Unusual scandium enrichments of the Tørdal pegmatites, south Norway. Part I: Garnet as Sc exploration pathfinder

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A R T I C L E   I N F O

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A B S T R A C T

The granitic pegmatites of Tørdal belong to the Late-Proterozoic Sveconorwegian pegmatite province of south Scandinavia. They form a cluster of about 300 bodies 20 km NW of the town Drangedal in southern Norway and have been known for their Sc enrichment for about 100 years. Scandium is a compatible element in garnet. In this study, 32 garnet samples from 16 pegmatite localities across the Tørdal pegmatite field were investigated to determine the Sc distribution within garnets (crystal scale), within pegmatite bodies (pegmatite scale) and across the Tørdal pegmatite field (regional scale). In the Tørdal pegmatites, Sc content in garnet is representative for the Sc bulk composition of pegmatites, defining garnet as a reliable pathfinder mineral for the exploration of Sc mineralization in pegmatite fields. Garnets with highest Sc concentrations of up to 2197 µg/g have a spessartine component ranging from 50 to 60 mol.%. Since most garnets crystallized during the early stage of pegmatite formation (wall zone stage) Sc decreases in the remaining pegmatite melt, as documented by generally decreasing Sc from core to rim of crystals and by the occurrence of late-stage garnets (albite zone stage) with low Sc. Thus, with progressing crystallization Sc decreases in the melt. The regional Sc distribution in the Tørdal pegmatite field revealed that the Skardsfjell-Heftetjern-Høydalen pegmatites have highest Sc enrichments to sub-economic levels, with an average bulk Sc content of 53 µg/g and an average Sc content in garnet of about 1900 µg/g in the Heftetjern 2 pegmatite. The assumed resources of the Skardsfjell-Heftetjern-Høydalen area are about 125,000 t ore grading c. 50 µg/g Sc resulting in a total of 625 t Sc, which is too small to have economic potential. However, the strong Sc enrichment of the Tørdal pegmatites is unusual for granitic pegmatites, making them a specific Sc deposit type. The amphibolitic host rocks of the Tørdal pegmatites are identified as the source rocks of Sc. The host rocks, which are part of the Nissedal Outlier supracrustals, are enriched in Sc (mean 34 µg/g) compared to average crustal compositions (mean 14 µg/g). Scandium of amphiboles was preferentially released at the onset of partial melting of the amphibolites. Thus, the Sc content in the pegmatite is strongly dependent on the degree of partial melting.

1. Introduction

The Sveconorwegian (Grenvillian) Tørdal pegmatite field, located in the county of Vestfold and Telemark in southern Norway, is known for local enrichments in Sc as well as other rare metals, such as Be, Y, Sn, Li and Mo (e.g. Bergstøl and Juve, 1988; Juve and Bergstøl, 1990, 1997; Oftedal, 1942; Raade and Kristiansen, 2000, 2003; Segalstad and Eggleston, 1993). Some of the pegmatites were mined for mica, amazoneit (green variety of K-feldspar) and molybdenite during World War II. For the last seven decades, the several hundred pegmatite bodies of the Tørdal area have been of little interest except for scientists and mineral collectors.

During the last decade, the interest in Sc has increased due to growing demands of the automotive, air- and space-craft industries using light-weight and strong Sc-Al-alloys. Currently, the Bayan Obo carbonatite-related REE deposit in China is the major producer of Sc with about 15 t annually (Zhao, 1987; Li et al., 2013). Principally Sc is a byproduct of mined Fe-Ti, U, REE, andapatite ore deposits, such as Bayan Obo, Zhovti Vody in Ukraine, and Kovdor and Tomtor in Russia (Williams-Jones and Vasyukova, 2018). Beside these carbonatite-
alkaline- and mafic-intrusion-related deposits, Sc can be enriched in residual deposits (laterites and bauxites) or in granitic pegmatites, such as the Evje-Ireland and Tørdal pegmatites in southern Norway. The grade of these operating deposits, where Sc is mined as by-product, are in the range of 100 to 150 µg/g. The Bayan Obo deposit produces about 15 t Sc annually (c. 90% of the world production) from 9.4 Mt resources grading about 150 µg/g Sc (Zhao, 1987; Li et al., 2013). The Zhovti Vody U-Fe deposit comprise 7.4 Mt resources grading 105 µg/g Sc (Mikhaylov, 2010). Ongoing Sc exploration projects at Tomtor in NW Yakutia, Russia, and Nyngan (laterite deposit) in New South Wales, Australia, comprise resources of 1.18 Mt grading 313 µg/g Sc (Tolstov and Gunin, 2001) and 16.9 Mt grading 235 µg/g Sc, respectively (Scandium International, 2020).

Recently, the Sc enrichment at Tørdal has been the target of exploration campaigns by the Scandium International Mining Corporation in 2011–2012. The Sc demand has motivated the present study, which aims to better understand the origin and the processes that have led to the Sc enrichments in the Tørdal pegmatites. Garnet, which is a common accessory mineral in the Tørdal pegmatites, preferentially incorporates Sc in the octahedrally coordinated B-site of its crystal structure (Raade et al., 2002). Because of its Sc compatible behavior garnet is, besides mica, the major host for Sc in the Tørdal and other pegmatites (Raade and Kristiansen, 2000, 2003). In addition, various Sc accessory minerals have been described for the Tørdal pegmatites including bazzite, cascandite, heftetjernite, kristiansenite, oftedalite, scandiobabingtonite, and thortveitite (Bergstøl and Juve, 1988; Eldjarn, 2002; Juve and Bergstøl, 1990, 1997; Kolitsch et al., 2010; Kristiansen, 2009; Raade et al., 2002) being indicative of local Sc enrichments. However, both the source and the reason for the enrichment of Sc in the Tørdal pegmatites has been debated since Goldschmidt (1934). The aims of this study are to determine the chemistry of pegmatite-hosted garnets and their Sc distribution at intra-crystal, intra-pegmatite and regional scale across the Tørdal pegmatite field. The results are discussed in terms of the behavior of Sc in pegmatite melts, the origin of the pegmatite melt and the economic potential of the Sc enrichment.

2. Regional geology

The pegmatites of the Tørdal area are geologically situated in the tectono-metamorphic domain of the Rogaland-Hardangervidda-Telemark sector of the Sveconorwegian orogeny (1.2–0.9 Ga; Bingen et al., 2008; Slagstad et al., 2017). The Tørdal pegmatite field comprises > 300 large (> 1000 m3) bodies, emplaced in a 3 km wide, NE-Telemark sector of the Sveconorwegian orogeny (1.2–0.9 Ga; Bingen et al., 2008; Slagstad et al., 2017). The Tørdal pegmatite field comprises > 300 large (> 1000 m³) bodies, emplaced in a 3 km wide, NE-SW striking 10 km belt, in the volcanosedimentary supracrustal sequence of the Nissedal Oulter (1300–1200 Ma) (Fig. 1). The pegmatites have sheet-like to irregular shapes and range from a few meters to 1 km in lateral extension. In most cases the pegmatites are concordant to the crystallization foliation of the amphibolites. Sub-horizontal pegmatite sheets show commonly boudinage structures. The supracrustal rocks comprise mainly amphibolites with intercalations of volcanic-sedimentary rocks and minor mafic to felsic intrusives. The entire sequence sits discordant on top of the underlying granitic gneisses (1520–1500 Ma) (e.g. Bergstøl and Juve, 1988). Immediately south of the pegmatite field and Nissedal Oulter is the Tørdal-Treungen granite, which intruded both the supracrustal rocks and granitic gneisses. The granite comprises mostly medium- to coarse-grained biotite granites with A-type signature. Dating of the granite comprises an uncertain U-Pb zircon emplacement age of 918 ± 7 Ma (Andersen et al., 2007) and two recent, well constrained ages of 957 ± 12 Ma (U-Pb zircon; Slagstad et al., 2018) and of 946 ± 4 Ma (Nb-Y-oxide; Rosing-Schow et al., 2020a). Two pegmatite crystallization ages exist from the Tørdal field: a U-Pb ilolite age of 892.7 ± 8.8 Ma for the Skardsfjell pegmatite and a U-Pb monazite age of 905.0 ± 2.4 Ma for the Upper Høydalen pegmatite (Rosing-Schow et al., 2020a) (for localities see Fig. 2). Thus, the Tørdal pegmatites are at least 40 Ma younger that the adjacent Tørdal-Treungen granite.

