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## Distinguishing magmatic and metamorphic processes in peralkaline rocks of the Norra Kärr complex (Southern Sweden) using textural and compositional variations of clinopyroxene and eudialyte-group minerals.

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 eudialyte-group minerals.

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17

18 Running Title: Magmatic and Metamorphic Processes in the Norra Kärr Alkaline Complex

19

#### 20 Abstract

21 The 1.49 Ga old Norra Kärr complex in Southern Sweden contains rocks characterized by a very high ratio of  $(Na+K)/Al \ge 1.2$  and a complex and highly unusual mineralogy, including 22 rock-forming catapleiite, eudialyte-group minerals as well as minor rinkite- and britholite-23 group minerals. In contrast to other well-studied examples of agpaitic rocks, the Norra Kärr 24 rocks have been deformed and partially metamorphosed during the 25 26 Sveconorvegian/Grenvillian orogeny, and are now preserved in a westward dipping synform. Magmatic and metamorphic processes at the Norra Kärr complex are distinguished by 27 combining rock fabrics of clinopyroxene and eudialyte-group minerals. Both mineral groups 28 29 are stable over a large P-T range, which makes them excellent monitors of the geochemical evolution of such systems and enables the reconstruction of magmatic and subsequent 30

31 metamorphic conditions.

The magmatic mineral assemblage crystallized from a subsolvus syenite at continuously decreasing temperatures (700 - 450°C) and silica activity (0.6 - 0.3). Due to initially relatively low peralkalinity and reducing conditions, Zr was first incorporated in Zraegirine. Subsequent destabilization of the latter indicates increasing peralkalinity, oxygen fugacity and water activity, which resulted in the crystallization of early magmatic catapleiite. Crystallization of presumably later magmatic Mn- and REE-poor eudialyte-group minerals, happened as soon as sufficient Cl, REE and HFSE were enriched in the residual melt.

Metamorphic conditions during the Sveconorvegian/Grenvillian orogeny are
constrained to T between 400 - 550°C and a<sub>SiO2</sub> range of 0.25 - 0.4. Due to deformation and
interaction with fluids, post-magmatic Al-rich aegirine as well as post-magmatic eudialytegroup minerals enriched in REE, Y and Mn formed. Subsequently, the eudialyte-group
minerals were destabilized and decomposed to post-magmatic catapleiite and secondary REE-

44	bearing minerals. During the whole history of the complex, $a_{SiO2}$ remains very similar,
45	indicating very little interaction with the surrounding granitic rocks.

46	Regardless of the intense deformation due to folding of the Norra Kärr body during
47	the Sveconorvegian/Grenvillian orogeny, indications for primary magmatic layering of the
48	intrusion are retained on the deposit scale. In addition, the compositional changes of
49	magmatic eudialyte-group minerals from the outer to the inner subunit indicate a primary
50	geochemical evolution feature due to fractional crystallization.

51

52 Keywords: deformed nepheline syenite; rare earth elements; clinopyroxene, eudialyte-group minerals

53

#### **INTRODUCTION** 54

55

56	During the last decade the economic interest in high field strength elements (HFSE) and rare
57	earth elements (REE) increased due to their broad application in high-tech products. In
58	addition to carbonatites, alkaline and especially peralkaline rocks (molar Na+K > Al) are
59	particularly enriched in HFSE and comprise one of the most promising sources for future
60	REE supply (e.g., Mitchell, 2015; Smith et al., 2015; Goodenough et al., 2016). The
61	extraordinary enrichment of HFSE and REE in such rocks was explained by the high
62	alkalinity and the reducing conditions during crystallization of the magma, which minimizes
63	the loss of volatile components and maximizes the ore precipitation potential during
64	magmatic differentiation (e.g., Kogarko, 1990; Marks et al., 2011).
65	This study investigates peralkaline rocks of the Norra Kärr complex in southern
66	Sweden, which are characterized by an unusual mineralogy including rock-forming
67	catapleiite, eudialyte-group minerals (EGM) and minor REE-bearing minerals of the rinkite-
68	and britholite-groups (Adamson, 1944; Eckermann, 1968; Sjöqvist et al., 2013). Such
69	lithologies are classified as agpaitic rocks, a term originally introduced by Ussing (1912) and
70	later complemented by Sørensen (1960, 1997) and Marks et al. (2011). Minerals of the
71	eudialyte group are the most common index minerals in agpaitic rocks (e.g., Sørensen, 1997;
72	Schilling et al., 2011b). Such minerals can incorporate significant concentrations of more than
73	30 elements, including Zr, Nb and naturally occurring lanthanides and Y, with LREE being
74	commonly more abundant than the HREE.

Unlike other well-studied examples of agpaitic complexes such as the Ilímaussaq 75 complex in Greenland (see recent reviews by Sørensen et al., 2006; Upton, 2013; Marks & 76 Markl, 2015; Dostal, 2015) or the Lovozero and Khibina complexes in Russia (e.g. Kogarko 77

et al., 1982; Kogarko, 1987; Pekov, 1998; Arzamastsev et al., 2001, 2005), the igneous Norra 78 79 Kärr body has been deformed and partially recrystallized during subsequent metamorphic events. This specific feature is used to amplify the restricted knowledge on the behavior of 80 agpaitic rocks during metamorphism, which is to date mainly limited to studies of: the Red 81 Wine and Kipawa complexes in Canada (Curtis & Gittins, 1979; Curtis & Currie, 1981; 82 Currie & van Breemen, 1996; van Breemen & Currie, 2004); nepheline syenites in Malawi 83 (e.g. Woolley et al., 1996); and peralkaline gneisses in India (Nanda et al., 2008; Goswami & 84 Basu, 2013; Chakrabarty et al., 2016). We present detailed observations on rock and mineral 85 textures combined with compositional data for the major rock-forming minerals to provide 86 87 some direct insight into the petrological and geochemical processes accompanied by the deformation and metamorphism of agpaitic rocks. 88

89

#### 90 GEOLOGICAL SETTING

91

The Norra Kärr complex is located approx. 2 km E of Lake Vättern, approx. 15 km NNE of 92 the township of Gränna in Southern Sweden (Fig. 1). It is situated in the Trans-scandinavian 93 Igneous Belt, which intruded into the Svecofennian domain of Fennoscandia in the course of 94 juvenile crust reworking between 1.85-1.75 Ga (Andersson et al., 2007 and references 95 96 therein). The Trans-scandinavian Igneous Belt rocks form a voluminous array of monzodioritic to granitic batholiths of alkali-calcic to calc-alkaline composition (Högdahl et 97 al., 2004; Fig. 1). They extend over ca. 1400 km from NW Norway to SE Sweden. Significant 98 99 igneous activity between 1.65–1.50 Ga was responsible for the formation of an active margin along the south-western border of the Fennoscandian Shield (McLelland, 1989). From ca. 100 101 1470 Ma onwards A- and I-type granitoids and symptotic were emplaced in a typical

volcanic-arc setting, marking the pre-collisional stage of the Danopolonian or Hallandian
orogeny in the area east and southeast of Lake Vättern (Brander, 2011, Brander & Söderlund,
2009). In the time of 1.5-1.4 Ga two possible settings for intra-cratonic magmatism are
discussed in the literature, an anorogenic and an orogenic extension. Aberg (1988) interpreted
the emplacement of alkali-calcic and calc-alkaline intrusions into the southernmost parts of
the Trans-scandinavian Igneous Belt as a product of continental rifting between 1.48 and 1.35
Ga (Aberg et al., 1984; 1985a; 1985b; Smellie & Stuckless, 1985).

During the period of around 1140 – 900 Ma wide areas of the southern and central
 Trans-scandinavian Igneous Belt, as well as broad areas of south-western Fennoscandia were
 subject to the collision of Fennoscandia with Amazonia during the

112 Grenvillian/Sveconorwegian orogeny (e.g. Bingen et al., 2008). These areas form today the

113 Sveconorwegian orogenic belt. The area east of Lake Vättern belongs to the frontal zone of

the orogen and was mainly affected by metamorphism during the late stages of the orogeny,

the so-called Falkenberg and Dalane phases (e.g. by Bingen et al., 2008 and references

therein). During the Falkenberg phase (980-970 Ma) crustal thickening and associated

eclogite facies conditions affected the Fennoscandian crust to at least 50 km depth. This was

118 followed by decompression, relaxation and gravitational collapse during the Dalane phase at

119 970-900 Ma (Bingen et al., 2006; 2008; Möller et al., 2007). During this time the N-S

- 120 trending Protogine Zone was formed as a steep, sheer zone at the very front of the
- 121 Sveconorvegian orogen (Andréasson & Rodhe, 1994; Wahlgren et al., 1994; Söderlund et al.,
- 122 2004).

123

124 The Norra Kärr complex

125

The relatively small Norra Kärr complex covers an area of approx. 350 x 1100 m and is
located in the Växjö Granite Suite (TIB I), between the Vimmerby Batholith in the east and
the major Protogine shear zone (PZ) in the west (Fig. 1b). The body is preserved within a
westwards dipping (approx. 40°) synform (Fig. 2), deformed by moderate E-W and late, weak
N-S directed compression under ductile conditions (Rankin, 2011).

