Tourmaline-group minerals from Norway, part II: Occurrences of luinaite-(OH) in Tvedalen, Larvik and Porsgrunn, and fluor-liddicoatite, fluor-elbaite and fluor-schorl at Ågskardet, Nordland

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Introduction

As part of a wider study on the crystal chemistry of tourmaline-group members from Norway, occurrences of luinaite-(OH), fluor-schorl and other members have been reported (Kolitsch et al. 2011). The present contribution presents further results based on characterisations of different samples from various pegmatite localities in the Langesundsfjord area (Tvedalen, Larvik, Porsgrunn), in Østfold, Nordland, Oppland and Telemark. The Langesundsfjord samples also include material described by Brøgger (1890). The following species were detected: schorl, fluor-schorl, luinaite-(OH), "luinaite-(F)", dravite, fluor-elbaite, fluor-liddicoatite and rossmanite. Additionally, bastnäsite-(La) and cassiterite were detected as unexpected inclusions in a polished section of a Langesundsfjord schorl sample.

As in our previous study the chemical compositions of the samples have been derived from a combination of single-crystal structure refinements and semiquantitative SEM-EDS analyses (Kolitsch et al. 2011, see there for additional details). The refinements were again done using intensity data collected at ambient temperature on a Nonius KappaCCD single-crystal X-ray diffractometer equipped with a CCD detector. The SXRD data were collected from selected crystal fragments with high crystal quality (a common case for tourmaline-group species) and average diameters between about 0.1 and 0.2 mm. For all samples, intensity data were measured with high redundancy for a complete Ewald sphere up to $2\theta = 75°$, ensuring high-resolution data sets and good statistics. The data were processed in a standard way, with absorption correction based on the multi-scan method. Final $R(F)$ values usually ranged between around 1 and 2%. Since an accurate determination of the F:(OH,O) ratio at the *W* site can be achieved very easily from such high-quality datasets, it was consequently easy to distinguish between F- and OH-dominant members of the tourmaline group.

From the refined crystal-structure model, the chemical formula of a given sample was indirectly estimated by means of numerous well-established relations between unit-cell parameters, bond lengths, site occupancies and polyhedral geometries in the tourmaline group, as well as bond-valence constraints (e.g. Ertl et al. 2001 & 2002, Hawthorne 2002, Bosi & Lucchesi 2004, Ertl & Tillmanns 2010, Ertl et al. 2010, Henry & Dutrow 2011, Henry et al. 2011, Ertl & Tillmanns 2012). This correlation-based identification method only fails if a given tourmaline sample is very or fairly near the compositional boundary between two or more species. In such cases, quantitative EPMA data will be necessary, in part to be supplemented by SIMS or wet-chemical analyses for Li and determination of the accurate Fe^{3+}:Fe^{2+} ratio by Mössbauer spectroscopy.

For the SEM-EDS analyses at the Natural History Museum Vienna, a new, state-of-the-art JEOL JSM-6610LV equipped with a high-resolution and high-sensitivity detector (e-FlashHR+; detector area 30 mm^2, resolution 127 eV) was employed. The data, obtained on carbon-coated samples (either polished sections or flat-lying fragments), were processed by Bruker Esprit 1.9.4 software, using an interactive PB-ZAF correction for the semi-quantitative analyses. This allowed surprisingly accurate determination of all non-oxygen and -hydrogen element constituents, including F (only F contents < 0.2-0.3 apfu are seemingly below the detection limit). Similarly to our previous study (Kolitsch et al. 2011), the largest variation within a given set of analysed fragments from the same sample was shown by the Al:Fe:Mg ratios.

Results from the SEM-EDS analyses all agree well with the results of the crystal-structure refinements and the derived structure models.

Samples and localities

The following sample descriptions are arranged in a geographical order. First, the tourmalines from the Langesundsfjord area (Vestfold and Telemark) are described, followed by those from Østfold, Nordland, Oppland and Telemark.

Previously, only schorl was reported from the wider Langesundsfjord area (Brøgger 1890, Larsen et al. 1999, Larsen 2010). The blackish, prismatic crystals have crystallised in the hydrothermal stage of the nepheline syenite pegmatites, and are generally embedded in analcime. The prisms may reach a length of 5 cm and are often arranged in divergent groups (Larsen 2010).

Midtfjellet quarry, Malerød, Larvik, Vestfold

Two samples from this operating larvikite quarry were studied. The first one (collected in 2007 by PA) shows a brown-black, radiating tourmaline (Fig. 1) embedded in an analcime/spreustein-type natrolite matrix, with minor pale blue sodalite and trace amounts of zircon and other minerals. Dark chlorite occurs in analcime voids.

The SXRD study clearly shows this sample to be luinaite-(OH) (IMA 2009-046). We remind that luinaite-(OH) is a monoclinic-pseudorhombohedral member of the tourmaline group, and has the simplified formula $(Na,\square)(Fe^{2+},Mg)_3Al_6Si_6O_{18}(BO_3)_3(OH)_3(OH)$. The decrease in space-group symmetry from *R*3*m* (rhombohedral) to *Cm* (monoclinic) is caused by an ordering of Fe^{3+} and Al^{3+} cations which appears to be governed by the conditions of crystallisation (Mills et al., to be submitted).
The ordering is strongly pronounced at the *Y* site, less so at the *Z* site. The $Y1O_6$ polyhedron is unusual because it shows a very strong bond-length distortion (range: 1.925(2) - 2.1632(18) Å), unlike the $Y2O_6$ polyhedron (range: 2.0269(11)- 2.1877(12) Å). The refined occupancies of the *Y*1 and *Y*2 sites are $Fe_{0.593(4)}Al_{0.407(4)}$ and $Fe_{0.803(3)}Al_{0.197(3)}$, respectively. Further details will be reported in the original description of luinaite-(OH) (Mills et al., to be submitted).
The only impurity element detected by SEM-EDS is Ti in trace amounts.

Refined unit-cell parameters: a = 10.453(2), b = 16.013(3), c = 7.232(1) Å, β = 117.64(3)°.
Refined chemical formula (bulk formula, occupancies of individual split *Y* and *Z* sites not indicated): $\sim(Na_{0.98}Ca_{0.02})(Fe_{0.70}Al_{0.30})_3(Al_{0.89}Fe_{0.11})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.8}F_{0.2})$.

The second sample from the Midtfjellet quarry was collected in September 2011 by PA. Although visually very similar to the first one and having practically the same Fe content, it was, somehow surprisingly, found to be a "normal" schorl. In the monoclinic model, all *Y* and *Z* subsites have, within error limits, identical occupancies. The Flack parameter is 0.02(1), indicating no racemic twinning and thus also typical of schorl. The SEM-EDS analyses show the only impurities to be trace amounts of Mg and Ti.

Refined unit-cell parameters: a = 16.008(2), c = 7.210(1) Å.
Refined chemical formula:
$\sim(Na_{0.99}\square_{0.01})(Fe_{0.66}Al_{0.34})_3(Al_{0.89}Fe_{0.11})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.9}F_{0.1})$.



Fig. 1. Luinaite-(OH) from the Midtfjellet quarry, Malerød, Larvik, Vestfold.
Field of view 7 mm. Photo Harald Schillhammer.

E18 roadcuts, Kokkersvold, Langangen, Porsgrunn, Telemark

Several syenite pegmatite dikes were exposed during construction of a new alignment of the highway E18 in the late 1970s. A sample (collected by PA) containing a spray of small blackish tourmaline prisms (max. length 4 mm; fragments dark brown translucent; Fig. 2) in white nepheline syenite pegmatite matrix was collected at Kokkersvold, between the former Lanner toll station and the Langangen bridge.

The structure refinement clearly indicated that the sample corresponds to luinaite-(OH). Both *Y* and *Z* subsites show different occupancies and geometric parameters, and the ordering on *Y* and *Z* is similar to that in the luinaite-(OH) sample from the Midtfjellet quarry. However, the deviation from rhombohedral symmetry is smaller in the E18 sample. The only impurity elements detected by SEM-EDS are Mg, Mn and Ti (all in trace amounts).