The Tørdal pegmatites are geochemically distinct compared to other Sveconorwegian pegmatite fields, by local enrichments of Sc, Mo, Y, Be, Sn, and Li (Bergstøl and Juve, 1988). Major minerals are K-feldspar, quartz, oligoclase, albite, biotite, and muscovite. The most common accessory mineral is garnet followed by lepidolite, gadolinite-(Y), beryl, monazite-(Ce), allanite-(Ce), topaz, fluorite, and cassiterite (Bergstøl and Juve, 1988; Raade and Kristiansen, 2000; Segalstad and Eggleston, 1993). In general, the pegmatites exhibit a Nb-Y-F (NYF) affinity. Chemical primitive pegmatites have very coarse granitic texture with crystal sizes of up to 20 cm (feldspars and quartz) and do not show mineralogical zoning. These pegmatites have commonly irregular to vein-like aplitic domains. Garnets occur in the coarse-grained as well as in the aplitic domains. Moderately evolved pegmatites show simple mineralogical zoning with a granitic boarder zone (not always developed), coarse-grained wall zone, blocky intermediate zone and a quartz core. Garnet occurs in the wall and intermediate zones. Some chemically evolved pegmatites, such as the Upper and Lower Høydalen, Skardsfjell, and Høftetjern 1, exhibit, in addition to the normal zoning, late-stage “cleavelandite” (platy albite) replacement zones with lepidolite. These albite zones contain occasionally large garnets (0.5–4 cm in size). This pegmatite zoning type is considered as complex zoning according to Jahns (1955). These small zones (< 5 vol% of the bulk pegmatite) represent a late-stage product of pegmatite-internal fractional melting and melt immiscibility (Müller et al., 2018). These zones led to occasional misinterpretation of the Tørdal pegmatites as Lithium-Caesium-Taumtalum (LCT) pegmatites due to minor occurrences of lepidolite and cassiterite (Kristiansen, 1998). Segalstad and Eggleston (1993) divided the pegmatite field into different regional zones based on K-feldspar colors: the green K-feldspar (amazonite), white K-feldspar, and pink K-feldspar zones (Fig. 2). Pegmatites with pink K-feldspar represent the most primitive, commonly unzoned pegmatites. Pegmatites with white K-feldspar are moderately evolved and show simple mineralogical zoning and amazonite pegmatites are the most evolved ones with complex zoning.

Recently an anatectic origin of the Tørdal pegmatite melts has been suggested (Müller et al. (2017) Rosing-Schow et al., 2020a) mainly because of the 40-Ma age difference of the pegmatites and the Tørdal-Treungen granite. The anatectic origin of the pegmatites is supported by field observations. At Kleppe quarry, for example, the amphibolites have textures typical for partial melting: networks of tiny leucocratic veinlets < 1 mm in width emerge in migmatic amphibolite and widen up to pegmatite veins when followed for several meters. About 10 to 20 m from their origin, these veins end up into up to 2–4 m thick pegmatite sheets (Fig. 3A), indicating relative short melt travel distances. The thicker, sub-horizontal pegmatite veins are syn-genetically boudinaged suggesting an extensional tectonic regime (Fig. 3B).

3. Samples and methods

3.1. Sampling

All together 32 garnet-bearing samples from 16 pegmatite localities across the Tørdal pegmatite field were sampled to achieve a reasonable regional cover of the entire area (Table 1; Fig. 2). It should be noted that not every Tørdal pegmatite contains garnet. Several garnet-bearing samples were taken from zoned pegmatites, in order to reveal possible variations of the garnet chemistry across pegmatite bodies. In addition, 6 bulk rock samples of the pegmatites and their host rocks were collected to compare the Sc contents of pegmatites with those of their host rocks (amphibolites, Tørdal-Treungen granite). The background is to identify possible sources of the high Sc in garnets from the pegmatites. The two pegmatite samples comprise c. 30 kg each. In the case of the Kleppe quarry pegmatite the entire section of the pegmatite sheet was sampled, being representative for the pegmatite melt composition during its initial stage of crystallization.
3.2. Whole rock

The bulk rock samples from two pegmatite, two amphibolite and two Tørdal-Treungen granite locations were collected. The two pegmatite samples, 25 kg each, were taken from unzoned pegmatites with coarse-grained granitic texture at Kleppe quarry and Heftetjern 2. Compositions of all bulk rock samples were determined at the Bureau Veritas Mineral Laboratories in Vancouver, Canada (Bureau Veritas, 2018). Major and minor elements were analyzed by ICP-ES and trace elements by solution ICP-MS using fused Li borate tablets. Peroxide sample fusion was applied to determine Li with ICP-ES. X-ray fluorescence analysis was performed for the determination of F. Detection limits for major elements are 0.01–0.04 wt%. The analytical accuracy was controlled using the internal geological reference materials STD SO-19, DS11, OREAS262, OREAS149, OREAS684, and MP1B. The accuracy was better than ± 1.5%. The precision was verified by duplicated samples in each analytical set. During repeated measurements, it was better than 0.5%. Loss on ignition (LOI) was determined by weight difference after 4 h ignition at 1000 °C.

3.3. Scanning electron microscopy and energy dispersive X-ray spectroscopy

For the identification of mineral inclusions within garnet crystals energy dispersive X-ray spectroscopy (EDS) was conducted both at the Department of Geosciences of the University of Oslo and at the Natural History Museum of Oslo. The SEMs used were a Hitachi SU5000 instrument equipped with a Dual Bruker XFlash 30 EDS system (Department of Geosciences) and a Hitachi S-3600N instrument equipped with a Bruker XFlash 5030 EDS system (Natural History Museum). In addition to EDS, back-scattered electron (BSE) images of the micro inclusions were obtained.

3.4. Electron probe microanalysis and back scattered electron imaging

Major and minor element compositions of 32 garnets were determined by Electron Probe Micro Analysis (EPMA) using a Cameca SX100 instrument equipped with five wavelength dispersive spectrometers (WDS) at the Department of Geosciences, University of Oslo (Supplementary Material A). The samples were prepared as polished...
thick (300 µm) sections. Beam conditions were for major elements (Si, Al, Mn, Fe, and Ca) 15 kV and 20nA, and for trace elements (Y, Yb, Sc, Na, and Sn) 20 kV and 100nA. The electron beam was focused. Peak count times for Si, Al, Mn, Fe, and Ti were 10 s, 20 s for Na and Mg, 40 s for Y, and 60 s for Sc and Yb. The calibration standards and their X-ray lines were wollastonite (Si Kα, Ca Kα), Al2O3 (Al Kα), MgO (Mg Kα), pyrophaneite (Ti Kα, Mn Kα), Fe metal (Fe Kα), albite (Na Kα), SnO2 (Sn Lα), and synthetic orthophosphates (Y Lα, Sc Kα, and Yb Lα) (Jarosewich and Boatner, 1991). All concentrations were corrected for matrix effects with the Cameca PAP procedure according to Pouchou and Pichoir (1984). Detailed WDS scans showed that there were no element peak overlaps. An Excel spreadsheet by Locock (2008) was applied for the calculation of garnet endmember proportions. BSE imaging was used to locate analyses in these zoned garnets.

