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Yttrian epidote and allanite-(Y) from a granite pegmatite in Bamble, Telemark, Norway

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Introduction

The pegmatites in the Bamble-Kragerø district have generally been regarded as rather poor in accessory minerals. Exceptions are the pegmatites in the vicinity of Kragerø city (Kalstadgangen, Lindvikskollen and Tangen quarries). Black tourmaline (mostly schorl), however, is widespread. These facts were pointed out already by Brøgger (1906) and confirmed through the descriptions of pegmatite localities in Bamble-Kragerø district by Andersen (1926, 1931) and Bjørlykke (1939). During an ongoing registration work on granite pegmatite quarries in Telemark county carried out by AOL it was therefore quite unexpected to find lumps up to several kilograms of an allanite-like mineral in a small pegmatite quarry at Kverndalen, Skogstad, Bamble in August 2015 (WGS 84: N58.99179°, E9.55021°). The first analysis showed that the mineral is an yttrium rich epidote group mineral (EGM). The extraordinary composition prompted the following study of the mineral.

REE-bearing epidote group minerals

The general formula of epidote group minerals is $A_2M_3[T_2O_7][TO_4]O(OH)$. The key cation- and anionsites in the different allanite group minerals are shown in Table 1. The relationship between epidote and allanite group minerals can be expressed with the substitution Ca + Fe³⁺ (epidote) $\leftrightarrow REE^{3+}$ + Fe²⁺ (allanite).

Allanite was first described by Thomson (1811) and named in honor of Thomas Allan (1733-1833), the Scottish mineralogist who discovered the mineral in a collection from East Greenland. A few years later, a new mineral named orthite was described from Sweden by Berzelius (1818). The name allanite was used for tabular, non-metamict varieties, while orthite was reserved for prismatic, metamict crystals from pegmatites. The two minerals were for many years regarded as identical species. The name allanite, however, has historical precedence over orthite, which is now obsolete (Nickel & Mandarino 1987). The allanite-orthite history has been described in detail by Alekseev *et al.* (2013). The introduction of the Levinson suffix (Levinson 1966) divided allanite (*sensu lato*) into several species, now members of the allanite subgroup of the epidote supergroup (Armbruster *et al.* 2006).

Members of the allanite subgroup that are usually found in granite pegmatites are shown in Table 1. In addition, there are at least 14 more species of the allanite subgroup, many of them dominated by either Mn^{2+} , Mn^{3+} , V^{3+} or Mg. Most of them are regarded as very rare species. A thorough compilation of the epidote group is given in <u>www.mindat.org/mesg-71-359316.html</u>.

Table 1. Species of the allanite subgroup with the key cation- and anion-sites.

Name	A1	A2	<i>M</i> 1	M2	<i>M</i> 3	T	04	O10
Allanite-(Ce)	Ca	$(Ce, REE)^{3+}$	Al	Al	Fe ²⁺	Si	0	OH
Allanite-(La)	Ca	$(La, REE)^{3+}$	Al	Al	Fe ²⁺	Si	0	OH
Allanite-(Nd)	Ca	$(Nd, REE)^{3+}$	Al	Al	Fe ²⁺	Si	0	OH
Allanite-(Y)	Ca	$(Y, REE)^{3+}$	Al	Al	Fe ²⁺	Si	0	OH
Ferriallanite-(Ce)	Ca	$(Ce, REE)^{3+}$	Fe ³⁺	Al	Fe ²⁺	Si	0	OH
Ferriallanite-(La)	Ca	$(La, REE)^{3+}$	Fe ³⁺	Al	Fe ²⁺	Si	0	OH

Geology and mineralogy of the Kverndalen pegmatite

Most of the pegmatite bodies in the Bamble-Kragerø district are believed to represent mobile fractions derived from partial anatexis of metasedimentary and metavolcanic sequence during the upper-amphibolite to granulite facies metamorphism with a Sveconorwegian age of 1070-1100 Ma (Morton *et al.* 1970; Kullerud & Dahlgren 1993).

The Kverndalen pegmatite is a pear-shaped body, around 40 m in length and 12 m on the widest, pinching out towards west (Fig. 1). The pegmatite strikes E-W, conformable with the foliation of the surrounding granitic gneiss. The pegmatite body has a 30 cm thick, relatively fine-grained wall zone. The core of the pegmatite body consists of beige, perthitic K-feldspar, yellowish white plagioclase and quartz. A slightly altered, black amphibole is common as coarse crystals up to 20 cm in length and 5-8 cm thick. Biotite is present as flakes up to 20-30 cm across. The epidote group mineral (EGM) was found as loose, massive lumps. The biggest fragment had a weight of 20 kg and was obviously a part of a larger crystal. Small amounts of titanite (partly altered into anatase), zircon, fergusonite-(Y) and uraninite (partly altered to "gummite") are present. A monomineralic mass of quartz, 11 m long and 7 m wide, occurs in the widest part of the pegmatite. Coarse graphic granite is a common constituent of the pegmatite.

