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Coupled Lu–Hf and Sm–Nd geochronology constrains prograde and exhumation histories of high- and ultrahigh-pressure eclogites from western Norway

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Abstract

Eclogites from the Western Gneiss Region (WGR), Norway, that formed over a wide range in temperature (~600 °C to >850 °C) and pressure (high- and ultrahigh-pressure conditions; UHP) have a diverse range of Lu–Hf and Sm–Nd ages that correlate with their P–T histories. Three eclogites (~676–850 °C and ~2.0–2.85 GPa) yield Lu–Hf ages of 419.5±4.3 Ma, 416.3±3.7 and 412.0±4.7 Ma, and two Sm–Nd ages of 402.7±4.6 and 398.3±5.5 Ma. The former are interpreted to date early garnet growth and the latter are interpreted to date near-peak metamorphism. These results support previous proposals that, for eclogites which recrystallized below Lu–Hf and Sm–Nd closure temperatures, the differences in ages for the two isotopic systems constrain the period of prograde garnet growth. In the case of the WGR, garnet growth is estimated to have occurred over a period of at least 20 m.y., beginning at ~425–420 Ma. In contrast, two UHP eclogites (>800 °C and >3 GPa) yield significantly younger and overlapping Lu–Hf and Sm–Nd ages of 390–370 Ma; these ages are significantly younger than ages that are generally accepted for peak eclogite-facies conditions in the WGR, although they overlap $^{40}Ar/^{39}Ar$ ages that have been previously determined on white mica from the same samples or localities, indicating that the Lu–Hf and Sm–Nd ages may reflect rapid exhumation and cooling during the latest stages of HP and UHP metamorphism in the WGR.

Keywords: Lu–Hf; Sm–Nd; Ultrahigh-pressure; Eclogite; Geochronology; Norway

1. Introduction

The Western Gneiss Region (WGR) of Norway exposes high-pressure (HP) and ultrahigh-pressure (UHP) rocks that were generated during the final stages of the Caledonian Orogeny (Fig. 1). The orogenic event culminated with collision of Laurentia with Baltica, emplacement of a stack of allochthons from ~435 to ~395 Ma (Hacker and Gans, 2005), and subduction of Baltica and allochthons to HP and UHP conditions. The bulk of the WGR consists of amphibolite-facies quartzofeldspathic gneiss. Over an area of >60,000 km^2

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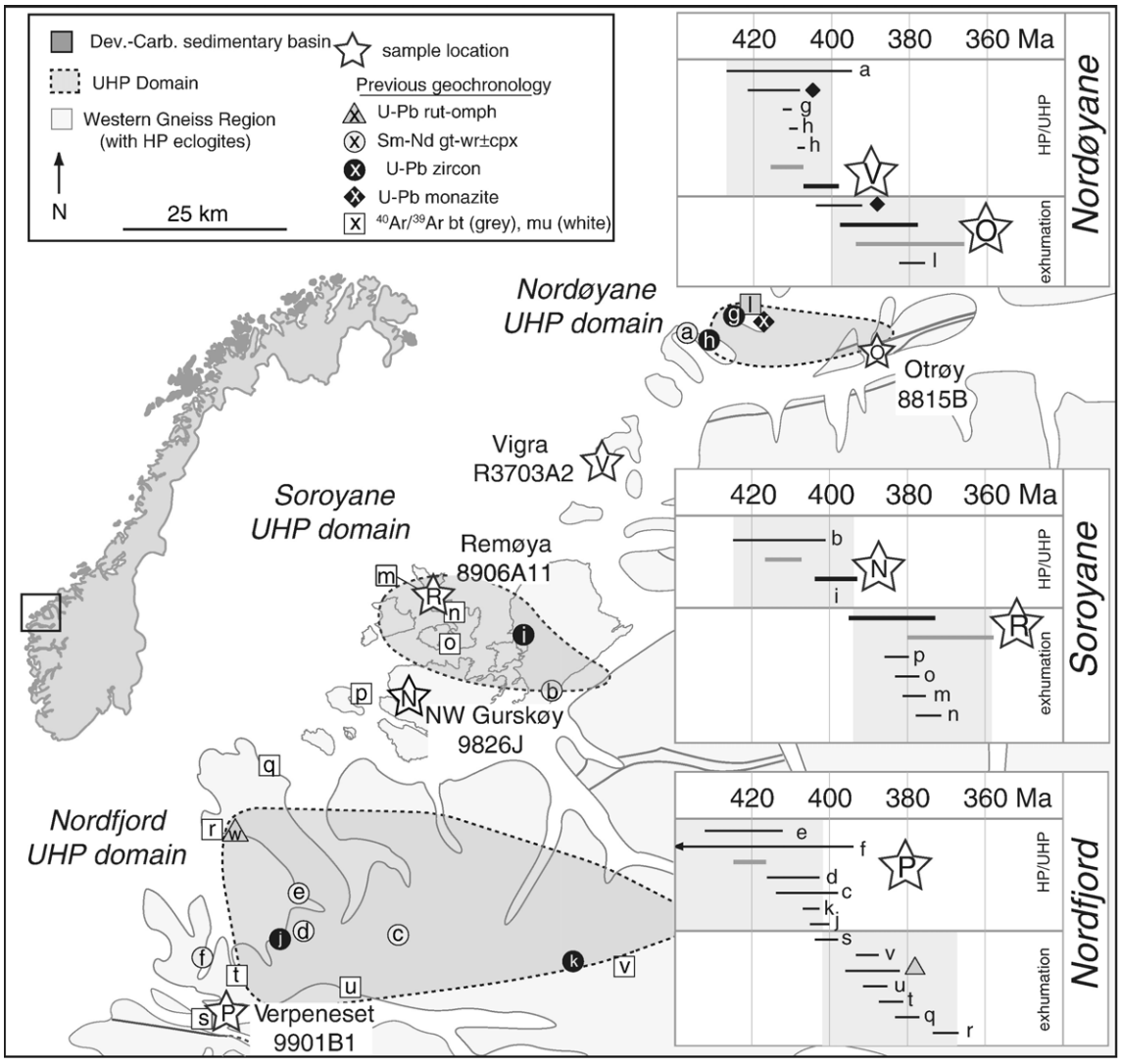