Refined unit-cell parameters: a = 10.421(2), b = 16.026(3), c = 7.241(1) Å, β = 117.56(3)°.
Refined chemical formula (bulk formula, occupancies of individual split *Y* and *Z* sites not indicated): ~$(Na_{0.98}Ca_{0.02})(Fe_{0.70}Al_{0.30})_3(Al_{0.87}Fe_{0.13})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.8}F_{0.2})$.



Fig. 2. Luinaite-(OH) from an E18 roadcut, Kokkersvold, Langangen, Porsgrunn, Telemark. Field of view 5 mm. Photo Harald Schillhammer.

AS Granit quarry, Tuften, Tvedalen, Larvik, Vestfold

This larvikite quarry, very rich in minerals, provided also very dark tourmaline. A sample collected on level 4 of the quarry by PA, provided small black prisms embedded in a white nepheline syenite pegmatite matrix (Fig. 3). Some of the prisms are developed as hollow crystals, the interior in part filled by tiny analcime crystals. Embedded in the white pegmatite matrix, small euhedral arsenopyrite crystals occur (confirmed by SEM-EDS-analyses).
The structure refinement unambiguously showed that the sample can be assigned to luinaite-(OH). The cation-ordering system at the *Y* and *Z* sites is, interestingly, somewhat different from that in the Midtfjellet and E18 luinaites-(OH) (see above) and the Hundholmen luinaite-(OH) (Kolitsch et al. 2011). According to the SEM-EDS analyses, the only impurity elements are Mg, Mn and Ti, all in trace amounts.

Refined unit-cell parameters: a = 10.431(2), b = 15.988(3), c = 7.226(1) Å, β = 117.56(3)°.
Refined chemical formula (bulk formula, occupancies of individual split *Y* and *Z* sites not indicated): ~$Na(Fe_{0.66}Al_{0.34})_3(Al_{0.88}Fe_{0.12})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.9}F_{0.1})$.

Almenningen quarry, Tvedalen, Larvik, Vestfold, Norway

Two visually very similar tourmaline samples were studied from this operating larvikite

quarry. The first one (collected by AOL) showed a spray of dark prisms up to ca. 2.5 cm (!) in length, embedded in white nepheline syenite pegmatite matrix (Fig. 4). The larger prisms appear black, while the smaller ones show a dark brownish colour. SEM-EDS analyses evidence minor Mg (Fe:Mg ~ 6:1 to 10:1) and trace amounts of Mn and Ti.

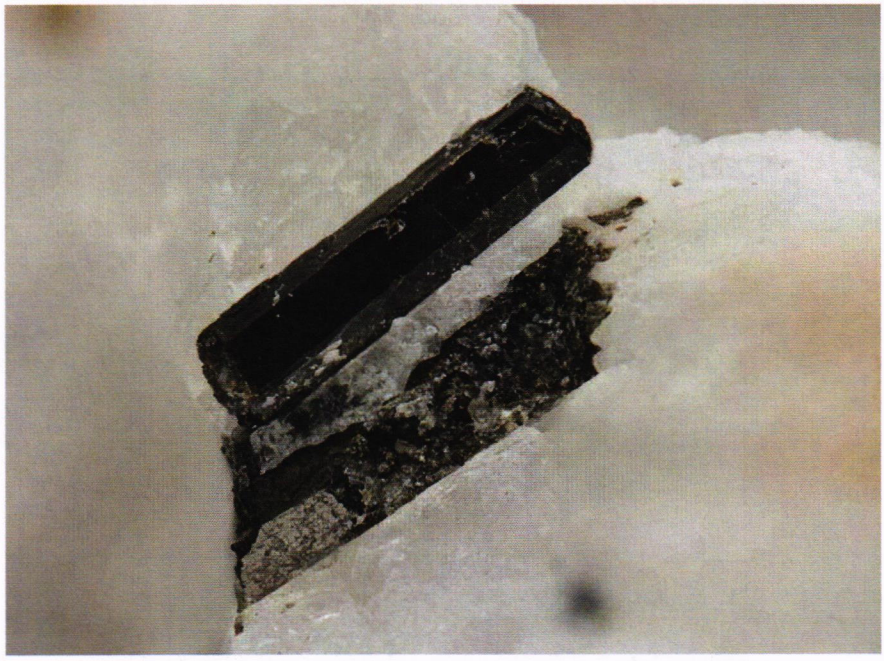


Fig. 3. Two prismatic crystals of luinaite-(OH) from level 4 of the AS Granit quarry, Tuften, Tvedalen, Larvik, Vestfold. Note that the broken lower crystal is hollow and filled with tiny analcime crystals. Field of view 4.8 mm. Photo Harald Schillhammer.



Fig. 4. A large spray of F-bearing schorl from Almenningen quarry, Tvedalen, Larvik, Vestfold. Field of view 2.9 cm. Photo Harald Schillhammer.

The second sample (collected by PA) consisted of a small part of a spray of black prisms in white nepheline syenite pegmatite matrix (Fig. 5). SEM-EDS analyses reflect a fairly homogeneous composition characterised by a minor amount of Mg (Fe:Mg ~ 5:1) and trace amounts of Mn and Ti. The Ca or F contents were below the detection limit, although the refinements of both samples clearly indicated very small amounts of both these elements at the *X* and *W* sites, respectively.

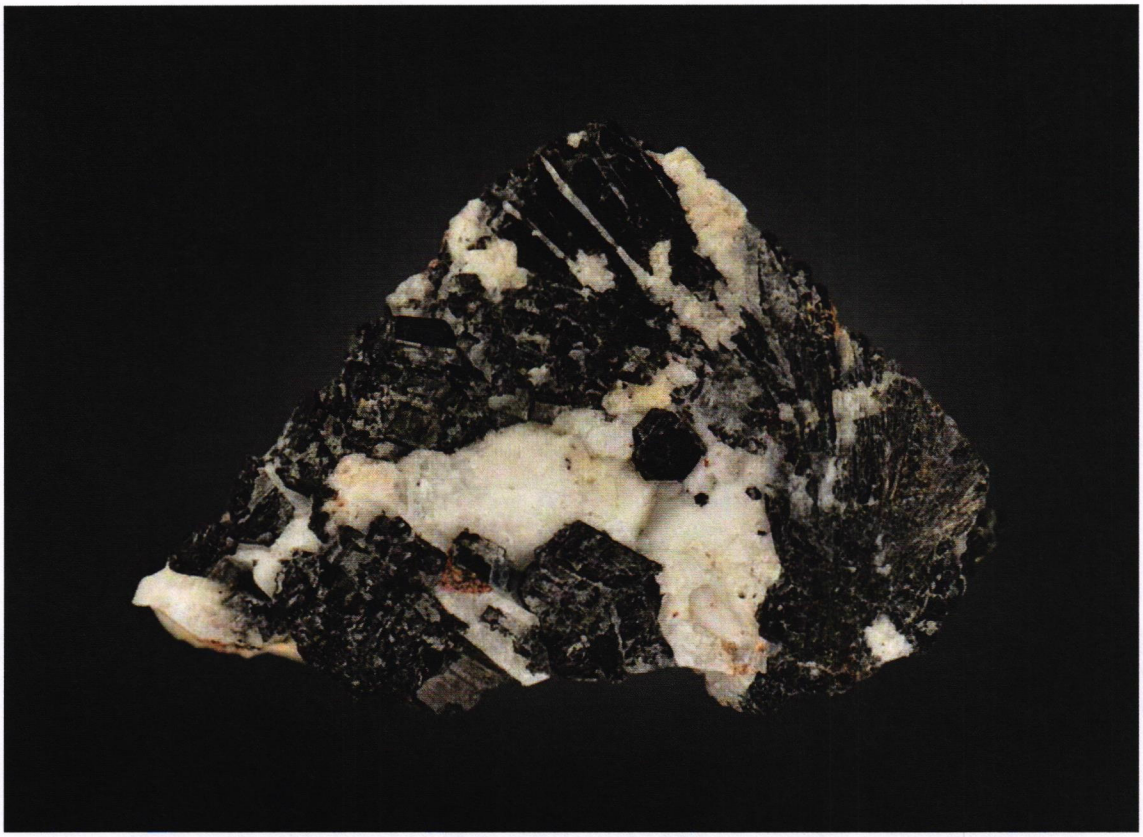


Fig. 5. F-bearing schorl from Almenningen quarry, Tvedalen, Larvik, Vestfold. This sample contains inclusions of thorite, xenotime-(Y), bastnäsite-(La), cassiterite and others (see text and Figs. 6-11). Field of view 1.8 cm. Photo Harald Schillhammer.

