International Journal of Earth Sciences (2020) 109:1727–1742
https://doi.org/10.1007/s00531-020-01866-0

ORIGINAL PAPER

Lu–Hf geochronology of ultra-high-pressure eclogites from the Tromsø-Nappe, Scandinavian Caledonides: evidence for rapid subduction and exhumation

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Received: 19 August 2019 / Accepted: 11 April 2020 / Published online: 1 May 2020

Abstract

Geochronology of ultra-high-pressure metamorphic rocks is able to constrain the timing and rates of subduction-zone processes. Lu–Hf garnet dating has the potential to yield information about the timing of the prograde evolution of subducting rocks under increasing pressure. In combination with other methods, it thus allows constraining the complete P–T–t path with high precision. Ultra-high-pressure eclogites from the Tromsø Nappe, the structurally highest tectonic unit of the Scandinavian Caledonides in northern Norway, were dated using Lu–Hf geochronology on garnet. A sample from Tromsdalstind yielded an age of 448.3 ± 3.6 Ma, interpreted as dating prograde garnet growth due to preserved zoning in the major-element and Lu contents of garnet grains. A sample from the diamond-bearing locality Tønsvika yielded an identical age of 449.4 ± 3.3 Ma. Garnet from this sample shows a weak zoning in Ca content and near-homogeneous Lu content. These ages are identical within error among each other and with published U–Pb ages of peak-eclogite-facies zircon and rutile/titanite from exhumation-related leucosome veins. Consequently, the entire subduction–exhumation cycle leading to the ultra-high-pressure eclogites lasted only very few millions of years during the Late Ordovician.

Keywords Lu–Hf geochronology · UHP metamorphism · Garnet · Scandinavian Caledonides · Tromsø Nappe

Introduction

Ultra-high-pressure (UHP) metamorphic rocks record pressures above the quartz–coesite equilibrium line, i.e., more than ~ 2.7 GPa, reflecting either subduction to mantle depths or, alternatively, strongly non-lithostatic pressure at shallower levels. Except for a few cases (e.g., Zermatt-Saas ophiolites in the Western Alps; Reinecke 1998), exposed UHP metamorphic rocks are mostly derived from continental crust of the lower plate in a collisional setting that is entering a subduction zone after the subduction of oceanic lithosphere. The mechanisms leading to the subduction and exhumation of continental crust are a matter of scientific debate (e.g., Kurz and Froitzheim 2002; Michard et al. 1993; Warren et al. 2008). Our understanding may be promoted by the study of the pressure, temperature, structural, and temporal evolution of HP and UHP rocks, in particular eclogites. Most geochronometers, like U–Pb dating on zircon and monazite, date either the pressure peak or stages along the retrograde P–T path. As these minerals are accessory and not unambiguously part of the peak-pressure

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assemblage, they may have grown at different stages of metamorphism, but their relation to the P–T evolution can be controlled via their trace-element contents (e.g., Rubatto and Hermann 2007). Information on the prograde path can be gained from Sm–Nd and Lu–Hf dating of garnet, a member of the eclogite peak-pressure assemblage which generally grows during pressure increase (e.g., Baxter and Scherer 2013). Lu–Hf geochronology is especially suitable, since Lu strongly fractionates into garnet, so that much of Lu is incorporated into the early grown garnet cores. This leads to strong variations in Lu/Hf ratios between different garnet fractions and between garnet, omphacite, and whole rock, resulting in a good chance for well-defined isochrons dating garnet growth. The method has been successfully applied in a variety of UHP terranes including the Scandinavian Caledonides (e.g., Cutts and Smit 2018; Kylander-Clark et al. 2007). Diffusion of Lu and Hf in garnet is slow, so that the isotopic system is generally not equilibrated after the pressure peak, except if extremely high temperatures prevail for a long time span or cooling is slow. In such cases, Lu–Hf geochronology may date a stage of cooling. This may be recognized from homogeneous, diffusionally equilibrated Lu contents throughout garnet grains. In this study, we applied Lu–Hf dating to UHP eclogites from the Tromsø Nappe, the structurally highest tectonic unit of the Caledonides in Northern Norway. For these rocks, a detailed petrological study (Janák et al. 2012, 2013a, b; Ravna and Roux 2006) as well as U–Pb dating of zircon, rutile, and titanite (Corfu et al. 2003; Ravna et al. 2017) had been performed before, so that the P–T evolution and the timing of peak metamorphism and the retrograde path are well constrained, but chronological data for the prograde path are still scarce.

Geological setting and age data

Scandinavian Caledonides

The Scandinavian Caledonides represent a stack of nappes emplaced southeast to eastward onto the margin of Baltica, due to its collision with Laurentia during the Scandian phase in Silurian-to-Early Devonian time (430–400 Ma; Fossen 2010; Gee et al. 2008). The nappes are grouped into four allochthons based on their structural level in the nappe stack which, in most cases, corresponds to their palaeogeographic affiliation (Lower, Middle, Upper, and Uppermost; Gee et al. 1985; Strand and Kulling 1972). The Lower and Middle Allochthons are interpreted to be derived from proximal and distal parts of the Baltican margin, respectively. The Upper Allochthon is derived from oceanic crust and volcanic arcs of the Iapetus Ocean, and the Uppermost Allochthon from the continental margin of Laurentia. The basement of Baltica is not only exposed in the foreland; it also re-appears as large tectonic windows through the allochthons, such as the Western Gneiss Region (Fig. 1). There, the basement has been overprinted to various degrees by Caledonian deformation and metamorphism. Basement and allochthonous inliers of the Western Gneiss Region reached UHP conditions, leading to the formation of coesite (e.g., Smith 1984), diamond (Dobrzhinetskaya et al. 1995), and majoritic garnet (Scambelluri et al. 2008; Van Roermund and Drury 1998). UHP metamorphism in the Western Gneiss Region occurred at ~ 430–400 Ma (e.g., DesOrmeau et al. 2015; Griffin and Brueckner 1980; Krogh et al. 2011; Kylander-Clark et al. 2007, 2009; Terry et al. 2000), i.e., during the Scandian phase. In recent years, two more UHP metamorphic units have been identified in the allochthons. The first one is the Tromsø Nappe (Uppermost Allochthon), where thermobarometry and thermodynamic modeling (Janák et al. 2012; Ravna and Roux 2006) as well as the finding of microdiamond in gneisses (Janák et al. 2013a) indicate UHP metamorphism at ~ 452 Ma, i.e., pre-Scandian (Corfu et al. 2003). The second one is the Seve Nappe Complex in Jämtland, Västerbotten, and Norrbotten representing the upper part of the Middle Allochthon (Gee et al. 2008), where the pre-Scandian UHP metamorphism was documented by thermobarometry and thermodynamic modeling of various rock types, and the occurrence of microdiamonds (Bukała et al. 2018; Fassmer et al. 2017; Gilio et al. 2015; Janák et al. 2013b; Klonowska et al. 2016, 2017; Majka et al. 2014; Petrík et al. 2019). The tectonic framework of the pre-Scandian HP/UHP metamorphism in the allochthons is still unclear. Suggestions for the Seve Nappe Complex include subduction under an island arc (Dallmeyer and Gee 1986), a microcontinent (Roberts 2003), a composite of arc and microcontinent (Brueckner and Van Roermund 2004), or Laurentia (Gilio et al. 2015). UHP metamorphism of the Tromsø Nappe is thought to be related to the Taconian/Grampian Orogeny at the Laurentian margin (Brueckner and Van Roermund 2007; Corfu et al. 2003; Roberts and Gee 1985). Alternatively, it has been suggested that the Tromsø Nappe belonged to a part of the continental margin of Baltica, which had already been subducted before the Scandian collision, and was emplaced by an out-of-sequence thrust during the Scandian phase (Janák et al. 2012).

Tromsø Nappe

The Tromsø Nappe comprises the structurally highest unit of the Uppermost Allochthon. It is underlain by the Skattøra Migmatite Complex (Selbekk et al. 2000; Skjerlie 2002) which is part of the Nakkedal Nappe. The Skattøra Migmatite Complex consists of migmatized metagabbros crosscut by a network of anorthosite and leucodiorite dykes, the migmatites being the source of the dykes. A migmatite leucosome and a dyke gave an age of