Fig. 1. Geologic map of study area in Norway (inset), showing (U)HP regions of the Western Gneiss Region and sample localities. Sample localities from this study are represented by a star. References for previous geochronology are as follows; 1) Sm/Nd: a) Mørk and Mearns (1986), b) Jamtveit et al. (1991), c) Mearns (1986), d) Carswell et al. (2003a), e and f) Griffin and Brueckner (1985); 2) U/Pb (zircon): g and h) Krogh et al. (2004), i) Carswell et al. (2003b), j) Root et al. (2004), k) Young et al. (in review); 3) $^{40}Ar/^{39}Ar$ biotite: l) Root et al. (2005); 6) $^{40}Ar/^{39}Ar$ muscovite: m, n, o, p, q, r, and s) Root et al. (2005), t and u) Andersen et al. (1998), v) Young et al. (in review); 4) U/Pb (rt–omp): Schärer and Labrousse (2003); 5) U/Pb (monazite): ~415 Ma in garnet, 398 in matrix: Terry et al. (2000).

the gneiss contains a few volume percent of HP eclogites. Three smaller, structurally lower domains are locally exposed through this HP layer, and these contain UHP eclogites Hacker, 2006a).

Because of the archetypal nature of the Norwegian (U)HP terrane, tectonostratigraphic models generated for its history serve to guide investigations of the formation and exhumation of (U)HP rocks as a whole. In turn, this allows a better understanding of how UHP tectonics influence changes in tectonic plate motions, exchange of material between the crust and the mantle, and generation of continental crust. Despite abundant structural, geochronologic and pressure–temperature data for parts of the WGR, fundamental questions remain about the formation and exhumation of the (U)HP metamorphic rocks: When did these eclogites form and how long were they at eclogite-facies conditions? When did they undergo post-eclogite-facies metamorphism and when did they reach shallow levels in the crust? How many eclogite-forming events were there and what is the areal extent of each event? These questions may be addressed through a variety of geochronological

systems, particularly those that can be tied directly to metamorphic conditions.

Thus far, the two primary geochronologic methods that have been used to constrain the timing of (U)HP metamorphism in the WGR are U–Pb on zircon and Sm–Nd on high-pressure minerals (Fig. 1). Uranium–lead zircon geochronology has the advantage of high analytical precision (thermal ionization mass spectrometry; TIMS) or high spatial resolution (laser ablation, inductively coupled plasma mass spectrometry; LA-ICPMS, and secondary ion mass spectrometry; SIMS). However, because zircon may grow over a range of pressures and temperatures, the ages require consideration of textural (e.g., coesite inclusions) and/or chemical relations (e.g., REE contents) to determine whether grains grew at eclogite-facies conditions (Carswell et al., 2003b; Root et al., 2004). In contrast, Sm–Nd geochronology potentially determines the ages of the (U)HP mineral assemblage (garnet+omphacite) directly. Several issues must, however, be addressed when using the Sm–Nd method. First, because garnet is stable over a wide range of pressures and temperatures, Sm–Nd ages may only reflect the 'average' age for the garnet growth *interval* (Lapen et al., 2003). Second, the spread in $^{147}Sm/^{144}Nd$ ratios, which directly affects isochron precision, may be diminished if garnet contains high-Nd and low-Sm/Nd inclusions such as zoisite, epidote, or apatite.

Lutetium–hafnium geochronology offers an additional approach to determining the timing of (U)HP metamorphism. Lutetium, a heavy-rare-earth element (REE), is partitioned into garnet much more strongly than Hf, a high-field-strength element. Thus, chondrite-normalized Lu/Hf ratios for garnet can be significantly higher than chondrite-normalized Sm/Nd ratios for garnet. Moreover, the very high affinity of garnet for Lu may produce strong core-to-rim zonation in Lu, producing a Lu–Hf age that is biased toward the early stages of prograde garnet growth (Lapen et al., 2003). In addition, whereas Sm/Nd ratios are diminished by LREE-rich inclusions, Lu/Hf ratios are not. Although phases that have low Lu/Hf and high Hf contents, such as zircon and rutile, can significantly decrease Lu/Hf ratios in garnet, zircons are relatively rare in basaltic eclogites. Rutile is another Lu/Hf phase that is common as a garnet inclusion in eclogites, but it is easily identified. In the case of rutile and zircon in basaltic eclogites, the Hf isotope compositions should lie on the same isochron, in contrast to, for example, supracrustal rocks that commonly contain inherited zircon.