The granitic host rocks at the western contact of the Norra Kärr complex and some 131 deeper parts in the east (only known from drilling cores) exhibit clear signs of fenitization 132 (Adamson, 1944; Eckermann, 1968; Sjöqvist et al., 2015). These fenites are up to 100 m wide 133 massive horizons, but also occur as decimeter-thick veins in the surrounding granite. They are 134 characterized by the absence of quartz, which is replaced by albite, magnetite, hematite and 135 fluorite, and the replacement of biotite by aegirine (Adamson, 1944; Sjöqvist et al., 2015). 136 Fenitization of the alkaline rocks itself is less prominent and rarely occurs in the outer 137 subunit, only at the direct contact to the fenitized host rocks. Recently, the fenitization of the 138 139 granitic gneisses was determined to have a U-Pb zircon age of  $1.49 \pm 0.01$  Ga (Sjöqvist et al., 2014), which is interpreted coeval with the age of magmatic emplacement of the Norra Kärr 140 complex in a presumably pre-collisional rifting setting. Younger ages determined by Sjöqvist 141 et al. (2014) constrain the deformation during the Sveconorvegian orogeny from  $1148 \pm 5$  Ma 142 onwards. At Norra Kärr neither the surrounding country rocks (granitic- to- syenitic gneisses) 143 nor the metamorphosed syenites of the complex itself provide any clear evidence indicating 144 the grade of metamorphism of the complex. Regional geological studies (Wahlgren & 145 Stephens, 2004) report lower greenschist facies conditions for the area to the East of Lake 146 147 Vättern and the Protogine shear Zone (Fig. 1). Considering this and the actual position of the complex within this major shear zone (Fig. 1), moderate- to- high greenschist facies 148 conditions can be assumed. 149

For this study, the peralkaline rocks of the Norra Kärr complex were collectively 150 151 classified as meta-nepheline syenites (after Gillespie & Styles, 1999). The most common rock type (85 vol.% of the exposed area), the so-called grennaite (Adamson, 1944) is a catapleiite-152 153 and EGM-bearing aegirine meta-nepheline syenite (Fig. 2). The texture of this unit varies systematically across the deposit (Figs 3, 4 and Electronic Appendix 1). On the basis of the 154 frequency of medium- to- coarse-grained lenses and bands or schlieren (Törnebohm, 1906; 155 Adamson, 1944; Sjöqvist et al., 2015), the frequency of catapleiite and the degree of 156 157 deformation, the following three subunits with gradual transitions between them are distinguished: The central part (inner subunit) was strongly foliated (Figs 3a-b and 4a-c) and 158 159 is best described as an aegirine leuco-meta-nepheline syenite (a.k.a. migmatitic grennaite; lithologic nomenclature by Tasman Metals, Sjöqvist et al., 2013). This area is surrounded by 160 a zone rich in pegmatoidal schlieren (mid subunit, Figs 3e-h and 4e and i-k) named pegmatite-161 162 bearing aegirine meta-nepheline syenite (a.k.a. pegmatitic grennaite; Adamson, 1944). The border area (outer subunit, Figs 3c and 4f-h) of the complex is defined by a foliated 163 catapleiite-bearing aegirine meta-nepheline syenite (a.k.a. catapleiite grennaite; Adamson, 164 1944). 165

Minor rock types of the Norra Kärr complex include the strongly folded fluoroleakeite-aegirine meta-nepheline syenite (previously called kaxtorpite, Fig. 4d), the aegirine amphibole-biotite meta-nepheline syenite (a.k.a. pulaskite) and the arfvedsonite-aegirine meta-nepheline syenite (former lakarpite), well-known from the discovery outcrop of Norra Kärr (Sjöqvist et al., 2013).

The most common deformation features of all rock types include the alignment and
stretching of certain minerals (e.g. clinopyroxene, EGM, catapleiite, Fig. 4a-e) and the
presence of porphyroclasts (mainly microcline, Fig. 4f-h), which have tails of recrystallized

material (Fig. 4h). They are commonly preserved in a finer-grained, probably recrystallized
matrix and form typical shear related patterns (sigma- and delta-clast, Fig. 4f).

176

### **177 PETROGRAPHY**

178

The phase assemblages and micro-textural characteristics of the investigated samples are
described in the following. A list of investigated samples is given in Table 1, sample locations
are indicated in Fig.2. The modal mineralogy of the main subunits is summarized in Table 2.

### 183 Catapleiite-and EGM-bearing aegirine meta-nepheline syenite (grennaite)

184 Inner subunit (aegirine leuco-meta-nepheline syenite)

185

186 This unit displays strong foliation and in places intense folding, with rather common crenulated foliation and gneissic textures (Figs 3a and b and 4a-c). The main felsic minerals 187 are subhedral- to- anhedral and fine-grained albite (up to 30 wt.%), microcline (up to 20 188 wt.%) and nepheline (approx. 10 wt.%), the latter being partly- to- significantly-replaced by 189 natrolite (10-35 wt.%). Fine- to- medium-grained aegirine (15-20 wt.%) occurs as subhedral-190 191 to- anhedral, needle or columnar-shaped crystals, which commonly exhibit irregular rims and/or replacement textures of darker BSE contrast (Fig. 5c). Fine- to- medium-grained EGM 192 (approx. 15 wt.%), can be concentrated in hinge zones of folds and be partly enriched in mm-193 194 wide bands, mainly composed of feldspar and clinopyroxene (Fig. 4c). In these bands elongated minerals are aligned while coarser-grained minerals form  $\sigma$ - and/or  $\delta$ -clasts. 195

Eudialyte-group minerals are commonly elongated and ductile deformed in the direction of
foliation (Figs 3a, 4a and 6c). The crystals show no zoning or overgrowth textures but are
commonly intergrown with fine-grained, anhedral catapleiite and minor britholite-group
minerals. The most common accessories include galena and sphalerite.

200

201 Mid subunit (pegmatite-bearing aegirine meta-nepheline syenite)

202

203 This subunit contains variable amounts of leucocratic, mid- to coarse-grained and partlypegmatitic nepheline syenite schlieren (up to ten cm in thickness) set in a fine-grained 204 205 aegirine meta-nepheline syenite matrix. The dark green-grey matrix (grain size < 1mm) is 206 characterized by a homogeneous mineral distribution with no specific accumulation of 207 minerals (Fig. 3d). Deformation is displayed by the alignment of most of the mineral grains (Fig. 4e) and stretching of rarely occurring larger crystals (e.g. catapleiite needles). The main 208 209 rock-forming minerals are anhedral albite (55 wt.%), nepheline (10 wt.%) and clinopyroxene (20 wt.%) with minor microcline (5 wt.%), catapleiite (3 wt.%), EGM (2 wt.%), natrolite (3 210 wt.%) and accessory britholite- and rinkite-group minerals ( $\leq 0.25$  wt.%). The latter are 211 always spatially associated with EGM. 212

The schlieren (Figs 3e-h and 4i-k) generally follow the foliation and the folding of the rock. However, they also may be intercalated with the fine-grained matrix. The following types of schlieren can be distinguished:

(A) Fine- to- medium-grained schlieren with no alignment of crystals, mainly
consisting of feldspar, clinopyroxene, euhedral to subhedral EGM and nepheline (e.g. Figs 3f
and h, 4i, 6a and b and 7d and e). In general, the relative content of clinopyroxene increases

towards the rims of these schlieren. Eudialyte-group minerals are medium- to- coarse-grained 219 220 reaching several mm in size (Figs 3f and h, 4k and 6a and b). Larger crystals are commonly sector- or oscillatory-zoned. Porous and irregular zones in the central parts of euhedral 221 222 crystals can be complexly overgrown by areas with lower BSE contrast and along the rims of such crystals flame textures with higher BSE contrast may be present (Figs 4k and6a and b). 223 224 Rims and cracks are commonly associated with catapleiite and britholite-group minerals, 225 occurring as filling of interstitial spaces or replacing EGM (Fig. 6a and b). Catapleiite occurs 226 as two textural varieties, (1) catapleiite spatially associated or intergrown with EGM, preferably occurring at the border area between clinopyroxene and EGM (Fig. 7e) and (2) 227 228 catapleiite inclusions in fan-shaped sectors of radiating clinopyroxene aggregates (Figs 4i and 7d). These radial aggregates of subhedral clinopyroxenes (Fig. 7d) are unique to this schlieren 229 type. They are irregularly rimmed by areas with darker BSE contrast. 230

(B) Medium- to- coarse-grained schlieren with no general alignment of crystals. They 231 232 are mainly composed of subhedral- to- euhedral feldspar, nepheline, clinopyroxene and EGM (Figs 3e and g, 4j, 5a and b and 7c). Euhedral- to subhedral eudialyte-group minerals mainly 233 exhibit sector zoning. Similar to schlieren (A) these are overgrown and/or replaced by 234 irregular or flamy areas with brighter BSE contrast (Fig. 4k). In cases EGM are extensively 235 236 altered and replaced by catapleiite and britholite-group minerals (Fig. 3g). In contrast to schlieren (A), catapleiite is not necessarily spatially associated with EGM or clinopyroxene. It 237 238 may form needles, laths (rarely with a bluish color in hand specimen) or subhedral crystals (Figs 3e and 7b). Clinopyroxene forms euhedral, coarse-grained and oscillatory- and/or 239 240 sector-zoned crystals (Fig. 5a and b). An exceptionally large (> 1 cm) and euhedral clinopyroxene crystal was observed in sample 5408 (Figs 5a and 7c). This crystal exhibits a 241 partly-resorbed Zr-rich core, surrounded by an area rich in anhedral catapleiite inclusions, 242 243 followed by well-developed Ti-rich sectors and late irregular rims of Al-rich aegirine.

In both schlieren types, large, patchy aggregates composed of numerous euhedral finegrained clinopyroxene crystals (Fig. 3e and h) occur. Nepheline and feldspar are extensively altered to natrolite (Figs 3e-h and 4e and j).

247

248 Outer subunit (catapleiite-bearing aegirine meta-nepheline syenite)

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Both, magmatic and metamorphic terminology is used to describe the textural appearance of
this subunit, although the classification of some of the features is not clear. This will be
further commented in the discussion section.

253 This unit is up to several hundred meters in width, is schistose and fine-grained- toaphanitic with porphyroclastic textures (Figs 3c and 4f-h). The contact towards the 254 255 surrounding host rocks is characterized by an intense bleaching zone. Mineralogically, this rock type is very similar to the matrix of the mid subunit described above (Table 2), but is 256 characterized by the absence of schlieren. Characteristic for this unit are medium-grained 257 feldspars that form  $\sigma$ - and/or  $\delta$ -clasts (Fig. 4f) as well as distinct EGM and catapleiite 258 textures: In addition to fine-grained EGM in the matrix, larger poikilitic EGM porphyroclasts 259 (Figs 3c, 4h and 6d) with abundant catapleiite (Figs 4h and 6d, Zr map), feldspar, nepheline 260 and clinopyroxene inclusions occur, commonly surrounded by columnar rinkite-group 261 minerals (Figs 4h and 6d). Furthermore, EGM in the outermost bleaching zones are partly- to-262 entirely replaced by zircon. Catapleiite forms up to 2 cm large, porphyroclasts (Fig. 4g) as 263 well as elongated aggregates composed of anhedral, recrystallized catapleiite crystals (Fig. 264 7f). Clinopyroxene occurs as fine-grained euhedral- to- anhedral crystals rimed by a later 265 clinopyroxene generation. 266

## **Other rock units**

269 Arfvedsonite-aegirine meta-nepheline syenite (a.k.a. lakarpite)

271	Although being only a minor rock type restricted to the eastern contact of the mid subunit
272	with the outer subunit (Fig. 2), this rock type is best known from the so-called "discovery
273	outcrop" of the complex (Sjöqvist et al., 2013). This fine- to medium-grained unit mainly
274	consists of feldspar (35-60 wt.%), arfvedsonite (up to 20 wt.%), clinopyroxene (up to 15
275	wt.%) and EGM (up to 12 wt.%) with minor nepheline and natrolite. Feldspar-rich schlieren
276	contain cm-sized, pinkish and mostly poikilitic EGM commonly surrounded by an amphibole-
277	and clinopyroxene-rich matrix. Clinopyroxene forms elongated to euhedral crystals, most
278	other minerals are anhedral- to- subhedral in their habit.
279	
280	Fluoro-leakeite-aegirine meta-nepheline syenite (a.k.a. kaxtorpite)
281	
282	This fine- to- medium-grained rock with dark green- to- black colour was first described by
283	Adamsson (1944) and is located in the very centre of the intrusion (Fig. 2). The rock is
284	variably deformed showing alignment of elongated minerals culminating in intense isoclinal
285	folding and crenulated foliation (Fig. 4d). Most minerals are anhedral, elongated and aligned
286	forming small alternating bands. The fine-grained matrix consists of albite, fluoro-leakeite
287	(Oberti et al., 2015), pectolite, clinopyroxene, nepheline and natrolite (± catapleiite, titanite,

fluorite and rosenbuschite) with large microcline augen preserved. The rock is commonlyinterfolded with the surrounding inner subunit.

