Metamorphic evolution of the lower nappes of the Kalak Nappe Complex in Eastern Finnmark (Norway)

by

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Abstract

Garnet grains in metapelites of the lower nappes of the Kalak Nappe Complex in Eastern Finnmark typically show two growth zones: Garnet 1 forms the cores of the grains and grew along a P-T path with a ~ 20 bar/ $^{\circ}\text{C}$ slope. Its growth started at ~ 515 $^{\circ}\text{C}$ and ~ 3250 - 5500 bar and finished at ~ 570 $^{\circ}\text{C}$. The maximum pressure experienced during garnet 1 growth increases down the nappe pile. Garnet 2, which forms the rims of the garnet grains, grew during a near-isothermal pressure increase of ~ 500 - 1500 bar. Microtextural evidence indicates pre- to syn-kinematic growth of garnet 1 and post-kinematic growth of garnet 2. Lu-Hf garnet/whole-rock age dating points to growth of garnet 1 at 463 ± 17 Ma and a maximum age of ~ 429 Ma for garnet 2. The hiatus between garnet 1 and garnet 2 growth was of short duration, and garnet growth might have been continuous in the lowest structural levels.

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Chapter 1: Introduction

The metasedimentary rocks of the Kalak Nappe Complex (KNC) dominate the Scandinavian Caledonides in Northern and Eastern Finnmark (N Norway). Over the last two decades numerous studies have revealed important information about the KNC's age and the magmatic, tectonic and metamorphic events it experienced. However, there are still unknowns and unsolved debates concerning the paleogeographic provenance of the KNC (Corfu et al., 2014; Slagstad and Kirkland, 2017; Zhang et al., 2016), and the conditions of metamorphism the KNC experienced are only vaguely constrained (Rice, 1984; Rice et al., 1989).

The aim of this study is to use thermodynamic and garnet growth modelling to characterize the metamorphic conditions of the rocks of the lower nappes of the KNC and derive metamorphic pressure (P) – temperature (T) paths for the study area. Given the extraordinarily well and wide exposure of the garnet-zone in the study area, the models will be tested with regards to their capability to resolve differences in the P-T trajectories associated with different structural levels of the KNC. This is necessary to identify the nature of Barrovian metamorphism in the study area and the tectonic processes that caused it. Furthermore, absolute ages of garnet growth will be presented based on Lu-Hf garnet/whole rock geochronology, and will be related to the relative timing of metamorphism with respect to deformation using microtextural evidence. Results will be discussed and integrated into a regional geology framework accounting for previously published ages and conditions of metamorphic and tectonic events.

Chapter 2: Regional Geology

2.1 The Scandinavian Caledonides

The Caledonides form a several 1000-km-long mountain range on both sides of the North Atlantic stretching from Ireland and Scotland over Scandinavia into the Arctic islands of Svalbard and Greenland. It developed in the Paleozoic when Laurentia, Avalonia and Baltica converged and finally collided also incorporating numerous terranes of the closing Iapetus Ocean (see Corfu et al., 2014a for a recent review).

The Scandinavian Caledonides are the portion of the Caledonides which are found in Scandinavia. They consist of numerous nappes which are traditionally grouped into the Lower, Middle, Upper, and Uppermost Allochthon, based on provenance (Roberts and Gee, 1985; Gee et al., 1985). In this classification scheme, the Lower and Middle Allochthon are Baltica-derived as well as the lower portions of the Upper Allochthon, whereas the rest of the Upper Allochthon comprises Iapetus-derived units, and the Uppermost Allochthon has a Laurentian affinity. However, this simplistic scheme has been criticized as it fails to reflect our recent, more complex understanding of orogens and because the paleogeographic implications are contested for various units, including the KNC (e.g., Corfu et al., 2014b). Despite the disputes, the classification in allochthons is still widely used in its original form.

In northern Finnmark, the highest unit is the Mageroy Nappe (Uppermost Allochthon). This is underlain by three nappe complexes; namely, in tectonostratigraphic order from top to bottom these are the Kalak Nappe Complex, Laksefjord Nappe Complex (LNC) and Gaissa Nappe Complex (GNC). The metamorphic grade decreases down the nappe pile from kyanite grade in the upper and garnet grade in the lower nappes of the KNC to epizone grade in the LNC and lower anchizone grade in the GNC (Rice 1984; Rice et al., 1989). All three nappe

complexes mainly consist of metasediments with Neoproterozoic to Early Paleozoic deposition ages (Roberts, 1985). For the GNC and the LNC, the precursor sediments were deposited on the shelf of Baltica, which is reflected in their allocation to the Lower Allochthon and Middle Allochthon, respectively (Roberts and Gee 1985; Andréasson 1994). With regards to the provenance of the KNC there exist two hypotheses. Traditionally, the sediments of the KNC were considered to comprise one conformable sedimentary sequence, the Sørøy- Succession, deposited on the margin of Baltica, which was first described on Sørøy (Ramsay 1971) and later correlated with the rocks on Porsangerhalvøya (Gayer et al., 1985). However, this view was contested by later studies and an alternative hypothesis was presented. Based on detrital zircon age distributions and ages of igneous intrusions, Kirkland et al. (2007a) showed that the sediments of the KNC belong to two different sedimentary successions or terranes with an origin exotic to Baltica. The deposition-age is bracketed by the ages of the youngest detrital zircon and the oldest intrusion, which gives a deposition age of ca. 910 to 840 Ma for the upper nappes termed Sørøy Succession and ca. 980 to 1030 Ma for the lower Nappes termed Sværholt Succession after the Sværholthalvøya east of Porsangerfjord, where correlated rocks are found (Kirkland et al., 2008b; 2007b). The division of the KNC into these two sedimentary successions was established based on rocks from Porsangerhalvøya and Sværholthalvøya but is not established for the whole KNC. Many areas of the KNC, including Nordkinnhalvøya and the region to its south have not been correlated with either the Sørøy or Sværholt Succession yet and even the correlation of Porsangerhalvøya and Sværholthalvøya is questioned as it only relies on detrital zircon ages (Roberts, 2007).

In the study area, the lowermost nappes of the KNC crop out. Nappe sheets can be traced across southern Laksefjord to the Bekkarfjord area and also across the buried trace of the Trollfjorden-Komagelva Fault to Nordkinnhalvøya (Figure 1) (Siedlicka and Roberts, 1996). Moreover, based on the overlapping Sm-Nd depleted mantle model ages between samples from the Sværholt Succession and Nordkinnhalvøya, Kirkland et al. (2008b) suggested the same provenance for these samples. Also, maximum deposition ages reported for two metasandstones from Nordkinnhalvøya by Zhang et al. (2016) are in agreement with the ages reported for the Sværholt-Succession, even though the authors propose a different hypothesis for their provenance. Using evidence of paleo-current data and palinspastic reconstructions combined with detrital zircon age spectra, the authors point out similarities between the LNC, which is accepted to be of Baltican origin, and the KNC and argue for a Baltican origin for the KNC too, at least for the lower nappes in Eastern Finnmark. There are no detailed structural maps identifying nappes and minor thrusts within the KNC for the study area. Moreover, the nappe allocation and classification used by Kirkland et al. (2006; 2007a; 2007b; 2008a) differs from the original classification established for Porsangerhalvøya by Gayer et al. (1984) and Ramsay et al. (1985), as the tectonostratigraphic model was revised. Even though Kirkland et al. (2008b) classify the rocks of the KNC on and south of Sværholthalvøya as belonging to the Kolvik Nappe, it was decided to not use this classification in this study, for the above-mentioned reasons. Furthermore, a correlation of the rocks in the study area with the Kolvik Nappe and the Sværholt Succession makes implications about the provenance, which are still debated (Zhang et al., 2016).

2.2 Geological History of the Kalak Nappe Complex

The KNC consists of at least two different metamorphosed sedimentary successions, termed Sørøy and Sværholt Successions, with deposition ages of 910 to 840 Ma and 1030 to 980 Ma respectively (Kirkland et al., 2007b). Paleocurrent data suggest a possible different sedimentary source for the lowermost nappes of the KNC in eastern Finnmark, which have suggested to belong to the Sværholt Succession but conclusive evidence is still lacking (Zhang et al., 2016). The Sværholt Succession was affected by a Grenvillian or Sveconorwegian deformation event at ~980 Ma when Baltica was part of the supercontinent Rodinia (Kirkland et al., 2006). During the ~850 Ma Porsanger Orogeny, first defined by Daly et al. (1991), deformation and zircon overgrowth occurred in the Sørøy Succession while Sm-Nd ages of intrusions in the Sværholt Succession were reset (Kirkland et al., 2006b). From the Porsanger event onwards the same ages are found in both successions, suggesting juxtaposition during the Porsanger Orogeny (Kirkland et al., 2006b; Kirkland et al., 2006a). The shared events after the Porsanger Orogeny include the ~710 Ma Snøfjord event, which caused migmatization in the Sørøy Succession and metamorphic overgrowth of zircons in the Sørøy and Sværholt Successions (Gasser et al., 2015; Kirkland et al., 2006; Kirkland et al., 2007b). The intrusion of the Seiland Igneous Province at ~560-570 Ma and ~530-520 Ma only affected the Sørøy Succession (Corfu et al., 2007; C. L. Kirkland et al., 2008b; Roberts et al., 2006). Ar-Ar cooling ages of ~500 Ma are found all over the KNC in northern Finnmark as well as in the KNC and GNC and ascribed to the Finnmarkian event. However, the tectonic setting for the KNC and GNC during this event are unclear (Dallmeyer, 1988; C.L. Kirkland et al., 2008a; Rice and Frank, 2003). The Scandian event in the KNC occurred in two distinct phases; an earlier phase at ~438 Ma associated with slab roll back and back arc

magmatism, and the final continent-continent collision of Laurentia and Baltica at ~430-420 Ma (Gee 1975; Kirkland et al., 2006a; Slagstad and Kirkland, 2018).

Cooling after the Scandian collision was relatively fast, and the closure temperatures for Ar-Ar in muscovite were reached at ~424 Ma and Rb-Sr in biotite at ~413 Ma (Kirkland et al., 2007a).

2.3 Sample locations

The sample area is the east coast of Svæholthavøya, the region south to it on the western coast of Laksefjorden, Kalak and Bekkarfjord, as well as Nordkinnhalvøya. Sample locations are listed in Table 1 and shown in Figure 1, and coordinates of all samples collected are listed in Appendix A.

Figure 1 Geological map of the study area. After Føyn et al. (1983), Rice and Roberts (1988), Roberts (1987, 1992, 2008a, 2008b, 2014, 2015), Williams and Roberts (2013, 2017), Roberts and Siedlecka (2001, 2013), Siedlicka and Roberts (1996).

Table 1 Sample locations, with orientation of the main foliation.

Sample	Location	Latitude	Longitude	Dip direction	Dip
28HF18	Svaerholtklubben	70.962758	26.689091	308	26
32HF18	Tømmervikklubben	70.82899	26.722264	301	45
34HF18	Stordalen	70.502566	26.554761	282	32
35HF18	Stordalen	70.50226	26.554967	320	30
36HF18	Fossvikneset	70.529807	26.575411	309	30
37HF18	Fossvikneset	70.529867	26.575533	317	10
38HF18	Masterneset	70.559025	26.601604	338	25
40HF18	Veidnes	70.649528	26.632971	295	34
88/83	Kalak	70.602378	27.000917	091	21
87/83	Kalak	70.610122	27.037567	177	83
86/83	Bekkarfjord	70.600802	27.158591	256	41
41HF18	Bekkarfjord	70.603585	27.123054	262	25
45HF18	Kobbevik	70.804184	27.881142	285	42

46HF18	Krampenes	70.912133	27.391717	287	45
14/92	Krampenes	70.912257	27.391422	343	49

Chapter 3: Methods

3.1 Sample Collection

In July 2018, garnet-bearing rocks of metapelitic to metapsammitic composition were collected in the study area of Eastern Finnmark, mostly from shore outcrops and road-cuts. These samples were labelled starting with the number of the sample and suffix HF18. Archived samples collected by Dr. Hugh Rice (University of Vienna) in 1983 and 1992 were also used and are labelled with the number of the outcrop and the year (e.g., 86/83).

3.2 Petrography

For all samples used in this study, polished petrographic thin-sections cut normal to the foliation and along the main thrusting direction of NW-SE (Rice, 1998) were prepared and investigated using a polarized light optical microscope to identify minerals and textural relationships.

3.3 Whole-rock chemistry

The chemical bulk rock compositions were analyzed by ALS Canada Ltd. (Sudbury) using inductively coupled plasma atomic emission spectroscopy (ICP-AES) for major elements and lithium borate fusion and inductively coupled plasma mass spectrometry (ICP-MS) for trace elements. Sample powders were produced at Carleton University using a jaw-crusher and an agate mill after removing altered surfaces.

3.4 X-Ray Micro-Computed Tomography

Whole-rock samples of about 3x3x3 cm were scanned using a SkyScan 1173 high resolution X-ray micro-computed tomography (XR- μ CT) scanner at Carleton University. The scans were conducted using 130 kV X-ray source voltage and a current of 61 μ A with an exposure time of 1350 ms, yielding resolutions ranging from 11.0 μ m to 19.6 μ m. Furthermore, a 0.25 mm brass filter was applied to reduce beam-

hardening. For the reconstruction of 3D data from the 2D attenuation slices, SkyScan NRecon software was used. Digital segmentation of garnet was conducted with the Blob3D software (Ketcham, 2005) after reducing the resolution of the XR- μ CT datasets by half to minimize computation time. Blob3D also allowed to calculate the location of the cores of every garnet grain, as well as volume, surface area, and length and orientation of the half axis of a best fit ellipsoid. Only garnet grains with a volume exceeding 0.004 mm^3 ($r \sim 0.1 \text{ mm}$) were considered when calculating the crystal size distributions. This conservative cut-off value was chosen as small grains are more susceptible to partial volume effects, and the resolution of the scan is not high enough to confidently distinguish garnet from other phases with similar attenuation coefficients like ilmenite. The crystal size distributions, which were used for garnet growth modelling, report the number of garnet grains per cm^3 of sample for 20 equally spaced size-classes based on the sphere normalized radii of the garnet grains.

3.5 Electron Probe Micro-Analysis (EPMA)

An automated four-spectrometer Cameca Camebax MBX electron microprobe was used to carry out quantitative wavelength dispersive X-ray analyses (WDX) on garnet. Operating conditions were 20 kV accelerating voltage and 20-22 nA beam current. Counting times for all elements are listed in Table 2, and the peak counting time for background data was half the value. The microprobe was calibrated using synthetic and natural mineral standards with known composition (see Table 2) and a natural garnet sample (Huebner and Woodruff, 1985). The accuracy of the measurements is $\pm 1\text{-}2 \%$ for major elements with errors approaching 100% at the

detection limit of 0.01 wt-%. Raw data was converted to wt-% of elements with the Cameca PAP matrix correction software program.

Table 2 Operating conditions for Electron Microprobe Analysis.

Element	Line	Standard	Counting Time (s)
Si	K α	synthetic (Mg,Fe) ₂ SiO ₄	15
Al	K α	synthetic MgAl ₂ O ₄	15
Fe	K α	synthetic Fe ₂ SiO ₄	20
Mn	K α	synthetic MnTiO ₃	30
Mg	K α	synthetic (Mg,Fe) ₂ SiO ₄	30
Ca	K α	natural wollastonite	50
Y	L α	synthetic Y ₃ Al ₅ O ₁₂	70

The spacing between the point analyses for the chemical profiles of garnet are 30 μm for the random sections on polished thin-sections, 20 μm for central sections of samples 14/92, 46HF18 and 40HF18, 10 μm for the central section of sample 28HF18 and 5 μm for the central sections of samples 45HF18 and 86/83. Compositional profiles of garnet are plotted as mole fraction of the end-members almandine, grossular, pyrope, and spessartine where xFe, xCa, xMg and xMn are calculated in the following format (all iron is assumed to be Fe²⁺):

$$xFe^{2+} = \frac{Fe^{2+}}{Fe^{2+} + Ca + Mg + Mn}$$

The compositional maps for the main elements Fe, Mg, Mn and Ca as well as Y were produced with a JEOL JXA-8200 electron microprobe at the University of Calgary and have resolutions of 3 μm (86/83, 88/83, 45FH18) and 4 μm (28HF18, 40HF18, 46HF18), respectively. Analytical conditions were 15 kV acceleration potential, 100 nA beam current, 200 ms dwell time.

3.6 Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS)

LA-ICPMS trace element maps were produced for garnet in 28HF18 and 45HF18, using a Photon Machines Analyte Excite 193 nm excimer laser coupled with an Agilent 7700x ICP-MS located at the University of Ottawa. The energy of the laser was 4.5 J/cm^2 , the repetition rate was set at 30 Hz and He-flow rate to 1 l/min. For ICP-MS analyses, Ar was used as a carrier gas flowing at 0.76 l/min.

For the two samples which were selected for Lu-Hf age dating, the central sections through the biggest garnet grains were mapped to get information on the abundance and distribution of Lu and Hf. The resolution of the maps is $10 \text{ }\mu\text{m}$ per spot for both maps. For sample 45HF18 the ablation time per spot was set to 1 s and the scan speed $10 \text{ }\mu\text{m/s}$, sample 28HF18 was mapped with 0.5 s ablation time per spot and $20 \text{ }\mu\text{m/s}$. Backgrounds were measured for 20 s before and 5 s after every line. The data was reduced using the LAMTRACE + Pixelate software (Jackson, 2008) with GSE1G as a primary reference material and NIST610 as a secondary standard.

3.7 SELFRAGTM high voltage comminution, garnet isolation and hand-picking

To isolate garnet from the whole rock for radiometric age dating, the SelfragTM high-voltage pulse power fragmentation facility of Natural Resources Canada in Ottawa was used to disintegrate the rock along grain boundaries. The two samples (28HF18 and 45HF18) were shocked five times with 50 pulses of 140 kV each. Intact crystals of garnet were then hand-picked under a binocular and attached matrix minerals removed in an ultrasonic bath.

3.8 Garnet Lu-Hf radiometric age dating

To construct whole rock garnet isochrons for 28HF18 and 45HF18, the garnet separates were prepared using SelfragTM high-voltage pulse power fragmentation and

hand picking, and the whole rock powder was the same as sent for whole rock chemistry analysis. To keep blanks low and avoid contamination, the sample dissolution and elementary separation were carried out in the Class 1000 clean lab facility at Carleton University, and only ultrapure reagents were used. The total blank of Lu was 29 ng and the total blank of Hf 340 pg. Isochron ages were calculated using isoplot 4.15 (Ludwig, 2012).

3.8.1 Sample dissolution

Before dissolution, the separated garnet grains were cracked open in an agate mortar and sieved with a 250 μm sieve to remove some of the inclusions and then ground to below 250 μm in size with an agate mortar. For sample 45HF18, bigger and smaller grains were treated separately. About 300 mg of each sample separate and standards were spiked with a ^{176}Lu - ^{178}Hf mixed spike, sample and spike masses are reported in Table 3. The sample dissolution method is based on the tabletop method by Blichert-Toft et al. (1997) and uses a mix of 4 ml concentrated HF and 2ml concentrated HNO_3 heated to 120 $^{\circ}\text{C}$ in a Teflon beaker for 2 days. This dissolution method strives to avoid dissolution of zircon, which often has an inherited Hf-isotopic composition and can cause erroneous isochrons. Phosphates are also dissolved in this method, however they do not have a significant effect on the Lu-Hf isochron (Scherer et al., 2000). After dissolution, the samples are dried down on a hotplate at 90 $^{\circ}\text{C}$ overnight. Three dry downs with a few drops of 15M HNO_3 to cover the residue were performed on a hotplate at 90 $^{\circ}\text{C}$ to break up fluorides. Then approximately 5 ml of 10M HCl was added and heated capped at 140 $^{\circ}\text{C}$ for 3 h. The HCl solution containing the dissolved sample was separated from the sample residue and the cycle repeated until all the sample was dissolved after 4 to 5 cycles.

Table 3 Sample and spike weights for the analyzed garnet and whole rock fractions as well as standards.

sample	sample weight (g)	spike weight (g)
28HF18 grt	0.2952	0.0930
28HF18 grt (a)	0.2925	0.0894
28HF18 grt (b)	0.2946	0.0923
28HF18 WR	0.3248	0.0671
45HF18 grt (big) II	0.2977	0.0579
45HF18 grt (s)	0.2962	0.0577
45HF18 grt (s) II	0.2955	0.0577
45HF18 WR	0.2934	0.0670
BHVO-2	0.0587	0.0991
BRC-2	0.0449	0.1199
blank	0	0.0287

3.8.2 Element separation

The separation of Lu and Hf involves three steps of separation in ion-exchange columns and the complete procedure is shown in Appendix B.

The first step separates high field strength elements (HFSE) from heavy rare earth elements (HREE) and Ti, Zr, Ta, Rb and Sr. Separation is performed in 20.5 cm long, 0.6 cm diameter Teflon columns filled with 5.8 ml of AG50WX8 resin (200-400 mesh). HFSE are eluted and collected in a mix of 1M HCl and 0.1M Hf, and HREE in 4N HCl. Both fractions are dried down, a drop of concentrated HNO₃ was added to the HREE fraction and a few drops of HClO₄ to the HFSE fraction.

For the separation of Lu from the other HREE, the dried down sample was dissolved and loaded in 250 µl 2.5N HCl onto a conditioned quartz glass column filled with 430 g of LnSpec resin (50-100 µm mesh). The unwanted HREE are rinsed first in 2.5N HCl and then Lu collected in 6N HCl. The Lu fraction was dried down and subsequently ready for analysis.

To separate Hf from the other HFSE, a 3.8 cm long, 0.6 cm wide Teflon column filled with 1 ml of LnSpec (100-150 µm mesh) resin was used. After conditioning of the columns, the sample was dissolved and loaded in 5 ml of 2.5N HCl. Other HFSE are rinsed in 2.5N and 6N HCl and remnants of Ti with a mix of 0.09N C₆H₈O₇ – 0.45N HNO₃ – 1wt.% H₂O₂ before collecting Hf in a mix of 6M HCl and 0.4M HF. After drying down on a hotplate, the Hf-fraction is ready for analysis.

3.8.3 Multi Collector Inductively Coupled Plasma Mass Spectrometry isotopic measurements

Lu and Hf isotope measurements were carried out on a multi collector inductively coupled plasma mass spectrometer (MC-ICP-MS) Thermo Scientific Neptune equipped with Aridus at Carleton University. The aim of the measurements was

twofold: (i) to calculate the concentrations of Lu and Hf via isotope dilution, (ii) and to determine the $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ ratios to construct isochron diagrams. The configuration of the Faraday cups of the MC-ICP-MS for Lu and Hf isotopic measurements are shown in Table 4 and Table 5, respectively.

Table 4 Configuration of Faraday cups for MC-ICP-MS measurements of Lu isotopes.

Cage	H4	H3	H2	H1	Ax	L1
Mass	177	176	175	174	173	172
Element	Hf	Yb Lu Hf	Lu	Yb Hf	Yb	Yb

Table 5 Configuration of Faraday cups for MC-ICP-MS measurements of Hf isotopes.

Cage	H6	H5	H4	H3	H2	H1	Ax	L1	L2	L3	L4
Mass	182	181	180	179	178	177	176	175	174	173	172
Element	W	Ta	Hf Ta W	Hf	Hf	Hf	Yb Lu Hf	Lu	Yb Hf	Yb	Yb

The samples were dissolved in 0.5M HNO₃ for Lu measurements and 0.5M HNO₃ with 0.01M HF for Hf analysis and diluted to concentrations of ~50 ppb. For Hf, 7 blocks of 10 cycles each were measured and 30 cycles for Lu. Peak centering was performed before each analysis and baselines were measured before each block for Hf and before each analysis for Lu.

Standard JMC 457 was measured three times before the Hf analysis and after every five samples. The obtained $^{176}\text{Hf}/^{177}\text{Hf}$ and $^{180}\text{Hf}/^{177}\text{Hf}$ ratios for the standard are consistent with the literature (Vervoort and Blichert-Toft, 1999; Weis et al., 2007), indicating accurate measurements. Standards BCR-2 and BHVO-2, which were processed together with the samples, yield Hf isotopic compositions which are in

agreement with the literature too (Weis et al., 2007), verifying the accuracy of the method (Table 7). Isobaric interference of ^{176}Yb and ^{176}Lu on ^{176}Hf was corrected using the natural abundances of Yb and Lu, respectively, with a $^{173}\text{Yb}/^{176}\text{Yb}$ ratio of 1.260962 and a $^{175}\text{Lu}/^{176}\text{Lu}$ ratio of 37.66478 (Vervoort et al., 2004 and references therein).

For the Lu measurements, a standard was measured after every three samples and isobaric interference for ^{176}Yb was corrected the same way as for Hf. The Lu concentrations measured for the two standards BCR-2 and BHVO-2 (Table 7) are very close to the published values (Kent et al., 2004). Hf measurements were corrected for the accepted values of the standards. Mass fractionation of Lu was corrected using Yb (Vervoort et al., 2004).

Chapter 4: Results

In the following sections the results and insights of petrographic observations, XR- μ CT scanning, whole rock chemical analysis, in situ EPMA analysis and LA-ICPMS element mapping, thermodynamic modelling and age dating are presented.

4.1 Petrography

In this section, the observed mineral assemblages and textures of the analyzed samples are presented following an order from northeastern Laksefjord to southwestern Laksefjord and western to eastern Nordkinnhalvøya. The dominant cleavage observed in the samples is referred to as S2 and is overprinting the earlier S1 foliation. Garnet porphyroblasts exhibit two distinct textural zones in most samples, garnet 1 and garnet 2, which coincide with compositional zones in most samples. A detailed petrographic description is important as the stable mineral assemblages give insight into the metamorphic conditions, and the textural relationships allow to determine the relative timing of porphyroblast growth and deformation.

4.1.1 Sample 28HF18

Sample 28HF18 is a dark grey graphitic white-mica-garnet-biotite-phyllite from a shore outcrop on Sværholtklubben, the north tip of Sværholthalvøya.

The peak mineral assemblage of 28HF18 consists of quartz, biotite, white mica, garnet, feldspar, graphite and ilmenite. Secondary chlorite and accessory apatite and tourmaline are also contained in this sample. The matrix of 28HF18 is fine grained, and quartz, feldspar, white mica and biotite are homogeneous distributed within it. Biotite and white mica define the foliation. Most feldspars are not twinned and have elongate shapes, while the quartz grains are equidimensional and do not have subgrains. Chlorite overgrows the matrix in random orientations and preferentially

occurs in the strain caps. Its crystal size is generally bigger than the matrix minerals (Figure 2).

Garnet porphyroblasts are idiomorphic to rounded and slightly resorbed. Around the garnet grains, white mica is compacted in strain caps without quartz. The strain shadows are not prominent. Inclusions in garnet often exhibit textural sector-zoning in form of crosses along the boundary between sectors of the grain (see Figure 2). Other than that, no inclusion trails are visible. The inclusions consist mainly of quartz but also ilmenite and minor apatite (see also element maps in Chapter 4.4.1).

Figure 2 Microphotograph of sample 28HF18 showing a texturally sector zoned garnet (grt) porphyroblast and secondary chlorite (chl) in plane polarized light (PPL).

