvus conditions.

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*Electronic supplementary material.* Supplementary table of feldspar analyses is available online at the Journal web site (*http://dx.doi.org/10.3190/jgeosci.375*).

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