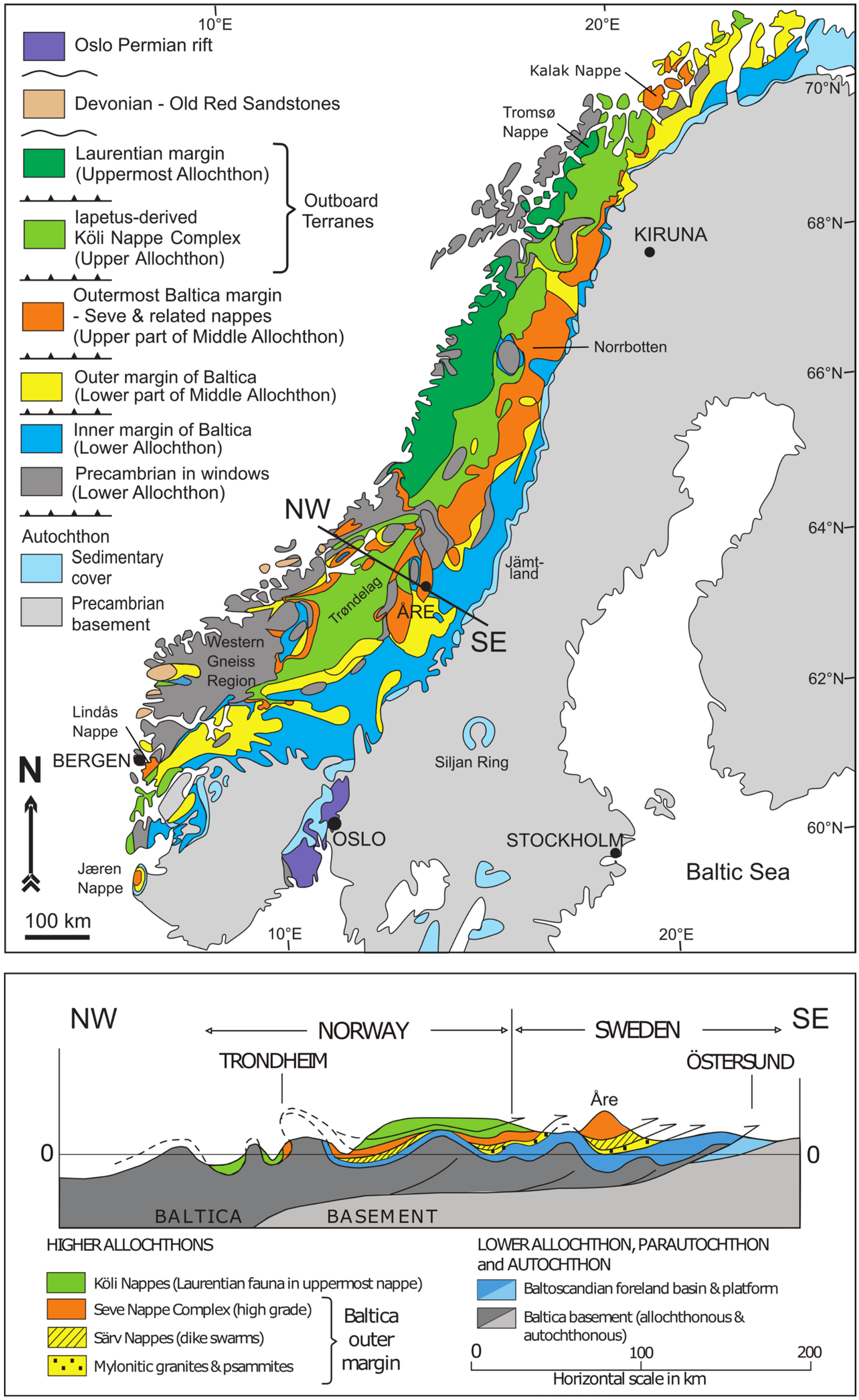

Fig. 1 Tectonostratigraphic map and cross section of the Scandinavian Caledonides after Gee et al. (2010). The black line shows the location of the cross section (vertical exaggeration × 10)

456 ± 4 Ma using U–Pb dating on titanite (Selbekk et al. 2000; Skjerlie 2002). The Skattøra Migmatite is strongly mylonitized towards its upper boundary and separated from the Tromsø Nappe by a major thrust fault (Binns 1978; Corfu et al. 2003). The Tromsø Nappe consists of partly retrogressed eclogites associated with pelitic-to-semi-pelitic schists, gneisses, marbles, calc-silicate rocks, ultramafites, and metacarbonatites (Krogh et al. 1990;

Ravna and Roux 2006; Ravna et al. 2006, 2017). There are three main localities where eclogites occur: Tønsvika, Holmevatn, and Tromsdalstind (Fig. 2).

At Tønsvika, eclogites occur as lenses within marbles, clinopyroxenites, and diamond-bearing garnet-biotite gneisses, intruded by carbonatites. Eclogite is essentially

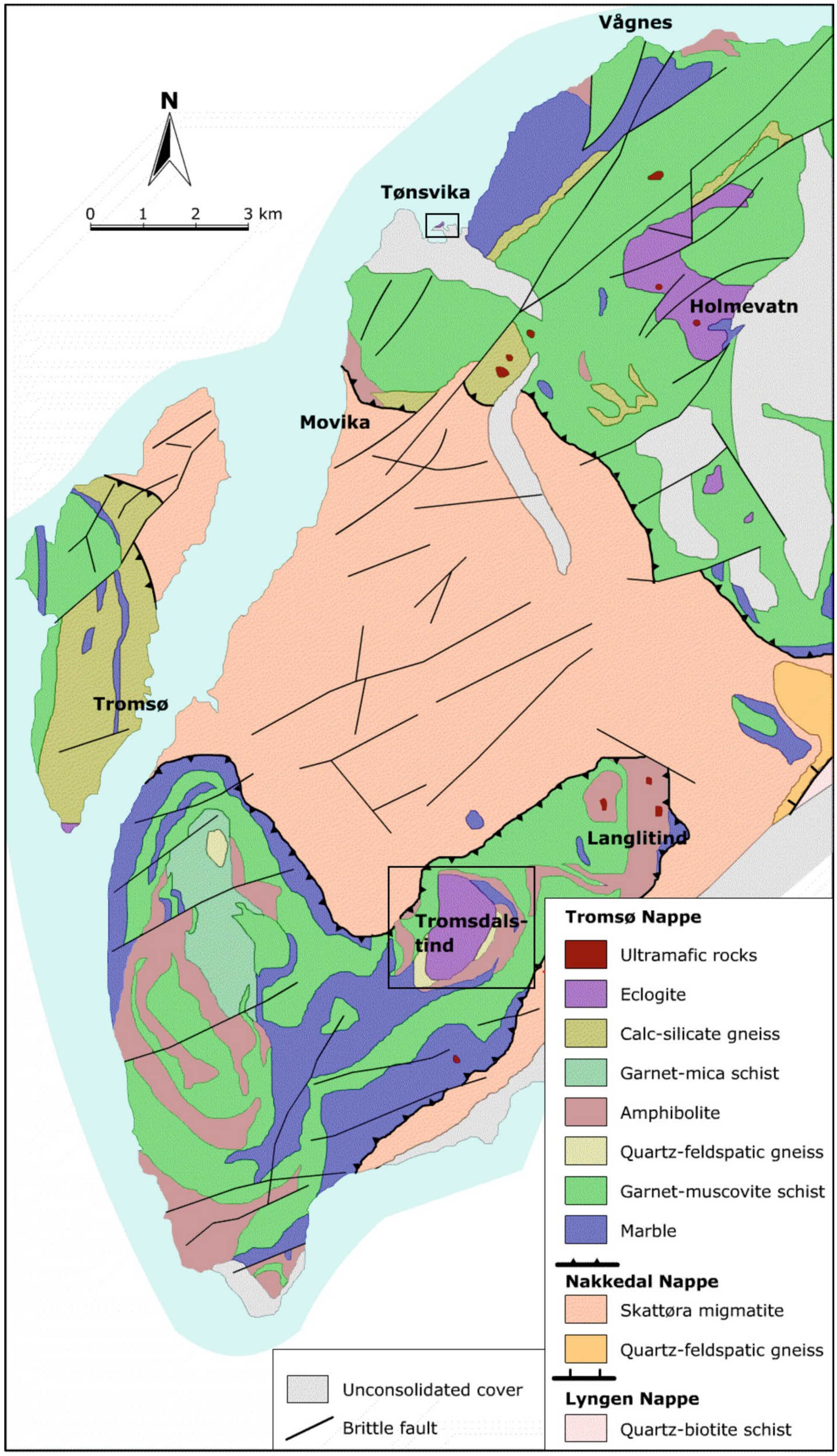

Fig. 2 Simplified geological map of the Tromsø area, modified after Zwaan et al. (1998). Black squares mark the sample areas

bi-mineralic (garnet + omphacite), with minor amphibole, white mica, rutile, carbonate, and quartz. In contact with carbonatite, the eclogite is strongly enriched in phlogopite and carbonate minerals (Ravna et al. 2017). The peak-pressure metamorphism was dated using U–Pb geochronology on zircon at 452.1 ± 1.7 Ma (Corfu et al. 2003). Peak P–T conditions of this eclogite were constrained to 3.4 GPa at 740 °C (Ravna and Roux 2006), and a diamond-bearing gneiss, sampled only a few meters away from our eclogite sample, reached 3.5 ± 0.5 GPa and 770 ± 50 °C as determined by thermodynamic modeling (Janák et al. 2013a). U–Pb–zircon dating of the carbonatite yielded ages of 454.5 ± 1.1 Ma (upper intercept age of prismatic zoned zircon) and 451.6 ± 1.7 Ma (concordia age of equant, subrounded zircons; Ravna et al. 2017). These authors proposed that the carbonatite was generated in situ by partial melting of carbonated eclogite under UHP conditions. The zircon ages of Ravna et al. (2017) thus give an additional constraint for the pressure peak of metamorphism.

At Holmevatn, chromium-rich kyanite eclogites (Janák et al. 2015) occur as layers and lenses of centimeter-to-meter size in serpentinized garnet peridotite (Ravna et al. 2006). Metamorphic P–T conditions of these rocks are ca. 2.6–3.0 GPa and 750–800 °C (Ravna et al. 2006; Janák et al. 2015). The garnet peridotite experienced two temperature maxima after peak-pressure metamorphism (Ravna et al. 2006): 750–800 °C at 1.8 GPa and > 750 °C at 1.0 GPa. The latter is considered to be related to the juxtaposition of the Tromsø Nappe onto the hot Skattøra Migmatite Complex (Krogh et al. 1990; Ravna and Roux 2006; Ravna et al. 2006; Skjerlie 2002).

At Tromsdalstind, the largest eclogite body within the Tromsø Nappe builds up the uppermost part of the mountain (Fig. 2). The mafic rocks of Tromsdalstind are interpreted to be metabasalts or gabbros, indicating a magmatically active setting (Corfu et al. 2003). Besides mafic rocks this body also contains tonalitic/trondhjemitic orthogneiss. One of those gneisses gave a protolith zircon age of 493 + 5/− 2 Ma (Corfu et al. 2003). This suggests that the intrusive activity was contemporaneous with the early generation of ophiolites and arc-related magmatism on both sides of the Iapetus Ocean (Dunning and Pedersen 1988). Corfu et al. (2003) also dated titanite and rutile in eclogites, leucosomes in eclogites, and calc-silicate rocks, giving ages between 448.8 ± 1.4 Ma and 451.0 ± 1.4 Ma that according to these authors postdate the eclogite-forming event. P–T conditions of kyanite–phengite eclogites from Tromsdalstind calculated from thermobarometry and thermodynamic modeling are 3.2–3.5 GPa at 730–780 °C (Janák et al. 2012). These UHP conditions are supported by microstructural features like polycrystalline quartz inclusions in omphacite indicating breakdown of coesite and needle-like inclusions of SiO_2 in omphacite, which may have been exsolved from Ca-Eskola clinopyroxene (Janák et al. 2012). These authors also constrained a clockwise P–T path with a maximum temperature of ca. 800 °C at 2.2–2.7 GPa (Janák et al. 2012). Heating during decompression led to partial melting which produced amphibole-bearing pegmatite veins (Corfu et al. 2003). Stevenson (2005) described two stages of migmatization of eclogite post-dating peak-pressure metamorphism. Krogh et al. (1990) proposed a second episode of metamorphism at low pressure following post-UHP decompression, involving renewed pressure increase from 0.8 GPa up to 1.0–1.1 GPa at maximum temperatures of 665 °C, which they related to an episode of thrusting and emplacement of the Nakkedal Nappe Complex onto the Lyngen Nappe Complex (Upper Allochthon).