4.1.2 Sample 32HF18

Sample 32HF18 is a graphitic white-mica-garnet-biotite-schist from Tømmervikklubben containing quartz and feldspar, accessory ilmenite and secondary chlorite. Biotite and garnet form porphyroblasts. In the matrix the fine-grained, graphite-rich layers dominated by white-mica alternate with layers consisting mostly

of more coarse-grained quartz and biotite (Figure 3). The garnets in sample 32HF18 are rounded and commonly exhibit sector zoning (Figure 4).

Figure 3 Microphotograph showing the white-mica (wm) and graphite-rich (gr) layers and coarse-grained quartz-(qtz) and biotite-rich (bio) layers (PPL).

Figure 4 Microphotograph of a texturally sector-zoned garnet (grt) with chlorite (chl) alteration in sample 32HF18 (PPL).

4.1.3 Sample 40HF18

Sample 40HF18 is a light grey, slightly graphitic white-mica-chlorite-biotite-garnet-schist, with biotite and garnet porphyroblasts. It was collected from a shore-outcrop east of Veidnes.

In 40FH18, quartz, white-mica, biotite, garnet, feldspar, graphite and ilmenite are part of the peak mineral assemblage, whereas chlorite grew both, during prograde and retrograde metamorphism. White mica forms the foliation and is concentrated in thin, graphite- and ilmenite-rich layers between pinching and swelling quartz-rich layers. Biotite only occurs as lens-shaped porphyroblasts, which are aligned with the foliation and rich in inclusions. Feldspar is found as elongate platy crystals in the white mica layers and as more equidimensional grains in the quartz layers. The garnets are relatively big, reaching diameters of more than 2 mm, and exhibit two textural zones; the inner inclusion-rich zone, garnet 1, is possibly texturally sector zoned, and the outer zone, garnet 2, is overgrowing the wrapping foliation and inheriting its texture. Whereas the inner zone is isometric, the outer garnet zone grew preferentially into white mica, resulting in rims with irregular thickness and shape (see also the element maps in Chapter 4.4).

Figure 5 Microphotograph of sample 40HF18 showing biotite (bio) and garnet (grt) porphyroblasts (PPL). Note the two growth zones of garnet, the outer one preferentially overgrowing mica-rich domains of the matrix foliation (outlined by the black line drawn on the microphotograph).

4.1.4 Samples 121/83 and 127/83

Samples 121/83 and 127/83 are similar to 40HF18 and were collected from outcrops near Veidnes in 1983 by Dr Hugh Rice. Their matrices consist of quartz, white mica, and chlorite with graphite and ilmenite and porphyroblasts of biotite and garnet.

Biotite in sample 121/83 is up to 3 mm in size, rich in quartz inclusions and contains graphite inclusion trails at a high angle to the matrix foliation which are occasionally s-shaped (Figure 7). Garnets in this sample are smaller than in the other two samples from the Veidnes area and commonly overgrew biotite grains. In some garnet grains, two textural zones are visible, with the inner one, garnet 1, being more inclusion-rich without clear inclusion trails and the outer zone, garnet 2, inheriting its texture from the matrix or from biotite porphyroblasts it replaced (Figure 6).

Figure 6 Microphotograph of sample 121/83 showing the two growth zones of garnet (grt) (outlined by the black line drawn on the microphotograph) and garnet overgrowing biotite (bio) (PPL).

Figure 7 Microphotograph of sample 121/83 showing the s-shaped graphite inclusion trails in the labelled biotite (bio) grain (PPL). Also note the strain-caps associated with the biotite porphyroblasts.

Sample 127/83 has less and smaller biotite porphyroblasts compared to samples 121/83 and 40HF18, but garnets are bigger and more abundant (Figure 8). Chlorite only occurs in quartz layers and strain shadows. The inclusion pattern in garnet is very different from the other two samples collected in the Veidnes area. There are a few small inclusions in the core, whereas the rim or garnet 2, which overgrew the matrix, is sharply marked by graphite inclusions and fractures. Occasionally, garnet grains show textural sector zoning for garnet 1. Graphite inclusion trails in biotite are not continuous with the matrix foliation, and biotite is commonly replaced by garnet (Figure 8).

Figure 8 Microphotograph of sample 127/83 showing a texturally sector zoned garnet (left), graphite (gr) inclusion rims in garnet and garnet overgrowing biotite (bio) (PPL).

4.1.5 Sample 38HF18

Sample 38HF18 is a graphitic white-mica-biotite-garnet-schist from a shore-outcrop on the west coast of Laksefjord about 10 km south of Veidnes.

The rock looks similar to the other samples from south of Veidnes, but it does not contain any chlorite. In addition, the rock texture, particularly the garnet inclusion

patterns are different. Biotite and thin, pinching lenses of white mica form the foliation of the rock, with elongate, platy feldspar and quartz layers between the micas (Figure 9). The matrix is gently crenulated. Feldspars are relatively abundant and are also found as inclusions in garnet. The garnets are heavily fractured and inclusion poor, especially in the rim. Cracks commonly outline the idiomorphic shape of a presumably earlier growth zone (Figure 9). Garnet 2 is overgrowing the matrix foliation (Figure 10).

Figure 9 Microphotograph of sample 38HF18 inclusion-poor garnet (grt) porphyroblasts in a matrix of quartz (qtz), biotite (bio), white mica (wm) and graphite (gr) (PPL). Note the cracks in the upper grain possibly outlining the garnet 1 growth zone and garnet overgrowing the foliation.

Figure 10 Microphotograph of a garnet in sample 38HF18 with a post-kinematic rim as evident from garnet 2 truncating the matrix foliation (white arrows) (PPL).

4.1.6 Samples 36HF18 and 37HF18

Like samples 34HF18 and 35HF18, samples 36HF18 and 37HF18 are graphitic white-mica-biotite-chlorite-garnet-schists from a shore-outcrop on the west-coast of Laksefjord, ca. 3 km further north. Whereas their stable mineral assemblages are the same as for samples 34HF18 and 35HF18, quartz, feldspar, biotite, white -mica, graphite and chlorite with garnet porphyroblasts and accessory ilmenite, their textures are different. In samples 36HF18 and 37HF18, S1 is not preserved and the matrix is folded into angular, isoclinal folds (Figure 11). Garnet porphyroblasts exhibit spiraling inclusion trails which are continuous from core to rim and merge with the matrix foliation and commonly have concave growth facets. In both samples the rims are inclusion-poor and statically overgrowing the external foliation. In sample 37HF18 graphite inclusion-bands are found in the rim parallel to the grain boundary of some garnet grains (Figure 12).

Figure 11 Microphotograph of sample 36HF18 showing the angular, isoclinal folds in the matrix and the spiral inclusion trails in garnet (grt), merging with the matrix (PPL).

Figure 12 Microphotograph of sample 37HF18 showing the s-shaped inclusion trails in garnet (grt) as well as the inclusion-poor rim with graphite (gr) inclusions (PPL).

4.1.7 Samples 34HF18 and 35HF18

Samples 34HF18 and 3HF18 are graphitic white-mica-biotite-chlorite-garnet-schists from a shore-outcrop on the west-coast of Laksefjord close to the base of the KNC.

Their peak mineral assemblages consist of quartz, feldspar, biotite, white mica, graphite and chlorite with garnet porphyroblasts and accessory ilmenite. Their matrices are divided into graphite-rich cleavage domains, consisting mainly of white mica and biotite, and microlithons. Between the cleavage domains an earlier foliation is occasionally preserved, defined by white mica. Chlorite grew during prograde and retrograde metamorphism (Figure 13, Figure 14). Garnet porphyroblasts in sample 34HF18 show a single growth zone with well-defined s-shaped inclusion trails in some grains, whereas in sample 35HF18 an inclusion-poor rim is observed which is statically overgrowing the S2 foliation. The s-shaped inclusion trails in garnet are not clearly continuous with the matrix foliation.

Figure 13 Microphotograph of sample 34HF18 (PPL). Note the preserved S1 foliation, the s-shaped inclusion trail in the garnet (grt) in the center and the small grain to its left.

Figure 14 Microphotograph showing prograde chlorite (chlr) in sample 35HF18 (left: PPL, right: XPL)

Figure 15 Microphotographs of a garnet (grt) in sample 35HF18 exhibiting s-shaped inclusion trails and an inclusion-poor rim overgrowing the external foliation (PPL).

4.1.8 Sample 88/83

Sample 88/83 is a graphitic white-mica-biotite-garnet-phyllite, collected by Dr Hugh Rice at a road-cut in Bekkarfjord west of Kalak in 1983.

The mineral assemblage of 88/83 is quartz, white mica, biotite, feldspar, graphite and garnet with minor amounts of ilmenite and secondary chlorite. It contains wavy and occasionally kinked lenses of white mica with some biotite and ilmenite, alternating with layers of relatively coarse-grained quartz and feldspar. In the quartz-rich layers,

biotite and white mica occur too, but they are more coarse-grained than in the mica-lenses and lack a consistent orientation. The feldspars are often elongate parallel to the foliation and strongly cleaved but rarely twinned. Quartz grains are big and recrystallized, occasionally exhibiting fluid inclusion trails. Chlorite is commonly associated with garnet, replaced biotite and white mica, or randomly overgrew the matrix.

The garnets in sample 88/83 are idiomorphic, have inclusion-free rims and a higher concentration of inclusions in their centers. Quartz constitutes most of the inclusions, though apatite, zircon, and ilmenite also occur. In some grains, spaced and coarse-grained quartz inclusions form straight trails possibly reflecting an earlier foliation with compositional layering. The garnet grains are commonly heavily fractured, and some are altered to chlorite along the cracks.

Figure 16 Microphotograph of sample 88/83 showing fluid inclusion trails in quartz, secondary chlorite (chlr) and heavily fractured and altered garnet (grt) (PPL).

4.1.9 Sample 87/83

Sample 87/83 is a fine-grained, graphitic white-mica-biotite-garnet-phyllite from a road outcrop southwest of Kalak and like samples 88/3 and 86/83 it was collected by Dr Hugh Rice in 1983.

Mineralogically, 87/83 is very similar to 88/83 but it does not contain secondary chlorite. Texturally, however, it is different. It consists of folded layers of biotite-rich zones and more mineralogically mixed zones and shows abundant micro-shearbands parallel to the trace of the axial plane of the folds (Figure 17).

The garnets are idiomorph without evidence for resorption and exhibit straight inclusion trails in their cores (garnet 1). Garnet rims (garnet 2) were formed by overgrowing the matrix and show a rim with a few coarse-grained, randomly oriented inclusions (Figure 18). Around garnets, strain-caps and strain-shadows formed, and the matrix was squished between garnet grains.

Figure 17 Microphotograph of sample 87/83 showing a micro-shearband separating the biotite- (bio) and quartz- (qtz) rich domain from the mineralogically mixed matrix domain (PPL).

Figure 18 Microphotograph of garnet (grt) porphyroblasts of sample 87/83 showing the straight inclusion trails in the core (grt 1) and the rim (grt 2) with more coarse-grained quartz inclusions and graphite (the boundary between garnet 1 and 2 is outlined by the black line drawn on the microphotograph) (PPL).

4.1.10 Sample 41HF18

Sample 41HF18 is a graphitic white-mica-biotite-garnet-phyllite, also from Bekkarfjord from the same road as 88/83, 87/83 and 86/83. The matrix is homogeneous and consists of quartz and feldspar together with biotite, white-mica, and some ilmenite, which define the foliation. Garnet forms about 1-1.5 mm big porphyroblasts with inclusion trails which are straight in the core and sigmoidal towards the rim (garnet 1). The rims (garnet 2) are inclusion-poor, occasionally marked by a rim of graphite inclusions and result from the overgrowth of the matrix, which forms strain caps and shadows around the garnet porphyroblasts. The garnets are idiomorphic, and grain indentation among touching garnet grains is observed.

Figure 19 Microphotograph of garnet (grt) porphyroblasts in sample 41HF18 showing the inclusion trails which are straight in the core and s-shaped towards the rim (PPL).

4.1.11 Sample 86/83

Sample 86/83 was also collected by Dr Hugh Rice during the same 1983 field season. It was collected along the coastal road ca. 7 km to the east from sample 88/83 and close to the location of sample 41HF18. It is a slightly graphitic white-mica-biotite-garnet-schist with the same mineralogy as 88/83 and is texturally similar but more coarse-grained and quartz-rich.

Garnets exhibit intact shapes without evidence of resorption but they are not perfectly idiomorph and occasionally rounded. Like in sample 88/83 the rims are inclusion-free but wider. However, the inclusion trails in the cores are not straight but s-shaped.

Parallel fluid inclusion trails in quartz are very abundant in sample 86/83 even though they are rarely observed in any other sample. They cross grain-boundaries between neighbouring quartz grains and are ca. normal to the foliation.

Figure 20 Backscattered electron image of a garnet (grt) grain in sample 86/83 showing s-shaped inclusion trails in the core and a wide inclusion-free rim.

Figure 21 Microphotograph of sample 86/83 showing the abundant fluid inclusion trails crossing boundaries of quartz (qtz) grains (XPL).

4.1.12 Samples 46HF18 and 14/92

Samples 46HF18 and 14/92 are both medium to dark grey banded graphitic white-mica-biotite-garnet-schists, with biotite and garnet porphyroblasts. They were collected from shore outcrops near Krampenes in Kifjord. The matrices of both samples are fine-grained consisting of quartz, white mica, feldspar, graphite and some ilmenite with biotite and garnet porphyroblasts and secondary chlorite. The matrices are separated into cleavage domains consisting predominantly of white-mica and graphite and microlithons of quartz with minor white mica and single chlorite grains. In some areas of the microlithons, a crenulated earlier foliation is preserved (Figure 23). The foliation wraps around the biotite porphyroblasts and is compacted in strain caps near the garnets. Biotite appears only as spindle- or flake-shaped porphyroblasts which are about the same size as the garnets and contain quartz inclusions and

occasionally graphite inclusion trails. These are not continuous with the matrix in sample 46HF18, however in sample 14/92 they are continuous in many grains and rotated with respect to the external foliation in others. In sample 46HF18 garnet is less abundant and the porphyroblasts are occasionally heavily fractured, nearly inclusion-free with some quartz and single ilmenite and apatite inclusions in the core area, in rare cases aligned in straight trails. Sample 14/92 is more abundant in garnet and straight inclusion trails (Figure 22), which are at an angle to the external foliation, or rings of quartz and ilmenite inclusions are common. Garnet also grows into the wrapping matrix, however without inheriting the texture. Also, there is evidence for grain indentation between touching garnets in both samples and mica-domes around garnet porphyroblasts indicate displacement growth.

Figure 22 Microphotograph of garnet (grt) and biotite (bio) porphyroblasts in sample 14/92 exhibiting straight inclusion-trails (PPL).

Figure 23 Microphotograph of sample 46HF18 showing inclusion-free garnet porphyroblasts (grt) and the preserved S1 foliation in the microlithon (PPL).

4.1.13 Sample 45HF18

Sample 45HF18 is a graphitic white-mica-biotite-garnet-phyllite to schist and was collected along a road-cut near Kobbevik on the southeastern shore of Nordkinhalvøya. It was the first garnet-bearing rock found along the road going West from Skjånes.

It has a mineral assemblage of quartz, white mica, biotite, feldspar, graphite and ilmenite with garnet porphyroblasts, secondary chlorite and accessory apatite and tourmaline. The matrix is fine-grained and consists of quartz, biotite, white-mica and feldspar. White mica defines the cleavage domain but a relic fabric is also visible defined by white mica and ilmenite in the microlithon.

Garnet porphyroblasts are up to 1 mm in diameter, idiomorph and have parallel inclusion trails which mainly consist of quartz but also ilmenite and some apatite. The inclusion trails are parallel to the early fabric but have an angle of about 40 ° to the main foliation (Figure 24). Garnet 2 overgrows the matrix in a thin, nearly inclusion-free rim.

Secondary chlorite is abundant and overgrew the matrix in random orientations.

Figure 24 Microphotograph of sample 45HF18 showing the straight, parallel inclusion trails found in garnet 1 (grt) and the thin inclusion-free rim of garnet 2(PPL).

4.2 Size, abundance and shape distribution of garnet

In this section, insights on the size, abundance, shape and spatial distribution of garnet porphyroblasts obtained through XR- μ CT are synthesized. XR- μ CT scans were performed for 7 samples selected for Theria_G garnet growth modelling which requires the crystal size distribution as an input. When referring to the size classes in crystal size distributions (CSDs) in this section, size class 1 contains the biggest garnet grains and size classes are counted from right to left. Even though garnet has an isometric symmetry, natural garnet grains are often not perfectly isometric and their orientations in space can be described based on the long and short axes of a best-fit ellipsoid. For the stereographic projections of long and short axes of garnet grains given below, a view along the pole to the plane parallel to the major rock matrix foliation S2 was chosen. This means that the equatorial plane in the presented view is parallel to that foliation. However, the cardinal directions do not show the orientation of the sample in the field but in the XR- μ CT scanner and are not the same for different samples. The samples are described in the same order as for the petrography. The significance of CSDs lies in the fact that they hold information about the nucleation history, which is needed for garnet growth modelling of a population of garnet grains with Theria_G. The orientation of elongate porphyroblasts is used to investigate the deformation history and determine whether porphyroblasts were rotated or not.

4.2.1 Sample 28FH18

Garnet grains in sample 28HF18 are relatively big with up to 2 mm in diameter and are idiomorphic to rounded. The modal amount of garnet is 3.8 %, and there are ~45 grains per cm³. Commonly, garnets are clustered but intergrowths between garnets are rare. There are also cases of grain indentation between touching garnets.

The average aspect ratio of the garnets is 1.23. Whereas the short axes of the garnet grains are consistently oriented normal to the foliation of the rock, their long axes lie within the foliation plane but do not form a clear preferred trend (Figure 26, Figure 27).

The CSD of garnet in sample 28HF18 is skewed to the left contrary to the CSDs obtained for all the other samples of this study. However, similar to the other samples, the garnet CSD of 28HF18 is polymodal with most garnets contained in size class 11 and a minor peak in the abundance of garnet in size classes 5 and 16 (Figure 25). The peak at size class 16 is obscured in a CSD with 20 bins due to binning artefacts. The peak in size class 5 which does not follow the general shape of the CSD also shows up in CSDs with different numbers of bins and might, hence, be the result of sample inhomogeneity.

Figure 25 Crystal size distribution of sample 28HF18 normalized per cubic centimetre.

Figure 26 Long axis orientation of garnet grains in sample 28HF18.

Figure 27 Short axis orientation of garnet grains in sample 28HF18.

4.2.2 Sample 40HF18

The garnet grains in sample 40HF18 are relatively big with radii measuring up to 1.2 mm, exhibit sub-idiomorphic shapes with irregular grain surfaces, and have an average aspect ratio of 1.34. The modal amount of garnet is 3.9 % with ~70 grains per

cm³. The long axes of garnet grains have a preferred orientation with a trend at a high angle to the foliation, whereas the short axes lie in a plane ~30° to the foliation with a weak preferred trend (Figure 29, Figure 30).

The garnet crystal size distribution of sample 40HF18 shows three peaks, with most grains part of size class 16 and minor peaks in the abundance of garnet at size classes 18 and 11 (Figure 28).

Figure 28 Crystal size distribution of sample 40HF18 normalized per cubic centimetre.

Figure 29 Long axis orientation of garnet grains in sample 40HF18.

Figure 30 Short axis orientation of garnet grains in sample 40HF18.

4.2.3 Sample 88/83

The garnet grains in sample 88/83 are idiomorphic to slightly rounded and make up 2.69 % of the rock volume with the biggest grain's radius measuring 0.76 mm. There are on average ~ 130 grains per cm^3 with an average aspect ratio of 1.21. As in sample

86/83, their long axes are parallel to the foliation with a preferred trend and the short axes are oriented normal to the foliation (Figure 32, Figure 33).

The crystal size distribution for sample 88/83 is left-skewed and polymodal with a peak in size class 18 and a minor peak in size class 8. Size class 14 has a very high frequency compared to the neighbouring size classes (Figure 31).

Figure 31 Crystal size distribution of sample 88/83 normalized per cubic centimetre.

Figure 32 Long axis orientation of garnet grains in sample 88/83.

Figure 33 Short axis orientation of garnet grains in sample 88/83.

4.2.4 Sample 86/83

In sample 86/83 the garnet grains are commonly idiomorphic with an average aspect ratio of 1.28. Their long and short axes both exhibit a preferred orientation, the former lying within the foliation, the latter perpendicular to it (Figure 35, Figure 36). The

grains are relatively densely packed with ~ 120 grains per cm^3 with the biggest grain having a radius of 0.71 mm. The modal amount of garnet is 2.38 %.

The crystal size distribution is polymodal and right-skewed with size class 17 being most abundant and a minor peak at size class 11. Size- lass 7 and 19 have a higher frequency than both their neighboring size classes (Figure 34).

Figure 34 Crystal size distribution of sample 86/83 normalized per cubic centimetre

Figure 35 Long axis orientation of garnet grains in sample 86/83.

Figure 36 Short axis orientation of garnet grains in sample 86/83.

4.2.5 Sample 46FH18

The garnets in sample 46HF18 are sub-idiomorphic, have an average aspect ratio of 1.25 with their long axes parallel and the short axes normal to the foliation (Figure 38,

Figure 39). The modal amount of garnet is 1.7 %, and there are ~100 grains per cm³ with a maximum radius of 0.9 mm, only about 1 % of them indenting each other. The crystal size distribution is bimodal, left skewed and the most frequent size class is size class 17 with a minor peak at size class 11 (Figure 37).

Figure 37 Crystal size distribution of sample 46HF18 normalized per cubic centimetre.

Figure 38 Long axis orientation of garnet grains in sample 46HF18.

Figure 39 Short axis orientation of garnet grains in sample 46HF18.

4.2.6 Sample 14/92

Garnet grains in sample 14/92 are idiomorph to subidiomorph, have an average aspect ratio of 1.23 with their long axes parallel and the short axes normal to the foliation, like in sample 46FH18 (Figure 41, Figure 42). The modal amount of garnet in the

scanned volume is 4.4 %, and there are ~100 grains per cm^3 , the biggest having a radius of 1.1 mm.

The crystal size distribution of sample 14/92 is very similar in shape to the one of sample 46HF18 and has its maximum at size class 17 and a minor peak at size class 9 (Figure 40).

Figure 40 Crystal size distribution of sample 14/92 normalized per cubic centimetre.

Figure 41 Long axis orientation of garnet grains in sample 14/92.

Figure 42 Short axis of garnet grains in sample 14/92.

4.2.7 Sample 45HF18

Garnet grains have idiomorphic shapes and are evenly distributed in the rock volume.

Touching grains are not common. The modal amount of garnet is ~1 %, and there are

on average ~ 110 garnet grains per cm^3 . The garnet crystal size distribution is right-skewed with one main peak at size-class 15 and other possible minor peaks at 6, 10, 13 and 19 (Figure 43).

The average aspect ratio of the garnet grains is ~ 1.26 and together, the long and short axes of garnet define a plane about 40° to the foliation (Figure 44, Figure 45).

The crystal size distribution is right-skewed with one main peak at size-class 15 and other possible minor peaks at 6, 10, 13 and 19.

Figure 43 Crystal size distribution of sample 45HF18 normalized per cubic centimetre.

Figure 44 Long axis orientation of garnet grains in sample 45FH18.

Figure 45 Short axis orientation of garnet grains in sample 45HF18.

4.3 Whole Rock Chemistry

The bulk rock chemical composition of selected samples is presented in form of an AFM-projection (Thompson, 1957) (Figure 46), as well as a table (Table 6) and web diagram showing major element compositions (Figure 47). Trace element contents and chemical compositions of additional samples from the study area are presented in Appendix G. For this study, all Fe was assumed to be ferrous as graphite is present in all samples, buffering the oxygen fugacity.

Figure 46 AFM-projection (Thompson, 1957) from muscovite, quartz and H₂O showing the compositions of the analyzed samples compared to the average metapelite (Shaw, 1956). All iron is assumed to be FeO.

The AFM-projection reveals that the analyzed samples used in this study are slightly enriched with regards to their FeO/MgO contents compared to the average metapelite (Shaw, 1956). There is some spread along the (Al₂O₃-3*K₂O)-direction (Figure 46)

among the samples but they are still within the range expected for average-Al metapelites (Spear, 1993).

Figure 47 Web diagram showing the whole rock chemistry of the samples normalized to the average metapelite (Shaw 1956) in wt-%. The MnO contents of samples 41HF18 and 14/92 are larger than the average metapelite (solid black line) by a factor of 2.63 and 3.75, respectively. Different linestyles were chosen for samples from different areas (wide dashed: Sværholthavøya, dash-dotted: south-west Laksefjord, narrow dashed: Bekkarfjord, dotted: Nordkinnhalvøya).

Table 6 Bulk rock chemical compositions (mayor elements) of the studied samples in weight percent of oxides.

	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MnO	MgO	CaO	Na ₂ O	K ₂ O	Total
14_92	58.9	1.13	19.15	10.25	0.3	1.69	0.7	1.87	3.92	100.2
28HF18	63.70	1.02	16.60	7.58	0.10	1.61	0.67	1.10	4.45	99.03
32HF18	59.20	1.14	18.85	7.51	0.08	1.97	1.24	1.76	4.58	100.45
34HF18	66.80	0.77	17.60	4.75	0.06	1.27	0.60	1.75	3.87	99.15
35HF18	65.90	0.72	16.50	5.40	0.06	1.32	1.13	2.12	3.27	98.78
36HF18	69.50	0.71	14.35	5.03	0.06	1.18	0.83	1.06	3.91	98.71
37HF18	67.10	0.74	15.00	5.84	0.09	1.40	0.91	1.39	4.09	98.48
38HF18	62.10	0.92	17.25	6.80	0.08	1.94	1.73	2.09	3.93	99.39
40HF18	65.30	0.97	15.80	7.37	0.09	1.82	1.02	1.70	3.51	99.37
41HF18	57.80	1.24	19.25	8.07	0.21	2.22	2.05	2.21	4.20	99.01
45HF18	60.30	1.06	17.60	7.31	0.12	2.40	1.97	2.17	3.79	100.81
46HF18	65.20	1.08	18.60	5.86	0.09	1.15	0.38	1.42	4.24	101.55
86_83	63.7	0.74	17.6	7.76	0.07	2.23	1.57	2.27	3.33	98.96

88_83	61.7	1	18.05	6.78	0.11	1.95	1.39	1.93	3.6	100.2
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4.4 Garnet Compositional Zoning

The results of this study show that typically, the compositional zoning of garnets from the lower KNC in Eastern Finnmark shows two distinct growth zones, with garnet 1 forming the core of the crystals, rimmed by garnet 2. Garnet 1 is characterized by a bell-shaped spessartine-profile, a grossular content decreasing from core to rim and increasing pyrope and almandine-contents, with the former exhibiting a flat profile in the core. Garnet 2 is characterized by a sudden increase in grossular content and drop in almandine content whereas the pyrope content remains constant or decreases slightly towards the outermost rim. There is no change observed in the spessartine-profile across the transition between garnet 1 and garnet 2, and the spessartine content continues to drop towards the rim.

Element distribution maps of garnet obtained for 6 samples (28HF18, 40HF18, 45HF18, 46HF18, 86/83, 88/83) reveal concentric zoning patterns for garnet 1 and garnet 2 following the shape of the grain in the rim region and becoming more rounded towards the core (Figure 49, Figure 56, Figure 59, Figure 61, Figure 64). Sample 40HF18 is an exception, for in this sample garnet 2 has irregular shapes and the thickness of garnet 2 differs between grains (Figure 52). In three samples (28HF18, 32HF18, 35HF18), garnet does not show the second growth zone, but only garnet 1.