3.5 Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)

Eighteen garnet grains from eight pegmatites were analyzed for trace elements with LA-ICP-MS at the Department of Geosciences of the University of Oslo. The instrument used was a Bruker Aurora Elite (QICPMS) with an attached Cetac LSX-213 G2 + laser. A total of 88 data points were acquired to explore core to rim compositional variations within garnet crystals (Supplementary Material B). The measured isotopes included 23Na, 45Sc, 89Y, 93Nb, 118Sn, 139La, 140Ce, 141Pr, 142Nd, 152Sm, 151Eu, 159Gd, 163Dy, 164Ho, 166Er, 169Tm, 171Yb, 172Lu, 173Hf, 181Ta, and 232Th. For calculation of the absolute element concentrations, the software Glitter was applied. The silicon content determined by EPMA was used as internal standard. Applied external standards were the reference materials NIST610, BCR2G, and GJ used to monitor instrument drift.

3.6 Scanning nuclear microprobe

Three garnet crystals from three different pegmatites (Svåhei 2a, Hefetjern I, and Hefetjern 2) were selected for mapping of Mn, Fe, Ca, Sc, Y, Yb, and Ti within crystals. The samples as prepared for EPMA were used. The methods used were Particle Induced X-ray Emission (PIXE) and Rutherford Backscattering Spectrometry (RBS) at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) in Germany. The applied ion beam was a 3 MeV H beam produced with a 3 MV Tandetron® accelerator focused to 5–8 μm in diameter. First, an overview scan of the target area (2 × 2 mm) of the sample was performed, to identify the exact position of the garnet crystal of interest. Then, a higher resolution scan with a step size of 8 μm was applied. Characteristic X-rays emitted from the samples were detected with a Ketek Silicon drift detector, which was collimated to 80 mm². The X-rays passed through a 1 μm silicon-nitride window, a 6 mm air layer and a 25 μm Be window before being detected. The high yield of X-rays from light elements was reduced using a 110 μm Mylar absorber. A strip detector was used to detect backscattered photons at a scattering angle of 173°. The data was gathered by the Fastcom MPA3 data acquisition program. Measurements obtained from RBS were used for affirming major element compositions, while the application of the CSIRO Dynamic Analysis method in the software GeoPIXE was used for analyzing the X-ray data (Ryan, 2000). As a first step in this analysis, all elements above the detection limit were identified and a matrix for the Dynamic Analysis method is created. This matrix is then applied to obtain spatial element images. The detection limits are based on the lowest peak size for an X-ray line, which is still discriminated from the background (including overlaps from X-ray lines of other elements).
characterized by low CaO, MgO and TiO₂ contents compared to the evolved Heftetjern 2 pegmatite are peraluminous in composition. Both the primitive, unzoned Kleppe quarry pegmatite and the more analyzed rocks: pegmatite, amphibolite and Tørdal-Treungen granite.

4. Results

4.1. The bulk chemistry of Tørdal pegmatites and their host rock

Table 2 displays major and trace element concentrations of the analyzed rocks: pegmatite, amphibolite and Tørdal-Treungen granite. Both the primitive, unzoned Kleppe quarry pegmatite and the more evolved Heftetjern 2 pegmatite are peraluminous in composition characterized by low CaO, MgO and TiO₂ contents compared to the Tørdal-Treungen granite. Major trace element differences are low Ba, Th, Nb, Zr, light rare earth elements (LREE) and high Rb of the pegmatites compared to the host rocks. The Sc content is < 1 µg/g in the Kleppe quarry pegmatite and 53 µg/g in the Heftetjern 2 pegmatite. The Tørdal-Treungen granite seems to have constantly low Sc of 2 to 3 µg/g. It is a peraluminous biotite granite with A-type signature according to (Wood, 1980) with transitional MORB-Alkalic signature (with an approximate Ti-V ratio of 50 according to (Shervais, 1982). The investigated amphibolites are strongly enriched in Sc with 29 and 30 µg/g, respectively, which is twice as high as the average Earth’s crust composition (14 µg/g Sc; Rudnick and Gao, 2005). Interestingly, the F contents of the amphibolites (0.08 and 0.16 wt%, respectively) are higher than those of the Tørdal-Treungen granite (0.01 and 0.04 wt%, respectively).

4.2. BSE imaging of pegmatite garnet

Garnets analyzed by EPMA and LA-ICP-MS were first examined by BSE imaging to reveal their growth zoning. In the studied garnets, the main zoning features comprise concentric oscillatory growth zoning, step zoning and resorption surfaces. Oscillatory growth zoning comprises thin (1–20 µm), alternating growth zones with relative low BSE signal contrast among the individual zones (Allègre et al., 1981; Haase et al., 1980; Loomis, 1982; Pearce, 1993; Shore and Fowler, 1996; Sibley et al., 1976; Simakin, 1984). Step zones are wider, non-periodic growth zones (> 20 µm) with strong contrasts and sharp zone boundaries (against other step zones) (e.g. Allègre et al., 1981; Bottinga et al., 1966). The growth of step zone ends occasionally with a resorption surface. A resorption surface is recognizable by the truncation of previous growth zones resulting commonly in the rounding and partial dissolution of crystals (Müller et al., 2010). Based on the observed growth structures, the investigated garnets are grouped into four structural types (A, B, C and D; Fig. 4):

Group A garnets (0.01–1.5 cm in size) have transitional almandine-spessartine compositions and are characterized by bright core (inner step zone) overgrown with dull margin (outer step zone). This is the most common garnet type found at the localities Bratterud, Butvatnet, Grenlilheii, Heftejtern 1 and 2, Kleppe quarry, Mjøldeledalen 2a, Sjåuset, and Upper Høydal (sample from intermediate zone). Both the bright core and the dull overgrowth contain low-contrast oscillatory growth zoning. The bright core is commonly bordered by a resorption surface. The resorption may have resulted in patchy structures. In many cases this resorption surface is accompanied by numerous, concentrically arranged quartz inclusions (5–350 µm). In some crystals the frequency of the inclusion is so high, that the crystals have an amoeboid to skeletal crystal habit. Garnets from Butvatnet, Heftejtern 1 and Heftejtern 2 samples have a volumetrically large bright core, which is overgrown by a relatively thin (up to 200 µm) dull margin.

Almandine garnets of group B (0.02–3.0 cm in size), which comprise the localities Svåheii 2a and 3, Lislegrønlia and Storeymr, show well developed concentric growth zoning. The transitions between bright and dark growth zones are relatively smooth and not related to trace element concentration steps (see also following chapters), thus they are classified as oscillatory zoning. Drop-like quartz inclusions (50–500 µm) are common.

Group C garnets comprise large spessartine crystals (0.5–4 cm), which do not show growth zoning in BSE imaging at all. Garnets of this group originate from albite zones of the Upper Høydal (sample 03071715) and Lower Høydal pegmatites (sample 23091545).

4.3. Micro inclusion inventory of pegmatite garnets

For further characterization of the garnets their micro inclusion inventory was examined. Micro inclusions observed in the Tørdal garnets comprise mainly quartz, zircon, Y- and F-bearing minerals and a few Sc-bearing minerals (Table 1). Quartz is commonly the most abundant inclusion phase except for garnets from the albite zones of the Høydal pegmatites. Garnets from the NE of the Tørdal pegmatite field (localities Heftejtern 1 and 2, Sjåuset, Bratterud, and the Storeymr 2) are rich in zircon inclusions, although Høydal garnets lack zircon inclusions. The abundance of zircons generally decreases towards the S and SW of the pegmatite field. The identified Y-rich inclusions comprise
Table 1
Locality and characteristics of investigated garnet samples. The average content of Sc were determined by EPMA and/or LA-ICP-MS. The number behind the analytical method in column average Sc content corresponds the number of analyses.

