

Alteration of steenstrupine-(Ce) from the Ilímaussaq alkaline complex, South Greenland

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Abstract: Steenstrupine-(Ce) from two localities, Taseq and Mellemelv, both in the Ilímaussaq complex of South Greenland has been studied. At Taseq ussingite veins contain idiomorphic steenstrupine-(Ce) crystals with decomposed central parts, marginal zones of very thin rhythmically/oscillatory precipitated layers exceptionally rich in Th (up to 10.6 wt% ThO₂) and rim zones with distinctly lower Th values (min. 5.5 wt% ThO₂). The low content of Na (between 0.9 and 3.8 wt% Na₂O) in the mineral has presumably been caused by protonation exchange of Na⁺ by H⁺. Two types of late- to post magmatic alteration have attacked the crystals. Decomposition is strictly confined either to distinct zones inside the crystals or to their cores and has resulted in the formation of extremely fine-grained crystalline phases. The other alteration product cuts into steenstrupine-(Ce) crystals as irregularly shaped botryoidal bodies, composed presumably of amorphous products. Hexagonally shaped crystals of britholite-(Ce) and presumably a new mineral species labelled A4 with square outlines and the composition Na_{1.41}(Ca_{0.14}Fe_{0.39}Mn_{0.24}) $\sum_{0.77}$ (REE_{5.39}Th_{0.22}) $\sum_{5.61}$ (Si_{5.36}P_{0.64}) $\sum_{6.00}$ F_{0.55}O_{22.02}·*n*(OH)_{2*n*}, are enclosed as idiomorphic crystals in many steenstrupine-(Ce) crystals. Britholite-(Ce) also forms radiating aggregates in adjacent silicate minerals. Britholite-(Ce) is characterized by exceptionally high contents of REE (73.0 wt% REE₂O₃) and low contents of CaO (2.2 wt%).

At the Mellemelv locality, both fresh and completely decomposed steenstrupine-(Ce) occurs in a complex naujaite pegmatite. Fresh steenstrupine-(Ce) differs in composition from steenstrupine-(Ce) at the Taseq locality. It has a lower (Si+P):REE ratio = 2.19 compared to 3.29 for steenstrupine-(Ce) from Taseq. It may represent a new steenstrupine-(Ce) variety. Two secondary and chemically well-defined minerals, labelled A5, (Na_{0.02}K_{0.01}) $\sum_{0.03}$ (Ca_{0.70}Fe_{0.07}Mn_{0.03}) $\sum_{0.80}$ (REE_{4.79}Th_{0.18}) $\sum_{4.97}$ (Nb_{0.01}Ti_{0.01}Zr_{0.02}) $\sum_{0.04}$ (Si_{1.97}P_{4.00}Al_{0.03}) $\sum_{6.00}$ F_{0.39}Cl_{0.02}O_{22.22}·*n*(OH)_{2*n*}, and A6, (Na_{0.10}K_{0.03}) $\sum_{0.13}$ (Ca_{0.36}Fe_{0.65}Mn_{0.19}) $\sum_{1.20}$ (REE_{3.25}Th_{0.34}) $\sum_{3.59}$ (Ti_{0.09}Zr_{0.25}) $\sum_{0.34}$ Nb_{0.03}(Si_{4.81}P_{0.56}Al_{0.63}) $\sum_{6.00}$ F_{0.57}Cl_{0.05}O_{19.88}·*y*(OH)_{2*y*}·*n*H₂O, appear to be new mineral species. They constitute major alteration products in the decomposed steenstrupine-(Ce) crystals; A5 also occurs closely associated with the unaltered steenstrupine-(Ce) variety.

Key-words: Ilímaussaq; South Greenland; steenstrupine-(Ce); britholite-(Ce); alteration; protonation; ussingite veins; thorium; rare-earth elements; mineral A4; mineral A5; mineral A6.

1. Introduction

Steenstrupine-(Ce) is a typical mineral of hypersodic rocks belonging to the Ilímaussaq massif, South Greenland and the Lovozero and Khibiny massifs, Kola Peninsula. It was first discovered in the Ilímaussaq massif (Lorenzen, 1881), where it is an important mineral in the hyperagpaitic lujavrites, pegmatites and hydrothermal veins (Sørensen, 1962, 2006; Sørensen & Larsen, 2001; Sørensen *et al.*, 2011). A comprehensive résumé on steenstrupine-(Ce) is given by Makovicky & Karup-Møller (1981) and by Khomyakov & Sørensen (2001). It is the main radioactive mineral in the Kvanefjeld uranium deposit in the northern part of the Ilímaussaq complex. It commonly occurs as trigonal crystals up to several centimeters in size and is

mostly metamict. Microprobe analyses on the mineral in the Kvanefjeld lujavrites and in pegmatites and mineral veins from different parts of the massif were completed by Makovicky *et al.* (1980). Crystalline non-metamict steenstrupine from Tunugdliarfik (Fig. 1) has the following empirical composition: Na_{1–12}H_{7–0}CaREE₆Me₅[Si₆O₁₈]₂[(P,Si)O₄]₆(F,OH)·*n*H₂O (Me = Fe, Mn, Al, Ti, Zr, Th, U, and *n* < 15) (Makovicky & Karup-Møller, 1981). A crystal structure analysis on material from this locality was completed by Moore & Shen (1983) who proposed the following ideal end-member composition of the mineral: Na₁₄Ce₆(Mn²⁺Mn³⁺)Fe³⁺₂(Zr,Ti)⁴⁺(PO₄)₆(Si₆O₁₈)₂·(OH)₂·3H₂O. The structure can be described as a rod structure, with two types of [001] rods: rod I at (0, 0, *z*), and rod II at (1/3, 1/6, *z*). Rod I has

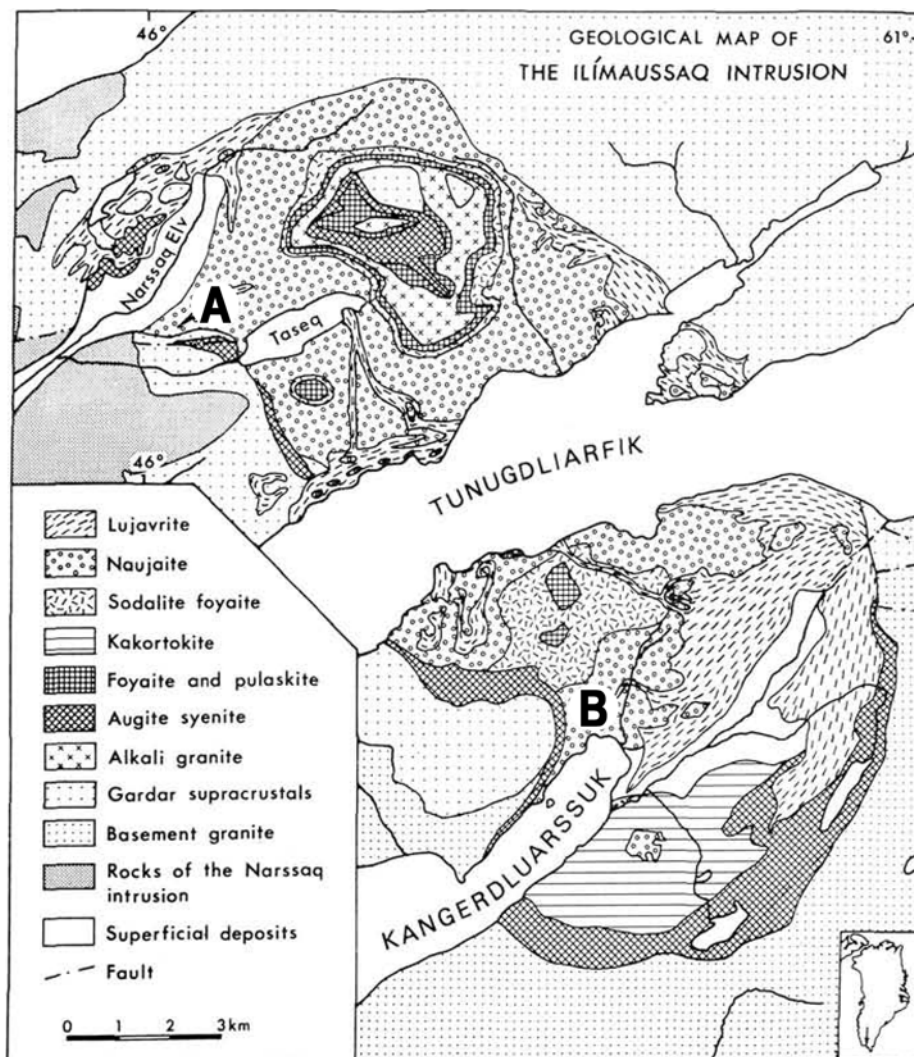


Fig. 1. Geological map of the Ilímaussaq complex based on [Ussing \(1912\)](#), [Ferguson \(1964\)](#) and [Andersen et al. \(1988\)](#). The Taseq (A) and Mellemelv (B) localities are indicated.

the sequence M(1)-Na(1)-OH-M(3)-M(2)-□(1)-T-□(1)-M(2)-(M3)-OH-Na(1) and Rod II Na(3)-P-P-Na(3)-Si(2)-Na(2)-REE-Si(1)-Si(1)-REE-Na(2)-Si(2), where M(1)=(Zr⁴⁺, Th⁴⁺, Ti⁴⁺), M(2)=(Mn²⁺, Mn³⁺), M(3)=Fe³⁺ and Ca²⁺ at both M(1) and Na(1) sites. In rod I, T is a disordered (PO₄) group and the sequence Na(1)-M(1)-Na(1) is a face-sharing octahedral trimer and M(3)-M(2) a face-sharing octahedral dimer. A (Si₆O₁₈) six-membered ring occurs. [Moore & Shen \(1983\)](#) suggest that the apical oxygens in the 6-ring can be hydroxylated, balancing the removal of Na(2) and Na(3): Na₁₂ → □₁₂ as (Si₆O₁₈)₂¹²⁻ → (Si₆O₁₂(OH)₆)₃⁶⁻. [Chukanov & Pekov \(2005\)](#) have suggested a more simple pattern characterized by SiO₄ tetrahedra forming six membered rings connected by alternating ZrO₆ and MnO₆ octahedra.

Thorostenstrupine from the Chergilen in the Khabarovsk region in Siberia was described by [Kupriyanova et al. \(1962\)](#). Later a similar mineral was found by [Pekov et al. \(1997\)](#) at the Karnasurt mine in the northern part of the Lovozero massif, Kola Peninsula. In spite of significant differences in composition between the mineral

at these two locations, [Pekov et al. \(1997\)](#) conclude that the mineral is a Th-dominant phosphorous-poor analogue of steenstrupine-(Ce) with the following composition: Na₀₋₅Ca₁₋₃(Th,REE)₆(Mn,Fe,Al,Ti)₄₋₅[Si₆O₁₈]₂[(Si,P)O₄]₆(OH,F,O)_x·nH₂O.

This composition and that of steenstrupine from Tunugdliarfik ([Makovicky & Karup-Møller, 1981](#)) are based on a total of 18 Si+P apfu (atoms per formula unit), whereas the ideal steenstrupine end-member composition by [Moore & Shen \(1983\)](#) has 19 Si+P apfu. The steenstrupine compositions used in this paper ([Table 1](#)) is based on the structure determination by [More & Shen, i.e. 19 Si+P apfu](#).

Steenstrupine-(Ce) from Ilímaussaq is commonly partly to completely altered to secondary minerals (e.g. [Sørensen, 1962](#); [Makovicky et al., 1980](#)). The secondary minerals belovite-(Ce) ([Chukanov et al., 2005](#)), seidite-(Ce) ([Khomyakov et al., 1998](#)), sazhinite-(Ce) ([Es'kova et al., 1974a](#); [Chukanov et al., 2005](#)) and laplandite-(Ce) ([Es'kova et al., 1974b](#)), associated with altered steenstrupine from the Lovozero/Khibiny massifs, have not been

Table 1. Microprobe analyses on steenstrupine-(Ce) from Taseq and Mellemelv localities. 1–5: from Taseq. 6: Secondary steenstrupine-(Ce) from Mellemelv. 7–8: Primary steenstrupine-(Ce) from Mellemelv. Atomic proportions based on Si+P=19.