The compositional zoning profiles are needed to compare them to the modelled profiles and find the model that best fits the observation. The P-T path used in that garnet growth model therefore describes the metamorphic evolution of the sample.

4.4.1 Sample 28HF18

All main-element maps for garnet in sample 28HF18 show zonation that follows the shape of the garnet grain itself (Figure 49). Only in the Ca map the chemical zones are

irregular on a small scale and have the appearance of flames. The grossular content in the core is about 14 mol-%, increases away from the core until it reaches a plateau of ~16 mol-% and decreases to ~10 mol-% at the rim (Figure 48). This low-Ca rim is thinner on the upper-right face and thicker on the lower faces, where the almandine contents are higher. The almandine content in the core region is antithetic to the grossular content and decreases slightly from ~64 mol-% to 62 mol-% before rising gradually to 81 mol-%. The pyrope content increases from ~3.5 mol-% in the core to ~8 mol-% in the rim with a steepening slope. The thickness of the outermost high pyrope-zone is variable: thinner towards the lower corner and thicker in the left and right corners. Mn and Y contents show patterns of a bell-shape for the former and a high central peak and an enriched rim for the latter (Figure 49). Garnet 2 is not observed in this sample.

Figure 48 Compositional profile across a central section through the biggest garnet grain in sample 28HF18.

Figure 49 Combined element map for sample 28HF18 of Ca (top left), Fe (top right), Mn (bottom left), Mg (bottom right), and Y (right). Image width is 2.4mm.

4.4.2 Sample 32HF18

Garnet in 32HF18 exhibits typical growth zoning (Figure 50). The spessartine and grossular contents decrease from core to rim in a bell-shaped manner (~23 mol-% - 15 mol-% and ~16 mol-% - 1 mol-%, respectively) whereas almandine increases antithetically to them (~58 mol-% - 76 mol-%). The pyrope content increases gradually from ~3 mol-% in the core of garnet to ~7.5 mol-% in the rim.

Figure 50 Compositional profile from core (0 μm) to rim of selected grains in sample 32HF18.

4.4.3 Sample 40HF18

In garnet grains of 40HF18 the two distinct growth zones of garnet 1 and garnet 2 are clearly visible. Garnet 1 is idiomorphic and exhibits the typical compositional zoning pattern of samples of the lower KNC, while garnet 2 varies in thickness and has an irregular shape (Figure 52). Grossular and spessartine contents in garnet 1 decrease from core to rim from about 11 mol-% to 6 mol-%, and 20 mol-% to 2 mol-%, respectively, whereas the almandine content increases from 65 mol-% to 83 mol-% and the pyrope content increases from 4 mol-% to 6 mol-% (Figure 51). Grossular and pyrope contents are constant over more than half the diameter of garnet 1. In garnet 2, the grossular content increases abruptly to 13 mol-% and fluctuates between 13 and 15 mol-% towards the rim, whereas the almandine content does the opposite and drops to ~ 78 mol-% and fluctuates between ~ 78 mol-% and 80 mol-%. The pyrope content drops at the transition to garnet 2 increasing to the original value towards the rim, whereas the spessartine content continues to drop gradually (Figure 51). The Y content is low over most of the grain but peaks at the boundary between the two growth zones. The core does not show a

clear peak in Y content (Figure 52).

Figure 51 Compositional profile across a central section through the biggest garnet grain in sample 40HF18. Garnet 2 is shaded in grey.

Figure 52 Combined element map for sample 40HF18 of Ca (top left), Fe (top right), Mn (bottom left), Mg (bottom right), and Y (right). Image width is 2.4mm.

4.4.4 Sample 38FH18

Garnet in sample 38HF18 exhibits two convex humps in the Ca-profile going from ~14 mol-% to ~13 mol-% grossular content close to the core, then back up to ~15 mol-% and down to 11 mol-% before rising steeply to more than 20 mol-% in the ~150-180 μm thick rim of garnet 2 (Figure 53). Similarly, the Fe-profile also shows two humps but mirrored, with ~65 mol-% to ~64 mol-% almandine content in the core region rising steeply to ~72 mol-% rimward and falling at the transition to garnet 2 to ~70 mol-%. In contrast to the Ca- and Fe-profiles, the Mg- and Mn-profiles are smooth. The pyrope content is constant in the core and starts to rise after the peak of the second grossular-hump from ~4.5 mol-% to ~7 mol-% at the transition to garnet 2 approaching ~6 mol-% at the rim. The Mn-profile is bell-shaped with a maximum of ~19 mol-% spessartine content in the core and 2.5 mol-% at the rim.

Figure 53 Compositional profiles from core (0 μm) to rim of selected grains in sample 38HF18.

Garnet 2 is shaded in grey.

4.4.5 Sample 35HF18

Garnets in sample 35FH18 exhibit Ca-profiles with a sharp low of ~ 17 mol-% in the core, followed by a plateau at ~ 22 mol-% grossular content and a drop to ~ 17 mol-% at the rim (Figure 54). The almandine content behaves antithetically to the grossular content: it decreases to ~ 55 mol-% from ~ 58 mol-% in the core and increases to ~ 75 mol-% in the rim. The pyrope content is constant over most of the grain but rises slightly from ~ 2.5 mol-% to ~ 5.2 mol-% towards the rim where the grossular is decreasing. The garnets have a relatively high spessartine content of ~ 22 mol-% in the core, which decreases to ~ 2 mol-% in the rim. There is only one chemical growth zone corresponding to garnet 1.

Figure 54 Compositional profiles from core (0 μm) to rim of selected grains in sample 35HF18.

4.4.6 Sample 88/83

For garnet in sample 88/83, all element maps show concentric compositional zoning mirroring the shape of the grain (Figure 56). However, the Fe-distribution suggests inheritance from the overgrown matrix as the shape of the Fe-poor region in the core is following a straight band of inclusions running through the garnet grain. The Ca-profile shows about 1 mol-% lower values in the center of the grain compared to the Ca plateau of ~14 mol-% grossular content which spans over approximately two thirds of the grain. Towards the rim, the grossular content drops to ~8 mol-% and then increases sharply to more than 10 mol-% at the transition to garnet 2 close to the rim. The almandine content increases from ~65 mol-% in the flat core region to ~80 mol-% in the rim, but then drops at the edge of the grain (garnet 2). Surprisingly, the drop in Fe occurs before the rise in Ca, and the Mg-profile reaches a plateau between them. The Mg-profile is flat over most of the grain with values of ~4.5 mol-% and rises to ~10 mol-% in the rim. Spessartine content in the core is ~17 mol-% and drops down to less than 1 mol-% in the rim along a bell-shaped curve (Figure 55). The Y-map shows very high Y-contents in the core (0.28 wt-% Y_2O_3) and low concentrations over the rest of the grain except for an increase of more than 10 wt-% Y_2O_3 at the transition between garnet 1 and garnet 2 (Figure 56).

Figure 55 Compositional profile across a central section through the biggest garnet grain in sample 88/83. Garnet 2 is shaded in grey.

Figure 56 Combined element map for sample 88/83 of Ca (top left), Fe (top right), Mn (bottom left), Mg (bottom right), and Y (right). Image width is 1.47mm.

4.4.7 Sample 41HF18

The compositional zoning of garnet in sample 41HF18 follows the trend observed in the region, with the grossular and spessartine contents decreasing from core to rim and the almandine and pyrope contents increasing (Figure 57). However, in the core region, the Ca-profile exhibits a plateau at ~21 mol-% grossular content, while the almandine content is at a low at ~54 mol-%. The grossular content then drops to ~16 mol-%, rises a few percent and then drops to ~15 mol-%. Over the same distance, the almandine content steeply increases to ~59 mol-%, drops a few percent and then continuously climbs to over 71 mol-%. Garnet 2 is marked by a steep increase in grossular and a decrease in almandine and pyrope contents towards the rim. The pyrope content steeply increases to ~6.5 mol-% towards the rim of garnet 1 after a minor increase from ~3 mol-% to ~5 mol-%.

Figure 57 Compositional profiles from core (0 μm) to rim of selected grains in sample 41HF18.

Garnet 2 is shaded in grey.

4.4.8 Sample 86/83

The element maps of garnet in sample 86/83 exhibit concentric compositional zones following the shape of the grain and getting more rounded towards the core (Figure 59).

The Ca-map shows a plateau with grossular contents of ~16-18 mol-% in the inclusion-rich core, then they drop to ~11 mol-% before rising sharply and forming the relatively thick Ca-rich rim of garnet 2 with up to 17 mol-% grossular content (Figure 58). The Fe map shows an antithetical pattern with respect to the Ca map and has low almandine contents of ~62 mol-% in the core, increases to 80 mol-% and then drops sharply to ~75 mol-% in garnet 2. The pyrope-content is constant in the inclusion-rich core and then rises from ~4 mol-% to ~7 mol-% and keeps that value in garnet 2. The Mn-profile is bell-shaped with flat tails in garnet 2 and has a spessartine content of ~17 mol-% in the core. The Y-content is relatively high with values of 0.06- 0.15 wt-% Y_2O_3 over most of the grain except in garnet 2 where they are lower. Surprisingly, the center of the grain has a lower Y content but similar to the other samples, there is a peak with over 0.2 wt-% Y_2O_3 at the transition between garnet 1 and garnet 2 (Figure 59).

Figure 58 Compositional profile across a central section through the biggest garnet grain in sample 86/83. Garnet 2 is shaded in grey.

Figure 59 Combined element map for sample 86/83 of Ca (top left), Fe (top right), Mn (bottom left), Mg (bottom right), and Y (right). Image width is 1.65mm.

4.4.9 Sample 46HF18

In garnets of sample 46HF18, the compositional zoning is concentric (Figure 61). The Ca-map shows a small peak of 7.5 mol-% grossular content in the center and then a decrease by 1 mol-% ~250 μ m from the core followed by an increase to ~7.5 mol-% (Figure 60). Towards the rim the grossular content drops gradually to ~4.5 mol-% before it jumps to ~7.5 mol-% in garnet 2 where it then increases to values of ~9.5 mol-%. The Fe-profile exhibits a flat core of ~67 mol-% almandine content and increases steadily to ~86 mol-% in the rim. In garnet 2 the almandine contents abruptly drop to ~83 mol-%. The Mg-profile shows a wide relatively flat core with pyrope contents of ~3.5 mol-% and an increase to 6.5 mol-% rimwards. The Mn-profile is bell-shaped with 22 mol-% spessartine content in its center, and the map shows concentric shells that become more and more rounded towards the core. The Y-map exhibits two distinct zones with sharp boundaries, which are not following the distribution in main elements. The inner zone is high in Y with an Y-poor core and the outer zone has lower Y values which decrease towards the rim but peak at the transition to garnet 2 (Figure 61).

Figure 60 Compositional profile across a central section through the biggest garnet grain in sample 46HF18. Garnet 2 is shaded in grey.

Figure 61 Combined element map for sample 46HF18 of Ca (top left), Fe (top right), Mn (bottom left), Mg (bottom right), and Y (right). Image width is 2.2mm.

4.4.10 Sample 14/92

Garnet in sample 14/92 exhibits flat compositional gradients in the core region for all endmembers (Figure 62). Spessartine shows the typical bell-shaped profile with ~22 mol-% in the core and ~2 mol-% in the rim. The grossular content in the core is ~7 mol-% and increases to ~9 mol-% before falling to 4.5 mol-%. In the rim (garnet 2) the grossular content jumps to ~7 mol-%. Almandine and pyrope contents rise from ~78 mol-% to 86 mol-% and ~3 mol-% to ~6 mol-%, respectively. In contrast to the almandine content which falls abruptly to ~85 mol-% in garnet 2, the pyrope content continues to increase steadily.

Figure 62 Compositional profile across a central section through the biggest garnet grain in sample 14/92. Garnet 2 is shaded in grey.

4.4.11 Sample 45FH18

All element maps for garnet in sample 45HF18 indicate a concentrically zoned compositional pattern (Figure 64). The shapes of the zones follow the shape of the grain. However, whereas the compositional patterns developed in the outer zones are almost perfectly parallel to the grain faces, they become more rounded and diffuse towards the core region. There are no signs of resorption of the grain, and irregular grain-boundaries are interpreted as the result of the overgrowth of inclusions in the matrix.

The Ca-profile is relatively flat throughout most of the grain with grossular contents of ~17-18 mol-%. In the core region, the Ca-content is lower with ~16 mol-% (Figure 63). Towards the rim of garnet 1 it decreases sharply to ~13 mol-% before a sudden rise in garnet 2 reaching up to 16 mol-% grossular content. The almandine content is about 1 mol-% higher in the core region where the grossular content is lower and rises gradually from ~59 mol-% to ~75 mol-% in the rim of garnet 1. In garnet 2, the almandine content falls to ~73 mol-%. Mg behaves similarly to Fe but the change in pyrope content from core to rim is only ~3 mol-% (from ~4.5 mol-% to ~7.5 mol-%). The Mn-profile exhibits the typical bell-shape and a spessartine content of ~18.5 mol-% at its maximum in the core. The Y-content is highest in the core and decreases towards the rim where another peak is observed at the transition to garnet 2 (Figure 64).

Figure 63 Compositional profile across a central section through the biggest garnet grain in sample 45HF18. Garnet 2 is shaded in grey.

Figure 64 Combined element map for sample 45HF18 of Ca (top left), Fe (top right), Mn (bottom left), Mg (bottom right), and Y (right). Image width is 1.1mm.

4.5 Thermodynamic Phase Equilibria and Garnet Growth Modelling

Thermodynamic phase equilibria and garnet growth modelling are central to this study. They are used to determine P-T paths, describe the metamorphic evolution of the study area and test model assumptions and if the resolution of the models are high enough to distinguish between different structural levels.

Of the 11 samples selected for garnet growth modelling, 7 samples (28HF18, 40HF18, 45HF18, 46HF18, 14/92, 86/83, 88/83) were scanned using XR- μ CT to locate the biggest grain and to obtain garnet CSDs. For the remaining four samples (32HF18, 35HF18, 38HF18, 41HF18), compositional zoning profiles were measured of garnet grains in random thin-sections, and garnet CSDs have not been obtained. Therefore, garnet grains of those four samples were selected to represent near central cross sections based on the grain sizes, shapes, and inclusion textures. Garnet growth in the four randomly sectioned samples was modelled using the Theriak software (de Capitani and Petrakakis, 2010) which only requires the bulk rock compositions of the samples as input for the modelling to predict the compositional zoning of garnet grown along a given P-T path. For the 7 samples with centrally sectioned garnet grains and quantified garnet CSDs, garnet growth of the entire garnet population was modelled using the Theria_G software (Gaidies et al., 2008).

Garnet core compositions are interpreted to reflect the metamorphic conditions experienced by the rocks during the initial garnet growth. If the garnet-in reaction was predicted at lower conditions than the initial garnet growth, the position of the garnet-in reaction was adjusted to cross the isopleth intersection (see chapter 5.2 for a detailed discussion).

4.5.1 Theriak garnet growth modelling of sample 32HF18

The measured core composition of the largest garnet grain in a random thin section of this sample cannot be predicted with our phase equilibria modelling. Instead, the observed spessartine content exceeds the predicted spessartine content by ca. 1 mol-% (Figure 66). However, if the predicted isopleths are extended, they intersect at P-T conditions slightly below the garnet-in reaction at about 510 °C and 5500 bar. Using this point as a coordinate along the metamorphic P-T trajectory of this sample, garnet crystallization is predicted to start at 514 °C and 5580 bar for a P-T slope of 20 bar/°C (Figure 66). The composition of garnet predicted at these conditions is observed $\sim 200 \mu\text{m}$ from the core with a fit better than $\pm 0.5 \text{ mol-\%}$ (Figure 65). Following the same P-T slope while growing and fractionating garnet, the measured rim composition is reached at 563 °C and 6570 bar (Figure 67) with all measured and modelled isopleths matching $\pm \sim 0.5 \text{ mol-\%}$ (Figure 65). About 2.7 vol-% garnet are predicted to form in this rock along this path, and the predicted peak mineral assemblage matches the observed one.

Figure 65 Modelled compositional zoning (left) compared to the observed compositional zoning (right) of sample 32HF18.

Figure 66 Phase equilibrium diagram for sample 32HF18 showing the core-isopleth intersection and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1)

Figure 67 Phase equilibrium diagram for sample 32HF18 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the rim-isopleth intersection and the modelled P-T-path. (and: andalusite, bio: biotite, chlrd: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, dashed light blue line: P-T path for garnet 1)

4.5.2 Theriak garnet growth modelling of sample 38HF18

The garnet core isopleth intersection for sample 38HF18 falls on the garnet-in curve (Figure 69), and the predicted garnet core composition fits the measured one with less than 1% difference (Figure 68). Growth and fractionation of garnet along a P-T path with 20 bar/°C until the composition of the rim of garnet 1 is reached indicates a temperature

of 550 °C and a pressure of 5350 bar for the conditions of outermost garnet 1 growth (Figure 70). In our simulations, the Ca-rich rim of garnet 2 is predicted to have grown during decreasing temperature and increasing pressure reaching at least 542 °C and 6400 bar (Figure 69). The observed maximum grossular content of ~25 mol-% (Figure 53) indicates a pressure of ~6900 bar at about 542 °C. The predicted peak mineral assemblage matches the observed one.

Figure 68 Modelled compositional zoning (left) compared to the observed compositional zoning (right) of sample 38HF18. Garnet 2 is shaded in grey.

Figure 69 Phase equilibrium diagram for sample 38HF18 showing the core-isopleth intersection and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, dashed red line: P-T path for garnet 2)

Figure 70 Phase equilibrium diagram for sample 38HF18 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the isopleth intersection of the rim of garnet 1 and the modelled P-T-path. (and: andalusite, bio: biotite, chlr: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, dashed red line: P-T path for garnet 2)

4.5.3 Theriak garnet growth modelling of sample 35HF18

Similar to 32HF18, the observed garnet core of 35HF18 is richer in spessartine content than what is predicted with our thermodynamic model. The measured core composition of garnet in this sample translates to an isopleth intersection below the garnet-in curve at approximately 505 °C and 5500 bar (Figure 72). In the model, garnet becomes part of the stable mineral assemblage at 512 °C and 5630 bar with a garnet composition matching the measured one about 200 μm away from the core (Figure 71). The observed rim composition of garnet can be predicted with less than $\pm 1\text{mol-\%}$ error for metamorphism along a P-T path with a 20 bar/°C slope and final garnet growth at 544 °C and 6250 bar. The predicted mineral assemblage at the end of the P-T path is feldspar, ilmenite, garnet, chlorite, white mica, biotite, quartz, and graphite and matches the observed one (Figure 73). About 1.5 vol-% of garnet are predicted in our model. However, since the modelled garnet-in reaction is predicted at slightly higher temperature than what the observed garnet core composition implies, the calculated modal abundance of garnet might be a slight underprediction.

Figure 71 Modelled compositional zoning profile (left) compared to the observed compositional zoning (right) of sample 35HF18.

Figure 73 Phase equilibrium diagram for sample 35HF18 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the isopleth intersection of the rim of garnet 1 and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1)

4.5.4 Theriak garnet growth modelling of sample 41HF18

Since the spessartine content of the garnet core of this sample is ~6 mol-% lower than the predicted spessartine content at the modelled garnet-in reaction, the garnet core isopleth intersection is not located on the garnet-in curve but ca. 22 °C above it, at ~505 °C and 4700 bar (Figure 75). At these conditions, less than 0.5 vol-% of garnet are predicted to be part of the stable mineral assemblage. Fractionation and growth of garnet along a P-T

path with a slope of 20 bar/°C, starting at the P-T conditions of the core isopleth intersection, predicts the general trend of the measured compositional profile of garnet, as well as the composition of the rim of garnet 1 (Figure 57 and Figure 74) for condition of ~538 °C and 5350 bar. The measured and modelled compositions agree within ± 0.5 mol-% for the core and ± 1 mol-% for the rim of garnet 1 (Figure 74). The isopleth intersection for garnet 2 is located at 550 °C and 6500 bar with an error of less than ± 1 mol-%.

Figure 74 Modelled compositional zoning (left) compared to the observed compositional zoning (right) of sample 41HF18. Garnet 2 is shaded in grey.

Figure 75 Phase equilibrium diagram for sample 41HF18 showing the core-isopleth intersection and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2)

4.5.5 Theria_G garnet growth modelling of sample 28HF18

The core isopleths of the biggest garnet grain in sample 28HF18 intersect on the garnet-in curve at 508 °C and 4100 bar (Figure 77). To predict the observed grossular increase in the core region of garnet in this sample (Figure 77), a P-T path with a slope of 110 bar/°C is required during prograde metamorphism up to conditions of ca. 513 °C and 4650 bar.

The P-T slope required to fit the rest of the compositional profile is ~32.5 bar/°C with the

final garnet growth predicted at 585 °C and 7000 bar. The modelled garnet rim composition agrees within about ± 1 mol-% with the observed rim composition (Figure 78). Also, the predicted modal abundance of ~ 3.5 vol-% garnet is close to the observed one, at ~ 3.8 vol-%. The radius of the largest garnet predicted in our simulations is ~ 100 μm smaller than observed (Figure 76).

Figure 76 Modelled compositional zoning profile (solid lines) compared to the measured compositional zoning profile of the biggest garnet grain in sample 28HF18.

Figure 77 Phase equilibrium diagram for sample 28HF18 showing the core-isopleth intersection of the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1)

Figure 78 Phase equilibrium diagram for sample 28HF18 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the rim-isopleth intersection of the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1)

4.5.6 Theria_G garnet growth modelling of sample 40HF18

For sample 40HF18, the garnet core isopleths intersect on the garnet-in curve at 518 °C and 4100 bar (Figure 80). As this sample only contains comparatively few large garnet grains (Figure 28), the compositional profiles for all endmembers in the core regions of these grains show hardly any zoning (Figure 79). Instead, the compositional patterns in the core regions of these large grains are relatively insensitive to the slope of the P-T path

as P-T conditions only changed minimally while these core regions grew. Using a P-T path of 20 bar/°C for garnet 1 growth yields a relatively good fit with the observed garnet compositional profile except for the predicted pyrope content, which increases too much towards the rim (Figure 79). Growth of garnet 1 is predicted to end at 560 °C and 4950 bar, where the observed almandine composition is reached. However, the predicted radius (0.73 mm) of garnet 1 is significantly smaller than the observed one (~0.88 mm), which causes the slopes of the profiles to be steeper than in the model (Figure 79). The variably thick rim of garnet 2 (Figure 52) cannot be predicted as it does not follow the assumption of spherical, concentric crystal growth inherent in Theria_G modelling (Gaidies et al., 2008). However, the P-T conditions for the initial stages of garnet 2 growth can be predicted using an equilibrium phase diagram calculated for the effective bulk rock composition after growth of garnet 1 (Figure 81). Accordingly, garnet 2 likely started growing at ~555 °C and 6000 bar - a lower temperature but higher pressure than predicted for the final growth of garnet 1 (see above).

Figure 79 Modelled compositional zoning profile (solid lines) compared to the measured compositional zoning profile of the biggest garnet grain of sample 40HF18.

Figure 80 Phase equilibrium diagram for sample 40HF18 showing the core-isopleth intersection for the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chlr: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2)

Figure 81 Phase equilibrium diagram for sample 40HF18 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the isopleth intersection of garnet 2 and the modelled P-T-path. (and: andalusite, bio: biotite, chlr: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2)

4.5.7 Theria_G garnet growth modelling of sample 86/83

The core isopleths for the biggest garnet in sample 86/83 intersect on the garnet-in curve at 519 °C and 5250 bar (Figure 83). Modelling garnet growth along a P-T path with a slope of 17 bar/°C yields a good fit for garnet 1 (Figure 82). The rim composition is predicted at ~560 °C and 5950 bar, with an overall good fit within ± 1 mol-% (Figure 84).

An isothermal pressure increase to ~6700 bar is used to predict the decrease in almandine and rise in grossular contents in garnet 2. However, the thickness of garnet 2, which has a nearly constant composition in the outermost 20 μm (Figure 82), cannot be predicted using Theria_G because the model predicts the composition of garnet to change during garnet growth as fractionation continuously changes the effective bulk rock composition.

Figure 82 Modelled compositional zoning profile (solid lines) compared to the measured compositional zoning profile of the biggest garnet grain of sample 86/83.

Figure 83 Phase equilibrium diagram for sample 86/83 showing the core-isopleth intersection for the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, dashed red line: P-T path for garnet 2)

Figure 84 Phase equilibrium diagram for sample 86/83 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the isopleth intersection of the rim of garnet 1 and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, dashed red line: P-T path for garnet 2)

4.5.8 Theria_G garnet growth modelling of sample 88/83

The core isopleths of sample 88/83 intersect at 524 °C and 4700 bar, ca. 10 °C above the garnet-in (Figure 86). For garnet growth modelling of sample 88/83, garnet was fractionated along a P-T path with a 20 bar/°C slope until the isopleth intersection point to adjust the position of the garnet-in reaction according to the core isopleth intersection.

Following the same P-T path, garnet growth is modelled until the stability field of garnet-bearing assemblages is left at 572 °C and 5675 bar (Figure 87). This yields a good fit for all garnet endmembers (Figure 85). However, the low in the grossular profile observed in the garnet core region was not predicted. Also, the radius of garnet 1 is underpredicted in the model and reaches 0.67 mm instead of 0.75 mm.

Figure 85 Modelled compositional zoning profile (solid lines) compared to the measured compositional zoning profile of the biggest garnet grain of sample 88/83.

Figure 86 Phase equilibrium diagram for sample 88/83 showing the core-isopleth intersection for the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2)

sample 88/83

Figure 87 Phase equilibrium diagram for sample 88/83 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the isopleth intersection of the rim of garnet 1 and the modelled P-T-path (and: andalusite, bio: biotite, chlr: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2)

4.5.9 Theria_G garnet growth modelling of sample 46HF18

The garnet core isopleth intersection lie on the garnet-in curve at about 510 °C and 3500 bar (Figure 89). The best fit model for the inner region of garnet follows a P-T path with a slope of 18.4 bar/°C until 548 °C and 4200 bar, where the stability field of garnet-bearing assemblages ends (Figure 89). Up until this point in P-T space the almandine,

grossular and spessartine profiles are predicted well, only the slope of the pyrope profile increases too much towards the rim reaching ~7 % pyrope content (Figure 88). However, the model fails to reproduce the last ~250 μm where the almandine content should rise and the grossular content falls further, because garnet growth is predicted to stop as staurolite becomes part of the stable assemblage. As a consequence, the thin rim of garnet 1 cannot be modelled. Nonetheless, the isopleth intersection for the innermost garnet 2 can be found, which lies at ca. 550 $^{\circ}\text{C}$ and 5000 bar with a fit of ± 1.5 mol-% for all endmembers except spessartine (Figure 89). The increase in grossular content observed can be predicted with Theriak along a near isothermal P-T path reaching 552 $^{\circ}\text{C}$ and 5450 bar. Furthermore, the measured garnet volume of 1.76 vol-% is close to the predicted one of ~2 vol-% at these conditions.

Figure 88 Modelled compositional zoning profile (solid lines) compared to the measured compositional zoning profile of the biggest garnet grain of sample 46HF18.