In this paper we report garnet+omphacite±whole-rock Lu–Hf and Sm–Nd ages for five eclogites from the WGR (Fig. 1). Both methods directly date minerals that grew during eclogite-facies metamorphism. The differences in parent/daughter partitioning for the Lu–Hf and Sm–Nd systems allow an estimate of garnet growth rates and aid in pinpointing the timing and duration of eclogite-facies conditions. This is the first application of Lu–Hf geochronology to Norwegian eclogite-facies metamorphism, and we investigate this system for eclogites that equilibrated at a range of pressures and temperatures to assess the effect of blocking temperature.

2. Geochronologic background

The first Sm–Nd geochronological studies of the Western Gneiss Region of Norway were conducted by Griffin and Brueckner (1980). They and subsequent authors produced three low-MSWD (mean square of the weighted deviates), multipoint (garnet–clinopyroxene–whole-rock) ages of 410±16 Ma (Mørk and Mearns, 1986), 408.3±6.7 Ma (Carswell et al., 2003a), and 408±8 Ma (Mearns, 1986), and an additional six two-point isochrons that have greater errors of 407±24 Ma to 423±30 Ma (Griffin and Brueckner, 1980; Jamtveit et al., 1991). Griffin and Brueckner (1985) also reported a Rb–Sr phengite–zoisite–whole-rock isochron from the Verpeneset eclogite of 397±8 Ma (recalculated by Root et al., 2004).

Eclogites from the Nordfjord UHP domain (Fig. 1) have been dated using the U–Pb zircon method through a variety of approaches, including chemical-abrasion thermal ionization mass spectrometry (CA-TIMS), which produced multi-grain ages of 405 to 400 Ma for the eclogite at Flatraket (Root et al., 2004); a multi-grain TIMS $^{207}Pb/^{206}Pb$ age of 401.6±1.6 Ma for the Ulsteinvik eclogite (Carswell et al., 2003b); and a weighted-mean U–Pb concordia age of 405±2 Ma for two single grains from a Nordfjord eclogite (Young et al., 2005). All ages are interpreted to reflect the time of eclogite-facies metamorphism based on textural relations among zircons and silicate phases, inclusions, and REE contents. These U–Pb ages are significantly younger than those from the Nordøyane UHP domain 100 km to the north, where Krogh et al. (2004) reported a $^{206}Pb/^{238}U$ zircon age of 415±1 Ma from Averøya, two fractions from Flemsøya that yielded 410±1 Ma and 408±1 Ma, and two fractions from Lepsøya that average 411.5±1.2 Ma. Terry et al. (2000) reported a U–Pb monazite SIMS age from Nordøyane of 415±7 Ma. The only U–Pb age from the WGR that is younger than 400 Ma, is a rutile–omphacite multi-point isochron of 389±7 Ma Schärer and Labrousse, 2003).

Exhumation of the WGR from mantle to crustal depths is constrained by multiple U–Pb and $^{40}Ar/^{39}Ar$ ages. Zircon from pegmatites from the Averøya–Soroyane area (Krogh et al., 2004), titanite from regional sampling (Tucker et al., 1990; Tucker et al., 2004), and monazite from Fjørtoft (Terry et al., 2000) all indicate that post-eclogite, amphibolite-facies metamorphism occurred between 395 and 390 Ma. Cooling through the closure temperature of muscovite (~400 °C) occurred as early as 390 Ma in the HP domains, and as late as 369 Ma in the UHP domains (Andersen, 1998; Root et al., 2005; Young et al., in review).

3. Methods

Major-element whole-rock compositions were determined using X-ray florescence (XRF) at the Geoanalytical Lab at Washington State University (WSU). Trace-element and REE abundances, primarily used for estimating spike amounts, were determined using both XRF (trace elements) and ICPMS (REE and some trace elements), also at WSU.

The procedures for conducting the Lu–Hf and Sm–Nd geochronology largely follow those outlined by Lapen et al. (2004, 2005). After samples were crushed, ~50 g of fresh chips were separated and ground in a Spex Mill alumina shatterbox for whole-rock analysis. The remaining chips were ground in a disk mill to a sufficient size from which to separate monocrystalline grains (typically 100–300 μm). Mineral grains separated with a Frantz isodynamic magnetic separators were hand picked to exclude inclusion-rich grains. For each sample, 2 or 3 mineral fractions were picked: 1) a relatively inclusion-free ('clean') garnet fraction, 2) a garnet fraction with few inclusions, and 3) an omphacite fraction. For some samples, the omphacite fraction contained rutile inclusions. Rutile, likely to have grown during (U)HP metamorphism, has relatively high Hf contents, thereby reducing the Lu/Hf ratio when included in omphacite. This allows for increased precision and a reduced sample size required for analysis.