<table>
<thead>
<tr>
<th>Locality</th>
<th>Sample number</th>
<th>UTM Zone</th>
<th>East</th>
<th>North</th>
<th>Garnet origin within pegmatite body</th>
<th>Garnet crystal size in sample (cm)</th>
<th>Inclusion inventory of garnets (in the order of frequency)</th>
<th>BSE-zoning type of garnets</th>
<th>Average Sc content of garnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bratterud</td>
<td>09061603</td>
<td>32 V</td>
<td>488817</td>
<td>6562727</td>
<td>Wall zone</td>
<td>0.02–0.4</td>
<td>Quartz, zircon, keiviite-(Y), Ca-Fe-LREE silicate, Ti-Y mineral, thorite</td>
<td>A</td>
<td>117 ± 55 (LA-ICP-MS, 12)</td>
</tr>
<tr>
<td>Butvatnet</td>
<td>05061618</td>
<td>32 V</td>
<td>481700</td>
<td>6557482</td>
<td>Wall zone</td>
<td>0.03–0.26</td>
<td>Keiviite-(Y), Ti-Y mineral, quartz, zircon, xenotime-(Y), Fe-REE silicate</td>
<td>A</td>
<td>66 ± 47 (EPMA, 27)</td>
</tr>
<tr>
<td>Gromilheii</td>
<td>06071703</td>
<td>32 V</td>
<td>482611</td>
<td>6557673</td>
<td>Close to contact (pegmatite is unzoned)</td>
<td>0.02–0.15</td>
<td>Quartz, zircon, Ti-Y mineral, Fe-REE silicate</td>
<td>A</td>
<td>362 ± 100 (LA-ICP-MS, 12)</td>
</tr>
<tr>
<td>Heftetjern 1</td>
<td>20091508</td>
<td>32 V</td>
<td>485407</td>
<td>6560383</td>
<td>Wall zone</td>
<td>0.01–0.6</td>
<td>Quartz, zircon, Ti-Y mineral, Cu-S oxide, U oxide, thorite</td>
<td>A</td>
<td>387 ± 47 (EPMA, 19)</td>
</tr>
<tr>
<td>Heftetjern 2</td>
<td>08061601</td>
<td>32 V</td>
<td>485238</td>
<td>6560598</td>
<td>Wall zone</td>
<td>0.02–0.7</td>
<td>Quartz, keiviite-(Y), Y-F silicate, zircon, Ti-Y mineral, Ti-Mn-Fe oxide</td>
<td>A</td>
<td>93 ± 30 (EPMA, 11)</td>
</tr>
<tr>
<td>Kleppe quarry</td>
<td>07061611</td>
<td>32 V</td>
<td>484884</td>
<td>6557627</td>
<td>Aplitic facies in unzoned pegmatite</td>
<td>0.02–0.15</td>
<td>Quartz, zircon, keiviite-(Y), Ti-Y mineral</td>
<td>A</td>
<td>1511 ± 260 (LA-ICP-MS, 12)</td>
</tr>
<tr>
<td>Lisdegrønlia</td>
<td>06071710</td>
<td>32 V</td>
<td>483592</td>
<td>6557878</td>
<td>Close to contact (pegmatite is unzoned)</td>
<td>0.03–0.12</td>
<td>Quartz, zircon</td>
<td>A</td>
<td>1462 ± 125 (EPMA, 34)</td>
</tr>
<tr>
<td>Mjeltdalen 2a</td>
<td>06071715</td>
<td>32 V</td>
<td>484311</td>
<td>6557191</td>
<td>Aplitic facies in unzoned pegmatite</td>
<td>0.06–0.3</td>
<td>Quartz, Ti-Y mineral, zircon, keiviite-(Y), polycrase-(Y), Al oxide, U oxide</td>
<td>A</td>
<td>1909 ± 177 (LA-ICP-MS, 12)</td>
</tr>
<tr>
<td>Sjauset</td>
<td>05061609</td>
<td>32 V</td>
<td>485640</td>
<td>6558697</td>
<td>Wall zone</td>
<td>0.01–0.15</td>
<td>Quartz, zircon, Ti-Y mineral, gadolinite-(Y), Ti-Fe oxide</td>
<td>B</td>
<td>987 ± 181 (LA-ICP-MS, 12)</td>
</tr>
<tr>
<td>Storemyr 1</td>
<td>06061609</td>
<td>32 V</td>
<td>485441</td>
<td>6558866</td>
<td>Close to contact (pegmatite is unzoned)</td>
<td>0.02–0.1</td>
<td>zircon</td>
<td>B</td>
<td>797 ± 321 (EPMA, 31)</td>
</tr>
<tr>
<td>Storemyr 2</td>
<td>06061604</td>
<td>32 V</td>
<td>485238</td>
<td>6560598</td>
<td>Wall zone</td>
<td>0.02–0.7</td>
<td>Quartz, zircon, Ti-Y mineral, Ti-Mn-Fe oxide, thorite</td>
<td>A</td>
<td>361 ± 19 (EPMA, 6)</td>
</tr>
<tr>
<td>Storemyr 3</td>
<td>07071703</td>
<td>32 V</td>
<td>485627</td>
<td>6558286</td>
<td>Close to contact (pegmatite is unzoned)</td>
<td>0.02–0.2</td>
<td>Quartz, zircon, Ti-Y mineral, Ti-Mn-Fe oxide, hematite</td>
<td>B</td>
<td>1016 ± 239 (EPMA, 24)</td>
</tr>
<tr>
<td>Svaheii 2a</td>
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<td>32 V</td>
<td>481596</td>
<td>6556927</td>
<td>Wall zone</td>
<td>0.07–0.2</td>
<td>Quartz, zircon, titanite, thoritevite, polycrase-(Y), hematite</td>
<td>B</td>
<td>56 ± 16 (EPMA, 8)</td>
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<tr>
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<td>481515</td>
<td>6557011</td>
<td>Wall zone</td>
<td>0.5–2.0</td>
<td>Y-F silicate, Ti-Y mineral, quartz, zircon, hematite</td>
<td>B</td>
<td>1475 ± 108 (LA-ICP-MS, 12)</td>
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<td>Upper Høydalen</td>
<td>08061612</td>
<td>32 V</td>
<td>486274</td>
<td>6560473</td>
<td>Intermediate zone</td>
<td>0.3–3.0</td>
<td>Keiviite-(Y), xenotime-(Y), Y-F silicate, thoritevite, Kfeldspar</td>
<td>A</td>
<td>1334 ± 114 (EPMA, 19)</td>
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<td>Lower Høydalen</td>
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<td>0486445</td>
<td>6560532</td>
<td>Albite zone</td>
<td>0.8–4.0</td>
<td>K-feldspar, Al oxide, keiviite-(Y), fluorite, Ca-REE oxide</td>
<td>C</td>
<td>79 ± 13 (EPMA, 24)</td>
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keiviite-(Y), yttrofluorite, Y-F-silicates, and Ti-Y minerals. The abundance of these minerals is high for some garnets from the SW of the field (Svåheii 3, and Butvatnet samples) but more common in the NE (Upper Høydalen 1, Lower Høydalen and Heftetjern 2 samples). Garnets from other locations either exhibit low abundances of Y-rich micro inclusions or completely lacking them. The F-rich minerals, comprising Y-F-silicate, fluorite, and yttrofluorite, are only found in garnets from the Heftetjern-Høydalen area. There is no distinct difference in the inclusion inventory between group A and B garnets. Garnets from the albite zones of the Upper and Lower Høydalen pegmatites (group C) have high abundances of fluorite and yttrofluorite, whereas the Heftetjern 2 garnets contain Y-F-silicates. The only Sc-rich micro inclusion species identified was thortveitite, which only occurs in garnets from the Svåheii 2a and Upper Høydalen localities.