Since the studies gave very similar unit-cell parameters and chemical compositions for both samples, the results will be described together. The two samples are both F-bearing schorl which showed no indication of lower (monoclinic) symmetry.

Refined unit-cell parameters: a = 16.004(2), c = 7.233(1) Å (AOL sample).
a = 16.011(2), c = 7.231(1) Å (PA sample).
Refined chemical formulae:
~$(Na_{0.98}Ca_{0.02})(Fe_{0.65}Mg_{0.15}Al_{0.20})_3(Al_{0.88}Fe_{0.12})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.8}F_{0.2})$ (AOL sample).
~$(Na_{0.98}Ca_{0.02})(Fe_{0.66}Mg_{0.15}Al_{0.19})_3(Al_{0.90}Fe_{0.10})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.6}F_{0.4})$ (PA sample).

The overall features of the two samples are also very similar to that of a schorl from the Østskogen quarry (see following description).

SEM-EDS analyses of a polished section of the second sample revealed a surprising wealth of inclusions (in either analcime or, less commonly, schorl) and secondary phases (in tiny voids or crack fillings). The dominant inclusion is thorite (an- to euhedral, up to ~100 µm) that

is generally highly inhomogeneous. As minor impurity elements Ca, Mn, Fe, Y, Na, F and trace amounts of Pb, U and P were observed, all in variable percentages. In near-end member thorite the only foreign elements were Y and P. An unidentified phase always concentrated at the rim of the thorite grains, which contains additional Nb and more Fe, Mn and/or Al, but less Th, seems to be an alteration phase and a mixture of different species. The second most common inclusion is xenotime-(Y) (mostly euhedral; sometimes in the core of thorite grains; Yb-, Er-, Dy- and Al-bearing; Fig. 6), followed by zircon (Hf-bearing, with Zr:Hf ~ 10:1). Very rare is cassiterite found as tiny (max. 5 µm), anhedral inclusions (Figs. 7, 8). The only observed impurity element was Fe in trace quantities. Cassiterite was a previously unknown component of the Langsundsfjord pegmatites. A further unidentified phase forming a larger grain featuring a system of mutually perpendicular cracks conforms a Ce silicate with minor Mn, Al, Ca, Y, Na and trace amounts of Pb and Ce. The ratio (Ce + metals):Si is around 2:1. Possibly this grain is tritomite-(Ce).

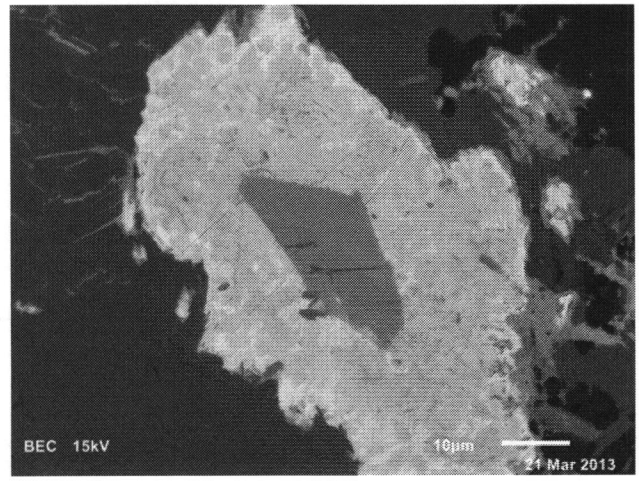


Fig. 6. Zoned xenotime-(Y) (the brighter areas contain more Yb) in the core of an inhomogeneous thorite, as inclusions in a sample of F-bearing schorl from Almenningen quarry (polished section). SEM micrograph (BSE mode) Uwe Kolitsch.

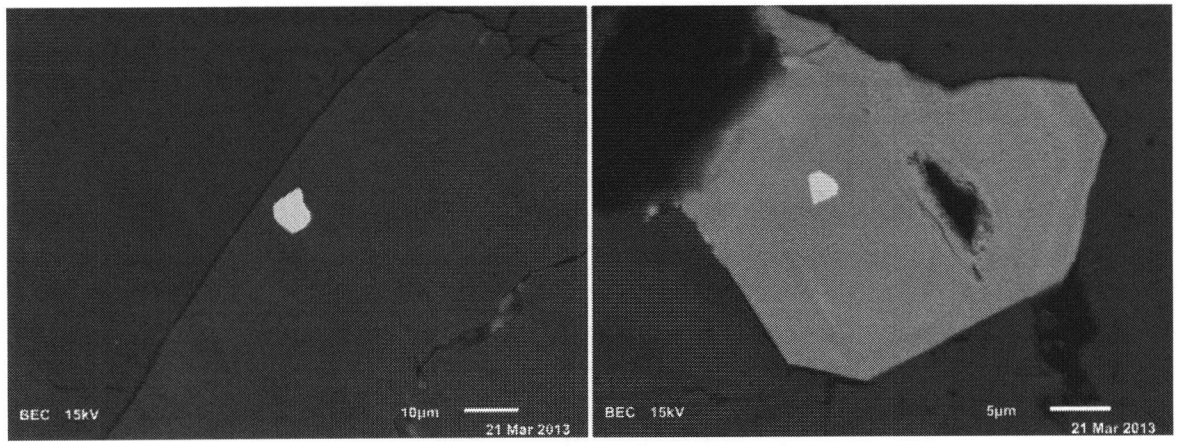
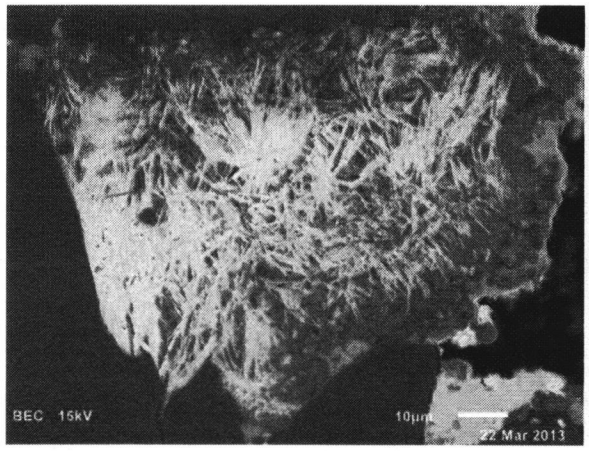


Fig. 7 (left). Tiny cassiterite grain (bright) in schorl, next to analcime (darker), in a sample of F-bearing schorl from Almenningen quarry (polished section). SEM micrograph (BSE mode) Uwe Kolitsch.
Fig. 8 (right). Tiny cassiterite grain (bright) within a zoned xenotime-(Y), in a sample of F-bearing schorl from Almenningen quarry (polished section). SEM micrograph (BSE mode) Uwe Kolitsch.

Further inclusions were near-stoichiometric annite, chamosite (Fe:Mg ~ 10:1; some with elevated Zn contents), very rare pyrophanite (containing trace amounts of Nb) and an alumosilicate clay (Al:Si ~ 1:1) with trace amounts of Na and Ca. Among the secondary phases, bastnäsite-(La) is dominant, followed by bastnäsite-(Ce). Both form tiny rounded platelets, either arranged in sprays embedded in matrix or as crusts covering surfaces of tiny voids (Figs. 9-11). They contain variable to trace amounts of (in decreasing order) Nd, Y, Ca, Pr, Na, Fe, Nb(!), Pb, Th, Al(?) and Si(?). Some bastnäsite-(La) is completely free of Ce and thus indicates a prior complete oxidation of the Ce^{3+} to Ce^{4+}, which then precipitates as CeO_2 and is removed from the mineralising solutions (a typical phenomenon during the alteration of primary LREE-bearing phases). Other bastnäsite-(La) aggregates are characterised by increased Ce contents, with La:Ce up to approximately 2:1 or even 1:1. Bastnäsite-(Ce) itself is less common and always La-rich (Ce:La ~ 3:2). The analytically determined F contents of the bastnäsites clearly indicate F-dominance, although some spot analyses also suggest decreased F contents and therefore an increased hydroxylbastnäsite-(La/Ce) component. Only quantitative EPMA would be able to prove if some aggregates actually correspond to F-bearing hydroxylbastnäsite-(La/Ce). Bastnäsite-(La) appears to be a new find for Norway. Ce-free hydroxylbastnäsite-(La) was analysed in a sample from Tuften, Tvedalen (Pavel M. Kartashov, unpubl. results; see http://www.mindat.org/photo-415857.html).