Anal. no. Figure No. anal.	1 2(a1) 4	2 2(a2) 8	3 4(a1) 4	4 4(a2) 4	5 4(d) 4	6 12(d) 5	7 13(a) 8	8 Close to Fig. 13 6
SiO ₂	32.05(.74)	30.26(.45)	31.97(.20)	30.18(.23)	27.06(2.78)	27.31(3.33)	27.27(.96)	27.35(.57)
TiO ₂	0.14(.01)	0.12(.04)	0.21(.08)	0.13(.04)	0.38(.16)	0.54(.08)	0.30(.10)	0.40(.03)
ZrO ₂	0.25(.03)	0.30(.09)	0.19(.11)	0.22(.02)	0.14(.06)	2.65(.13)	1.14(.16)	1.30(.23)
ThO ₂	10.09(.27)	5.54(.39)	10.59(.62)	5.84(.66)	12.13(1.00)	7.48(.05)	3.58(1.15)	3.42(.39)
UO ₂	0.16	0.05	0.15	0.09	0.25	n.a.	n.a.	n.a.
Al ₂ O ₃	—*	—	—	—	—	0.08(.07)	1.37(.05)	1.25(.06)
P ₂ O ₅	8.72(.19)	10.85(.61)	8.11(.58)	11.01(.11)	9.77(3.45)	4.97(2.25)	5.32(.67)	5.59(.33)
Nb ₂ O ₅	0.07(.03)	0.36(.19)	0.11(.05)	0.43(.10)	0.82(.45)	0.01(.01)	0.30(.13)	0.38(.09)
Y ₂ O ₃	1.02(.05)	0.89(.06)	1.12(.08)	0.87(.07)	0.80(.09)	1.07(.10)	3.08(.21)	3.01(.14)
La ₂ O ₃	4.62(.01)	4.42(.37)	4.65(.11)	4.38(.23)	4.82(.28)	10.42(.80)	9.77(.39)	9.35(.24)
Ce ₂ O ₃	15.41(.23)	16.90(.32)	14.88(.21)	16.40(.30)	17.33(1.30)	17.89(.49)	18.15(.31)	18.07(.17)
Pr ₂ O ₃	1.87(.07)	1.76(.29)	1.52(.34)	2.07(.20)	1.90(.28)	1.32(.32)	1.48(.32)	1.54(.35)
Nd ₂ O ₃	7.01(.15)	8.36(.27)	6.76(.15)	8.42(.09)	8.48(.57)	4.98(.18)	5.18(.12)	5.28(.14)
Sm ₂ O ₃	1.29(.15)	1.40(.26)	1.53(.27)	1.38(.16)	1.57(.15)	0.62(.13)	0.78(.15)	0.95(.14)
Gd ₂ O ₃	0.42(.31)	0.35(.20)	n.a.	n.a.	n.a.	0.06(.11)	0.38(.18)	0.22(.22)
FeO	2.80(.15)	2.61(.20)	3.00(.24)	2.45(.08)	2.56(.88)	4.62(.14)	2.36(.14)	2.67(.19)
MnO	6.71(.24)	6.62(.24)	6.92(.14)	6.46(.27)	4.42(.64)	1.62(.12)	2.07(.19)	2.57(.24)
CaO	1.18(.07)	1.19(.09)	1.14(.09)	1.15(.07)	1.02(.04)	4.52(.58)	5.33(.08)	5.29(.07)
K ₂ O	—*	—	—	—	—	0.09(.02)	0.16(.01)	0.14(.02)
Na ₂ O	3.08(1.04)	3.78(.05)	1.01(.08)	0.89(.10)	1.66(.47)	—	1.50(.16)	1.92(.25)
F	0.12(.08)	0.18(.06)	—	—	0.20(.06)	0.62(.22)	1.06(.13)	1.02(.14)
Cl	0.02(00)	—	n.a.	n.a.	—	0.11(.01)	0.08(.01)	0.07(.02)
F—O	0.05	0.08	—	—	0.08	0.26	0.45	0.43
Cl—O	—	—	—	—	—	0.03	0.02	0.02
Total	96.98	95.85	93.86	92.37	95.23	90.69	90.19	91.34
Si	15.44	14.56	15.64	14.51	14.56	16.46	16.30	16.20
Ti	0.05	0.04	0.08	0.05	0.15	0.24	0.13	0.18
Zr	0.06	0.07	0.04	0.05	0.04	0.78	0.32	0.38
Th	1.11	0.61	1.18	0.64	1.48	1.02	0.49	0.46
Al	—	—	—	—	—	0.05	0.97	0.87
P	3.56	4.43	3.36	4.49	4.45	2.53	2.70	2.80
Nb	0.01	0.08	0.02	0.09	0.20	—	0.08	0.10
Y	0.26	0.23	0.29	0.22	0.23	0.34	0.98	0.95
La	0.82	0.79	0.84	0.78	0.95	2.31	2.15	2.04
Ce	2.72	2.98	2.67	2.89	3.41	3.95	3.98	3.92
Pr	0.33	0.31	0.27	0.36	0.37	0.29	0.32	0.33
Nd	1.21	1.44	1.18	1.45	1.63	1.07	1.10	1.12
Sm	0.21	0.23	0.26	0.23	0.29	0.13	0.16	0.19
Gd	0.07	0.06	—	—	—	0.01	0.07	0.04
REE tot.	5.62	6.04	5.51	5.93	6.88	8.10	8.76	8.59
Fe	1.13	1.05	1.23	0.99	1.15	2.32	1.18	1.31
Mn	2.74	2.70	2.87	2.63	2.01	0.82	1.05	1.29
Ca	0.61	0.62	0.60	0.59	0.59	2.92	3.43	3.36
K	—	—	—	—	—	0.07	0.11	0.10
Na	2.88	3.53	0.96	0.84	1.73	—	1.74	2.21
F	0.18	0.27	0.05	—	0.34	1.19	2.01	1.91
Cl	0.01	0.01	—	—	—	0.11	0.07	0.08

* below detection limit. n.a.: not analyzed.

() values in parentheses are standard deviations.

found within the Ilímaussaq complex. Polyphase pseudomorphs after steenstrupine in pegmatites with ussingite or natrolite in the Lovozero and Khibiny massifs contain solid bituminous matters (Chukanov *et al.*, 2005). Similar bituminous matters have not been found associated with altered steenstrupine within the Ilímaussaq complex. Only very small amounts of dispersed bituminous material have

been identified. It is assumed to be of post-Cretaceous age, generated by thermal maturation of a marine source and migrated into the rocks of the complex (Laier & Nytoft, 2012). Hydrogen gas in fluid inclusions has been identified in rocks from the Ilímaussaq complex (Petersilie & Sørensen, 1970; Kornerup-Madsen *et al.*, 1979). Milli-metre-size hydrocarbon accumulations have only been

observed at two locations in cavities in pegmatitic veins and labelled as an evenkite-like mineral (Kornerup-Madsen *et al.*, 1979). The stability of steenstrupine under hydrothermal conditions at a pressure of 1000 atm. and at temperatures between 700 and 1000 °C was studied by Sørensen *et al.* (1985).

Khomyakov & Sørensen (2001) studied zoned steenstrupine-(Ce) crystals in hydrothermal veins in arfvedsonite lujavrite in drill cores from the Kvanefjeld plateau. During the present study, we have examined zoned steenstrupine-(Ce) and its decomposition products from two localities within the Ilímaussaq complex, from ussingite veins on the Taseq slope in the northern part of the complex and from a naujaite pegmatite at Mellemelv in the southern part of the complex (Fig. 1).

In transmitted and reflected light microscopy, the steenstrupine-(Ce) decomposition products generally appear opaque or semi-transparent, with yellow brown to deep dark brown colours (*e.g.* Sørensen, 1962; Khomyakov & Sørensen, 2001). Optical study is therefore impossible by transmitted or reflected light. However, by electron microprobe analyses (EMPA) it is possible to distinguish between the different phases present, unless the grain size is extremely fine. We have identified three secondary minerals, here labelled A4, A5, and A6, which have not yet been described. The labels are given in analogy to Ca-rich A1, Ca-poor A1, A2 and A3, which have been assigned to new phases identified in eudialyte decomposition aggregates from the marginal pegmatite (Karup-Møller *et al.*, 2010) and from the kakortokite area (Karup-Møller & Rose-Hansen, 2013) of the Ilímaussaq complex.

2. Methods

Electron microprobe analyses were carried out at the Department of Geoscience and Natural Resource Management, University of Copenhagen, using a JEOL 733 superprobe in wavelength dispersive mode with an on-line correction program supplied by JEOL. The accelerating voltage was 15 kV and beam current 15 nA. The beam diameter was 1 µm (focused beam) or 3 µm dependent on size and type of mineral grains analyzed. Counting time was 30 s on peak positions and 15 s on background positions. Wavelengths and standards used were Na $K\alpha$ (NaAlSi₃O₈), K $K\alpha$ (KAlSi₃O₈), Ca $K\alpha$ and Si $K\alpha$ (CaSiO₃), Mn $K\alpha$ (MnTiO₃), Fe $K\alpha$ (Fe₂O₃), Ti $K\alpha$ (TiO₂), Zr $L\alpha$ (ZrO₂), Al $K\alpha$ (Al₂O₃), Ce $L\alpha$ (CeO₂), La $L\alpha$ (18 wt% La₂O₃ in synthetic glass), Nd $L\alpha$ (Nd₃Ga₅), Pr $L\beta$ (Pr₃Ga₅O₁₂), Sm $L\alpha$ (SmFeO₃), Y $L\alpha$ (Y₃Al₅O₁₂), Gd $L\alpha$ (GdFeO₃), Dy, Yb and Er $L\alpha$ (all three elements in synthetic silica glass standards), P $K\alpha$ and F $K\alpha$ (apatite-Wilberforce), Nb $L\alpha$ (columbite), Th $M\alpha$ (ThO₂), U $M\alpha$ (UO₂), Cl $K\alpha$ (sodalite). Decomposition of minerals caused by the electron beam was not observed. The Ce $L\alpha$ and Nd $L\alpha$ lines lie close to each other and therefore microprobe analyses for Ce on the Ce-standard yielded false Nd values of 0.36 wt%. The mineral in the present study with highest content of Ce is britholite, with

approximately 36 wt% Ce, while other minerals analyzed contained <30 wt% Ce, and steenstrupine and its decomposition products less than 16 wt%. We therefore conclude that the Nd value recorded on these minerals is the true content with no significant interference from Ce. Analyses on the Nd-standard did not produce false Ce values. The estimated detection limit was 0.02 wt% for all elements. In the tables, values in parentheses are standard deviations (1 σ). Molar ratios for steenstrupine were calculated on basis of Si+Al+P = 19 apfu; for unidentified phases Si+Al+P = 6; for lueshite Si+Ti+Nb+Al = 10 and for britholite = 16 apfu.

2.1. Geological setting

The Ilímaussaq complex (Fig. 1) belongs to the late Precambrian Gardar province in South Greenland (*e.g.* Upton *et al.*, 2003; Upton, 2013). The complex is characterized by agpaitic nepheline syenites and represents the most silica-undersaturated and differentiated rocks of the region. Three major intrusive stages have been established: a partial rim (the border pegmatite) of augite syenite separates the complex from the country rocks (stage 1), followed by the formation of alkali granite and alkali syenite in the top of the complex (stage 2). The main intrusive stage (stage 3) consists of a roof series, an intermediate series and a floor series. The roof series consists from the roof downwards of pulaskite, foyaite, sodalite foyaite and naujaite, of which the two last-named rocks are of agpaitic composition, *i.e.* peralkaline nepheline syenites characterized by the presence of complex silicates such as eudialyte instead of zircon (*e.g.* Ussing, 1912; Sørensen, 1960). The exposed part of the floor series consists of layered agpaitic nepheline syenites, the kakortokites. The intermediate series are lujavrites which lie between the roof series and the floor series (*e.g.* Ussing, 1912; Ferguson, 1964; Rose-Hansen & Sørensen, 2002). The present paper describes the occurrence of steenstrupine-(Ce) from two localities within the naujaite, A and B in Fig. 1.