Samples were spiked with a mixed ^{176}Lu–^{178}Hf spike and a mixed ^{149}Sm–^{150}Nd spike. It is important to note that Lu–Hf and Sm–Nd ages were obtained on the exact same dissolved sample. The less-pure garnet fraction was only spiked with the ^{176}Lu–^{178}Hf spike because it was anticipated that Sm/Nd ratios would be very low, and thus Sm–Nd analyses are not available. To minimize errors in spike subtraction, the ^{178}Hf spike that was used had been adjusted to a $^{176}Hf/^{177}Hf$ ratio of 0.28268 so that it is similar to that of samples (Scherer et al., 1995); this allows a total spike approach and avoids uncertainties in aliquoting. Following spike addition, samples were dissolved in a 10:1 mixture of HF and HNO_3 using Parr Instrument high-pressure dissolution vessels. Ion exchange separation of Hf, Lu, Sm, and Nd was accomplished using Eichrom Ln-spec resin where an initial bulk REE and major-element cut was extracted from the high field strength elements in 6 M HCl, followed by separation of Hf using a combination of citric acid, H_2O_2, and HCl and a mixture of HCl and HF. The bulk REE cut was separated from the major elements using cation exchange resin and HCl. Lu was separated from the bulk of the REEs using 0.1 M 2-methylactic acid and cation exchange resin at a pH of 3.8, followed by extraction of the remaining REE. Separation of Sm and Nd was accomplished using 0.15 and 0.2 M 2-methylactic acid and cation exchange resin at a pH of 4.6.

Isotopic analysis of Lu and Hf was accomplished using a Micromass *IsoProbe* MC-ICPMS at the University of Wisconsin, Madison and followed the methods of Lapen et al. (2004). During this study the measured $^{176}Hf/^{177}Hf$ of JMC-475 was 0.282156±14 (2-SD; $n=7$). Sm and Nd isotope analysis was accomplished using a VG Instruments *Sector 54* TIMS at the University of Wisconsin, Madison following the methods of Lapen et al. (2005) for Sm and Beard et al. (1995) for Nd. Nd was analyzed as NdO^+ using single Re filaments loaded with silica gel and phosphoric acid, and an O_2 gas bleed ($P \sim 1\times10^{-6}$ Torr). Filament current was adjusted to maintain a $^{144}Nd^{16}O$ ion intensity of 2×10^{-12} A, and typically 200 ratios were collected per analysis. Oxygen isotope corrections were made using $^{18}O/^{16}O=0.002110$ and $^{17}O/^{16}O=0.000387$, and Nd isotope ratios were corrected for instrumental mass fractionation using a power law normalization to $^{146}Nd/^{144}Nd=0.7219$. The measured $^{143}Nd/^{144}Nd$ of two ultra-pure in-house standards obtained from Ames Laboratory were: Ames I $^{143}Nd/^{144}Nd$ was 0.512133±18 (2-SD; $n=8$) and for Ames II $^{143}Nd/^{144}Nd$ was 0.511964±21 (2-SD; $n=8$). The measured $^{143}Nd/^{144}Nd$ ratio of BCR-1 (pooled 8 unspiked samples and 7 spike-subtracted ratios) was 0.512638±24 (2-SD; $n=15$). Based on replicate analysis of spiked standard solutions and rock standards the reproducibility of Lu/Hf and Sm/Nd is ±0.2% (2-SD).

Lu–Hf ages were calculated using the decay constant of Scherer et al. (2001). Lu–Hf and Sm–Nd isochrons were produced with the program *Isoplot* (Ludwig, 2001). Our reported errors only include analytical errors. Errors in the decay constants for ^{176}Lu and ^{147}Sm would increase the overall age error by approximately 1 Ma in the 'older' eclogites (see below) and ~0.5 Ma in the 'younger' eclogites (see below).

Major-element zoning within grains was obtained using a Cameca SX-50 electron microprobe at the University of California, Santa Barbara. Peak metamorphic pressures and temperatures have already been published for one sample in our study; for other samples, they were determined using Fe–Mg exchange between garnet and pyroxene (Brey and Koehler, 1990; Carswell and Harley, 1990; Krogh Ravna, 2000) and the Al solubility in orthopyroxene in equilibrium with garnet (Brey and Koehler, 1990; Aranovich and Berman, 1997). Because these equilibria have relatively similar slopes, the intersections are imprecisely determined. This problem is compounded by our reliance on Fe–Mg exchange, which is unlikely to record peak temperatures at UHP conditions.