290

291 Aegirine-amphibole-biotite meta-nepheline syenite (a.k.a. pulaskite)

292

This rock is only present in the western and northern part of the complex, mostly forming 293 elongated bodies in the outer subunit (catapleiite-bearing aegirine meta-nepheline syenite; 294 295 Fig. 2). This unit is dark bluish and fine- to- coarse-grained with white- to- colourless feldspar schlieren and contains boudin-shaped pods (up to decimetre size) of mafic rocks not yet 296 297 investigated in detail. The rock consists of large and anhedral microcline crystals embedded 298 or engulfed in fine- to medium-grained bands consisting of albite, clinopyroxene, biotite, 299 amphibole ± fluorite. Most of these minerals are aligned, elongated and anhedral, only clinopyroxene and amphibole form euhedral crystals. 300

301

### 302 MINERAL COMPOSITIONS

### 303 Analytical techniques

304

Drill core samples were collected along two drill sections (J and P, nomenclature by Tasman
Metals) at different depths of the intrusion (Fig. 2b and c). The investigated samples were
selected to represent different styles of mineralization and degrees of alteration. Polished
thick sections (120 µm) have been used for all analyses and a list of analyzed samples is given
in Table 1.

Carbon-coated thick sections were studied by SEM-based Mineral Liberation 310 311 Analyzer (MLA) and an Electron Probe Microanalyzer (EPMA) at the Helmholtz-Institute Freiberg for Resource Technology. The MLA studies used an FEI MLA Quanta 650F 312 313 scanning electron microscope equipped with a field emission gun and two energy dispersive X-ray spectrometers (Bruker AXS Xflash® 5010) combined with image analysis software 314 (Fandrich et al., 2007). Grain-based X-ray mapping (GXMAP) with resolution 500 x 500 315 pixels by a pixel size of 2µm with 5 pixel step size was applied at an acceleration voltage of 316 317 25 kV and a spot size of 5. The data was classified using the software package MLA Suite 3.0. 318

Electron Probe Microanalyzer measurements were performed with a JEOL JXA 319 320 8530F equipped with a field emission electron gun and five wavelength-dispersive spectrometers (WDS). Two of these spectrometers are provided with H-type crystals for high 321 sensitivity and one with L-type crystals for good energy resolution. The X-ray element 322 323 distribution maps were acquired with an acceleration voltage of 20 kV, a beam current of 50 nA, beam diameter of 14 µm and a dwell time of 140 ms. Aluminum, Y, Cl, and Ce were 324 measured using the WDS, while Si, K, Ca, Mn, Zr, and Fe were measured with an energy 325 dispersive spectrometer (EDS). Quantitative analyses of EGM were performed at an 326 accelerating voltage of 20 kV and a beam current of 20 nA applying scanning mode as further 327 details are described in Atanasova et al. (2015). Clinopyroxene, catapleiite, feldspar, 328 nepheline and natrolite single point analyses were conducted at an accelerating voltage of 20 329 kV and a beam current of 20 nA. All further details are given in Electronic Appendix 2. Only 330 aggregated analytical results are reported in Tables 3-7 and in Electronic Appendix 3. All 331 detailed data is available on request by the senior author. 332

333

## 334 Clinopyroxene

335

336	Structural formula calculations for clinopyroxene are based on 4 cations and 6 oxygens,
337	assuming stoichiometry. Average clinopyroxene analyses are given in Table 3. For
338	classification we used the International Mineralogical Association (IMA/CNMMN)
339	nomenclature (Morimoto et al., 1988; Rock, 1990) applying the classification diagram Jadeite
340	(Jd) – Aegirine (Ae) – Quad (Q) with Quad (Q) being the sum of Ca-Mg-Fe pyroxene
341	components (enstatite, ferrosilite, diopside and hedenbergite)
342	In the investigated samples, clinopyroxene is invariably sodic with a compositional
343	range of Jd <sub>2-40</sub> Ae <sub>45-98</sub> Q <sub>0-18</sub> (Table 3, Fig. 8). Based on their textural appearance (see above),
344	we distinguish the following five varieties, showing distinct compositions in an aegirine –
345	(Ti+Zr)aegirine – jadeite ternary (Fig. 5).
346	(1) Resorbed cores (Fig. 5a) of zirconian aegirine (Zr-Ae) with compositions of Ae <sub>68-</sub>
347	75Ti/Zr-Ae <sub>14-16</sub> Jd <sub>3-4</sub> featuring high Zr (up to 0.06 apfu) but low Ti (<0.02 apfu) contents.
348	(2) Clinopyroxene areas containing anhedral catapleiite inclusions (Fig. 5a), having
349	compositions of Ae <sub>77-88</sub> Ti/Zr-Ae <sub>2-7</sub> Jd <sub>4-10</sub> with low Zr and Ti (<0.01 apfu) contents.
350	(3) Subhedral to anhedral, needle- or columnar-shaped clinopyroxene (Fig. 5c)
351	exhibiting compositions of Ae <sub>76-88</sub> Ti/Zr-Ae <sub>1-6</sub> Jd <sub>5-14</sub> . Most of these data fall into the field for
352	aegirine (sensu stricto) with Ae $\ge$ 80, some of the data indicate calcian aegirine (Q $\ge$ 10) and a
353	notable number of analyzes represent aluminian aegirine (Jd >10; Fig. 8).
354	(4) Titanian aegirine (Ti-Ae) with compositions of Ae <sub>67-87</sub> Ti/Zr-Ae <sub>3-15</sub> Jd <sub>6-12</sub> exhibiting
355	low Zr (up to 0.03 apfu) but high Ti (up to 0.06 apfu) occurring as well-defined sectors and
356	irregular areas. (Fig. 5a-c).

- 357 (5) Aluminian aegirine (Al-Ae) with compositions of Ae<sub>56-75</sub>Ti/Zr-Ae<sub>1-5</sub>Jd<sub>17-35</sub> forming
  358 anhedral rims (Fig. 5a-c) and/or irregular patchy areas crosscutting clinopyroxene types (3)
  359 and (4).
- The frequency of the different clinopyroxene types varies strongly throughout the complex: In the mid subunit (1)-(5) occur, but in samples from the inner and the outer subunits (1) and (2) are absent, while (4) is rarely present. While (3) and (5) occur in similar amounts in the inner unit, in the outer unit (5) predominates over (3) (Fig. 5d).
- The various clinopyroxene types are not only observed in the different subunits, but in 364 single crystals too. As illustrated for samples 7315 and 6105 (Fig. 5b and c) from the inner 365 unit, clinopyroxene (3) is anhedrally overgrown by (5). All five above-defined clinopyroxene 366 types are present in a single crystal from the coarse-grained, undeformed schlieren (type B) of 367 the mid subunit (sample 5408; Fig. 5a). Here, a Zr-aegirine core (1) is irregularly overgrown 368 by aegirine (2) containing numerous anhedral catapleiite inclusions. Titanian-aegirine sectors 369 (4) and aegirine (3) overgrow this most central part of the crystal. Aluminian-aegirine (5) 370 371 anhedrally rims the crystal.

372

### 373 Eudialyte-group minerals

374

Formula calculations for EGM were carried out by normalizing the sum of (Si + Zr + Ti + Nb
+ Al + Hf) to 29 apfu (see details in Pfaff et al., 2010). In total 91 EGM grains from 13
samples were analyzed. The compiled data for each sample including an average for the
particular units is given in Electronic Appendix 3.

The textural and compositional diversity of EGM analyzed is illustrated in Table 4 and Figs 3, 6 and 9. In common with clinopyroxene, four textural varieties of EGM, which show clear compositional differences are distinguished (Figs 6 and 9):

382 (1) Sector-zoned EGM enriched in Zr and depleted in REE and Nb.

383 (2) Oscillatory-zoned EGM that overgrow EGM (1); slightly enriched in Ca, Fe and384 Cl, but depleted in REE.

(3) Irregular, up to several tens of micrometers wide areas with bright BSE contrast,
which replace and/or infiltrate EGM (1) and (2) (Fig. 4k). These are enriched in LREE and
show highest #Mn and ∑REE.

388 (4) Few micrometers wide rims or areas around vugs and/or cracks being enriched in
389 Y, HREE and #Mn, depleted in LREE with the highest ∑REEY and Nb.

In a given sample, sector and oscillatory-zoned EGM (1) and (2) are comparably REEpoor and exhibit low #Mn (defined as Mn/(Fe+Mn)), whereas types (3) and (4) are REE-rich and exhibit higher #Mn (Figs 6 and 9).

The most significant textural and compositional complexity is observed for EGM from 393 schlieren of the mid subunit, as was the case for clinopyroxene (see above). Sector-zoned 394 EGM (1) is observed in samples 7308 and 5618 (Figs. 6a and b), where sectors with high BSE 395 contrast are richer in Zr, REE and Y compared to sectors with low BSE contrast. These most 396 central parts of the crystals are overgrown either by oscillatory-zoned EGM (2) with 397 comparably higher Si, Ca, MREE and HREE but low LREE (Fig. 6b) or by irregular shaped 398 399 areas of type (3) with very high BSE contrast being enriched in REE and Y. Higher Y contents are documented at the rim of the crystals as well as in poikilitic areas of type (4). 400

EGM type (3) mainly occurs in the inner subunit. These are fine-grained, deformed
and texturally less complex crystals with no significant compositional variation (Fig. 6c).
They coexist with clinopyroxene types (3) and (5) (Fig. 5c) and have the highest LREE and
Mn enrichments (Fig. 9). EGM in the outer subunit are fine-grained of types (1) and (2) or
poikilitic type (4) (Fig. 6d). Poikilitic EGM have the lowest LREE content compared to all
EGM studied and show a particular depletion of REE at the rims (Fig. 6d, BSE and Ce map).