Figure 89 Phase equilibrium diagram for sample 46HF18 showing the core-isopleth intersection for the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2, dashed red line: P-T path for garnet 2)

4.5.10 Theria_G garnet growth modelling of sample 14/92

The observed garnet core isopleths intersect at a point ~40 °C above the predicted garnet-in reaction at 503 °C and 3270 bar (Figure 91). To adjust the position of the garnet-in-reaction to that point, garnet was fractionated along a P-T-path with a 20 bar/°C slope. When garnet is grown along a P-T path with a slope of 20 bar/°C from the isopleth

intersection on, the model successfully predicts the changes in composition except for the observed slight increase in grossular content $\sim 700 \mu\text{m}$ from the core (Figure 90). However, the radius is underpredicted, leading to steeper slopes for the modelled profiles (Figure 90). The composition of the rim of garnet 1 is reached $\pm 1 \text{ mol-\%}$ when garnet stops growing and staurolite enters the stable assemblage at 543°C and 4050 bar (Figure 92). Between the rim of garnet 1 and the first shell of garnet 2, a sharp decrease in almandine and increase in grossular contents is observed (Figure 90). Isopleth intersections for garnet 2 record P-T conditions of 545°C and 4700 bar with a fit of less than $\pm 1 \text{ mol-\%}$ (Figure 90).

Figure 90 Modelled compositional zoning profile (solid lines) compared to the measured compositional zoning profile of the biggest garnet grain of sample 14/92.

Figure 91 Phase equilibrium diagram for sample 14/92 showing the core-isopleth intersection for the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chlr: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2)

sample 14_92

Figure 92 Phase equilibrium diagram for sample 14/92 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the isopleth intersection of the rim of garnet 1 and the modelled P-T-path. (and: andalusite, bio: biotite, chl: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, red hexagon: isopleth intersection for garnet 2)

4.5.11 Theria_G garnet growth modelling of sample 45HF18

The garnet core isopleths intersect at 521 °C and 5130 bar, ~10 °C above the conditions predicted for the garnet-in reaction in this rock (Figure 94). To be able to model garnet growth, the garnet-in reaction has to be moved to the core isopleth intersection area by fractionating garnet. Growing garnet along a P-T-path with a 20 bar/°C, the rim

composition of garnet 1 is predicted at 560 °C (Figure 95) and results in a good match between predicted and observed garnet compositional zoning, except for the slight increase in grossular contents observed ~350-400 µm from the core and the slight decrease ~100 µm from the core (Figure 93). Garnet 2 is modelled with a nearly isothermal pressure increase to 558 °C and 6400 bar, which fits the almandine and grossular contents but results in a ~1 mol-% too high pyrope content and a ~1.5 mol-% too low spessartine content. The predicted amount of garnet at the conditions of garnet 2 is ~1 vol% higher than the observed one.

Figure 93 Modelled compositional zoning profile (solid lines) compared to the measured compositional zoning profile of the biggest garnet grain of sample 45HF18.

Figure 94 Phase equilibrium diagram for sample 45FH18 showing the core-isopleth intersection for the biggest grain and the modelled P-T-path. (and: andalusite, bio: biotite, chlr: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, dashed red line: P-T path for garnet 2)

sample 45HF18

Figure 95 Phase equilibrium diagram for sample 45FH18 calculated for the effective bulk rock composition at the end of garnet 1 growth showing the isopleth intersection of the rim of garnet 1 and the modelled P-T-path (and: andalusite, bio: biotite, chlr: chlorite, cord: cordierite, cz: clinozoisite, fsp: feldspar, grt: garnet, ilm: ilmenite, kya: kyanite, ru: rutile, sill: sillimanite, stau: staurolite, wm: white mica; blue line: pyrope isopleth, red line: grossular isopleth, green line: almandine isopleth, orange line: spessartine isopleth, dashed light blue line: P-T path for garnet 1, dashed red line: P_T path for garnet 2).

4.6 Lu-Hf Whole-Rock-Garnet Age Dating

In order to determine which of the metamorphic events reported for the KNC caused the growth of garnet 1 and to compare the results of thermodynamic modelling and textural evidence of deformation to other studies, garnet was age-dated using Lu-Hf garnet whole-rock geochronology. Two samples were selected: samples 28HF18 and 45HF18. To avoid mixing ages between garnet 1 and garnet 2, samples without garnet 2 (28HF18) or with a very thin overgrowth of garnet 2 (45HF18) were chosen.

4.6.1 Lu and Hf concentrations and isotopic compositions

Isotope ratios of $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ for the sample fractions and reference materials BHVO-2 and BCR-2 are reported in Table 7. The JMC-475 standard was measured 5 times and the average and 2σ standard deviation are reported in Table 7. For samples 28HF18 and 45HF18 as well as for the standards, Lu and Hf concentrations were measured via isotope dilution. The Hf concentrations of the whole rock fractions of the samples obtained by this technique are 9.171 ppm for 28HF18 and 4.730 ppm for 45HF18. Lu concentrations of the whole rock fractions are 0.842 ppm and 0.877 ppm, respectively (Table 7). Concentrations of Hf and Lu in the whole rock fractions were also measured by lithium borate fusion ICP-MS yielding 21 ppm Hf and 0.83 ppm Lu for sample 28HF18 and 7.2 ppm Hf and 0.9 ppm Lu for sample 45HF18 (Table 7). If the $^{176}\text{Lu}/^{177}\text{Hf}$ ratios for the whole rocks are calculated using the Hf concentrations obtained via lithium borate fusion ICP-MS, lower values of 0.0098 and 0.0170 for 28HF18 and 45HF18 respectively are obtained (vertical lines in Figure 96 and Figure 97). For garnet, the Hf concentrations obtained via isotope dilution range between 5.468 ppm and 5.688 ppm in sample 28HF18 and between 3.079 ppm and 3.472 ppm in sample

45HF18. Lu concentrations are 5.921 ppm to 5.985 ppm in garnets of sample 28HF18 and 14.370 ppm to 17.761 ppm in sample 45HF18 (Table 7). LA-ICPMS yields lower Hf concentrations for the garnets of ~0.6 ppm in sample 28HF18 and ~0.4 ppm in sample 45HF18. Similar results are reported by Smitt et al. (2013) for the same dissolution protocol.

To evaluate the effect the dissolution of zircon might have had on the isochron, the $^{176}\text{Hf}/^{177}\text{Hf}$ ratios for zircon was estimated. The Hf isotopic composition of detrital zircon is unknown, but the $^{176}\text{Hf}/^{177}\text{Hf}$ ratio for zircon that grew or was reset during metamorphism can be calculated based on an estimated age of 440 Ma for metamorphism and today's whole rock $^{176}\text{Hf}/^{177}\text{Hf}$. Based on the assumption that zircon does not incorporate Lu, and therefore preserves the Hf isotopic composition of its reservoir at the time of growth or resetting, the reset zircon is estimated to have a $^{176}\text{Hf}/^{177}\text{Hf}$ ratio of 0.282233 in sample 28HF18 and 0.282190 in sample 45HF18 (Figure 96, Figure 97).

Figure 96 $^{176}\text{Lu}/^{177}\text{Hf}$ vs. $^{176}\text{Hf}/^{177}\text{Hf}$ diagram for sample 28HF18 showing the measured isotope ratios of whole rock and garnet fractions, as well as calculated isotopic compositions of zircon for which the Hf-isotope ratios were reset during metamorphism (at 440 Ma) and the $^{176}\text{Lu}/^{177}\text{Hf}$ ratio calculated for the whole rock including undissolved zircon (vertical line).

Figure 97 $^{176}\text{Lu}/^{177}\text{Hf}$ vs. $^{176}\text{Hf}/^{177}\text{Hf}$ diagram for sample 45HF18 showing the measured isotope ratios of whole rock and garnet fractions, as well as calculated isotopic compositions of zircon for which the Hf-isotope ratios were reset during metamorphism (at 440 Ma) and the $^{176}\text{Lu}/^{177}\text{Hf}$ ratio calculated for the whole rock including undissolved zircon (vertical line).

Table 7 Lu and Hf concentrations and $^{176}\text{Lu}/^{177}\text{Hf}$ and $^{176}\text{Hf}/^{177}\text{Hf}$ isotope ratios for the measured samples and standards. The 2σ error for the $^{176}\text{Lu}/^{177}\text{Hf}$ ratio is assumed to be 0.5%.

Sample	Hf (ppm)	Lu (ppm)	$^{176}\text{Lu}/^{177}\text{Hf}$	2σ error (0.5%)	$^{176}\text{Hf}/^{177}\text{Hf}$	2σ error
28HF18WR	9.171	0.842	0.0131	0.0001	0.282313	0.000005
28HF18 grt	5.509	6.037	0.1567	0.0008	0.283560	0.000004
28HF18 grt (a)	5.688	6.102	0.1533	0.0008	0.283519	0.000005
28HF18 grt (b)	5.468	6.104	0.1596	0.0008	0.283592	0.000005
45HF18WR	4.730	0.877	0.0265	0.0001	0.282409	0.000006
45HF18 grt (s)	3.409	15.562	0.6524	0.0033	0.289128	0.000005
45HF18 grt (s) II	3.079	19.593	0.9096	0.0045	0.289819	0.000005
45HF18 grt (big)	3.487	15.659	0.6420	0.0032	0.288136	0.000006
45HF18 grt (big) II	3.472	17.902	0.7370	0.0037	0.288121	0.000005
BHVO-2	4.816	0.284	0.00836	0.00004	0.283095	0.000005
BCR-2	7.058	0.517	0.01040	0.00005	0.282878	0.000009
JMC-475 Hf standard					0.282170	0.000010

4.6.2 Lu and Hf zoning in garnet

LA-ICPMS maps of central sections of the biggest garnet grains in 28HF18 and 45HF18 reveal zoning patterns in Lu (Figure 98), whereas the Hf concentrations are close to the detection limit over the whole grains (Appendix H). There is a peak in Lu contents in the core regions of both garnets, and Lu is slightly enriched in the rim. In the garnet core of sample 28HF18, the concentration of Lu is up to 2000 ppm, less than 2.5 ppm over most of the grain, and ca. 10 ppm in the irregularly shaped rim (Figure 99). In sample 45HF18, the Lu concentration in the core region of garnet is ~500 ppm, 1-5 ppm over most of the grain and up to 50 ppm in the 10-30 μm thick rim (Figure 99). However, considering the volume/radius relationship of garnet in this sample, the amount of Lu contained in the relatively small volume of the garnet core is less than the amount of Lu fractionated into the comparatively large volume contained in the garnet rim of sample 45HF18 (Figure 99).

Figure 98 LA-ICP-MS element map for Lu of the central section of the biggest garnet grains in samples 28HF18 (left) and 45HF18 (right). The positions of the profiles (Figure 99) are indicated with white lines.

Figure 99 Lu concentration along a profile from core to rim (white lines in Figure 98) and the calculated relative amount of Lu per shell based on the volume of the grain (right y-axis) for samples 28HF18 (left) and 45HF18 (right).

4.6.3 Age dating

Two-point isochrones of each garnet fraction with the whole rock yield ages of $458.6 - 465.6 \pm 3.6$ Ma for sample 28HF18. For sample 45HF18 the spread is wider with ages of 428.9 ± 2.3 Ma (45FH18 grt (big) II), 447.6 ± 2.3 Ma (45HF18 grt (s) II) and one significantly older age of 571.9 ± 3 Ma (45HF18 grt (s)) considered erroneous because of the very different initial $^{176}\text{Hf}/^{177}\text{Hf}$ -isotope ratio (Table 7, Table 8). Calculated initial $^{176}\text{Hf}/^{177}\text{Hf}$ -isotope ratios based on these two-point isochrons yield values which are identical within error for all garnet fractions of sample 28HF18 with an average of 0.282200. Two of the garnet fractions of sample 45FH18, grt (big) II and grt (s) II, have identical initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios within error and overlap with the range of garnet in sample 28HF18 (Table 8). The calculated initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios for the whole rock fractions at the estimated time of metamorphism (440 Ma) are 0.282205 and 0.282190 respectively for samples 28H18 and 45HF18 (the same as reset zircons (Chapter 4.6.1)).

Table 8 Isochron ages and initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios for combined and 2-point isochrons of samples 28HF18 and 45HF18.

Sample	isochron age	($^{176}\text{Hf}/^{177}\text{Hf}$)₀	2σ error	MSWD
28HF18 grt - WR	463.2 $\pm$ 3.5 Ma	0.2821994	0.0000058	
28HF18 grt (a) - WR	458.6 $\pm$ 3.7 Ma	0.2822005	0.0000058	
28HF18 grt (b) - WR	465.6 $\pm$ 3.6 Ma	0.2821988	0.0000058	
45HF18 grt (s) - WR	571.9 $\pm$ 3.0 Ma	0.2821244	0.0000066	
45HF18 grt (s) II - WR	447.6 $\pm$ 2.3 Ma	0.2821865	0.0000064	
45HF18 grt (big) II - WR	428.9 $\pm$ 2.3 Ma	0.2821958	0.0000064	
28HF18 all fractions	463 $\pm$ 13 Ma	0.282199	0.000029	5.2
45HF18 all fractions	457 $\pm$ 200 Ma	0.2824	0.0025	2486
45HF18 grt (s, big) II -WR	457 $\pm$ 200 Ma	0.2822	0.0025	134
Combined 28HF18 45HF18 (excluding 45HF18 grt (s))	438 $\pm$ 15 Ma	0.28223	0.00013	116

All fractions of sample 28HF18 together form a well constrained errorchron with an age of 463 ± 17 Ma and a MSWD of 5.2 (Figure 100). An errorchron for all fractions of sample 45HF18 except 45HF18 grt(s), gives an age of 442 ± 200 Ma with an MSWD of 134 (Figure 101).

Figure 100 Isochron diagram for whole rock and garnet of sample 28HF18 calculated using Isoplot 4.15. (Ludwig, 2012). Model 3 Solution ($\pm 95\%$ -conf.) on 4 points; Age = 463 ± 17 Ma; Initial $^{176}\text{Lu}/^{177}\text{Hf} = 0.282199 \pm 0.000042$; MSWD = 5.2, Probability = 0.005; Initial $^{176}\text{Lu}/^{177}\text{Hf}$ variation = 0.000017 (2σ).

Figure 101 Isochron diagram for whole rock and garnet of sample 45HF18 calculated using Isoplot 4.15. (Ludwig, 2012). Model 3 Solution ($\pm 95\%$ -conf.) on 3 points; $442 \pm 200 \text{ Ma}$; Initial $^{176}\text{Lu}/^{177}\text{Lu}=0.2822 \pm 0.0025$; MSWD = 134, Probability = 0.000; Initial $^{176}\text{Lu}/^{177}\text{Lu}$ variation = $0.00038 (2\sigma)$.

Chapter 5: Discussion

In the following chapter, the implications of the obtained results are discussed. First, textural constraints on the relative timing of garnet growth are discussed, followed by a discussion of the results of garnet growth modelling. This chapter closes with a discussion of the absolute age of metamorphism and garnet growth.

5.1 Inclusion Textures and Relative Timing of Garnet Growth with respect to Deformation

Inclusion textures in porphyroblasts are widely used to distinguish growth during different deformation regimes (e.g. Passchier et al., 1992; Zwart, 1962). Shape-preferred orientations, such as a preferred orientation of the long and short axes of elongate garnets can also hold information on deformation during or after porphyroblast growth. Together, these two measures can be used to infer the relative timing of garnet growth with respect to deformation.

Of the five deformation events described by Gayer et al. (1985) only two are recorded in the relationships of garnet with the foliation in the study area. These are referred to as D1 and D2 in this research. During the first deformation period D1, a planar fabric S1 was formed, which is preserved as inclusion trails of quartz and ilmenite in garnet, and as a relic fabric defined by white mica and ilmenite preserved in the microlithon between later cleavage domains in samples 34HF18, 35HF18, 14/92, 46HF18 and 45HF18 (see Chapter 4.1). The S1 fabric is at an angle of $\sim 40^\circ$ to the penetrative S2 fabric (Figure 13, Figure 23, Figure 24), which formed during D2, the main deformation episode, correlated to the nappe thrusting and peak metamorphism during the Scandian continent-continent collision (Gayer et al., 1985; C. L. Kirkland et al., 2006b). The crenulation associated

with D3 grew on the retrograde path and was described in the Revsbotn-Repparfjord area, is only weakly developed in some samples of the study area. Since garnet growth is only observed post-D1, for the sake of simplicity, syn-kinematic will be used to refer to D2, inter-kinematic to refer to the period between D1 and D2, and post-kinematic to refer to events after D2.

The garnets in rocks from the KNC exhibit a variety of different inclusion textures, which were previously described by Rice (1984) and Rice and Roberts (1988). Generally, two distinct textural zones termed garnet 1 and garnet 2 can be distinguished, which can be further subdivided in some samples (Rice, 1984). Furthermore, garnet occasionally inherited its inclusion texture from biotite grains it replaced, as reported for samples from the Nordkinn area (Rice and Roberts, 1988) and also observed in the area around Veidnes. In most cases, the boundary between textural zones coincides with changes in the chemical zoning. However, since the boundary between textural zones is not always sharp, especially when the inclusion density is low, the relationship between chemical and textural zones is not always clear.

5.1.1 Garnet 1

For garnet 1, the inner growth zone, there are four different types of inclusion textures observed: straight inclusion trails, textural sector zoning, s-shaped to spiral inclusion trails, and garnets without any clear inclusion trails either because there are very few inclusions or a high inclusion density but randomly distributed. Of these, the straight inclusion trails and the textural sector zoning indicate growth during the inter-kinematic period (Zwart 1962; Ferguson, 1980; Passchier et al. 1992).

The s-shaped or spiral inclusion trails are clearly continuous with the matrix and therefore syn-kinematic in samples 36HF18 and 37HF18 (Figure 11, Figure 12). In samples 34HF18 and 35HF18, the relationship between inclusion trails and external foliation is not clear (Figure 13, Figure 15).

In cases where there are no inclusion trails, but strain-caps and strain-shadows around the porphyroblasts, it is not clear whether garnet growth happened before or during deformation, but other observations might help to elucidate the deformation history.

Parallel inclusion trails indicating inter-kinematic growth were observed in four samples: in sample 45HF18 from Kobbevik (Figure 24), samples 46HF18 (Figure 23) and 14/92 (Figure 22) from Kifjord, all three on Nordkinnhalvøya and in sample 87/83 (Figure 18) collected near Kalak in the Bekkarfjord area. Sample 88/83 which is from the same area as 87/83 has a very low inclusion density, but some grains show weak straight inclusion trails (Figure 56). Sample 41HF18 has straight inclusion trails in the core, which bend towards the rim (Figure 19).

Textural sector zoning is observed in samples 28HF18 from Sværholtklubben on the Northern tip of the Sværholthavøya, 32HF18 from Tømmervikklubben on Sværholthavøya and 127/83 from Veidnes (Figure 2, Figure 4, Figure 8). Since sector zoning requires hydrostatic pressure (Rice and Mitchell, 1991), these samples therefore grew in the inter-kinematic period between D1 and D2.

The other samples from Veidnes, 40HF18 and 121/83 do not show evidence of textural sector zoning in garnet 1 but randomly oriented densely packed inclusion (Figure 5, Figure 6). However, strain-caps and shadows associated with garnet indicate pre or syn-kinematic growth. Biotite porphyroblasts in sample 121/83 further show s-shaped

graphite inclusion trails which are not continuous with the external foliation and therefore pre-kinematic. Together with signs of garnet overgrowing biotite, this indicates that garnet 1 growth occurred after biotite growth, before or during D2.

S-shaped inclusion trails are observed in the samples from south west Laksefjord (34-37HF18) and in two samples from Bekarfjord (41HF18 and 86/83). In samples 36HF18 and 37HF18 the inclusion trails are clearly continuous from core to rim and with the external S2 foliation and therefore syn-kinematic. Garnet growth also continued after the deformation as shown by static overgrowth of the external foliation by the inclusion-poor rim. The same is observed for inclusion poor garnet rims in sample 35HF18. In samples 34HF18 and 35HF18 there is no clear evidence for continuity of the inclusion trails with the external foliation, so theoretically the porphyroblasts could have grown during D1 too. However, given the geographical proximity to sample 36HF18 which is clearly syn-kinematic with respect to D2, this is most likely the case for samples 34HF18 and 35FH18, too.

In garnets of sample 38HF18, quartz and ilmenite inclusions are rare and randomly oriented. Most garnet grains are heavily fractured, and in some grains the fractures seem to follow the boundary of garnet 1 and garnet 2, outlining hexagonal shapes. Similar cracks are also observed in sample 86/83, however, there are not enough chemical profiles or element maps for those garnets to prove a consistent relationship between the cracks and the chemical growth zones. Similar cracks are also observed in sample 86/83 from Bekkarfjord which also shows a relatively thick rim of garnet 2.

The inclusion textures of samples from the Bekkarfjord area are interesting because three types of inclusion textures are observed: spiral-shaped inclusion trails (86/83), s-shaped

inclusion trails with a straight segment in the core-region (41HF18) and straight inclusion trails (87/83). This could either indicate strain partitioning within the thrust sheet, where simple shear increases significantly within 500 m towards the floor thrust (Law et al., 1984), or by different timing of garnet growth with respect to deformation. An explanation by strain partitioning is consistent with the distance of the samples, which all lie within the same thrust sheet, to the floor-thrust (Figure 1). Sample 86/83 lies very close to the thrust and the locations of samples 41HF18 and 87/83 are further away. Moreover, sample 88/83 which does not show any evidence for spiral inclusion trails but few straight inclusion trails, has a very similar garnet-in temperature compared to sample 86/83 and should therefore have started growing at the same time. Strain partitioning can also explain the different degree of rotation between samples 34HF18 and 35HF18 which lie within a thrust sheet and samples 36HF18 and 37HF18 (Figure 1). The latter are from a fissile portion of rocks just below the mapped thrust, which suggests that a substantial amount of strain was accommodated by the rocks below the thrust too in this location. The samples from Kifjord, 14/92 and 46HF18, are also positioned below a near thrust fault (Figure 1), but their inclusion textures do not show evidence for rotation during growth. Instead the sparse inclusions aligned in straight lines, or parallel elongate quartz inclusions in samples from the area suggest inter-kinematic growth. In deformed garbenschiefer sheets intruding the schists and phyllites in the area, garnets exhibit textural sector-zoning (Appendix E), and in sample 14/92 displacement growth, evident by the formation of mica-domes, further strengthening the case for inter-kinematic garnet growth.

5.1.2 Garnet 2

The outer growth zone of garnet 2, chemically marked by a sudden, sharp increase in grossular content, can be found in all samples except for the two samples from Northern Sværholt, 28HF18 and 32HF18, which show textural sector zoning (Figure 2, Figure 4). Sample 35HF18 only shows a texturally different rim without the associated change in garnet composition. However, the lower inclusion density in the rim of this sample could also be the result of other factors like a reduced radial growth rate or a change of the mineral proportions in the matrix (Powell and Vernon, 1979).

In most samples, the thickness of garnet 2 is less than 100 μm and therefore textural relationships are difficult to decipher. Of the three samples with wider garnet 2 zones, two samples 38HF18 and 86/83, exhibit nearly inclusion-free garnet 2. In sample 86/83, it is impossible to find conclusive evidence to distinguish syn- and post-kinematic growth in the relationship between garnet and the rock matrix foliation. However, in sample 38HF18 a graphite-rich rim close to the edge of garnet 2 and the relationship with the matrix suggest that garnet 2 overgrew the matrix foliation and is therefore post-kinematic (Figure 10). Similar graphite inclusion rims are also observed in some garnet grains of samples 127/83, 41HF18 and 45HF18 (Figure 8, Figure 19). In these samples the graphite rims approximately coincide with the boundary between garnet 1 and 2 and overgrowth of the S2-foliations suggests post-kinematic growth of garnet 2.

Garnet 2 in samples 40HF18 and 121/83 is clearly overgrowing the S2 foliation and therefore post-kinematic. In samples 88/83, 46FH18 and 14/92 there is no clear textural evidence for garnet 2 (Figure 16, Figure 22, Figure 23) and therefore no information is available about the relative timing of garnet growth with respect to deformation.

5.1.3 Orientation of garnet grains

The orientation of the short and long axes of naturally grown not perfectly isometric garnet grains can help to decipher how the samples were deformed.

During simple shear, garnet grains are expected to rotate, and as a consequence their long axes should be oriented in the foliation plane normal to the direction of shearing (i.e., top to the SE). This kind of preferred orientation is expected in samples with spiral inclusion trails. Sample 86/83 confirms this hypothesis as the garnet long-axes are parallel to the foliation (Figure 35). Samples 14/92 and 46HF18 also have their long-axes parallel to the foliation (Figure 38, Figure 41). However, they show straight inclusion trails, but are also located close to a thrust fault, which indicates that they were rotated after garnet growth.

Long-axes consistently oriented at an angle to the foliation together with parallel inclusion trails, as observed in sample 45FH18 (Figure 44), indicate that simple shear during the formation of the foliation was not high enough to rotate the garnet grains. The orientation of the axes was likely preserved from an earlier event.

Garnet long-axes with a preferred orientation normal or sub-normal to the external foliation can be a result of preferential overgrowth of strain caps as observed in sample the sample 40HF18 (Figure 29).

Garnet in sample 28HF18 has its short axes oriented normal to the foliation plane and its long axis parallel to the foliation but without a preferred direction. This is the only XR- μ CT scanned sample showing this pattern and also the only one with textural sector zoning without an overgrowth of garnet 2.

5.1.4 Relative timing of garnet growth with respect to deformation

Collectively, textural evidence indicates that garnet 1 growth in the study area started in the inter-kinematic period between D1 and D2 and continued during the D2 deformation event. Samples from the lowest structural levels (samples 34-37HF18, 86/83, 41HF18) show syn-kinematic garnet 1 growth, whereas samples from higher structural levels and from Nordkinnhalvøya grew in the inter-kinematic period. The structural settings of samples with different inclusion textures allow an interpretation of later garnet growth (or earlier deformation) for the syn-kinematic garnets in the lower structural levels.

However, an explanation by strain partitioning is also possible. Moreover, strain partitioning can also explain the occurrence of syn- and pre-kinematic garnet 1 within the same thrust sheet. The orientation of garnet long-axes parallel to the foliation further suggests that the pre-kinematic garnets with straight inclusion trails from Bekkarfjord (88/83) and Kifjord (14/92, 46FH18) were rotated after garnet 1 growth. However, sample 87/83 from Bekkarfjord shows contradicting evidence in form of garnet long-axes parallel to the foliation indicating rotation and parallel inclusion trails in garnet contradicting rotation unless all grains were rotated the same amount.

Garnet 2 growth occurred exclusively after the S2 foliation was formed, only one sample (sample 86/83) does not offer conclusive evidence and might have grown during D2. This indicates a garnet growth hiatus for the samples with evidence of inter-kinematic growth of garnet 1 and/or for samples with a clear textural boundary between the growth zones.

Figure 102 Visual schematic representation of the relative textural information, showing the development of micro-structures.

5.2 Garnet Growth Modelling and Compositional Zoning

In the following chapter, the results of garnet growth modelling of each sample are discussed and interpreted comparing them to the observed compositional zoning and other samples.

