

# A unique assemblage of Scandium-bearing minerals from the Heftetjern-pegmatite, Tørdal, south Norway

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*At the very end of the 20th century or at the beginning of the 3rd millennium we are about to encounter one of the most interesting geochemical and mineralogical discoveries in Norway in modern time, viz. probably the richest diversity of Scandium-bearing minerals in the world, with 8 different Scandium-minerals + an additional 14 species with Sc-content > 0,5 % wt. Sc<sub>2</sub>O<sub>3</sub> and 10 minerals between 200 – 3000 ppm Sc.*

## INTRODUCTION

The centennial of the first discovery of a true scandium mineral in nature, viz. thortveitite (Sc<sub>2</sub>Si<sub>2</sub>O<sub>7</sub>), was marked by an International symposium on the Mineralogy and Geochemistry of Scandium in August 2003 in Oslo, organized by the Geological Museum, University of Oslo (Raade & Segalstad 2003). Up to 2003, only ten scandium minerals have been described. In the last twenty years there has been an increasing interest world-wide in scandium minerals and their formation, as well as in the utilisation of scandium in fields of technical application, like high-strength Sc-Al alloys.

There is also an increasing number of publications on the mineralogy and geochemistry of Scandium, including the discovery of several new species, viz. pretulite (Bernhard et al. 1998, Moëlo et al. 2002) - the Sc-analogue of xenotime; juonniite (Liferovich et al 1997) - the Sc-analogue of overite and robertsite; scandiobabingtonite (Orlandi et al. 1998, Gramaccioli et al. 1998, Raade & Erambert 1999) - the Sc-analogue of babingtonite; kristiansenite, with a new structure type (Ferraris et al. 2001, Nespolo et al. 2001, Nespolo 2004, Nespolo & Ferraris 2004, Ferraris et al. 2004, Raade et al. 2002); the scandium-dominant analogue of milarite named oftedalite (Cooper et al. 2005, Hatert & Burke 2008, Kristiansen 2005), and recently the first natural scandium oxide, heftetjernite, the natural analogue of synthetic monoclinic ScTaO<sub>4</sub> (Kolitsch et al. 2009); the three latter from the type locality at Heftetjern in Tørdal, in the county of Telemark, Norway.

New data of Scandium-minerals from Baveno were published by Pezzotta et al. (1999, 2005), and Gramaccioli et al. (2004), as well as papers on the formation of Scandium minerals (Gramaccioli et al. 1999, 2000), and experimental report by Shchekina & Grametutskii (2008).

Besides there are several papers focused on the Sc-content in niobates and tantalates as well as in other minerals (Badanina et al. 2008, Bernhard 2001, Bergstøl & Juve 1988, Foord et al. 1993, Novak & Cerny 1998, Wise et al. 1998, Pezzotta et al. 1999, Gramaccioli et al. 1999, Cerny et al. 2000, Cerny & Chapman 2001, Gramaccioli et al. 2000, Raade & Kristiansen 2003, Okrusch et al. 2003, Shimazaki et al. 2008)

A new type of Scandium mineralization has been reported from Russia (Liferovich et al. 1998). Borisenko & Polikashina (1991) and Solodov et al. (1991) reported on recommendations for the exploration/exploitation of Scandium.

Extra-terrestrial scandium-phases have been reported by Weber & Bischoff (1994), as inclusions in carbonaceous chondrites: Ca<sub>2</sub>Sc<sub>4</sub>Al<sub>6</sub>TiO<sub>19</sub> and Sc<sub>2</sub>Zr<sub>2</sub>O<sub>7</sub>, named respective "Sc-hibonite", and "Sc-zirkelite" by Semenov (2001). These are, however, not valid names. The latter phase (loc.cit) may be related or identical to the new species allendeite,

$\text{Sc}_4\text{Zr}_3\text{O}_{12}$ , found as inclusions in the Allende meteorite (Ma et al. 2009). Another approved species is IMA 2008-030 = davisite, also identified in the Allende meteorite.

El Goresy et al. (2002) and Lin et al. (2003) describes Sc-Zr-rich fassaites in carbonaceous chondrites with up to 16.4%  $\text{Sc}_2\text{O}_3$ .

Since the description of the first true Scandium-mineral thortveitite (Schetelig 1911) only eight more Sc-minerals were described in the 20<sup>th</sup> century, but six of these were described in the last two decades. Thortveitite is the most common of them (Kristiansen 1997), and the mineral is reported mostly from granitic pegmatites, but also from carbonatites, greenstone, volcanoclastic breccia and others. Discoveries and investigation of thortveitite is still continuing today (Kimata et al. 1998, Nishida et al. 1999, Gramaccioli et al. 2000), and additional findings are reported from time to time, like Germany (Witzke 2003), in France (Gatell et al. 2002, Marty 2004), Poland (Chabros et al. 2002), New Caledonia (Spandler et al. 2004), Canada (Potter & Mitchell 2005), and lately reported as a gemstone, originally bought as a pebble on the market in Bangkok (Chapman et al. 2008).

Other scandium-minerals are less common, like kolbeckite (Dill et al. 2006), and bazzite (Artini 1915, Armbruster et al. 1995, Demartin et al. 2000), the latter recently reported from Sweden (Nysten & Gustafsson 2006) and Japan (Endo 2007), or very rare, restricted to a few locations in the world, like cascandite, scandiobabingtonite, jervisite, and pretulite (Mellini et al. 1982, Orlandi et al. 1998, Bernhard et al. 1998, Moëlo et al. 2002, Merlino & Orlandi 2006).

Several unknown phases are known, but still not characterized, like:

- 1) a tentatively identified unstable hydrous Sc-carbonate in microscopic veins in alkaline metasomatites in Ukraine (Pavlishin et al. 1993);
- 2) a grey Sc-Al-silicate from the Animikie Red Ace pegmatite in Wisconsin, USA, by Falster et al. (1996);
- 3) a Sc-arsenate,  $\text{ScAsO}_4$ , from Varenche Mn-mine, Italy (Barresi et al. 2005), the P-analogue of kolbeckite, and isomorphous with metavariscite (Yang et al. 2007).
- 4) an exsolution phase,  $\sim (\text{Sc Fe}^{3+}) (\text{Nb,Ta})\text{O}_4$  in niobian rutile from Håverstad, Iveland, Norway, by Cerny et al. 2000, 2001.
- 5) and two new Sc-phases from a Hagendorf-locality in Germany (Dill et al. 2008) viz.
  - K-Ba-Sc-Zr-phosphate
  - Zr-Sc-phosphate silicate

Hopefully some of these will be characterized, and approved as new species.

In spite of the rather wide distribution of scandium in the lithosphere (21.9 ppm), only eleven scandium minerals has been defined as such, so far, excluding the two extraterrestrial (table 1). However, the great bulk of Sc is contained in the ferromagnesian minerals, which explains the rarity of minerals containing Scandium as an essential constituent.

Discoveries of new scandium-minerals may be expected in the years to come, as we know that Sc may substitute for  $\text{Fe}^{3+}$  -  $\text{Al}^{3+}$  in pyroxenes and amphiboles in Sc-rich environment (Foord et al. 1991). According to Frondel (1968), scandium in the ferromagnesian minerals apparently substitutes for iron in sites occupied by either ( $\text{Fe}^{3+}$  Al) or ( $\text{Fe}^{3+}$ , Mg). Scandium can also form limited solid solution with  $\text{Y}^{3+}$ Al, the heavy lanthanides,  $\text{Ti}^{4+}$ ,  $\text{Sn}^{4+}$ ,  $\text{Zr}^{4+}$  and  $\text{W}^{6+}$  in certain geochemical environments.

Before 1988 thortveitite was the only scandium-mineral in Norway. Today we know eight species of which three are new to science: kristiansenite, oftedalite and heftetjernite, in addition to cascandite, scandiobabingtonite, bazzite, pretulite and the orthorhombic scandian ixiolite\* (Juve & Bergstøl 1990, Raade & Erambert 1999, Ferraris et al. 2001,

Raade et al. 2002, Eldjarn 2002, Ellingsen & Haugen 2002, Kristiansen 2005, Cooper et al 2006, Kolitsch et al. 2009, Rondeau et al. 2008).

\* which is new if Sc exceeds the other elements in the cation-disorder ixiolite structure.

As a curiosity we may mention that the first and last discovered Sc-mineral in the 20th century were both found by Norwegian amateur-mineralogists, and named after them, viz. thortveitite and kristiansenite.

This compilation is mainly devoted to the scandium-minerals and scandium-bearing minerals at Heftejern as a result of ten years of collecting and investigation in the period 1998-2008.