407 Furthermore, regional compositional differences in EGM compositions exist for Ca, 408 Na, Y and the ΣHREE, where a general decrease from the outer to the inner subunit is present 409 (Fig. 9). The opposite trend is noted for #Mn, ΣREE and ΣLREE, which increase from the 410 border to the centre of the intrusion (Fig. 9). Niobium (apfu) and Zr/Hf ratios however, do not 411 show such systematic changes, and Cl contents are mostly relatively low ( $Cl_{apfu} < 0.5$ ), with 412 one sample containing exceptionally Cl-rich EGM. These observations are in accordance with 413 observations made by Sjöqvist et al. (2013).

414

### 415 Catapleiite

416

417 Structural formula calculations for catapleiite are based on 10 cations and 11 oxygens,

418 assuming stoichiometry. Representative compositions are given in Table 5 and Fig. 7a.

419 Catapleiites from two samples of the mid subunit were analyzed. In sample 5408 both textural

420 varieties of Ca-catapleiite, namely coarse-grained subhedral crystals (Fig. 7b) and fine-

421 grained anhedral inclusions in clinopyroxene (Fig. 7c) have very similar compositions with up

422 to 7 wt.% CaO (Table 5). Similarly, in sample 5618 catapleiite occurrences at the border area

423 between clinopyroxene and EGM and catapleiite inclusions in clinopyroxene (Fig. 7d and e)

424 exhibit quite similar compositions with CaO = 0.3-1.3 wt.% and  $Na_2O = 13.0-14.0$  wt.% 425 (Table 5).

426

### 427 Feldspars, feldspathoids and zeolithes

428

429	Feldspars occur in all investigated samples as distinct albite and microcline grains and no
430	perthitic exsolution textures were observed. There are no significant differences between the
431	various samples and units with albite being almost pure (< 1 mol.% microcline) and
432	microcline containing up to 5 mol.% albite (Table 6).
433	Nepheline compositions (Ne <sub>74-77</sub> Ks <sub>21-25</sub> An <sub>0</sub> Qz <sub>0-1</sub> ) in all samples are very similar (Table
434	7). According to the diagram after Hamilton (1961), the majority of analyses plot between the
435	ideal compositions of Morosewicz (M) and Buerger (B) (Fig. 10) and generally fall below the
436	isotherm at T = 700°C, with two exceptional analyses indicating T > 775°C.
437	Albite and nepheline are variably replaced by zeolithes. Natrolite is largely dominant
438	and shows a very restricted compositional variation. Analcime was found only in one sample
439	(Table 7).

440

### 441 DISCUSSION

The aim of this study is to distinguish the magmatic signature of an agpaitic complex from features related to subsequent deformation and metamorphism using mineral textures and compositions. In the course of the study, minerals of the feldspar-group and nepheline were proven less beneficial probably due to their relatively simple structure and composition. In 446 contrast, structurally and compositionally more complex minerals of the eudialyte-group,

catapleiite as well as clinopyroxene appeared more appropriate to reflect physico-chemicalchanges.

449

### 450 Discrimination between magmatic and metamorphic features

The agpaitic Norra Kärr complex was subsequently overprinted and deformed during two successive orogenic events and is now preserved in a well-defined syncline with near parallel occurrence of major rock units (Fig. 2b und c). In the following we assign the various textures and compositions of the rock forming minerals to either magmatic relics or metamorphic features in order to reconstruct the magmatic and the subsequent metamorphic history of the Norra Kärr rocks.

457

### 458 Preserved magmatic features

459

Feldspars from the Norra Kärr rocks do not exhibit perthite or antiperthite textures preserved 460 (in agreement with Adamson 1944). We take this as evidence for the crystallization from a 461 subsolvus (low T) syenite (Sood & Edgar, 1970; Larsen & Sørensen, 1987; Markl, 2001; 462 Markl & Baumgartner, 2002; Chakrabarty et al., 2016). Alternatively, this could also reflect 463 464 the metamorphic recrystallization, but considering the observation that even feldspar 465 inclusions in EGM and clinopyroxene represent near end member compositions, a primary subsolvus origin is considered most probable. This hypothesis is further supported by 466 467 temperatures derived from nepheline compositions, which generally do not exceed 700°C (Fig. 10). The two exceptional nepheline compositions that indicate T > 775 °C might 468 469 represent early magmatic (phenocrystic) relict nepheline.

Relics of an early magmatic crystallization stage of the Norra Kärr rocks might be 470 471 represented by the Zr-aegrine cores of clinopyroxene (1) (Figs 5a and 7c). At constant P and T, Zr-aegirine is stable at moderate a<sub>Nds</sub> (activity of Na<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>) and under relatively reducing 472 473 conditions (Andersen et al., 2012). At this stage clinopyroxene could act as asink for Zr, preventing the crystallisation of early magmatic Zr-silicates. Similar relic clinopyroxene 474 475 crystals were reported from the deformed Red Wine intrusion (Currie & Curtis, 1976), resulting from the large stability field of clinopyroxene and its ability to adapt its 476 477 composition to the prevailing P-T-X conditions. Subsequent destabilization of Zr-aegirine (Fig. 7c and d) results in the exsolution of 478

catapleiite and Zr-poor clinopyroxene (2). The catapleiite inclusions occur in well-defined areas in clinopyroxene and are characterized by irregular shapes (Figs 5a and 7c). This process happened probably due to an increase of  $a_{Nds}$ ,  $a_{H2O}$  or  $f_{O2}$  during a later crystallization stage and can be described by the schematic reaction:

483

484 
$$4Na[Zr_{0.5} Fe_{0.5}]Si_2O_6 (Zr-Aegirine) + Na_2Si_2O_5 + \frac{1}{2}O_2 + 4H_2O =$$
  
485  $2NaFeSi_2O_6 (Aegirine) + 2Na_2ZrSi_3O_9 * 2H_2O (Catapleiite)$  (1)

486

This hypothesis was tested by reintegrating the Zr-aegirine composition, using the 487 molar volumes of catapleite inclusions contained in well-defined areas of aegirine (2) (Fig. 488 7d) as well as measured mineral compositions (Tables 3 and 5). Reintegrated Zr-aegirine 489 compositions correspond very well with measured compositions (Table 8) supporting the 490 491 argument for catapleiite formation by Zr-aegirine destabilization and subsequent exsolution. Considering the textural relationships illustrated in Fig. 7e, we assume that further catapleiite 492 crystallized prior to EGM, forming euhedral crystals, which were later encased in EGM. In 493 494 contrast, the textural relationships illustrated in Fig. 7d provide evidence that both minerals

may have replaced each other. In addition, it is not clear if the above-described catapleite 495 496 exsolutions in clinopyroxene and coarse, euhedral catapleite intergrown with EGM represent different stages during the magmatic evolution of these rocks. Indeed, they may be two 497 different generations. Compositionally, however, there are no differences between these two 498 types of catapleiite (Fig. 7a). In general, both catapleiite and EGM occur in Zr-rich 499 peralkaline magmatic systems. However, the formation of magmatic EGM seems to require 500 relatively low water activities, but high Cl activities, conditions that are typically met in 501 502 reduced nepheline synitic systems, whereas magmatic catapleiite seems to be restricted to peralkaline (granitic) systems being relatively H<sub>2</sub>O-rich (e.g., Andersen et al. 2010; Marks et 503 504 al., 2011; Andersen & Friis, 2015). Note that catapleiite can also form (along with many other phases) during the hydrothermal alteration of EGM (e.g., Salvi et al., 2000; Karup-Møller et 505 al., 2010; Karup-Møller & Rose-Hansen, 2013; Borst et al., 2016). The catapleiite-eudialyte 506 507 equilibrium can be expressed by the following schematic reaction:

508

$$3Na_2ZrSi_3O_9 (Catapleiite) * 2H_2O + 6CaO + 4Na_2O + NaCl + 3FeO + 17SiO_2 =$$

510 
$$Na_{15}Ca_{6}Fe_{3}Zr_{3}Si_{26}O_{72}(OH)_{4}Cl (Eudialyte) + 4H_{2}O (2).$$

511

The Cl contents in EGM from the Norra Kärr rocks mostly vary between 0.2-0.4 apfu (Fig. 9a) and are relatively low compared to EGM in other alkaline complexes with  $Cl_{apfu}$  up to 1.9 (see Schilling et al., 2011b). EGM from Norra Kärr may contain up to about 3 wt.% H<sub>2</sub>O (Atanasova et al., 2015). This implies that EGM may be stable even at relatively-low a<sub>HCl</sub> but relatively-high a<sub>H2O</sub>. We propose that in the case of Norra Kärr a<sub>H2O</sub> was not high enough to stabilize catapleiite over a long crystallization interval. In addition, initial catapleiite formation lead to subsequent REE enrichment of the melt, which probably was thecrucial promoting factor stabilizing EGM in this relatively Cl-poor environment.

On the deposit scale, we observe a continuous decrease in Ca, Na, Y and the HREE 520 with increasing #Mn, ΣREE and LREE from the outer to the inner subunit as demonstrated in 521 Fig. 9. Such compositional changes of EGM are attributed to primary magmatic evolution 522 (Sjöqvist et al., 2013) also known from EGM-bearing layered intrusions (e.g. Pfaff et al., 523 2008; Schilling et al., 2011a; Sheard et al., 2012; Lindhuber et al., 2015; Ratschbacher et al., 524 2015; Möller & Williams-Jones, 2016). These studies report compositional evolution in terms 525 of the Mn/(Fe+Mn) ratio and the content of the different REE, which is considered to be the 526 result of fractional crystallization during primary, magmatic layering of agpaitic intrusions 527 528 (Fig. 11). Early magmatic EGM are enriched in Fe and the HREE, which leads to subsequent Mn- and- LREE-enrichment of the residual melt and to crystallization of late magmatic Mn-529 and LREE-dominated EGM. Similarly, primary layering of the Norra Kärr complex (Fig. 11), 530 531 is indicated by early Fe- and- HREE-dominated EGM from the outer subunit as well as by continuous Mn and LREE enrichment in the mid and inner subunits (Fig. 11) and are still 532 preserved within the fold structure. 533

534

535

536 Textures assigned to metamorphic overprint

537

- 538 The magmatic textures described above such as sector and oscillatory zoning in
- clinopyroxene and EGM are partly-overgrown and/or replaced by late anhedral Al-aegirine
- and REE-enriched EGM, respectively. The formation of Al-aegirine is a general feature of

metamorphosed syenites (Wooley et al., 1996) and is probably formed by the following
schematic reaction (Curtis & Gittins, 1979):

543

544 NaAlSiO<sub>4</sub> (Nepheline) + NaAlSi<sub>3</sub>O<sub>8</sub> (Albite) = 2 NaAlSi<sub>2</sub>O<sub>6</sub> (Jadeite) (3).