The tight grouping of ages demonstrates that the UHP event with subsequent uplift and partial melting of eclogite happened within only a few million years (Corfu et al. 2003). To add constraints on the timing of subduction of the Tromsø Nappe, we dated UHP eclogites from Tromsdalstind and Tønsvika using Lu–Hf geochronology on garnets.

Analytical methods

XRF and electron microprobe analysis

Mechanical sample preparation was done at the Institute of Geosciences, University of Bonn (Germany). One aliquot of each eclogite sample was crushed and powdered to analyze the bulk rock composition of both eclogite samples with a PANanalytical Axios X-ray fluorescence spectrometer. The remaining aliquot was crushed for digestion and subsequent Lu and Hf separation via column chemistry to future isotope measurements. Electron microprobe analyses were carried out using a JEOL 8200 Superprobe at the Institute of Geosciences in Bonn. A beam current of 15 nA and an accelerating voltage of 15 kV were set for single spot measurements. Well-defined natural minerals (Fe-magnetite, Mg-olivine, Ca-anorthite, Na-scapolite, Si/Al-garnet, and K-sanidine) and pure metals were used as standards (Jarosewich et al. 1980). Major-element distribution maps of Ca, Mg, Fe, and Mn in garnets were obtained with a beam current of 50 nA, an accelerating voltage of 15 kV, and a measurement time of 100 ms per point.

Laser ablation analysis

The trace-element contents in selected garnet grains were measured via LA-ICP-MS using a Thermo Scientific X-Series 2 Q-ICP-MS, coupled to a Resonetics RESOlution M50-E 193 nm Excimer Laser Ablation System at the Institute of Geosciences, University of Bonn (Germany), following the procedure described in Kirchenbaur et al. (2012)

and Sandmann et al. (2014). Laser ablation spot sizes were 44 and 58 µm, depending on the garnet grain size, and 12–13 spots per garnet profile were chosen manually to avoid inclusions. Measurements were performed with a laser repetition rate of 15 Hz and a laser fluency at the sample surface of 7 J/cm^2. Nuclides of ^{29}Si, ^{43}Ca, ^{47}Ti, ^{55}Mn, ^{91}Zr, ^{177}Hf, ^{178}Hf, ^{180}Hf, and ^{175}Lu were analyzed, measuring for 15 s on the gas background and 30 s on each measured point, followed by 15 s of gas background to allow the complete washout of the sample's signal. Count rates were normalized to ^{29}Si, as the internal standard, and to NIST-612 as an external glass reference material (Jochum et al. 2011). Normalized count rates were then converted into concentrations using the procedure described by Longerich et al. (1996).

Lu–Hf isotope measurements

The crushed parts of the eclogites were sieved to retrieve garnet- and omphacite-rich mineral fractions for Lu and Hf isotope measurements. Only the fractions with the highest amount of optically inclusion-poor minerals were separated with a Frantz L-1 magnet separator. Fractions of 250–355 µm and 355–500 µm were used for handpicking of nearly inclusion-free grains of garnet and omphacite. Three-to-four whole-rock powders, three garnet, and one omphacite separate were measured for each sample. A mixed ^{176}Lu-^{180}Hf tracer was added to the samples prior to digestion. Two different procedures for sample digestion were applied: (1) a tabletop digestion procedure after Lagos et al. (2007) was applied to the mineral separates and 2–3 of the whole-rock powders, using 6 ml of a mixture of conc. HF and conc. HNO_3 (2:1), which was left for at least 48 h at 120 °C. Afterwards, 1 ml of $HClO_4$ was added to the samples and dried down at 180 °C. The samples were then dissolved in 6 N HCl at 120 °C and dried down again. The whole digestion procedure was repeated until complete digestion was accomplished. (2) One whole-rock powder of each sample was digested in a Parr® bomb for 4 days at 180 °C using a 1:1 mixture of conc. HF and conc. HNO_3 to achieve complete dissolution, including Hf-rich phases like zircon or rutile. All separates and whole-rock splits were dissolved in 5 ml 3 N HCl to apply the one-column chemistry after Münker et al. (2001), using Eichchrom® Ln-spec. Eluted Lu and Hf cuts were dried down at 120 °C on a hotplate and organics were removed with 1 ml of a mixture of 0.14 N HNO_3 (Lu) or 0.56 N HNO_3/0.24 N HF (Hf) and 30% H_2O_2 (9:1). Hf cuts were further purified by applying a clean-up chemistry, after Lagos et al. (2007).

All Lu and Hf isotope measurements were carried out using a Thermo Scientific Neptune Multicollector ICP-MS at the joint Cologne-Bonn isotope facility. The measured $^{176}Hf/^{177}Hf$ was given relative to the Münster AMES standard ($^{176}Hf/^{177}Hf = 0.282160$), which is isotopically indistinguishable from the JMC-475. The instrumental bias on Hf was corrected using a $^{179}Hf/^{177}Hf$ ratio of 0.7325 and the exponential law. Isobaric interferences on ^{176}Hf and ^{180}Hf were accounted for by measuring ^{173}Yb, ^{175}Lu, ^{181}Ta, and ^{183}W and using their natural isotopic compositions (Vervoort et al. 2004). Likewise, the interferences on ^{176}Lu were corrected by monitoring ^{173}Yb and ^{177}Hf. To account for the mass bias correction of Lu ratios, naturally occurring Yb in the Lu cuts was used (Lapen et al. 2007; Vervoort et al. 2004). The typical external reproducibility for Hf measurements is ± 0.4 epsilon units. Isochrons were calculated using Isoplot 4.1 (updated version of Isoplot 2.49, Ludwig 2001). A decay constant of $\lambda^{176}Lu = 1.867 \times 10^{-11}$ a^{-1} (Scherer et al. 2001; Söderlund et al. 2004) and 2 σ uncertainties for $^{176}Lu/^{177}Hf$ and $^{176}Hf/^{177}Hf$ ratios were used for isochron calculations.

Sample description

For Lu–Hf-dating, we selected two eclogite samples from Tønsvika and Tromsdalstind which are described below. Detailed petrology and P–T path reconstructions of eclogites from both locations can be found in Ravna and Roux (2006) and Janák et al. (2012). Major-element compositions of both samples are typical for metabasalts and shown in Table 1.

Tromsdalstind

The peak-pressure assemblage of the Tromsdalstind eclogite comprises garnet, omphacite, rutile, quartz, and probably epidote (Fig. 3a, c). Representative microprobe analyses of the major minerals in this sample can be found in Table 2. Omphacite is partly converted to symplectites of plagioclase

Table 1 XRF analyses of the samples from Tromsdalstind and Tønsvika

	Tromsdalstind	Tønsvika
SiO_2 (%)	48.2	39.3
Al_2O_3 (%)	14.1	9.86
Fe_2O_3 (%)	12.2	20.0
MnO (%)	0.19	0.25
MgO (%)	7.97	8.23
CaO (%)	11.04	16.93
Na_2O (%)	4.17	1.93
K_2O (%)	bd	bd
TiO_2 (%)	1.77	2.06
P_2O_5 (%)	0.05	0.28
L.O.I. (%)	< 0.1	< 0.1
Total (%)	99.69	98.84

bd below detection limit

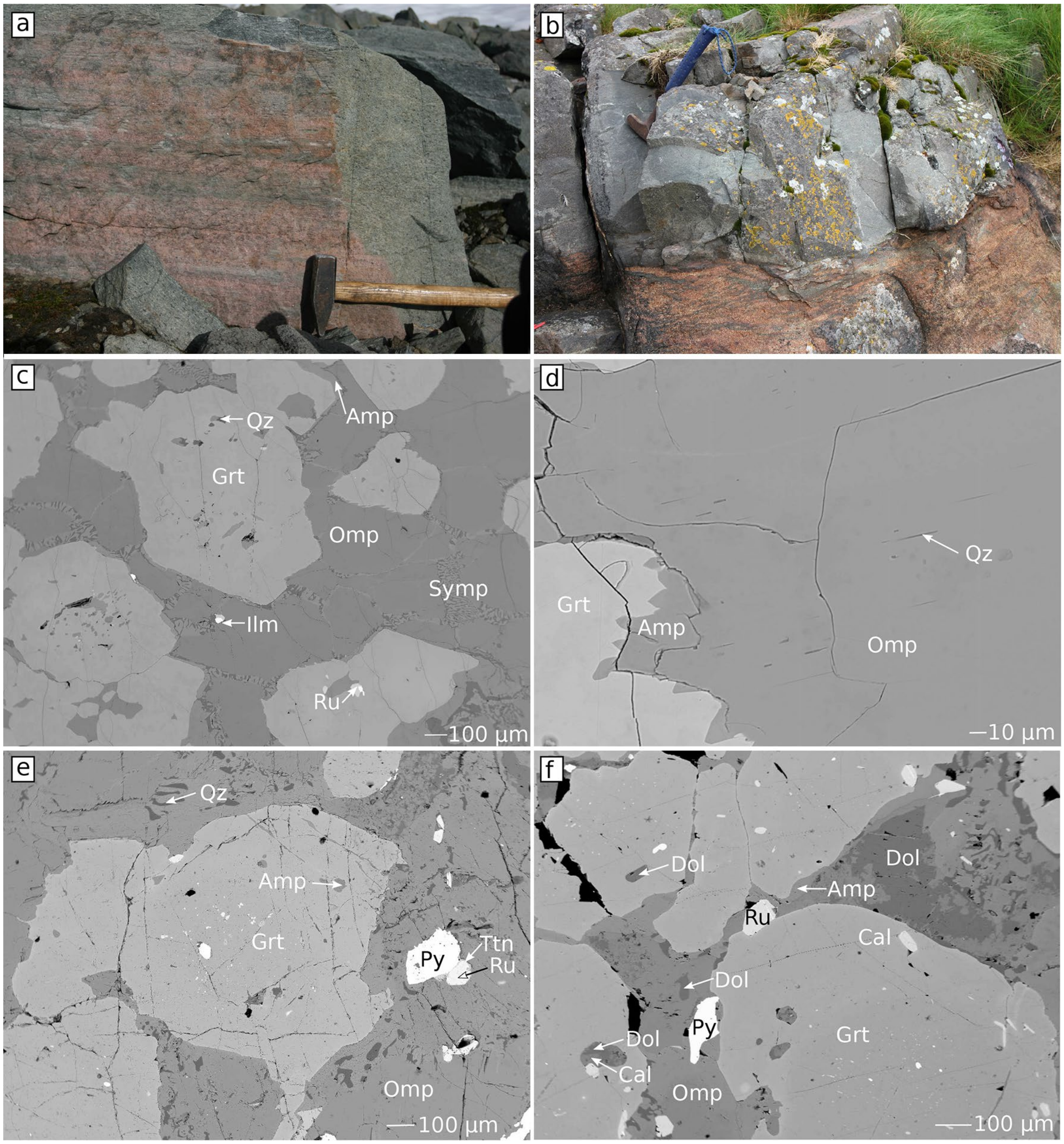

Fig. 3 Photos of the outcrops of the **a** Tromsdalstind and **b** Tønsvika eclogites (red colors are weathered surfaces) and BSE images of both eclogite samples. **c** The main mineral assemblage of the sample from Tromsdalstind; **d** elongated quartz rods in clinopyroxene in the sample from Tromsdalstind; **e**, **f** the main mineral assemblage of the sample from Tønsvika. *Amp* amphibole, *Cal* calcite, *Dol* dolomite, *Grt* garnet, *Ilm* ilmenite, *Omp* omphacite, *Py* pyrite, *Qz* quartz, *Ru* rutile, *Symp* symplectite, *Ttn* titanite