The shallow quarry is situated in a hillslope and is about 18×5 m. It was worked for feldspar probably in the 1920's. Further history about the quarrying operation is unknown today.



Fig. 1. Geological and topogra-phical sketch map showing the situation of Kverndalen pegmatite (in red). Pale rose is granitic gneiss. Slashed lines indicate the site of the quarry. Dotted area shows the mono-mineralic mass of quartz. Contour lines at 1 meter equidistance.

Physical and optical properties

The Kverndalen EGM is pitch black in hand specimens, but shows a pale bottle green colour in very thin splinters. The mineral is completely isotropic due to its metamict state. The refractive index $n_D = 1.682 \pm 0.002$. The EGM shows a conchoidal fracture and has a greyish green streak (powder). The density measured by a pycnometer is 3.17 g/cm³. When heated above red heat the mineral effervesces, swells to several times its original volume and melts.

X-ray crystallography

The Kverndalen EGM was investigated using a Panalytical X'pert diffractometer. The powder diffraction pattern consists of a high background superimposed by a few, very broad and weak diffraction peaks corresponding to the major peak positions of minerals of the allanite group. This is consistent with the nearly completely metamict state of the mineral. Heating at 1000° C in air decomposes the mineral into a mixture of phases that can be identified as anorthite, hematite and britholite. The same phases were identified from annealed allanite by Janeczek & Eby (1993).

Chemical composition

Chemical composition of the Kverndalen EGM was determined using a CAMECA SX100 electron microprobe (EMP) analyzer operated in wavelength dispersive mode at an accelerating voltage of 15 kV, a sample current of 20 nA and a beam diameter of 8 μ m. Back-scattered electron (BSE) images show that the EGM is rather heterogeneous (Fig. 2*a*, *b*, *c*) and partly replaced by secondary minerals (gadolinite-(Y) and a hellandite-like phase) in small, confined areas and along fractures (Fig. 2*b*, *c*). The analytical results are shown in Table 2. The lower part of Table 2 shows the *apfu* of Ca, Y and *REE*, where 1 Ca *pfu* fills up the *A*1 position and the rest is distributed into the *A*2 position together with the total *REE*. From these calculations it is evident that the Kverndalen EGM is close to the midpart of solid-solution between epidote and allanite-(Y); some domains are Y-rich epidote, while other domains are allanite-(Y).



Fig. 2. BSE SEM images showing the inhomogenity of the Kverndalen EGM with its secondary, alteration minerals. SEM image by R. Škoda. Carefully handpicked material was dissolved in a mixture of hydrofluoric acid and sulphuric acid and analysed by ICP-MS. The results for the main and minor elements are in good accordance with the EMP analyses. In addition, the following elements were quantified: $Li_2O 0.009$ wt.%, BeO 0.07 wt.%, 0.19 % B_2O_3 , and PbO 0.04 wt.%.

Water was determined using a LECO RC412 analyzer by heating the sample from room temperature and up to 1100 °C with concomitant recording of the amount of released water. From handpicked material the total amount of water was measured to be 6.5 wt.% H₂O, released in three distinct stages (Fig. 3). The first stage (1.5 wt.% H₂O) is due to loss of absorbed water, while the second and third stages (3.0 wt.% and 2.0 wt.% H₂O, respectively) are due to dehydroxylation. The total amount of water is approximately what is missing / the deficiency in EMP analytical data in order to reach a total of 100 wt.%.



Fig. 3. Curve from the LECO RC412 analyzer showing the three stages of released water as a function of temperature. See text for details.

Discussion

Fleischer (1985) compared analytical data of 506 allanites and 53 REE-bearing epidotes. He found that 497 of the allanites were Ce dominant, and the average Y content of 114 allanites from granite pegmatites was just 9.6 atomic-% of the total Y+REE content. This is a solid proof that yttrium rich members of the allanite group are of rare occurrence. In Norway allanite-(Y) has been identified from the Hundholmen pegmatite, Tysfjord, Nordland (Husdal 2008). However, relatively few allanites from Norway have been chemically analyzed in modern time. An ongoing project will hopefully shed light on this issue.