The aim of the garnet growth modelling conducted in this research was to identify the simplest possible P-T paths that reproduce the observed compositional zoning of garnet in samples from Eastern Finnmark. Therefore, the presented P-T paths can be considered simplifications of the actual P-T trajectories experienced by the rocks during their metamorphism but should capture the general evolution of P and T during garnet growth. These simplifications are preferred to models trying to fit the observed chemical profile exactly, as natural garnet crystals do not grow perfectly concentric and exhibit small scale variations in their chemical compositions for example due to local variations in the bulk rock chemistry.

5.2.1 Accuracy and limitations of the modelling technique

As for any model, there are also uncertainties in the data used for the modelling conducted in this study. The largest contributions to these uncertainties stem from the uncertainty on the formation enthalpies of endmembers and from uncertainties on equilibrium constants of mixing phases (Powell and Holland, 1988), whereas the uncertainties on EPMA analyses are relatively insignificant (Chapter 3.5). For the relatively simple NASH-system, the uncertainties are on the order of $\pm 4-8$ °C (2σ) for most reactions with steep slopes in P-T space, and on the order of $\pm 200-500$ bar (2σ) for most reactions with shallow slopes (Powell and Holland, 1988). For an invariant point on the garnet-in curve for a blueschist in the NFMASH system, Holland and Powell (1990)

report 2σ uncertainties of ± 6 °C and ± 900 bar. Although these examples are calculated for older versions of the thermodynamic data compared to those used here, the order of magnitude of uncertainties expected on the results in this study are similar, if not higher, given the more complex chemical system used and the higher number of endmembers considered in this study.

To assess the quality of a fit between model and observation it is important to know how a misfit of the composition translates into an error in pressure and temperature. The almandine and pyrope isopleths of metapelitic garnet are generally steep in P-T space and therefore good thermometers (Figure 103, Figure 105). One percent of almandine content difference is equal to ~ 1 - 1.25 °C, and after the chlorite-out reaction, which usually occurs at ~ 72 - 82 mol-% almandine content or ~ 550 °C for the rocks studied here, the spacing of almandine isopleths increases and their slopes become horizontal or even negative (Figure 103). The pyrope isopleth spacing in P-T space is wider than for almandine, which results in a temperature difference of 8 - 15 °C per mol-% of pyrope content, with higher differences at lower temperatures close to the garnet-in reaction (Figure 105). The grossular isopleths have a slope of roughly 40 bar/°C in garnet of metapelites of average bulk rock composition, and, hence, grossular content in such systems is a good indicator of the metamorphic pressure during garnet growth (Figure 104). The spacing between the grossular isopleths decreases with increasing pressure, which results in a pressure difference of up to 500 bar per 1 mol-% grossular at lower pressures and 200 bar at higher pressures. Hence, a fit ± 0.5 - 1 mol-% for pyrope, ± 1 mol-% for grossular and ± 2 mol-% for almandine is within the uncertainty of the model. Spessartine isopleths are ca.

parallel to the garnet-in reaction line like the volume isopleths for garnet and therefore a good indicator of the total amount of garnet grown (Figure 106, Figure 107).

Figure 103 Calculated almandine (xFe) isopleths for garnet of a representative garnet-bearing metapelite of the study area (sample 45HF18).

Figure 104 Calculated grossular (xCa) isopleths for garnet in a representative garnet-bearing metapelite of the study area (sample 45HF18).

Figure 105 Calculated pyrope (xMg) isopleths for garnet in a representative garnet-bearing metapelite of the study area (sample 45HF18).

Figure 106 Calculated spessartine (xMn) isopleths for garnet in a representative garnet-bearing metapelite of the study area (sample 45HF18).

Figure 107 Calculated volume (vol-%) isolines for garnet in a representative garnet-bearing metapelite of the study area (sample 45HF18).

Since the uncertainties on the database are systematic, for any two neighbouring points on a P-T path they will be very similar and hence the slope of the P-T path is not affected. In samples modelled with Theria_G, the thickness of successive shells and therefore the slope of the chemical profiles can be used to assess the quality of the fit, too. Especially the spessartine-profile is well suited, as the negative slope of these isopleths makes the spessartine content relatively insensitive with regards to the slope of the P-T path (Figure 106). However, the compositional gradient of the spessartine content from core to rim of a crystal will only match if the predicted and observed amount of garnet and therefore the radii of the biggest grains match. If they do not match, that might have several reasons.

On the one hand, it might be the uncertainty of the model with respect to the amount of garnet predicted. On the other hand, it could be the inhomogeneous distribution of garnet over the rock volume. The size of the sample for XR- μ CT scanning is limited by the scanner specifications, and the diameter of the sample dictates the maximal resolution achievable. For these reasons, the samples studied have a typical volume of about 10-25 cm³, whereas the sizes of the samples used for the chemical analyses are larger (ca. fist-sized). Also, for garnet growth modelling using Theria_G, a spherical geometry for garnet crystals and concentric growth are assumed. For each garnet grain segmented from the XR- μ CT-data, the radius of a sphere with the same volume is calculated- the sphere-normalized radius.

For the chemical zoning profiles calculated with Theriak, where no information on the nucleation history from XR- μ CT-scanning is available, intersections between the profiles for different endmembers can be used as a visual measure of fit. If the profiles of two (or more) garnet endmembers intersect at the same concentration value in the predicted and the observed profile, this implies isopleths intersecting at the corresponding point in P-T space, indicating a perfect fit of the model.

The comparison of the observed compositional zoning profiles and the modelled ones further indicated that the assumptions of an interface-controlled growth rate, concentric growth and successive fractionation and nucleation are justified as the model is able to predict the observation very well.

5.2.2 The garnet-in reaction line

For the modelling conducted in this research it is assumed that the compositions of the cores of the biggest garnet grains reflect the relationship between P-T and bulk rock

composition at the time of initial garnet growth. If this assumption is true, then the position of the garnet-in reaction in P-T space may be defined by the core isopleth intersection of this grain predicted in our models. However, of the 11 samples for which P-T paths of garnet growth were modelled, 5 have garnet core isopleth intersections that directly position on or very close to the garnet-in reaction. These samples (28FH18, 38HF18, 40HF18, 46HF18, and 86/83) are therefore perfect for the modelling of P-T paths as the model succeeds to predict the observation. Of the remaining samples, garnet core isopleths for 32HF18 and 35HF18 do not intersect in the field of garnet-bearing assemblages but can be extended to intersect at temperatures below the garnet-in reaction. Samples 41HF18, 45HF18, 88/83 and 14/92 show core-isopleths intersecting at P-T conditions higher than the predicted garnet-in reaction. As a consequence, the position of the garnet-in reaction had to be adjusted for these samples in order to be able to use the models.

There are several possible reasons for the discrepancy between the garnet chemical compositions at the garnet-in reaction predicted for some samples and their observed garnet core compositions: (i) the measured compositions may not reflect the compositions of initial garnet growth, (ii) there may have been local chemical heterogeneities and small scale disequilibrium across the volumes of these samples, (iii) uncertainties in the thermodynamic input parameters of the models used, (iv) disequilibrium growth of garnet.

The first explanation likely contributed to the misfit in sample 41HF18, where the core-composition of garnet was measured on thin sections and are therefore likely not perfect central sections capturing the garnet core. However, for the samples where the core

composition was measured on sections through the geometrical center of the biggest garnet grain, the confidence is high that this composition does reflect initial garnet growth. Local compositional heterogeneities are expected in these metasedimentary rocks if their precursors were layered. Small-scale disequilibrium due to stress could have played a role for syn-kinematic garnet growth (e.g., Wheeler, 2014) and disequilibrium growth and overstepping could also be a possible reason (e.g., Gaidies et al., 2011; Spear, 2017). However, given the fact that the isopleth intersections are still within error of the thermodynamic model, uncertainties in the model are the best explanation. For example, the position of the garnet-in reaction is very sensitive to the amount of Mn in the rock. Unfortunately, the mixing models for chlorite and ilmenite, which are the only other Mn-bearing phases considered in the model, are poorly constrained. This might have led to the observed discrepancy between model and observation in some of the samples. Furthermore, recent studies argue that unreactive ilmenite can also alter the Mn-budget of the effective bulk rock and affect garnet stability (McCarron et al., 2019). Given these uncertainties, it seems justified to move the P-T conditions of the garnet-in reaction to the P-T conditions of isopleth intersection, as conducted in this study.

For samples with garnet core compositions reflective of P-T conditions slightly higher than those predicted for the garnet-in reaction, the adjustment of the position of the garnet-in reaction was achieved by fractionating garnet up unto the observed isopleth intersection along a P-T-path with a slope of 20 bar/°C typical for garnet 1 in the study area. The change in bulk rock chemistry associated with the fractionation of small volumes of garnet is minimal for all elements but Mn. In sample 88/83 for example, at the conditions of isopleth intersection 10 °C above the garnet-in, the Mn content of the

fractionated rock is 27 % lower than the original, Fe and Ca contents are 1.65 % and 1.26 % lower, respectively, and all other elements contained in garnet changed by less than 0.5 %. Furthermore, based on the phase relations calculated for samples with isopleth intersections exactly on the garnet-in curve it can be shown that fractionating small amounts (<1 vol-%) of garnet only effects the P-T conditions of the garnet-in reaction but not the positions of the garnet endmember isopleths.

5.2.3 Sample 28HF18

Garnet in sample 28HF18 is characterized by a decreased grossular content in the core (Figure 48). Even though a similar lower grossular content in the garnet core region is observed in four more studied samples (35HF18, 88/83, 45HF18, 14/92), only in sample 28HF18 the low grossular region makes up a considerable portion of the grain. In this sample, it is roughly 600 μm wide in the biggest grain and can be observed in the five biggest garnet size classes. In the same region where the grossular content is low, the Y content of garnet is elevated (Figure 49). This correlation is also observed in samples 35FH18 and 45HF18, and probably indicates a mineral reaction involving accessory phases, which are not considered in the thermodynamic data used for the modelling. Such accessory phases that could influence the Ca and Y partitioning with garnet are allanite and xenotime. Reliable thermodynamic data for these phases do not exist, possibly explaining the misfits obtained for garnet growth modelling in some of the samples. Therefore, the P-T path used to fit this part of garnet in 28HF18, which is very steep with a slope of 110 bar/ $^{\circ}\text{C}$, might not be reliable. On the other hand, Kelly et al. (2015) observed similar grossular profiles and also explained the Ca-increase in the core with a very steep P-increase. However, all the garnet that grew after this low grossular core

should not be affected. So, the P-T path modelled for the rest of the garnet grains with a ~ 32.5 bar/ $^{\circ}\text{C}$ slope reflects the growth conditions of the volumetrically most abundant portion of garnet in this sample. The humps in the almandine and grossular profiles which are observed on one side of the compositional profile (Figure 48) coincide with the temperature at which chlorite is predicted to leave the stable assemblage, providing another indicator for a good fit of the model.

Nonetheless, the obtained P-T path of garnet growth in this sample is significantly steeper than the other P-T paths of garnet growth in the study area, which typically have slopes of ~ 20 bar/ $^{\circ}\text{C}$. Even 32HF18, sampled geographically closest to 28HF18 and petrographically very similar, with garnet exhibiting textural sector zoning and lacking the garnet 2 overgrowth, has a P-T path with a 20 bar/ $^{\circ}\text{C}$ slope. However, garnet in sample 32HF18 lacks the Ca-poor and Y-rich core.

The main element maps for the biggest garnet in sample 28HF18 (Figure 49) do not show evidence for chemical sector zoning as might have been expected based on the existence of textural sector zoning in the same garnet grain (Figure 2). However, since the section used for the X-ray mapping is normal to one of the 4-fold axes of the dodecahedral grain, all sectors belong to faces with the same miller index and should incorporate the same elements. It is impossible to distinguish such a case from the chemical zoning expected from growth of concentric dodecahedral shells.

The element distribution maps further reveal signs of resorption of garnet, which can be seen in the differing compositions along the edge of the grain (Figure 49). Furthermore, compositional zoning profiles obtained for garnet grains in a random thin-section of sample 28HF18 document lower grossular contents and higher almandine contents in the

rim compared to the biggest grain (Appendix F). Growth of a rim with this composition is unlikely given that it would require a drop in temperature and pressure, and that the modal amount of garnet decreases along such a path (Figure 107). However, if garnet was resorbed prior to the growth of the rim, then that may have resulted in a change of the thermodynamically effective bulk rock composition, stabilizing garnet-bearing assemblages also during retrogression.

5.2.4 Samples 32HF18 and 35HF18

For samples 32HF18 and 35HF18 the core isopleths of garnet do not intersect at the modelled garnet-in reaction but if extended, they intersect at P-T conditions below it, at conditions at which garnet is not predicted to be part of the stable assemblage (Figure 66, Figure 72). This is surprising, as the garnet core-isopleth intersections obtained for these samples are based on random sections through garnet. Therefore, it is unlikely that the observed core compositions reflect the oldest garnet portions crystallized in these samples but rather younger garnet that formed during a later point in the P-T history of the sample. In such a scenario the garnet-core isopleths are expected to intersect at P-T conditions above the garnet-in. This apparent discrepancy can best be explained by the chemical heterogeneity in the metasedimentary rock, whose precursor sediments were likely layered. Small local increases in Mn-content can affect the stability of garnet-bearing assemblages and locally decrease the temperature required to grow garnet. In both samples, the isopleth intersection is positioned ~5 °C below the garnet-in reaction. As a comparison, 0.5 vol-% of garnet are predicted ca. 15 °C and 20 °C above the garnet-in for the two samples, respectively. So, 5 °C are equivalent to less than 0.2 vol-% of

garnet. Furthermore, the 5 °C departure from the garnet-in reaction is within the error of the thermodynamic data used.

In addition, garnet in 32HF18 as well as in 35HF18 does not show the high Ca-contents in the rims (garnet 2) observed in other samples (Figure 50, Figure 54). In sample 32HF18, there is only one textural zone. In sample 35HF18, however, a texturally distinct rim is observed (Figure 15) but the corresponding change in chemistry is lacking except for elevated contents of Y on the outermost ~60 µm of the profile (Appendix F).

5.2.5 Sample 40HF18

The element maps of garnet in sample 40HF18 (Figure 52) together with evidence from petrographic thin-sections (Figure 5) show clearly that the textural and the chemical zoning coincide and that garnet 1 is idiomorphic while garnet 2 has an irregular shape and thickness resulting from preferential overgrowth of micas. This causes a problem when modelling the sample, because the assumption of concentric growth is not met for the growth of garnet 2. Because the thickness of garnet 2 is irregular over each grain and not the same for all grains, the biggest grain is not necessarily the oldest grain. Moreover, the core of garnet 1 cannot be precisely located based on the geometry of the grain. However, the fact that the core-isopleths of the central section of the biggest grain intersect on the garnet-in curve indicates that the grain was among the first ones to nucleate. Still, the radius for garnet 1 is underpredicted (Figure 79). The reason for this underprediction is probably also the irregular thickness of garnet 2, which overprinted the nucleation information in the measured crystal-size distribution. However, if the measured profile is compressed to the radius of the predicted one, the slopes match well. The rim composition of garnet 1 corresponds to the P-T conditions where garnet-bearing

assemblages become unstable and staurolite enters the assemblage (Figure 81). However, staurolite is not observed in this sample, which is consistent with the stable assemblage predicted for garnet 2. The transition between garnet 1 and garnet 2 is a sharp jump in the composition along a textural boundary (Figure 51) and is also marked by high Y-contents (Figure 52). Garnet 2 re-enters the assemblage at a ~ 5 °C lower temperature but ~ 1000 bar higher pressure compared to the rim of garnet 1 (Figure 81). This is a clear indication of a hiatus in garnet growth. The P-T path connecting the conditions of final garnet 1 growth and the onset of garnet 2 growth is unknown. However, given the microstructural and chemical evidence for a hiatus of garnet growth between the formation of the two growth zones, cooling and subsequent heating separating garnet 1 and garnet 2 growth is a better explanation than continuous garnet crystallization.

5.2.6 Sample 38HF18

The uncommon chemical zoning in garnet 1 of sample 38HF18 with two convex humps in the grossular profile accompanied by concave counterparts in the almandine profile (Figure 53) can best be explained by a cyclical event such as pulses of fluid infiltration, which temporarily changed the Ca and Fe partitioning into garnet. However, these patterns are impossible to reproduce with the garnet growth modelling conducted in this research, and since neither the spessartine nor the pyrope content are affected, the model was fit to produce the general compositional trend instead. The resulting P-T path for garnet 1 growth has a slope typical for the region ($20 \text{ bar}/^\circ\text{C}$) (Figure 69). The transition to garnet 2 coincides with a sharp kink in the grossular and almandine gradients but is continuous without a jump in concentrations (Figure 53). Garnet 2 zoning can be predicted with a steep counter-clockwise P-T path (Figure 70). The compositions at the

rim of garnet 2 varies between grains (Figure 53), and in the grain with the highest grossular and lowest almandine contents the recorded P-T conditions are 4 °C lower and 350 bar higher than in the other two grains.

The fit between model and observation is evaluated to be good, as start and endpoints of garnet growth, as well as the values at which the compositional profiles intersect, are in good agreement (Figure 53).

5.2.7 Sample 88/83

Since the isopleth intersection for the core of garnet in sample 88/83 lies about 10 °C above the predicted conditions of the garnet-in reaction (Figure 86) and the garnet-in curve was moved to that position by fractionating garnet along a P-T path with the 20 bar/°C slope typical for the P-T path of metamorphism in the study area. For the modelling of garnet growth in this sample, the ~150 µm wide core region with lower Ca and higher Y contents was neglected (Figure 56). As argued for sample 28HF18, this pattern might be traced back to a mineral reaction involving accessory phases containing Y and Ca. In contrast to sample 28HF18, this low Ca region of the grain in sample 88/83 only recorded a very short period of garnet growth and was therefore not considered in the model.

The slopes and positions of the modelled and the measured zoning profiles match well, if the measured profile is shortened to the radius of the modelled profile (Figure 85). This indicates that the garnet crystal size distribution obtained from the µCT-scanned rock volume, is not perfectly representative for the entire rock. The composition of garnet observed at the rim of garnet 1 is predicted for the P-T conditions at which chlorite leaves the assemblage and staurolite enters it (Figure 87). Garnet 2 is only present as a thin rim

of ~60 μm thickness (Figure 55). There is a sharp but continuous change in the chemical composition of garnet at the transition between garnet 1 and garnet 2 indicating one growth event with changing conditions (near isothermal pressure increase).

5.2.8 Sample 86/83

In sample 86/83, all garnet grains have a relatively thick, concentric rim of garnet 2 with a thickness of ~90-120 μm . The widths of garnet 2 are very similar, and geometric effects of non-central sections and the resolution of the profiles with 15-30 μm can explain the observed differences. This means that the assumption of concentric growth is met and Theria_G can be used to model garnet growth. A good fit is obtained for a P-T path with a slope of 17 bar/ $^{\circ}\text{C}$, slightly shallower than most samples in the region. Growth of garnet 1 ends within the garnet field and as for the garnet in, the modelled composition fits the observed one $\pm 1\%$ (Figure 84). There is no clear textural discontinuity observed at the boundary between garnet 1 and garnet 2 but a sharp change in the gradients of all endmember concentrations but spessartine content (Figure 59, Figure 57). Similar to garnet in sample 88/83, there is no jump in the composition but a gradual change at the transition from garnet 1 to garnet 2, suggesting one continuous growth event. This transition, which is ~60 μm wide can be modelled with an isothermal pressure increase of ~750 bar (Figure 82).

The Y content in garnet 1 is consistently higher than in garnet 2 (Figure 59). This means that Y was partitioned into a mineral other than garnet during the growth of garnet 2 that was not stable before.

5.2.9 Sample 41HF18

For sample 41HF18, which is comparatively Mn-rich, the general trend of the compositional zoning of garnet 1 could be predicted after fractionating garnet to move the P-T conditions of the garnet-in curve up to the P-T conditions of the garnet core isopleth intersection. The P-T conditions of isopleth intersection exceed the conditions predicted for the garnet-in reaction by ca. 12 °C, and the modal abundance of garnet calculated at these conditions is less than 0.5 vol-% (Figure 75). The alternating flat and steep concentration gradients of grossular and almandine indicate nucleation in pulses, as a steep profile is produced when the garnet volume grown during a certain P-T step is distributed among many grains in thin shells and shallow gradients if the same volume of garnet is distributed over few grains in thick shells.

Sample 41HF18 is from the same locality as sample 86/83. Because of the different bulk rock composition, garnet growth in sample 41HF18 is predicted to start at a ~15 °C lower temperature compared to sample 86/83. Whereas both samples are characterized by similar metamorphic P-T slopes, the pressure recorded in garnets in sample 41HF18 is ~250 bar lower and garnet 1 stops growing at a ~20 °C lower temperature compared to garnet in 86/83 (Figure 109). The conditions for garnet 2 growth are more similar again, as the isopleths for garnet 2 in sample 41HF18 intersect at a 12°C higher temperature than the rim of garnet 1 (Figure 75). Compared to the rim of garnet 2 in sample 86/83, garnet 2 in 41HF18 records P-T conditions ~10 °C and 200 bar lower (Figure 111), so they are within error of each other.

5.2.10 Sample 46HF18

For sample 46HF18, garnet 1 growth can be modelled with a good fit for a P-T-path with a 18.4 bar/°C slope until a temperature of 548 °C, at which garnet is predicted to stop

growing as staurolite enters the stable assemblage (Figure 89). However, staurolite is not present in this sample, and additional garnet growth segments can be observed indicating that the formation of staurolite-bearing assemblages is predicted in the model at slightly too low temperatures. This is the only sample of this study with evidence for a too low St-in temperature predicted by the model, and reasons for this misfit are not clear. Also, even if garnet growth would not have been affected by the presence of staurolite, growth along the same path would not have produced the observed compositional profile, as the pyrope content would have increased too much and the low grossular content observed in the rim of garnet 1 would not have been reached. The transition between garnet 1 and garnet 2 is marked by a jump in the grossular and almandine concentration gradients and indicates that garnet stopped growing between the two zones (Figure 60).

The Y-zoning of garnets in sample 46HF18 shows a continuous increase from the core until a sharp boundary $\sim 700\ \mu\text{m}$ away from the core (Figure 61). This indicates mineral reactions involving Y-bearing accessory phases not considered in the modelling.

Identifying these reactions would require detailed analyses of accessory phases and their distribution in garnet and the matrix, which is beyond the scope of this project.

5.2.11 Sample 14/92

Sample 14/92 is from the same locality as sample 46HF18 (Figure 1). However, its bulk Mn content is significantly higher and, therefore, garnet is predicted to enter the stable assemblage at significantly lower temperatures than in 46HF18. Due to complications during the sample preparation, the section through the biggest grain is slightly off-centered. Nonetheless, the core isopleths intersect at a well-defined P-T point but not on the garnet-in curve (Figure 91). Since the compositional gradients are flat in the analysed

garnet core region (Figure 62), the apparent garnet core composition should still be close to the composition of the first nucleated garnet and hence define the approximate P-T position of the garnet-in reaction. Accordingly, the garnet-in reaction for this sample is predicted at a 7°C lower temperature than in sample 46HF18 (Figure 109). The P-T conditions obtained from the garnet core isopleth intersection in sample 46HF18 are positioned only 100 bar below the P-T path of garnet growth in sample 14/92, and the predicted end conditions of garnet growth in both samples differ only by ca. 5 °C and 140 bar (Figure 110). Also, the isopleth intersections for garnet 2 in both samples are similar with a small difference of 5 °C and 300 bar (Figure 111). All these differences are within the uncertainty inherent in the modelling conducted, and the agreement between the results obtained for the two samples from the same location points to the reliability of the model.

5.2.12 Sample 45HF18

To match the core composition of the biggest garnet grain in this sample, the garnet-in curve was moved ~10 °C by fractionating garnet (Figure 94). At the isopleth intersection ~0.11 vol-% of garnet are predicted. The core regions of the garnets in sample 45F18 are marked by a decrease in grossular content and increase in Y, similar to garnet in samples 28HF18 and 88/83. As in sample 88/83, this region is very small and was therefore not considered for modelling, and constant grossular contents in the core were assumed. This results in a good fit for garnet 1 (Figure 93), and also the transition into garnet 2 can be modelled as one continuous growth event, changing the slope of the P-T path from 20 bar/°C to a nearly isothermal counter-clockwise loop (Figure 95).

5.3 Metamorphic Conditions of Garnet Growth

In the following chapter, the metamorphic conditions of garnet 1 and garnet 2 growth of all samples and the associated P-T paths are synthesized to describe the metamorphic evolution of the lower nappes of the KNC in the study area. For this purpose, the conditions of initial garnet 1 growth, P-T paths for garnet 1, the conditions of final garnet 1 growth and the conditions of garnet 2 growth are presented.

The presented P-T paths are the first P-T paths for the study area. Garnet-biotite thermometry on rocks from the lower parts of the KNC yielded temperatures of $ca. 491 \pm 43$ °C averaged over six samples on Nordinnhalvøya, and 530 ± 58 °C for six samples on Sværholthavøya interpreted as peak temperatures (Rice and Roberts, 1988). The apparent trend of higher temperatures on Sværholthavøya compared to Nordkinnhalvøya is refuted by the current study. Furthermore, the current study shows that garnet did not grow below a temperature of ~ 505 °C for any of the analyzed samples and peak temperatures on Nordkinnhalvøya reached ~ 560 °C and on Sværholthavøya up to ~ 585 °C.

5.3.1 P-T conditions of the garnet-in reaction

For garnet growth modelling the assumption of interface-limited garnet growth is followed, meaning that garnet grown during a given step in P-T-composition space, has the same composition and is deposited on all existing or newly formed nuclei in shells with the same thickness. Therefore, the core of the biggest garnet grain records the P-T conditions of the first nucleated garnet, the garnet-in conditions. The formation temperatures of the garnet cores investigated in this study all fall in a temperature interval of ~ 20 °C between ~ 505 °C and 525 °C and pressures span 2250 bar ranging from ~ 3250

bar to 5500 bar (Figure 109). Whereas the temperature of the initial garnet growth depends on the bulk rock chemistry and the resulting position of the garnet-in reaction line in P-T space, the pressure of initial garnet growth should reflect the tectonic position.

Figure 108 Sketch of a tectonic map for the study area showing the tectonic positions of the samples.

The depths calculated for the rocks at the beginning of garnet growth based on a density of 2.83 g/cm^3 for the overlying rock range from ca. 12 km to 20 km. Except for the two sample from Northern Sværholt (32HF18 and 28HF18), there is a systematic trend of higher pressure down the nappe pile, for the samples that can be correlated (Figure 108). Sample 35HF18, which records the highest pressure of initial garnet growth, is from the lowest nappe on the west coast of Laksefjord (Figure 108). However, initial garnet growth in sample 32HF18 is predicted for nearly the same pressure even though this sample is located two nappes above (Figure 109). If the nappes are correlated across Laksefjord, sample 86/83 is at the boundary between the lowest nappe and the second

lowest nappe (Figure 108) and it has a correspondingly high pressure (Figure 109).

Sample 41HF18, which was collected ~1.5 km west of sample 86/83 (Figure 1) records a ~550 bar lower pressure for initial garnet growth and the P-T paths are ~250 bar apart at the same given temperature (Figure 109). Another sample from the second nappe is 88/83 (Figure 108), which is located 4.5 km further west and records a 650 bar lower pressure associated with initial garnet growth than sample 86/83, and a P-T path shifted 550 bar down (Figure 109). Sample 38HF18 from the same structural level across Laksefjord (Figure 108) has a very similar pressure of initial garnet growth as sample 88/83. In the next higher structural level, sample 40HF18 yields a ~600 bar lower pressure, and the pressure difference between the P-T-paths is ~520 bar.