2.2. Ussingite veins, Taseq

The ussingite veins on the Taseq slope in the northern part of the complex occur in naujaite intruded by lujavrites and are believed to have formed from fluids expelled from the locally injected lujavrite magma (Engell, 1968; Engell *et al.*, 1971). The veins are symmetrical, with an outer contact zone of felted aegirine (up to 5 cm thick) followed by an analcime zone up to 30 cm thick composed of analcime, sodalite, chkalovite and epistolite. The ussingite zone forms the central part of the veins and may reach a thickness of almost 2 m. It consists of ussingite, analcime, microcline, albite, sodalite, natrolite, arfvedsonite, aegirine, beryllite, cuprostibite, chalcophyllite, chkalovite, epistolite, gerasimovskite, pyrochlore, niobophyllite, astrophyllite, steenstrupine-(Ce), galena, chalcocite and sphalerite. Steenstrupine-(Ce) was identified in three

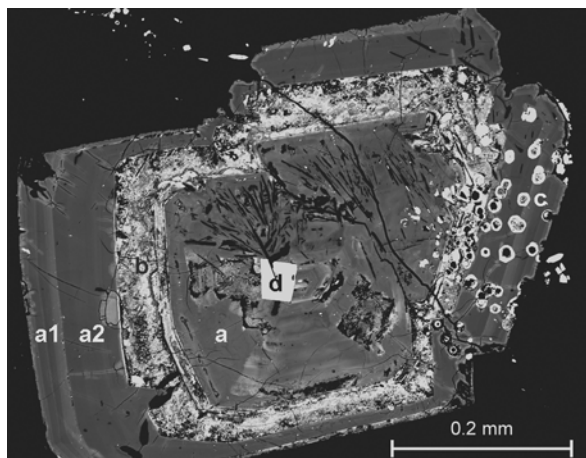


Fig. 2. Backscattered-electron (BSE) image of steenstrupine-(Ce) crystal with zoned margins (a1, a2) and decomposed zone (b), which precisely follows one or several layers of the crystal. A cubic A4 crystal (d) lies in the central part and numerous hexagonal britholite-(Ce) crystals (c) lie in the marginal areas of the host steenstrupine-(Ce) crystal. The central part (a) of the steenstrupine-(Ce) crystal contains numerous small crystals of an unidentified silicate mineral, possibly aegirine; Taseq locality. All following images are also BSE images.

samples associated with the astrophyllite–niobophyllite group of minerals (GGU 157103, GGU 159103 and GGU 65410) described by MacDonald *et al.* (2007).

2.3. Complex naujaite pegmatite, Mellemelv

A simple 10–30 cm thick, conformable naujaite pegmatite, traceable over a distance of at least 125 m, has locally been intruded by late lujavritic material. This has resulted in the development of an at least 25 m long and 1–3 m thick complex pegmatite body superimposed upon and replacing the original conformable naujaite pegmatite. It is characterized by irregular zones dominated by variable proportions of coarse arfvedsonite, eudialyte and sodalite. Within these zones are found fine-grained veins of lujavritic material which in some places contains fine- to coarse-grained albitic bodies and in other places concentrations of both unaltered and mainly totally decomposed steenstrupine-(Ce). Two samples with both unaltered and strongly decomposed steenstrupine-(Ce) (samples GGU 230737 and GGU 230738) are part of the present study.

2.4. Mineral descriptions

2.4.1. Steenstrupine-(Ce) and associated minerals, Taseq

The steenstrupine-(Ce) crystals in the ussingite veins rarely exceed 0.5 mm in size and are perfectly idiomorphic and lie randomly enclosed in the rock-forming silicates. All steenstrupine-(Ce) crystals are distinctly zoned and closely resemble the “altered zoned (Ac) steenstrupine-(Ce) variety” described by Makovicky *et al.* (1980; see their Figs. 16 and 17). In BSE images, decomposed cores

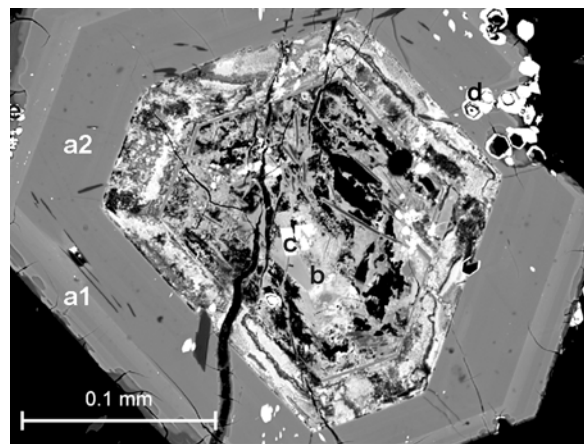
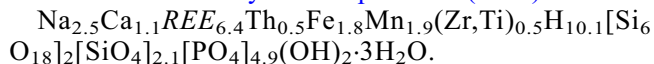


Fig. 3. Steenstrupine-(Ce) crystal with zoned margins (a1, a2). The central part (b) with an A4 crystal (c) has been completely decomposed. Small britholite crystals (d) at upper right in the image; Taseq locality.

are surrounded by light grey oscillatory zoned mantles succeeded by darker grey and likewise oscillatory zoned rims (Figs. 2–6). The boundaries between individual cores, mantles and rims and the oscillatory outlines are always sharp and strictly parallel to the crystal boundaries. The greatest differences in chemical composition between light grey and dark grey zones were recorded on the crystals shown in Figs. 2 and 4 (analyses no. 1–4 in Table 1). The relevant empirical formulae, based on 19 (Si+P), 2(OH,F, Cl)+3H₂O and H included for charge balance, are:

1. $\text{Na}_{2.9}\text{Ca}_{0.6}\text{REE}_{5.6}\text{Th}_{1.1}\text{Fe}_{1.1}\text{Mn}_{2.7}(\text{Ti}, \text{Zr})_{0.1}\text{H}_{13.3}[\text{Si}_6\text{O}_{18}]_2[\text{SiO}_4]_{3.4}[\text{PO}_4]_{3.6}(\text{OH})_{1.8}\text{F}_{0.2}\cdot 3\text{H}_2\text{O}$
2. $\text{Na}_{3.5}\text{Ca}_{0.6}\text{REE}_{6.0}\text{Th}_{0.6}\text{Fe}_{1.1}\text{Mn}_{2.7}(\text{Ti}, \text{Zr})_{0.1}\text{H}_{12.7}[\text{Si}_6\text{O}_{18}]_2[\text{SiO}_4]_{2.6}[\text{PO}_4]_{4.4}(\text{OH})_{1.7}\text{F}_{0.3}\cdot 3\text{H}_2\text{O}$
3. $\text{Na}_{1.0}\text{Ca}_{0.6}\text{REE}_{5.5}\text{Th}_{1.2}\text{Fe}_{1.2}\text{Mn}_{2.9}(\text{Zr}, \text{Ti})_{0.1}\text{H}_{14.4}[\text{Si}_6\text{O}_{18}]_2[\text{SiO}_4]_{3.6}[\text{PO}_4]_{3.4}(\text{OH})_{1.8}\text{F}_{0.1}\cdot 3\text{H}_2\text{O}$
4. $\text{Na}_{0.8}\text{Ca}_{0.6}\text{REE}_{5.9}\text{Th}_{0.6}\text{Fe}_{1.0}\text{Mn}_{2.6}(\text{Zr}, \text{Ti})_{0.1}\text{H}_{16.2}[\text{Si}_6\text{O}_{18}]_2[\text{SiO}_4]_{2.5}[\text{PO}_4]_{4.5}(\text{OH})_{2.0}\cdot 3\text{H}_2\text{O}$

The corresponding formula for steenstrupine-(Ce) from Tunugdliarfik based on the average composition listed in Table 8 in Makovicky & Karup-Møller (1981) is:



The major difference in chemistry between light grey and dark marginal zones in the steenstrupine-(Ce) crystals is their Th content and to some extent also their content of Si, P and REE. The maximum difference in the content of ThO₂ was recorded in the crystal shown in Fig. 4, which has 10.59 wt% ThO₂ in the light grey layer and 5.84 wt% ThO₂ in the dark layer (Table 1, nos. 4–5). In the same crystal the SiO₂ content was 31.97 and 30.18 wt%, the P₂O₅ content 8.11 and 11.01 wt% and the REE content 30.46 and 33.52 wt%, respectively. Thus, increase in Th and Si is accompanied by decrease in P and REE which implies that the coupled substitution (ThSi)(REEP)_{–1} is significant. The UO₂ content was less than 0.2 wt%.

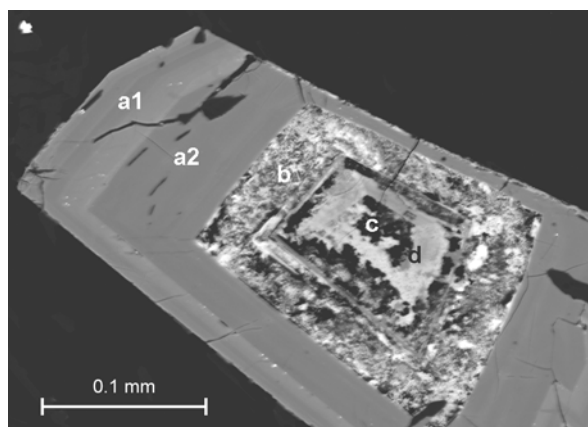


Fig. 4. Steenstrupine-(Ce) crystal with zoned margin (a1, a2) with a completely decomposed central part (b), consisting of two subzones, b and c+d. Subzone b is heterogeneous (Table 4, no. 2). The central zone is dominated by a grey phase (d) with a composition close to steenstrupine-(Ce) (Table 1, no 5), and a black phase (c, Table 4, no. 3); Taseq locality.

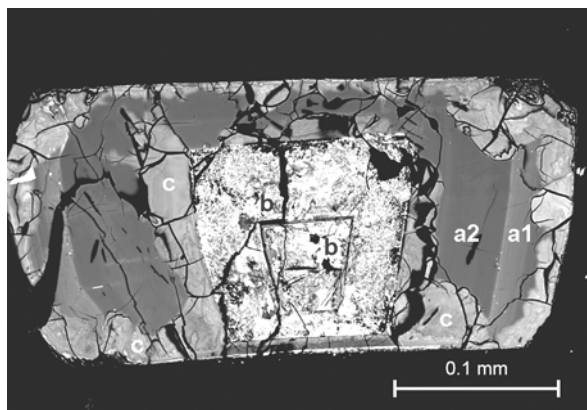


Fig. 5. Zoned steenstrupine-(Ce) crystal (a1, a2) exposed to two types of alteration. The central part (b) of the crystal is decomposed into small crystals (compare Figs. 2 and 4) and late alteration (c) produced marginal botryoidal areas; Taseq locality.

The Fe, Mn and Ca contents do not vary significantly in the analyzed samples, and no differences have been found between light grey and dark layers of individual crystals. The Na content is the same in light grey and dark layers within the same crystal, but may vary from crystal to crystal. Maximum differences recorded are from 3.78 wt% Na₂O in the dark layer of the crystal shown in Fig. 2 to 0.89 wt% in the dark layer of the crystal in Fig. 4.

The exceptionally low contents of Na, between 3.53 and 0.84 apfu, compared to the ideal content of 14 atoms, is explained by extensive protonation. This was first recognized by Makovicky & Karup-Møller (1981) for steenstrupine-(Ce) from sodalite–natrolite–aegirine veins on the north shore of Tunulliafik (Fig. 1). Similarly low Na contents were identified in steenstrupine-(Ce) from other mineral veins and pegmatites, but rarely in steenstrupine-(Ce) disseminated in lujavrites (Makovicky *et al.*, 1980). The Na content of steenstrupine-(Ce) from this locality ranged from 0.60 to 6.15 apfu. It was concluded that in

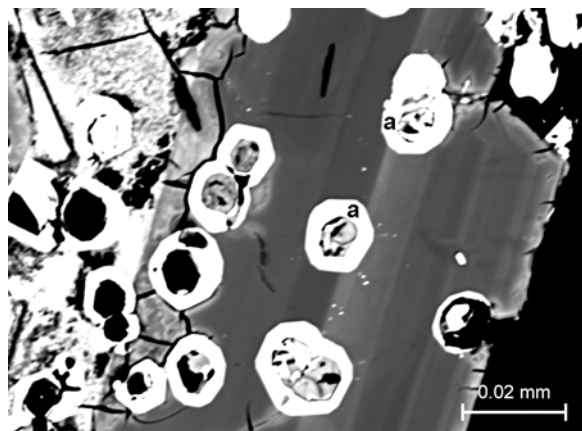


Fig. 6. Britholite-(Ce) crystals with hexagonal outlines (a) and cavities in their central part. Enlarged right part of the steenstrupine-(Ce) crystal in Fig. 2; Taseq locality.

such Na-rich environments, steenstrupine-(Ce) was unlikely to have crystallized with the low Na contents, which were more likely to be secondary, produced by leaching of Na and protonation. The ability to withstand such high degree of protonation without disrupting the crystal structure is remarkable.

Small but distinct differences in chemistry exist between steenstrupine-(Ce) at Taseq and at Tunugdliarfik (see formulae above). The content of Na varies due to different degrees of leaching of the minerals. The Ca content is lower in steenstrupine-(Ce) from Taseq (0.6 vs. 1.1 apfu), the Fe content is lower (1.1 vs. 1.8 apfu), the Mn content higher (2.7 vs. 1.9 apfu), the Zr–Ti content is lower (0.1 vs. 0.5 apfu), the REE content lower (5.8 vs. 6.4), the P content lower (4.0 vs. 4.9 apfu) and the Si content higher (15.0 vs. 14.1 apfu). The content of Th in steenstrupine from Tunugdliarfik is slightly lower than in the Th-poor layers of the Taseq steenstrupine (0.5 vs. 0.6 apfu). In the Th-rich layers it is more than twice as high (1.2 apfu).