The complete description of the mineralogy of the pegmatite is not provided except for an updated list of all mineral species found, so far (table 2).

Most of the background and geological informations is quoted from several sources (Bergstøl & Juve 1988, Raade & Kristiansen 2000a, 2000b, Raade et al. 2002 etc.), but more or less modified, which is essential for completeness to understand the scandium mineralization in the Heftejern pegmatite.

TABLE 1. Scandium minerals of the world – in chronological order of description.

MINERAL	TYPE LOCALITY	DESCRIBED	IN NORWAY
Thortveitite	Iveland, Norway	1911	Yes
Bazzite	Baveno, Italy	1915	Yes
Kolbeckite	Schmiedeberg, Germany	1926	
Cascandite	Baveno, Italy	1982	Yes
Jervisite	Baveno, Italy	1982	
Juoniite	Kovdor, Kola, Russia	1997	
Scandiobabingtonite	Baveno, Italy	1998	Yes
Pretulite	Styria, Austria	1998	Yes
Kristiansenite	Heftejern, Norway	2002	Yes
Oftedalite	Heftejern, Norway	2006	Yes
Heftejernite	Heftejern, Norway	2009	Yes
EXTRATERRESTRIAL			
Allendeite	Allende-meteorite	2009	
Davisite	Allende-meteorite	2009	

### History, geology and geochemistry of the Heftejern-pegmatite in Tørdal

The numerous granite pegmatites of the Tørdal area are situated within the Nissedal volcano-sedimentary outlier. Both the outlier (1300-1200 Ma) and the older basement (1520-1500 Ma) are intruded by the Tørdal granite (960-850 Ma) which is regarded as the source of the pegmatite swarms (Bergstøl & Juve 1988). Rb-Sr dating of lepidolite and microcline from Skarsfjell pegmatite gave ages between 950 and 880 Ma (Neumann 1960), but Kulp et al. (1963) estimated the age to be closer to 1000 Ma. From trace-element analyses of different rock types it has been suggested that some of the tin and a major part of scandium in the amazonite-cleavelandite pegmatites of the area probably have their source in the volcanogenic rocks of the Nissedal outlier, which were penetrated by the pegmatitic fluids (Bergstøl & Juve 1988).

The Tørdal area in Telemark is geochemically different from other granite pegmatites in south Norway, being characterized by tin, scandium, beryllium and lithium. Amazonite-cleavelandite pegmatites in Høydalen and at Skarsfjell were described by Oftedal (1942). Here lithium occurs in lepidolite and zinnwaldite, and tin in cassiterite.

Already in 1943 Oftedal found that the brown Li-micas from Skarsfjell showed an higher Sc-content than the micas from thortveitite-bearing dykes in Iveland (Setesdal).

Additional findings in these pegmatites were reported by Bergstøl et al.(1977), Raade et al. (1993) and Kristiansen (1998).



Fig. 1. John P. Tveit (1909-1978), landowner and the first to blast at the Heftetjern pegmatite. He is the namesake of tveitite-(Y).

### Geochemistry of the Heftetjern pegmatite

The most striking geochemical feature of the Heftetjern pegmatite is the high level of scandium. Seven minerals with scandium as a major element are now known from the pegmatite, viz. bazzite, cascandite, scandiobabingtonite, thortveitite, the type species kristiansenite (Ferraris et al. 2001, Raade et al. 2002), oftedalite (Raade & Kristiansen 2000a & 2000b, Hawthorne 2002, Cooper et al. 2006), and the new heftetjernite (Kolitsch et al. 2009). In addition, several minerals containing scandium at levels up to several wt.%  $\text{Sc}_2\text{O}_3$  have been encountered (Raade et al. 2002, Raade & Kristiansen 2003).

Bergstøl and Juve (1988) have shown that some of the tin and a major part of scandium in the amazonite-cleavelandite pegmatites of the area may have their source in volcanogenic rocks of the Nissedal outlier, which were penetrated by the pegmatitic fluids. The Heftetjern and Høydalen pegmatites are situated less than 1 km apart (but at different altitude, ~ 450 resp. ~ 650 m asl), and yet there are major differences in their geochemistry, the former showing a remarkably strong concentration of scandium and the latter being enriched in lithium and fluorine, elements that are typically concentrated in fluids derived from granitic magmas.

Interesting is the observations by Radek Skoda (pers. comm. 2007) who reports that he have found high content of scandium in the primary biotite, and low content of Sc in the chlorite it originated from. That means during chloritization of biotite a lot of Sc was released, and may well be a source for the formation of the late hydrothermal Sc-minerals in vugs and fissures.

It is no doubt that scandium is the most common distributed rare element at Heftetjern, conf. table 3 and 4, - not only represented as seven different genuine scandium-minerals, but also as 14 species with > 0.5 wt.%  $\text{Sc}_2\text{O}_3$ , besides an additional 10 minerals with 200 – 3000 ppm Sc! That is unique, in my opinion.

Beryllium is another widely distributed element with no less than 11 different species. The most common is beryl, mostly yellow in colour, and gadolinite-(Y). Next comes milarite. The secondary minerals bertrandite, bavenite, and hingganite-(Y) appears occasionally. Milarites with high yttrium, also reported from Canada, Brazil and Sweden (Cerny et al. 1991, Nysten 1996) are rare at Heftetjern, and may represent the the new species already postulated by Hawthorne (2002) with an ideal formula  $\text{K}(\text{CaY})\text{Be}_3\text{Si}_{12}\text{O}_{30}$ , and  $\text{Y} > \text{Ca}$ .

Tin (Sn) is an interesting element and represented by cassiterite, although not common, and often altered with porous surface, occasionally with inclusions of kristiansenite and rynersonite, as well as stannian microlite, and may be the very rare tantite (Raade et al. 2002). But it seems that tin is an essential substituent in the morphological- and color-variable titanites, which occur rather often as a late stage mineral in vugs and fissures, with up to 13 wt.%  $\text{SnO}_2$ , which is on its way to the tin-analogue of titanite, - malayaite.

And thortveitite have a remarkable high content of Sn, reaching a maximum of 5.67 wt.%  $\text{SnO}_2$  (Raade et al. 2004). Conf. thortveitite.

And minerals of the pyrochlore-microlite group contains from 1-5 wt.%  $\text{SnO}_2$ , while the scandian ixiolite may attain 13 wt.%  $\text{SnO}_2$ .

Tantalum is more abundant than Nb in the niobate-tantalates at Heftetjern.



*Fig 2. Sveinung Bergstøl, the author and Gunnar Juve (Kongsberg 2002).*



*Figure 3. Blasting at Heftetjem September 1998. From left Hans Jørgen Berg, the land-owner Kaj Peder Tveit and Harald Folvik.*

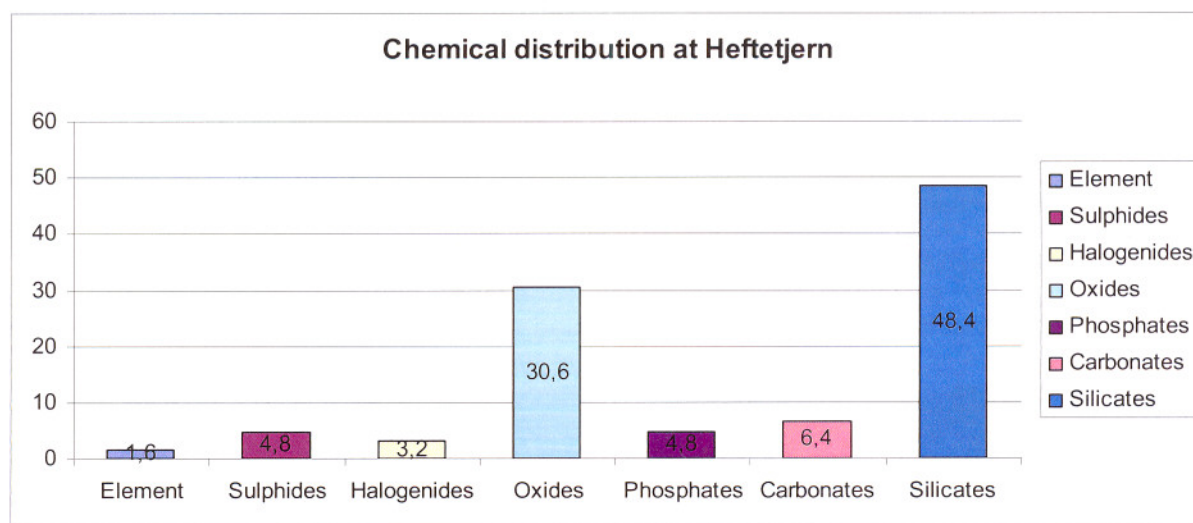
Yttrium is absolutely dominant among the REE-minerals, with monazite-(Ce) and allanite-(Ce) as an exceptions.