Sample 45HF18 from Nordkinhalvøya has a similar pressure to the samples from Bekkarfjord (41HF18 and 86/83), indicating it might belong to the same nappe (Figure 108). The pressures recorded by samples 14/92 and 46HF18 are lower than for all other samples (Figure 109). Compared to sample 40HF18 which has the same characteristic big biotite porphyroblasts the pressure for initial garnet growth is ~900 bar and ~600 bar lower, respectively for samples 14/92 and 46HF18 and at 518°C, the temperature of initial garnet growth in sample 40HF18, the pressure differences are ~530 bar and ~450 bar respectively (Figure 109). This indicates that samples 14/92 and 46HF18 are likely from a higher structural level.

Garnet in sample 28HF18 would be expected to have started growing at the lowest pressure of all the samples studied since it is from a nappe two levels higher (Figure 108), but nonetheless records the same garnet-in pressure as sample 40HF18 (Figure 109). However, the P-T path for garnet growth in this sample is very different (Figure 109),

which could mean that this sample experienced a different tectono-metamorphic history compared to the other samples of this study.

The results show that the pressure resolution of the results is high enough to distinguish different structural levels.

Figure 109 P-T paths for garnet 1 growth. The green rectangle outlines the range of P-T conditions modelled for the garnet cores.

5.3.2 P-T paths for garnet 1

Except for sample 28HF18, which also does not follow the trend of decreasing pressures at higher structural levels, all samples have very similar P-T paths with slopes of 18.5 bar/°C to 20 bar/°C (Figure 109). For sample 28HF18, a steep first P-T segment is

modelled, similar to the results of Kelly et al. (2015) who studied garnets exhibiting a similar grossular zoning compared to that of 28HF18. However, the slope of the P-T path of metamorphism of 28HF18 is steeper than the trend observed for the other samples of the region also after the initial high-pressure increase recorded in the garnet core. This points at a different metamorphic evolution for sample 28HF18. Furthermore, this sample is from a structurally higher nappe and was collected at the hanging wall of a normal fault, so it might be derived from an even higher structural level (Figure 108).

The 20 bar/°C slope of the P-T paths is equivalent to 50 °C/kbar or 14 °C/km, which is a low geotherm typical of collisional tectonics.

5.3.3 Metamorphic conditions at the end of garnet 1 growth

If the samples were metamorphosed during the same event and along the same P-T paths, the peak temperatures are expected to be similar. In the studied samples, the maximum temperatures recorded in the rims of garnet 1 range from 538 °C to 572 °C and the pressures from 4050 bar to 6675 bar (Figure 110). Again, there is only one outlier, sample 28HF18, which reaches a temperature during garnet 1 rim growth more than 10 °C and 300 bar higher than in all the other samples. Of the ten samples with similar temperatures at the rim of garnet 1, garnet growth has been predicted to have ceased in four samples shortly before the P-T conditions at which staurolite is predicted to enter the stable assemblage (Figure 110). These four samples all grew garnet at relatively low pressures. At higher pressures, staurolite is not part of the stable assemblage, and hence, the P-T paths miss the P-T field of staurolite-bearing assemblages. Since garnet growth is predicted to stop upon entering the P-T field of staurolite-bearing assemblages, it is not possible to discern the P-T-trajectory of the rock from garnet zoning anymore and the

temperature could theoretically have further increased. However, staurolite is not present in any rocks of the study area and therefore the temperatures at the end of garnet 1 growth are likely the maximum temperatures experienced. Given the fact that the highest temperature for the samples with a P-T path of a ~ 20 bar/ $^{\circ}\text{C}$ slope is recorded in a sample where staurolite is predicted in the stable assemblage (sample 88/83), the maximum temperature for these samples is expected to be close to the conditions at the end of garnet growth.

The pressures at the end of garnet 1 growth indicate a burial depth of ca. 15 km to 24 km (Figure 110).

Figure 110 P-T paths for garnet 1 growth. The green rectangle outlines the range of P-T conditions at the end of garnet 1 growth.

5.3.4 Metamorphic conditions of garnet 2 growth

The fields of the peak conditions associated with garnet 1 growth, and the conditions of garnet 2 growth have the same temperatures but garnet 2 records pressures ~500 bar higher, an equivalent of ~2 km (Figure 111). For individual samples, the pressure differences range between ~400 bar in sample 88/83 up to ~1500 bar in sample 38HF18. In three samples, 86/83, 38HF18 and 45HF18, the rim is thick enough compared to the resolution of the EPMA profile to clearly see that the transition between garnet 1 and

garnet 2 is not a jump in the chemical composition but continuous (see Chapter 4.4). For these samples it was possible to model the continuous decrease in almandine content and increase in grossular content in garnet 2 with a near isothermal pressure increase.

Similarly, the rim of garnet 2 in sample 46HF18 can be predicted with a near isothermal pressure increase too, but not the transition between garnet 1 and garnet 2, which is marked by a small jump in the compositional profiles (Figure 60). A similarly steep P-T path with near isothermal pressure increase after an initial phase of garnet growth was reported by Kelly et al. (2015) for garnet bearing schists of the Sevier Orogeny in Idaho. Similar P-T paths have also been reported by Burton et al. (1989) for garnet-bearing metapelites from the Sulitjelma fold nappe in central Norway, with inclusion textures and compositional zoning profiles of garnet similar to the ones observed in this study. The P-T path obtained for the growth of the inclusion-free rims by Burton et al. (1989) has also been interpreted to be the result of a near isothermal pressure increase during the Scandian continent-continent collision.

Of all the samples with a second growth zone, only sample 40HF18 from Veidnes shows a clear jump in the chemical zoning profiles between garnet 1 and garnet 2 indicating that garnet growth ceased (Figure 51). For the samples from Kifjord, 46HF18 and 14/92, a smaller jump of 2-3 mol-% difference in grossular and almandine contents is observed between the last point of garnet 1 growth and the first point of garnet 2 growth, which are of 20 μm apart (Figure 60, Figure 62). Since the P-T paths for these samples are predicted to have entered the stability field of staurolite-bearing assemblages (Figure 110), a hiatus in garnet growth as observed in sample 40HF18 is likely. On the other hand, sample 88/83 is also predicted to reach P-T conditions at which staurolite forms at

the end of garnet 1 growth, but for this sample there is a continuous change in chemistry between garnet 1 and garnet 2 (Figure 55). This further strengthens the argument, that the maximum temperature recorded in garnet 1 for this sample is the maximum temperature the rock experienced and the P-T-path did not continue into the stability field of staurolite-bearing assemblages.

Garnet growth modelling, however, fails to predict the outer rim of garnet 2 in sample 86/83 and the thickness of the rim in sample 40HF18, indicating that garnet 2 growth had a different mechanism than assumed in the model. These two samples both have a relatively constant composition in their rims, which seem to be chemically buffered. In sample 86/83, fluid inclusion trails are abundant in quartz (Figure 21). However, it is not clear when they formed and if fluid infiltration was the reason for the extended growth of garnet 2. In contrast to sample 86/83, in which the thickness of garnet 2 is about the same for all grains, in sample 40HF18 garnet 2 has irregular thicknesses varying between grains and along single grains. Furthermore, there is no evidence for fluid infiltration. The preferential overgrowth of mica-rich domains, which caused the irregular shape and thickness, could indicate a diffusion-limited growth mechanism in a dry rock, where garnet grew preferentially in Al-rich areas. However, it would need detailed further investigations to test these hypotheses, which are beyond the scope of this study. Another factor that could have played a role is a change in oxygen fugacity. In garnets from metapelites in central Norway, Burton (1986) observed a similar zoning pattern with increasing grossular and decreasing almandine contents in their rims, which are devoid of graphite inclusions as opposed to the inner growth zone, possibly indicating an increased

oxygen fugacity. In the model used in our study, the oxygen fugacity is buffered by graphite which is considered an excess phase and the fluid is modelled as a COH fluid. In all possible scenarios for garnet 2 growth the question remains where the significant amount of Ca was sourced from, whether it be a mineral reaction or metasomatism. The main Ca-bearing phase in garnet-zone metapelites is plagioclase, and in the model, it is the breakdown of plagioclase with increasing pressure that provides the Ca for garnet growth. Plagioclase breakdown during near isothermal pressure increase can explain garnet 2 growth in all but two samples (40HF18 and 86/83). Another Ca-rich phase is apatite, which is however not considered in the thermodynamic model. Apatite occurs as an accessory mineral within the matrix and as inclusion in cores and rims of garnet in the modelled samples and is easiest to see in the Ca-maps (Chapter 4.4). This indicates that the stability of apatite did not change significantly over the course of garnet growth. The breakdown of a small fraction of apatite, which would not be reflected in the inclusion pattern, could have provided Ca for samples with thin rims and relatively high modal amounts of apatite. Simple stoichiometric estimations show that if all the P of the samples was hosted in apatite, the breakdown of less than 15 % of the total apatite could have provided all the Ca present in garnet 2 in samples 45HF18 and 88/83, whereas ~37 % of the apatite would be needed to break down in samples 14/92 and 86/83, 76 % in sample 46HF18. For sample 40HF18 the estimation of the total amount of Ca in the rims is difficult because of the irregular thickness of garnet 2. Nonetheless, conservative estimates show that apatite-breakdown alone would probably not be sufficient if it were the only Ca-source. Furthermore, the only other phase which could host significant

amounts of P after the breakdown of apatite is xenotime but this mineral has not been observed in the samples studied.

Figure 111 P-T paths for garnet 1 growth (green), isopleth intersections (hexagons) and P-T paths for garnet 2 growth (red). The green rectangle outlines the range of P-T conditions at the end of garnet 1 growth and the red rectangle the P-T conditions of garnet 2 growth.

5.4 Absolute Timing of Garnet Growth and Metamorphism

In the following sections the Hf isotopic compositions of garnet and whole rock separates of the two age-dated samples and their implications for the isochron age are discussed.

The obtained age is further put into context of the magmatic, metamorphic and deformation-history of the KNC reported in the literature.

5.4.1 Lu-Hf isotopic composition and ages

In order to form a valid isochron, two conditions have to be fulfilled: (i) the system has to remain closed for the parent and daughter isotopes after metamorphism, and (ii) all fractions used in the isochron must have been reset at the same time and equilibrated, meaning that the initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratio was the same for all fractions. The first condition is certainly fulfilled as high gradients in profiles for Lu are preserved (Figure 99) and there are no signs of diffusion in the compositional profiles for the faster diffusing major element either. As shown in Table 8, the second condition is fulfilled too and all initial $^{176}\text{Hf}/^{177}\text{Hf}$ ratios are within error of each other, except for fraction 45HF18 grt(s), which also yields a more than 100 Ma older age and is considered to be erroneous and therefore not further discussed. However, in sample 28HF18 only one garnet growth zone (garnet 1) is present, whereas in garnet grains of sample 45HF18 two garnet growth zones are present and Lu is enriched in the thin outer rim of garnet 2 as well as in the core.

Inclusion textures show that there was a growth hiatus between the growth of garnet 1, which is pre-kinematic, and garnet 2, which is post-kinematic.

Furthermore, the high MSWDs demands geological reasons and questions arise if zircon was dissolved and how this might have affected the isochron, what effect Lu-zoning and

the thin rim of garnet 2 in sample 45HF18 could have and finally what the age spread of individual garnet fractions means.

Comparing the Hf concentrations of garnet obtained by isotope dilution to the concentration obtained by LA-ICP-MS, shows that the dissolution protocol also dissolved a highly Hf enriched phase, most likely zircon. Also, the Hf-concentration of the whole rock fractions are higher than expected if no zircon was dissolved. However, from comparing the concentrations obtained by the whole rock isotope dilution to the concentrations obtained via lithium borate fusion ICP-MS, it can further be inferred that not all zircon was dissolved, as the former is lower than the latter. Moreover, the difference between the concentrations for the total sample versus the dissolved fraction is similar for both samples even though the total Hf concentration and the Zr-concentration for sample 28HF18 are about two thirds higher. This indicates that more zircon was dissolved with sample 28HF18, consistent with the lower Lu/Hf ratios measured via isotope dilution.

Zircon can incorporate very high amounts of Hf (up to 6,000 ppm in sample 45HF18, see element maps in Appendix H) but does not take up Lu, which means that its isotopic composition does not change over time and reflects the composition of the reservoir at the time of zircon crystallization. Furthermore, zircon has a high closure temperature for the Lu-Hf system and is usually not homogenized and reset even during high grade metamorphism (Scherer et al., 2000). So, if zircon inclusions are dissolved together with the whole rock or garnet fractions, they would add Hf with a different Hf isotopic composition. Mixing with zircon causes the datapoints of the garnet and whole rock fractions to move towards the zircon along a straight mixing line, causing them to scatter

instead of forming an isochron. Another indication for mixing with inherited material are variations in the initial $^{176}\text{Hf}/^{177}\text{Hf}$ -isotope ratio, which should then correlated with the inverse Hf concentration of the sample fraction. This relationship is not observed in the analyzed samples. Hence, it is concluded that at least the dissolved fraction of zircon was in isotopic equilibrium with garnet and the matrix at the time of garnet growth, similarly to the study of Smit et al. (2013), which used a similar low-pressure dissolution protocol. Mixing with zircon that was reset or grew at the time of metamorphism and therefore is in isotopic equilibrium with the garnet and whole rock, only causes the garnet and whole rock points to move towards lower $^{176}\text{Lu}/^{177}\text{Hf}$ values along the isochron (Smit et al., 2013), which could explain the lower $^{176}\text{Lu}/^{177}\text{Hf}$ values for garnet fractions in sample 28HF18 compared to sample 45HF18. Sample 28HF18 also has higher Hf and Zr concentrations and bigger zircon inclusions are observed, however, the difference in Hf-concentration between the total whole rock and the dissolved whole rock fraction in both samples are very similar (Figure 112, Figure 113), indicating that more zircon was dissolved with sample 28HF18. The dissolution of different amounts of reset zircon and possibly also minor amounts of inherited zircon best explains the elevated MSWD of 5.2 for sample 28HF18.

Furthermore, metamorphic zircon overgrowth and fluid assisted equilibration of metamict zircon domains with an age of 470-450 Ma, peaking at ~450 Ma are reported for the KNC west of the study area (Kirkland et al., 2009). Similar rims characterized by their low cathode luminescence response are also found on zircons from Nordkinnhalvøya (Zhang et al., 2016). However, Zhang and coworkers avoided these rims in their study of detrital zircon, so their age is not known.

Figure 112 Isochron diagram for sample 28HF18 also showing the calculated isotopic composition of reset zircon as well as the $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of the whole rock including undissolved zircon (vertical line). Note how mixing with reset zircon would move the garnet datapoints downwards along the isochron causing lower $^{176}\text{Lu}/^{177}\text{Hf}$ ratios as compared to sample 45FH18.

Figure 113 Isochron diagram for sample 45HF18 also showing the isotopic composition of reset zircon as well as the $^{176}\text{Lu}/^{177}\text{Hf}$ ratio of the whole rock including undissolved zircon (vertical line).

When the two-point isochron ages of individual garnet fractions are compared, it is striking that whereas they overlap in sample 28HF18, they differ by nearly 20 Ma for sample 45HF18 (Table 8). Moreover, the MSWD for sample 45HF18 is very high (134), indicating that the small and big garnet grains do not report the same age and record different events; growth of garnet 1 and garnet 2. Hence, it is not justified to combine the small and big garnet fractions of sample 45HF18 in one isochron diagram.

The zoning of Lu in sample 45HF18 shows that for big garnet grains, where the rim has a much higher volume than the core, most of the Lu is hosted in the rims, i.e. garnet 2.

Therefore, the age obtained from big grains will be biased towards the age of garnet 2.

However, the age of 428.9 ± 2.3 Ma is a maximum age of garnet 2 growth as mixing with the older, Lu-rich cores (garnet 1) does not allow to date garnet 2 only.

For small grains, on the other hand, the rims have a much smaller volume compared to the core and therefore the age of garnet 1 dominates the obtained isochron age. In this case, the obtained age for garnet 1 of 447.6 ± 2.3 Ma is a minimum age due to the contribution of the younger garnet 2.

5.4.2 Discussion of the age in the regional context

The obtained ages for garnet 1 growth of 463 ± 17 Ma (sample 28HF18) and the minimum age for garnet 1 growth in sample 45HF18 of 447.6 ± 2.3 Ma, as well as the maximum age for garnet 2 growth in sample 45HF18 of 428.9 ± 2.3 Ma, fit very well with previously reported ages of metamorphism and deformation in the KNC and also corroborate the relative timing established from textural evidence in this study.

Inclusion textures in garnet show that garnet 1 growth started in the inter-kinematic period between D1 and D2 and is syn-kinematic for samples of the lowermost nappes of the study area (but not for the two age dated samples). The D1 deformation happened during the Finnmarkian event during which the S1 foliation, still preserved as a relic in some samples from the study area, was formed. Kirkland et al. (2008a) performed in situ LA Ar-Ar on S1 muscovite grains yielding an inverse isochron age of 498 ± 13 Ma for a sample on western Sværholthavøya and an inverse isochron age of 506 ± 17 Ma for matrix phyllosilicates of a phyllite from Hopsfjord ~8km east of sample 45HF18.

Furthermore, the ages for garnet 1 growth are indistinguishable within error from a Sm-Nd garnet age from a metamorphosed metabasic dike intruding the Kolvik Nappe (lowermost nappe of the Sværholt Succession) with an age of 436 ± 21 Ma (Kirkland et

al., 2007a). As tectonic setting for the metamorphic event causing garnet growth, Kirkland et al. (2007a) propose the Sværholt and Sørøy Terranes, which were amalgamated in the Neoproterozoic, to be in a back arc setting, where heating and magmatism occurred due to the slab-rollback of Baltica underneath the closing Iapetus ocean, its terranes and Laurentia. Muscovite Ar-Ar ages of 437.6 ± 1.6 Ma are interpreted as cooling after the heating of the back arc (Kirkland et al., 2007a) before the Scandian continent-continent collision at 431 - 428 Ma (Kirkland et al., 2006a). The D2 deformation associated with the Scandian collision was of short duration and is constrained by the age of an undeformed cross-cutting pegmatite with a U-Pb zircon age of 425 ± 5 Ma (Kirkland et al., 2006a). This shows that the ages of garnet 1 growth in the two inter-kinematic age dated samples (463 ± 17 Ma and $> 447.6 \pm 2.3$ Ma) fall into the period between the two deformation events reported for the KNC in the literature. The maximum age for the post-kinematic garnet 2 in sample 45FH18 (428.9 ± 2.3 Ma) overlaps with the D2 deformation during the Scandian collision [431 - 428 Ma (Kirkland et al., 2006a)]. However, the minimum age for garnet 2 growth is constrained by cooling after the Scandian collision. The closure temperature for Ar-Ar in muscovite was reached at 422 ± 2 Ma in the KNC and at 413 ± 3 Ma for Rb-Sr in biotite of the KNC and the overlying Mageroy Nappe (Kirkland et al., 2007a).

Based on the ages obtained in the current study, it is hard to estimate the duration of the growth hiatus between garnet 1 and garnet 2, as apparent from textural evidence and discontinuous P-T paths in some samples, as the duration of garnet 1 growth is unknown. However, the seemingly continuous P-T paths for 45HF18 requires the hiatus to be of short duration as no cooling is observed. This is in agreement with the short duration of

the D2 deformation between the inter-kinematic garnet 1 and the post-kinematic garnet 2 of the sample. For samples 40HF18, 88/83, 14/92 and 46HF18 with inter-kinematic garnet 1 and post-kinematic garnet 2, the hiatus might have been longer as there is a jump in composition between garnet 1 and garnet 2. On the other hand, for sample 86/83 and 41HF18 with at least partly syn-kinematic garnet 1, the hiatus must have been shorter or nonexistent for sample 86/83 as suggested by the continuous P-T paths.

Chapter 6: Conclusions

Metamorphic garnet in metapelites from the lower nappes of the KNC in eastern Finnmark shows two growth zones, with garnet 1 forming the cores of the grains, rimmed by garnet 2, as evidenced by textural and sharp chemical discontinuities separating the two.

Thermodynamic phase equilibria and garnet growth simulations indicate a P-T path with a ~ 20 bar/ $^{\circ}\text{C}$ slope associated with garnet 1 growth. The conditions for initial garnet 1 growth span an interval of ~ 20 $^{\circ}\text{C}$ and 2250 bar from 505 $^{\circ}\text{C}$ to 525 $^{\circ}\text{C}$ and 3250 bar to 5500 bar, respectively. The pressure increases systematically down the nappe pile except for two samples from northern Sværholthalsvøya. Final growth of garnet 1 occurred at P-T conditions of 538 $^{\circ}\text{C}$ to 572 $^{\circ}\text{C}$ and 4050 bar to 6675 bar, spanning ~ 35 $^{\circ}\text{C}$ and ~ 2600 bar. Growth of garnet 2 is marked by a steep increase in the grossular content and a decrease in the almandine content interpreted here to reflect a near isothermal pressure increase of ~ 500 bar to 1500 bar, reaching 6900 bar.

Microtextural evidence shows that garnet 1 growth started in the inter-kinematic period between two deformation events D1 (Finnmarkian) and D2 (Scandian) and continued during D2. In higher structural levels growth of garnet 1 was inter-kinematic, whereas towards the base of the nappe pile, it was inter to syn-kinematic or completely syn-kinematic. Lu-Hf garnet whole-rock geochronology confirms this result as the age of garnet 1 in sample 28HF18 is 463 ± 17 Ma (MSDW 5.2, $n=4$) and in sample 45HF18 older than 447.6 ± 2.3 Ma ($n=2$) is older than the Scandian event reported in the literature, which happened in two phases at ~ 438 Ma and 431 – 428 Ma (Kirkland et al., 2006a; Kirkland et al., 2007a). Growth of garnet 2 was post-kinematic, overgrowing the

D2 foliation. The maximum age of garnet 2 in sample 45FH18 is determined at 428.8 ± 2.3 Ma (n=2), which coincides with the age of the Scandian continent-continent collision at $\sim 431 - 428$ Ma (Kirkland et al., 2006a).

In five of the modelled samples there is evidence for a hiatus in garnet growth after garnet 1 formation and prior to the crystallization of garnet 2, based on microstructural observations and or the compositional zoning of garnet developed across the garnet 1 – garnet 2 transition. This hiatus was of short duration, and temperatures did not change more than ~ 5 °C during that period. Garnet growth might have been continuous in two samples from a lower structural level (samples 38HF18 and 86/83), which lack textural evidence of a hiatus and rather point to a single growth event with a counter-clockwise metamorphic P-T path and a sharp change in the slope of the P-T path at the transition between garnet 1 and garnet 2.

Figure 114 Visual synthesis of the structural and microtextural relationships combined with the relative timing of garnet 1 and garnet 2 growth. Samples in italics are from Nordkinnhalvøya.

Appendices

Appendix A Sample locations

sample	location	Area	Latitude	Longitude
99/83	SE-Kifjord	Nordkinn	70.892441	27.31127
98/83	Kifjord	Nordkinn	70.89523	27.3417
94/83	Kifjord	Nordkinn	70.912159	27.391365
91a/83	Krampenes	Nordkinn	70.912159	27.391365
88/83	Kalak	Lebesby	70.602378	27.000917
87/83	Kalak	Lebesby	70.610122	27.037567
86/83	Bekkarfjord	Lebesby	70.600802	27.158591
28/74	Havvatnet	Porsanger		
14/92	Krampenes	Nordkinn	70.912257	27.391422
129/83	Ytre Leirpollen	Svaerholt	70.434125	25.611924
128/83	Veidnes	Svaerholt		
127/83	Veidnes	Svaerholt	70.6485	26.610086
114/83	Hoppseidet	Nordkinn	70.799153	27.710008
112b/83	Kobbevik	Nordkinn	70.803034	27.886188
01Hf18	Storbukt	Kvaløy	70.533859	24.003148
02HF18	Storbukt	Kvaløy	70.533894	24.004246
03HF18	Rypefjord	Kvaløy	70.627022	23.660427
04HF18	Masterelv	Porsanger	70.613067	24.592766
05HF18	Masterelv	Porsanger	70.613412	24.592836

06HF18	Masterelv	Porsanger	70.613214	24.592664
07HF18	Masterelv	Porsanger	70.611497	24.561888
08HF18	Masterelv	Porsanger	70.608539	24.543993
09HF18	Masterelv	Porsanger	70.608276	24.543056
10HF18	Masterelv	Porsanger	70.602981	24.527694
11HF18	Masterelv	Porsanger	70.60259	24.527803
12HF18	Kokelv	Porsanger	70.619767	24.717533
13HF18	Kokelv	Porsanger	70.6206	24.720133
14HF18	Kokelv	Porsanger	70.618083	24.74015
15HF18	Kokelv	Porsanger	70.6184	24.73605
16HF18	Lillefjord	Porsanger	70.678483	24.620167
17HF18	Lillefjord	Porsanger	70.678667	24.620217
18HF18	Lillefjord	Porsanger	70.688083	24.603483
19HF19	Snøfjord	Porsanger	70.828517	24.634733
20HF18	Snøfjord	Porsanger	70.84655	24.68935
21HF18	Nordkapphalvøya	Margerøy	71.106966	25.730768
22HF18	Jalgavárri	Margerøy	71.021686	25.71343
23HF18	Kafjord	Porsanger	70.887159	25.707645
24HF18	Repparfjord	Porsanger	70.495134	24.276023
25HF18	Repparfjord	Porsanger	70.495134	24.276023
26HF18	Repparfjord	Porsanger	70.495132	24.276024
27HF1	Svaerholtklubben	Svaerholt	70.962922	26.688147

28HF18	Svaerholtklubben	Svaerholt	70.962758	26.689091
29HF18	N-Svaerholt	Svaerholt	70.944515	26.710798
30HF18	Risvikklubben	Svaerholt	70.91357	26.714898
31HF18	Risvikklubben	Svaerholt	70.91357	26.714898
32HF18	Tømmervikklubben	Svaerholt	70.82899	26.722264
33HF18	Veidgamklubben	Svaerholt	70.743756	26.669865
34HF18	Stordalen	Lebesby	70.502566	26.554761
35HF18	Stordalen	Lebesby	70.50226	26.554967
36HF18	Fossvikneset	Lebesby	70.529807	26.575411
37HF18	Fossvikneset	Lebesby	70.529867	26.575533
38HF18	Masterneset	Lebesby	70.559025	26.601604
39HF18	Masterneset	Lebesby	70.559025	26.601604
40HF18	Veidnes	Svaerholt	70.649528	26.632971
41HF18	Bekkarfjord	Lebesby	70.603585	27.123054
42HF18	Gamvik	Nordkinn	71.064238	28.261301
43HF18	Slettnes	Nordkinn	71.08787	28.207537
44HF18	Skjånes	Nordkinn	70.801172	28.112317
45HF18	Kobbevik	Nordkinn	70.804184	27.881142
46HF18	Krampenes	Nordkinn	70.912133	27.391717
47HF18	Krampenes	Nordkinn	70.912143	27.391798
48HF18	Kifjord	Nordkinn	70.895013	27.339511
49HF18	Kifjord	Nordkinn	70.895167	27.337611