The ideal end-member formula by Moore & Shen (1983) has 1 Zr at the M(1) site and 6 REE. Formulae 2 and 4 above have 6.0 and 5.9 apfu REE respectively. Substitution of REE by Th thus appears not to have taken place in formula 2 whereas, in formula 4, 0.1 apfu Th may have substituted for REE. All Th present (except for the 0.1 apfu in formula 4) must therefore be placed at the M(1) site. Formula 2 thus has 0.7 apfu Th, Zr and Ti in this site, and formula 4 0.6 apfu. The remaining 0.3 and 0.4 apfu respectively are considered to have been taken up by Ca and the remaining Ca would then occur at the Na(1) site. In formula 1 and 3, 0.4 and 0.5 apfu REE appears to have been replaced by Th. The remaining 0.5 and 0.7 Th would then occupy the M(1) site in the two formulae, leaving room for 0.2 apfu Ca in both of these sites.

Thus, in the present study steenstrupines with more than 0.5 Zr apfu corresponding to a content of ~1.9 wt% ZrO₂ have not been identified. By far the majority of the numerous steenstrupine-(Ce) analyses completed by Makovicky *et al.* (1980) and Makovicky & Karup-Møller (1981) have ZrO₂ concentrations ranging between 0.2 and

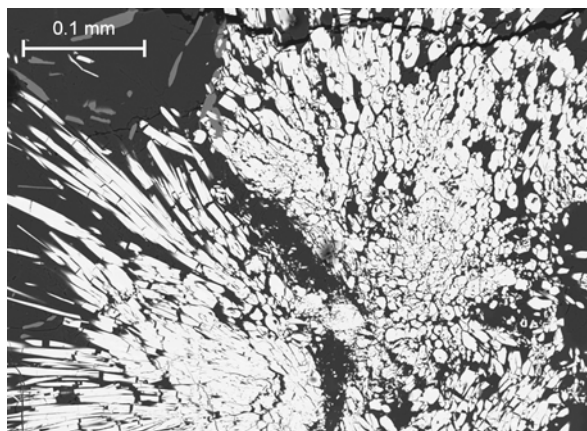


Fig. 7. Radiating aggregate of britholite-(Ce) in silicates adjacent to steenstrupine-(Ce) crystals; Taseq locality.

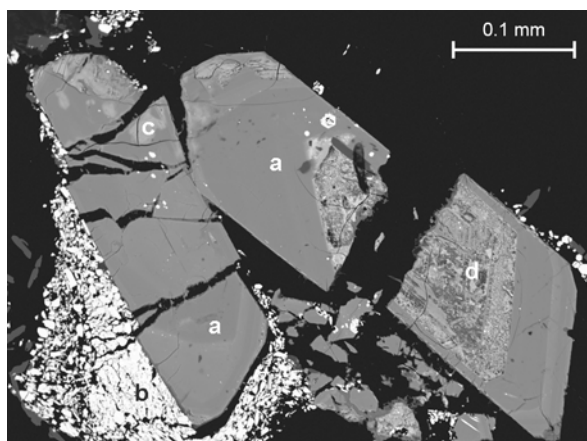


Fig. 8. Steenstrupine-(Ce) crystal (a) partly enclosed in an aggregate of britholite-(Ce) (b). Both steenstrupine-(Ce) crystals and the britholite-(Ce) aggregate are broken and the veins are filled with silicate minerals. A similar decomposition process as in Fig. 5 has taken place: slight botryoidal alteration (c) and complete decomposition (d) of the central part of the crystal to the right; Taseq locality.

2.0 wt%. Natural steenstrupines with 1 Zr apfu would have ~4.0 wt% ZrO_2 . Steenstrupines with the ideal end-member formula of Moore & Shen (1983), with 14 Na and 1 Zr, may not exist in nature.

Nearly all crystals from Taseq are characterized either by the total decomposition of specific zones (Fig. 2) or their entire central areas (Figs. 3–6 and 8). Rarely, late botryoidal replacement has taken place (Fig. 5). Small idiomorphic britholite-(Ce) crystals with hexagonal habits occur in many steenstrupine-(Ce) crystals (Figs. 2–3 and 6). Many of these have a central core, filled either with epoxy (black, Fig. 6) or with unidentified phases (mottled grey). Britholite-(Ce) also forms radiating aggregates in the silicates adjacent to the steenstrupine-(Ce) crystals (Fig. 7). In some places, steenstrupine-(Ce) crystals are partly enclosed in such aggregates (Fig. 8). Late fractures cut across partly altered steenstrupine-(Ce) and britholite-(Ce) aggregates (Fig. 8). Some steenstrupine-(Ce) crystals contain one relatively large crystal (up to 35 μm in size) in

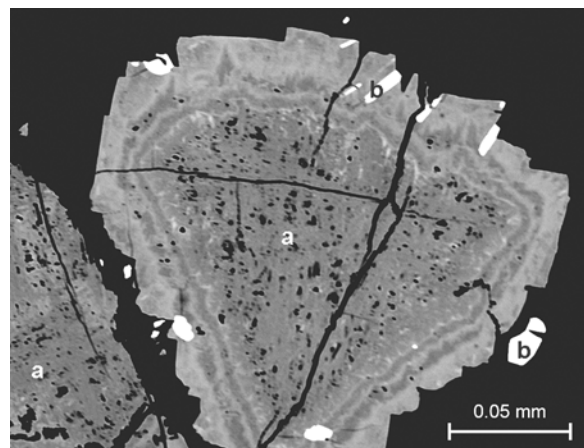


Fig. 9. Two distinctly zoned NaNbO_3 (lueshite or natroniobite) crystals (a) with crystals of britholite-(Ce) (b); Taseq locality.

the central part (Figs. 2 and 3). This crystal is believed to represent a new mineral species. It has been labelled A4 and is described below.

2.4.2. Alteration zones in steenstrupine-(Ce)

The alteration zones consist of an extremely fine-grained intergrowth of unidentified minerals. In general, their small grain size prevents microprobe analyses on individual grains to be carried out. A relatively large number of analyses were therefore completed on different areas of alteration products in order to obtain their bulk chemical composition (Figs. 2b–4b and 5b; Table 2, nos. 1, 2, 4). Seven analyses were completed on the “white” appearing decomposition products at b in Fig. 5. The average of six of these analyses is listed in Table 2 (no. 4). One analysis gave a totally different composition: ThSi_3O_8 (Table 2, no. 5). The most significant chemical difference between the decomposition products and primary steenstrupine-(Ce) is a significantly higher Th-content in these than in steenstrupine-(Ce) and highly variable contents of Si and P. The central area (Fig. 4) is composed of two phases, a black phase (c, Table 2, no. 3) and unreplaced steenstrupine-(Ce) relics (d, Table 1, no. 5) with the composition: $\text{Na}_{1.7}\text{Ca}_{0.6}\text{REE}_{6.9}\text{Th}_{1.5}\text{Fe}_{1.2}\text{Mn}_{2.0}(\text{Zr}, \text{Ti})_{0.2}\text{H}_{9.6}[\text{Si}_6\text{O}_{18}]_2[\text{SiO}_4]_{2.6}[\text{PO}_4]_{4.4}(\text{OH})_{1.7}\text{F}_{0.3}\cdot 3\text{H}_2\text{O}$

Steenstrupine-(Ce) here has higher contents of Th and lower contents of Si and Mn. The black phase has lower contents of REE, P and Th but higher contents of Si, Na, Fe and in particular Mn than steenstrupine-(Ce).

2.4.3. Botryoidal replacement of steenstrupine-(Ce)

In addition to the decomposition phases described above, some steenstrupine-(Ce) crystals have been partly replaced by botryoidal products (Figs. 5 and 8). They are extremely fine grained and are probably amorphous. Microprobe analyses on two areas selected at random within the steenstrupine-(Ce) crystal (Fig. 5; Table 2, nos. 6 and 7) show significantly smaller amounts of Si and no Na but larger amounts of P, REE (in particular Ce) than steenstrupine-(Ce). The Th content is similar to or lower than that of the original steenstrupine-(Ce) host.

Table 2. Microprobe analyses on steenstrupine alteration products, Taseq locality.

Anal. no. Phase No. anal.	1 Fig. 2(b) 8	2 Fig. 4(b) 9	3 Fig. 4(c) 4	4 Fig. 5(b) 6	5 Fig. 5(b) 1	6 Fig. 5(c) 3	7 Fig. 5(c) 3
SiO ₂	25.68(2.87)	34.76(3.44)	49.23(1.52)	19.79(3.99)	38.85	19.77(1.17)	14.40(1.76)
TiO ₂	0.49(0.12)	0.58(0.25)	0.31(0.09)	0.41(0.12)	0.10	0.24(0.05)	0.16(0.10)
ZrO ₂	0.93(0.56)	0.28(0.15)	0.04(0.03)	0.21(0.09)	0.07	0.72(0.12)	0.36(0.20)
ThO ₂	16.44(2.51)	16.79(1.86)	3.23(0.99)	17.17(4.52)	58.94	6.74(0.46)	5.49(1.31)
UO ₂	0.51	0.54	0.08	0.25	n.a.	0.12	0.14
Al ₂ O ₃	0.76(0.68)	—	—	—	—	0.01(0.01)	0.04(0.03)
P ₂ O ₅	4.67(1.76)	2.80(0.89)	0.97(0.58)	8.01(4.81)	0.90	12.60(0.31)	14.07(1.83)
Nb ₂ O ₃	0.82(0.38)	0.93(0.64)	0.56(0.42)	0.58(0.15)	—	0.10(0.07)	0.49(0.10)
Y ₂ O ₃	0.63(0.19)	0.86(0.19)	0.86(0.25)	1.12(0.10)	0.04	1.12(0.10)	1.36(0.04)
La ₂ O ₃	2.88(0.45)	2.61(0.59)	1.00(0.23)	4.41(2.66)	0.56	5.67(0.20)	6.53(0.70)
Ce ₂ O ₃	13.34(1.39)	12.14(2.47)	4.17(1.62)	14.24(1.54)	1.41	20.83(73)	21.24(0.69)
Pr ₂ O ₃	1.83(0.31)	1.52(0.39)	0.61(0.45)	1.89(0.63)	0.33	2.34(0.11)	2.31(0.45)
Nd ₂ O ₃	9.02(0.97)	7.47(1.40)	2.86(1.35)	10.72(2.57)	0.93	9.99(0.07)	10.73(0.88)
Sm ₂ O ₃	1.50(0.27)	1.42(0.29)	1.18(0.50)	1.86(0.46)	0.24	1.47(0.12)	1.77(0.24)
Gd ₂ O ₃	0.15(0.17)	—	—	—	—	—	—
FeO	3.57(1.90)	3.02(1.06)	6.32(5.07)	2.83(0.89)	0.22	3.81(0.26)	3.24(0.39)
MnO	4.50(4.61)	6.46(1.86)	14.69(2.58)	7.50(4.83)	0.61	2.54(0.32)	6.09(0.42)
CaO	0.90(0.14)	—	2.30(0.42)	1.35(0.56)	0.23	0.50(0.03)	0.73(0.11)
Na ₂ O	2.67(0.79)	2.31(0.47)	6.03(1.44)	0.85(0.62)	—	—	—
K ₂ O	0.26(0.27)	—	—	—	—	—	—
F	0.13(0.06)	0.10(0.08)	0.03(0.04)	0.04(0.04)	0.11	—	—
F–O	0.05	0.04	0.01	0.02	0.04	—	—
Total	91.63	94.55	94.46	93.21	103.50	89.49	89.15
Si	5.05	5.61	5.89	4.00	3.00	3.89	3.28
Ti	0.07	0.07	0.03	0.03	—	0.04	0.03
Zr	0.09	0.02	—	0.05	—	0.07	0.04
Th	0.74	0.62	0.09	0.35	1.04	0.34	0.28
U	0.02	0.02	—	0.01	—	0.01	0.01
P	0.08	0.38	0.10	3.31	0.06	2.10	2.71
Nb	0.07	0.07	0.03	0.07	—	0.01	0.05
Y	0.07	0.07	0.05	2.16	—	0.12	0.16
La	0.21	0.16	0.04	0.20	0.02	0.41	0.55
Ce	0.96	0.72	0.18	0.67	0.04	1.50	1.77
Pr	0.13	0.09	0.03	1.07	0.01	0.17	0.19
Nd	0.63	0.43	0.12	0.23	0.03	0.70	0.87
Sm	0.10	0.08	0.05	0.17	0.01	0.10	0.14
Gd	0.01	—	—	—	—	—	—
REE total	2.11	1.55	0.47	4.50	0.11	3.00	3.68
Fe	0.59	0.41	0.63	0.75	0.02	0.63	0.62
Mn	0.75	0.88	1.49	1.43	0.05	0.42	1.18
Ca	0.19	0.27	0.30	0.22	0.03	0.10	0.18
K	0.06	—	—	—	—	—	—
Na	1.02	0.72	1.40	0.33	—	—	—
F	0.08	0.05	0.01	—	0.03	—	—

2.4.4. Britholite-(Ce)

Many steenstrupine-(Ce) crystals contain randomly distributed britholite-(Ce) crystals with hexagonal habits (Figs. 2–3 and 6). Britholite-(Ce) also forms radiating aggregates in adjacent silicates, and sometimes they partly enclose steenstrupine-(Ce) crystals (Figs. 7 and 8). Microprobe analyses on britholite-(Ce) in steenstrupine-(Ce) (Table 3, no. 1), and in radiating aggregates adjacent to steenstrupine-(Ce) (Fig. 7; Table 3, no. 2) gave nearly identical results.