In contrast to the Høydalen mine (Kristiansen 1998) with 8 fluorine-minerals, - Heftetjern have only ONE, – yttrian fluorite, and some F in the micas. No trace of topaz.

Among the alkali metals Caesium is a significant element like the exceptional high content reported in bazzite up to 8.55 wt.%  $\text{Cs}_2\text{O}$  (Raade et al. 2004), while Juve & Bergstøl (1990) reported ca 3% in their first paper on bazzite in Norway.

Some of the host minerals like microcline, beryls and the dark micas shows high contents of not only Cs, but also Rb; dark micas 11400 ppm Rb, and Cs 400 ppm (Raade & Kristiansen 2003). Bergstøl (pers.comm. 2007-2008) found already in the 1980-ties high Cs and Rb in the different micas from Heftetjern, - a project that unfortunately was left without final results. Ca is a common element in many minerals.

The majority of minerals at Heftetjern are silicates, ca 50 %, while oxides comes next with ca. 30% .



Geochemically, the Tørdal area has been regarded as a lithium-scandium-tin province (Ofteidal 1956), and he discussed the behaviour of certain elements during the replacement of amazonite pegmatite by cleavelandite pegmatite in the Tørdal area.

Following Cerny (1992), the Tørdal pegmatites are of a mixed LCT-NYP family. The LCT family typically carries Li, Rb, Cs, Be, Sn, Ga, Ta>Nb, (B, P, F) and the NYP family is marked by a Nb>Ta, Ti, Y, Sc, REE, Zr, U, Th, F signature.

#### Activities in the Heftetjern pegmatite.

The Heftetjern cleavelandite-amazonite pegmatite, named after the small tarn Heftetjern, is situated in a marshy area between Høydalen and Skarsfjell in Tørdal, southern Norway, at an altitude of ~ 650 m above sea level, at 59° 8.6' N 8° 45.4' E.

The pegmatites in this area were first exposed by some small blastings performed by the land-owner, the late John P. Tveit (1909-1978) (Fig. 1) in the early 1970's mainly looking for good-quality amazonite, which he had been quarried since the early 40's in his amazonite-lepidolite pegmatite in the nearby Høydalen quarry (Ofteidal 1943, Kristiansen 1998).

The mineralogy of this pegmatite and the general geology of the area were described by Bergstøl & Juve (1988) (Fig.2), who reported on an unusual occurrence of a scandian ixiolite with up to ~ 19%  $\text{Sc}_2\text{O}_3$  and scandian members of the pyrochlore-microlite group. Shortly after they also reported finding of a caesian bazzite in rather large crystals (Juve & Bergstøl 1990). A striking geochemical feature of the Heftetjern pegmatite, already noted in these two papers, is the high level of scandium. Also beryllium, tin, yttrium and tantalum are

characteristic elements. About 20 minerals were reported from the Heftetjern pegmatite at that time.

Previous to my visit several collectors and professionals had visited Heftetjern over the years, like Petr Cerny, University of Manitoba and world leading pegmatologist, and the late François Fontan, Toulouse, wellknown french mineralogist.

Early 1998 I initiated an investigation of other minerals, and shortly after the first visit several rare or unusual minerals were identified, e.g. nice milarite crystals, including Y- and Sc-rich milarites, several unusual tantalates, a calcian hingganite-like mineral, stannian titanite, scandian ixiolite, scandian cerian epidote and allanite-(Ce), cassiterite, kainosite-(Y), ilmenorutile (= niobian rutile), rynersonite (Kristiansen 2008), plumbomicrolite (Raade & Kristiansen 2000a), and a possible new Sc-mineral (later confirmed as the new kristiansenite). This pointed towards a unique type of pegmatitic mineralization in Norway, with a strong enrichment of Sc, Sn, Ta, Be, Ca, Y and Ti, which confirm previous reports.

A special feature compared to other granitic pegmatites in Norway is the frequent appearance of vugs andmiarolitic cavities, which houses numerous well-crystallized rare species, and seems to be confined to a late hydrothermal phase of pegmatite formation.

A second visit were undertaken during the summer 1998, and new material were encountered, which resulted in an agreement between the "Friends of the Geological museum" (Oslo) and the landowner Kaj Peder Tveit to do some blastings in the pegmatite. That took part in September 1998 (Fig. 3), and nice crystals of beryllium-minerals were exposed in vugs, like milarite and bazzite associated with helvite, bavenite, and bertrandite.

Additionally, other unusual minerals were encountered, including an intimate intergrowth of scandiobabingtonite and cascandite (Raade & Erambert 1999, Eldjarn 2002), hellandite-(Y), besides several "unknowns" still under investigation at that time.

In connection with the International symposium on the mineralogy and geochemistry of Scandium 2003 new blastings took place in the summer 2003 performed by the landowner and his son, with a team from the Friends of the Geological museum, University of Oslo.

This was done to ensure that the participants could find "virgin" material! Among the participants at the excursion were wellknown mineralogists, like Evgenii Semenov, Russia; Carlo Gramaccioli, Italy; Satoshi Matsubara, Japan; Yves Moëlo, France; Carl Francis, USA; Scott Wood, USA; Uwe Kolitsch, Austria; Louis Raimbault, France etc., guided by Gunnar Raade and Tom Victor Segalstad from the the Geological Museum, Natural History museum University of Oslo.

The most recent report on the mineral findings is the description of the new scandium minerals kristiansenite (Raade et al.2002, Ferraris et al. 2001, Ellingsen & Haugen 2002, Eldjarn 2002), oftedalite (Cooper et al.2006), and heftetjernite (Kolitsch et al. 2009).

A preliminary check-list today counts approx. 70 species and varieties (table 2).

Even after the blastings in fall 1998, and the summer 2003 the quarry is still rather modest in size. Today approx. 1m deep, 1 - 2 m broad and less than 10 m long in extension

**TABLE 2. LIST OF MINERALS FROM HEFTETJERN**

Mineral	Appearance	% of total number
<b>Elements:</b>		1.6
Bismuth	Rare	
<b>Sulphides:</b>		4.8
Galenite	Not common	

Pyrite	Occasional	
Molybdenite	Rare	
<b>Halogenides:</b>		
Fluorite (yttrian)	Common	3.2
Bismoclite	Very rare	
<b>Oxides/ hydroxides:</b>		
Quartz	Very common	30.6
Opal	Common	
Limonite	Occasional	
Gahnite	Very rare	
Ilmenite (manganian)	Rare	
Tantalite-Fe	Rare	
Brookite	Very rare	
Anatase	Very rare	
Cassiterite	Occasional	
Ytropyrochlore-(Y)	Occasional	
Microlite (scandian, uranoan)	Occasional	
Yttrobetafite-(Y)	Occasional	
Plumbomicrolite	Rare	
" Ilmenorutile " (scandian)	Rare	
Rynersonite	Extremely rare	
Tantite ? (very little Nb,Pb, Ti)	?	
Ixiolite (scandian)	Uncommon	
Heftetjernite	Extremely rare	
TL		
Polycrase-(Y)	Rare	
<b>Phosphates:</b>		
Monazite-(Ce)	Occasional	4.8
Apatite	Rare	
Xenotime-(Y) not confirmed	?	
<b>Carbonates:</b>		
Calcite	Occasional	6.4
Cerussite	Rare	
Bismutite	Rare	
Kamphaugite-(Y) ?	?	
<b>Silicates:</b>		
Microcline	Very common	48.4
Microcline var. amazonite	Very common	
Albite-oligoclase	Very common	
Albite var. cleavelandite	Common	
Zinnwaldite	Occasional	
Biotite	Common	
Muscovite	Occasional	
Nontronite	Occasional	
Spessartine	Common	
Zircon	Occasional	
Schorl	Very rare	
Thorite	Extremely rare	



Epidote (cerian scandian)	Not common	
Allanite-(Ce)	Occasional	
Kainosite-(Y)	Very rare	
Hellandite-(Y)	Very rare	
Titanite (stannian)	Occasional	
Titanite var. triclinic	?	
Thortveitite	Very rare	
Cascandite	Very rare	
Scandiobabingtonite	Very rare	
Kristiansenite	Rare	
TL		
Bazzite (caesian)	Rare	
Bertrandite	Occasional	
Bavenite	Rare	
Phenacite	Rare	
Gadolinite-(Y)	Not common	
Hingganite-(Y) (calcian)	Rare	
? Minasgeraisite-(Y)	?	
Milarite	Occasional	
Oftedalite	Exceedingly rare	
TL		
Yttrian milarite (new species)	Very rare	
?)		
Helvite (scandian)	Vety rare	

### MINERAL DESCRIPTIONS (genuine Scandium minerals)

For chemical analysis and technical data of Scandium minerals from Heftetjern consult table 6 and 7.