and Na-poor clinopyroxene (diopside), with or without amphibole. Elongated quartz rods in omphacite (Fig. 3d), which have been also observed in kyanite eclogite from the same locality (Janák et al. 2012), suggest exsolution from the more silicic Ca-Eskola clinopyroxene stable at UHP conditions (e.g., Katayama et al. 2000; Smith 1984).

Most garnets contain a few inclusions, mostly concentrated in the garnet cores. Inclusions comprise clinopyroxene, amphibole, epidote, quartz, rutile, and ilmenite. Zoning of major elements in garnet differs between garnet grains in the sample. Fe is only weakly zoned (decreasing from rim to core) to unzoned in all garnets, while Mg is more strongly zoned and always increases towards the rim. Therefore, FeO/(FeO + MgO) has always a bell-shape pattern in profiles through garnet grains (Fig. 4). Ca content in all analyzed garnets decreases from core to rim (Figs. 4, 5). Mn shows an enrichment in the core in comparison with the rim in large garnet grains (Fig. 4), while small garnet grains are nearly unzoned with respect to Mn (Fig. 5). The general composition of garnet is

Table 2 Representative electron microprobe analyses of the samples from Tromsdalstind and Tønsvika

Sample	Tromsdalstind						Tønsvika				
Mineral	Grt	Omp	Cpx	Ep	Amp	Plag	Grt	Omp	Cpx	Plag	Amp
SiO_2	38.4	56.1	53.1	39.2	40.2	64.8	39.5	54.1	53.7	68.1	40.8
TiO_2	0.07	0.06	0.17	0.18	0.17	bd	0.03	0.23	0.12	0.02	0.73
Al_2O_3	21.9	9.3	6.4	28.7	21.0	22.6	22.6	7.3	4.27	21.2	20.4
FeO	23.3	4.73	6.8	6.9	12.0	0.19	22.2	5.7	6.0	0.20	10.8
MnO	0.46	0.05	0.05	0.02	0.08	0.01	0.23	bd	0.09	bd	0.04
MgO	7.2	9.3	11.5	0.12	11.6	0.01	7.4	11.2	12.9	0.02	11.2
CaO	8.7	14.2	18.6	23.7	10.2	3.27	9.11	17.9	22.1	1.03	11.0
Na_2O	0.06	6.9	3.43	bd	3.21	9.4	0.05	3.71	1.68	10.0	2.92
K_2O	bd	bd	bd	0.01	0.24	0.01	0.01	bd	0.01	0.13	0.96
Cr_2O_3	bd	0.02	bd	0.02	0.02	bd	0.05	0.10	0.04	bd	0.05
Total	100.1	100.2	99.9	98.9	98.6	100.4	101.1	100.2	101.0	100.7	98.8
Si	5.93	2.00	1.95	2.92	5.81	11.36	5.97	1.96	1.95	11.79	5.87
Ti	0.01	0.00	0.00	0.01	0.02	0.00	0.00	0.01	0.00	0.00	0.08
Al	3.98	0.39	0.27	2.52	3.57	4.68	4.03	0.31	0.18	4.33	3.47
Fe	3.00	0.14	0.21	0.43	1.44	0.03	2.81	0.17	0.18	0.03	1.30
Mn	0.06	0.00	0.00	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.01
Mg	1.64	0.49	0.63	0.01	2.49	0.00	1.67	0.60	0.70	0.00	2.39
Ca	1.44	0.54	0.73	1.89	1.58	0.61	1.48	0.69	0.86	0.19	1.70
Na	0.02	0.45	0.24	0.00	0.90	3.21	0.02	0.26	0.12	3.35	0.82
K	0.00	0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.03	0.18
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.01
Total	16.08	4.02	4.03	7.80	15.86	19.90	16.01	4.01	4.01	19.73	15.81
O	24.00	6.00	6.00	12.00	23.00	32.00	24.00	6.00	6.00	32.00	23.00

bd below detection limit, values are given in weight%

$Alm_{43\text{-}52}Gr_{18\text{-}32}Py_{19\text{-}37}Sps_{0.5–1.9}$. Amphibole occurs at the rims of some garnets. In some garnet grains, there are veins filled with matrix minerals: omphacite with a matrix-like composition, amphibole with a composition as those at garnet rims, and albite. Clinopyroxene in the matrix shows homogenous compositions with $Jd_{41\text{-}43}$ and can be classified as omphacite. Omphacite grains of similar chemical composition can be found also as inclusions in garnet. In symplectitic intergrowth with plagioclase, omphacite is relatively Na-poor ($Jd_{22\text{-}28}$). Amphibole occurring as inclusions in garnet shows highly variable compositions and can be classified as taramite, barroisite, or sadanagaite. Some of these inclusions have a remarkable high Ti content of up to 4 wt%. At some of the garnet rims, amphibole with sadanagaite composition occurs in a flame-like structure, where the two minerals seem to be intergrown with each other (Fig. 3d). Amphibole grains at garnet rims and in flame-like structures around garnets correspond to sadanagaite. Amphibole can also be found in symplectites with plagioclase after omphacite, where it can be classified as taramite. Plagioclase is found only in symplectitic intergrowth with omphacite or amphibole and classifies as oligoclase with a varying chemical composition ($Ab_{79\text{-}87}$). Epidote is found only as inclusions in garnet, so it is difficult to determine if it is part of the peak-pressure paragenesis or a prograde mineral which was not stable at peak-pressure conditions.

Tønsvika

The peak-pressure mineral assemblage of the eclogite from Tønsvika consists only of garnet and omphacite with minor rutile (Fig. 3b, e, Table 2). This eclogite shows almost no retrogression apart from some scarce symplectites of Na-poor clinopyroxene and plagioclase after omphacite. Garnet grains are anhedral without retrogression at their rims. They show rather homogenous compositions with respect to major elements, except for a slight increase of Fe and a decrease of Mg at the outer rims, and a faint zoning of Ca, showing a slightly Ca-richer core and Ca-poorer rim (Fig. 6). This Ca zoning is similar but weaker than in the sample from Tromsdalstind. Overall garnet composition is $Alm_{43\text{-}53}Gr_{22\text{-}26}Py_{21\text{-}33}Sps_{0.2–0.8}$. Inclusions in garnet are rare, comprising clinopyroxene, amphibole, paragonite, biotite, plagioclase, pyrite, titanite, rutile, zircon, and carbonate. The composition of clinopyroxene inclusions in garnet corresponds to omphacite with $Jd_{26\text{-}27}$ or augite and is similar to those in the matrix, whereas clinopyroxene in the

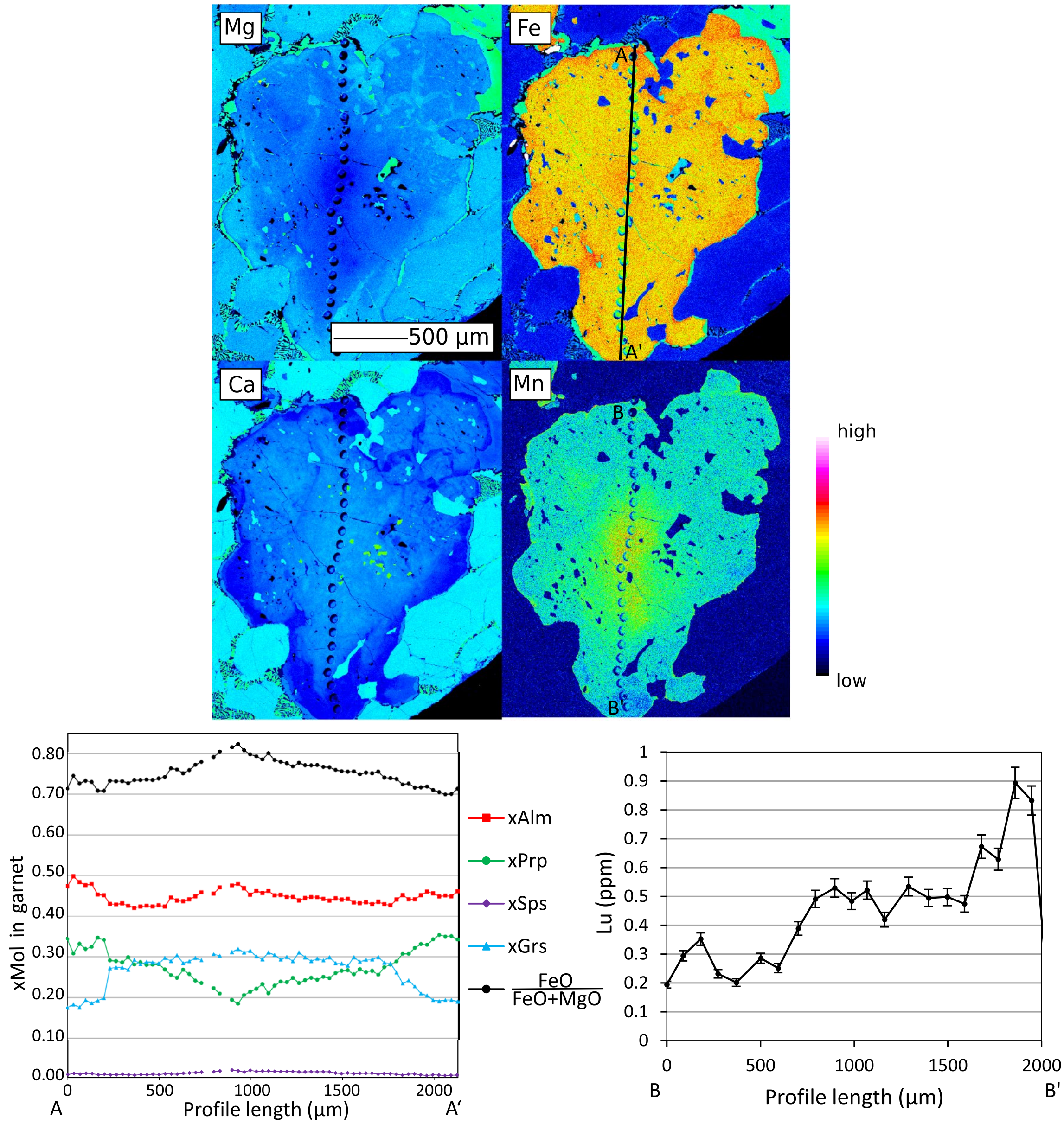

Fig. 4 Major-element distribution maps of the sample from Tromsdalstind. Maps show a garnet grain that retained its growth zonation. The black line in the Fe map shows the path of the profile shown in the lower left (obtained by electron microprobe). The dots in the maps show the measurement points of laser analyses, which can be found in the lower right of the figure