4.4. Major and trace element chemistry of garnets

The investigated garnets of the Tørdal pegmatites have variable almandine-spessartine component ratios with a spessartine component ranging from 29 to 93 mol.%. Almost pure spessartines (> 90 mol.%) are found only in late-stage albite zones of the Upper Høydalen pegmatite. Less spessartine-rich garnets (60–85 mol.%) occur in albite zones of the Lower Høydalen pegmatite and in the Sjauset albite pegmatite. These three localities comprise the chemically most evolved

<table>
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<th>Rock type</th>
<th>Amphibolite</th>
<th>Amphibolite</th>
<th>Tørdal granite</th>
<th>Tørdal granite</th>
<th>Pegmatite</th>
<th>Pegmatite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
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<td>Mjeltedalen</td>
<td>Kleppe road</td>
<td>Dalane</td>
<td>Kleppe quarry</td>
<td>Heftetjern 2</td>
</tr>
<tr>
<td>Sample nr.</td>
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<td>06071716</td>
<td>04071707</td>
<td>07071704</td>
<td>07061613</td>
<td>20091506</td>
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<table>
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<th>Rock type</th>
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<th>Amphibolite</th>
<th>Tørdal granite</th>
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<th>Pegmatite</th>
<th>Pegmatite</th>
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<tr>
<td>Location</td>
<td>Kleppe quarry</td>
<td>Mjeltedalen</td>
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<tr>
<td>Sample nr.</td>
<td>04071705</td>
<td>06071716</td>
<td>04071707</td>
<td>07071704</td>
<td>07061613</td>
<td>20091506</td>
</tr>
</tbody>
</table>

Table 2

Major and trace element concentrations of Tørdal pegmatites and their host rocks (amphibolites and the Tørdal granite). In addition to the listed elements, concentrations of As, Cd, Sb, Bi, Ag, Au, Hg, Se, and W were analyzed but were below the limits of detection. MDL – Mean detection limit.
pegmatises of the Tørdal field investigated in this study. The pyrope component of all Tørdal garnets varies between 0 and 5.5 mol.%, the andradite component between 0 and 3.4 mol.%, the grossular component between 0 and 2.8 mol.%, the yttrogarnet component between 0.5 and 2.6 mol.%, and the Sc garnet component between 0 and 1.0 mol.%. Other components are negligible (Supplementary Material A).

Garnet compositions in the almandine versus spessartine plot (Fig. 5A) form two parallel linear trends evolving both from Fe-rich and Mn-poor to Mn-rich and Fe-poor garnets. The first trend generated by the samples from the Svåheii 3, Bratterud, Heftetjern 1, Heftetjern 2, Upper Høydalen, Lower Høydalen and Sjauset locations. Garnets from the Mjeltedalen 2a, Kleppe quarry, Storemyr 1 to 3, Svåheii 2a, Lislegrønlia, Grønliheii, and Butvatnet locations form the second trend, which is shifted to slightly lower almandine contents. This shift is mainly due to the pyrope component in these garnets. In the pyrope vs spessartine plot of Fig. 5B pyrope-bearing garnets ( > 0.01 mol.%) representing trend 2 in Fig. 5A, clearly separate from pyrope-poor and -free garnets of trend 1. The pyrope-bearing garnets originate from the chemically primitive pegmatites of the Tørdal field.

Scandium concentrations of the investigated garnets range from 14 to 2197 µg/g. Highest Sc concentrations are found in garnets from the wall zone of the Heftetjern 1, Heftetjern 2 and Upper Høydalen pegmatites (bulk grain averages of 1568, 1945 and 1460 µg/g, respectively) in the central NE of the pegmatite field. Garnets from the Svåheii 2a, Lislegrønlia, Kleppe quarry, and all Storemyr pegmatites located in the center of the field exhibit moderate high Sc contents (c. 400 to 1000 µg/g), whereas garnets from the Svåheii 3, Mjeltedalen 2a, Grønliheii, Sjauset, Bratterud, and Butvatnet pegmatites from the SW and far NE of the field have low Sc ( < 400 µg/g). The Sc₂O₃ versus MnO/(MnO + FeO) plot (Fig. 5C) illustrates that Sc generally increases with increasing MnO/(MnO + FeO) ratio (spessartine component) until a MnO/(MnO + FeO) ratio of c. 0.6. Garnets with a MnO/(MnO + FeO) ratio > 0.6 (garnets from Sjauset and albite zones of Lower and Upper Høydalen) exhibit a drastic drop in the Sc content with concentrations < 0.03 Sc₂O₃ wt.% (< 196 µg/g Sc). Spessartine with the highest MnO/(MnO + FeO) ratio (sample Upper Høydalen 12) does not contain Sc. Thus, evolved, complex zoned pegmatites contain two populations of garnets: Sc-rich garnets in the wall zone and Sc-poor to –free garnets in the late-stage albite zones (Høydalen pegmatites). These late-stage garnets and have similar low Sc as garnets from primitive pegmatites such as Grønliheii. The detected Sc abundances indicate that the Sc concentrations are highest in garnets from the wall zone of the chemically most evolved pegmatites.

The most abundant trace element detected in the investigated garnets is Y, with the highest concentrations found in the Butvatnet sample (grain 1) up to 24,935 µg/g (LA-ICP-MS). Other Y-rich garnets (mean ≥ 10,000 µg/g Y) include crystals from the Kleppe quarry (grain 2), Svåheii 2a (grain 4), Svåheii 3, Storemyr 1, Storemyr 2, Storemyr 3, Lislegrønlia, Mjeltedalen 2a, Butvatnet, Bratterud (grain 4), Grønliheii, Heftetjern 1, Upper Høydalen 1 and Lower Høydalen. Lowest Y (6000 to 10000 µg/g) is observed in grains from Svåheii 2a, Bratterud (grains 1 and 3), Kleppe quarry (grain 1a), and albite zone of the Upper Høydalen pegmatite. The Y₂O₃ versus MnO/(MnO + FeO) plot reveals that the average Y content is lower for garnet crystals with high spessartine component (MnO/(MnO + FeO ratio > 0.6; Fig. 5D).

In the Sc versus Ca (apfu – atoms per formula unit) plot in Fig. 5E the data reveal an approximately positive correlation up to a Ca content of 0.06 apfu and a Sc content of 0.02 apfu. Garnets with > 0.06 apfu Ca samples from the primitive Kleppe quarry, Storemyr 3, and Mjeltedalen pegmatites) exhibit a negative correlation with Sc. In the Sc versus Mg (apfu) diagram the data plot in three clusters: (1) low Mg/low Sc garnets (Sjauset, Bratterud, Svåheii 3), (2) low Mg/high Sc
garnets (Heftetjern1, Upper Høydalen 1, Heftetjern 2); and (3) high Mg/moderate Sc garnets (pyrope-bearing samples) (Fig. 5F). The pattern indicates that there is not a simple relationship between the Sc and Mg content of garnets.

4.5. Trace element distribution within garnets

Core-rim compositions of selected garnet crystals (31 grains) were determined with EPMA and LA-ICP-MS. Elements of major interest for the crystal-internal distribution were Sc, Y, and REE, beside the Mn/(Mn + Fe) ratio. The Mn/(Mn + Fe) ratio is more or less constant (< 0.02 difference) from core to the rim for most investigated garnets including crystals from Grønliheii, Lislegrenlia, Kleppe quarry, Mjelletalen 2a, Butvatnet, and Storemyr 2 and 3 (Fig. 6). The ratio decreases slightly from the core to rim of crystals from the Bratterud, Heftetjern 2, Svåheii 3, Storemyr 1 and Sjauset pegmatites.

Yttrium either remains relatively constant (< 0.02 apfu difference) across the grains, or decreases from the core to the rim, in particular in crystals with high average Y (Fig. 6). Crystals with a significant drop of Y content in the outer growth zones correspond generally to the BSE-zoning group A with bright crystal cores.

LA-ICP-MS traverses across garnets reveal that Sc is more or less consistent across in most of the investigated grains or decreases slightly from the core to the rim (Supplementary Material B). Examples of Sc decrease are the high-Sc grain 3 from Svåheii 2a where Sc decreases from 1137 to 726 µg/g and the low-Sc grain 1 from Bratterud with a drop from 143 to 78 µg/g. Exceptions are grain 2 from Heftetjern 2 where Sc slightly increases towards the rim with a difference of about 20 µg/g. Scandium contents in the Kleppe quarry garnets generally increase from the core to the rim (compositional differences of 16 to 55 µg/g). An irregular intra-crystal distribution for Sc is observed for garnets from the Lislegrenlia pegmatite.