Britholite-(Ce) is known from numerous localities. Generally the REE₂O₃ content is close to 60 wt% and the CaO content between 12 and 16 wt%. Kalsbeek *et al.*

(1990) determined the structure of britholite-(Ce) and “lessingite-(Ce)” from the type localities. A third mineral, mineral-X, from a sodalite–natrolite–aegirine mineral vein in the Ilímaussaq massif, which shows structural and chemical similarities to both britholite-(Ce) and “lessingite-(Ce)”, has a composition very similar to that of britholite-(Ce) associated with steenstrupine from the Taseq locality. Both are characterized by an exceptionally low content of CaO (4.68 and 2.21 wt% respectively) and high content of REE (68.53 and 72.97 wt% respectively). This is explained by the coupled substitution $\text{Ca}^{2+} + \text{P}^{5+} = \text{REE}^{3+} + \text{Si}^{4+}$ (Kalsbeek *et al.*, 1990; Arden & Halden,

Table 3. Microprobe analyses of britholite, mineral A4 and lueshite, Taseq locality. 1: Britholite crystals in steenstrupine-(Ce) (Fig. 2). 2: Britholite in aggregates (Fig. 4). 3 and 4: Marginal zone and central area respectively of the mineral A4 crystal at d in Fig. 2. 5: Mineral A4 crystal at c in Fig. 5. 5 and 6: Core and rim respectively of the lueshite (or natroniobite) crystal shown in Fig. 6. Atomic proportions based on: 16 cations for britholite; Si+Al+P=6 for A4; Si+Ti+Nb+Al=10 for lueshite.

Anal. no. Phase Figure No. anal.	1 Britholite 2(c) 8	2 Britholite 3(e) 10	3 A4 2(d) 2	4 A4 2(d) 2	5 A4 3(c) 3	6 Lueshite 2	7 Lueshite 2
SiO ₂	21.12(.25)	20.86(.22)	22.63(.15)	22.19(.23)	22.56(.40)	3.39(.09)	1.20(.09)
TiO ₂	—	—	—	0.02(0)	0.07(.04)	0.82(.01)	1.14(.11)
ZrO ₂	0.01(.01)	—	—	—	0.08(.07)	—	—
ThO ₂	1.58(.45)	1.41(.25)	8.32(.61)	3.31(.77)	4.64(.34)	0.14(00)	0.16(.06)
Al ₂ O ₃	0.02(.02)	—	—	—	0.03(.01)	0.24(.05)	0.01(.01)
P ₂ O ₅	1.08(.37)	1.11(.21)	2.06(.25)	2.84(.29)	3.42(.34)	—	0.05(.01)
Nb ₂ O ₅	0.04(.05)	0.01(.03)	—	0.03(.04)	0.15(.02)	74.81(.59)	77.88(.56)
Y ₂ O ₃	0.02(.03)	—	—	—	—	0.08(.04)	0.09(.05)
La ₂ O ₃	16.50(.70)	16.86(1.03)	8.34(.20)	13.42(1.18)	12.41(.68)	0.16(.01)	0.04(.02)
Ce ₂ O ₃	41.03(.86)	40.92(1.04)	33.61(.56)	35.58(1.31)	34.46(.52)	0.50(.06)	0.44(.01)
Pr ₂ O ₃	3.24(.34)	3.43(.24)	3.67(.08)	2.85(.25)	2.94(.24)	—	0.08(.01)
Nd ₂ O ₃	10.87(.50)	10.77(.89)	12.69(.16)	9.39(.11)	10.38(.18)	0.05(.08)	0.09(.02)
Sm ₂ O ₃	1.05(.17)	1.00(.24)	1.04(.01)	0.63(.10)	1.03(.17)	0.08(.11)	0.17(.23)
Gd ₂ O ₃	0.11(.12)	0.12(.16)	0.20(.29)	0.17(.23)	0.11(.11)	0.03(.04)	0.02(.02)
FeO	—	—	1.88(.02)	1.97(.03)	1.92(.16)	0.56(.06)	0.47(.12)
MnO	—	—	1.00(.11)	1.07(.30)	1.30(.13)	0.05(.01)	0.07(.03)
CaO	2.22(.13)	2.17(.11)	0.43(.01)	0.47(.01)	0.58(.07)	0.03(.04)	0.04(.01)
K ₂ O	0.01(.01)	—	—	—	0.01(.01)	0.21(.01)	0.05(.01)
Na ₂ O	2.16(.10)	2.27(.09)	2.63(.15)	2.89(.24)	3.18(.33)	19.76(.01)	20.28(.38)
F	0.82(.07)	0.79(.08)	0.61(.06)	0.74(.06)	0.72(.05)	0.05(.04)	0.03(.02)
Cl	0.03(.02)	0.03(.01)	0.02(.01)	0.02(.02)	0.03(.01)	—	—
F—O	0.35	0.34	0.26	0.31	0.30	0.02	0.01
Cl—O	0.01	0.01	—	—	0.01	—	—
Total	101.55	101.40	98.87	97.28	99.19	100.71	102.30
Si	6.07	6.01	5.57	5.41	5.31	0.88	0.32
Ti	—	—	—	—	0.01	0.16	0.23
Zr	—	—	—	—	0.01	—	—
Th	0.11	0.09	0.47	0.18	0.25	0.01	—
Al	—	—	—	—	—	0.07	0.01
P	0.26	0.27	0.43	0.59	0.68	—	—
Nb	—	—	—	—	0.02	8.89	9.44
Y	—	—	—	—	—	0.01	0.02
La	1.76	1.79	0.76	1.21	1.08	0.02	0.01
Ce	4.32	4.32	3.03	3.18	2.97	0.05	0.04
Pr	0.34	0.36	0.33	0.25	0.25	—	0.01
Nd	1.12	1.11	1.12	0.82	0.87	0.01	0.01
Sm	0.11	0.10	0.09	0.05	0.08	0.01	0.02
Gd	0.01	0.01	0.02	0.01	0.01	0.01	—
REE total	7.66	7.69	5.35	5.52	5.26	0.11	0.11
Fe	—	—	0.39	0.40	0.38	0.12	0.10
Mn	—	—	0.21	0.22	0.26	0.01	0.02
Ca	0.69	0.67	0.11	0.12	0.15	0.01	0.01
K	—	—	—	—	—	0.07	0.02
Na	1.21	1.27	1.25	1.37	1.45	10.04	10.52
F	0.74	0.72	0.48	0.57	0.53	0.04	0.02
Cl	0.01	0.01	0.01	0.01	0.01	—	—

1999). Similar high *REE* oxide contents (73.6 wt%) were also recorded on britholite-(Ce) from the Morro Redondo complex in Southern Brazil by Vilalva *et al.* (2013).

Britholite-(Ce) associated with steenstrupine-(Ce) from Taseq contains small amounts of Th. Th-bearing members of the britholite-(Ce)-apatite series have been described by several authors, *e.g.* Hughson & Sen Gupta (1964), Özgenç & Kibici (1994), Arden & Halden (1999).

2.4.5. Mineral A4

Many steenstrupine-(Ce) crystals enclose relatively large bright white crystals with an equant, approximately cuboidal habit of an unidentified, possibly new mineral species which has been labelled A4 (Figs. 2 and 3; Table 3, nos. 3–5). The A4 crystal of Fig. 2 is characterized by a narrow, 5 µm thick marginal zone (not visible in Fig. 2) considerably enriched in Th (8.32 wt% ThO₂, Table 3, no. 3) compared to the central and major part of the crystal (3.31 wt% ThO₂, Table 3, no. 4). This enrichment in Th is compensated for by lower contents of *REE*. The analytical total for A4 is close to 100 wt%, which shows that the mineral most probably is an anhydrous silicate, although in addition to F, it may contain small amounts of (OH). The following empirical formula for A4 based on the analyses nos. 4 and 5 in Table 3 with Si+P=6 is: Na_{1.41}(Ca_{0.14}Fe_{0.39}Mn_{0.24})_{Σ0.77}(REE_{5.39}Th_{0.22})_{Σ5.61}(Si_{5.36}P_{0.64})_{Σ6.00}F_{0.55}O_{22.02–n}(OH)_{2n}, ignoring the small contents of Ti, Zr, Nb and Cl present.

Mineral A4 has a composition close to that of Th-bearing britholite-(Ce) (Table 3). However, the equant habit of the mineral compared to the hexagonal habit of the britholite-(Ce) crystals (Figs. 2 and 3) appears to exclude that A4 is a britholite-(Ce) variety. This assumption is also supported by its exceptionally low CaO contents and the contents of Fe and Mn.

2.4.6. Lueshite or other NaNbO₃ polymorph

Lueshite from the Ilímaussaq massif was first found by Danø & Sørensen (1959) and provisionally described as “igdlite” but later reclassified as lueshite. Lueshite (*Pbnm*, orthorhombic with perovskite structure) was originally described by Safiannikoff (1959). At present there are four known polymorphs of NaNbO₃: in addition to lueshite there are natroniobite (monoclinic but not fully characterized and hence questionable; Bulakh *et al.*, 1960), isolueshite (*Pm-3m* cubic perovskite structure; Chakhmouradian *et al.*, 1997) and pauloabibite (R3, ilmenite structure; Menezes *et al.*, 2015).

Two crystals with composition near NaNbO₃ were identified during the present study in sample GGU 65410 (Fig. 9). They are isolated in silicate minerals and contain inclusions of britholite-(Ce). The marginal area of the crystal in Fig. 9 is distinctly zoned. Microprobe analyses were carried out on the central part of the crystal (Table 3, no. 6) and on the brightest bands in the marginal area of the crystals (Table 3, no. 7). The central area has higher contents of SiO₂ (3.39 wt%) and Al₂O₃ (0.24 wt%) and lower contents of Nb₂O₅ (74.81 wt%) than the marginal part of the crystal with 1.20 wt% SiO₂, 0.01 wt% Al₂O₃ and

77.88 wt% Nb₂O₅. Assuming that Na, K, Ca and Si occupy the A positions in the structure of the mineral and Nb, Ti, Si and Al the B-positions, the empirical formula for the central part of the crystal based on Nb+Ti+Si+Al = 10 is (Na_{10.04}K_{0.07}Ca_{0.01}Mn_{0.01}Fe_{0.12}REE_{0.11}Th_{0.01})_{Σ10.25}(Nb_{8.89}Ti_{0.16}Si_{0.88}Al_{0.07})_{Σ10.00}F_{0.04}O_{29.67}. The empirical formula for the marginal part of the crystal may be written as: (Na_{10.52}K_{0.02}Ca_{0.01}Mn_{0.02}Fe_{0.10}REE_{0.11})_{Σ10.78}(Nb_{9.44}Ti_{0.23}Si_{0.32}Al_{0.01})_{Σ10.00}F_{0.02}O_{30.25}.

2.5. Steenstrupine-(Ce) pseudomorphs, Mellemelv

At this locality, semi-massive aggregates of a mixture of two steenstrupine-(Ce) varieties have crystallized in a matrix of K-feldspar and aegirine. Steenstrupine-(Ce) crystals, 0.5–1.5 mm large, have been completely decomposed into secondary phases (Figs. 10–12). Between these steenstrupine-(Ce) pseudomorphs, smaller fresh steenstrupine-(Ce) crystals (0.05–0.3 mm in size) are abundant (Figs. 13–17), together with two secondary minerals, labelled A5 and A6, which are probably new mineral species.

2.5.1. Minerals A5, A6 and other phases

In the pseudomorphs (Figs. 10 and 11), the zoned structure of the original crystals is easily recognized. It consists of at least two phases, mineral A5 and A6. Phase A5 is represented by the bright areas and A6 is represented by the grey areas (b and c respectively in Figs. 10 and 11); A5 also occurs disseminated in the silicate minerals (a in Fig. 10).

