# An unique mineral suite in a syenite pegmatite at Virikkollen, Sandefjord, Larvik Plutonic Complex, Norway

Knut Edvard Larsen & Uwe Kolitsch

## Introduction

In April 2010, a cavity in a small syenite pegmatite dike was discovered at Virikkollen, Sandefjord in the southern part of Norway. The cavity was formed by the interstices between large K-feldspar and aegirine crystals, and revealed a mineral suite unique among the pegmatites associated with larvikite hitherto reported from the Larvik Plutonic Complex (LPC). About 20 different minerals, all belonging to the hydrothermal stage of the pegmatite formation, have so far been identified from the cavity. Especially notable were the presence of beryllium minerals as epididymite, bertrandite and milarite, but also minerals new to the LPC and Norway were found. The first find of zektzerite from Norway is reported from here, besides the find of an aspedamite-like mineral (UK-17).
In this paper we will give a preliminary description of the locality and the minerals found in this cavity.

## Regional geology

The Virikkollen pegmatite belongs to the Larvik Plutonic Complex (LPC) which was formed within the early Permian Oslo rift, in the southern segment, the Vestfold segment, of the Oslo graben (Oftedahl & Petersen 1978, Dahlgren 2010). The alkaline LPC covers today an area about 50 km x 20 km in the southern part of the Vestfold County, between the Langesundsfjord in the west and Tønsberg in the east. Petersen (1978) studied the internal structures of the LPC, and found that the complex consist of a series of individual plutons that can be seen as roughly semi-circular series suggesting that the centres of igneous activity shifted from east to west (Fig. 1).
U-Pb dating on zircons and baddeleyites gave an age of 297.3 +/- 1.2 Ma for one of the oldest larvikite plutons in the east (pluton II), and 292 +/- 0.8 Ma for the younger lardalite pluton (pluton IX). This shows that the complex with its igneous rocks and pegmatites was emplaced over a period of 5-6 million years (Dahlgren et al. 1998). Raade (1993, cited in Raade 2008) has shown that the larvikites vary from silica-saturated in the east to silica-undersaturated in the west, and with intermediate larvikites without quartz or nepheline in the middle.

A large number of syenite pegmatites occur within the LPC and the large number of minerals found here has made this area famous (Brøgger 1890, Larsen et al. 2010). The Virikkollen pegmatite is situated within the pluton IV and thus in an area of a quartz- or nepheline-free to slightly undersaturated larvikite.
The pegmatites of the pluton IV in the LPC are generally characterized as pegmatites of the *Stavern-type* (Brøgger 1890, Larsen et al. 2010), but not all are fitted into this simplified classification. They are coarse-grained pegmatites related to the larvikite and typically dominated by K-feldspar, black amphiboles, zircon, titanomagnetite, lesser biotite, fluorapatite, pyrochlore and zirconolite (metamict variety "polymignite"). Accessory minerals are relatively few in number. Compared to the pegmatites of the Tvedalen-type, the lack of zones with extensive zeolitisation is striking. This may indicate that the content of water was lower in the hydrothermal stage of the pegmatite formation in the *Stavern-type* pegmatites than in those of Tvedalen.

A survey of the most interesting pegmatites found in Sandefjord area is given in Berge & Andersen (2002).