Fig. 7 displays representative chondrite-normalized REE patterns of 18 garnet crystals that were examined (Supplementary Material B). Concentrations of La, Ce, and Eu are below the limit of detection for most analyzed grains. The chondrite-normalized REE patterns are relatively consistent for all grains. They are characterized by a strong depletion in LREE, a pronounced Eu anomaly and steeply increasing HREE with increasing atomic number. The highest HREE content was detected in one garnet from the Butvatnet location ($\Sigma$HREE = 12,839 µg/g, grain 3). The same sample also has the highest LREE abundance ($\Sigma$LREE = 147 µg/g, grain 2). Significant core-rim variations of HREEs are observed for a number of the analyzed crystals (mostly Group A grains), as for example grain 1 from the Bratterud (Fig. 7A). Group B garnets show less pronounced core-rim variations of HREE (Fig. 7B), whereas garnets originating from albite zones (Group C) do not exhibit core-rim differences (Fig. 7C).
4.6. Element mapping of garnets by scanning nuclear microprobe

Scanning nuclear microprobe mapping was applied to examine the crystal-internal distribution of Sc, Mn, Fe, Ca, Y, Yb, and Ti of three representative, Sc-rich garnet crystals from Svåheii 2a, Heftetjern 1, and Heftetjern 2. Crystals with Sc concentrations well above the high detection limit of scanning nuclear microprobe element mapping (> 600 µg/g Sc per pixel) had to be chosen to achieve interpretable results. The maps are presented in Figs. 8 to 10, except for the Fe maps, which are very similar to the Mn maps. Manganese has high concentrations (~8e3 cps) and its distribution appears more or less homogeneous across the investigated crystals (Fig. 8A and 9A) except...
grain 3 from Heftejern 2 which is most enriched in Mn in the central left part of the grain (Fig. 10A).

The Svaheii 2a crystal (group B) shows a decrease of Sc from core (c. 1000 µg/g) towards margin (< 800 µg/g) (Fig. 8D). Calcium behaves in the opposite way to Sc (Fig. 8C) confirming the negative Ca-Sc correlation for high-Sc garnets demonstrated in Fig. 5E. The Y and Yb distribution reveals a concentric growth zoning with a Y- and Yb-rich zone around the crystal core and one at the crystal margin (Fig. 8E and F). The distribution corresponds to the zoning observed in BSE imaging (Fig. 4), confirming that fluctuations of the Y and HREE content are responsible for the BSE contrasts. Titanium is slightly enriched in the inner Y-Yb-rich growth zone (Fig. 8B). The high-Ti, needle-like structure in the center of the crystal is a titanite inclusion.

In the crystal from Heftejern 1 (group A), Sc is more or less homogeneously distributed (c. 1200 µg/g) except some irregular patches close to the crystal margin (600 µg/g) (Fig. 9D). Calcium shows a star-like distribution in the crystal center and is enriched at the margin (Fig. 9C). The irregular pattern, which is decoupled from the growth zoning imitated by the Y and Yb distribution (Fig. 9E and F), indicates a secondary, alteration-driven redistribution of Ca. Titanium follows the zoning pattern of Y and Yb (Fig. 9B).

The Heftejern 2 crystal (group A) displays the most complex Sc distribution pattern comprising a relative Sc-rich core, followed by a Sc-poor zone following the resorption of core and a final Sc-rich overgrowth (Fig. 10D). Similar to the Heftejern 1 crystal, Ca is heterogeneously distributed across the crystal with a general enrichment at the crystal margin implying a secondary redistribution of the Ca (Fig. 10C). The Ca pattern does not show any relationship and is decoupled from the Sc, Y, Yb, Mn or Ti distribution. Yttrium, Yb and Ti are strongly enriched in the resorbed crystal core. Both the enrichments and core resorption are typically for Group A grains (Fig. 4A and B).

Summarizing, the Sc distribution is different for all three grains implying that multiple processes control the intra-crystalline Sc distribution.

5. Discussion

5.1. Sc variation within garnets and within pegmatite bodies

Scandium is a compatible element in garnet (and mica) and, thus,
will be consumed by these minerals during pegmatite crystallization as long they are present (Table 3). The incorporation of Sc$^{3+}$ in the B-site of almandines and spessartines occurs through replacement of Al and trivalent Fe by Sc (Sc$^{3+} \leftrightarrow$ Al$^{3+}$, Fe$^{3+}$; e.g. Raade et al., 2002). The Tørdal garnets with highest Sc have a spessartine component between 50 and 60 mol.$\%$. Besides being enriched in Y and HREE, the Sc-rich garnets are characterized by very low Mg contents ($< 0.03$ apfu) and a distinct Ca concentration window of 0.03 to 0.06 apfu (Fig. 5). The Sc$_2$O$_3$ content in garnets with $> 60$ mol.$\%$ spessartine (Sps) drops from 0.35 to $< 0.04$ wt%.

The low-Sc garnets with $> 60$ mol.$\%$ Sps originate from highly evolved, layered albite pegmatites (Sjauset) or from late-stage albite zones of evolved, complex zoned pegmatites (Upper and Lower Høydalen). The late-stage albite-zone-forming melts of the Høydalen pegmatites were depleted in Sc due to its consumption by garnet and mica during earlier crystallization stages. The highly evolved melt of the Sjauset albite pegmatite had initially low Sc documented by low Sc in wall zone garnet and mica (Rosing-Schwø et al., 2018). However, the question remains why the Sc concentration drops at $> 60$ mol.$\%$ Sps rather than decreasing continuously. The Sc drop is partially associated with a decrease of Y in garnets (Fig. 5C and D). All Sc-rich garnets (Heftetjern 1, Heftetjern 2, Upper Høydalen 1, and Svåheii 2a) originate from the wall zone of the sampled pegmatites, representing a relatively early stage of pegmatite crystallization. This observation confirms the highly garnet-compatible behavior of Sc. Furthermore, it suggests that the Tørdal pegmatite melts were initially enriched in Sc but to different degrees. With progressing pegmatite crystallization (from the pegmatite/wall rock contact inward) the Sc content in the remaining melt decreased due to consumption of Sc by garnet (and mica). Highly evolved, late stage pegmatite melts, which crystallized garnets with $> 60$ mol.$\%$ spessartine, was depleted in Sc.

One could assume that the Sc content within garnet crystals decreases with progressing growth due to the strong Sc consumption by the growing garnet and the accompanied decrease of Sc in the remaining melt. The progress was forced by the co-genetic growth of mica, which is also Sc-compatible. A decrease of Sc towards the margin of garnet crystals is observed for most of the Sc-rich samples, for example grain 2 from the Svåheii 2a pegmatite (Fig. 8). Sc-poor garnets
(from the Lislegrønlia, Svåheii 3, and Butvatnet localities) show homogenous Sc distribution across the crystals indicating that Sc was consistently available during garnet growth. However, the garnets from the Heftetjern 2 pegmatite show beside the grain-internal Sc decrease a final high-Sc overgrowth (Fig. 10D). This Sc-rich overgrowth may indicate a late-stage Sc increase due to Sc remobilization as observed for the Heftetjern1 pegmatite (Bergstøl and Juve, 1988; Raade et al., 2002; Raade and Kristiansen, 2000, 2003).

Group A garnets (from the Bratterud, Buvatnet, Sjauset, Grønliheii, Heftetjern, Mjeldealen and Kleppe quarry locations) exhibit a sudden drop in the Y (HREE) content during crystal growth. The drop is associated with a resorption event of garnet. The concentration drop might be caused either by sudden changes in the PT conditions (which seems unlikely), the buffering of Y (HREE) by co-genetic minerals, such as gadolinite-(Y), or by melt–melt or fluid–melt immiscibility. Gadolinite-(Y) is one of the most common accessory minerals of the Tørdal pegmatites and has been identified macroscopically in the wall zone of the Høydalen, Heftetjern, Svåheii 2a pegmatites. However, garnets from

Fig. 10. Scanning nuclear microprobe maps of garnet (grain 3) from Heftetjern 2 showing the distribution of (A) Mn, (B) Ti, (C) Ca, (D) Sc, (E) Y, and (F) Yb.
these localities do not necessarily exhibit the sudden, intra-crystal Y decrease meaning that the Y-drop and related garnet resorption might have other causes. The observed replacement structures (resorption surfaces) most likely record the dissolving nature (with respect to garnet) of fluids or melt portions formed as a result of melt–melt or fluid-melt immiscibility during melt cooling. Müller et al. (2018) suggested that immiscibility was presumably responsible for the formation of resorption surfaces developed in garnets from the Sveconorwegian Evje-Iveland pegmatites. about 80 km SW of Tørdal. It is suggested that the more H2O- and alkaline enriched immiscible phase reacted with already crystallized garnet causing their partial dissolution.