The average composition recorded for mineral A5 in different positions (Fig. 10) and for another decomposed crystal present just outside the area covered by Fig. 10 is listed in Table 4, no. 1. Mineral A5 also occurs intergrown with the fresh steenstrupine-(Ce) as described below.

Mineral A6 (Figs. 10 and 11, analyses nos. 5–6 in Table 4) is cut by shrinkage fractures. Nearly identical analyses were obtained. Although homogeneous in appearance, the analyses on A6 indicate significant differences in composition from one analyzed point to another (see standard deviation, Table 4). The low wt% total indicates that the mineral contains OH/H₂O and/or CO₃^{2–}. The empirical formula calculated for mineral A6 on the Si+Al+P=6 basis is (Na_{0.10}K_{0.03})_{Σ0.13}(Ca_{0.36}Fe_{0.65}Mn_{0.19})_{Σ1.20}(REE_{3.25}Th_{0.34})_{Σ3.59}(Ti_{0.09}Zr_{0.25})_{Σ0.34}Nb_{0.03}(Si_{4.81}P_{0.56}Al_{0.63})_{Σ6.00}F_{0.57}Cl_{0.05}O_{19.88–y}(OH)_{2y}·nH₂O.

The central part of the completely decomposed steenstrupine-(Ce) crystal in Fig. 12 appears to consist of secondary very fine grained, possibly cryptocrystalline or amorphous phases. Mineral A5 (a in Fig. 12), represented by the white areas in the rather broad marginal layer of the decomposed crystal (analyzed in two positions, Table 4, no. 2), is similar to A5 in Fig. 10 except for a higher content of Th and lower contents of La and Ce. Mineral A5 also occurs as extremely small grains disseminated in the presumably amorphous phases.

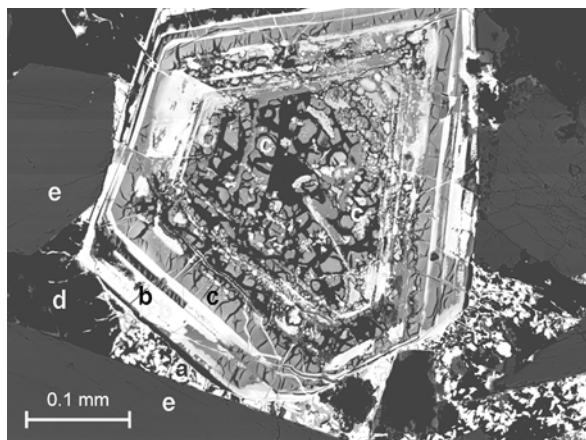


Fig. 10. Pseudomorph after steenstrupine-(Ce). Mineral A5 occurs as distinct although partly fragmented layers in the pseudomorph (b) and also occurs disseminated in silicates (analcime?) interstitial to aegirine crystals (a), both enclosing a completely decomposed steenstrupine-(Ce) crystal. The major steenstrupine-(Ce) decomposition product, mineral A6 (c), appears with shrinkage fractures filled presumably with analcime; Mellemelv locality.

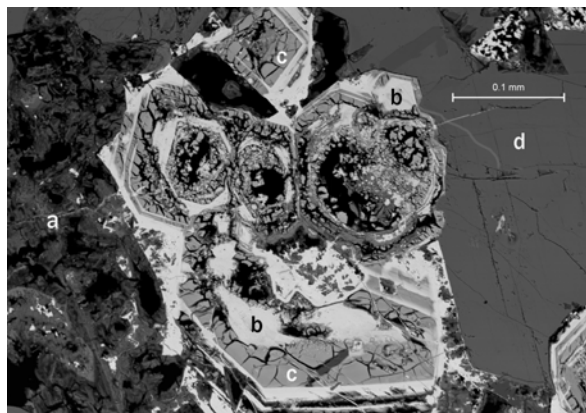


Fig. 11. Aggregate of several steenstrupine-(Ce) crystals replaced by mineral A5 (b) and mineral A6 (c) in contact with a crystal of aegirine (d) and unidentified silicates (a, left dark grey in the image); Mellemelv locality.

The secondary products consist of at least three rather well defined phases (b, c and d in Fig. 12). The brightest of these (d, Table 1, no. 6) has a composition similar to that of steenstrupine-(Ce), and can be recalculated as: $K_{0.1}Ca_{2.9}REE_{8.1}Th_{1.0}Fe_{2.31}Al_{0.1}Mn_{0.8}Zr_{1.0}H_{3.7}[Si_6O_{18}]_2[SiO_4]_{4.5}[PO_4]_{2.5}(OH)_{0.7}F_{1.2}Cl_{0.1} \cdot 2H_2O$. It distinctly cuts across and partly replaces the earlier formed grey (b, Table 4, no. 7) and dark grey (c, Table 4, no. 8) phases.

The chemical compositions of the two similar alteration products at b and c in Fig. 12 are strikingly different from that of steenstrupine-(Ce). They have higher contents of Th, Ti, Zr and Al, lower contents of REE (except Y), Mn and P and almost no Na. The content of Si in the alteration products is comparable to that of steenstrupine-(Ce). The low totals, <79 wt%, show that considerable amounts of OH/H₂O and/or CO₂ were added during the alteration process.

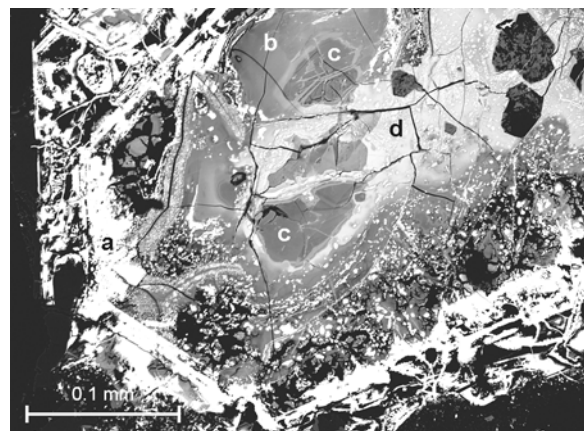


Fig. 12. Pseudomorph after steenstrupine-(Ce). The marginal part is dominated by mineral A5 (a), the central part by secondary phases (b, c) displaying colloform botryoidal textures, cut by veins of late secondary steenstrupine-(Ce) (d); Mellemelv locality.

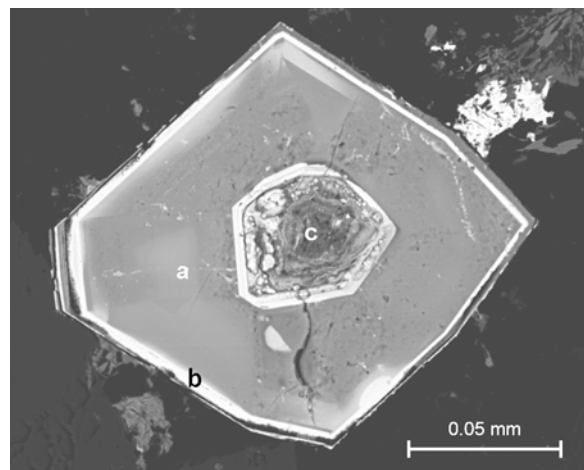
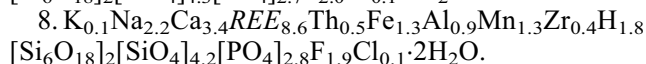
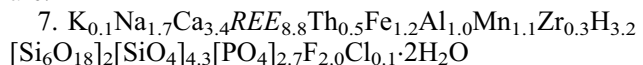


Fig. 13. Steenstrupine-(Ce) crystal (a) with a marginal layer of mineral A5 (b). The central part of the crystal (c) is dominated by poorly defined Mn- and Fe-rich phases and separated from the host steenstrupine-(Ce) by a narrow rim of presumably mineral A5; Mellemelv locality.

2.5.2. Fresh steenstrupine-(Ce) and mineral A5

Microprobe analyses were completed on two fresh steenstrupine-(Ce) crystals (Fig. 13; Table 1, nos. 7 and 8). The corresponding formulae, based on the same structural principles as for steenstrupine-(Ce) from Taseq, are:



As for steenstrupine-(Ce) at Taseq, the low Na content of the two analyzed crystals has presumably been caused by protonation of the mineral. The major chemical difference between the mineral from Mellemelv and the fresh steenstrupine-(Ce) from Taseq is their distinctly

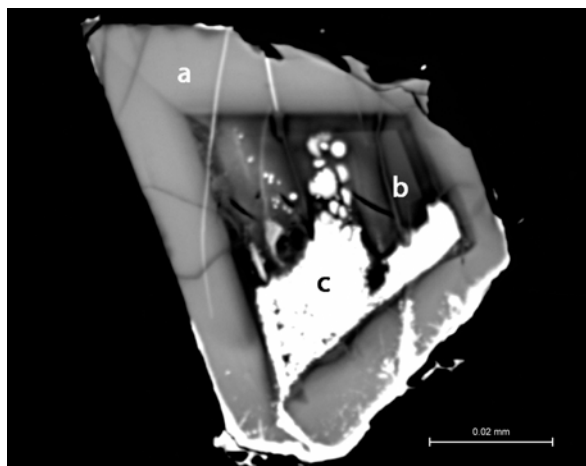


Fig. 14. Steenstrupine-(Ce) crystal with marginal replacement rim (rim: a) and in the central area (c) by mineral A5. The light grey marginal zone (a) has a lower ThO_2 content (~ 1 wt%) than the central (b) darker core (~ 6 wt% ThO_2); Mellemelv locality.

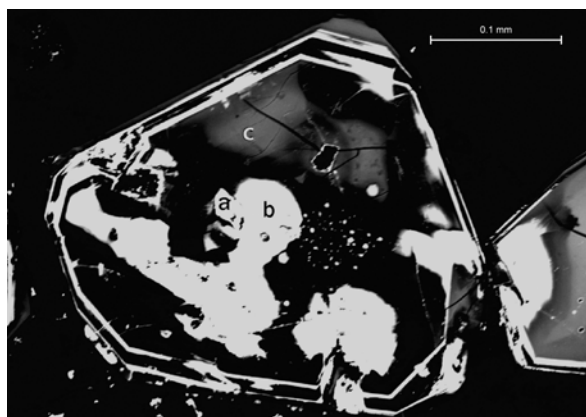


Fig. 15. Steenstrupine-(Ce) crystal (c) with marginal replacement by mineral A5 in thin layers following the crystalline outline of the steenstrupine-(Ce) crystal, and a central area with more massive mineral A4 (b) and one relatively small britholite-(Ce) crystal (a). Mellemelv locality.

different $(\text{Si}+\text{P})/\text{REE}$ molar ratios, 2.19 and 3.29 respectively. For comparison, the same ratio for steenstrupine-(Ce) from Tunugdliarfik (Makovicky & Karup-Møller, 1981) is 2.98 and for ideal steenstrupine-(Ce) (Moore & Shen, 1983) 3.17. The proportion between several of the REE in steenstrupine-(Ce) from Taseq and fresh steenstrupine from Mellemelv vary significantly. The Y content is about three times as large, that of La twice as large, while that of Pr, Nd and Sm is slightly lower in the fresh steenstrupine-(Ce) than in the steenstrupine-(Ce) from Taseq. Furthermore, the fresh steenstrupine-(Ce) has a considerable higher Ca content (3.4 vs. 0.6 apfu), similar Fe contents, but lower Mn contents (1.1 vs. 2.7 apfu), higher Zr contents (0.5 vs. 0.1 apfu) and no Ti. The content of F is higher (2.0 vs. 0.2 apfu). In addition the mineral contains 1 apfu Al. The balanced H^{1+} is lower in the fresh steenstrupine-(Ce) crystals than in the crystals from Taseq (2.5 vs. ~ 14 apfu).

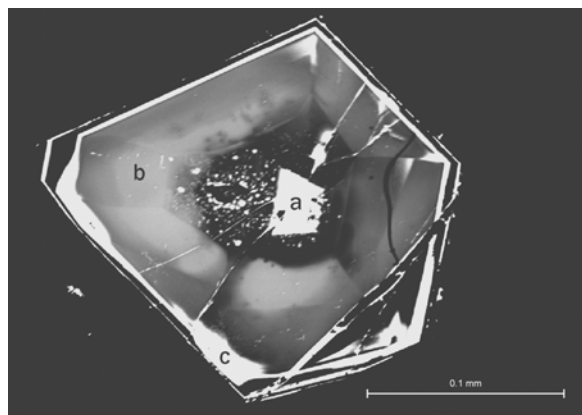


Fig. 16. Sector-zoned steenstrupine-(Ce) crystal (b) corroded by mineral A5 (c, white rim). An idiomorphic crystal of A5 (a) lies in the central part of the steenstrupine-(Ce) crystal and thin veinlets connect it with the marginal rim. Mellemelv locality.