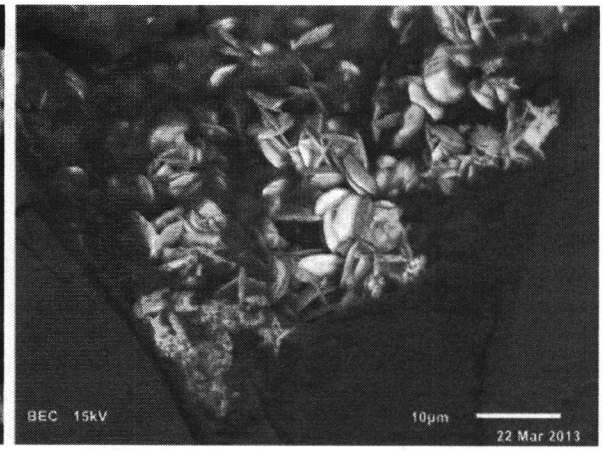


Fig. 9 (left). Fibrous, Ce-rich bastnäsite-(La), in a sample of F-bearing schorl from Almenningen quarry (polished section). SEM micrograph (BSE mode) Uwe Kolitsch.
Fig. 10 (right). Bastnäsite-(La) as tiny rounded platelets, in a void in a sample of F-bearing schorl from Almenningen quarry (polished section). SEM micrograph (BSE mode) Uwe Kolitsch.

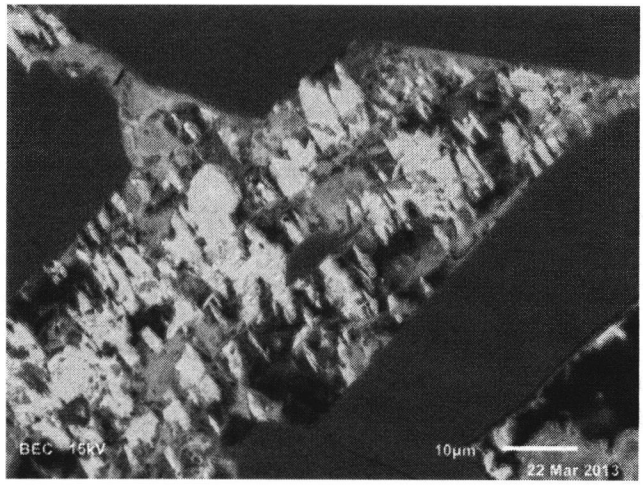


Fig. 11. Bastnäsite-(La) as bright parallel lamellae, associated with an unidentified phase (bright grey) containing Ce, Si, Al and various other elements. The dark matrix is schorl. Sample of F-bearing schorl from Almenningen quarry (polished section). SEM micrograph (BSE mode) Uwe Kolitsch.

Østskogen quarry, Tvedalen, Larvik, Vestfold

Two small specimens from this larvikite quarry (material collected in 2006 by PA) contained an inconspicuous tourmaline showing small black, indistinct prisms and sprays in white nepheline syenite matrix, associated in part with considerable greenish, fine-grained chlorite and white analcime crystals in voids (Fig. 12).
According to the X-ray study, this tourmaline is again a fairly pure schorl which has less F than the two, otherwise very similar Almenningen samples described above. The SEM-EDS analyses show the only impurities to be trace amounts of Mg, Ti and Mn. Although any Ca content was below the detection limit, the refinement clearly indicated very minor Ca (and/or K) at the *X* site.

Refined unit-cell parameters: a = 16.006(2), c = 7.225(1) Å.
Refined chemical formula:
$\sim(Na_{0.98}Ca_{0.02})(Fe_{0.66}Al_{0.34})_3(Al_{0.88}Fe_{0.12})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.8}F_{0.2})$.

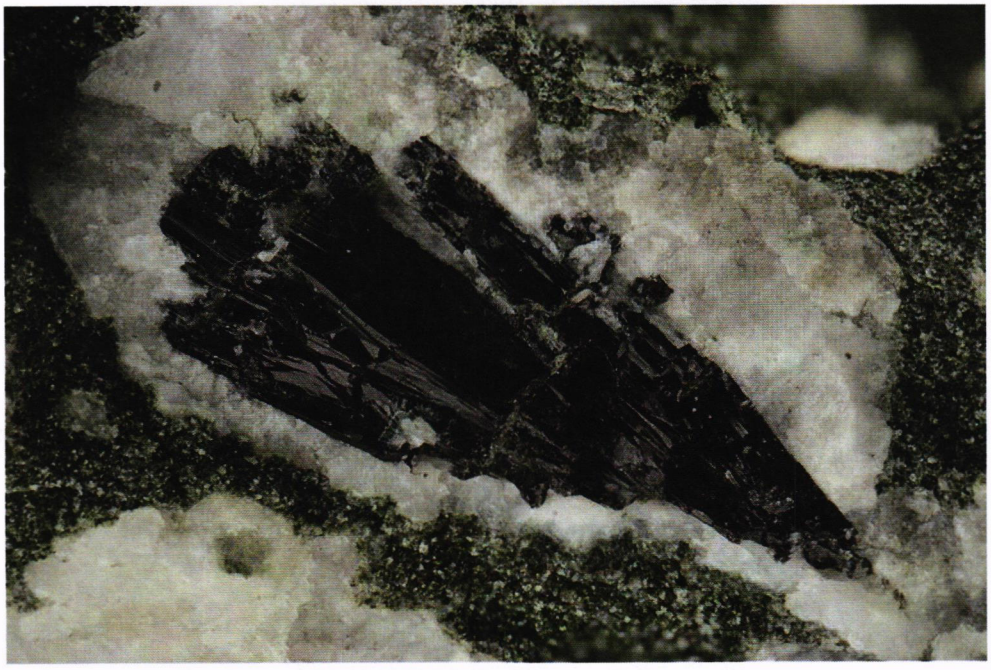


Fig. 12. Schorl associated with greenish chlorite, from Østskogen quarry, Tvedalen, Larvik, Vestfold. Field of view 7 mm. Photo Harald Schillhammer

Arøya(?), Langesundsfjorden, Larvik, Vestfold

Brøgger (1890) describes, in an addendum, a black tourmaline from the Langesundsfjord, probably from the Arøya island. The tourmaline forms a rosette of radiating black prisms which are zoned (thin sections show a blue core, a deep blue main zone and a thin brown rim). The material is currently preserved in the collection of the Swedish Museum of Natural History, Stockholm. According to curator Jörgen Langhof, who kindly provided part of the material for this study (two small grains removed from catalogue nos. NRM252408 and NRM252410), Brøgger's material comprises six catalogued pieces of which five contain the dark tourmaline, and came into the collection in 1925 from the Stockholm Highschool.

The structure solution of a dark brown fragment of NRM252408 revealed a very unusual tourmaline.