545

Same reaction is observed in samples studies from Norra Kärr as well. According to 546 (Curtis & Gittins, 1979) equation (3) could take place in a huge P- and- T-range of conditions, 547 548 between 450-700°C and 2-10 kbar, covering both, higher greenshist and lower- to- moderate amphibolite facies conditions. In contrast to Red Wine, where amphibolite facies conditions 549 550 are reported, at Norra Kärr moderate- to- high greenshist facies conditions are only roughly 551 estimates. These estimates are supported by the observation that relic magmatic textures are 552 preserved due to assumed relatively low P and T during deformation of the rocks (Wooley et al., 1996). 553

In EGM, flamy BSE textures (Figs 4k, 6a and b) as well as very late Y enrichments 554 and LREE depletions at the rim of crystals, along cracks, vugs (Figs 6a, b and d) and in highly 555 poikilitic areas (Figs 6b and d) are observed. Flamy textures as shown in Fig. 4k indicate 556 both, new formation of compositionally different EGM of type 3, (straight boundaries 557 558 between EGM (1) and (3)) as well as recrystallization or replacement of EGM types (1) and/or (2) by EGM of type (3) (flamy EGM (3) permeating EGM (1) and/or (2)). Both can be 559 explained by the interaction with fluids, presumably generated during the metamorphic 560 overprint of the rocks. Yttrium and HREE enrichments accompanied by LREE depletion at 561 the rims of crystals (Fig. 6a, b and d) might document an even later event causing further 562 compositional adaptation of EGM, in this case accompanied by the re-distribution of REE and 563 Y, spatially-associated with the formation of late catapleiite and secondary LREE-rich 564

minerals (Fig. 6a, Ce map). We suggest that these textures could potentially be caused by
recrystallization of EGM in response to metamorphic deformation.

The widespread alteration of albite and nepheline to natrolite (Fig. 3) is also a late 567 process, probably related to fluid-assisted overprint during deformation. Importantly, 568 analcime is only very rarely observed (actually in only one sample, see above). This 569 570 corresponds to observations from the Mont Saint-Hilaire complex and Shushina Hill (Schilling et al., 2011a; Chakrabarty et al., 2016, respectively) and it was suggested that 571 572 under such conditions analcime is only stable at low T < 150 °C. Accordingly, this argues for higher temperatures for natrolite formation. In the case of Norra Kärr a further indication for 573 574 the "metamorphic" origin is given by the spatial distribution of natrolite alteration, which preferably occurs in the mid and inner units, while the very fine-grained rocks from the outer 575 unit are less affected, although these rocks are in direct contact with the granitic country rock. 576

577

### 578 Thermodynamic modelling to constrain the p-T-conditions

579

The albite – nepheline – aegirine assemblage of the Norra Kärr rocks permit estimations of temperature and silica activity at the assumed pressure of the magmatic stage (e.g. Mitchell & Platt, 1978; Markl et al., 2001, Schilling et al., 2011a) and may shed light into the so farpoorly constrained conditions during metamorphic overprint during the Sveconorvegian (Grenvillian) orogeny. We performed thermodynamic calculations applying the GEOCALC software of Berman et al. (1987) and Liebermann & Petrakakis (1990) with the database of Berman (1988) using the following three schematic equilibria.

587

589

592 NaAlSiO<sub>4</sub> (Nepheline) + 
$$2SiO_2$$
 (liq) = NaAlSi<sub>3</sub>O<sub>8</sub> (Albite) (6)

593

594 End member activities were calculated using a one-site mixing model for nepheline 595 and applying the solution activity formulations of Green et al. (2007) and Holland & Powell 596 (2003) for clinopyroxene and feldspar, respectively.

597 Assuming typical emplacement pressures of 1-2 kbar for syenitic peralkaline intrusions (e.g., Konnerup-Madsen & Rose-Hansen, 1982; Salvi et al., 2000) and using the 598 mean compositions of Zr-aegirine (1), which we interpret as early magmatic clinopyroxene 599 (see above), equilibrium conditions of 600 - 700°C at asio2 values of 0.5-0.6 are indicated 600 (Fig. 12a). Such conditions are consistent with estimations for other peralkaline complexes 601 602 and are in agreement with the absence of perthitic alkali feldspar (see above) and the temperature estimates based on nepheline thermometry (Fig. 10). Compositions of 603 presumably late-magmatic aegirine (2) and (3) indicate equilibration to lower temperatures (< 604 605 450°C) and  $a_{SiO2}$  values of < 0.3 (Fig. 12a).

Taken together, we interpret these data as representing the magmatic evolution of the
Norra Kärr rocks, indicating a relatively low liquidus temperature of <700°C and a relatively</li>
extensive crystallization interval down to temperatures < 400°C, which has been</li>
demonstrated before, based on both field studies (Markl et al., 2001; Marks et al., 2003;
Marks & Markl, 2003) and experimental work (Piotrowski & Edgar, 1970; Sood & Edgar,
1970; Giehl et al., 2013; 2014).
To constrain the metamorphic conditions of the Norra Kärr rocks during the

613 Sveconorvegian orogeny, we used the mean compositions of Al-aegirine (clinopyroxene 4;

see above) computed at pressures of 2.5, 5 and 8 kbars to represent general greenshist as well 614 615 as lower amphibolite facies conditions (Fig. 12b). The calculated equilibrium temperatures range from 350 to 650°C with asiO2 values from 0.55 to 0.15, with both T and asiO2 decreasing 616 617 with decreasing pressure. Comparing these estimates with proposed moderate to high greenschist facies conditions, temperatures from 400-550°C at pressure of 5 kbar with an asio2 618 619 range between 0.25 and 0.4 are considered as most reasonable. These values are similar to 620 those estimated for late magmatic conditions. This might indicate that asi02 during the metamorphic stage did not essentially change, suggesting that fluid-rock interaction during 621 this stage was largely (locally) rock-buffered and that the responsible fluids were not 622 623 especially SiO<sub>2</sub>-rich, as there is no late-stage quartz formed as might be expected from fluids derived from granitic country rocks. 624

625

#### 626 CONCLUSIONS

627

Even after metamorphic overprint and deformation, it remains possible to identify primary magmatic textures and compositions in EGM and clinopyroxene from peralkaline rocks and to find evidence for primary magmatic layering of the intrusion with continuous enrichment of REE, LREE and Mn from the outer to the inner subunit. The multi-stage evolution of such rocks can be reconstructed using clinopyroxene and EGM, as both minerals cover a large stability range (in term of P and T) and are able to adapt their composition to changing conditions, thereby recording the magmatic and metamorphic history of the complex.

The minerals investigated probably crystallized from a subsolvus syenite and
crystallization took place during a relatively extensive temperature interval from about 700°C
to 450°C with a correspondent decrease in a<sub>SiO2</sub> from 0.6 to about 0.3. Initially, Zr-aegirine

crystallized at relatively low peralkalinity and reducing conditions. Due to an increase in a<sub>Nds</sub> 638 639 and at moderate- to- high fo2 and aH20, Zr-aegirine was destabilized and crystallization continued forming aegirine (2) of sensu stricto compositions and catapleiite as the main Zr-640 641 bearing silicate mineral. Due to the absence of sodalite and the very early formation of catapleiite, a<sub>HCl</sub> further increased and REE and HFSE were enriched in the residual melt, 642 promoting EGM crystallization. Crystallization of EGM seems not necessarily restricted to 643 644 specific conditions, forming even at very low a<sub>HCl</sub> and at relatively high a<sub>H2O</sub>, but to the availability of specific elements in the melt. 645

During the Sveconorvegian/Grenvillian orogeny, the Norra Kärr rocks were deformed 646 and folded at presumably moderate greenshist facies conditions (Fig. 12) and late EGM and 647 648 Al-aegirine formed at 400°C - 550°C and in a asi02 range of 0.25-0.4 at pressures not 649 exceeding 5 kbar. We suggest that during this deformation event EGM interacted with metamorphic fluids, either changing its composition or being partly-destabilized to catapleiite 650 651 and secondary REE-bearing minerals. During the whole history of the complex, asi02 remains very similar, indicating very little interaction with the surrounding granitic rocks. This 652 assumption is confirmed by the relatively-restricted occurrence of natrolite alteration, 653 preferably occupying the more central part of the intrusion. 654

655

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657

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Fig.1. (a) Simplified geological map of Fennoscandia illustrating major lithological units (modified after Högdahl et al., 2004). Red box is enlarged in (b), where the red ellipse resembles the Norra Kärr complex. The white arrow indicates the direction of decreasing regional deformation during the Sveconorwegian orogeny. PZ-Protogine Zone, SFDZ - Sveconorwegian Frontal Deformation Zone (simplified after Sönderlund et al., 2002; Wahlgren et al., 1994).

Fig.2. (a) Simplified geological map of the Norra Kärr complex illustrating major lithological units (modified after Tasman Metals Ltd). The deformation is well visualized in W-E cross sections (b) J and (c) P. The sampling locations as given in Table 1 are marked as black crosses.

Fig.3. Mineral Liberation Analyzer (MLA) classified-color images (EDX-GXMAP mode) of the different subunits of Norra Kärr. Illustrated are characteristic textures of a) the incipient alignment and stretching of minerals and b) the macroscopic scale folding and alignment of minerals in the inner subunit; (c) poikilitic EGM in a fine grained matrix of the outer subunit; (d) homogeneous matrix of the mid subunit; (e)-(h) thoroughly preserved euhedral to subhedral EGM and clinopyroxene in leucocratic schlieren of the mid subunit. Nepheline is partly to strongly altered to natrolite. Areas marked as red boxes are enlarged in Figs 4, 5 and 6.