### OXIDES

#### Heftetjernite, $\text{ScTaO}_4$ (Kolitsch, Kristiansen, Raade & Tillmanns in press)

Empirical formula:  $\text{Sc}_{0.64} \text{Sn}_{0.13} \text{Mn}_{0.12} \text{Fe}_{0.08} \text{Ti}_{0.06} \square_{1.03} (\text{Ta}_{0.69} \text{Nb}_{0.30}) \square_{0.99} \text{O}_4$

IMA 2006-056 Vote: 19-1-1

Named after the type-locality: Heftetjern in Tørdal, Telemark county.

This is the first terrestrial scandium oxide in nature.

Heftetjernite (Fig. 4) is the third new scandium mineral originally described from Heftetjern, and is the natural analogue of synthetic monoclinic  $\text{ScTaO}_4$  (Kolitsch et al. 2009). The mineral was found by the author in 2004 in one specimen. It crystallises in the wolframite structure type.

The type specimen, ~2x2.5 cm, consists mainly of albite with minor violet fluorite, muscovite, traces of altered milarite and a metamict, dark greyish brown mineral of the pyrochlore-microlite group, besides an unidentified, orange-brown, tabular, nearly X-ray amorphous Ti-Y-Ta/Nb-mineral, which is close to polycrase-(Y) in composition.

Heftetjernite occurs in a single small vug in the albite, and appears on the surface or in between the polycrase-like mineral as only a few elongate tabular to columnar, subparallel crystals (max. length ca. 0.4 mm, max. width ca. 0.1 mm), more or less broken up by cracks. The tabular form is {100}; no other distinct forms are observable. The very small amount of material available for the characterisation precluded measurements of some physical properties.

The mineral is very dark brown (to greenish brown in part) and translucent to transparent with an adamantine lustre. It is non-fluorescent, brittle, with a perfect {010} cleavage and



Fig. 4. SEM-photo. Tabular crystals of heftetjernite (photo Harald Folvik).

irregular fracture, and a dark brownish (with reddish hue) streak. The very sparse material and the very high density value did not allow a direct measurement of the density. The calculated X-ray density is  $6.44 \text{ g/cm}^3$  for the fragment used for the crystal-structure solution.

A second sample found in 2007 consists of kalifeldspar and biotite, and traces of altered milarite. Imbedded in the biotite flakes there is one almost

complete tabular very dark brown crystal, < 0.3 mm in length. It has almost the same composition as in the type specimen.

A third specimen was collected 2008, showing elongate tabular subparallel crystals, < 0.5 mm in extension, broken up by cracks just like the type. The crystals are shiny, dark brown and developed on the surface of fresh the polycrase-like mineral of platy habitus, and it is surely that heftetjernite is *not* an alteration product of it. Other associated minerals are kristiansenite, milarite, zircon, monazite and stannian titanite in a matrix of kalifeldspar, albite and biotite.

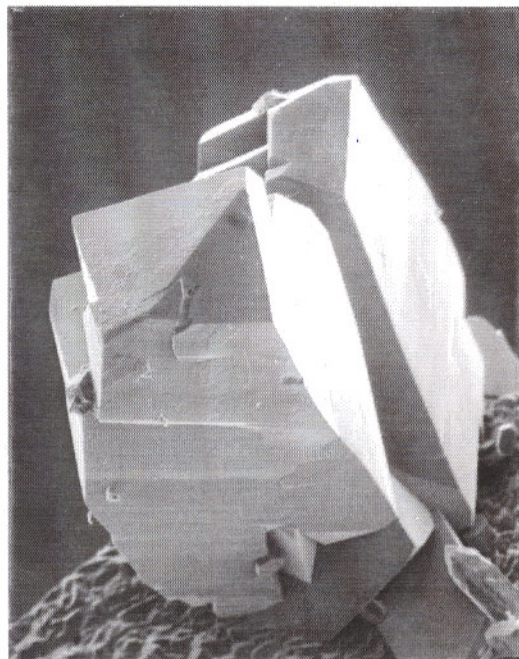
Heftetjernite is chemically like the orthorhombic scandian ixiolite already mentioned on several occasions (Bergstøl & Juve 1988, Wise et al. 1998, Raade et al. 2002),

## SILICATES

### *Soro-silicates*

#### **Kristiansenite $\text{Ca}_2\text{ScSn}(\text{Si}_2\text{O}_7)(\text{Si}_2\text{O}_6\text{OH})$**

Named after Roy Kristiansen, Norway (1943 -). IMA 2000-051 Vote 22-0-0



This mineral (Fig. 5), with its unique composition and new structure type (Raade et al. 2002, Ferraris et al. 2001) was first observed and collected by the author in May 6 1998, during his first visit to the pegmatite, in company with Thor Sørli.

In the first specimen (H06/98) the new mineral occurs as yellowish grey prismatic crystals in vugs. This is a handspecimen consisting of feldspar, quartz and a biotite, and vugs filled with a cerian scandian epidote in nice lath-like crystals, and yellowish aggregates of a hingganite-like mineral, and the new mineral.

An x-ray diffractometer pattern gave an unknown phase, - not identical to any known mineral or synthetic compound.

Fig. 5. SEM-photo. Kristiansenite crystals (photo A. O. Larsen).

The first EDS-SEM analysis done in USA showed a Calcium-tin-scandium-tantalate, but it was unfortunately a wrong interpretation, which created some confusion and extra work. But in January 1999 another analysis was performed and the actual composition was a Calcium-tin-scandium-silicate. Shortly after Franz Bernhard at the Technical University of Graz in Austria analysed greyish inclusions occurring as irregular veins or rarely as crystals in cassiterite, which were identical to the Calcium-tin-scandium-silicate above with minor iron and aluminium. The mineral also appeared as small colourless tapering crystals in vugs in feldspar. And sometimes as colorless grains in altered spessartine.

Gunnar Raade at the Geological museum, University of Oslo organized an co-operation with Prof. Giovanni Ferraris, at the University of Torino in Italy, in order to solve the structure, and Dr. Franz Bernhard, Technical University in Graz, Austria, to do the chemistry. By the middle of the year the work on the new mineral had started! During the first stage of the crystal structure determination it was confirmed that the mineral possessed a complex twinning, already postulated (theoretically) to occur in nature by Nespolo & Ferraris (2000). The first official presentation of kristiansenite was at the International Crystallographical Congress in Nancy in August 2000, but without a name (Ferraris et al. 2000) "Solving the structure of a new Ca-Sc-Sn disilicate twinned by metric merohedry. "

In October-November 2000 all necessary data was ready to be submitted to the Commission for New Minerals and Mineral names/ IMA, and the proposed name was kristiansenite. In the end of 2000 Gunnar Raade went to Australia to attend the Mineralogy & Museums 4th/IMA, where he had a talk on the Sc-minerals at Heftejern, and also invited people to a possible Scandium symposium in Oslo 2003 (Raade & Kristiansen 2000b).

The mineral and name was approved in February 2001 as IMA 2000-051. Because of the special nature of the structure, called twinning by metric merohedry, the structure was described before the actual mineral description (Ferraris et al. 2001).

In April 2001 I proposed to arrange an international symposium on the mineralogy and geochemistry of SCANDIUM in Norway on the occasion of the first discovery of a scandium mineral in the world, viz. thortveitite 1903. Consult Raade & Segalstad (2003).

The original description of kristiansenite appeared in 2002 (Raade et al.), and was followed by several papers: Ellingsen & Haugen (2002), Olsen (2002), Ferraris et al. (2003), Nespolo (2004), Nespolo & Ferraris (2004), and Ferraris et al.(2004).

Then in 2005 kristiansenite was discovered in Baveno in Italy, - a mineral that was found already in 1997, but not identified before Federico Pezzotta (pers. comm.) obtained kristiansenite from me! Also in Baveno it occurs in nice crystals described and illustrated by Guastoni & Pezzotta (2005).

### **Thortveitite, $\text{Sc}_2\text{Si}_2\text{O}_7$**

It is well known that thortveitite was originally discovered by the young geologist Per Schei already 1903 at Landsverk in Evje, Setesdal, but thought to be an epidote-like mineral (Kristiansen 1997). Later on the famous farmer and miner Olaus Thortveit in Iveland found many larger specimens, and Schetelig (1911) named the mineral after him (Kristiansen loc.cit.)