Firstly, it is strongly monoclinic, with a composition corresponding to that of an OH-rich F-analogue of luinaite-(OH), "luinaite-(F)". This F-analogue of luinaite-(OH) is already known since some time from a German locality [Kolitsch et al., unpublished results; mentioned in the IMA proposal for luinaite-(OH)], but the Langesundsfjord area now represents a second confirmed locality.
Secondly, one of the two B subsites (B1) is partially replaced by a tetrahedrally coordinated cation (peak height 3.3 electrons in the difference-Fourier map) which is located on a new site 0.655(5) Å away from the B1 atom. The tetrahedral coordination of the cation is comprised of three O ligands from the planar $B1O_3$ group and one partially occupied O atom at a novel site [refined occupancy 0.105(10)] which might represent an OH group involved in strongly localised hydrogen bonding. The O10 site is only 0.579(19) Å away from the new O site and therefore must be partially occupied. The new cation was modeled as a sulfur atom, since SEM-EDS analyses surprisingly revealed reproducibly very minor S contents (see below). The refined S occupancy is 0.071(3). Modeling the site as a tetrahedrally coordinated B atom results in an occupancy of ca. 0.35 and would contradict the lower refined occupancy of the associated partially occupied O ligand. If the cation site is modeled as a Si atom, the refined Si occupancy is 0.076(3). The refined bond distances for this new cation site range between 1.449(4) and 1.648(19) Å (average 1.56 Å).
The unit cell of this anomalous monoclinic tourmaline is characterised by an unusually small c parameter and the largest β angle measured so far. The cation (Fe:Mg/Al) order is not very strong on both *Y* and *Z* sites. According to the refinement, the *X* site contains distinct amounts of Ca replacing Na. Unlike other luinaites, the average Si-O distances of the three Si subsites are slightly different (1.620, 1.623, 1.622 Å), as well as the average B-O distances of the two B subsites (1.385 and 1.378 Å).

SEM-EDS analyses were performed on numerous tiny fragments removed from the samples NRM252408 and NRM252410. For NRM252408 they revealed, apart from high Na contents, minor Mg and Ti (Fe:Ti roughly 7.8:1), and, as already mentioned, very minor S contents apparently present as sulphate (SO_4) groups. To our knowledge, S has never been reported in any chemical analyses of tourmaline-group members. A general variability of the cation contents is observable, but relatively small. The EDS data obtained from NRM252410 are very similar, albeit showing smaller Ti contents. Ca was below the detection limit in either sample, although the structure refinement of the grain from NRM252408 clearly indicated very minor Ca (and/or K) at the *X* site.

Refined unit-cell parameters: a = 10.451(2), b = 16.016(3), c = 7.196(1) Å, β = 117.68(3)°.
Refined chemical formula (bulk formula, occupancies of individual split *Y* and *Z* sites not indicated):
$\sim(Na_{0.9}Ca_{0.1})[Fe_{0.55}(Mg,Al)_{0.37}Ti_{0.08}]_3(Al_{0.90}Fe_{0.10})_6Si^*{}_6O_{18}(B^*O_3)_3(OH)_3(F_{0.6}OH_{0.4})$.
(* The additional tetrahedrally coordinated, partially occupied cation site described above is neglected.)

It is planned to refine also the crystal structure of a fragment from NRM252410 and to quantitatively analyse the chemical composition of the material described by Brøgger (1890).

Sandvann, Aremark, Østfold

A relatively large black prism from this locality was part of material collected by Thore Henning Kristoffersen in the 1970s, and was kindly supplied by Roy Kristiansen. The structure refinement clearly indicated a schorl containing minor F.
No SEM-EDS analyses were carried out.

Refined unit-cell parameters: a = 16.001(2), c = 7.188(1) Å.
Refined chemical formula:
$\sim(Na_{0.9}\square_{0.1})(Fe_{0.61}Al^*_{0.39})_3(Al_{0.97}Fe_{0.03})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.7}F_{0.3})$ (* includes Mg).

Tennvatn, Sørfold, Nordland

Previous studies of two dark tourmalines from this amazonite pegmatite locality confirmed both to be fluor-schorl (Kolitsch et al. 2011).
A study of a third sample (collected by TH), which consisted of two small, thin black prisms with flat crystal terminations, confirmed again an Fe-rich fluor-schorl, but this time richer in OH on the *W* site. A cross-section of one crystal (Fig. 13), which contained a small quartz inclusion in its centre, was studied in detail in the SEM. As impurity elements, the EDS spectra showed very minor to trace amounts of Mg, Mn, Ti and Zn. Only in a few spot analyses traces of Ca or Cu were noticed. No clear major-element zonation was observed although the F contents vary strongly from values hardly above the detection limit to values approaching those of OH-bearing fluor-schorl. From core to rim, a clear tendency for decreasing F contents was observed. Thus, while the bulk composition of the fragment studied by SXRD corresponds to an OH-bearing fluor-schorl, the spot analyses demonstrate that locally both OH-bearing fluor-schorl and F-bearing schorl occur. As rare and small inclusions, albite was detected.
The overall features of this sample are very similar to those of a fluor-schorl from Kjerstadfjellet (Kolitsch et al. 2011). The unusually large <*Y*-O distance, 2.067 Å, is noteworthy. It reflects the high Fe^{2+} content of the *Y* site.

Refined unit-cell parameters: a = 16.025 (2), c = 7.210(1) Å.
Refined chemical formula:
$\sim(Na_{0.85}Ca_{0.05}\square_{0.1})(Fe_{0.75}Al_{0.25})_3(Al_{0.90}Fe_{0.10})_6Si_6O_{18}(BO_3)_3(OH)_3(F_{0.6}OH_{0.4})$.

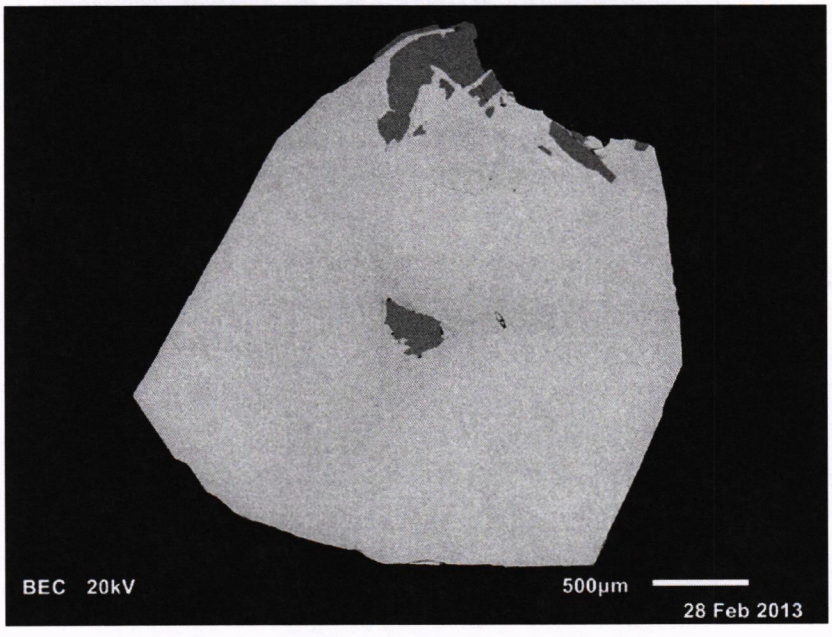


Fig. 13. Cross-section of an OH-rich fluor-schorl from Tennvatn, Sørfold, Nordland. The dark inclusions are quartz and albite. The crystal appears fairly homogeneous (the SEM photo was taken under conditions of maximum BSE contrast), although the F contents are highly variable according to spot analyses (see text). SEM micrograph (BSE mode) Uwe Kolitsch.

Ågskardet, Holandsfjord, Meløy, Nordland

Previous studies of a black prismatic tourmaline from this elbaite-rich LCT-pegmatite had revealed a F-rich (OH:F ~ 1:1), Al-rich schorl (Kolitsch et al. 2011). Analyses of elbaites from this locality are given by Larsen et al. (1999); however, the F contents were not measured. Strongly colour-zoned "elbaite" crystals (collected by TH) were investigated in detail to determine which colour corresponds to which species. These colour zonation may be divided into two types. The first one, typical of larger crystals, contains a dark grey-blue to blackish core, followed by a pale pink to nearly colourless area and a thin dark yellowish rim. The second type, typical of smaller crystals, is very similar, but lacks completely a dark core (Figs. 14-17).