4. Sample descriptions

Five samples were chosen out of nearly 50 collected throughout the western portion of the WGR. The samples were selected based on i) preservation of the peak mineral assemblage, ii) inclusion types and textures, and iii) geologic context. Two were taken from HP domains, two from UHP domains, and one from a HP–UHP transition (Root et al., 2004). Neither the HP eclogites nor the UHP eclogites exhibit the specific textures once considered characteristic of each group (Wain et al., 2000). The two HP eclogites of this study have a low modal abundance of hypidioblastic to idioblastic garnet that is homogeneous with respect to its major-element composition (Fig. 2) and does not include prograde metamorphic minerals. The UHP samples studied have more garnet, but are otherwise not texturally distinguishable from the HP samples. Only the eclogite from Verpeneset in the HP–UHP transition has a 'typical' HP texture, in which the sample has a relatively low modal abundance of hypidioblastic to idioblastic garnet with prograde major-element zoning (Fig. 2); inclusions of primary amphibole in the interior of the garnets are consistent with prograde garnet growth. Clinopyroxenes in all samples are unzoned.

Sample 9901B1, previously studied by Krogh (1982) and Root et al. (2004), is an unretrogressed, foliated kyanite–phengite–coesite eclogite (Fig. 3) from Verpeneset at the southern edge of the Nordfjord UHP domain (Fig. 1). It consists of mostly xenoblastic omphacite (<100 μm) is very minor. Hacker (2006b) estimated that crystallization occurred at 676±68 °C and 2.51±0.34 GPa.

Sample 9826J is a weakly retrogressed HP eclogite (Fig. 3) from NW Gurskøy and contains 1–5 mm, randomly oriented, xenoblastic omphacite (~50 vol.%)

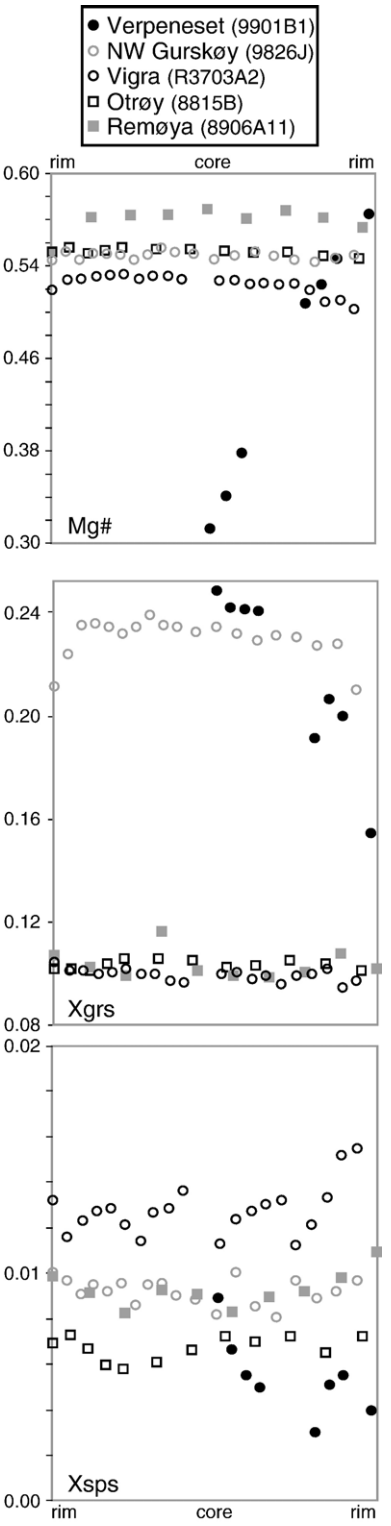
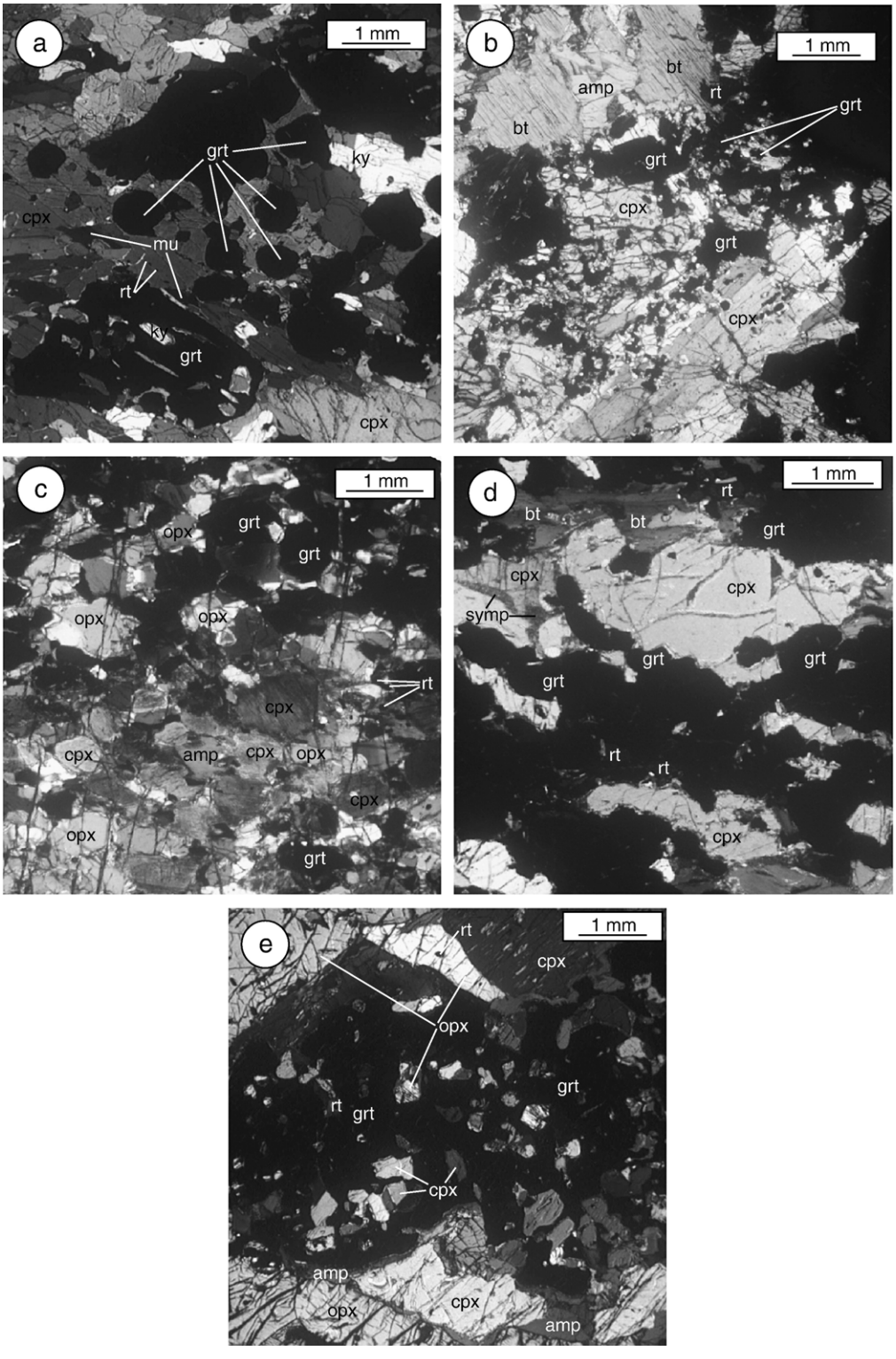