Thortveitite was reported by Juve & Bergstøl (1996), but later discarded by Fontan (pers. comm. 1998). It is a rather common mineral in Iveland-Evje (Neumann 1961), but not at Heftejern.

A sample of bazzite found June 2001 showed, however, thin glassy needles of a greyish green mineral which turned out to be thortveitite. But the size of the crystals is only a couple of mm.

It also appears as glassy light greenish columnar crystals only a few mm in length imbedded in greyish black chlorite.

Another very interesting specimen was collected 2003, and shows in polished section that early formed thortveitite is broken up by bazzite and scandian milarite, or partly replaced by kristiansenite, viz. four different scandium minerals intimately intergrown!

This specimen was carefully analyzed and thortveitite is exceptional in composition as it contains an appreciable content of tin, with a maximum of 5.67 wt.% SnO<sub>2</sub>.

The content of tin is balanced by Mn according to the substitution  $2\text{Sc}^{2+} \Leftrightarrow \text{Sn}^{4+} + \text{Mn}^{2+}$ , already proposed by Oftedal (1969). This is an additional evidence that the pegmatite is very rich in Sn.

In 2007-2008 I found three larger specimens which seemed to fit together in one, but with several smaller missing parts. All three specimens showed areas of stilpnomelane of several square cm in size, in which there is imbedded a large number of cross-cutting colorless or slightly yellowish columnar more or less damaged crystals up 12 mm in length. The crystals are twinned, and are currently being investigated by Massimo Nespolo, University of Nancy (pers. comm. 2009).

Compared to thortveitite from Iveland, which contains up to 30 wt.% Y<sub>2</sub>O<sub>3</sub> in substitution for scandium (Bianchi et al. 1988), - the thortveitite from Heftefjern are much purer in composition, with less than 2 wt.% Y+REE<sub>2</sub>O<sub>3</sub>.

### **Cyclosilicates**

**Bazzite**, Be<sub>2</sub>(Sc,Al)<sub>2</sub> Si<sub>6</sub>O<sub>18</sub>, the scandium-dominant analogue of beryl (Fig. 6).

Bazzite was originally described from Baveno in Italy (Artini 1915), and is rather common in the Swiss Alps (Armbruster et al. 1995).

This is the first finding of bazzite in Norway (Kristiansen 2003), which was described and analyzed by Juve & Bergstøl (1990). Their analyses showed ~ 3 % CsO<sub>2</sub>, which is rather



high. Several other bazzites, however, contains little or no Cs.

The first crystals of bazzite occurs as sky-blue hexagonal crystals in feldspar and quartz, often also as needles along the the faces and edges of larger yellow beryl crystals. It may appear as small crystals in fibrous aggregates of bavenite, - an alteration product of beryl. The crystals are often filled with cracks and become brittle. The largest crystal found was 3 cm in length (Werner 1993), which may be the largest single crystals in the world.

However, larger irregular masses up to 7-8 cm across occurs intergrown with kristiansenite (consult photo in Kristiansen 2003).

Crystals may be deep blue, greenish blue, sky-blue and even colorless or bluish white.

*Fig. 6. SEM-photo. Tiny bazzite crystals on cascandite (photo Franz Bernard).*

Demartin et al. (2000) have done a structure refinement of bazzite based on a large crystal fragment from Heftetjern as well as from Baveno.

The very interesting specimen collected 2003 (consult thortveitite above) shows in polished section that early formed thortveitite is broken up by bazzite and scandian milarite, or partly replaced by kristiansenite. The bazzite is strongly zoned with respect to Cs with increased  $\text{Cs}_2\text{O}$  towards the center part of the crystal (Raade & Bernhard 2003, Raade et al. 2004). A maximum content of 8.55 wt.%  $\text{Cs}_2\text{O}$  must be the highest ever reported in a bazzite.

Very tiny hexagonal crystals have developed on the surface of cascandite.

A very small hexagonal crystal of light blue bazzite was recently found in the nearby Høydalen mine (Kristiansen 2008), which is the first true scandium mineral in this mine.

Previous to that we only had indication of 1.5 wt.%  $\text{Sc}_2\text{O}_3$  on a wodginite-like mineral (Raade & Kristiansen 1983).

### Oftedalite, $(\text{ScCa,Mn}^{2+})_2(\text{Be,Al})_3\text{Si}_{12}\text{O}_{30}$

The scandium-dominant analogue of milarite (Fig. 7). IMA 2003-043a Vote: 22-0-1  
Named after Ivar W. Oftedal (1894-1976), professor at the University of Oslo, who was the first to describe the mineralogy of the Tørdal area already in 1942.

The second new mineral from Heftetjern, also turned out to be a Scandium-mineral - in the milarite group.

Colourless hexagonal crystals of milarite is not uncommon at Heftetjern, and crystals up to 15 mm length were collected. Occurs also as whitish sugary masses, or tan irregular sprays. Milarite is one of the most common minerals in the pegmatite.

There are three different species of milarite at Heftetjern:

1 ) Normal composition without indications of substitutions, and < 200 ppm Sc. The majority of specimens have normal composition.

2 ) Yttrian milarite, with ca. 5 - 10 %  $\text{Y}_2\text{O}_3$ , which indicates a substitution towards the composition  $\text{K}(\text{CaY})\text{Be}_3\text{Si}_{12}\text{O}_{30}$  with  $\text{Y} > \text{Ca}$  and almost lack of Al (see Cerny et al. 1991, Nysten 1996, Hawthorne 2002 ). This mineral occurs only occasionally, which warrants description of a new mineral of the milarite group if  $\text{Y} > \text{Ca}$ , which require equal rule as for oftedalite (consult Hatert & Burke 2008 below).

3 ) Scandian milarite, with 5 - 7 %  $\text{Sc}_2\text{O}_3$  was first indicated by Franz Bernhard at the Technical University in Graz. (pers. comm. 29.03.1999) It was collected May 6 1998, and varies in composition between scandian milarite and oftedalite.

This is extremely rare and found in only one sample (my sample no. H 04/98), occurring as short greyish hexagonal crystals usually < 100 m across, lining minute cavities in kalifeldspar along with small



Fig. 7. SEM-photo. Hexagonal oftedalite crystals (photo Harald Folvik).

amounts of bazzite, yttrian milarite and green needles of scandian schorl partly replaced by kalifeldspar.

Both the scandian and yttrian milarites were mentioned by Grew (2002).

Further work was postponed because of the sparse material. However, experts at the University of Manitoba in Winnipeg, Canada, continued to work on it, with the supermicro-mineralogist Mark Cooper, and his supervisor professor Frank Hawthorne, in addition to Prof. emeritus Petr Cerny. Previous to the finding I had already asked Cerny 1998 about the possibility of finding a milarite with scandium, and he replied, quote: "you may have some scandium surprises there, and quite possible a milarite with some Sc in ... ". And in the following spring we had it!

During the final stage of the manuscript the first submission to CNMMN/IMA was rejected because of lack of convincing chemical data. New analyses, however, was accepted and the mineral, IMA no. 2003-045a, was approved 2005 (Cooper et al. 2006, Kristiansen 2005).

The interesting specimen from 2003 (see thortveitite and bazzite above) also contained scandian milarite in the textural replacement of the four scandium minerals (Raade et al. 2004).

The oftedalite was recently treated as a special case because it was first rejected when submitted. The following quotation explains why it was a difficult case to handle, and it was already discussed by Burke (2004) during the 5<sup>th</sup> International conference "Mineralogy & Museums".

Quoted from Hatert & Burke (2008):

Page 720: "Hawthorne (2002) has extensively discussed such valency- imposed double site-occupancy for some end members, notably in the milarite group.

*Example:* The end-member formula of milarite (omitting H<sub>2</sub>O for simplicity) is Ca<sub>2</sub>K[(Be<sub>2</sub>Al)Si<sub>12</sub>O<sub>30</sub>]. The coupled substitution Ca<sup>2+</sup> + Al<sup>3+</sup> → Sc<sup>3+</sup> + Be<sup>2+</sup> leads to the end member (ScCa)K[Be<sub>3</sub>Si<sub>12</sub>O<sub>30</sub>] in which the A site must have a double occupancy (ScCa) because there is only one Al that can be replaced by Be at the T2 site. This end member is to be named oftedalite. On the basis of the strict application of the current dominant-constituent rule, however the IMA- CNMNC approved in 2004 the mineral oftedalite as being Sc-dominant at the A site with the formula (Sc,Ca,Mn)<sub>2</sub>K[(Be,Al)<sub>3</sub>Si<sub>12</sub>O<sub>30</sub>] (Cooper et al. 2006). But milarite can only become Sc-dominant (and thus be named oftedalite, according to the rules valid in 2004) if some Ca is partly replaced by a third cation at that site; otherwise Ca will usually have more than 50% occupancy, and such specimens are then simply Sc-rich milarite. The adoption of the new dominant-valency rule, however, causes additional problems about the current definition of oftedalite (see below)."