Fig. 14. Hand specimen (11 x 8 x 4.5 cm) containing zoned tourmaline from Ågskardet, Holandsfjord, Meløy, Nordland. Although the crystal seems dark brownish, the colour is only caused by a thin brown-yellow outer rim (fluor-liddicoatite grading into Ca-rich fluor-elbaite) on a pale pink to nearly colourless core (fluor-elbaite). Photo Alice Schumacher.



Fig. 15. Zoned tourmaline from Ågskardet, Nordland (top view of a broken prism): Pale pink = fluor-elbaite, dark yellowish rim = fluor-liddicoatite to Ca-rich fluor-elbaite, dark brown, very thin rim = Fe-rich). Field of view 4.5 mm. Photo Harald Schillhammer.

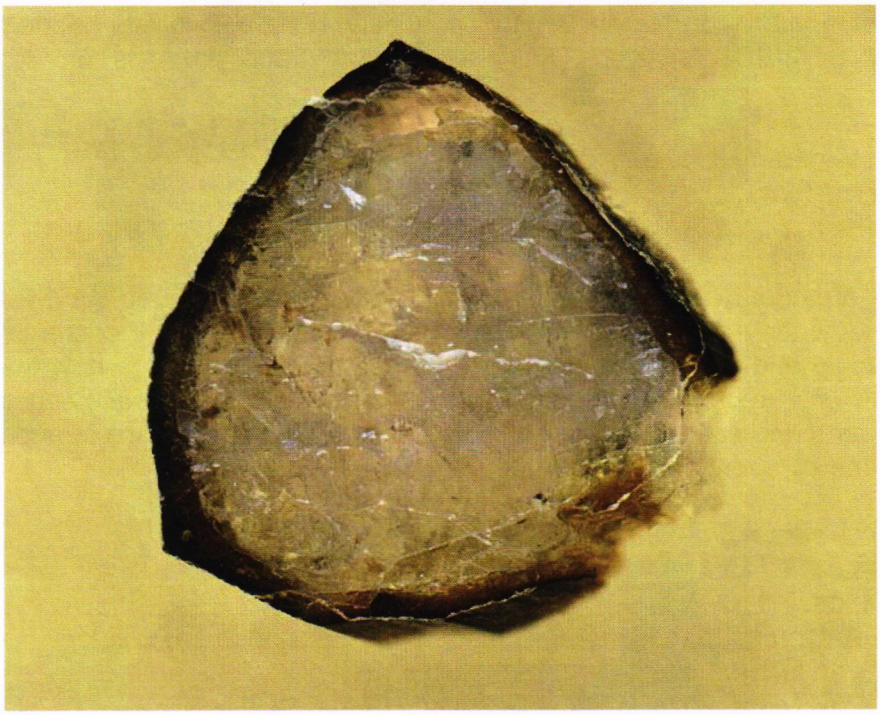


Fig. 16. Zoned tourmaline from Ågskardet, Nordland (view of a polished and carbon-coated cross-section of a prism embedded in pale yellow resin; the prism was taken from the same small specimen as that shown in Fig. 15). Pale pink = fluor-elbaite, dark yellowish rim = fluor-liddicoatite to Ca-rich fluor-elbaite, dark brown, very thin rim = Fe-rich. Field of view 5 mm. Photo Harald Schillhammer.

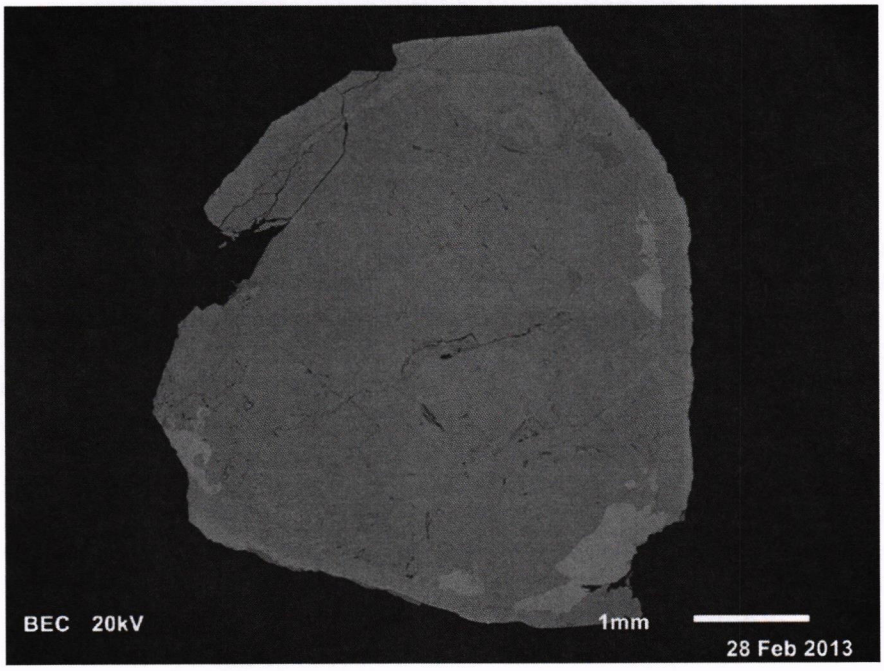


Fig. 17. Zoned tourmaline from Ågskardet, Nordland (SEM view of the same polished and carbon-coated cross-section shown in Fig. 16). For details see Figs. 18-19. SEM micrograph (BSE mode) Uwe Kolitsch.

A fragment of a dark core is shown to be (OH,O)-rich, possibly Li-bearing fluor-schorl, confirmed by SEM-EDS analyses which show only trace amounts of Mg and Mn as impurities.

Refined unit-cell parameters: a = 15.976(2), c = 7.148(1) Å.
Refined chemical formula:
~$(Na_{0.72}\square_{0.28})(Fe_{0.55}Al_{0.40}Li_{0.05})_3(Al_{0.97}Fe_{0.03})_6Si_6O_{18}(BO_3)_3(OH)_3(F_{0.6}OH_{0.4})$.

The pale pink areas of three different samples are very similar according to the results of the structure refinements. All are more or less Ca-rich fluor-elbaites with F contents very close to those of the ideal end-member. SEM-EDS analyses confirm this and show that, apart from minor Mn, the only impurity components are Ca and Fe, both in trace amounts. The Ca contents appear to increase, on average, from the core outwards. Trace Mg contents are not detectable in the core, only towards the rim.

Refined unit-cell parameters: a = 15.876(2), c = 7.116(1) Å.
a = 15.871(2), c = 7.115(1) Å.
a = 15.882(2), c = 7.118(1) Å.
Refined chemical formulae (only approximate since Li was not measured):
~$(Na_{0.8}Ca_{0.1}\square_{0.1})(Li_{0.25}Al_{0.62}Mn_{0.13})_3Al_6Si_6O_{18}(BO_3)_3(OH)_3F$.
~$(Na_{0.8}Ca_{0.1}\square_{0.1})(Li_{0.25}Al_{0.62}Mn_{0.13})_3Al_6Si_6O_{18}(BO_3)_3(OH)_3F$.
~$(Na_{0.8}Ca_{0.1}\square_{0.1})(Li_{0.25}Al_{0.62}Mn_{0.13})_3Al_6Si_6O_{18}(BO_3)_3(OH)_3F$.

The thin (brown-)green to brownish-yellow rim of a zoned "elbaite" prism was partly Na-rich fluor-liddicoatite, partly Ca-rich fluor-elbaite (Fig. 18-20). In both, the *W* site is fully occupied by F within error limits. Very similar results were obtained from the thin dark yellow rim of another zoned crystal. SEM-EDS line scans and elemental maps recorded from a polished cross-section of a zoned prism showed that the brownish to dark yellow, thin rim has the highest Ca-content in its central part.

Refined unit-cell parameters: a = 15.892(2), c = 7.120(1) Å.
a = 15.877(2), c = 7.115(1) Å.
Refined chemical formulae (only approximate since Li was not measured):
~$(Ca_{0.6}Na_{0.3}\square_{0.1})(Li_{0.15}Al_{0.65}Mn_{0.20})_3Al_6Si_6O_{18}(BO_3)_3(OH)_3F$.
~$(Ca_{0.6}Na_{0.3}\square_{0.1})(Li_{0.25}Al_{0.62}Mn_{0.13})_3Al_6Si_6O_{18}(BO_3)_3(OH)_3F$.