Fig. 2. Major-element profiles of garnets from core to rim (Verpeneset) and from rim to rim (all others). Open symbols correspond to the upper scale; solid symbols correspond to the lower scale. Aside from minor resorption at rims, only garnets from Verpeneset show significant zoning.

grains, of which a few contain areas of abundant μm-scale rutile inclusions. Many omphacite grains exhibit undulatory extinction; a few have subgrains that were produced by eclogite-facies dislocation creep. Garnet (~40 vol.%) occurs as ~100 μm hypidioblastic grains that are speckled throughout omphacite and in massive pure-



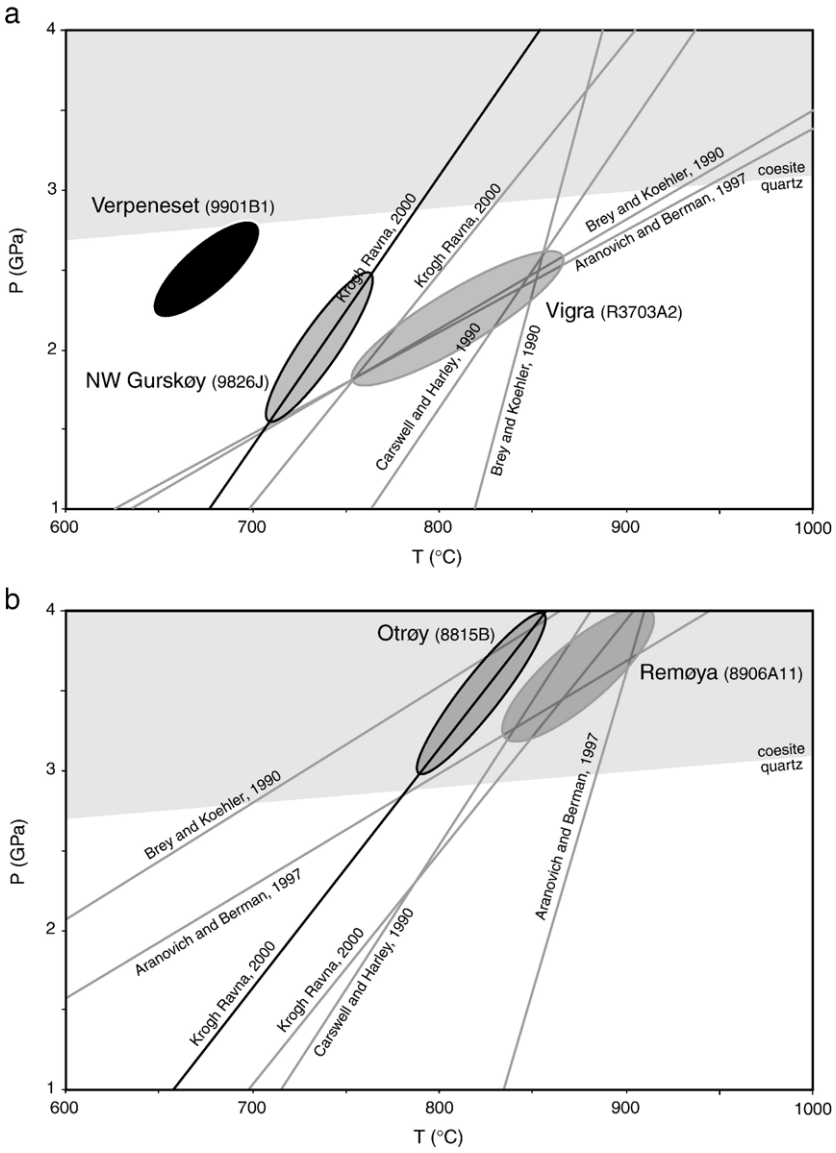


Fig. 4. Pressure and temperature data for eclogites from this study. Ellipses indicate approximate equilibration pressures and temperatures. (a) HP and HP/UHP transitional eclogites from Verpeneset (black circle), Vigra (grey lines) and NW Gurskøy (black line). (b) UHP eclogites from Remøya (grey lines) and Otrøy (black line).

garnet zones with inclusions of rutile, omphacite, and amphibole. Where μm-scale rutile inclusions are present in omphacite, they are also abundant in the cores of nearby small garnets. Biotite (<10 vol.%) forms isolated patches of a few grains up to 2 mm, where it is associated with coarse amphibole (<5 vol.%); the textures of both phases suggest stability at high pressures. Large (~500 μm) rutile (<2 vol.%) grains are also present. Symplectite, along omphacite boundaries, is rare. Mapping and petrography by Root et al. (2005) suggest that 9826J is a HP eclogite that likely formed at pressures of 2.0–2.7 GPa. Garnet–clinopyroxene thermometry indicates that at pressures of

Fig. 3a–c. Photomicrographs of the HP eclogites and the HP/UHP transitional eclogite. a) Verpeneset eclogite (9901B1). b) Eclogite from NW Gurskøy (R9826J). c) Vigra eclogite (R3703A2). With the exception of amphibole (amp), all labeled minerals in all samples are prograde or peak phases (garnet: grt, clinopyroxene: cpx, rutile: rt, orthopyroxene: opx). d and e. Photomicrographs of the eclogites from the Soroyane and Nordøyane UHP domains. a) Otrøy eclogite (8815B). b) Remøya eclogite (8906A11). With the exception of amphibole (amp) and symplectite (symp), all labeled minerals in all samples are prograde or peak phases (garnet: grt, clinopyroxene: cpx, rutile: rt, orthopyroxene: opx).