50HH18	Kifjord	Nordkinn	70.89508	27.338522
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Appendix B XR- μ CT scanning parameters

sample	scan #	pixelsize μm	voxelsize μm^3
99/83	CT_391	19.588937	7.5168E+03
98/83	CT_381	16.349448	4.3703E+03
94/83	CT_388	18.481274	6.3124E+03
91a/83	CT_386	18.125118	5.9545E+03
88/83	CT_378	11.729641	1.6138E+03
87/83	CT_390	18.83743	6.6844E+03
86/83	CT_385	13.861467	2.6633E+03
28/74	CT_387	13.50531	2.4633E+03
14/92	CT_379	16.349448	4.3703E+03
129/83	CT_380	18.125118	5.9545E+03
128/83	CT_383	11.017329	1.3373E+03
127/83	CT_382	17.770665	5.6119E+03
114/83	CT_375	11.729641	1.6138E+03
112b/83	CT_374	12.084093	1.7646E+03
108/83	CT_392	17.414509	5.2812E+03
131/83	CT_389	19.58837	7.5161E+03
01Hf18	CT_452	17.770665	5.6119E+03
02HF18	CT_407	17.060057	4.9653E+03
20aHF18	CT_403	16.349448	4.3703E+03

22HF18	CT_402	15.993292	4.0909E+03
28HF18	CT_471	17.060057	4.9653E+03
40HF18	CT_453	17.060057	4.9653E+03
45HF18	CT_472	16.349448	4.3703E+03
46HF18	CT_470	16.349448	4.3703E+03

Appendix C Elementary separation protocol

Separation of HFSE from HREE

Step	Reagent	Volume
Conditionning	1M HCl - 0.1M HF	20 mL
Load and collect HFSE	1M HCl - 0.1M HF	5 mL
Collect HFSE	1M HCl - 0.1M HF	4 mL
Elute (Ti, Zr, Ta)	1M HCl - 0.1M HF	2 mL
Rinse (Rb-Sr)	HCl 2.5N	42 mL
Collect HREE	HCl 4N	10 mL
Wash	back wash H ₂ O	10 mL
	HF 2N	full reservoir
		2 full
	HCl 6N	reservoirs
	back wash H ₂ O	10 mL

Separation of Hf from HFSE

Steps	Reagent	Volume
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Conditioning	HCl 2.5N	5mL
Load HFSE	HCl 2.5N	5 mL
Rinse	HCl 2.5N	10 mL
	HCl 6N	10 mL
	H ₂ O	4 mL
Rinse (Ti)	HCit 0.09M-HNO ₃ 0.45M- 1wt%H ₂ O ₂	60 mL
Wash H ₂ O ₂	HCit 0.09M-HNO ₃ 0.45M	5 mL
Rinse HCit	HCl 6M-HF 0.06M	25 mL
Collect Hf	HCl 6M-HF 0.4M	13 mL
Wash H ₂ O ₂	HF 2N	10 mL
	HCl 6N	10 mL
	HCl 0.2N	full reservoir

Separation of Lu from HREE

Steps	Reagent	Volume
Conditioning	HCl 2.5N	5 mL
Load HREE	HCl 2.5N	250 µL
Rinse	HCl 2.5N	250 µL
	HCl 6N	30 mL
Collect Lu	HCl 6N	5 mL
Wash	HCl 6N	full reservoir
Rinse	HCl 0.2N	15 mL

Appendix D Thermodynamic database

tcd55c2_COH

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O	AL	BA	C	CA	CL	CO
CU	F	FE	H	K	MN	MG
NA	NI	P	S	SI	SR	TI
ZN	ZR	B	E			

15.99940 26.98154 137.32700 12.01100 40.07800 35.45270 58.93320

63.54600 18.99840 55.84700 1.00794 39.09830 54.93085 24.30500

22.98977 58.69000 30.97362 32.06600 28.08550 87.62000 47.88000

65.39000 91.22400 10.81000 1.00000

0.0 1.5 1.0 2.0 1.0 0.0 1.0

1.0 0.0 1.0 0.5 0.5 1.0 1.0

0.5 1.0 1.0 0.0 2.0 1.0 2.0

1.0 2.0 0.0 0.0

****MINERAL DATA***** from Holland and Powell (1998+)

pyrope SI(3)AL(2)MG(3)O(12) py 3nh

ST 0.0 -6284720.000 266.3000 11.3180

C3 633.50000 0.0000000 -5196100.0 -4315.200 0.00

VHP 0.000043600 1737.0 0.0000 0.00 0.00000

VH2 10.0000 4.0000 -0.000260550

almandine SI(3)AL(2)FE(3)O(12) alm 3nh

ST 0.0 -5263520.000 340.0000 11.5110

C3	677.30000	0.0000000	-3772700.0	-5044.000	0.00
VHP	0.000040300	1690.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000253500		
spessartine SI(3)AL(2)MN(3)O(12) spss 3nh					
ST	0.0	-5646400.000	367.0000	11.7920	
C3	584.60000	-0.0015930	-7516700.0	-2750.100	0.00
VHP	0.000046200	1790.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000268500		
grossular SI(3)AL(2)CA(3)O(12) gr 3nh					
ST	0.0	-6644150.000	255.0000	12.5350!	
C3	626.00000	0.0000000	-5779200.0	-4002.900	0.00
VHP	0.000039300	1680.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000252000		
andalusite SI(1)AL(2)O(5) and 1nh					
ST	0.0	-2588800.000	92.7000	5.1530	
C3	277.30000	-0.0065880	-1914100.0	-2265.600	0.00
VHP	0.000041100	1334.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000200100		
kyanite SI(1)AL(2)O(5) ky 1nh					
ST	0.0	-2593110.000	83.5000	4.4140	
C3	279.40000	-0.0071240	-2055600.0	-2289.400	0.00
VHP	0.000040400	1590.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000238500		

sillimanite	SI(1)AL(2)O(5)	sill	1nh		
ST	0.0	-2585680.000	95.5000	4.9860	
C3	280.20000	-0.0069000	-1375700.0	-2399.400	0.00
VHP	0.000022100	1320.0	2200.0000	4.00	0.03500
VH2	10.0000	4.0000	-0.000198000		
Mg-staurolite	SI(7.5)AL(18)MG(4)O(48)H(4)	mst	4nh		
ST	0.0	-25101490.000	910.0000	44.2600	
C3	2820.50000	-0.0593660	-13774000.0	-24126.000	0.00
VHP	0.000012000	1200.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000180000		
Fe-staurolite	SI(7.5)AL(18)FE(4)O(48)H(4)	fst	4nh		
ST	0.0	-23753930.000	1010.0000	44.8800	
C3	2880.00000	-0.0565950	-10642000.0	-25373.000	0.00
VHP	0.000012000	1200.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000180000		
Mn-staurolite	SI(7.5)AL(18)MN(4)O(48)H(4)	mnst	4nh		
ST	0.0	-24203880.000	1024.0000	45.4600	
C3	2873.30000	-0.0890640	-12688000.0	-24749.000	0.00
VHP	0.000012000	1200.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000180000		
Mg-chloritoid	SI(1)AL(2)MG(1)O(7)H(2)	mctd	1nh		
ST	0.0	-3551420.000	140.0000	6.8750	
C3	464.40000	-0.0126540	-1147200.0	-4341.000	0.00

VHP	0.000054200	1465.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000219750		
Fe-chloritoid	SI(1)AL(2)FE(1)O(7)H(2)			fctd	1nh
ST	0.0	-3215380.000	155.0000	6.9800	
C3	484.60000	-0.0138080	-198900.0	-4762.200	0.00
VHP	0.000054200	1465.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000219750		
Mn-chloritoid	SI(1)AL(2)MN(1)O(7)H(2)			mnctd	1nh
ST	0.0	-3329280.000	166.0000	7.1750	
C3	464.40000	-0.0126540	-1147200.0	-4341.000	0.00
VHP	0.000054200	1465.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000219750		
clinozoisite	SI(3)AL(3)CA(2)O(13)H(1)			czo	1nh
ST	0.0	-6898150.000	301.0000	13.6300	
C3	567.00000	0.0180630	-7034000.0	-2603.000	0.00
VHP	0.000046000	1120.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000168000		
Fe-epidote	SI(3)AL(1)FE(2)CA(2)O(13)H(1)			fep	2nh
ST	0.0	-6002180.000	357.0000	14.1900	
C3	520.10000	0.0314990	-15426000.0	218.800	0.00
VHP	0.000050500	1294.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000199280		
epidote	SI(3)AL(2)FE(1)CA(2)O(13)H(1)			ep	2nh

ST	0.0	-6463210.000	328.0000	13.9100	
C3	544.60000	0.0247810	-11230000.0	-1192.100	0.00
VHP	0.000050500	1233.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000184950		
cordierite	SI(5)AL(4)MG(2)O(18)	crd	1nh		
ST	0.0	-9163370.000	407.5000	23.3220	
C3	821.30000	0.0433390	-8211200.0	-5000.000	0.00
VHP	0.000007600	810.0	1800.0000	20.00	0.20000
VH2	10.0000	4.0000	-0.000121500		
Fe-cordierite	SI(5)AL(4)FE(2)O(18)	fcrd	2nh		
ST	0.0	-8436070.000	475.0000	23.7100	
C3	851.50000	0.0447240	-6645000.0	-5623.400	0.00
VHP	0.000007600	810.0	1800.0000	20.00	0.20000
VH2	10.0000	4.0000	-0.000121500		
Mn-cordierite	SI(5)AL(4)MN(2)O(18)	mncrd	1nh		
ST	0.0	-8681180.000	475.0000	24.0270	
C3	847.70000	0.0284900	-7668200.0	-5311.400	0.00
VHP	0.000007600	810.0	1800.0000	20.00	0.20000
VH2	10.0000	4.0000	-0.000121500		
phase-A	SI(2)MG(7)O(14)H(6)	phA	7nh		
ST	0.0	-7130410.000	350.0000	15.4420	
C3	964.00000	-0.0115210	-4517800.0	-7724.700	0.00
VHP	0.000082600	1450.0	0.0000	0.00	0.00000

VH2	10.0000	4.0000	-0.000217500		
Mg-carpholite	SI(2)AL(2)MG(1)O(10)H(4)	mcar	1nh		
ST	0.0	-4781240.000	210.0000	10.5900	
C3	667.80000	-0.0125590	-1167100.0	-6440.000	0.00
VHP	0.000050000	525.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000078750		
Fe-carpholite	SI(2)AL(2)FE(1)O(10)H(4)	fcar	1nh		
ST	0.0	-4413200.000	255.0000	10.6900	
C3	674.80000	-0.0100920	-715800.0	-6554.500	0.00
VHP	0.000050000	525.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000078750		
muscovite	SI(3)AL(3)K(1)O(12)H(2)	mu	2nh		
ST	0.0	-5984180.000	292.0000	14.0830	
C3	756.40000	-0.0198400	-2170000.0	-6979.200	0.00
VHP	0.000059600	490.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000073500		
celadonite	SI(4)AL(1)MG(1)K(1)O(12)H(2)	cel	1nh		
ST	0.0	-5842420.000	290.0000	13.9570	
C3	741.20000	-0.0187480	-2368800.0	-6616.900	0.00
VHP	0.000059600	700.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000105000		
Fe-celadonite	SI(4)AL(1)FE(1)K(1)O(12)H(2)	fcel	1nh		
ST	0.0	-5477430.000	329.0000	14.0700	

C3	756.30000	-0.0191470	-1586100.0	-6928.700	0.00
VHP	0.000059600	700.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000105000		
paragonite	SI(3)AL(3)NA(1)O(12)H(2)	pa	1nh		
ST	0.0	-5946340.000	276.0000	13.2110	
C3	803.00000	-0.0315800	217000.0	-8151.000	0.00
VHP	0.000077400	550.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000082500		
margarite	SI(2)AL(4)CA(1)O(12)H(2)	mrg	1nh		
ST	0.0	-6241230.000	267.0000	12.9640	
C3	744.40000	-0.0168000	-2074400.0	-6783.200	0.00
VHP	0.000048700	1300.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000195000		
phlogopite	SI(3)AL(1)MG(3)K(1)O(12)H(2)	phl	2nh		
ST	0.0	-6219160.000	328.0000	14.9640	
C3	770.30000	-0.0369390	-2328900.0	-6531.600	0.00
VHP	0.000057900	513.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000076950		
annite	SI(3)AL(1)FE(3)K(1)O(12)H(2)	ann	3nh		
ST	0.0	-5151670.000	418.0000	15.4320	
C3	815.70000	-0.0348610	19800.0	-7466.700	0.00
VHP	0.000057900	513.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000076950		

Mn-biotite	SI(3)AL(1)MN(3)K(1)O(12)H(2)				mnbi	2nh
ST	0.0	-5462840.000	433.0000	15.2640		
C3	809.90000	-0.0592130	-1514400.0	-6998.700	0.00	
VHP	0.000057900	513.0	0.0000	0.00	0.00000	
VH2	10.0000	4.0000	-0.000076950			
eastonite	SI(2)AL(3)MG(2)K(1)O(12)H(2)				east	2nh
ST	0.0	-6338170.000	318.0000	14.7380		
C3	785.50000	-0.0380310	-2130300.0	-6893.700	0.00	
VHP	0.000057900	513.0	0.0000	0.00	0.00000	
VH2	10.0000	4.0000	-0.000076950			
Na-phlogopite	SI(3)AL(1)MG(3)NA(1)O(12)H(2)				naph	1nh
ST	0.0	-6172820.000	318.0000	14.4500		
C3	773.50000	-0.0402290	-2597900.0	-6512.600	0.00	
VHP	0.000057900	513.0	0.0000	0.00	0.00000	
VH2	10.0000	4.0000	-0.000076950			
clinochlore	SI(3)AL(2)MG(5)O(18)H(8)				clin	2nh
ST	0.0	-8912410.000	430.5000	21.0900		
C3	1161.80000	0.0101330	-7657300.0	-9690.900	0.00	
VHP	0.000039800	870.0	0.0000	0.00	0.00000	
VH2	10.0000	4.0000	-0.000130500			
amesite	SI(2)AL(4)MG(4)O(18)H(8)				ames	2nh
ST	0.0	-9034440.000	410.0000	20.5200		
C3	1177.00000	0.0090410	-7458700.0	-10053.000	0.00	

VHP	0.000039800	870.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000130500		
daphnite	SI(3)AL(2)FE(5)O(18)H(8)		daph	3nh	
ST	0.0	-7134850.000	565.0000	21.3400	
C3	1237.40000	0.0135940	-3743000.0	-11250.000	0.00
VHP	0.000039800	870.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000130500		
Mn-chlorite	SI(3)AL(2)MN(5)O(18)H(8)		mnchl	2nh	
ST	0.0	-7666530.000	595.0000	22.5900	
C3	1227.80000	-0.0269900	-6299800.0	-10469.400	0.00
VHP	0.000039800	870.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000130500		
high-albite	SI(3)AL(1)NA(1)O(8)		abh	1nh	
ST	0.0	-3924800.000	223.4000	10.1090	
C3	452.00000	-0.0133640	-1275900.0	-3953.600	0.00
VHP	0.000045600	593.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000088950		
microcline	SI(3)AL(1)K(1)O(8)		mic	1nh	
ST	0.0	-3975110.000	216.0000	10.8920	
C3	448.80000	-0.0100750	-1007300.0	-3973.100	0.00
VHP	0.000033500	574.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000086100		
sanidine	SI(3)AL(1)K(1)O(8)		san	1nh	

ST	0.0	-3964960.000	230.0000	10.9000	
C3	448.80000	-0.0100750	-1007300.0	-3973.100	0.00
VHP	0.000033500	574.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000086100		
anorthite	SI(2)AL(2)CA(1)O(8)	an	+1nh		
ST	0.0	-4233480.000	200.0000	10.0790	
C3	371.60000	0.0126150	-4110200.0	-2038.400	0.00
VHP	0.000023800	919.0	2300.0000	11.00	0.05000
VH2	10.0000	4.0000	-0.000137850		
quartz	SI(1)O(2)	q	1nh		
ST	0.0	-910830.000	41.5000	2.2688	
C3	110.70000	-0.0051890	0.0	-1128.300	0.00
VHP	0.000006500	750.0	847.0000	4.95	0.11880
VH2	10.0000	4.0000	-0.000112500		
rutile	Ti(1)O(2)	rt	1nh		
ST	0.0	-944180.000	50.6000	1.8820	
C3	90.40000	0.0029000	0.0	-623.800	0.00
VHP	0.000044300	2225.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000333750		
hematite	FE(2)O(3)	hem	2nh		
ST	0.0	-825710.000	87.4000	3.0274	
C3	163.90000	0.0000000	-2257200.0	-657.600	0.00
VHP	0.000059900	1996.0	955.0000	15.60	0.00000

VH2	10.0000	4.0000	-0.000299400		
pyrophanite	Ti(1)MN(1)O(3)	pnt	1nh		
ST	0.0	-1359240.000	104.9000	3.2880	
C3	141.90000	0.0033730	-1940700.0	-407.600	0.00
VHP	0.000049500	1770.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000265500		
geikielite	Ti(1)MG(1)O(3)	geik	1nh		
ST	0.0	-1567490.000	74.6000	3.0860	
C3	151.00000	0.0000000	-1890400.0	-652.200	0.00
VHP	0.000049500	1770.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000265500		
ilmenite	Ti(1)FE(1)O(3)	ilm	1nh		
ST	0.0	-1231300.000	108.9000	3.1690	
C3	138.90000	0.0050810	-1288800.0	-463.700	0.00
VHP	0.000049500	1770.0	1900.0000	11.00	0.02000
VH2	10.0000	4.0000	-0.000265500		
magnetite	FE(3)O(4)	mt	2nh		
ST	0.0	-1115510.000	146.1000	4.4520	
C3	262.50000	-0.0072040	-1926200.0	-1655.700	0.00
VHP	0.000069600	1850.0	848.0000	35.00	0.00000
VH2	10.0000	4.0000	-0.000277500		
graphite	C(1)	gph	1nh		
ST	0.0	0.000	5.8500	0.5298	

C3	51.00000	-0.0044280	488600.0	-805.500	0.00
VHP	0.000048400	390.0	0.0000	0.00	0.00000
VH2	10.0000	4.0000	-0.000058500		

!

***** GAS DATA *****

Water H(2)O(1) H2O nh

SPC HHP98

ST	0.0	-241810.000	188.8000	0.0000
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C3	40.10000	0.0086560	487500.0	-251.200	0.00
----	----------	-----------	----------	----------	------

Carbon-dioxide C(1)O(2) CO2 nh

SPC CHP98

ST	0.0	-393510.000	213.7000	0.0000
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C3	87.80000	-0.0026440	706400.0	-998.900	0.00
----	----------	------------	----------	----------	------

CO C(1)O(1) CO use

ST	0.0	-110530.000	197.6700	0.0000
----	-----	-------------	----------	--------

C3	45.70000	-0.0000970	662700.0	-414.700	0.00
----	----------	------------	----------	----------	------

CS2	0.03498700	132.900
-----	------------	---------

CH4 C(1)H(4) CH4 use

ST	0.0	-74810.000	186.2600	0.0000
----	-----	------------	----------	--------

C3	150.10000	0.0020620	3427700.0	-2650.400	0.00
----	-----------	-----------	-----------	-----------	------

CS2	0.046000	190.600
-----	----------	---------

***** SOLUTION DATA *****

FLUID3 (SITE,MARGULES) M(1):H2O,H2S,CH4,CO2,S2,O2,H2,CO

```

Water      H2O      -1.0  0.0  0.0

H2S        H2S      -1.0  0.0  0.0

CH4         CH4      -1.0  0.0  0.0

Carbon-dioxide  CO2    -1.0  0.0  0.0

S2          S2      -1.0  0.0  0.0

O2          O2      -1.0  0.0  0.0

H2          H2      -1.0  0.0  0.0

CO          CO      -1.0  0.0  0.0

!

****MINERAL DATA****Baldwin et al. (05)

anorthiteC1      CA(1)AL(2)SI(2)O(8)  anc1      nh

ST              0.0    7030.000      4.6600      0.0000

COM anorthite[1]  0    anorthite

!

***** SOLUTION DATA *****

FSP (MARGULES,IDEAL) M(1):Na,K,Ca

sanidine      K      1.0    0    0

high-albite   Na      0.643  0    0

anorthiteC1   Ca      1.0    0    0

!

***** MARGULES PARAMETER *****

high-albite - anorthiteC1

12    3100.    0.00    0.00

```

sanidine - high-albite

12 25100. 10.80 0.338

sanidine - anorthiteC1

12 40000. 0.00 0.00

!

***** SOLUTION DATA *****

ILM (IDEAL)

ilmenite

geikielite

pyrophanite

!

***** SOLUTION DATA ***** Gt(HP) in PerpleX (Connolly, 05)

GARNET (MARGULES,IDEAL)3 M(3):Ca,Mg,Fe,Mn

grossular Ca,Ca,Ca - Al,Al

pyrope Mg,Mg,Mg - Al,Al

almandine Fe,Fe,Fe - Al,Al

spessartine Mn,Mn,Mn - Al,Al

!

***** MARGULES PARAMETER *****

pyrope - grossular

12 33000. 0.00 0.00

pyrope - almandine

12 2500. 0.00 0.00

pyrope - spessartine

12 4500. 0.00 0.00

almandine - spessartine

12 240. 0.00 0.00

!

***** SOLUTION DATA ***** White et al. (00) + Mn-end-member

Cld (IDEAL,MARGULES) M(1):Mn,Mg,Fe

Mg-chloritoid Mg

Fe-chloritoid Fe

Mn-chloritoid Mn

***** MARGULES PARAMETER *****

Mg-chloritoid - Fe-chloritoid

12 1000. 0.00 0.00

!

***** SOLUTION DATA ***** Gaidies et al. (08)

CHL (-SITE,MARGULES) M23(4):Mg,Fe,Mn - M1(1):Mg,Fe,Al,Mn -

M4(1):Mg,Al,Fe,Mn - T1(2):Si,Al

clinochlore Mg,Mg,Mg,Mg - Mg - Al - Al,Si

daphnite Fe,Fe,Fe,Fe - Fe - Al - Al,Si

amesite Mg,Mg,Mg,Mg - Al - Al - Al,Al

Mn-chlorite Mn,Mn,Mn,Mn - Mn - Al - Al,Si

***** MARGULES PARAMETER *****

clinochlore - daphnite

12 2500.0 0.0 0.0

clinochlore - amesite

12 18000.0 0.0 0.0

daphnite - amesite

12 13500.0 0.0 0.0

!

***** SOLUTION DATA ***** Coggon and Holland (02)

WM (-SITE,MARGULES) A(1):K,Na - M2A(1):Al,Mg,Fe - T1(2):Al,Si

muscovite K - Al - Al,Si 0.63 0.0 0.0

celadonite K - Mg - Si,Si 0.63 0.0 0.0

Fe-celadonite K - Fe - Si,Si 0.63 0.0 0.0

paragonite Na - Al - Al,Si 0.37 0.0 0.0

!

***** MARGULES PARAMETER *****

muscovite - paragonite

12 10120. -3.40 0.353

muscovite - celadonite

12 0. 0.00 0.200

muscovite - Fe-celadonite

12 0. 0.00 0.200

paragonite - celadonite

12 52000. 0.00 0.000

paragonite - Fe-celadonite

12 52000. 0.00 0.000

!

****MINERAL DATA**** White et al. (2005) without Ti-end-member

obiotite K(1)MG(2)FE(1)AL(1)SI(3)O(12)H(2) obi xnh

ST 0.0 -10730.000 0.0000 0.0000

COM phlogopite[2/3]annite[1/3]

!

***** SOLUTION DATA *****

BT (-SITE,MARGULES) M2(2):Mg,Fe,Mn - M1(1):Mg,Fe,Al,Mn - T1(2):Si,Al

phlogopite Mg,Mg - Mg - Al,Si

annite Fe,Fe - Fe - Al,Si

eastonite Mg,Mg - Al - Al,Al

obiotite Mg,Mg - Fe - Al,Si

Mn-biotite Mn,Mn - Mn - Al,Si

!

***** MARGULES PARAMETER *****

phlogopite - annite

12 9000.0 0.0 0.0

phlogopite - eastonite

12 10000.0 0.0 0.0

phlogopite - obiotite

12 3000.0 0.0 0.0

annite - eastonite

12 -1000.0 0.0 0.0

annite - obiotite

12 6000.0 0.0 0.0

eastonite - obiotite

12 10000.0 0.0 0.0

!

***** SOLUTION DATA ***** Holland and Powell (98) extended to Mn-end-member

ST (IDEAL,MARGULES)4 M(4):Fe,Mg,Mn

Mg-staurolite Mg,Mg,Mg,Mg

Fe-staurolite Fe,Fe,Fe,Fe

Mn-staurolite Mn,Mn,Mn,Mn

***** MARGULES PARAMETER *****

Mg-staurolite - Fe-staurolite

12 -8000.0 0.0 0.0

Appendix E Petrography

Microphotograph of sample 49HF18 showing texturally sector zoned garnet in a metadolerite dike intruding the metapelites in Krampenes near samples 14/92 and 46HF18.

Appendix F Garnet compositional zoning

Compositional zoning profile of selected garnet grains in sample 28HF18.

Y-zoning profile for garnet in sample 32HF18.

Y-zoning profile for selected garnet grains in sample 38HF18.

Y-zoning profile for selected garnets in sample 35HF18.

Y-zoning profile for garnet in sample 41HF18.