symplectites is diopside (Jd_{13}). Amphibole occurs only as inclusions in garnet and therefore is not regarded as a peak-pressure phase. Both clino- and ortho- amphibole have been identified as sadanagaite and gedrite. Inclusions of plagioclase in garnet are nearly pure albite (Ab_{98}), whereas plagioclase in symplectites with clinopyroxene has a composition of Ab_{93}. Pyrite is abundant in this sample and occurs both in the matrix and as inclusions in garnet. Rutile and titanite are often associated with pyrite, but occur also as tiny inclusions in garnet. Carbonates, mostly dolomite, are quite abundant in the matrix and as inclusions in garnet (Fig. 3f).

Results

Lu distribution in garnet

In Figs. 4, 5, and 6, Lu profiles are plotted through the same garnet grains that were measured with electron microprobe. The large garnet grain No. 1 from Tromsdalstind (Fig. 4), which exhibits prograde growth zoning in Mn, shows an asymmetric Lu profile with a maximum close to one rim, a shoulder in the core, a minimum between the core and the other rim, and a small secondary maximum close to the

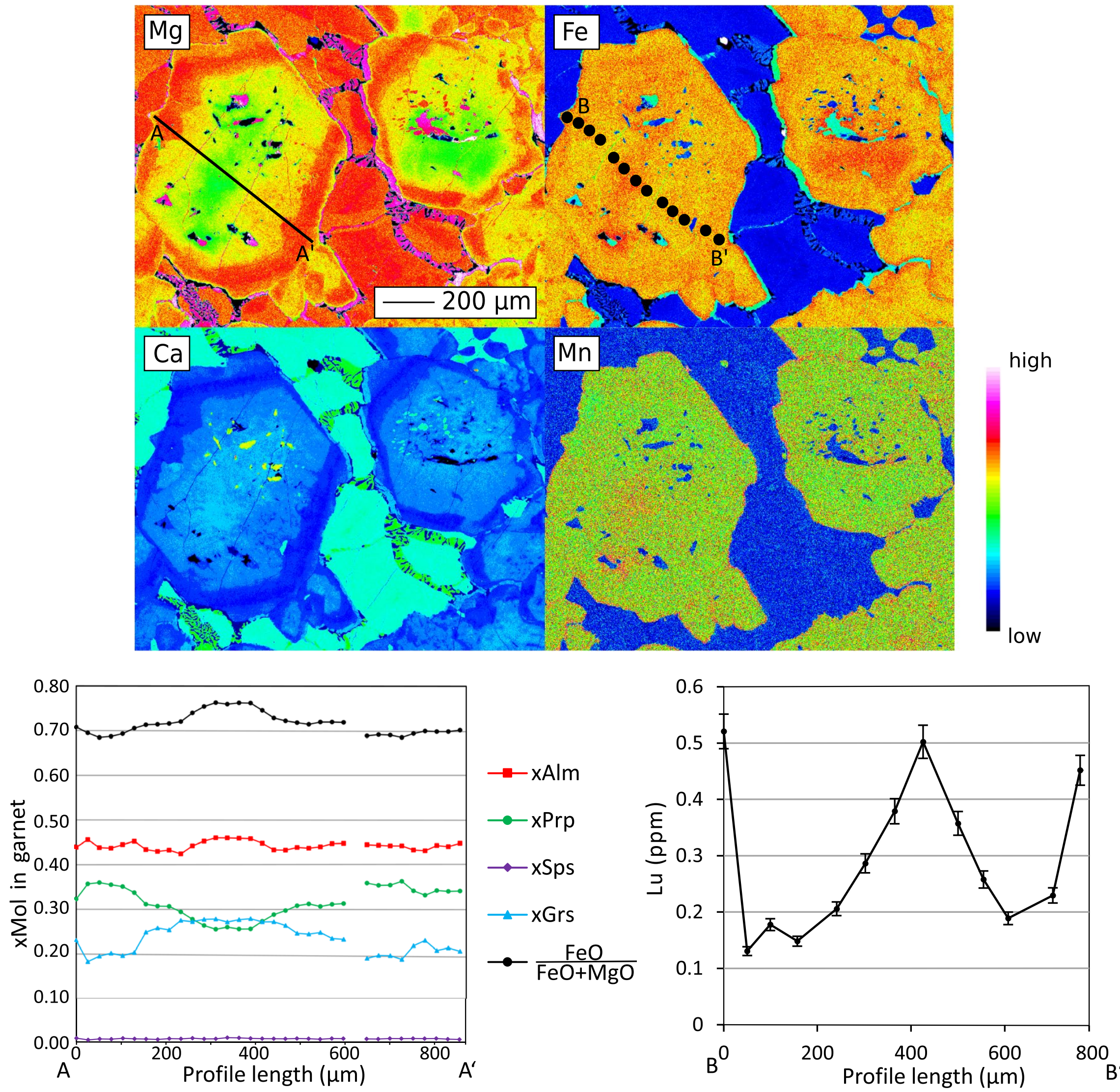

Fig. 5 Major-element distribution map through garnet grains of the sample from Tromsdalstind. Maps show two garnet grains that are partly thermally re-equilibrated in terms of their major-element zonation. The black line in the Mg map shows the path of the major-element profile (obtained by electron microprobe). The black dots in the Fe map show the measurement points of laser analyses, which can be found in the lower right of the figure. The garnet grain shows a typical growth zoning concerning Lu

other rim. The small garnet grain No. 2 from the Tromsdalstind eclogite (Fig. 5) with a homogenous Mn content shows a Lu peak in the core and two equally high peaks immediately at the rim of garnet. In the garnet grain from the Tønsvika eclogite (Fig. 6), the Lu content is almost homogeneous, varying between 0.4 and 0.55 ppm.

Lu–Hf geochronology

Lu and Hf isotopic compositions of both studied eclogite samples are shown in Table 3. For the sample from Tromsdalstind, we plotted one bomb-digested and two table-top-digested whole-rock splits, one clinopyroxene separate, and three garnet separates on an isochron which yields an age of 448.3 ± 3.6 Ma (MSWD = 1.19, n = 7). For the Tønsvika eclogite, we also obtained a statistically good isochron with all measured data points which gives an age of 449.4 ± 3.3 Ma (MSWD = 1.14, n = 8). One of the garnet separates has a distinctly larger error, because uncertainties also include propagated errors from interference corrections and interferences of Lu and Yb on Hf were higher than in the other separates. As the larger error does not influence the age, we see no reason for excluding this point from the isochron. Both isochrons are shown in Fig. 7. The ages of both eclogites are identical within their uncertainty.