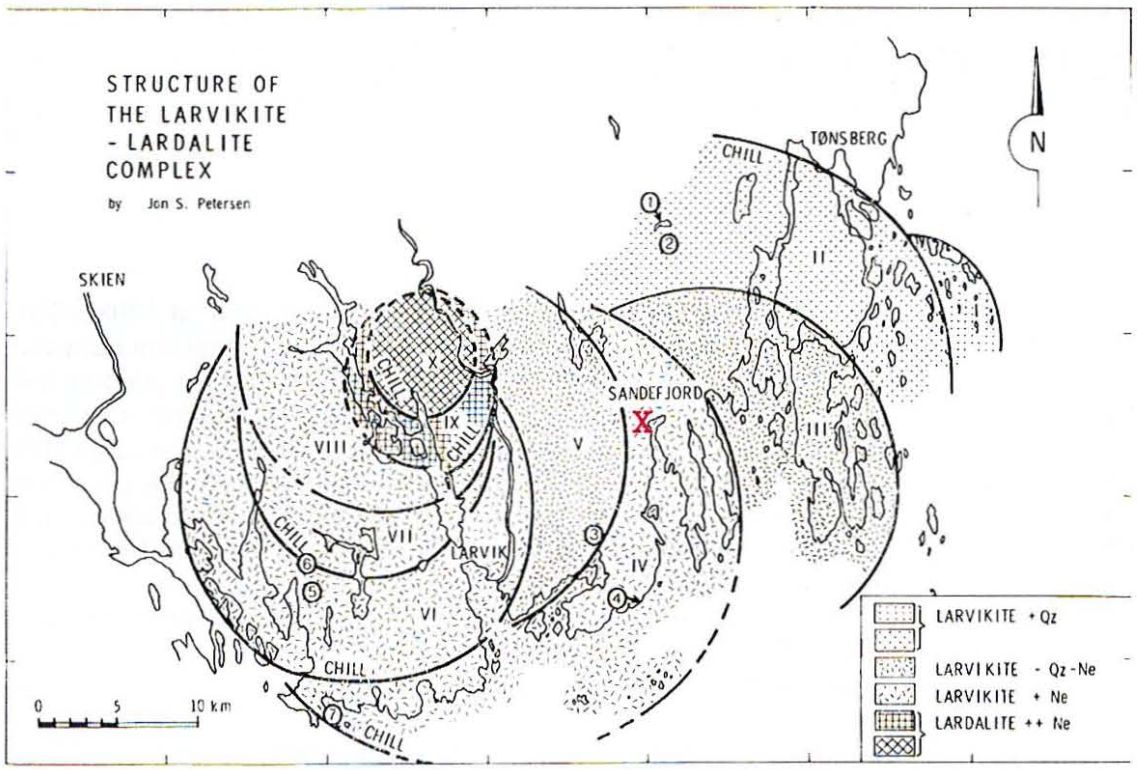


***Fig. 1**. The semi-circular intrusions showing the plutons I-X in the Larvik Plutonic Complex of the Southern Oslo Region, Norway (after Oftedahl & Petersen 1978). The Virikkollen pegmatite is marked with an "x" within the pluton IV.*

## The pegmatite dike

The Virikkollen pegmatite outcrops in larvikite on the western side of a small hill called Virikkollen, located 1 km SW of the centre of the town of Sandefjord. It is exposed partially in a road cut on the eastern side of the hill, along the road Haneholmveien. The coordinates are 59°7'30.73"N 10°12'37.29"E. The pegmatite dike appears to have a sheet-like morphology and is situated about 4 - 5 m above the street level. It is inaccessible without a ladder from below (Fig. 2) or climbing gear from above. From the road cut, the pegmatite dike can be traced in a SSW direction, along a narrow mountain shelf for about 5 m before it is covered by overburden of vegetation, mostly heather plants, and disappears. The road cut was made during an expansion of Haneholmveien in the beginning of the 1980s, and some part of the pegmatite was then exposed during blasting. The most interesting mineral which local collectors had found among the little material then available, was aegirine as a few poorly developed crystals. One such crystal (5 x 2.5 cm) is included in the first author's collection (# 594). Microcrystals of albite, zircon, beside fluorapatite and possible milarite can be observed in small cavities in the crystal.

The pegmatite is coarse-grained and its main minerals are K-feldspar, black amphiboles, aegirine and magnetite. Albite, zircon and fluorapatite, pyrochlore (s.l.) and biotite have also been observed. All these belong to the magmatic, early formed minerals in the assemblage. Fluorapatite, zircon and pyrochlore (s.l.) are observed embedded in K-feldspar, amphibole or aegirine, and are among the earliest formed minerals in the magmatic stage of the formation of the pegmatite. The black amphibole is formed later than the aegirine.

Another, larger pegmatite dike, which can be followed for about 20 m, is situated at the southern end of Virikkollen, about 65 m south-southwest of our pegmatite, and approximately parallel to it. This second pegmatite is called Virikkollen South (Virikkollen S) to distinguish it

from the pegmatite described in this article. There may be a connection between the two pegmatites.

## The cavity

In April 2010, due to expansion of the roots system of a small rowan tree (Sorbus aucuparia) together with frost cracking, small boulders broke free from the pegmatite above and revealed a cavity. The material first found at the ground below showed clusters of small smoky quartz with epididymite crystals, which caught interest, and samples were later collected from the revealed cavity for further study.