5.2. Sc variation across the Tørdal pegmatite field and possible sources of Sc enrichment

In Fig. 11 average Sc concentrations of garnets of all investigated locations are displayed in the regional map covering the area of the Tørdal pegmatite field. At the regional scale, Sc in garnets is highest in the Skardsfjell-Heftetjern-Høydalen area. The high abundance of Sc in these pegmatites is also reflected by the presence of a diversity of Sc minerals, including bazzite, cascandite, heftetjernite, kristiansenite, oftedalite, scandiobabingtonite, and shortveitite (Kristiansen, 2009). These are 7 out of the 14 known terrestrial Sc mineral species. Due to the small crystal sizes (up to 2 mm for kristiansenite and up to 1 cm for bazzite; e.g. Raade et al., 2002) and the very rare occurrence at Hef tetjern, they represent a very small proportion of the Sc bulk content of the pegmatite. These Sc minerals were formed during the latest stages of the pegmatite formation by remobilization of Sc bound in primary mica and/or garnet by intrinsic pegmatitic fluids (e.g. Raade et al., 2002; Chukanov et al., 2017). From this area the average Sc content of garnets decreases towards NE (Sjauset and Bratterud) and towards SW (Storemyr, Kleppe, Mjel tedalen, Lislegranlia, Granliheii, Butvatnet). Further towards SW, in the Svåhei area, the Sc content of garnets increases again, but not as high as in the Skardsfjell-Heftetjern-Høydalen area.

The high-Sc Skardsfjell-Heftetjern-Høydalen area lies in the amaz onite zone of the Tørdal pegmatite field, which hosts the most evolved pegmatites. The regional zoning, introduced by Segalstad and Eggleston (1993), comprises, from S-SW to N-NE, the pink K-feldspar zone, white K-feldspar and the amazonite zone (Fig. 11). One could assume that the highly evolved pegmatites are most Sc-rich. However, the amazonite-albite pegmatites of the Sjauset area are the chemically most evolved pegmatites of Tørdal and these contain spessartine (> 60 mol.% Sps) with low Sc. The most Sc-rich pegmatites (Heftetjern 2, Upper and Lower Høydalen, Svåhei 2a) have in common that they are chemically evolved (but not to the highest degree) and show a distinct complex zoning with border zone, wall zone, blocky intermediate zone and quartz core superimposed by late-stage albite (cleavelandite) zones. Svåhei 2a is different to the other Sc-rich pegmatites that it does contain white K-feldspar and no amazonite.

The Tørdal pegmatite melts were initially high in Sc, because Sc is compatible with pegmatitic garnet and mica and decreases in the melt with progressing fractionation and crystallization. In the following the

<table>
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<tr>
<th>Mineral</th>
<th>Sc KD mineral/melt</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Garnet</td>
<td>13.6–19.2</td>
<td>Irving and Frey (1978)</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>Sisson and Bacon (1992)</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>0.029</td>
<td>Leeman and Phelps (1981)</td>
</tr>
<tr>
<td></td>
<td>0.01–0.04</td>
<td>Nash and Crecraft (1985)</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>0.01</td>
<td>Bacon and Druit (1988)</td>
</tr>
<tr>
<td></td>
<td>0.02–0.06</td>
<td>Nash and Crecraft (1985)</td>
</tr>
</tbody>
</table>

Fig. 11. Geological map of the Tørdal pegmatite field showing the regional distribution of average Sc content of garnets from 15 pegmatite localities. The bubble diameter corresponds to the average Sc content of garnet. Garnets from pegmatites of the Skardsfjell-Heftetjern-Høydalen area are most enriched in Sc. The legend of Fig. 2 applies.

Table 3
Available mineral/melt Sc partition coefficients KD for pegmatite-forming minerals crystallizing from rhyolitic/granitic melts with low MgO contents (< 0.5 wt%). The partition coefficients were determined rhyolite melt compositions which are generally similar to the chemistry of granitic pegmatites.
possible sources of Sc in the Tørdal pegmatites are discussed.

The Tørdal pegmatite field is situated immediately NE of the Tørdal-Treungen granite. The Tørdal-Treungen granite is a composite A-type pluton, which extends for about 40 km in SW-NE direction (Fig. 1). Until recently, it has been assumed that the Tørdal pegmatites represent fractionated residual melts derived from the Tørdal-Treungen granite pluton, because of their immediate spatial relationship (Raade and Kristiansen, 2000; Segalstad and Eggleston, 1993).

However, several facts speak against the pluton-derived origin of the Tørdal pegmatite melts. Firstly, recent dating of the Tørdal pegmatites and Tørdal-Treungen granite by Rosing-Schow et al. (2020a) revealed that the emplacement of the granite pluton predates the pegmatite formation by about 40 Ma. Thus, the Tørdal-Treungen granite cannot be the source of the Tørdal pegmatite melts. Secondly, because Sc behaves compatible in granitic systems it will not become enriched by fractional crystallization and, thus, residual pegmatite melts derived from the Tørdal-Treungen granite would be Sc-poor. Thirdly, the pattern of mineralogical zoning of the pegmatite field, first mapped by Segalstad and Eggleston (1993) and modified by Rosing-Schow et al. (2020b), is discordant to the pluton contact. This zoning pattern contradicts the conventional model introduced by Černý (1991). According to Černý’s model, the zone boundaries should be concentric and/or parallel to contacts of the parental pluton but this is not the case for the zoning of the Tørdal field (Fig. 11). Thus, the Tørdal-Treungen granite can be excluded as source of the pegmatite melts and of Sc, because the granite is very poor in Sc (mean 2 µg/g).

Already Goldschmidt (1934) and later Bergstøl and Juve (1988) suggested that the major sources of Sc of the Tørdal pegmatites are the Sc-rich amphibolites of the Nissedal Outlier (mean 34 µg/g Sc; this study), the host rocks of the Tørdal pegmatites which underwent higher amphibolite facies metamorphism under the Sveconorwegian orogenesis. According to the latter authors, the enrichment of Sc occurred while the pegmatite melts moved from the pluton (the authors assumed a pluton-derived origin of the Tørdal pegmatite melts) through the host rocks to their final emplacement, up to 4 km away from the pluton. On their way the pegmatite melts “leached” Sc from the amphibolites.

Firstly, the pegmatite melts do not originate from the pluton as discussed above. Secondly, long lateral travelling of the pegmatite melts (> 1 km) is not supported by field observations (Rosing-Schow et al., 2020a; see also chapter Regional Geology Fig. 3).