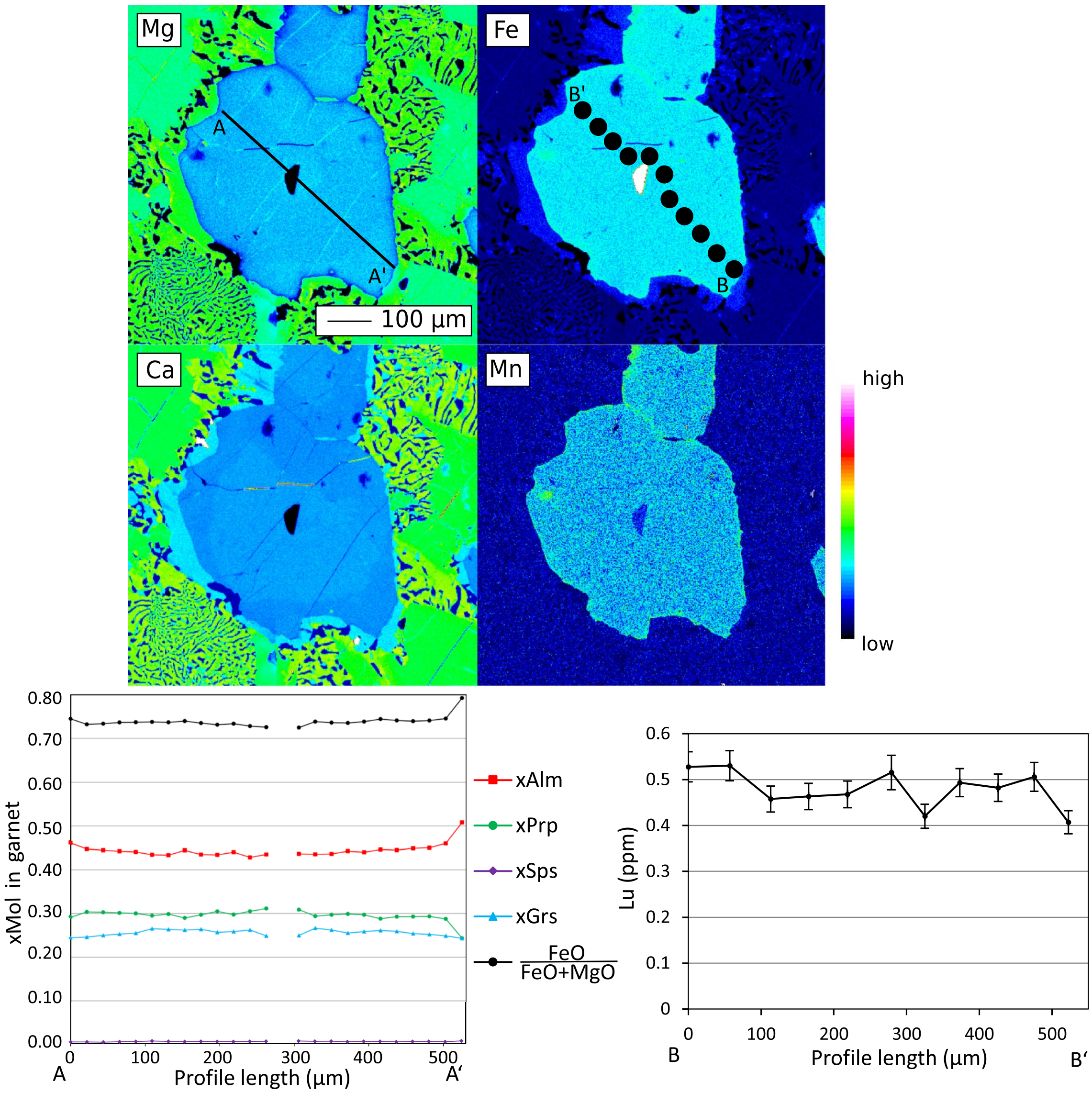

Fig. 6 Major-element maps through a representative garnet grain of the sample from Tønsvika. Below these maps, a major-element profile (path marked by the black line in the Mg map) and a Lu profile (marked by the black dots in the Fe map) are shown

Discussion

Subduction and exhumation of the Tromsø Nappe

Garnets from the Tromsdalstind eclogite retained their Lu growth zonation even where major elements were partly thermally re-equilibrated (Fig. 5). In grain No. 1, we interpret the strongly variable Lu contents as a proof that it has not been homogenized after garnet growth, although the shape of the profile is difficult to interpret. Such irregular Lu distribution patterns may potentially be interpreted as directly inherited from Lu-rich and Lu-poor minerals that were present before garnet grew, in situations of low intergranular REE mobility (Moore et al. 2013). In grain No. 2, we interpret the central peak as resulting from the strong fractionation of Lu into garnet as it began to grow. The maxima at the rim may be explained by a progressive temperature increase during the final stage of garnet growth, leading to an increase of the diffusion rate and thereby allowing the diffusion of Lu from the more distant parts of the rock into the garnet grain (diffusion-limited REE uptake; Skora et al. 2006). Alternatively, resorption of garnet and back-diffusion of Lu into the remaining garnet could also lead to a Lu increase at the rim (Kelly et al. 2011), but the well-preserved shape and major-element zonations of this garnet grain speak against a significant resorption. As Lu is concentrated in the core on one hand

Table 3 Lu and Hf isotopic compositions of whole rocks (wr), garnet separates (Grt), and clinopyroxene separates (Cpx)

Sample	Mineral	Lu (ppm)	Hf (ppm)	$^{176}Lu/^{177}Hf$	Error	$^{176}Hf/^{177}Hf$	Error
Tromsdalstind	Grt 1	0.770	0.156	0.7020	0.0014	0.288533	0.000066
	Grt 2	0.732	0.180	0.5777	0.0012	0.287484	0.000074
	Grt 3	0.796	0.161	0.7025	0.0014	0.288630	0.000088
	Cpx	0.00683	0.329	0.002947	0.000006	0.282670	0.000032
	wr b	0.305	1.54	0.02804	0.00006	0.282896	0.000011
	wr tt 1	0.322	0.872	0.05243	0.00010	0.283087	0.000015
	wr tt 2	0.313	0.622	0.07145	0.00014	0.283261	0.000034
Tønsvika	Grt 1	0.735	0.199	0.5246	0.0010	0.286850	0.000029
	Grt 2	0.725	0.257	0.4016	0.0008	0.285789	0.000133
	Grt 3	0.732	0.171	0.6075	0.0012	0.287032	0.000511
	Cpx	0.0123	1.42	0.001222	0.000002	0.282422	0.000034
	wr b	0.342	1.79	0.02704	0.00005	0.282658	0.000016
	wr tt 1	0.344	1.03	0.04758	0.00010	0.282835	0.000012
	wr tt 2	0.350	1.06	0.04689	0.00009	0.282819	0.000013
	wr tt 3	0.339	1.07	0.04498	0.00009	0.282800	0.000032

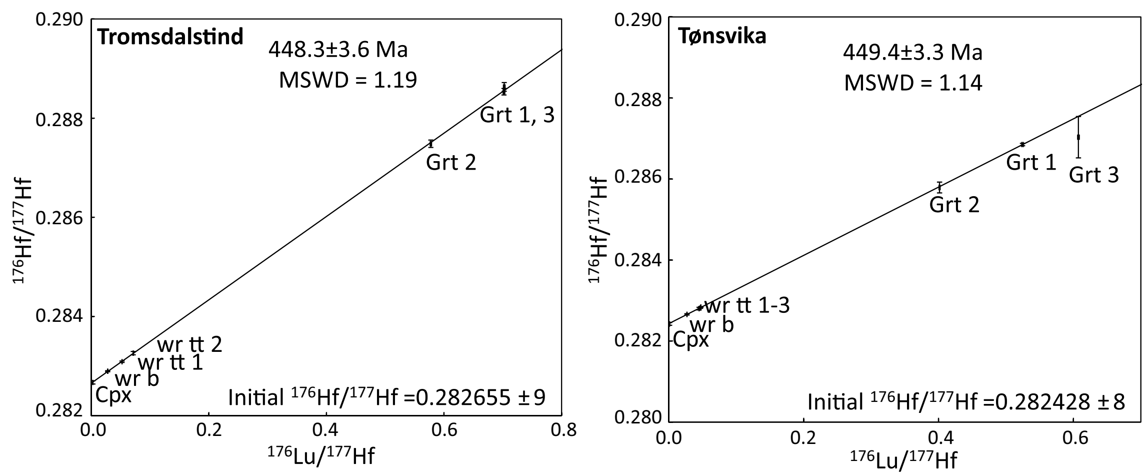

Fig. 7 Lu–Hf isochrons for both eclogite samples. 2σ uncertainties are used. Calculated initial values and ages are based on $\lambda^{176}Lu = 1.867 \times 10^{-11}$ year^{-1} (Scherer et al. 2001; Söderlund et al. 2004), Grt 1–3: garnet separates, Cpx: clinopyroxene separate, wr (tt): tabletop-digested whole-rock split, wr (b): Parrbomb-digested whole-rock split

and near the rim on the other hand, the resulting age is likely related to prograde garnet growth.

In contrast to Tromsdalstind, the garnet in the eclogite from Tønsvika shows nearly homogeneous Lu content. This could be explained by post-growth diffusional equilibration. In this case, the age would likely represent a cooling age. However, two observations speak against this: first, the age for Tønsvika is identical within error, but the mean age is slightly older than for Tromsdalstind, which would be difficult to reconcile with a post-peak age for Tønsvika. Furthermore, a weak but clear prograde zoning is seen in the Ca content of garnet (Fig. 6). If a part of the original Ca zoning survived diffusional equilibration, the even more immobile Lu is unlikely to have become completely equilibrated. Under these circumstances, we find it more logical to assume that the uniform Lu content is an original feature of the garnet grain. This particular garnet grain could have started growing relatively late, when most of the available Lu had already been used up in the cores of earlier grown garnets. Alternatively, if a narrow Lu peak existed in the core of the grain, the exact center with the Lu peak may have been missed by the cutting of the thin section. Cutts and Smit (2018) described similarly homogenous profiles that they interpreted as being recrystallization during prograde high-grade metamorphism. Therefore, we also interpret the age from Tønsvika to represent prograde garnet growth (Fig. 8).

The Lu–Hf ages for both eclogite samples from the Tromsø Nappe overlap with the ages obtained by U–Pb

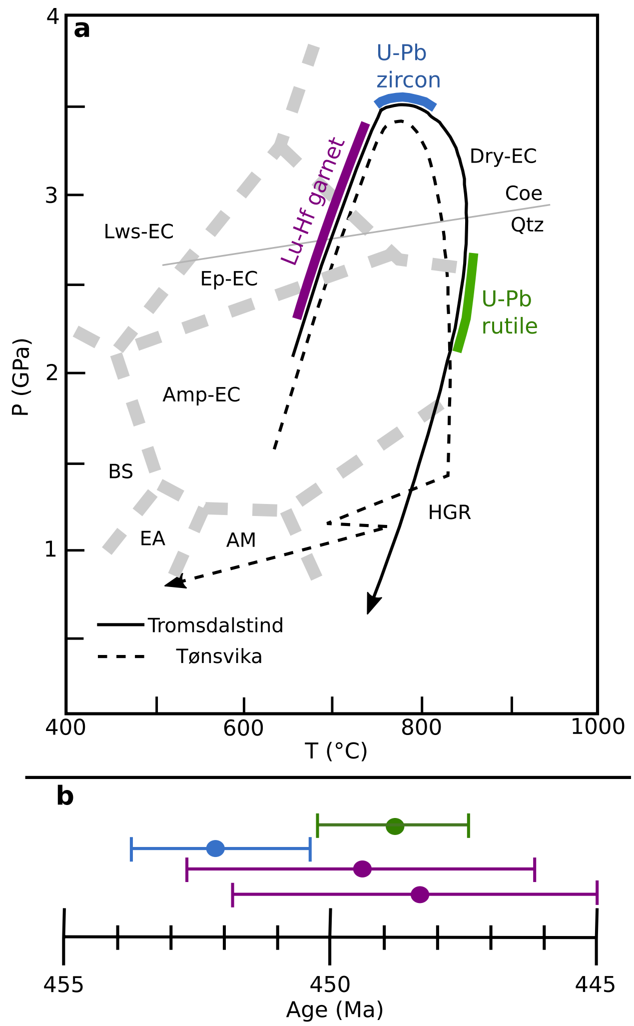

Fig. 8 **a** PT paths of the eclogite bodies in Tønsvika and Tromsdalstind modified after Janák et al. (2012). Tromsdalstind eclogite: Janák et al. (2012); Tønsvika eclogite: Ravna and Roux (2006). Different dating methods and their attribution to different parts the PT path are marked in different colors. Metamorphic facies grid is from Okamoto and Maruyama (1999). *BS* blueschist facies; *EA* epidote amphibolite facies; *AM* amphibolite facies; *HGR* high-pressure granulite facies; *Lw-EC* lawsonite eclogite facies; *Ep-EC* epidote eclogite facies; *Amp-EC* amphibole eclogite facies; *Dry-EC* dry eclogite facies. The quartz–coesite line is calculated from thermodynamic data of Holland and Powell (1998). **b** Graphic presentation of isotopic ages with the same color coding as in part (**a**), which shows a fast subduction-exhumation cycle. Lu–Hf ages are from this study and U–Pb ages are from Corfu et al. (2003)