***Fig. 2**. The Virikkollen pegmatite in the roadcut at Haneholmveien, as it is seen from below. The cavity is seen just right above the ladder. Note the little rowan tree.*

The cavity area investigated, as seen in Figs. 2 and 3, measured 54 cm wide and 56 cm high, and was limited by large aegirine and K-feldspar crystals. The voids between the aegirine and K-feldspars were completely filled by clusters of intermingled microcrystals or masses, mainly of quartz, intergrown or dusted with albite, epididymite, ilmenite, bastnäsite-(Ce), aegirine and a mica mineral. The minerals were generally covered with dirt and small-grained debris and often partially covered with clay minerals (montmorillonite?) and locally stained brownish with oxidic iron compounds.

Late stage (hydrothermal) minerals can be observed in small vugs occurring in quartz. Crystals of zircon (of a second generation) and bertrandite, both often covered by opal-$A_N$, occurr together with zektzerite, cream-yellow spheres of an unidentified mineral, and sometimes also with aegirine. In the upper part of the cavity, close to the large upper aegirine crystal (Fig.3), the minerals of this paragenesis were covered partially by a thin crust of a botryoidal, non-fluorescent silica mineral, probably chalcedony. Small cavities in the aegirines from this part of cavity also hosted tiny crystals of albite, quartz, mica, and occasionally bertrandite and tiny milarite(?) crystals, besides a crust of chalcedony and clay minerals.

At the contact with the K-feldspar, and in cracks along the cleavage planes of the feldspars close to the contact, the following assemblage was observed: albite, minor quartz, ilmenite, epidydimite, a pyrochlore-group mineral, a mica mineral, arfvedsonite(?), aegirine and bastnäsite-(Ce) besides clay minerals and Fe- and/or Mn-hydroxides. It was in this paragenesis, located close to the right-hand corner of the cavity (Fig. 3), that the aspedamite-like mineral (UK-17) was found, as one of the youngest formed mineral.

The minerals in the cavity have been formed in several stages during the hydrothermal formation. A schematic presentation of the paragenetic sequence of the minerals occurring in the cavity is given in Table 1.

***Fig. 3**. The cavity in the Virikkollen pegmatite as seen in August 2011, after some minor collecting. The lens cap in the photo centre is 5.8 cm across. A root from the rowan tree is seen in the left side of the photo. A large aegirine crystal, 30 x 17 cm, is seen just above the lens cap, and the area under the lens cap consists of masses with intermingled small quartz crystals covered with dirt and clay. The zektzerite was found in the area around the lens cap, and UK 17 at the contact with the feldspar in the lower right side of the photo.*

## Minerals

25 different minerals have been identified so far from the cavity and in the pegmatite area immediately close to it. A description of the most important minerals is given below. The list may not be complete; there are still some yet unidentified phases among the collected material. The mineral species are listed in alphabetical order. The chemical formulas used for the species follow mainly Larsen et al. (2010).

**Aegirine.** $NaFe^{3+}Si_2O_6$. Pyroxene group.
Large, prismatic aegirine crystals occur as one of the main minerals in the pegmatite. They are elongated along the *c*-axis and commonly show the forms {100} and {110}, sometimes also with well-developed {111}. A large crystal which measured 30 cm x 17 cm is seen in Fig. 3. The colour varies from greyish green to greenish black, often with zones of yellowish-brown in the interior of the crystals. A thin white-yellow-brownish crust of chalcedony may be observed on part of the faces, as well as mica and clay minerals, especially on the faces that

are exposed into the cavity. In cleavages, small vugs with well-developed tiny crystals of zircon, albite, quartz or occasionally bertrandite or milarite may be observed.
A second generation of elongated prismatic aegirine crystals up to 1 cm long occurs in the cavity. Most are a few millimetres long and have a typical square cross-section with colour variation from black-green to yellowish brown. The identity of these is confirmed by single-crystal X-ray diffraction (SXRD).

**Albite.** $NaAlSi_3O_8$. Feldspar group.
The mineral occurs both as a colourless thin, epitaxial growth on the surface of the K-feldspar, and commonly as small, colourless to white euhedral crystals in the cavity.

**Amphibole group**
Crystalline masses of black amphiboles up to several cm long are found as one of the main minerals in the pegmatite. No study has been done to confirm the exact mineral species. The amphiboles in the Sandefjord area, especially on Vesterøya nearby, are mostly magnesiokatophoritic in composition (Larsen et al. 2010), but further studies are needed to conclude anything concerning the amphiboles from this locality.

**Arfvedsonite**, $Na_2(Fe^{2+}_4,Fe^{3+})Si_8O_{22}(OH)_2$. Amphibole group.
Aggregates up to 2 cm wide of black, parallel growing, prismatic crystals occur in the cavity at the contact with the K-feldspar, in the lower right part of the cavity. The individual crystals are up to 0.8 mm thick, needle-shaped and vertically striated. The streak is bluish grey. The arfvedsonite is indentified only visually. Similar crystals have, however, been reported from other localities nearby in Sandefjord (Larsen et al. 2010), although no modern analysis have been done on these.