Appendix G Whole-rock chemistry

Whole-rock chemistry

Method	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES	ICP-AES		
element	SiO2	Al2O3	Fe2O3	CaO	MgO	Na2O	K2O	Cr2O3	TiO2	MnO	P2O5	SrO	BaO	Total	LOI
unit	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
14_92	58.9	19.15	10.25	0.7	1.69	1.87	3.92	0.011	1.13	0.3	0.07	0.02	0.09	100.2	2.1
01HF18	60.4	20.1	8.7	1.14	2.04	1.99	3.46	0.009	0.97	0.11	0.17	0.02	0.07	101.16	1.98
02HF18	60.5	19.5	8.83	1.03	2.19	1.6	3.76	0.01	0.85	0.17	0.18	0.01	0.08	101.38	2.67
04HF18	69.5	13.1	4.68	2.65	2.4	0.56	2.16	0.005	0.65	0.11	0.08	0.03	2.14	99.87	1.8
05HF18	67	15.7	6.04	1.49	1.75	2.96	2.8	0.007	0.81	0.07	0.17	0.03	0.07	100.74	1.84
06HF18	66.2	16.1	7.07	1.52	1.86	3.08	2.7	0.007	0.91	0.11	0.17	0.03	0.05	101.47	1.66
07HF18	60.7	17.15	9.68	1.62	2.55	2.25	3.27	0.009	0.94	0.1	0.22	0.02	0.07	100.6	2.02
08HF18	56	21.5	7.98	2.3	1.79	2.15	4.49	0.01	1.07	0.14	0.19	0.03	0.14	100.16	2.37
10HF18	59.8	20.4	8.07	0.92	2.13	1.54	3.69	0.01	1.01	0.07	0.23	0.02	0.12	99.06	1.05

11HF18	57	19.45	7.88	2.48	1.95	4.56	3.13	0.008	0.89	0.1	0.37	0.05	0.07	98.89	0.95
128_83	60	18.4	8.83	1.41	1.31	1.99	3.8	0.008	1	0.12	0.16	0.03	0.09	98.97	1.82
129_83	61.3	17.9	6.36	1.13	1.88	1.39	4.52	0.009	0.99	0.07	0.31	0.02	0.12	98.01	2.01
12HF18	61.2	20.2	7.31	1.06	1.7	2.24	3.72	0.011	0.95	0.16	0.43	0.02	0.08	101.66	2.58
14HF18	61.7	20.5	8.05	1.27	1.75	2.04	3.23	0.01	0.95	0.13	0.22	0.02	0.08	101.44	1.49
16HF18	62.7	19.4	6.36	1.57	1.74	1.83	3.87	0.007	0.91	0.09	0.47	0.02	0.09	101.52	2.46
17HF18	64.7	17.2	7.18	1.47	1.93	2.08	3.45	0.007	0.99	0.1	0.23	0.02	0.08	100.96	1.52
18HF18	65.8	17.05	5.56	1.59	1.62	2.5	3.18	0.007	0.91	0.08	0.15	0.03	0.08	100.19	1.63
20HF18	59.8	16.65	8.82	2.61	5.22	1.7	2.88	0.018	1	0.12	0.23	0.02	0.04	99.83	0.72
21HF18	61.6	14.6	7.25	5.31	4.75	2.2	1.95	0.017	0.85	0.08	0.19	0.02	0.04	99.77	0.91
22HF18	38.4	25.7	13.85	2.79	8.1	1.17	5.38	0.033	1.54	0.08	0.22	0.02	0.09	99.14	1.77
23HF18	65.7	17.05	5.52	1.36	1.57	1.92	3.16	0.008	0.88	0.06	0.16	0.02	0.07	99.71	2.23
24HF18	65.4	16.1	6.14	0.96	1.5	2.04	3.39	0.008	0.71	0.1	0.1	0.02	0.07	98.44	1.9
25HF18	67.3	15.2	5.76	1.07	1.55	2.29	3.18	0.005	0.71	0.07	0.14	0.02	0.07	99	1.63
26HF18	71.1	13.7	5.04	2.17	1.5	2.77	1.95	0.005	0.66	0.1	0.13	0.02	0.04	100	0.81

28HF18	63.7	16.6	7.58	0.67	1.61	1.1	4.45	0.006	1.02	0.1	0.16	0.02	0.09	99.03	1.92
29HF18	59.2	19.05	8.19	0.34	1.88	1.91	3.47	0.009	0.95	0.09	0.24	0.01	0.08	99.07	3.65
30HF18	67.9	15.9	5.57	0.57	1.5	2.33	3.83	0.006	0.77	0.03	0.08	0.01	0.06	100.45	1.89
31HF18	67.3	16.95	5.21	0.41	1.53	1.66	4.53	0.006	0.78	0.03	0.1	0.01	0.07	100.76	2.17
32HF18	59.2	18.85	7.51	1.24	1.97	1.76	4.58	0.008	1.14	0.08	0.3	0.02	0.12	99.28	2.5
33HF18	65.8	16.3	6.65	0.86	1.4	1.28	4.28	0.006	0.91	0.09	0.15	0.02	0.1	99.89	2.04
34HF18	66.8	17.6	4.75	0.6	1.27	1.75	3.87	0.009	0.77	0.06	0.06	0.02	0.08	100.45	2.81
35HF18	65.9	16.5	5.4	1.13	1.32	2.12	3.27	0.008	0.72	0.06	0.08	0.02	0.07	99.15	2.55
36HF18	69.5	14.35	5.03	0.83	1.18	1.06	3.91	0.006	0.71	0.06	0.23	0.01	0.08	98.78	1.82
37HF18	67.1	15	5.84	0.91	1.4	1.39	4.09	0.007	0.74	0.09	0.17	0.01	0.07	98.71	1.89
38HF18	62.1	17.25	6.8	1.73	1.94	2.09	3.93	0.008	0.92	0.08	0.22	0.03	0.11	99.1	1.89
39HF18	59.5	17.4	8.33	1.27	2.06	0.29	5.43	0.009	1.07	0.16	0.15	0.01	0.15	98.48	2.65
40HF18	65.3	15.8	7.37	1.02	1.82	1.7	3.51	0.006	0.97	0.09	0.11	0.02	0.11	99.39	1.56
41HF18	57.8	19.25	8.07	2.05	2.22	2.21	4.2	0.011	1.24	0.21	0.24	0.03	0.12	99.37	1.72
42HF18	67.7	16.1	4.54	1.81	1.24	3.01	2.62	0.007	0.84	0.13	0.17	0.03	0.06	100.23	1.97

44HF18	65.7	15.95	6.14	0.38	1.65	1.8	3.61	0.008	0.8	0.05	0.15	0.01	0.07	99.88	3.56
45HF18	60.3	17.6	7.31	1.97	2.4	2.17	3.79	0.009	1.06	0.12	0.27	0.03	0.12	99.01	1.86
46HF18	65.2	18.6	5.86	0.38	1.15	1.42	4.24	0.009	1.08	0.09	0.04	0.02	0.11	100.81	2.61
47HF18	75.5	12.15	4.66	0.69	0.92	2.42	1.84	0.005	0.71	0.06	0.03	0.02	0.04	100.32	1.27
48HF18	67.6	16.1	5.69	0.68	1.45	2.07	3.18	0.007	0.91	0.05	0.06	0.02	0.09	100.15	2.24
86_83	63.7	17.6	7.76	1.57	2.23	2.27	3.33	0.008	0.74	0.07	0.2	0.03	0.08	101.55	1.96
88_83	61.7	18.05	6.78	1.39	1.95	1.93	3.6	0.009	1	0.11	0.23	0.02	0.1	98.96	2.09

	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-	ICP-
	AES	AES	AES	AES	AES	AES	AES	AES	AES	AES	AES	AES	AES
element	Ag	As	Cd	Co	Cu	Li	Mo	Ni	Pb	Sc	Tl	Zn	
unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
14_92	<0.5	<5	<0.5	23	11	50	1	14	22	19	<10	132	
01HF18	<0.5	<5	<0.5	33	48	70	<1	34	31	19	<10	119	
02HF18	<0.5	<5	<0.5	25	61	60	<1	40	19	17	<10	110	

04HF18	<0.5	<5	0.5	10	6	20	<1	23	6	11	<10	43
05HF18	<0.5	<5	<0.5	15	26	30	<1	27	29	13	<10	91
06HF18	<0.5	<5	<0.5	16	15	30	<1	31	24	16	<10	111
07HF18	<0.5	<5	<0.5	17	39	40	<1	28	29	17	<10	101
08HF18	<0.5	<5	<0.5	17	24	50	<1	32	27	21	<10	101
10HF18	<0.5	<5	<0.5	23	8	70	<1	43	23	19	<10	133
11HF18	<0.5	7	<0.5	16	9	90	<1	29	37	17	<10	143
128_83	<0.5	<5	<0.5	18	43	40	<1	30	27	17	10	106
129_83	<0.5	<5	<0.5	18	27	30	1	34	17	17	<10	106
12HF18	<0.5	<5	<0.5	25	44	60	1	36	35	17	<10	115
14HF18	<0.5	6	<0.5	14	8	70	<1	24	27	18	10	97
16HF18	<0.5	7	<0.5	13	18	60	<1	29	25	17	10	76
17HF18	<0.5	6	<0.5	19	20	40	<1	33	22	17	<10	128
18HF18	<0.5	<5	<0.5	13	23	30	1	27	31	14	<10	111
20HF18	<0.5	<5	<0.5	23	26	50	<1	81	25	23	<10	113

21HF18	<0.5	<5	<0.5	19	17	30	<1	72	19	18	<10	104
22HF18	<0.5	<5	<0.5	30	21	90	<1	154	24	26	<10	112
23HF18	<0.5	7	<0.5	17	53	40	1	31	30	15	<10	123
24HF18	<0.5	<5	<0.5	17	42	40	<1	25	23	15	<10	88
25HF18	<0.5	<5	<0.5	12	23	40	<1	27	22	14	<10	93
26HF18	<0.5	<5	<0.5	10	13	40	<1	18	22	12	<10	66
28HF18	<0.5	<5	<0.5	18	9	40	<1	29	16	16	<10	126
29HF18	<0.5	23	<0.5	14	26	80	<1	29	25	18	<10	100
30HF18	<0.5	<5	<0.5	5	12	30	<1	8	21	14	<10	98
31HF18	<0.5	<5	<0.5	7	5	30	<1	13	20	15	<10	86
32HF18	<0.5	<5	<0.5	11	36	50	2	18	26	18	<10	94
33HF18	<0.5	<5	<0.5	16	11	30	<1	25	20	14	<10	100
34HF18	<0.5	13	<0.5	13	5	40	<1	30	24	16	<10	87
35HF18	<0.5	8	<0.5	11	23	40	1	21	26	14	<10	87
36HF18	<0.5	10	<0.5	12	14	40	<1	20	18	14	<10	78

37HF18	<0.5	14	<0.5	14	35	40	1	24	21	15	<10	92
38HF18	<0.5	20	<0.5	19	47	20	<1	32	22	17	<10	120
39HF18	<0.5	291	<0.5	28	35	20	1	37	17	18	<10	128
40HF18	<0.5	<5	<0.5	21	14	40	<1	32	22	15	<10	131
41HF18	<0.5	<5	<0.5	19	34	30	<1	35	24	20	<10	120
42HF18	<0.5	<5	<0.5	11	8	20	<1	20	29	15	<10	74
44HF18	<0.5	5	<0.5	12	25	40	<1	26	19	15	<10	96
45HF18	<0.5	<5	<0.5	20	25	30	<1	37	24	19	<10	126
46HF18	<0.5	<5	<0.5	20	11	30	<1	27	26	18	<10	90
47HF18	<0.5	<5	<0.5	13	14	20	<1	17	22	10	<10	80
48HF18	<0.5	<5	<0.5	13	25	30	1	22	23	15	<10	99
86_83	<0.5	<5	<0.5	20	119	30	1	38	27	14	<10	129
88_83	<0.5	<5	<0.5	17	22	20	1	36	19	17	<10	82

Method	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium
	borate	borate	borate	borate	borate	borate	borate	borate	borate	borate
	fusion	fusion	fusion	fusion	fusion	fusion	fusion	fusion	fusion	fusion
	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
element	Ba	Ce	Cr	Cs	Dy	Er	Eu	Ga	Gd	Hf
unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
14_92	946	21.9	90	9.84	13.15	7.51	0.68	27.6	6.09	8.1
01HF18	638	61.7	90	7.86	5.82	3.75	1.13	29	5.32	4.8
02HF18	712	94.5	80	4.92	6.4	3.75	1.43	27.4	7.95	4.1
04HF18	>10000	60.5	40	0.5	4.69	3.2	0.92	16.8	4.57	7.9
05HF18	588	106	50	6.02	7.57	4.92	1.72	21.6	8.35	8.6
06HF18	474	98.7	70	6.46	7.42	4.92	1.7	22.9	8.54	12.1
07HF18	548	29.8	60	8.05	3.73	2.94	0.56	22.2	2.48	6.2
08HF18	1085	114	70	4.66	6.76	4.45	1.71	28.6	7.52	5.8
10HF18	1055	133	100	5.67	8.45	4.33	1.63	31.5	9.46	5.8

11HF18	679	125.5	80	7.43	7.45	4.46	2.32	26.6	8.99	4.6
128_83	1015	115.5	80	4.74	8.16	4.95	2.07	31.5	9	8.4
129_83	1180	94.1	80	4.79	8.41	4.69	1.57	27.3	8.62	8.5
12HF18	649	93	80	1.13	8.34	4.88	1.44	29.1	7.66	5.4
14HF18	699	124.5	90	5.76	7.74	4.72	1.75	31.8	9.28	5.7
16HF18	844	117.5	70	4.96	10.2	6.23	1.97	29.3	11.7	8
17HF18	713	93.9	70	7.58	8.14	5.32	1.55	26.1	7.58	9.1
18HF18	677	120	50	6.4	9.56	6.18	1.83	26.2	9.73	10
20HF18	343	53.5	150	5.89	6.22	3.72	1.33	22.6	5.7	5.3
21HF18	411	40.3	150	5.38	4.82	3.08	1.24	19.5	5.21	5.3
22HF18	841	106	280	8.67	6.54	4.01	1.63	40.1	6.94	9.1
23HF18	595	147	60	6.69	11.75	7.31	2.11	27	12.2	7.9
24HF18	617	74.8	80	4.82	5.43	3.38	1.12	22.3	5.69	5.3
25HF18	653	92.3	60	5.15	6.11	4.21	1.36	21.3	7.1	6.5
26HF18	398	38.1	50	5.13	3.89	3.27	0.75	17.1	3.01	7

28HF18	827	122	70	8.28	9.64	5.52	2.15	26.6	11.2	12
29HF18	725	253	80	2.42	9.24	5.19	2.67	28.1	12.95	5.1
30HF18	582	24.3	70	5.86	3.18	2.79	0.41	23.5	1.81	7.5
31HF18	644	33.7	60	4.59	4.53	2.75	0.75	24.6	3.62	6.5
32HF18	1090	44.4	70	5.41	4.71	4.15	0.5	27.9	2.24	6.4
33HF18	982	62.4	60	6.72	5.93	3.73	1.17	21.8	4.59	6.3
34HF18	712	100	80	5.21	6.92	4.17	1.37	26.2	7.2	6.3
35HF18	631	91	70	5.56	5.88	3.63	1.43	25	6.43	5.9
36HF18	726	89.8	60	6.36	6.87	4.23	1.48	21.1	7.17	8.7
37HF18	684	88	60	6.35	7.19	4.72	1.39	21.8	7.86	7
38HF18	1010	98.4	70	5.11	7.48	5.12	1.71	26.1	8.68	6.3
39HF18	1410	122.5	80	5.48	8.8	5.37	1.97	27.6	10.1	9
40HF18	1025	100	60	7.39	6.06	3.79	1.63	25.9	6.39	6
41HF18	1020	107	70	5.56	8.58	5.87	1.7	27.2	7.95	7.7
42HF18	591	102.5	60	3.87	7.91	4.79	1.83	21.2	9.29	7.2

44HF18	693	84.9	70	5.59	6.23	3.76	1.38	22.6	6.68	7.4
45HF18	1140	99.3	70	5.49	8.23	5.29	1.74	25.5	8.45	7.2
46HF18	1040	63.2	80	6.26	7.97	5.43	1.16	26.5	6.26	7.2
47HF18	421	21.2	40	6.19	4.43	2.93	0.46	14.2	2.4	5.9
48HF18	816	85.4	60	3.67	5.4	3.2	1.61	22.2	5.78	5.8
86_83	701	72.7	60	7.5	5.8	4.2	1.29	24.7	5.74	3.9
88_83	991	90.5	80	3.81	7.98	5.54	1.27	29.1	5.8	8.1
Method	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium
	borate	borate	borate	borate	borate	borate	borate	borate	borate	borate
	fusion	fusion	ICP-fusion	ICP-fusion	ICP-fusion	ICP-fusion	ICP-fusion	ICP-fusion	ICP-fusion	ICP-fusion
	ICP-MS	MS	MS	MS	MS	MS	MS	MS	MS	MS
element	Ho	La	Lu	Nb	Nd	Pr	Rb	Sm	Sn	Sr
unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
14_92	2.69	9	1.09	21.3	9.4	2.43	191.5	2.42	4	185

01HF18	1.36	28.3	0.73	19.1	27.9	7.51	161.5	5.57	3	189.5
02HF18	1.34	47	0.68	16.8	42.4	11.1	170	8.76	3	128.5
04HF18	1.01	27	0.56	13.7	27	6.91	55.2	5.06	3	209
05HF18	1.53	51.1	0.72	15.8	49.6	12.45	145.5	10.25	2	238
06HF18	1.77	50	0.84	18.5	46.3	12.1	147	9.21	3	247
07HF18	0.92	13.2	0.51	17.3	13.7	3.61	175.5	2.8	2	177
08HF18	1.4	54.9	0.61	18.4	50.9	13.35	153	9.22	4	202
10HF18	1.7	62	0.6	21.4	55.5	15.35	161.5	11.45	4	140
11HF18	1.64	60.7	0.66	19.3	54.4	14.45	156	10.25	4	451
128_83	1.75	56.4	0.73	20.2	54.7	14.25	161	10.3	4	238
129_83	1.78	41.3	0.68	16.7	45	11.15	149.5	9.89	5	159
12HF18	1.76	42.2	0.75	19.1	38.7	10.15	137	8.72	4	182.5
14HF18	1.64	59.3	0.73	18.1	54.3	14.6	132.5	10.55	4	180.5
16HF18	2.17	55.3	0.95	20.2	55.5	14.75	163.5	11.85	4	177.5
17HF18	1.79	37.4	0.84	20.1	40.4	10.8	168.5	8.5	5	176

18HF18	1.98	55.2	0.96	20.1	56.5	14.2	171	10.75	4	223
20HF18	1.35	28.4	0.6	18.3	25.6	7.02	118	5.81	3	122.5
21HF18	1.03	16.8	0.46	13.8	18.1	4.86	104.5	4.87	2	149
22HF18	1.44	34.3	0.58	17.6	38.8	10.45	205	8.72	5	166
23HF18	2.37	72.6	1.01	19.7	67.7	17.45	165	13.2	4	202
24HF18	1.16	34.1	0.54	14	31.3	8.43	150.5	6.58	3	145
25HF18	1.44	43.5	0.68	14.6	41.4	11.15	144.5	8.42	3	174.5
26HF18	1.02	16.9	0.58	12.5	16.7	4.42	98.9	3.42	2	192.5
28HF18	2.08	63.1	0.83	21.2	58.4	15.4	185.5	12.55	5	162.5
29HF18	1.87	94.5	0.72	18.9	92.9	25.1	136.5	19	4	125
30HF18	0.88	6.2	0.46	17.2	7.3	1.82	176.5	1.7	4	100.5
31HF18	0.97	15.6	0.47	17.7	14.8	4.16	176	3.61	4	84.2
32HF18	1.34	14.3	0.66	21.5	16.9	4.23	163	3.33	4	172
33HF18	1.35	25.3	0.6	16.2	26.4	7.11	181.5	6.02	3	170
34HF18	1.44	43.4	0.59	15.9	42.1	11.55	152.5	9.25	4	129

35HF18	1.22	45	0.53	15.2	40.6	11.05	143.5	8.37	4	147.5
36HF18	1.47	44.6	0.76	16	42.1	11.3	158.5	8.72	4	105
37HF18	1.61	41.8	0.81	15.9	40.1	10.9	171	8.46	4	110
38HF18	1.84	48.7	0.85	15.3	47.7	12.45	147	9.93	4	248
39HF18	1.97	59.2	0.84	21.6	59.4	15.4	199	11.7	4	106
40HF18	1.28	46.7	0.57	18	44.3	11.8	166.5	8.4	4	173.5
41HF18	1.85	50	0.95	18.1	51.7	12.8	145.5	10.3	4	239
42HF18	1.71	52.1	0.79	14.4	49.1	12.95	109	10.5	3	270
44HF18	1.27	40.4	0.58	16.1	40.1	10.7	155	8.3	3	103
45HF18	1.73	46.9	0.9	17.8	46.5	12.55	142	9.62	4	221
46HF18	1.76	29.6	0.74	19.2	29.5	7.63	162	6.42	4	142.5
47HF18	1.08	7.1	0.46	13.4	7.7	1.98	97.8	1.76	2	181.5
48HF18	1.12	37	0.46	15.4	37	9.49	128	7.28	3	177
86_83	1.34	38.2	0.6	14.4	35	9.17	145.5	6.87	3	232
88_83	1.84	31.5	0.86	17.2	34.4	8.7	135	7.22	5	201

Method	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium	lithium
	borate	borate	borate	borate	borate	borate	borate	borate	borate	borate
	fusion	fusion	fusion	fusion	fusion	fusion	fusion	fusion	fusion	fusion
	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS	ICP-MS
element	Ta	Tb	Th	Tm	U	V	W	Y	Yb	Zr
unit	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
14_92	1.3	1.87	13.5	1.07	3.31	110	2	78.1	7.22	306
01HF18	1.2	0.93	15.65	0.6	3.37	116	2	34.7	4.75	181
02HF18	1.1	1.14	13.25	0.6	3.62	107	2	34.6	4.48	153
04HF18	1.1	0.67	7.96	0.52	2.38	68	2	28.8	3.57	323
05HF18	1	1.16	12.8	0.71	3.17	84	1	44.9	4.88	349
06HF18	1.2	1.25	13.55	0.76	2.57	100	1	45.9	5.36	472
07HF18	1	0.48	11.8	0.44	2.08	100	1	25.3	3.21	236
08HF18	1.1	1.09	14.75	0.69	4.37	110	2	40.9	4.22	225
10HF18	1.4	1.41	19.4	0.63	3.97	142	2	42.7	4.52	218

11HF18	1.3	1.34	17.65	0.66	3.93	123	2	40.1	4.77	178
128_83	1.2	1.45	13.55	0.71	4.44	127	2	45.5	5.03	315
129_83	1.1	1.44	10.7	0.68	1.67	104	3	46.4	4.6	314
12HF18	1.2	1.37	18.5	0.75	3.82	126	2	43.5	5.29	213
14HF18	1.3	1.37	18.35	0.67	3.52	132	2	40.6	4.65	220
16HF18	1.4	1.69	18.25	0.92	5.95	105	2	61.7	6.37	301
17HF18	1.4	1.32	16.05	0.83	4.7	101	2	49.7	5.64	348
18HF18	1.4	1.44	17.45	0.93	5.23	94	2	54.3	6.23	386
20HF18	1.2	1	9.35	0.57	2.21	165	2	36.1	3.98	212
21HF18	0.9	0.8	8.76	0.43	1.97	145	1	28.7	3.3	201
22HF18	1.2	1.15	17.35	0.58	4.4	277	1	32.1	4.16	350
23HF18	1.3	1.79	17.4	1	5.45	98	2	69	6.67	312
24HF18	1.1	0.9	12.95	0.5	2.83	86	2	30.4	3.39	203
25HF18	1.1	1.09	12.55	0.56	2.95	79	2	36.1	4.26	243
26HF18	0.9	0.54	8.51	0.52	1.3	79	1	26.8	4	282

28HF18	1.4	1.61	17.35	0.82	4.26	103	3	57	5.89	477
29HF18	1.2	1.86	16.65	0.71	2.3	126	2	44.6	5.25	219
30HF18	1.3	0.41	13.85	0.44	1.96	103	2	22.4	3.12	281
31HF18	1.2	0.65	13.2	0.47	1.71	106	2	25.5	3.08	254
32HF18	1.4	0.55	17.35	0.73	4.87	124	3	36.3	4.72	242
33HF18	1	0.75	9.79	0.55	1.86	98	2	34.8	4.06	253
34HF18	1.2	1.18	15.4	0.66	2.31	98	3	35.4	4.51	233
35HF18	1.1	1.04	14.3	0.52	3.05	91	2	31	3.62	224
36HF18	1.1	1.2	13.45	0.68	2.44	83	3	40.1	4.71	339
37HF18	1.1	1.17	13.75	0.76	3.26	91	44	40.5	5.64	272
38HF18	1	1.28	11.1	0.82	2.42	107	3	47.7	5.33	247
39HF18	1.1	1.52	13.85	0.86	4.61	118	2	51.3	6.06	357
40HF18	1.1	1.03	10.1	0.64	1.16	100	2	34.1	3.68	237
41HF18	1.1	1.27	14.6	0.87	4.01	132	2	48.5	6.15	301
42HF18	1	1.34	10.85	0.77	3.32	86	1	46.7	4.77	290

44HF18	1.1	1.05	12.95	0.55	3.41	78	2	34.6	3.99	288
45HF18	1.1	1.31	12.85	0.88	3	116	2	48.7	5.86	285
46HF18	1.3	1.18	12.4	0.75	3	119	2	49.2	5.14	272
47HF18	0.9	0.57	8.75	0.5	1.77	65	1	27.6	3.18	235
48HF18	1	0.95	10.4	0.44	2.53	118	2	26.4	2.97	209
86_83	0.9	0.94	11.35	0.61	1.62	99	2	35.5	4.15	148
88_83	1.2	1.14	13.15	0.79	3.2	108	3	46.4	5.58	304

Appendix H LA-ICPMS element maps

H.1 Sub-Appendix: LA-ICPMS element maps for sample 28HF18

Al₂O₃

Ba

CaO

Co

59/ppm/Log/10

555 μm

CO2

13/Wt%/Log/10

555 μm

Cr

53/ppm/Log/10

555 μm

Dy

163/ppm/Log/10

555 μm

Er

167/ppm/Log/10

555 μm

Eu

151/ppm/Log/10

555 μm

Fe

57/ppm/Log/10

555 μm

Ga

71/ppm/Log/10

555 μm

Gd

Hf

Ho

165/ppm/Log/10

555 μm

K2O

Li

7/ppm/Log/10

555 μm

Lu

175/ppm/Log/10

555 μm

MgO

Mn

Na₂O

Nb

93/ppm/Log/10

555 μm

Nd

P205

Pb 206

Pb 207

Pb 208

Pb tot

Rb

85/ppm/Log/10

555 μm

S

34/ppm/Log/10

555 μm

Sc2O3

SiO₂

Sm

147/ppm/Log/10

555 μm

Sr

88/ppm/Log/10

555 μm

Tb

Th

232/ppm/Log/10

555 μm

Ti

TIC

Tm

169/ppm/Log/10

555 μm

U

238/ppm/Log/10

555 μm

V

Y

Yb

173/ppm/Log/10

555 μm

Zn

66/ppm/Log/10

555 μm

Zr

H.2 Sub-Appendix: LA-ICPMS element maps for sample 45HF18

Al₂O₃

Ba

137/ppm/Log/10

312 μm

CaO

42/Wt%/Log/10

312 μm

Co

CO2

13/Wt%/Log/10

312 μm

Cr

53/ppm/Log/10

312 μm

Dy

163/ppm/Log/10

312 μm

Er

167/ppm/Log/10

312 μm

Eu

151/ppm/Log/10

312 μm

Fe

57/ppm/Log/10

312 μm

Ga

71/ppm/Log/10

312 μm

Gd

157/ppm/Log/10

312 μm

Hf

177/ppm/Log/10

312 μm

Ho

165/ppm/Log/10

312 μm

K2O

Li

7/ppm/Log/10

312 μm

Lu

175/ppm/Log/10

312 μm

884
471
251
134
71.2
38.0
20.2
10.8
5.74
3.06
1.63
0.869
0.463
0.247
0.131
0.07

MgO

Mn

55/ppm/Log/10

312 μm

Na2O

23/Wt%/Log/10

312 μ m

Nb

93/ppm/Log/10

312 μm

Nd

146/ppm/Log/10

312 μm

P205

31/Wt%/Log/10

312 μm

Pb tot

Rb

85/ppm/Log/10

312 μ m

S

34/ppm/Log/10

312 μm

Sc203

SiO₂

Sm

147/ppm/Log/10

312 μm

Sr

88/ppm/Log/10

312 μm

Tb

159/ppm/Log/10

312 μm

Th

232/ppm/Log/10

312 μm

Ti

TIC

Tm

169/ppm/Log/10

312 μm

U

238/ppm/Log/10

312 μm

V

51/ppm/Log/10

312 μm

Y

89/ppm/Log/10

312 μm

Yb

173/ppm/Log/10

312 μm

Zn

66/ppm/Log/10

312 μm

Zr

90/ppm/Log/10

312 μm

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