Fig.4. (a) Alignment of minerals as well as (b) and (c) microscopic- to macroscopic scale folding as common features of the inner subunit; EGM crystals in (a) are slightly stretched. (d) Folding of the fluoro-leakeite-aegirine meta-nepheline syenite rock. (e) Fine-grained metanepheline syenite with a band of mid- to- coarse-grained nepheline and eudialyte. The nepheline crystals show alteration. (f) Microcline  $\delta$ -clast, (g) catapleiite and (h) EGM (type (4)) porphyroclasts are characteristic for the outer subunit. EGM contain inclusions of catapleiite, feldspar, nepheline and clinopyroxene. Catapleiite (Cat) forms tails and replaces EGM mainly at the rim. EGM are surrounded by columnar rinkite-group minerals (Rink). (i) Medium-grained schlieren of the mid subunit with feldspar, aegirine and eudialyte show no particular alignment, aegirine crystals (CPX) form radiating aggregates. (i) Coarse-grained microcline and extensively altered nepheline from schlieren of the mid subunit. (k) EGM (3) overgrow and/or replace the compositionally different EGM (1) in schlieren of the mid subunit; visible white spots represent EPMA measurement locations.

Fig.5. Compositional and textural characteristics of clinopyroxene from the Norra Kärr rocks. (a) Euhedral clinopyroxene from the mid unit (sample 5408). The resorbed Zr-aegirine core is irregularly rimmed by aegirine s.s. rich in catapleiite inclusions. Both are overgrown by alternating sectors of inclusion-free titanoan-aegirine and aegirine s.s. Anhedral Al-aegirine rims irregularly the crystal. (b) Subhedral clinopyroxene from the mid subunit exhibiting well defined Ti-rich sectors overgrown by Al-aegirine. In the center a large catapleiite is enclosed. (c) Subhedral to anhedral clinopyroxene of the inner subunit; (d) Anhedral clinopyroxene from the outer subunit. See also detailed descriptions in the main text.

Fig.6. Compositional and textural characteristics of EGM from the Norra Kärr rocks. At the top of the diagram, textural varieties 1-4 from all EGM investigated are collated considering the #Mn and the REEY<sub>apfu</sub>. Representative grains of the different units are shown in (a)-(d). In the mid subunit (a) single EGM crystal (sample 5618) shows sectors (1) being Zr-rich, but REE-poor, overgrown by an irregular flamy area (3) of high BSE contrast, rich in REE and Y. Highest Y is detected along rims and cracks (4). The crystal is closely associated with catapleite (Cat) and britholite group minerals (Brit). Red box is enlarged in Fig. 4k. (b) Subhedral EGM featuring sector (1) and oscillatory (2) zoning, as well as irregular flamy textures (3) and poikilitic Y-rich areas (4). (c) EGM crystals from the inner subunit commonly show deformation features like stretching and alignment and are high in #Mn and REE. (d) Poikilitic EGM porphyroclast from the outer unit showing LREE depletion and Y enrichments at the rim. Catapleite (Cat) and rinkite group minerals (Rink) are visible as white areas in the Zr and Ce maps. Visible spots in (a) and (b) represent EPMA (white) and LA-ICP-MS (dark) measurement locations.

Fig.7. Compositional (a) and textural (b-f) characteristics of catapleite from the Norra Kärr rocks. (b) A single euhedral Ca-catapleiite crystal (Ca-Cat) and (c) Ca-catapleiite inclusions (Ca-Cat) in clinopyroxene, aegirine s.s. (CPX) (Fig. 4a) from schlieren of the mid subunit, sample 5408; (d) and (e) show characteristic catapleiite (Cat) and EGM textures in the mid subunit, sample 5618. Zones in radial aegirine s.s. (CPX), rich in catapleiite inclusions (Cat) are remarkably well defined. Catapleiite occurs enclosed in EGM, between and within EGM crystals and at the grain boundaries between clinopyroxene and EGM. (f) Catapleiite aggregates (Cat) from the outer subunit, sample 5611. Visible spots in (b) and (c) represent EPMA (white) and LA-ICP-MS (dark) measurement locations.

Fig.8. (a) Classification diagram for Ca-Na and Na pyroxenes with the endmembers Jadeite (Jd) – Aegirine (Ae) – Quad (Q) modified after Morimoto et al. (1988) and Rock (1990). The marked area is enlarged in (b) showing that pyroxene composiitons from Norra Kärr include aegirine s.s., zirconian aegirine, calcian aegirine, titanoan aegirine and aluminian aegirine.

Fig.9. Distribution of (a) major and (b) minor elements in EGM according to the relative sampling location within the fold structure. Samples from the discovery outcrop are displayed for comparison. Colour coding displays EGM textural varieties 1-4 as defined in Fig. 5.

Fig.10. Diagram of the system nepheline-kalsilite-silica (wt.%) with isotherms showing the limit of nepheline solid solution at the indicated temperatures (after Hamilton 1961). The majority of analyses plot within the Morosewicz (M) – Buerger (B) convergence field (after Tilley, 1954). Most of the analyses indicate  $T \le 500^{\circ}$ C. Only two analyses indicate  $T \ge 700^{\circ}$ C.

Fig.11. Suggested primary magmatic layering of the intrusion with upwards enrichment of REE, LREE and #Mn, preserved within the present fold structure.

Fig.12. Two silica activity (a<sub>SiO2</sub>) - temperature diagrams calculated based on equilibria (4)-(6). Different sets of conditions (different lines in (b)) are calculated due to variable activities of nepheline (aNe) and jadeite (aJd), while the activity of albite (aAb) is 1 for all reactions. (a) Magmatic conditions are estimated for 1-2 kbar using early- and late-magmatic clinopyroxene compositions, respectively. (b) The metamorphic evolution of the Norra Kärr complex is illustrated for pressures representing general greenshist (grey area) to lower amphibolite facies conditions, considering metamorphic clinopyroxene textures and compositions. Details are given in the main text.

Electronic Appendix 1. Selected scans of core samples. (a) Folded fluoro-leakeite-aegirine meta-nepheline syenite. (b) Catapleiite-and EGM-bearing aegirine meta-nepheline syenite with 5 % pegmatoidal schlieren shows folding of the rock. (c) Catapleiite-and EGM-bearing aegirine meta-nepheline syenite with 30 to 50 % pegmatoidal schlieren with small scale folding of the schlieren, minerals show hematization. (d) Foliated fine- to- medium-grained aegirine leuco-meta-nepheline syenite. (e) Coarse-grained schlieren with microcline, albite and EGM, fine-grained euhedral aegirines form patchy aggregates.































## Table 1: List of investigated samples

Sample	Drill core	Position	Subunit	Analytical method (mineral)
5403	NKA 11054 P7	16.66-17.00m	Mid	MLA
5405	NKA 11054 P7	25.08-25.29m	Mid	MLA
5406	NKA 11054 P7	34.31-34.60m	Mid	MLA
5407-1	NKA 11054 P7	37.43-37.86m	Mid	MLA
5407-2	NKA 11054 P7	37.43-37.86m	Mid	MLA
5408	NKA 11054 P7	42.44-42.71m	Mid	MLA, EPMA (cpx, EGM, Cat)
5409	NKA 11054 P7	45.85-46.20m	Mid	MLA
5411	NKA 11054 P7	54.56-54.78m	Mid	MLA
5611	NKA 11056 J1	110.20-110.34m	Outer	MLA, EPMA (cpx, EGM)
5612	NKA 11056 J1	119.60-119.90m	Mid	MLA, EPMA (cpx, EGM)
5613	NKA 11056 J1	126.00-126.25m	Mid	MLA, EPMA (cpx, EGM)
5618	NKA 11056 J1	198.60-198.86m	Mid	MLA, EPMA (cpx, EGM, Cat)
5631	NKA 11056 J1	350.20-350.40m	Outer	MLA, EPMA (cpx)
6105	NKA 12061 J7	29.85-30.02m	Inner	MLA, EPMA (cpx, EGM)
6108	NKA 12061 J7	43.44-43.55m	Inner	MLA, EPMA (cpx, EGM)
6115	NKA 12061 J7	83.36-83.59m	Inner	MLA, EPMA (cpx, EGM)
6123	NKA 12061 J7	163.61-163.80m	Outer	MLA, EPMA (cpx, EGM)
6124-1	NKA 12061 J7	182.30-182.56m	Outer	MLA, EPMA (cpx)
6124-2	NKA 12061 J7	182.30-182.56m	Outer	MLA
6125	NKA 12061 J7	189.90-190.30m	Outer	MLA
7305-1	NKA 12073 P5	~ 22.94m	Mid	MLA
7305-2	NKA 12073 P5	~26.50m	Mid	MLA
7308	NKA 12073 P5	52.81-52.97m	Mid	MLA, EPMA (cpx, EGM)
7310	NKA 12073 P5	64.37-64.51m	Mid	MLA
7311	NKA 12073 P5	71.35-71.43m	Mid	MLA
7314	NKA 12073 P5	89.44-89.57m	Mid	MLA
7315	NKA 12073 P5	91.50-91.61m	Mid	MLA, EPMA (cpx, EGM)
7320	NKA 12073 P5	156.31-156.44m	Outer	MLA

MLA = Mineral Liberation Analyzer; EPMA = Electron Probe Microanalyzer; cpx = clinopyroxene; EGM = Eudialyte-group minerals; Cat = catapleiite

 Table 2: Modal mineralogy of subunits of the Norra Kärr complex

		Inne N=	er 3		Mid (Matrix) N=1	Ν	/lid (Sch N=1	lieren) 7		Outer N=7				
	Mean	CI	95%	Interval		Mean	CI	95%	Interval	Mean	Mean Cl		Interval	
wt.%		(+/-)	Min	Max			(+/-)	Min	Max		(+/-)	Min	Max	
Albite	22.88	4.15	13.27	31.66	57.87	4.43	0.84	0.00	21.83	39.66	1.44	29.73	53.85	
Microcline	16.80	3.05	15.21	19.03	4.41	25.13	1.85	2.98	58.98	13.17	0.43	8.35	15.83	
Aegirine	17.60	3.19	15.24	19.69	19.42	18.20	1.23	2.86	34.03	13.47	0.55	9.42	17.49	
Nepheline	9.39	1.70	4.83	12.72	10.30	8.84	1.14	0.02	32.98	20.15	1.61	3.17	29.14	
Natrolite	22.11	4.01	12.12	36.86	2.57	27.12	1.47	12.12	51.24	8.16	1.72	0.39	27.19	
Catapleiite	1.74	0.32	0.94	2.19	2.97	2.45	0.23	0.10	6.29	1.13	0.14	0.14	2.63	
Eudialyte	7.25	1.32	1.11	14.43	2.19	13.39	1.15	2.70	35.39	3.81	0.37	0.38	6.25	
Other REE minerals	1.80	0.33	0.07	4.96	0.25	0.14	0.01	0.04	0.43	0.11	0.03	0.00	0.46	