A question may be raised if the *REE* distribution in the EGM reflects the *REE* content of its host rock, or alternatively, if it is petrogenetic processes that controlled the *REE* abundance in the EGM. No data exist today about the *REE* content and distribution in the actual region and these questions remain open.

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Table 2. Chemical analyses by EMP (wt.% and apfu) of the Kverndalen REE minerals. 1-4: EGM, calculated on 3 Si pfu.

5: Hellandite-like mineral, calculated on 8 Si pfu.

6: Gadolinite-(Y), calculated on 2 Si pfu.

	1	2	3	4	5	6
SiOa	34.09	34.07	33.99	34.45	33,30	26.07
TiO	0.18	0.18	0.19	0.19	0.21	0.00
AlaOa	19.23	18 75	19.08	18.97	7.61	0.00
ThO	0.29	0.26	0.25	0.22	0.31	0.02
	0.17	0.15	0.20	0.22	0.36	0.05
$\mathbf{Y}_{2}\mathbf{O}_{2}$	8 39	7 94	7.80	8 13	19.12	35.99
1203 LaoOa	0.03	0.04	0.04	0.04	0.05	0.00
	0.05	0.10	0.13	0.13	0.05	0.00
Pr ₂ O ₂	0.10	0.00	0.13	0.00	0.13	0.02
Nd ₂ O ₂	0.03	0.00	0.04	0.03	0.04	0.02
Sm_2O_3	0.13	0.03	0.10	0.03	0.10	0.01
Gd_1O_2	0.04	1.09	1.07	1.06	1.01	1 79
Ou_2O_3 TheO-	0.55	0.04	0.10	0.08	0.35	0.05
D_2O_3	1.41	1.44	1.53	1.44	2.80	3.24
Dy_2O_3 Ho.O.	0.22	0.25	0.10	0.22	0.59	0.08
$F_{r}O$	0.22	0.25	0.19	0.22	0.59	2.00
EI_2O_3	0.51	0.49	0.45	0.52	0.12	0.09
111_2O_3	0.02	0.00	0.00	0.00	0.13	0.27
10_20_3 MgO	0.15	0.16	0.17	0.17	0.52	1.52
MgO EaO	12 22	0.13	11.22	0.03	0.02	0.02
FeO MrO	12.52	11.67	0.71	10.79	4.30	9.30
	0.75	0.70	0.71	0.75	0.50	0.05
CaO N= O	14.47	14.80	13.97	0.10	15.10	5.05
Na ₂ O	0.07	0.10	0.09	0.10	0.07	0.03
	0.04	0.01	0.04	0.04	0.11	0.07
Total	93.87	92.85	93.49	93.56	89.00	85.89
		2 000		2 0 0 0	0.000	
S1	3.000	3.000	3.000	3.000	8.000	2.000
Ti	0.012	1.946	0.012	0.012	0.039	-
Al	1.994	0.005	1.984	1.947	2.154	-
Th	0.006	0.005	0.005	0.004	0.017	-
U	0.003	0.003	0.004	0.005	0.019	0.001
Y	0.393	0.372	-	0.377	2.444	1.469
La	0.001	0.001	0.366	0.001	0.005	-
Ce	0.003	0.003	0.001	0.004	0.013	-
Pr	0.002	-	0.001	-	0.003	-
Nd	0.004	0.005	0.005	0.001	0.009	-
Sm	0.001	0.001	0.001	0.001	0.002	-
Gd	0.029	0.032	0.031	0.030	0.152	0.046
Tb	0.003	0.001	0.003	0.002	0.028	0.001
Dy	0.040	0.041	0.043	0.041	0.217	0.080
Ho	0.006	0.007	0.005	0.006	0.045	0.024
Er	0.014	0.014	0.013	0.014	0.095	0.075
Tm	0.001	-	-	-	0.010	0.006
Yb	0.004	0.005	0.005	0.004	0.038	0.036
Mg	0.019	0.017	0.004	0.003	0.006	0.003
Fe	0.907	0.874	0.828	0.786	0.903	0.613
Mn	0.054	0.052	0.053	0.054	0.061	0.003
Ca	1.365	1.402	1.510	1.487	3.903	0.251
Na	0.012	0.018	0.015	0.017	0.034	0.004
F	0.010	0.003	0.012	0.011	0.085	0.016
AI(Ca)	1.000	1.000	1.000	1.000		
A2(Ca)	0.365	0.402	0.510	0.487		
A2(Y+REE)	0.501	0.482	0.479	0.483		

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