The outermost, very thin (20-50 µm) rim in one area of the polished crystal section has a Na-free composition (Al:Si ~ 1.75:1; very minor F, traces of Fe and Mn) that appears to correspond to rossmanite. However, the latter has the ideal formula $\square(Li_{0.33}Al_{0.67})_3Al_6Si_6O_{18}(BO_3)_3(OH)_3(OH)$ and therefore would require a lower Al:Si ratio of 1.33:1. Nonetheless, in an "oxy-rossmanite" from a pegmatite near Eibenstein an der Thaya, Lower Austria (Ertl et al. 2005), the Al:Si ratio approaches 1.58. Further small areas with the above Na-free composition were also observed in other, more inner parts of the crystal section, in immediate contact with fluor-elbaite. In one case a rossmanite-like tourmaline, which fills a thin crack within fluor-elbaite (Fig. 19), shows only trace amounts of Na, Fe and Mg, and very minor F, therefore indirectly indicating Li depletion in remnant hydrothermal solutions. Similar veinlets of rossmanite in the main mass of elbaite crystals from a granite pegmatite in China were described by Zhang et al. (2004). A more thorough characterisation of the Ågskardet rossmanite by single-crystal X-ray methods is planned, provided an extraction of phase-pure grains will be successful. According to the EDS data, it is possible that the chemical formula involves an "oxy" component. As rare inclusions and crack fillings in the crystal section, K-feldspar and quartz were observed.

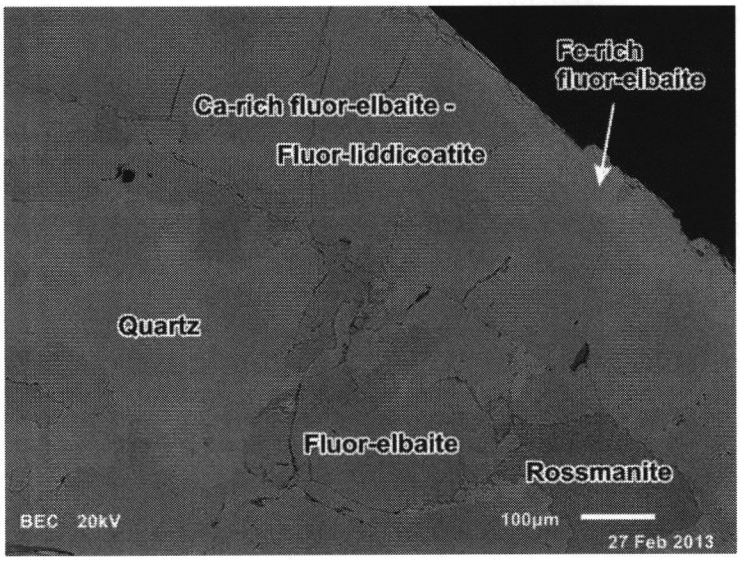


Fig. 18. Zoned tourmaline from Ågskardet, Nordland (area on top right of Fig. 17). SEM micrograph (BSE mode) Uwe Kolitsch.

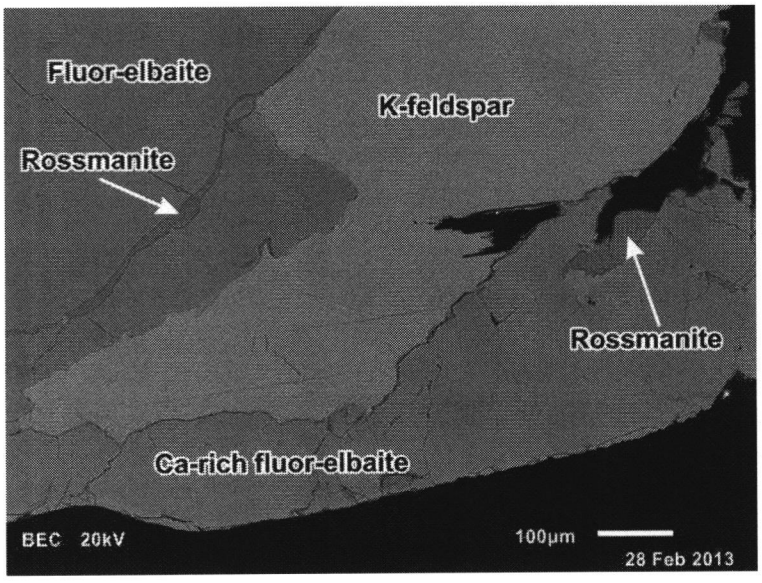


Fig. 19. Zoned tourmaline from Ågskardet, Nordland (area on bottom right on Fig. 17). SEM micrograph (BSE mode) Uwe Kolitsch.

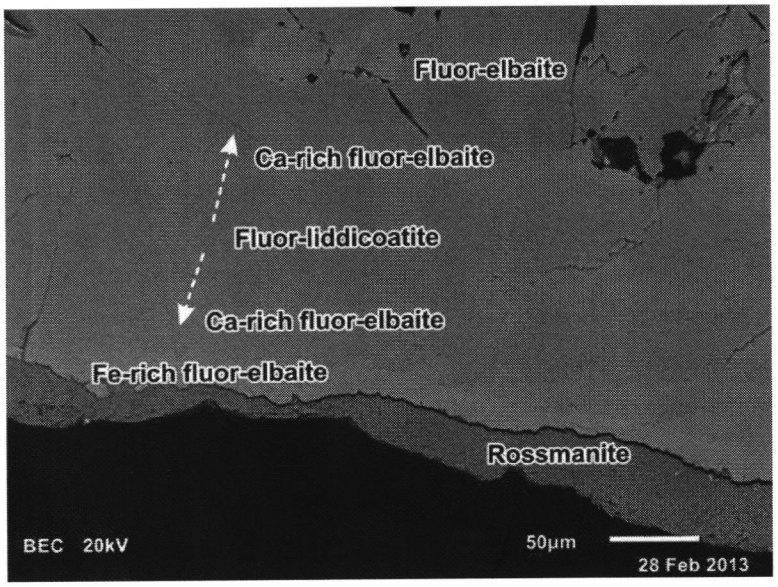


Fig. 20. Zoned tourmaline from Ågskardet, Nordland (area on bottom left on Fig. 17). SEM micrograph (BSE mode) Uwe Kolitsch.

Slunkajavre, Hamarøy, Nordland

In the Tysfjord granite, a recrystallized gneiss granite with annite, Fe-rich «hastingsite hornblende», fluorite and epidote-allanite (Foslie 1941, Andresen & Tull 1986), a number of quartz-microcline pegmatites of the NYF family, in part very rich in F-bearing mineral species (Husdal 2008), occur as lenticular bodies concordant with foliation of the granite. Outside of the Tysfjord granite area, different pegmatoid quartz-mica lenses occur which are hosted by a mica schist of Caledonian age. At Slunkajavre (in the area between Tennvatn and Drag, Tysfjord), there is a kyanite-bearing narrow quartz lens about 1-2 km long.
A dark brown to brown-black tourmaline was collected at this locality by AH and HVE in 1995. The structure refinement unambiguously indicated a dravite containing minor Fe and Ca, and no F at all. The <Z-O> distance of 1.929 Å indicates some Al-Mg disorder on the *Z* site. According to SEM-EDS analyses, the tourmaline contains Fe and Mg in the approximate ratio 3.5:1, and trace amounts of Ca and Ti.

Refined unit-cell parameters: a = 15.951(2), c = 7.202(1) Å.
Refined chemical formula:
~$(Na_{0.8}Ca_{0.06}\square_{0.14})(Mg_{0.79}Fe_{0.21})_3(Al_{0.9}Mg_{0.1})_6Si_6O_{18}(BO_3)_3(OH)_3(OH)$.