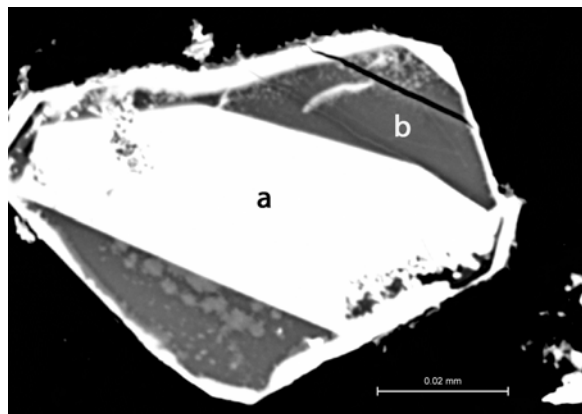


Fig. 17. Large idiomorphic mineral A5 crystal (a) enclosed in a steenstrupine-(Ce) crystal (b). Mellemelv locality.

These major differences in composition between steenstrupine-(Ce) from the two localities indicate that two different steenstrupine-(Ce) varieties are present. Alternatively, the low $(\text{Si}+\text{P})/\text{REE}$ could be explained by vacancies on the $(\text{Si}+\text{P})$ sites. The small size of the fresh steenstrupine-(Ce) crystals does not permit extraction of these for structural analysis to verify this possibility.

The secondary steenstrupine-(Ce) at d in Fig. 12 (Table 1, no. 6) has a composition closer to that of the fresh steenstrupine-(Ce) than that of steenstrupine-(Ce) at Taseq. It has a $(\text{Si}+\text{P})/\text{REE}$ ratio equal 2.35 and it has no Na.

Two morphological features characterize the steenstrupine-(Ce) crystal in Fig. 13. It has a thin marginal layer of mineral A5 (Table 4, no. 3) and a core of relatively Mn-rich and REE-poor phases, which may either be a mixture of distinct minerals or perhaps amorphous. Analyses on individual well-defined phases are accordingly not possible. Analyses were completed on light grey and dark grey areas of the core (Table 4, nos. 9 and 10). The core is separated from the steenstrupine-(Ce) host by a thin layer of a white phase which morphologically resembles the A5 marginal phase. Homogeneous regions are too small for analysis of any individual phases that are present.

Table 4. Microprobe analyses of minerals A5, A6 and steenstrupine decompositions products, Mellemelv locality. 1: Average of 14 analyses on mineral A5 in different positions in Fig. 10. 2: Mineral A5 in Fig. 12. 3: Mineral A5 forming the margin of the steenstrupine-(Ce) crystal shown in Fig. 13. 4: Mineral A5 crystal enclosed in the steenstrupine-(Ce) crystal the composition of which is listed in Table 1, No. 8. 5 and 6: Mineral A6 at c in Fig. 10 and at b in Fig. 11 respectively. 7 and 8: Steenstrupine-(Ce) alteration products in Fig. 12 at b and c, respectively. 9 and 10: Light grey and dark grey areas respectively, in the central part of the steenstrupine-(Ce) crystal shown in Fig. 13. Atomic proportions based on Si+Al+P = 6.

Anal. no.	1	2	3	4	5	6	7	8	9	10
Mineral	A5	A5	A5	A5	A6	A6				
Figure	10(a)	12(a)	13(b)	No figure	10(c)	11(b)	12(b)	12(c)	13(c)	13(c)
No anal.	14	4	2	6	9	5	5	5	5	2
SiO ₂	8.73(.76)	10.58(.99)	8.65(.94)	8.22(.24)	21.48(.97)	20.25(.86)	28.50(.53)	32.49(.30)	9.71(1.11)	26.45(.30)
TiO ₂	0.09(.07)	0.09(.03)	0.08(.03)	0.04(.03)	0.52(.06)	0.48(.11)	1.08(.04)	0.58(.03)	0.21(.01)	0.09(.01)
ZrO ₂	0.59(.24)	0.12(.03)	0.17(.11)	0.12(.04)	2.00(.23)	2.34(.32)	4.14(.18)	0.39(.11)	0.17(.07)	0.03(0)
ThO ₂	1.72(.29)	7.30(1.70)	2.71(.00)	2.58(.18)	6.79(1.69)	5.88(1.33)	15.38(.71)	14.14(.59)	4.57(.37)	0.65(.07)
Al ₂ O ₃	0.26(.11)	0.13(.06)	0.05(.01)	0.07(.04)	2.61(.18)	2.05(.13)	1.68(.09)	1.70(.06)	1.92(.23)	2.45(.01)
P ₂ O ₅	21.25(1.24)	19.98(1.51)	22.09(1.41)	23.29(.28)	2.51(.30)	3.15(.92)	0.34(.04)	0.39(.04)	4.30(.68)	0.18(.01)
Nb ₂ O ₅	0.05(.05)	0.08(.04)	0.08(.02)	0.09(.03)	0.32(.04)	0.31(.08)	0.04(.03)	0.32(.07)	0.19(.05)	0.17(.04)
Y ₂ O ₃	1.04(.24)	1.28(.49)	0.82(.08)	0.72(.35)	1.53(.08)	1.32(.22)	2.83(.17)	4.07(.23)	1.40(.17)	0.32(.03)
La ₂ O ₃	21.10(.87)	16.81(.36)	20.25(.01)	19.95(.42)	6.17(.45)	6.14(1.40)	2.39(.18)	3.33(.10)	5.72(.84)	0.73(.03)
Ce ₂ O ₃	28.41(.75)	27.75(.09)	28.87(.47)	29.32(.26)	23.93(1.32)	24.46(2.88)	9.10(.43)	10.21(.23)	9.68(1.36)	1.12(.07)
Pr ₂ O ₃	2.08(.33)	1.90(.29)	2.12(.36)	2.09(.21)	1.05(.23)	0.90(.16)	0.78(.29)	0.85(.21)	0.60(.20)	0.17(.20)
Nd ₂ O ₃	6.94(.36)	7.66(.53)	7.06(.10)	7.75(.07)	4.18(.28)	4.07(.50)	3.17(.23)	4.50(.11)	2.74(.24)	0.39(.04)
Sm ₂ O ₃	0.78(.13)	0.82(.16)	0.75(.06)	1.05(.15)	0.64(.19)	0.78(.13)	0.47(.19)	0.63(.06)	0.30(.03)	0.09(.12)
Gd ₂ O ₃	0.32(.22)	0.08(.11)	0.51(.01)	0.29(.31)	0.27(.21)	0.29(.26)	0.38(.19)	0.59(.15)	—	—
FeO	0.92(.23)	0.22(.10)	0.25(.19)	0.12(.09)	3.34(.25)	3.39(.52)	1.49(.06)	0.99(.07)	2.08(.42)	16.94(.34)
MnO	0.38(.32)	—	0.10(.01)	0.04(.07)	0.83(.13)	1.05(.24)	0.39(.06)	0.18(.05)	28.23(3.31)	27.12(.58)
CaO	2.40(.32)	3.31(.15)	3.16(.19)	3.09(.06)	1.58(.15)	1.35(.20)	2.79(.15)	2.67(.14)	3.96(.26)	2.21(.08)
K ₂ O	0.04(.02)	0.03(.00)	0.07(.04)	0.03(.01)	0.07(.03)	0.12(.07)	0.19(.02)	0.17(.03)	0.16(.02)	4.13(.09)
Na ₂ O	0.01(.01)	0.10(.07)	0.05(.01)	0.04(.02)	0.28(.14)	0.16(.13)	0.27(.03)	0.21(.03)	0.41(.04)	0.60(.00)
F	0.78(.15)	0.46(.05)	0.51(.04)	0.47(.08)	0.78(.13)	0.79(.15)	0.31(.06)	0.35(.11)	0.73(.16)	0.55(.04)
Cl	0.06(.01)	0.04(.01)	0.02(.03)	0.04(.02)	0.14(.04)	0.10(.05)	0.11(.02)	0.12(.04)	0.13(.03)	0.03(0)
F—O	0.03	0.19	0.21	0.20	0.32	0.33	0.13	0.15	0.31	0.23
Cl—O	0.01	0.01	—	0.01	0.03	0.02	0.02	0.03	0.07	0.01
Total	97.61	98.55	98.16	99.20	80.67	75.64	75.68	78.70	76.83	84.18
Si	1.94	2.29	1.89	1.76	4.83	4.79	5.56	5.60	3.73	5.38
Ti	0.01	0.02	0.01	0.01	0.09	0.09	0.16	0.08	0.06	0.01
Zr	0.06	0.01	0.02	0.01	0.22	0.27	0.39	0.03	0.03	
Th	0.09	0.36	0.14	0.13	0.35	0.32	0.68	0.55	0.40	0.03
Al	0.07	0.03	0.01	0.02	0.69	0.57	0.39	0.35	0.87	0.59
P	4.00	3.67	4.10	4.22	0.48	0.63	0.06	0.06	1.40	0.03
Nb	0.01	0.01	0.01	0.01	0.03	0.03		0.03	0.03	0.02
Y	0.12	0.15	0.10	0.08	0.18	0.17	0.29	0.37	0.29	0.03
La	1.73	1.35	1.64	1.58	0.51	0.54	0.17	0.21	0.81	0.05
Ce	2.31	2.21	2.31	2.30	1.97	2.12	0.65	0.64	1.36	0.08
Pr	0.17	0.15	0.17	0.16	0.09	0.08	0.06	0.05	0.08	0.01
Nd	0.55	0.59	0.55	0.59	0.34	0.34	0.22	0.28	0.38	0.03
Sm	0.06	0.06	0.06	0.08	0.05	0.06	0.03	0.04	0.04	0.01
Gd	0.02	0.01	0.04	0.02	0.02	0.02	0.02	0.03		
REE total	4.96	4.50	4.87	4.82	3.16	3.33	1.44	1.62	2.96	0.21
Fe	0.17	0.04	0.04	0.02	0.63	0.67	0.24	0.14	0.67	2.89
Mn	0.07		0.02	0.01	0.16	0.21	0.06	0.03	9.19	4.68
Ca	0.57	0.77	0.74	0.71	0.38	0.34	0.58	0.49	1.63	0.48
K	0.01	0.01	0.02	0.01	0.02	0.04	0.05	0.04	0.08	1.07
Na		0.04	0.02	0.02	0.12	0.07	0.10	0.07	0.31	0.24
F	0.55	0.31	0.36	0.32	0.55	0.59	0.19	0.19	0.88	0.36
Cl	0.02	0.01	0.01	0.02	0.05	0.04	0.04	0.04	0.09	0.01

Figures 14–17 further illustrate the mode of occurrence of mineral A5. The central area contains irregularly shaped grains or grain aggregates of mineral A5 (Figs. 14 and 15). At b in Fig. 15, A5 lies in contact with one relatively small britholite-(Ce) crystal (a). Britholite-(Ce) is also found adjacent to the steenstrupine-(Ce) crystal inside the surrounding silicate minerals. In Figs. 16 and 17, the central parts of the steenstrupine-(Ce) crystals contain idiomorphic crystals of mineral A5.

The marginal areas of all the steenstrupine-(Ce) crystals contain a thin layer of mineral A5. In Figs. 14–17, the central mineral A5 connects with the marginal mineral A5, which suggests that the central mineral A5 crystallized simultaneously with the marginal A5 rim.

The steenstrupine-(Ce) crystal shown in Fig. 13 is rather homogeneous (Table 1, no. 7) but the crystals in Figs. 14–16 are heterogeneous and have not been analyzed in detail. Analyses completed on the crystal shown in Fig. 14 gave lower sum values on the darker shaded areas than on the light grey areas. This may indicate intake of OH/H₂O without causing a breakdown of the crystal structure. Due to the low electron flux used in taking the images, the central areas of the steenstrupine-(Ce) crystals appear very dark to black. In Fig. 16, the central A5 crystal is associated with a late replacing silicate mineral, possibly analcime.

The only significant chemical variation of mineral A5 (Table 4, nos. 1–4) is that of Th, La and Ce. Increasing contents of Th have correspondingly lower contents of La and Ce indicating Th substitution for REE. The analytical total is close to 100 wt%, which suggests that the mineral is anhydrous although in addition to F it could also contain small amounts of OH. The following empirical formula for A5 is based on the average of the analyses in Table 4 and Si+P+Al=6: $(\text{Na}_{0.02}\text{K}_{0.01})_{\Sigma 0.03}(\text{Ca}_{0.70}\text{Fe}_{0.07}\text{Mn}_{0.03})_{\Sigma 0.80}(\text{REE}_{4.79}\text{Th}_{0.18})_{\Sigma 0.97}(\text{Nb}_{0.01}\text{Ti}_{0.01}\text{Zr}_{0.02})_{\Sigma 0.04}(\text{Si}_{1.97}\text{P}_{4.00}\text{Al}_{0.03})_{\Sigma 6.00}\text{F}_{0.39}\text{Cl}_{0.02}\text{O}_{22.22-n}(\text{OH})_{2n}$ or simplified: $\text{Ca}_{1-x}(\text{REE}, \text{Th})_5\text{Si}_2\text{P}_4\text{F}_{0.4}(\text{O}, \text{OH})_y$.