geochronology on zircon (Corfu et al. 2003). The ages dating prograde garnet growth, peak metamorphism, and cooling through the closure temperature of the Lu–Hf system in garnet all overlap and fall into a time frame from 454.5 ± 1.1 Ma (one zircon age from carbonatite at Tønsvika; Ravna et al. 2017) to 448.8 ± 1.4 Ma (post-eclogite rutile; Corfu et al. 2003). Our prograde Lu–Hf ages, 449.4 ± 3.3 Ma and 448.3 ± 3.6 Ma, also fall into this time span. The maximum duration of the subduction–exhumation cycle is thus about 6 Ma, and probably less. These results support the inference of Corfu et al. (2003) that subduction and exhumation of the Tromsø Nappe happened within a few million years. For the locality Tromsdalstind, our prograde Lu–Hf age (448.3 ± 3.6 Ma) is identical to the post-eclogitic rutile age (448.8 ± 1.4 Ma; Corfu et al. 2003), which suggests very fast exhumation.

Paleogeography

The paleogeographic origin of the Tromsø Nappe is still an open question. It could either have been derived from the distal margin of Baltica, together with the rocks of the Seve Nappe Complex. These units were subducted towards west and metamorphosed under HP to UHP conditions at ~ 460–450 Ma in Jämtland (e.g., Brueckner and Van Roermund 2007; Fassmer et al. 2017) and ~ 500–480 Ma in Norrbotten (e.g., Root and Corfu 2012 and references therein). If the Tromsø Nappe shared its early history with these units, it must later have been placed on top of the other nappes of the Uppermost Allochthon by an east- to southeast-directed Scandian out-of-sequence thrust (e.g., Janák et al. 2012). Alternatively, the Tromsø Nappe could be an original part of the Uppermost Allochthon, derived from the Laurentian continental margin. This would imply that subduction of continental crust happened roughly synchronously on both sides of Iapetus (e.g., Brueckner and Van Roermund 2007; Corfu et al. 2003). The subduction of the Laurentian margin, named the Grampian Orogeny on the British Isles and the Taconian Orogeny in the Appalachians, occurred at 475–465 Ma (e.g., Chew and Strachan 2014) and 470–460 Ma (e.g., Van Staal et al. 2013), respectively. The timing of eclogite-facies metamorphism in the Tromsø Nappe (~ 448–450 Ma) fits both paleogeographic derivations equally well (or badly). Detailed structural, petrological, and geochronological work along the transect from the Tromsø Nappe towards east into Seve Nappe Complex might help to clarify the tectonic history and the origin of the Tromsø Nappe.

Conclusion

We obtained the first Lu–Hf isochron ages for eclogites from the Tromsdalstind and Tønsvika localities in the Tromsø Nappe. The samples yielded ages of 448.3 ± 3.6 Ma and 449.4 ± 3.3 Ma which we interpret as dating prograde garnet growth. All ages for prograde, peak, and retrograde parts of the UHP metamorphic cycle in the Tromsø Nappe overlap around 454–448 Ma. The maximum duration of the subduction-exhumation cycle is thus c. 6 Ma, and probably less. The palaeogeographic framework of subduction and

UHP metamorphism in the Tromsø Nappe, i.e., whether the processes occurred along the Baltican or the Laurentian side of Iapetus, is still unclear. More work on the structural and pressure–temperature evolution of the Tromsø Nappe and adjacent tectonic units is needed to sort this out.

Acknowledgements Open Access funding provided by Projekt DEAL. This work was supported by the German Science Foundation (DFG) Grant no. FR700/18-1 to N. F. and by the Slovak Research and Development Agency project APVV-18-0107 to M.J. We would like to thank two anonymous reviewers for their constructive criticism which strongly improved the paper and gave it a clearer focus.

References

Baxter EF, Scherer EE (2013) Garnet geochronology: timekeeper of tectonometamorphic processes. Elements 9:433–438

Binns RE (1978) Caledonian nappe correlation and orogenic history in Scandinavia north of lat 67°N. Geol Soc Am Bull 89:1475–1490

Brueckner HK, van Roermund HLM (2004) Dunk tectonics: a multiple subduction/education model for the evolution of the Scandinavian Caledonides. Tectonics 23:2

Brueckner HK, Van Roermund HLM (2007) Concurrent HP metamorphism on both margins of Iapetus: Ordovician ages for eclogites and garnet pyroxenites from the Seve Nappe Complex, Swedish Caledonides. J Geol Soc Lond 164:117–128

Bukała M, Klonowska I, Barnes C, Majka J, Kośmińska K, Janák M, Fassmer K, Broman C, Luptáková J (2018) UHP metamorphism recorded by phengite eclogite from the Caledonides of northern Sweden: P-T path and tectonic implications. J Metamorph Geol 36:547–566

Chew DM, Strachan RA (2014) The Laurentian Caledonides of Scotland and Ireland. Geol Soc Lond Spec Publ 390(1):45–91

Corfu F, Ravna EJK, Kullerud K (2003) A late Ordovician U-Pb age for the Tromsø Nappe eclogites, Uppermost Allochthon of the Scandinavian Caledonides. Contrib Mineral Petrol 145:502–513

Cutts JA, Smit MA (2018) Rates of deep continental burial from Lu-Hf garnet chronology and Zr-in-rutile thermometry on (ultra)high-pressure rocks. Tectonics 37:71–88

Dallmeyer RD, Gee DG (1986) 40Ar/39Ar mineral dates from retrogressed eclogites within the Baltoscandian miogeocline: implications for a polyphase Caledonian orogenic evolution. Geol Soc Am Bull 87:26–34

DesOrmeau JW, Gordon SM, Kylander-Clark ARC, Hacker BR, Bowring SA, Schoene B, Samperton KM (2015) Insights into (U)HP metamorphism of the Western Gneiss Region, Norway: a high-spatial resolution and high-precision zircon study. Chem Geol 414:138–155

Dobrzhinetskaya LF, Eide EA, Larsen RB, Sturt BA, Tronnes RG, Smith DC, Taylor WR, Posukhova TV (1995) Microdiamonds in high-grade metamorphic rocks of the Western Gneiss region, Norway. Geology 23:597–600

Dunning GR, Pedersen RB (1988) U/Pb ages of ophiolites and arcrelated plutons of the Norwegian Caledonides: implications for the development of Iapetus. Contrib Mineral Petrol 98:13–23

Fassmer K, Klonowska I, Walczak K, Andersson B, Froitzheim N, Majka J, Fonseca ROC, Münker C, Janák M, Whitehouse M (2017) Middle Ordovician subduction of continental crust in the Scandinavian Caledonides: an example from Tjeliken, Seve Nappe Complex. Sweden Contrib Mineral Petrol 172:103

Fossen H (2010) Extensional tectonics in the North Atlantic Caledonides: A regional view. In: Law R, Butler R, Holdsworth B, Krabbendam RA, Strachan M (eds) Continental tectonics and mountain building: the legacy of Peach and Horn. Geol Soc Spec Pub, vol 335, pp767–793

Gee DG, Kumpulainen R, Roberts D, Stephens MB, Thon A, Zachrisson E (1985) Scandinavian Caledonides, Tectonostratigraphic map, scale 1:2 000 000. In: Gee DG, Sturt BA (eds) The Caledonide Orogen—Scandinavia and Related Areas. Whiley, Chichester

Gee DG, Fossen H, Henriksen N, Higgins AK (2008) From the early paleozoic platforms of Baltica and Laurentia to the Caledonide Orogen of Scandinavia and Greenland. Episodes 31(1):44–51

Gee DG, Juhlin C, Pascal C, Robinson P (2010) Collisional orogeny in the Scandinavian Caledonides (COSC). GFF 132(1):29–44

Gilio M, Clos F, Van Roermund HLM (2015) The Friningen Garnet Peridotite (central Swedish Caledonides). A good example of the characteristic P-T–t path of a cold mantle wedge garnet peridotite. Lithos 230:1–16

Griffin WL, Brueckner HK (1980) Caledonian Sm–Nd ages and a crustal origin for Norwegian eclogites. Nature 285:319–321

Holland TJB, Powell R (1998) An internally consistent thermodynamic data set for phases of petrological interest. J Metamorph Geol 16:309–343

Janák M, Krogh Ravna EJ, Kullerud K, Yoshida K, Milovsky R, Hirajima T (2013a) Discovery of diamond in the Tromsø Nappe, Scandinavian Caledonides (N. Norway). J Metamorph Geol 31:691–703

Janák M, Ravna EJK, Kullerud K (2012) Constraining peak P-T conditions in UHP eclogites: calculated phase equilibria in kyanite- and phengite-bearing eclogite of the Tromsø Nappe, Norway. J Metamorph Geol 30:377–396

Janák M, Uher P, Ravna EK, Kullerud K, Vrabec M (2015) Chromium-rich kyanite, magnesiostaurolite and corundum in ultrahigh-pressure eclogites (examples from Pohorje Mountains, Slovenia and Tromsø Nappe, Norway). Eur J Mineral 27:377–392

Janák M, Van Roermund HLM, Majka J, Gee DG (2013b) UHP metamorphism recorded by kyanite-bearing eclogite in the Seve Nappe Complex of northern Jämtland, Swedish Caledonides. Gondwana Res 23:865–879

Jarosewich E, Nelen JA, Norberg JA (1980) Reference samples for electron microprobe analysis. Geostand Newsl 4:43–47

Jochum KP, Weis U, Stoll B, Kuzmin D, Yang Q, Raczek I, Jacob DE, Stracke A, Birbaum K, Frick DA, Günther D, Enzweiler J (2011) Determination of reference values for NIST SRM 610–617 glasses following ISO guidelines. Geostand Geoanal Res 35:397–429