Page: 723

*Example:* This very special case is oftedalite. It is unique; perhaps with the exception of the hypothetical Y dominant analogue of milarite and oftedalite, which may also exist in nature (Hawthorne 2002). It has been stated (see above) that milarite can only become Sc-dominant at the A site (and thus be named oftedalite following the old dominant-constituent rule) if some Ca is replaced by a third cation at that site, otherwise Ca will usually have more than 50% occupancy, such specimens are then simply milarite. But if that third cation also is divalent, then the application of the dominant-valency rule changes oftedalite back to milarite! The empirical formula of oftedalite is (Sc<sub>0.96</sub>Ca<sub>0.79</sub>Mn<sup>2+</sup><sub>0.18</sub>Fe<sup>2+</sup><sub>0.04</sub>Y<sub>0.03</sub>)<sub>Σ2.00</sub>K<sub>0.98</sub>(Be<sub>2.91</sub>Al<sub>0.09</sub>)<sub>Σ3.00</sub>Si<sub>11.98</sub>O<sub>3.00</sub> (Cooper et al. 2006).

It is true that Sc is dominant as a single element at the A site, but the sum of divalent ions

(Ca+Mn+Fe) is greater ( $1.01 \text{ apfu}$ ) than the sum of the trivalent ions ( $\text{Sc}+\text{Y} = 0.99 \text{ apfu}$ ). The new valency-dominant rule implies that in oftedalite, Sc must be the dominant cation of the dominant valency at the A site (except for the end member, which has a valency-imposed double site-occupancy; see above). Current samples of "oftedalite", as previously defined by the old constituent rule, are thus simply Sc-rich milarite as defined by the new constituent rule. It is of course possible, however, that Ca is replaced by a monovalent ion, e.g.  $\text{Na}^{1+}$ , so that Sc is the dominant cation of the then dominant trivalent ions, in that case producing an oftedalite specimen that obeys both the dominant-constituent and the dominant-valency rules. "

It is unfortunate that the name *scandiomilarite* was erroneously used in a paper by Galuskina et al. (2005). It is not a valid name.

### Inosilicates

#### Cascandite, $\text{Ca}(\text{Sc}, \text{Fe}^{2+})\text{Si}_3\text{O}_8(\text{OH})$

Originally described from the famous Baveno granite in Italy (Mellini et al. (1982) together with the much rarer jervisite (Merlino & Orlandi 2006). Another finding of cascandite in Italy was recently reported by Albertini et al. (2006).

This very rare mineral (Fig. 6) has been reported on as an intergrowth with scandiobabingtonite (Raade & Erambert 1999), and consists of light green fibrous and porous masses 2-3 mm across. It is also found as pale greenish partly transparent broken crystal imbedded in bazzite matrix. Minute irregular colorless grains have been identified intergrown with a metamict mineral of the pyrochlore-microlite group, and as tiny inclusions in allanite-(Ce) (Laukert 2008).

Both cascandite and the following scandiobabingtonite are pyroxenoid minerals (Raade & Erambert 1999).

#### Scandiobabingtonite, $\text{Ca}_2(\text{Fe}^{2+}, \text{Mn}) \text{ScSi}_5\text{O}_{14} (\text{OH})$

Described from Baveno in Italy by Orlandi et al. (1998), and Gramaccioli et al. (1998).

At Heftetjern scandiobabingtonite (Fig. 10) was found surprisingly shortly after its description from Baveno, and intimately intergrown with cascandite (Raade & Erambert 1999).

It is a rare mineral occurring in irregular greenish masses to several mm, or more rarely as delicate bottlegreen to dark green equant or rectangular crystals, and not always mixed with cascandite. Also epitaxially intergrown with kristiansenite.



Fig. 8. SEM-photo. Scandiobabingtonite crystal intergrown with tiny kristiansenite crystals (photo Franz Bernard).

#### Scandian ixiolite, $(\text{Sc}, \text{Ta}, \text{Nb}, \text{Sn}, \text{Fe}, \text{Mn}, \text{Ti})_4\text{O}_8$

This mineral is included here as a potential new mineral.

Scandian ixiolite occurs as dull blackish shiny crystals up to 5-6 mm, sometimes as well-developed rectangular or even square orthorhombic crystals.

It is a less common mineral. The content of scandium in ixiolite from Heftetjern exceed considerably the scandian ixiolite reported by v.Knorrning & Sahama (1969) and Borisenko et al. (1969). The analyses by Bergstøl & Juve (1988) and Wise et al. (1998) shows usually between 14 and 19 %  $\text{Sc}_2\text{O}_3$ , and is a phase chemically similar to heftetjernite.

One of the analyses of Bergstøl & Juve (1988) in fact conforms to a Sc-dominant "ixiolite" with the empirical formula  $(\text{Sc}_{1.46}\text{Ta}_{1.16}\text{Nb}_{0.76}\text{Sn}_{0.26}\text{Fe}_{0.24}\text{Mn}_{0.18}\text{Ti}_{0.03})_{4.09}\text{O}_8$  (Raade et al. 2002), and is in fact a new mineral when Sc exceeds the other elements in the cation-disorder ixiolite structure. Wise et al. (1998) have discussed the structural behaviour of scandian ixiolite from several localities (including Heftefjern, Mozambique and Madagascar), and the following is quoted from their work : "The structure of natural, unheated scandian ixiolite has been described as orthorhombic. (...) However, a recent refinement of the structure of scandian ixiolite from the Heftefjern locality indicates that the structure is highly disordered and pseudo-orthorhombic, with a slight departure toward monoclinic symmetry (unpubl. data of MW). The monoclinic symmetry of the structure, which is apparently related to that of wolframite, becomes more obvious after heating."

The structure of scandian ixiolite is probably a modification of the monoclinic wolframite-type structure.

Bergstøl & Juve (1988) emphasized that the scandian ixiolite samples are more or less altered and that some grains are completely altered to metamict members of the pyrochlore group; the degree of alteration. By heating partly altered ixiolite, Bergstøl & Juve (1988) obtained an X-ray powder diffraction pattern of a mixture of pyrochlore (cubic) and wodginite (monoclinic).

No structural details on this anomalously monoclinic scandian ixiolite were subsequently published by Wise and coworkers. Nonetheless, the results of Wise et al. (1998) indicate that the very Sc-rich parts the reported scandian ixiolites from Mozambique and Madagascar (von Knorring et al. 1969) represent a disordered Nb-analogue of the Ta-dominant scandian ixiolite from Heftefjern by Bergstøl & Juve (1988) and Wise *et al.* (1998). Further details of this species is discussed by Kolitsch et al. (2009).

Borisenko et al. (1969) used the name scandium ixiolite for the the scandian ixiolite from Mocambique, while Galuskina et al. (2005) used "scandioixiolite ". None of these names are valid mineral names.

### SCANDIUM-PHOSPHATES

There are only three Sc-phosphates world-wide, viz. kolbeckite, juonniite and pretulite, but none are found at Heftefjern due to their different paragenesis, although pretulite,  $\text{ScPO}_4$ , have been found as nanometer inclusions in emerald from Byrud, Minnesund (Rondeau et al. 2008).

### SCANDIUM -BEARING MINERALS

**TABLE 3.** SCANDIUM-BEARING MINERALS FROM HEFTETJERN

Mineral name	Content of wt. % $\text{Sc}_2\text{O}_3$
Scandian tantalite-Fe	7
Scandian ytropyrochlore	6
Scandian cerian epidote	2-5
"Scandium microlite" (uranian)	3.4
Scandian yttrian microlite	2.4 – 3.9
Scandian titanite	3.5
Scandian wolframian microlite	3
Scandian "ilmenorutile"	1.6
Scandian helvite	1.5
Scandian uranian ytrobetafite	~1.0
Schorl	0.6
Brookite	~0.5
Spessartine	~0.5



**TABLE 4.** Instrumental neutron-activation analysis for Scandium, Caesium and Rubidium

Instrumental neutron-activation analysis *			
	Sc ppm	Rb ppm	Cs ppm
Cassiterite	3860		
Zircon	3070		
Dark mica II	1790	8860	3940
Gadolinite	1450		
Beryl, yellowish	940		3420
Dark mica I	917	11400	
Beryl, colourless	763		1880
Muscovite	748	7070	2670
Spessartine	727		
Phenakite	246		
Chlorite	220		
Fluorite	177		
Milarite	174	682	975
Monazite	2,5		
Albite, replacing microcline	2.1		
Microcline	0.6	3650	
Microcline, var.amazonite	0.5	5490	
Quartz	0.2		

\* Numbers from Raade & Kristiansen (2003)

#### Minerals of the microlite-pyrochlore group.

Minerals of the microlite-pyrochlore group shows very variable compositions and are not uncommon, but without analyses it is almost impossible to specify what the mineral is. Bergstøl & Juve (1988) analyzed several samples and identified them as:

Scandian ytropyrochlore; Yttrian scandian microlite "Scandium microlite" (uranian) and uranian ytrobetafite. The term " Scandium microlite " was erroneously used as a new mineral name , but without the proper approval of IMA (Jambor 1990 ).