**Bastnäsite-(Ce).** $(Ce,La)(CO_3)F$.
The mineral occurs as well-developed, hexagonal, barrel-shaped crystals up to 3 mm long. The dominating forms observed are the pedion {0001} and the hexagonal pyramid $\{11\bar{2}1\}$. Lateral faces often exhibit horizontal grooves. The external colour of the crystals may vary in the individual crystal, from pale white termination to yellow-brown, sometimes with patches of pale white on the lateral faces. The internal colour, as observed from broken crystals or poorly developed crystalline masses, is a more homogenous yellow-brown. A few crystals show cavities parallel to {0001} on the lateral faces caused by dissolution. The crystals occur in between quartz crystals and in cracks and small vugs in the K-feldspar. The identification was done by SXRD (unit-cell parameters: $a$ = 7.13, $c$ = 9.78 Å). An additional EDS analysis gave Ce > Nd/La, and thus confirmed a bastnäsite-(Ce).

**Bertrandite.** $Be_4Si_2O_7(OH)_2$.
Euhedral colourless, up to 1 mm large crystals, tabular parallel to $c$, with a rectangular outline, occur in vugs in quartz in the cavity together with zircon, opal-$A_N$ and zektzerite. Beautiful trillings, contact twins after {021}, which radiate from a common point, giving 120 degrees orientation difference between the individuals, are relatively common in this paragenesis. Tiny bertrandite twins are also observed in tiny vugs formed inside or on aegirine crystals.

**Epididymite.** $Na_2Be_2Si_6O_{15}\cdot H_2O$.
The mineral occurs relatively abundantly in the cavity as well-developed, highly elongated, prismatic and thin to thick platy on {001} crystals. They measure up to 1 cm in length. The colour is white to colourless. The crystals show commonly the forms {001} and {100}, more rarely {203} and {110}. They seem to be somewhat corroded on the surface, especially on their terminations. The crystals are heavily striated along the $a$-axis (vertical), and have normally a multiple termination giving an irregular, splintery, multipointed appearance. This habit is similar to the one observed for epididymite from the Husebyåsen feldspar quarry

some km further east in Sandefjord. The crystals which sometimes occur in irregular, intermingled clusters, are commonly very fragile and free-standing crystals are thus easily broken. Pieces of broken epididymites are often found in the small-grained debris in the cavity. The voids between the crystals may be completely filled by a clay mineral (montmorillonite ?). Syngenetic inclusions of epididymite in quartz as well as epididymite crystals on quartz crystals are observed.

**Ilmenite**, $FeTiO_3$. Ilmenite group.
Black, small, shiny, thin platy crystals, often forming irregular aggregates or groups of intergrown crystals are found on K-feldspar or on albite or quartz crystals. An EDS analysis showed that the ilmenite is Mn-bearing.

**K-feldspar.** $KAlSi_3O_8$.
The dominating mineral in the pegmatite is a greyish-white to cream-yellow brownish K-feldspar. Rather large individual crystal can be seen close to the cavity in Fig. 3. No analysis has been done to establish the species. The most common feldspar in the LPC is microcline (Larsen et al. 2010).

**Mica-group mineral.**
A light-coloured mica mineral occurs locally abundantly as thin plates or blades on other minerals, sometimes as a continuous lining. The mica crystals are often covered by a thin film of a clay mineral. They are colourless to pale yellowish white and translucent in thin blades. Crystals showing zonation with a darker core and a lighter rim have been observed in a few cases.

**Milarite.** $KCa_2AlBe_2Si_{12}O_{30}$. Osumilite group.
Colourless to white, transparent to translucent, strongly elongated (along the *c*-axis), mm-sized hexagonal crystals occur sparingly in the cavity. Close to the contact with the feldspar milarite is observed together with albite, ilmenite, a clay mineral and occasionally also bertrandite. Tiny colourless crystals have been observed in vugs in cleavages of aegirine crystals. An EDS-analysis was made at the Natural History Museum in Oslo to confirm the identity (Roy Kristansen, pers. comm., Oct. 2011). Milarite has previously been reported from the LPC at only one locality, as a rarity, as microcrystals in vugs at Fuglevika near Stavern (Larsen et al. 2010).