Katayama I, Parkinson CD, Okamoto K, Nakajima Y, Maruyama S (2000) Supersilicic clinopyroxene and silica exsolution in UHPM eclogite and pelitic gneiss from the Kokchetav massif. Kazakhstan Am Mineral 85(10):1368–1374

Kelly ED, Carlson WD, Connelly JN (2011) Implications of garnet resorption for the Lu/Hf garnet geochronometer: an example from the contact aureole of the Makhavinekh Lake Pluton, Labrador. J Metamorph Geol 29:901–916

Kirchenbaur M, Pleuger J, Jahn-Awe S, Nagel TJ, Froitzheim N, Fonseca ROC, Münker C (2012) Timing of high-pressure metamorphic events in the Bulgarian Rhodopes from Lu–Hf garnet geochronology. Cont Mineral Petrol 163:897–921

Klonowska I, Janák M, Majka J, Froitzheim N, Kosminska K (2016) Eclogite and garnet pyroxenite from Stor Jougdan, Seve Nappe Complex, Sweden: implications for UHP metamorphism of allochthons in the Scandinavian Caledonides. J Metamorph Geol 34:103–119

Klonowska I, Janák M, Majka J, Petrík I, Froitzheim GDG, Sasinková V (2017) Microdiamond on Åreskutan confirms regional UHP metamorphism in the Seve Nappe Complex of the Scandinavian Caledonides. J Metamorph Geol 35:541–564

Krogh EJ, Andresen A, Bryhni I, Broks TM, Kristensen SE (1990) Eclogites and polyphase P-T cycling in the Caledonian Uppermost Allochthon in Troms, northern Norway. J Metamorph Geol 8:289–309

Krogh TE, Kamo SL, Robinson P, Terry MP, Kwok K (2011) U-Pb zircon geochronology of eclogites from the Scandian Orogen, northern Western Gneiss Region, Norway: 14–20 million years between eclogite crystallization and return to amphibolite facies conditions. Can J Earth Sci 48:441–472

Kurz W, Froitzheim N (2002) The exhumation of eclogite-facies metamorphic rocks—a review of models confronted with examples from the Alps. Int Geol Rev 44:702–743

Kylander-Clark ARC, Hacker BR, Johnson CM, Beard BL, Mahlen NJ (2009) Slow subduction of a thick ultrahigh-pressure terrane. Tectonics 28:14

Kylander-Clark ARC, Hacker BR, Johnson CM, Beard BL, Mahlen NJ, Lapen TJ (2007) Coupled Lu–Hf and Sm–Nd geochronology constrains prograde and exhumation histories of high- and ultrahigh-pressure eclogites from western Norway. Chem Geol 242:137–154

Lagos M, Scherer EE, Tomaschek F, Münker C, Keiter M, Berndt J, Ballhaus C (2007) High precision Lu-Hf geochronology of Eocene eclogite-facies rocks from Syros, Cyclades, Greece. Chem Geol 243:16–35

Lapen TJ, Johnson CM, Baumgartner LP, Dal Piaz GV, Skora S, Beard BL (2007) Coupling of oceanic and continental crust during Eocene eclogite-facies metamorphism: evidence from the Monte Rosa nappe, western Alps. Contrib Miner Petrol 153:139–157

Longerich HP, Jackson SE, Günther D (1996) Laser ablation inductively coupled plasma mass spectrometric transient signal data acquisition and analyte concentration calculation. J Anal Atom Spectrom 11:899–904

Ludwig KR (2001) Isoplot/Ex version 2.49, Geochronological toolkit for microsoft excel. Berkeley Geochron Center Special Publications 1a

Majka J, Janák M, Andersson B, Klonowska I., Gee DG, Rosen Å, Kosminska K. (2014) Pressure-temperature estimates on the Tjeliken eclogite: new insights into the (ultra)-high-pressure evolution of the Seve Nappe Complex in the Scandinavian Caledonides. In: Corfu F, Gasser D, Chew DM (eds) New perspectives on the Caledonides of Scandinavia and related areas. Geological Society, London, Special Publications, vol 390, pp 369–384

Michard A, Chopin C, Henry C (1993) Compression versus extension in the exhumation of the Dora-Maira coesite-bearing unit, Western Alps, Italy. Tectonophysics 221:173–193

Moore SJ, Carlson WD, Hesse MA (2013) Origins of yttrium and rare earth element distributions in metamorphic garnet. J Metamorphic Geol 31:663–689

Münker C, Weyer S, Scherer E, Mezger K (2001) Separation of high field strength elements (Nb, Ta, Zr, Hf) and Lu from rock samples for MC-ICPMS measurements. Geochem Geophys Geosys 2001:2

Okamoto K, Maruyama S (1999) The high-pressure synthesis of lawsonite in the MORB + H2O system. Am Miner 84:362–373

Petrík I, Janák M, Klonowska I, Majka J, Froitzheim N, Yoshida K, Sasinková V, Konečný P, Vaculovič T (2019) Monazite behaviour during metamorphic evolution of a diamond-bearing gneiss: a case study from the Seve Nappe Complex Scandinavian Caledonides. J Petrol 2019:51

Ravna EJK, Kullerud K, Ellingsen E (2006) Prograde garnet-bearing ultramafic rocks from the Tromsø Nappe, northern Scandinavian Caledonides. Lithos 92:336–356

Ravna EJK, Roux MRM (2006) Metamorphic evolution of the Tønsvika eclogite, Tromsø Nappe—evidence for a new UHPM province in the Scandinavian Caledonides. Int Geol Rev 48:861–881

Ravna EJK, Zozulya D, Kullerud K, Corfu F, Nabelek PI, Janák M, Slagstad T, Davidsen B, Selbekk RS, Schertl HP (2017) Deep-seated carbonatite intrusion and metasomatism in the UHP Tromsø Nappe, Northern Scandinavian Caledonides—a natural example of generation of carbonatite from carbonated eclogite. J Petrol 58:2403–2428

Reinecke T (1998) Prograde high- to ultrahigh-pressure metamorphism and exhumation of oceanic sediments at Lago di Cignana, Zermatt-Saas Zone, western Alps. Lithos 42:147–189

Roberts D (2003) The Scandinavian Caledonides: event chronology, palaeographic settings and likely modern analogues. Tectonophysics 365:283–299

Roberts D, Gee DG (1985) An introduction to the structure of the Scandinavian Caledonides. In: Gee DG, Sturt BA (eds) The Caledonide Orogen—Scandinavia and related areas. Wiley, Chichester, pp 55–68

Root DB, Corfu F (2012) U-Pb geochronology of two discrete Ordovician high-pressure metamorphic events in the Seve Nappe Complex, Scandinavian Caledonides. Contrib Miner Petrol 163:769–788

Rubatto D, Hermann J (2007) Experimental zircon/melt and zircon/garnet trace element partitioning and implications for the geochronology of crustal rocks. Chem Geol 241:38–61

Sandmann S, Nagel TJ, Herwartz D, Fonseca ROC, Kurzawski RM, Münker C, Froitzheim N (2014) Lu–Hf garnet systematics of a polymetamorphic basement unit: new evidence for coherent exhumation of the Adula Nappe (Central Alps) from eclogite-facies conditions. Contrib Mineral Petrol 168:1075

Scambelluri M, Pettke T, Van Roermund HLM (2008) Majoritic garnets monitor deep subduction fluid flow and mantle dynamics. Geology 36:59–62

Scherer EE, Münker C, Mezger K (2001) Calibration of the Lutetuim-Hafnium clock. Science 293:683–687

Selbekk RS, Skjerlie KP, Pedersen RB (2000) Generation of anorthositic magma by H2O-fluxed anatexis of silica-undersaturated gabbro: an example from the north Norwegian Caledonides. Geol Mag 137:609–621

Skjerlie KP (2002) Partial melting during exhumation of eclogite, evidence from experiments and the Tromsdalstind sequence, north Norway. In: Selbekk RS and Eklund O (eds) Lofoten, Geocenter Rep No 19, Turku Univ-Åbo Akad Univ, p 15

Skora S, Baumgartner LP, Mahlen NJ, Johnson CM, Pilet S, Hellebrand E (2006) Diffusion-limited REE uptake by eclogite garnets and its consequences for Lu–Hf and Sm–Nd geochronology. Contrib Miner Petrol 152:703–720

Smith DC (1984) Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. Nature 310:641–644

Söderlund U, Patchett PJ, Vervoort JD, Isachsen CE (2004) The 176Lu decay constant determined by Lu-Hf and U-Pb isotope systematics of Precambrian mafic intrusions. Earth Planet Sci Lett 219:311–324

Stevenson J.A (2005) High pressure partial melting of eclogite and garnet amphibolite rocks during decompression and heating, Tromsø Nappe, Norway. In: EOS Transactions American Geophysical Union 85, Abstract T23C-03

Strand T, Kulling O (1972) Scandinavian Caledonides. Whiley Interscience, Chichester

Terry MP, Robinson P, Hamilton MA, Jercinovinic MJ (2000) Monazite geochronology of UHP and HP metamorphism, deformation, and exhumation, Nordøyane, Western Gneiss Region, Norway. Amer Miner 85:1651–1664

Van Roermund HLM, Drury MR (1998) Ultra-high pressure (P %3e 6 GPa) garnet peridotites in Western Norway: exhumation of mantle rocks from %3e 185 km depth. Terra Nova 10:295–301

Van Staal CR, Chew DM, Zagorevski A, Mcnicoll V, Hibbard J, Skulski T, Castonguay S, Escayola MP, Sylvester PJ (2013) Evidence of Late Ediacaran Hyperextension of the Laurentian Iapetan Margin in the Birchy Complex, Baie Verte Peninsula, Northwest Newfoundland: Implications for the Opening of Iapetus, formation of PeriLaurentian Microcontinents and Taconic—Grampian Orogenesis Geological Assoc Canada. Geosci Can 40(2):94–117

Vervoort JD, Patchett PJ, Soderlund U, Baker M (2004) Isotopic composition of Yb and the determination of Lu concentrations and Lu–Hf ratios by isotope dilution using MC-ICPMS. Geochem Geophys Geosys 5:Q11002

Warren CJ, Beaumont C, Jamieson RA (2008) Modelling tectonic styles and ultra-high pressure (UHP) rock exhumation during the transition from oceanic sucduction to continental collision. Earth Planet Sci Lett 267:129–145

Zwaan KB, Fareth E, Grogan PW (1998) Geologisk kart over Norge, berggrunnskart Tromsø, M 1:250.000. Norges Geologiske Undersøkelse