3. Discussion

3.1. The Taseq locality

The idiomorphic steenstrupine-(Ce) crystals in ussingite veins are considered to be primary. Their regular zoning is explained by variation in the composition of the fluids from which the mineral was precipitated. The ThO₂ content of the light grey layers in the original steenstrupine-(Ce), of up to 10.6 wt%, is the highest ThO₂ content recorded for steenstrupine-(Ce), except for the steenstrupine-(Ce) remnant at d in Fig. 4, which contains 12.13 wt% ThO₂. Makovicky *et al.* (1980) found 5.69 wt% ThO₂ as a maximum value. The U content is less than 0.2 wt% UO₂.

“Steenstrupine-(Ce)” with exceptionally high contents of Th, named thorosteenstrupine, was found at two localities, at the Chergien rare-earth deposit in eastern Siberia (Kupriyanova *et al.*, 1962) and at the Karnasurt mine in the Lovozero massif, Kola peninsula (Pekov *et al.*, 1997). At the Chergien deposit, the mineral occurs as

metamict crystals in metasomatic veins. Based on microchemical analyses the following composition was obtained: $(\text{Ca}_{1.11}\text{Th}_{1.01}\text{Mn}_{0.81}\text{Fe}_{0.06}^{3+}\text{REE}_{0.06})_{\Sigma 3.05}(\text{Si}_{3.96}\text{Al}_{0.04})_{\Sigma 4.00}[\text{O}_{11.24}(\text{OH})_{0.76}]_{\Sigma 12.00}\text{F}_{0.95}\cdot 5.32\text{H}_2\text{O}$. Being metamict, its structural relationship with steenstrupine-(Ce) has not been resolved. After heating for 30 min at 900 °C it gave a powder pattern different from those of steenstrupine-(Ce) and thorite.

At the Karnasurt deposit thorosteenstrupine is claimed to occur as fresh crystals. Microprobe analyses on the mineral from this locality show the existence of solid solution from $(\text{REE}_{5.40}\text{Th}_{0.89})$ to $(\text{Th}_{3.81}\text{REE}_{2.59})$. Microprobe analyses were also completed on the thorosteenstrupine holotype material from the Chergien deposit. Despite some chemical differences, the mineral from these two localities is considered to be similar, although thorosteenstrupine from the Chergien deposit is entirely without P. Thorosteenstrupine-(Ce) is proposed to be the Th-dominant, P-poor analogue of steenstrupine-(Ce) with the following composition: $\text{Na}_{0-5}\text{Ca}_{1-3}(\text{Th}, \text{REE})_6(\text{Mn}, \text{Fe}, \text{Al}, \text{Ti})_{4-5}[\text{Si}_6\text{O}_{18}]_2[(\text{Si}, \text{P})\text{O}_4]_6(\text{OH}, \text{F}, \text{O})_x \cdot n\text{H}_2\text{O}$. Since the mineral occurs as fresh crystals, it should be possible by X-ray diffraction to determine its structural relationship to steenstrupine-(Ce) to confirm this conclusion.

Manganosteenstrupine with 17.98 wt% MnO, 1.99 Fe₂O₃, 0.70 MgO, 4.66 CaO, 0.10 PbO, 0.48 Na₂O, 0.24 K₂O, 11.28 ThO₂, 0.20 UO₂, 1.49 TiO₂, 1.08 ZrO₂, 20.19 REE₂O₃, 21.36 SiO₂, 0.65 P₂O₅, 12.86 H₂O⁺, 3.58 H₂O[−], sum 99.75 wt% was described by Vlasov *et al.* (1959). The mineral name was discredited by the Commission on New Minerals and Mineral Names (*Mineral. Mag.*, 33, 261, 1962). Further investigation of this phase appears not to have taken place.

There is no evidence of a replacement relationship between steenstrupine-(Ce) and eudialyte as seen in less hyperagpaitic rocks (Sørensen & Larsen, 2001).

Zoned steenstrupine-(Ce) crystals up to a few millimetres across in drill cores from the Kvanefjeld area were studied by Khomyakov & Sørensen (2001). The interior parts of some crystals are turbid; other crystals have dark-coloured, isotropic cores. Microprobe analyses have shown distinct chemical differences between core and rim of crystals. The cores have 3.95–4.13 wt% ThO₂ and the rims 0.42–1.40 wt% ThO₂ and from centre to rim there is an increase in the content of Nb, Mn, REE, and P and decrease in Ti, Fe, Ca and Y (Khomyakov & Sørensen, 2001). At the Taseq locality, the opposite is the case. The marginal zone (a1 in Figs. 2–4) has the highest content of Th (<10.59 wt% ThO₂), Si, Y, Mn, Fe and Ti and lowest contents of P, Nb and REE compared to the inner zone (a2 on the figures) with halved Th contents (<5.62 wt% ThO₂). The decomposed zones (Figs. 2 and 4) have even higher contents of Th and U (16.62 wt% ThO₂ and 0.54 wt% UO₂). Khomyakov & Sørensen (2001) did not analyze for U in steenstrupine-(Ce) from Kvanefjeld. These authors assumed that the decrease in the content of Th from centre to margin in the Kvanefjeld steenstrupine-(Ce) was caused by decreasing Th content in the hydrothermal fluids. The opposite trend, increasing content of Th in the fluids,

explains the higher content of Th in the marginal zone compared to the inner zone of the steenstrupine-(Ce) crystals at Taseq.

Alternatively, [Khomyakov & Sørensen \(2001\)](#) suggested that the marginal anisotropic zone in the Kvanefjeld steenstrupine-(Ce) formed from a secondary process with leaching of Th and U, either before or after decomposition followed by recrystallization of the rim of the leached crystals. The higher Th content of the marginal bands of the Taseq steenstrupine-(Ce) crystals excludes such secondary processes as the cause of the layers of these crystals.

The decomposed areas, strictly confined to well-defined bands or to the very central part of individual crystals, are assumed to be due to recrystallization following metamictization. The Th contents of these products (mean 16.6 wt% ThO₂), are considerably higher than those of the host steenstrupine-(Ce), and white crystal/crystal aggregates (central in [Fig. 5](#)) contain >17.2 wt% ThO₂ but the black areas only 3.2 wt%. The decomposed areas thus have significantly higher ThO₂ content than the original steenstrupine-(Ce). The relict steenstrupine-(Ce) at d in [Fig. 4](#) has a total of 12.1 wt% ThO₂. It is assumed that this high content represents the composition of the original steenstrupine phase before its partial decomposition, and has not been caused by enrichment due to leaching of elements from the mineral. It is possible that such high Th contents caused its decomposition, although cracking of the host steenstrupine-(Ce) which generally accompanies decomposition (*e.g.* [Khomyakov & Sørensen, 2001](#)) was not observed. Alternatively, protonation may have caused the decomposition of the mineral. The altered zones and central areas in the steenstrupine-(Ce) crystals may thus represent those parts of the crystals that could not survive the protonation process. The high Th content of the decomposed areas may in part also have resulted from exchange of elements during the decomposition and recrystallization processes.

The botryoidal replacement of steenstrupine-(Ce) ([Fig. 5](#)) attacks individual crystals in an irregular fashion, totally independent of their zoned structure and has resulted in distinct exchange of elements. Sodium has been completely removed and the content of Si has been almost halved, whereas the contents of P and REE have been increased. The content of the remaining elements are similar to those of the original steenstrupine-(Ce). Presumably these botryoidal replacement products are non-metamict, being caused by late hydrothermal fluids, or they may be supergene.

A characteristic feature of some steenstrupine crystals is the presence of a relatively large A4 crystal, which occurs in the central area of both fresh and decomposed steenstrupine ([Figs. 2 and 3](#)). Most probably these crystals grew during the steenstrupine decomposition process.

3.2. The Mellemelv locality

At this locality two steenstrupine-(Ce) varieties have been identified. One is totally decomposed, while the other displays no or little signs of alteration.

Recrystallization following metamictisation seems to be responsible for the total destruction of the original steenstrupine-(Ce) crystals in [Figs. 10–12](#). The decomposition products in [Fig. 12](#) were in turn overprinted by later mineralizing fluids, which caused their replacement by a new phase with steenstrupine-(Ce) composition.

When comparing the estimated bulk chemical composition of the decomposition products (the minerals A5 and A6 which constitute the major part of the pseudomorphs, [Figs. 10 and 11](#)) with that of “average steenstrupine-(Ce)”, it is seen that substantial element exchanges took place during the decomposition process. Sodium was almost totally removed, and the content of Si and Mn reduced. In contrast, the content of REE was increased, and small amounts of Al appear to have been added from an external source, together with H₂O/OH. No chemical match between A5 and A6 and the steenstrupine-(Ce) alteration minerals described by [Makovicky *et al.* \(1980\)](#) and [Chukanov *et al.* \(2005\)](#) was found.

Zonation, which is characteristic for steenstrupine-(Ce) from the Taseq locality and the now totally decomposed steenstrupine-(Ce) variety from Mellemelv, was not found in the fresh steenstrupine-(Ce) variety at Mellemelv. The marginal A5-rim of these unaltered crystals ([Figs. 15–17](#)) may have resulted from reaction between early formed steenstrupine-(Ce) crystals and late mineralizing fluids. The centrally placed A5 crystals and rare associated britholite-(Ce) crystals (*e.g.* [Fig. 15](#)) may have formed at the same time as the marginal rim during replacement of the steenstrupine-(Ce) host.

The central part of the steenstrupine-(Ce) crystal shown in [Fig. 13](#) consists of irregular layers of dark and light grey phases, both extremely rich in Mn. The chemistry and texture excludes that this core material formed from near isochemical decomposition of the steenstrupine-(Ce). It is possible that these are Mn-rich materials which were entrapped in the steenstrupine-(Ce) crystal, and are extremely fine-grained and cryptocrystalline in nature.

4. Conclusion

Steenstrupine-(Ce) at the Taseq locality contains up to 10.6 wt% ThO₂. It has been partly decomposed and to some extent replaced by late botryoidal cryptocrystalline products, assumed to be either hydrothermal or supergene in origin. The low Na content of both steenstrupine-(Ce) varieties is presumably the results of protonation.

The relatively high contents of Th in the steenstrupine-(Ce) remnants in areas of decomposed steenstrupine-(Ce) is likely to reflect the original composition, given the limited mobility of Th, and to be a result of removal of other components rather than gain of Th. It is possible that radiation damage by Th facilitated this decomposition, although protonation by acidic fluids may also have been important.

Two steenstrupine-(Ce) varieties were found at the Mellemelv locality. One of these has been completely decomposed and its original composition therefore

remains unknown. The other variety is present as relatively small homogeneous fresh crystals. It has an unusually low (Si+P):REE ratio equal to 2.29 compared to 3.29 for steenstrupine-(Ce) from Taseq and the value for ideal steenstrupine-(Ce) of 3.17. It may represent a new variety in the steenstrupine-(Ce) group of minerals.

Decomposition of steenstrupine-(Ce) at Mellemelv has resulted in the formation of a late phase which also has steenstrupine-(Ce) composition. It has a (Si+P):REE ratio = 2.34, close to the ratio 2.29 for the fresh steenstrupine-(Ce) variety at this locality. However, it has a higher Th content than the first generation of steenstrupine-(Ce) (7.48 wt% ThO₂) and no detectable Na.

Decomposed steenstrupine-(Ce) contains at least three minerals which are believed not to have been described previously, provisionally called A4, A5 and A6. Mineral A4 was found in decomposed steenstrupine-(Ce) from Taseq, and A5 and A6 in decomposed steenstrupine-(Ce) from Mellemelv. A5 is also associated with fresh steenstrupine-(Ce) from Mellemelv. Decomposition of eudialyte has resulted in four rather similar minerals: Ca-rich A1, Ca-poor A1, A2 and A3 (Karup-Møller *et al.*, 2010; Karup-Møller & Rose-Hansen, 2013). The minerals appear chemically related to britholite-(Ce) but the difference in proportions of (Na,Ca,Fe,Mn), REE and (Si,P) cations between britholite-(Ce) and in the A1–A6 mineral varieties suggests that they are not structurally related.

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