	(1) Zr-aegirine			(2) Aegirine				(3) Aegirine			(4) Ti-aegirine				(5) Al-aegirine					
	Mean CI 95% Interval			terval	Mean CI 95% Interval			Mean CI 95% Interval			Mean	CI	95% In	terval	Mean	CI	95% In	95% Interval		
wt.%	38		Min	Max	155		Min	Max	3053		Min	Max	541		Min	Max	1350		Min	Max
SiO <sub>2</sub>	50.82	0.11	50.25	51.31	51.54	0.06	50.69	52.20	51.49	0.02	50.41	52.43	51.44	0.05	50.13	52.24	52.74	0.03	51.60	53.83
TiO <sub>2</sub>	0.51	0.01	0.47	0.55	0.43	0.02	0.21	0.60	0.31	0.00	0.12	0.61	1.10	0.03	0.66	2.10	0.21	0.01	0.03	0.56
$AI_2O_3$	0.86	0.02	0.78	0.94	1.56	0.06	0.87	2.25	1.93	0.02	1.26	3.03	1.99	0.03	1.46	2.56	6.02	0.04	4.28	7.63
FeO	25.78	0.04	25.55	25.95	27.54	0.07	26.61	28.24	27.58	0.02	26.08	28.53	26.35	0.06	24.84	27.53	22.45	0.05	20.54	24.55
MnO	0.64	0.01	0.59	0.70	0.28	0.02	0.14	0.61	0.18	0.00	0.09	0.33	0.31	0.01	0.20	0.49	0.15	0.00	0.07	0.26
MgO	0.43	0.01	0.41	0.48	0.33	0.02	0.17	0.49	0.25	0.00	0.12	0.40	0.35	0.01	0.24	0.48	0.17	0.00	0.08	0.35
ZrO <sub>2</sub>	3.20	0.02	3.11	3.28	0.44	0.03	0.15	0.94	0.29	0.01	0.05	0.92	0.53	0.03	0.08	1.69	0.08	0.00	0.02	0.20
CaO	1.61	0.03	1.50	1.77	1.02	0.04	0.61	1.57	0.81	0.01	0.34	1.53	0.60	0.02	0.36	1.01	0.74	0.01	0.32	1.31
Na <sub>2</sub> O	11.84	0.05	11.54	12.13	12.32	0.04	11.73	12.95	12.43	0.01	11.86	12.90	12.52	0.02	12.11	12.86	12.76	0.01	12.20	13.26
K <sub>2</sub> O	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.02	0.01	0.00	0.00	0.03	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.05
Total	95.69	0.14	94.98	96.39	95.45	0.08	94.48	96.35	95.27	0.02	93.78	96.44	95.19	0.06	93.52	96.56	95.33	0.04	93.87	96.50
Fe <sub>2</sub> O <sub>3</sub>	23.42	0.32	22.03	25.41	27.32	0.20	24.94	30.09	27.64	0.05	24.98	29.97	25.91	0.16	22.49	29.51	21.96	0.08	18.76	24.68
FeO	4.70	0.29	2.98	5.97	2.96	0.17	0.79	5.23	2.70	0.04	0.38	4.97	3.03	0.11	0.38	5.26	2.69	0.07	0.42	5.07
Ferric Total	98.04	0.14	97.31	98.94	98.19	0.08	97.22	99.19	98.04	0.02	96.59	99.22	97.79	0.06	96.37	99.00	97.53	0.04	96.04	98.73
Formulae base	ed on 4 cat	ions and	6 oxygens																	
Si	2.01	0.00	1.99	2.02	2.01	0.00	1.99	2.03	2.01	0.00	1.98	2.03	2.01	0.00	1.98	2.03	2.01	0.00	1.99	2.04
Al	0.04	0.00	0.04	0.04	0.07	0.00	0.04	0.10	0.09	0.00	0.06	0.14	0.09	0.00	0.07	0.12	0.27	0.00	0.19	0.34
Ti	0.02	0.00	0.01	0.02	0.01	0.00	0.01	0.02	0.01	0.00	0.00	0.02	0.03	0.00	0.02	0.06	0.01	0.00	0.00	0.02
Fe3+	0.70	0.01	0.66	0.75	0.80	0.01	0.73	0.88	0.81	0.00	0.73	0.88	0.76	0.00	0.66	0.87	0.63	0.00	0.54	0.71
Mg	0.03	0.00	0.02	0.03	0.02	0.00	0.01	0.03	0.01	0.00	0.01	0.02	0.02	0.00	0.01	0.03	0.01	0.00	0.00	0.02
Fe2+	0.16	0.01	0.10	0.20	0.10	0.01	0.03	0.17	0.09	0.00	0.01	0.16	0.10	0.00	0.01	0.17	0.09	0.00	0.01	0.16
Mn	0.02	0.00	0.02	0.02	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.01	0.01	0.00	0.01	0.02	0.00	0.00	0.00	0.01
Zr	0.06	0.00	0.06	0.06	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.02	0.01	0.00	0.00	0.03	0.00	0.00	0.00	0.00
Ca	0.07	0.00	0.06	0.08	0.04	0.00	0.03	0.07	0.03	0.00	0.01	0.06	0.02	0.00	0.01	0.04	0.03	0.00	0.01	0.05
Na	0.91	0.00	0.89	0.92	0.93	0.00	0.89	0.97	0.94	0.00	0.90	0.97	0.95	0.00	0.92	0.97	0.94	0.00	0.91	0.98
К	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
χ Ае	78.43	0.38	76.98	81.31	87.86	0.27	84.67	92.03	87.77	0.08	82.58	92.23	81.70	0.38	72.70	90.23	68.92	0.20	61.53	76.54
χ Jd	4.39	0.16	3.23	4.93	7.70	0.28	4.43	10.92	9.32	0.08	5.79	14.84	9.51	0.15	5.83	12.74	29.53	0.21	21.23	37.41

Table 3: Average compositions of the various clinopyroxene types of the Norra Kärr complex

<u>x Ti-Zr-Ae</u> 17.18 0.25 15.47 18.11 4.44 0.21 1.87 7.32 2.91 0.05 0.71 6.37 8.79 0.30 3.00 16.35 1.55 0.05 0.19 3.86 Cl = confidential interval

	(1	I) Secto	r zoning		(2) (	Oscillato	ory zoning	g	(3) Irregular replacement textures			extures	(4) Rims			
	Mean	CI	95%	Interval	Mean	CI	95% l	nterval	Mean	CI	95%	Interval	Mean	CI	95%	Interval
	321	(+/-)	Min	Max	180	(+/-)	Min	Max	374	(+/-)	Min	Max	139	(+/-)	Min	Max
SiO <sub>2</sub>	51.56	0.05	50.59	52.36	51.09	0.04	50.49	51.57	51.20	0.08	49.95	52.55	50.91	0.11	49.69	51.85
TiO <sub>2</sub>	0.16	0.00	0.08	0.22	0.09	0.00	0.06	0.14	0.16	0.00	0.07	0.21	0.12	0.01	0.04	0.20
ZrO <sub>2</sub>	11.92	0.06	11.35	13.65	11.67	0.06	11.06	12.40	11.53	0.02	11.12	11.99	11.38	0.05	11.03	11.83
HfO <sub>2</sub>	0.24	0.00	0.18	0.35	0.31	0.00	0.24	0.35	0.27	0.00	0.21	0.35	0.29	0.01	0.21	0.37
$AI_2O_3$	0.25	0.01	0.16	0.41	0.28	0.01	0.19	0.39	0.20	0.00	0.13	0.28	0.32	0.03	0.13	0.59
Nb <sub>2</sub> O <sub>5</sub>	0.50	0.02	0.21	0.85	0.74	0.02	0.47	1.07	0.94	0.03	0.44	1.54	0.89	0.05	0.30	1.36
La <sub>2</sub> O <sub>3</sub>	0.48	0.01	0.26	0.68	0.41	0.01	0.30	0.61	0.89	0.03	0.50	1.63	0.44	0.03	0.18	0.73
Ce <sub>2</sub> O <sub>3</sub>	1.32	0.02	0.79	1.63	0.95	0.03	0.74	1.45	2.01	0.05	1.07	2.86	0.98	0.07	0.40	1.63
$Nd_{2}O_{3}+Pr_{2}O_{3}+Sm_{2}O_{3}$	1.16	0.02	0.67	1.42	0.70	0.03	0.50	1.21	1.33	0.03	0.67	1.95	0.83	0.06	0.28	1.37
$Tb_2O_3+Gd_2O_3+Dy_2O_3$	0.69	0.01	0.32	0.88	0.68	0.01	0.56	0.79	0.67	0.01	0.48	0.89	1.03	0.03	0.76	1.29
$Er_2O_3+Yb_2O_3$	0.51	0.01	0.24	0.67	0.66	0.01	0.41	0.78	0.53	0.01	0.36	0.82	1.14	0.09	0.54	2.10
Y <sub>2</sub> O <sub>3</sub>	2.41	0.06	1.02	3.06	2.34	0.03	1.90	2.67	2.45	0.04	1.90	3.12	3.96	0.09	3.19	4.89
FeO	2.84	0.04	2.12	3.83	3.35	0.04	2.68	3.76	2.01	0.06	1.27	3.26	2.21	0.06	1.60	2.87
MnO	2.23	0.03	1.57	2.63	1.83	0.03	1.61	2.43	3.37	0.09	2.07	4.69	2.13	0.06	1.52	2.76
CaO	7.04	0.08	5.71	8.38	7.91	0.06	7.16	8.47	6.47	0.10	4.57	8.36	6.86	0.05	6.32	7.39
Na <sub>2</sub> O	13.42	0.06	12.33	14.48	13.73	0.05	13.11	14.35	12.61	0.13	7.73	13.74	13.58	0.16	11.31	14.92
K <sub>2</sub> O	0.46	0.01	0.19	0.63	0.35	0.01	0.21	0.51	0.50	0.01	0.26	0.95	0.46	0.02	0.28	0.73
CI	0.36	0.01	0.29	0.59	0.68	0.03	0.31	0.93	0.35	0.01	0.28	0.88	0.41	0.02	0.23	0.56
O=CI	0.08	0.00	0.07	0.13	0.15	0.01	0.07	0.21	0.08	0.00	0.06	0.20	0.09	0.00	0.05	0.13
Total, corrected	97.45	0.07	96.24	98.36	97.62	0.07	96.67	98.57	97.40	0.07	95.61	98.64	97.85	0.12	96.24	98.89
TREO total	4.16	0.06	2.79	4.89	3.40	0.05	2.98	4.45	5.43	0.09	3.76	6.97	4.41	0.08	3.52	5.22
Formula based on Σ(Si	Al Zr Ti H	f Nb) na	ormalized	to 29 apf	u											
Si	25.75	0.02	25.36	25.91	25.72	0.01	25.57	25.86	25.75	0.01	25.63	25.85	25.72	0.01	25.60	25.84
Ti	0.06	0.00	0.03	0.08	0.03	0.00	0.02	0.05	0.06	0.00	0.03	0.08	0.04	0.00	0.02	0.08
Zr	2.90	0.01	2.79	3.27	2.87	0.01	2.73	3.03	2.83	0.01	2.74	2.96	2.80	0.01	2.74	2.90
Hf	0.03	0.00	0.03	0.05	0.04	0.00	0.03	0.05	0.04	0.00	0.03	0.05	0.04	0.00	0.03	0.05
AI	0.15	0.00	0.09	0.23	0.17	0.00	0.12	0.23	0.12	0.00	0.07	0.16	0.19	0.02	0.08	0.35
Nb	0.11	0.00	0.05	0.19	0.17	0.01	0.11	0.25	0.21	0.01	0.10	0.35	0.20	0.01	0.07	0.31
La	0.09	0.00	0.05	0.12	0.08	0.00	0.06	0.11	0.17	0.01	0.09	0.30	0.08	0.01	0.03	0.14
Ce	0.24	0.00	0.14	0.30	0.18	0.00	0.14	0.27	0.37	0.01	0.20	0.54	0.18	0.01	0.07	0.30
Nd+Pr+Sm	0.21	0.00	0.12	0.26	0.13	0.00	0.09	0.22	0.24	0.01	0.12	0.36	0.15	0.01	0.05	0.25