**Opal-$A_N$.** $SiO_2 \cdot nH_2O$.
Colourless to white, globular concretions that occur as a non-fluorescent crust on other minerals are common in quartz together with zircon, bertrandite and zektzerite. The identification is done visually.

**Pyrochlore group.**
Millimeter-sized, resinous, (probably) metamict, brownish, poorly developed pyrochlor (s.l.) crystals are observed in the pegmatite embedded both in K-feldspar and aegirine. Brownish pyrochlore has also been observed in K-feldspar on the cavity wall in the area where the UK-17 occurred.

A second generation of tiny, octahedral, yellow to orange, translucent to transparent, non-metamict crystals and grains occur on samples collected at the contact with the K-feldspar together with albite, ilmenite, quartz, epididymite, aegirine, bastnäsite-(Ce), a clay mineral, arfvedsonite and UK-17. An SXRD analysis gave a mineral in the pyrochlore group ($a$ = 10.44 Å). An additional EDS analysis showed major Nb and minor Ca, Na (Ca:Na ~ 1.6:1), Ce, and traces of Ti, Si, and possible Sr. More detailed analyses would be required for an exact assignment of the species.

A late-stage, yellow, non-metamict pyrochlore has earlier been described from the Håkestad Quarry in Tjølling (Larsen et al. 2010). It was first erroneously reported as microlite in Engvoldsen et al. (1991).

**Riebeckite**. $Na_2(Fe^{2+}{}_3Fe^{3+}{}_2)Si_8O_{22}(OH)_2$. Amphibole group.
Riebeckite (fibrous variety "crocidolite") is commonly found as filling the interstices between feldspar crystals in several pegmatites in the Sandefjord area. It is also been reported from the Virikkollen S pegmatite (Larsen 2010: 197; found in 1974 by R. Hansen and S.A. Berge). A 4.5 cm x 2 cm mass of greyish blue, fibrous riebeckite crystals was found a few cm below the cavity at Virikkollen. The mineral has been visually identified.

**Quartz.** $SiO_2$
Quartz is the most abundant mineral in the cavity, besides masses filling out the voids, It occurs as pale smoky crystals up to 8 mm in size. A thin crust of a botryoidal silica mineral, visually identified as chalcedony, occurs as a late-stage phase on minerals from the upper part of the cavity, partially or completely covering surfaces.

***Fig. 4**. Corroded zektzerite crystals with globules of an unidentified mineral covered by a thin botryoidal crust of silica mineral (chalcedony ?)and a brownish clay-mineral. FOV: 6 mm.*

**Zektzerite.** $NaLiZrSi_6O_{15}$. Tuhualite group.
Vitreous, strongly hydrothermally etched crystals of a colourless transparent mineral occurs in vugs in quartz together with zircon, opal-$A_N$, bertrandite and aegirine. Due to the etching, crystal faces have been recognised in only a few crystals, found in the upper part of the cavity where the minerals are partially covered by a thin crust of botryoidal chalcedony (?) (Fig. 4). The faces may show a somewhat curved appearance. It shows a light yellow fluorescence in SW UV light. A SXRD analysis gave an orthorhombic unit-cell ($a$ = 14.34, $b$ = 17.36, $c$ = 10.17 Å), which is identical within error limits to that of the structure determination of zektzerite by Ghose and Wan (1978).
Zektzerite was described as a new mineral from the Golden Horn batholith, near Washington Pass in Okanogan County, Washington, USA, by Dunn et al. (1977). Here it occurred as euhedral, colourless to pink crystals up to 37 x 35 x 15 mm in miarolitic cavities in a riebeckite granite together with microcline, quartz, riebeckite, zircon, astrophyllite, elpidite and aegirine (Dunn et al. 1977). The crystal structure was subsequently solved by Ghose & Wan (1978).

The mineral has later been reported from three other localities worldwide, all alkaline: at the Dara-i-Pioz glacier in Tajikistan, at Ampasimbitika in Madagascar and the Del Salto Pluton in Chile (for references see www.mindat.org).
This is the first reported find of zektzerite from the LPC and Norway. Llithium minerals are very rare in pegmatites in the LPC. Previously, polylithionite, tainiolite and ephesite have been known (Raade & Larsen 1980; Larsen et al. 2010).