2.0–2.7 GPa, temperatures of recrystallization were ~740–780 °C (Fig. 4a, Table 1); this is a minimum because of the probability of Fe–Mg exchange.

Sample R3703A2 (Fig. 3) is from a layered HP ultramafic–mafic body on SW Vigra (Fig. 1). The sample is mildly retrogressed and contains mostly omphacite (<5 vol.% of total volume). Garnets are hypidioblastic and range in size from 0.1 to 1.5 mm (typically ~500 μm). Inclusions of omphacite, rutile, and biotite occur in garnet, typically in the cores. Orthopyroxene (0.2–1 mm) is xenoblastic, has minor subgrains, common undulatory extinction, and minor rutile inclusions. Biotite (~5 vol.%) varies greatly in size (10 μm–1 mm), is xenoblastic, and uncommon in omphacite-rich bands. Rutile is a minor phase (~2 vol.%), ranging from 50 to 200 μm in size. Garnet–clinopyroxene–orthopyroxene thermobarometry yields temperatures of 750–850 °C and pressures of 1.8–2.5 GPa (Fig. 4a, Table 1). Because the minerals used for thermobarometry in this sample are homogeneous with respect to major elements, these pressures and temperatures are minima.

Eclogite sample 8815B (Fig. 3) from Otrøy within the Nordøyane UHP domain (Fig. 1) is weakly retrogressed and contains mostly garnet (~50 vol.%) and omphacite (~40 vol.%). There is minimal symplectite (2–4 vol.%) along omphacite grain boundaries and cracks. The omphacite grains are large (up to several mm), contain rare silica rods, have undulatory extinction, and define a weak lineation; rare grains have straight-walled subgrains, implying significant dislocation creep at eclogite-facies conditions. Many garnets occur in 400–800 μm diameter aggregates. Rutile inclusions are very rare in garnet and omphacite, except for a very few garnet cores that have abundant rutile (tens of μm). Xenoblastic biotite, 0.2–2 mm in diameter, is relatively minor (<5 vol.%), rutile is minor (<2 vol.%; 200–300 μm), and zircon is very minor (<50 μm). Because of its close proximity to the microdiamond-bearing gneiss on Fjørtoft (Dobrzhinetskaya et al., 1995) and the ~3.2 GPa garnet peridotite at Ugelvik on Otrøy (van Roermund and Drury, 1998), sample 8815B likely crystallized within the coesite stability field. Garnet–clinopyroxene thermometry indicates temperatures in excess of ~800 °C at these pressures (Fig. 4b, Table 1). Because garnets and pyroxenes are unzoned with respect to Fe and Mg in this sample, peak temperatures may have been higher.