The major host of Sc in the Tørdal amphibolites is amphibole. Amphiboles of the metagabbro at Høydalen, for example, contain about 50 µg/g Sc, whereas biotite contains 5 µg/g only (Oftedal, 1943; Wilhelmsen, 2020). The Sc content in amphibolitic biotites is low, because MgO-containing melts have low Sc mineral/melt partition coefficients (about 0.2; Adam and Green, 2006; Table 3). Scandium is strongly bound in amphibole (substituting for Al) (e.g. O’Brien, 1966; Wood and Samson, 2006) and can be released efficiently only if amphibole undergoes partial melting. In silicate melts Sc preferentially partitions into F-bearing Na-rich and, in particular, into F-bearing K-rich melts forming Sc-F complexes (Gramaccioli et al., 2000; Shchekina and Garmenitskii, 2008). The amphiboles of the Tørdal amphibolites contain considerable amounts of F reflected by the high whole rock F content of the Tørdal amphibolites (Table 2). Because F as well as K is released preferentially at the onset of melting of mafic rocks (e.g. Kushiro et al., 1996), such as amphibolites, Sc would be highest in anatetic melts created by low partial melting degrees. In the crystal

The study revealed that the Sc content of garnets is representative for the Sc bulk composition of the pegmatites. This is because Sc behaves compatibly to garnet in pegmatitic melts and Sc will preferentially enter garnet (beside mica) during early crystallization stages of the pegmatite. Thus, garnet is a robust and useful pathfinder mineral for Sc-mineralized, granitic pegmatites. Mica of the Tørdal pegmatites may incorporate significant amounts of Sc (Rosing-Schow et al., 2018), but it is more sensitive to alteration and weathering than garnet. Another advantage of garnet as pathfinder mineral over mica is that the Sc content of garnets is much more consistent in one pegmatite body than that of micas (Rosing-Schow et al., 2018). That is because garnet crystallizes predominantly at the early crystallization stage of the pegmatite (which corresponds to the wall zone/intermediate zone crystallization), whereas mica crystallizes continuously throughout all stages of pegmatite solidification. However, some garnets (spessartines), which are co-genetic with the late-stage albite zones, have low Sc, despite the fact that high-Sc garnets occur in the wall and intermediate zone of the same pegmatite. These late-stage garnets (which form a very small proportion of the bulk garnet in the Heftetjern and Høydalen pegmatites) do not reflect the Sc bulk content of pegmatites and, thus, they should not be used as Sc mineralization indicator. Therefore, it is crucial to pay attention during sampling from which zone of the pegmatite the garnets originate, before making any conclusions on the overall Sc distribution and economic potential of an area. According to this study, the Tørdal garnets yield bulk average concentrations of c. 880 Sc µg/g (average of 88 LA-ICP-MS analyses). The highest Sc concentrations were detected in garnets from the Heftetjern 2 pegmatite with up to 2197 µg/g Sc. These values confirm previous studies of garnets from the Heftetjern 2 pegmatite revealing ~ 0.3 to ~ 0.5 wt% Sc₂O₃ (Raade and Kristiansen, 2000, 2003). Biotites in the Heftetjern 2 pegmatite also exhibit the highest Sc concentrations of up to 2806 µg/g (Rosing-Schow et al., 2019).

Because no higher average Sc concentrations in garnet has been reported for an entire pegmatite field, the Tørdal pegmatite field hosts the most Sc-enriched pegmatites known so far. The Evje-Iveland pegmatites, about 80 km SW of Tørdal, has been considered as the most Sc-enriched pegmatites worldwide (e.g. Williams-Jones and Vasylkova, 2018) based on rare findings of thortveitite crystals in about 23 pegmatites (Pedersen et al., 2007; Schetelig, 1911, 1922). These pegmatites are similar in age and tectonometamorphic setting as the Tørdal pegmatites (Müller et al., 2015, 2017; Rosing-Schow et al., 2020a) with the difference that the amphibolite host rocks contain less Sc of about 23 ± 6 µg/g (n = 3; unpubl. data; Müller). In the 1950s and 60s, thortveitite crystals of about 200 kg in total were mined as rare and valuable by-product of the K-feldspar-producing Evje-Iveland pegmatites (Pedersen et al., 2007). However, garnets and micas, which are representative indicators of the bulk content of Sc in the pegmatite, contain less Sc (Rosing-Schow et al., 2018; Stokkeland, 2016) than those of the Tørdal pegmatites. Average Sc contents in garnets and micas are at least twice as high in the Tørdal as in the Evje-Iveland pegmatites. In addition, garnet, as major Sc carrier, is much less abundant in the Evje-Iveland pegmatites (Müller et al., 2012). In conclusion, the Tørdal pegmatites are more enriched in Sc than the Evje-Iveland pegmatites. In the case of mining, Sc would be easier mineable and processable from the Tørdal pegmatites because of the high abundance of Sc-rich garnets and micas compared to very rare occurrences of thortveitite in the Evje-Iveland pegmatites.

The regional distribution of the Sc content in garnets of the Tørdal pegmatites displays a distinct pattern with highest Sc abundance in the Skardsfjell-Heftetjern-Høydalen area. Less pronounced and smaller enrichments are identified at the Svåhei 2a, Storemyr 2 and Lislegrenland localities. Thus, from the economic perspective, the Skardsfjell-Heftetjern-Høydalen area has the highest economic potential. The finding confirms earlier scientific studies by Bergstøl and Juve (1988)
and Juve and Bergstøl (1990). Juve and Bergstøl (1997) and results of exploration campaigns carried out by the Scandium International Mining Corporation in 2011–2012. The detected Sc concentration of 53 µg/g of the representative bulk sample of the Heftetjern 1 pegmatite is almost twice as high as the Sc content of the amphibolite host rocks. Considering that there are about 50 exposed pegmatites in the Skardsfjell-Heftetjern-Høydalen area with an average volume of 1000 m³, the assumed resources are about 125,000 t ore grading c. 50 µg/g Sc with a total of 625 t Sc. Compared to Sc resources of ongoing and potential mining (see chapter Introduction), the resources Sc-bearing pegmatites of the Tørdal areas are by far too small to have economic potential. However, in the case, the Tørdal pegmatites will be mined for quartz, feldspar and/or mica in future, Sc could be a by-product.

6. Conclusions and outlook

The results of this study are summarized as follows:

- Scandium contents in garnet is representative for the Sc bulk composition of pegmatites, defining garnet as a useful and reliable pathfinder mineral for the exploration of Sc mineralization in granitic pegmatite fields. However, spessartine (> 60 mol% Sps) from late-stage albitic zones of evolved NYF pegmatites with complex mineralogical zoning do not reflect the Sc bulk composition of the pegmatite and, thus, garnets from the wall and intermediate zones should be sampled.

- Scandium is a compatible element in garnet and substitutes the B-site of almandines and spessartines through replacement of Al and trivalent Fe by Sc. Garnets with highest Sc of up to 2197 µg/g have a spessartine component ranging from 50 to 60 mol%.

- Scandium crystallized during the early stage of pegmatite formation (wall zone stage) Sc decreases in the remaining pegmatite melt, as documented by generally decreasing Sc from the core to margin of crystals and by the occurrence of late-stage garnets (albite zone stage) with low Sc. Thus, with increasing pegmatite melt fractionation Sc decreases.

- Sc-poor garnets (from the Lislegornlia, Svåheii 3, and Butvatnet localities) show homogenous Sc distribution across the crystals indicating that Sc was consistently available throughout garnet growth. Sc-rich garnets show a general decrease of Sc from core to rim. However, the garnets from the Heftetjern 2 pegmatite show, besides the grain-internal Sc decrease, a final high-Sc overgrowth. This Sc-rich overgrowth may indicate a late-stage Sc increase due to Sc remobilization as observed previously for the Heftetjern 1 pegmatite.

- The source rocks of Sc in the pegmatites are the amphibolitic host rocks of the Tørdal pegmatites. The host rocks, which are part of the Nissedal Outlier supracrustals, contain in average 34 µg/g Sc. Scandium in amphibole was preferentially released at the onset of partial melting of the amphibolites. Sc would be highest in anatectic melts created by low partial melting degrees due to its affinity to F

- The regional Sc distribution revealed that the pegmatites of the Skardsfjell-Heftetjern-Høydalen and Svåheii area of the Tørdal pegmatite field in south Norway have unusual high Sc enrichments to sub-economic levels. A bulk analysis of the Heftetjern 2 pegmatite revealed an average Sc content of 53 µg/g. The average Sc content of garnets in this pegmatite is about 1900 µg/g. The assumed resources of the Skardsfjell-Heftetjern-Høydalen area are about 125,000 t ore grading about 50 µg/g Sc with a total of 625 t Sc, which is too small to have economic potential. However, the strong Sc enrichment of the Tørdal pegmatites is rather unusual for granitic pegmatites, making them a specific Sc deposit type.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.oregeorev.2020.103729.

References