Wolframian scandian microlite. This is another sample from the author with more than 3 %  $WO_3$  and 3 %  $Sc_2O_3$ .

Minerals of this group all seems to be metamict, and of brownish green to greenish colour, glassy luster, and conchoidal fracture. They are probably all the result of metamict transformation of ixiolite (Bergstøl & Juve 1988).

#### Scandian helvite and helvite.

Helvite is very rare, and occurs as irregular masses up to several cm of deep brown-red color intimately with large bazzite crystals. In another sample the helvite is only of millimetric size, glassy appearance and pinkish. This is also intimately intergrown with light blue bazzite. This helvite was found to contain appreciable amounts of scandium, and micro-probe analyses shows up to 1,7%  $Sc_2O_3$  (Raade & Kristiansen 2000), which seems to be the first record of Sc in a helvite. The helvite has Mn:Fe:Zn = 41:34:25 mol % .

Holtstam & Wingren (1991) report a zincian helvite from a pegmatite in Stora Viken in Sweden with approx. the same ratio as the above. Mn:Fe:Zn ratio 37:28:35 mol %.

Analyses on helvites from Norwegian granite-pegmatites are being investigated by Raade & Bernhard (in prep.)

#### Ilmenorutile (= niobian rutile )

A rare mineral at Heftejern, occurring as millimetric tabular crystals with submetallic luster and steel-blue colour.

Analyses shows an empirical formulae approx.:  $(\text{Ti}_{2.80} \text{Nb}_{0.08} \text{Sc}_{0.06} \text{Ta}_{0.05})_{2.99} \text{O}_6$  with approx. 1.6 %  $\text{Sc}_2\text{O}_3$ .

The ilmenorutile from thortveitite-bearing dykes in Iveland-Evje in Setesdal are found to contain more Sc than those without (Neumann 1961).

The high content of Sc in ilmenorutile from Heftetjern seems to confirm the analyses of Neumann (loc.cit.), except there are other Sc-minerals at Heftetjern.

Cerny et al. (2000,2001) have described Sc-bearing minerals as exsolved phases in niobian rutile from Iveland, so the high content of Sc in ilmenorutile by Neumann et al (loc.cit.) may actually be caused by inclusions of these phases.

## COMPARABLE SCANDIUM LOCALITIES

The only comparable locality in the world is the very extensive granite quarries in Baveno in Italy, situated near Lago Maggiore not far from Milano in Italy.

Dimensionally, however, the quarries at Baveno is huge, and dates back to the 18<sup>th</sup> century (Gramaccioli 2003, Gramaccioli et al. 1998).

This is the type locality for bazzite (Artini 1915, Demartin et al. 2000)), cascandite and jervisite (Mellini et al.1982), and scandiobabingtonite (Orlandi et al.1998). Likewise thortveitite have been found in several varieties (Gramaccioli et al. 2000), and kristiansenite was found and described recently (Guastoni & Pezzotta 2005).

Although the dimensional differences are enormous between Baveno and Heftetjern, it is a remarkable local enrichment of scandium in the two geographically different areas not comparable to any other places in the world.

The term "Unique assemblage ...." in my title is used here to emphasize that Heftetjern is unique in the sense that Sc is incorporated in far more minerals than reported from Baveno, and the quarry is very much smaller and the "hotspot" is investigated only in recent time, known for less than 30 years, while the activity at Baveno have existed since the 18<sup>th</sup> century.

**Table 5. Scandium-minerals from Heftetjern and Baveno.**

OXIDES	Heftetjern, Norway	Baveno, Italy
Heftetjernite	x TL	-
Scandian ixiolite	x TL	-
<b>SILICATES</b>		
Thortveitite	X	X
Bazzite	X	x TL
Cascandite	X	x TL
Jervisite	-	x TL
Scandiobabingtonite	x	x TL
Kristiansenite	x TL	X
Oftedalite	x TL	

TL = type locality

## PERSPECTIVES and FUTURE CONSIDERATIONS

After ten years of meticulous collecting and investigation we have, so far, ended up with at least seven true Scandium-minerals of which three are new to science: kristiansenite, oftedalite and heftetjernite. In addition we have found a large number other minerals with Sc-content exceeding 1 wt %  $\text{Sc}_2\text{O}_3$ , and all these in one small quarry.

Still very much remains to be done, and several projects are going on, like:

- analysis of titanites of different morphology and colours with significant substitutions by Sn, Ta, Sc, Al, Nb (University of Vancouver).
- structural work on triclinic titanite (University of Manitoba)
- Scandium-content of cerian epidotes/allanites (University of Freiburg)
- analysis of minerals in the gadolinite-hingganite group (University of Rome).
- Yttrian milarite = new mineral (University of Manitoba)
- scandian ixiolite = new species if Sc is dominated cation in the dis-ordered structure.
- quantitative analysis of the micas for Cs, Rb, Li, Sc, Sn
- identification of unknown phases
- looking for jerviste!

After the blastings at Heftetjern in fall 1998 and summer 2003, the exposed pegmatite working is still rather modest in size, and today approximately 1 m deep, 1–2 m broad and less than 10 m in extension.

However, the total length of the steeply dipping pegmatite may be as much as 300 m with a thickness of 5–40 m; the pegmatite is partly covered by glacial drift and vegetation (Bergstøl & Juve 1988).

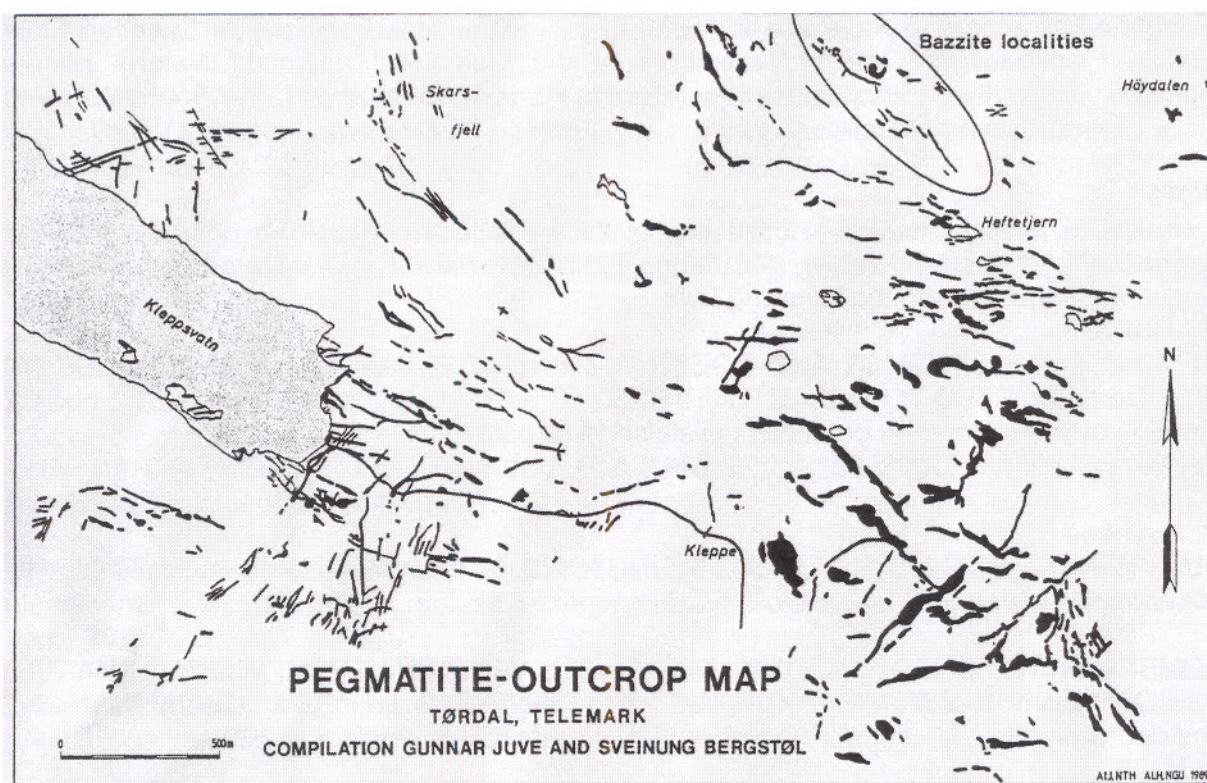


Fig. 11. Pegmatite-outcrop map showing the large number of pegmatites in a small part of the Nissedal supracrustal outlier. With permission from the authors (Juve & Bergstøl 1990).