Hellstugubreen (Hellstugu glacier), Jotunheimen, Lom, Oppland

At this locality, a pegmatite is hosted by a metamorphic gabbro belonging to the Jotun Nappe Complex. Grains of a blackish tourmaline from Hellstugubreen were collected, along with garnet (probably almandine) and epidote, by AH and HVE in 1991. The refinement indicated an Al- or Mg-bearing schorl with only minor F contents and some Ca occupying the *X* site. Subsequent SEM-EDS analyses showed considerable Mg contents (which, along with Fe, fill up the *Y* site) and trace amounts of Ca, Ti and Mn. Therefore, the sample is a Mg-bearing schorl.

Refined unit-cell parameters: a = 16.009(2), c = 7.212(1) Å.
Refined chemical formula:
~$(Na_{0.9}Ca_{0.1})(Fe_{0.66}Mg_{0.34})_3(Al_{0.95}Fe_{0.05})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.8}F_{0.2})$.

Heimre Ilåbreen (Heimre Ilå glacier), Jotunheimen, Lom, Oppland

Similar to the Hellstugubreen locality, a pegmatite at Heimre Ilåbreen is hosted by a metamorphic gabbro belonging to the Jotun Nappe Complex. A black to partly dark brown tourmaline whose loose fragments in part showed numerous thin cracks was found at this locality by AH and HVE in 1982.
The refinement suggested an Al- and/or Mg-rich schorl, with not much F and apparently considerable Ca (+ K?). SEM-EDS analyses confirmed the presence of much Mg (Fe:Mg ~ 4:3, somewhat variable), distinct amounts of Ca (Na:Ca ~ 4:1) and also showed trace amounts of Mn and Ti.

Refined unit-cell parameters: a = 15.997(2), c = 7.212(1) Å.
Refined chemical formula:
~$(Na_{0.75}Ca_{0.20}\square_{0.05})(Fe_{0.59}Mg_{0.41})_3(Al_{0.97}Fe_{0.03})_6Si_6O_{18}(BO_3)_3(OH)_3(OH_{0.8}F_{0.2})$.

Lindvikskollen, Kragerø, Telemark

In our previous tourmaline study (Kolitsch et al. 2011), a black-brown tourmaline from the Lindvikskollen NYF-pegmatite could be identified as a Ca-, Al- and Mg-rich schorl containing minor F.

A further sample, collected by the first author in May 2011, was studied for comparison purposes. The sample, a large black, short prism (6 x 4 x 3.5 cm) was investigated by SXRD (no structure refinement, only determination of the unit-cell parameters) and detailed SEM-EDS analyses of a polished cross-section. The unit cell, a = 16.03 ± 0.01, c = 7.25 ± 0.01 Å, is slighter larger than that determined from the previously studied schorl sample (a = 16.005(2), c = 7.227(1) Å; Kolitsch et al. 2011), and indicates a comparatively higher Fe content.

The SEM-EDS analyses revealed an overall similar chemical composition (although with additional minor Ti contents and trace amounts of K and, in part, Mn) and negligible zoning. Of special interest were, however, macroscopically visible, pale yellowish inclusions in the polished cross-section (Fig. 21). These inclusions were found to mainly consist of prismatic, more or less euhedral fluorapatite (partly zoned, with some areas containing minor Na and Si, or Cl and Fe), highly inhomogeneous, eu- to anhedral zircon (with Fe, Hf, Ca, U, Al, REE and Ti as impurity elements), xenotime-(Y) (containing minor HREE) and monazite-(Ce) (in part very Nd-rich, with a Ce:Nd ratio of up to 5.3:5.0). The zircon, xenotime-(Y) and monazite-(Ce) are very often attached to the crystal faces of the fluorapatite. Xenotime-(Y) also occurs within fluorapatite.

As further inclusions, rare Nb- and Fe-bearing rutile, a single, tiny grain of an Y-, U- and P-bearing thorite, and a relatively common, highly inhomogeneous oxidic Y-Ti-Nb-Ta-U-(REE-Ca-K-Al-Fe-Si-Pb) phase (most probably an alteration product of an originally metamict phase) and an Y-Ca-(Be?-)silicate [hellandite-(Y)?] were observed.

Monazite-(Ce), xenotime-(Y) and rutile were previously not reported from the locality, although rutile was collected by Knut Edvard Larsen in 2009 (pers. comm., March 2013); it is also known from the nearby rutile mine (1901-1927) that worked on a rutile-bearing albitite.

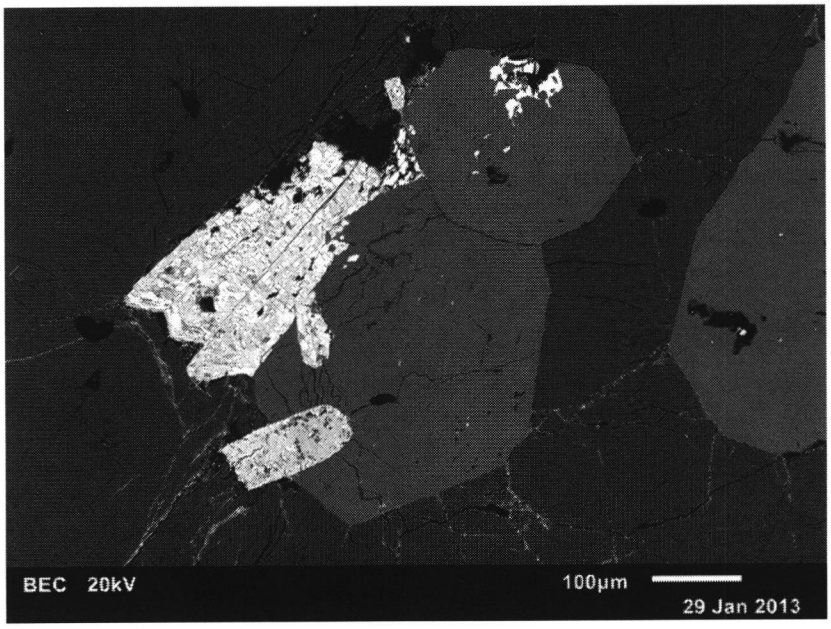


Fig. 21. Fluorapatite (grey, zoned), inhomogeneous zircon (more or less bright) and xenotime-(Y) (bright in fluorapatite, top), all as inclusions in a Ca-, Al- and Mg-rich schorl (dark grey) from Lindvikskollen, Kragerø, Telemark (polished section). SEM micrograph (BSE mode) Uwe Kolitsch.

Conclusions

Ongoing studies of the crystal-chemistry of tourmalines from Norway revealed surprising results. Luinaite-(OH) is confirmed for the first time from several nepheline syenite pegmatites in the Langesundsfjord area, but is visually indistinguishable from "normal" schorl which also occurs in these pegmatites, within more or less identical parageneses and with very similar chemical composition. In one case (Midtfjellet quarry) both species occur in the same quarry. This suggests that luinaite-(OH) may originate due to different (slower?) cooling paths and/or overall temperature conditions.
From the chemical compositions of the studied luinaite-(OH) samples, it can also be concluded that the occurrence of this species requires high Fe contents in the mineralising hydrothermal solutions, and almost no Mg contents. Although all Langesundsfjord area samples have a relatively similar composition, the luinaite-(OH) samples are characterised by a comparatively higher Fe content. The latter is also reflected by the considerable Fe-for-Al substitution on the *Z* site (up to $Al_{0.87}Fe_{0.13}$). Similarly high Al:Fe ratios were found in the luinaite-(OH) from Hundholmen, Tysfjord ($Al_{0.85}Fe_{0.15}$ and $Al_{0.87}Fe_{0.13}$, Kolitsch et al. 2011).

The *X* site (Na site) in all the Langesundsfjord tourmalines is almost fully occupied, a feature attributed to very Na-rich hydrothermal solutions from which the crystals grew (analcime is always closely associated with these tourmalines).

Finally, we conclude that none of the studied samples from Norway contains any significant B at the *T* site.

Acknowledgements

The authors thank Harald Schillhammer and Alice Schumacher for colour photography. Roy Kristiansen is thanked for providing a tourmaline from Sandvann. Knut Edvard Larsen pointed the first author to the description of a black tourmaline in Brøgger (1890) and Jörgen Langhof kindly provided part of the material described by Brøgger (1890).

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