Table 4: Average compositions of the various types of eudialyte-group minerals observed in the Norra Kärr rocks

Tb+Gd+Dy	0.06	0.00	0.03	0.07	0.06	0.00	0.05	0.07	0.06	0.00	0.04	0.07	0.09	0.00	0.06	0.11
Er+Yb	0.04	0.00	0.02	0.05	0.05	0.00	0.03	0.06	0.04	0.00	0.03	0.06	0.09	0.01	0.04	0.17
Y	0.64	0.01	0.27	0.81	0.63	0.01	0.51	0.72	0.66	0.01	0.51	0.83	1.07	0.03	0.85	1.32
Fe	1.19	0.02	0.88	1.59	1.41	0.02	1.13	1.59	0.85	0.02	0.54	1.38	0.93	0.03	0.67	1.20
Mn	0.94	0.01	0.67	1.11	0.78	0.01	0.68	1.04	1.43	0.04	0.90	2.02	0.91	0.03	0.65	1.17
Ca	3.77	0.04	2.98	4.49	4.27	0.03	3.84	4.60	3.48	0.05	2.50	4.55	3.72	0.03	3.40	4.03
Na	12.99	0.05	11.90	14.00	13.40	0.04	12.84	13.92	12.30	0.14	7.37	13.57	13.31	0.18	11.04	14.62
К	0.29	0.01	0.12	0.40	0.22	0.01	0.14	0.33	0.32	0.01	0.17	0.59	0.30	0.01	0.18	0.47
Cl	0.31	0.01	0.24	0.50	0.58	0.03	0.27	0.80	0.30	0.01	0.24	0.76	0.35	0.01	0.20	0.49

	(	Ca-Cata	pleiite		Catapleiite								
	sai	sample 5408, n=24 sample 5618, n=12											
	Mean	Mean CI 95% Interval Mean CI 99											
wt %		(+/-)	Min	Max		(+/-)	Min	Max					
SiO <sub>2</sub>	45.85	0.18	45.04	46.53	46.54	0.16	46.18	46.93					
TiO <sub>2</sub>	0.02	0.00	0.01	0.03	0.03	0.01	0.02	0.05					
ZrO <sub>2</sub>	29.07	0.09	28.61	29.39	29.92	0.37	27.80	29.56					
HfO <sub>2</sub>	0.59	0.07	0.47	0.91	0.69	0.06	0.54	0.83					
REEY <sub>2</sub> O <sub>3</sub>	0.41	0.03	0.30	0.56	0.46	0.05	0.31	0.58					
FeO	0.20	0.13	0.04	0.95	1.10	0.55	0.10	2.80					
CaO	5.99	0.18	5.41	6.99	0.68	0.20	0.35	1.30					
Na <sub>2</sub> O	9.55	0.16	8.75	10.14	13.83	0.23	13.30	14.33					
K <sub>2</sub> O	0.04	0.01	0.01	0.09	0.05	0.02	0.02	0.10					
Total	91.71	0.31	90.63	93.14	92.30	0.38	91.66	93.27					
H <sub>2</sub> O (calc)	7.44	0.02	7.37	7.49	7.76	0.02	7.70	7.78					
Total (incl H <sub>2</sub> O)	99.15	0.31	98.10	100.56	100.06	0.39	99.37	101.08					
Formulae based or	n 10 cations	and 11	oxygens										
Si	3.02	0.00	3.00	3.04	3.06	0.01	3.05	3.07					
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
Zr	0.93	0.00	0.92	0.94	0.93	0.01	0.89	0.95					
Hf	0.01	0.00	0.01	0.02	0.01	0.00	0.01	0.02					
REEY	0.01	0.00	0.01	0.01	0.01	0.00	0.01	0.01					
Fe	0.01	0.01	0.00	0.05	0.06	0.03	0.01	0.15					
Ca	0.42	0.01	0.38	0.50	0.05	0.01	0.02	0.09					
Na	1.22	0.02	1.11	1.29	1.76	0.03	1.70	1.82					
К	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01					
H (calc)	3.76	0.01	3.72	3.78	3.92	0.01	3.89	3.95					

 Table 5: Catapeliite compositions from the Norra Kärr complex

		Albite							
		n=3	338		n=122				
	Mean	CI	95%	Interval	Mean	CI	95%	95% Interval	
wt %		(+/-)	Min	Max		(+/-)	Min	Max	
SiO <sub>2</sub>	65.03	0.03	64.39	65.44	69.44	0.04	68.92	69.87	
$AI_2O_3$	18.99	0.01	18.76	19.18	19.54	0.02	19.32	19.72	
FeO	0.10	0.01	0.01	0.34	0.09	0.01	0.00	0.23	
BaO	0.06	0.00	0.00	0.12	0.03	0.00	0.00	0.07	
CaO	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	
Na <sub>2</sub> O	0.38	0.02	0.06	0.60	11.85	0.03	11.56	12.11	
K₂O	17.15	0.03	16.81	17.64	0.10	0.01	0.05	0.17	
TOTAL	101.70	0.04	100.81	102.26	101.06	0.06	100.36	101.70	
Formulae based on 32 oxygens									
Si	12.03	0.01	11.92	12.11	12.74	0.01	12.64	12.82	
Al	4.14	0.00	4.09	4.18	4.22	0.00	4.18	4.26	
Fe <sup>2+</sup>	0.02	0.00	0.00	0.05	0.01	0.00	0.00	0.03	
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
Na	0.14	0.01	0.02	0.21	4.22	0.01	4.11	4.31	
К	4.05	0.01	3.97	4.16	0.02	0.00	0.01	0.04	
Ва	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01	
X <sub>An</sub>	0.01	0.00	0.00	0.05	0.02	0.00	0.00	0.06	
X <sub>Ab</sub>	3.23	0.15	0.52	5.12	99.42	0.05	99.08	99.69	
X <sub>Or</sub>	96.76	0.15	94.88	99.45	0.56	0.05	0.28	0.91	

 Table 6: Average feldspar compositions in metasyenites from the Norra Kärr complex

	Nepheline N=108					Natrolite N=104			Analcime N=4			
	Mean	CI	95%	6 Interval	Mean	CI	95%	Interval	Mean	CI	95%	hterval
wt %		(+/-)	Min	Max		(+/-)	Min	Max		(+/-)	Min	Max
SiO <sub>2</sub>	42.23	0.16	41.45	43.25	47.66	0.06	47.18	48.99	50.17	7.24	46.77	52.30
$AI_2O_3$	34.27	0.13	33.41	34.92	27.39	0.09	26.69	28.11	26.30	4.60	25.12	28.35
Fe <sub>2</sub> O <sub>3</sub>	0.12	0.02	0.04	0.33	0.13	0.04	0.00	0.44	0.13	0.23	0.04	0.23
BaO	0.04	0.00	0.00	0.09	0.03	0.00	0.00	0.07	0.04	0.07	0.01	0.06
CaO	0.02	0.02	0.00	0.27	0.01	0.01	0.00	0.06	0.03	0.03	0.02	0.03
Na <sub>2</sub> O	16.08	0.10	14.92	16.52	15.24	0.04	14.92	15.60	13.50	2.64	12.25	14.17
K <sub>2</sub> O	7.59	0.10	6.87	8.03	0.06	0.01	0.01	0.15	0.53	1.49	0.05	1.10
Total	100.35	0.09	99.66	101.07	90.53	0.12	89.52	91.66	90.71	5.05	88.51	92.52
	Formulae based on 16 oxygens			Formula	Formulae based on 10 oxygens			Formulae based on 6 oxygens				
Si	0.70	0.00	0.69	0.72	3.01	0.00	2.98	3.03	1.90	0.27	1.77	1.98
Al	0.67	0.00	0.66	0.69	2.04	0.01	1.99	2.09	1.17	0.21	1.12	1.27
Fe <sup>3+</sup>	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.01	0.00	0.01
Ca	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.52	0.00	0.48	0.53	1.87	0.01	1.83	1.91	0.99	0.19	0.90	1.04
К	0.16	0.00	0.15	0.17	0.00	0.00	0.00	0.01	0.03	0.07	0.00	0.05
В	-	-	-	-	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 7: Average nepheline, natrolite and analcime compositions from Norra Kärr rocks

	Rei	Measured	
Vol %	1	2	
Срх	89	84	
Catapleiite	11	16	
SiO <sub>2</sub>	51.07	50.94	50.83
TiO <sub>2</sub>	0.51	0.49	0.50
$AI_2O_3$	1.13	1.10	0.85
FeO	25.93	25.15	25.78
MnO	0.34	0.33	0.64
ZrO <sub>2</sub>	2.11	2.96	3.21
CaO	1.20	1.17	1.63
Na₂O	12.25	12.30	11.83
K₂O	0.01	0.01	0.00
Total	94.55	94.46	95.27

Table 8: Reintegrated compositions of Zr-aegirine (based on the composition, frequency and molar volumes of catapleite and aegirine s.str.) compared with measured compositions of Zr-aegirine core from sample 5408