I do not believe this quarry is the only place in Tørdal where you have an enrichment of scandium of the magnitude we have encountered.

The whole area and the surroundings of Heftetjern contains numerous pegmatites, excluding the Høydalen mine and Skarsfjell, - and only further blastings and systematic sampling would provide evidence how scandium and its minerals are distributed in other pegmatites, which cover several square kilometers. Consult map by Juve & Bergstøl (1990).

Only future generations will be able to verify the distribution of scandium in this area as a possible potential resource of scandium. Closer paragenetic studies and determination of the scandium content are needed to substantiate this view.

Finally, after more than 60 years, at least we have the first indication of a true scandium mineral at the Høydalen mine in one tiny crystal of bazzite (Kristiansen 2008).

### Acknowledgement

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### NOTE

I would like to emphasize that collecting at the Heftetjern-pegmatite is only allowed with permission from the land-owner, Kaj Peder Tveit. Be aware that a label with a warning is placed at the quarry with the following text:

WARNING !

REMOVING OF MINERALS AND ROCKS WITHOUT THE LANDOWNERS PERMISSION WILL BE REPORTED TO THE AUTHORITIES.

Fjerning av mineraler uten grunneiers tillatelse vil bli påtalt/anmeldt.

Kaj Peder Tveit (tlf. 35998221)

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TABLE 6 ANALYSIS OF SCANDIUM-MINERALS FROM HEFTETJERN, TØRDAL

	Heftetjernite	Heftetjernite	Sc-ixiolite	Sc-ixiolite	Kristiansenite	Kristiansenite	Kristiansenite	Oftedalite	Scandian milarite	Scandian milarite
Ref.	Kolitsch et al. 2009	This paper	Bergstøl & Juve 1988	Wise et al. 1998	Raade et al. 2002 *	Raade et al. 2004 *	This paper	Cooper et al. 2006	Cooper et al. 2006	Raade et al. 2004
Sc <sub>2</sub> O <sub>3</sub>	15.59	13.95	18.80	15.17	8.47	11.74	10.23	6.77	5.90	6.47
CaO					19.27		17.18	4.49	5.88	6.43
MnO	3.02	3.67	2.40	2.87		<0.02		1.32	0.63	0.20
FeO	2.07	3.35	3.20	1.65	3.04 Fe <sup>3+</sup>	0.50 Fe <sup>3+</sup>		0.26	0.22	0.09 Fe <sup>3+</sup>
SnO <sub>2</sub>	6.93	6.55	7.30	7.66	25.67	25.42	24.05			
Y <sub>2</sub> O <sub>3</sub>			0.10			<0.01		0.36	0.15	0.42
Ta <sub>2</sub> O <sub>5</sub>	53.58	58.52	48.00	51.57						
Nb <sub>2</sub> O <sub>5</sub>	14.25	12.37	18.80	17.58	0.11	0.29				
TiO <sub>2</sub>	1.61	1.60	0.40	0.41	0.15	0.18				
Al <sub>2</sub> O <sub>3</sub>					0.40	0.13	4.15	0.47	0.75	0.92
Cs <sub>2</sub> O										
K <sub>2</sub> O								4.71	4.78	4.82
Na <sub>2</sub> O							0.50			0.02
BeO								7.41	7.27	
SiO <sub>2</sub>					41.08	40.05	44.12	73.32	73.44	73.24

\* + ZrO<sub>2</sub>: 0.28

	Bazzite	Bazzite	Bazzite	Thortveitite	Thortveitite	Thortveitite	Cascandite	Scandiobabingtonite	Scandian milarite
Ref.	Juve & Bergstøl 1990	Raade et al. 2004 (mean)	Raade et al. 2009	Raade et al. 2004	This paper	F. Bernhard (pers.comm.2002)	Raade & Erambert 1999	Raade & Erambert 1999	F. Bernhard (Pers.comm.2002)
Sc <sub>2</sub> O <sub>3</sub>	14.50	14.60	14.68	46.76	46.88	50.85	16.92	11.06	6.34
CaO		0.02	0.02	0.11	0.17	<0.10	16.88	18.74	4.33
MnO	1.4	1.38	1.38	1.74	1.04	0.90	0.91	2.83	1.56
FeO	5.7 Fe <sup>3+</sup>	5.81	5.79	0.99 Fe <sup>3+</sup>	2.19	0.40	3.90	9.20 + 0.64 Fe <sup>3+</sup>	0.29
MgO						<0.26	0.07	0.19	
SnO <sub>2</sub>				3.64	2.25	1.36			<0.25
Y <sub>2</sub> O <sub>3</sub>				1.78		0.79			0.56
Ta <sub>2</sub> O <sub>5</sub>									
Nb <sub>2</sub> O <sub>5</sub>									
TiO <sub>2</sub>									
Al <sub>2</sub> O <sub>3</sub>	0.8	0.81	0.81	0.04		<0.21			0.59
Cs <sub>2</sub> O	2.93	8.41	8.55						
K <sub>2</sub> O	0.13	0.15	0.15			<0.09			4.69
Na <sub>2</sub> O	1.6	1.73	1.74			<0.27			<0.27
BeO	14.5	11.52	11.52						
SiO <sub>2</sub>	58.0	58.54	58.59	44.36	47.48	45.06	54.94	52.27	72.46
Li <sub>2</sub> O									
H <sub>2</sub> O							2.72	1.55	

TABLE 7 SIGNIFICANT PARAMETERS FOR SCANDIUM MINERALS OCCURRING AT HEFTETJERN, TØRDAL

MINERAL:	Heftejernite	Oftedalite	Kristiansenite	Bazzite	Thortveitite	Cascandite	Scandiobabingtonite
Formula:	ScTaO <sub>4</sub>	(Sc,Ca,Mn) <sub>2</sub> K(Be,Al) <sub>3</sub> Si <sub>12</sub> O <sub>30</sub>	Ca <sub>2</sub> ScSn(Si <sub>2</sub> O <sub>7</sub> )(Si <sub>2</sub> O <sub>6</sub> OH)	Be <sub>2</sub> (Sc,Al) <sub>2</sub> Si <sub>6</sub> O <sub>18</sub>	Sc <sub>2</sub> Si <sub>2</sub> O <sub>7</sub>	Ca(Sc,Fe)Si <sub>2</sub> O <sub>6</sub> (OH)	Ca <sub>2</sub> (Fe,Mn)ScSi <sub>5</sub> O <sub>14</sub> (OH)
Crystal syst.	Monoclinic	Hexagonal	Triclinic	Hexagonal	Monoclinic	Triclinic	Triclinic
Space group	P2/c	P6/mcc	C1	P6/mcc	C 2/m	P 1	P 1
a <sub>0</sub>	4.784	10.097	10.028	9.549 - 9.555	6.65	7.529	7.536
b <sub>0</sub>	5.693		8.408		8.62	7.051	11.734
c <sub>0</sub>	5.120	13.991	13.339	9.152 - 9.160	4.69	6.755	6.748
α			90.01			92.2	91.70
β	91.15		109.10		102.65	93.6	93.86
γ			90.00			104.5	104.53
Volume Å <sup>3</sup>	139.42	1235.3	1062.7	722.73- 732.1	257.91		576.06
Colour	Dark brown	Greyish white	Colourless, grey	Blue, azurblue	Green, grey	Pink	Green – grey green
Density	6.44 (calc.)	2.614 (calc.)	3.64 (calc.)	2.85	3.61 (calc.)	3.02 ?	3.24 (calc.)
Optical prop.	Biaxial	Unaxial -		Unaxial	Biaxial	Biaxial ?	Biaxial
		ε: 1.553		ε: 1.622	α: 1.756	α: 1.663	α: 1.686
	n: 2.23	ω: 1.556	n: 1.74	ω: 1.637	β: 1.793	β: 1.694	β: 1.694
Locality:	Heftejern	Heftejern	Heftejern	Heftejern			
Reference:	Kolitsch et al. 2009	Cooper et al. 2006	Raade et al. 2002	Juve & Bergstøl (1990) Demartin et al. (2000)	In literature	Mellini et al. 1982	Orlandi et al. 1998