**Zircon.** $ZrSiO_4$.
Zircon occurs in the pegmatite as one of the early crystallized minerals in the magmatic stage of the pegmatite formation. It occurs as brown, vitreous, poorly developed, prismatic crystals up to 1 cm long.
In the cavity it occurs as a second generation of very tiny, pale yellowish-green translucent crystals, dominated by the tetragonal dipyramidal {101}. It is the most abundant mineral in the zircon-opal-$A_N$-bertrandite-zektzerite paragenesis, where it occurs as aggregates of intergrown groups of crystals, often covered with opal-$A_N$. The mineral is identified visually.

***Fig. 5**. Red, garnet-like dodecahedral crystals of the aspedamite-like mineral (UK 17) associated with black, platy ilmenite, orange pyrochlore, albite, mica etc. Note darker zone in the crystal in the middle. FOV: ~4 mm.*

**Aspedamite-like mineral (UK 17).**
One of the most interesting minerals found in the cavity occurs as small (up to 0.1 mm), well-developed, red, dodecahedral crystals with a deceptively garnet-like appearance (Fig. 5). The mineral is among the latest to have crystallised in the cavity and was found only in a limited area close to the cavity wall and in contact with the K-feldspar in the lower right-hand side of the cavity (see Fig. 3). Here it occurred together with albite, quartz, epididymite, ilmenite, bastnäsite-(Ce), aegirine, mica, a yellow to orange pyrochlore-group mineral, arfvedsonite, a clay mineral and Fe- and/or Mn-hydroxides. The crystals are distributed unevenly sprinkled on the associated minerals, as individual crystals or more rarely as aggregates of intergrown crystals forming a crust. The colour may vary from brownish red to deep red and blackish red. Some crystals exhibit a zoned band of darker colour in the centre (Fig. 5). The only crystal form observed is the dodecahedron {110}.

Preliminary analysis by EDS and SXRD (full crystal-structure refinement) showed this to be a complex cubic mineral, essentially a Th-heteropolyniobate, which is either identical to the newly IMA-approved species aspedamite from Herrebøkasa, Østfold, Norway (IMA2011-056, Cooper et al. 2011), or very closely related to it. The cubic cell parameter, $a$ = 12.962(1) Å, is only slightly larger than that of type aspedamite, $a$ = 12.9078(6) Å.
Further investigations are under way to establish if the Virikkollen phase is identical to aspedamite or a new species. The mineral has been designated, as a working name, as UK 17, following the ongoing list of unknown species from the LPC (Larsen et al. 2010).

**Table 1**: A schematic presentation of the paragenetic sequence of some of the minerals occurring in the cavity at the Virikkollen locality.

| **Mineral** | **Magmatic stage** | **Hydrothermal stage** | | |
|---|---|---|---|---|
| Aegirine | ---------- | ---------- | | |
| K-feldpar | ---------- | | | |
| Albite | | ---------- | | |
| Quartz | | ---------- | | ---------- |
| Epididymite | | ---------- | | |
| Ilmenite | | ---------- | | |
| Mica group mineral | | ---------- | | |
| Bastnäsite-(Ce) | | ---------- | | |
| Bertrandite | | | ---------- | |
| Zektzerite | | | -------- | |
| Milarite | | | ---------- | |
| Pyrochlore group minerals | ------ | ---------- | | |
| Zircon | ------ | | ---------- | |
| UK 17 | | | | ------- |
| Clay mineral(s) | | | | ?---------- |

## Discussion

The Virikkollen pegmatite is unique compared to other reported pegmatites within the LPC, both mineralogically and geochemically.
Further study may give new insights in the mechanisms that formed the late-stage hydrothermal beryllium minerals in the LPC. Three specimens of secondary beryllium minerals are found rather abundantly in the cavity. The absence of primary beryllium minerals (such as meliphanite, leucophanite) or nepheline, sodalite (which are the source for late-stage beryllium minerals in the pegmatites in the Langesundsfjorden and Tvedalen areas; Larsen et al. 2010, Raade 2008) in the pegmatite, indicates that beryllium must have been available concentrated in the latest hydrothermal fluids only.
The presence of one lithium mineral (zektzerite) also makes this pegmatite unique. Even though lithium minerals are rare in the LPC, analysis of primary minerals as aegirine, biotite and amphiboles has showed that they may contain a significant amount of Li. Analysis of the Li-content of minerals from the upper Vøra pegmatite dike, Vesterøya, Sandefjord, showed a content ranging from 1.35 wt. % $Li_2O$ in arfvedsonite to 0.25 wt. % $Li_2O$ in aegirine (Raade & Larsen 1998).
The most likely source of the Nb for the formation of UK-17 is the brownish, metamict (?) pyrochlore found in the K-feldspar in the wall of the cavity.

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