Sample 8906A11 (Fig. 3) is an undeformed and mildly retrogressed eclogite from Remøya in the Soroyane UHP domain (Fig. 1). It consists of omphacite (35 vol.%), garnet (25 vol.%), and orthopyroxene (35 vol.%). Omphacite is typically 1–3 mm in size, xenoblastic, contains minor silica rods and rutile inclusions, and is rimmed by retrograde amphibole (<5 vol.%). Garnet is massive and poikiloblastic, surrounding large grains of orthopyroxene (100–500 μm), rutile (50–100 μm), and omphacite (100–500 μm). Hypersthene is xenoblastic and large (1–5 mm) and contains few inclusions (rutile > omphacite). Zircon is small (<50 μm), very minor (<<1 vol.%) and exists along grain boundaries. Homogeneous garnets, clinopyroxenes and orthopyroxenes indicate that temperatures were sufficiently high for major-element diffusion

Table 1
Representative analyses used for thermobarometric estimates

Sample[a]	SiO_2	TiO_2	Al_2O_3	FeO′	MgO	MnO	CaO	K_2O	Na_2O	Cr_2O_3	Total
9826J (NW Gurskøy)											
gt	38.5	0.0	23.6	16.9	0.4	0.4	8.6	0.0	0.0	0.0	99.7
cpx	54.9	0.1	6.5	3.7	12.6	0.0	18.6	0.0	3.5	0.0	100.0
R3703A2 (Vigra)											
gt	39.9	0.0	21.8	21.3	12.6	0.6	3.8	0.0	0.0	1.0	100.9
cpx	54.8	0.1	5.1	5.5	11.9	0.0	16.9	0.0	4.0	1.6	99.9
opx	55.5	0.0	0.7	15.3	28.8	0.2	0.2	0.0	0.0	0.1	100.9
8815B (Otrøy)											
gt	40.0	0.0	22.6	19.3	13.7	0.3	3.9	0.0	0.0	0.0	100.0
cpx	54.9	0.2	7.5	4.7	11.4	0.0	16.0	0.0	4.7	0.0	99.4
8906A11 (Remøya)											
gt	40.2	0.0	22.4	18.3	14.7	0.4	3.9	0.0	0.0	0.3	100.1
cpx	54.2	0.0	3.1	7.2	13.2	0.1	18.7	0.0	2.9	0.3	99.7
opx	56.9	0.0	0.4	12.4	31.1	0.1	0.2	0.0	0.0	0.1	100.4

Analysis accomplished with a Cameca SX-50 electron microprobe at the University of California, Santa Barbara.
[a]For sample names and locations, see Fig. 1.

Table 2
Major-element data for eclogites from the Western Gneiss Region, Norway

Sample[a]	SiO_2	TiO_2	Al_2O_3	FeO^t	MgO	MnO	CaO	K_2O	Na_2O	P_2O_5	Total
9901B1 (Verpeneset)	48.33	0.78	18.49	8.08	9.96	0.15	11.52	0.15	2.76	0.06	100.29
9826J (NW Gurskøy)	44.77	0.37	15.47	10.52	11.61	0.23	11.69	0.25	1.61	0.01	96.55
R3703A2 (Vigra)	48.76	1.31	8.14	13.09	19.72	0.24	5.42	0.18	0.94	0.01	97.83
8815B (Otrøy)	44.66	1.21	15.83	11.86	12.15	0.18	8.65	0.17	1.97	0.21	96.90
8906A11 (Remøya)	48.12	1.20	7.90	10.25	18.33	0.18	9.46	0.06	0.99	0.15	96.66

Analysis accomplished with an X-ray fluorescence spectrometer (XRF) at Washington State University (Johnson et al., 1999).
[a]For sample names and locations, see Fig. 1.

in this sample. Garnet–clinopyroxene–orthopyroxene thermobarometry thus indicates minimum pressures and temperatures of 3.2–4.2 GPa and 825–900 °C, respectively (Fig. 4b, Table 1).

5. Results

Major- and trace-element compositions, as well as initial Nd and Hf isotope ratios, indicate that the eclogites

Table 3
Trace- and rare earth element data for eclogites from the Western Gneiss Region, Norway

Concentration[a] (ppm)	Sample[b]				
	9901B1 (Verpeneset)	9826J (NW Gurskøy)	R3703A2 (Vigra)	8815B (Otrøy)	8906A11 (Remøya)
Ba	28	42	28	55	7.8
Cr	221	116	5730	92.7	1260
Cs	1.2	0.11	0.33	0.41	1.6
Cu	90	310	37	36	99
Ga	14	12	12	14	14
Hf	1.35	0.659	0.583	2.07	1.82
Nb	0.88	2.7	3.0	5.8	8.8
Ni	155	103	554	234	819
Rb	4.7	13.1	8.3	4.3	5.0
Sc	20	52	35	23	29
Sr	41	86	51	300	137
Ta	0.06	0.05	0.07	0.3	0.6
Th	0.05	0 06	1	0.6	0.7
V	136	177	252	171	211
Y	16.9	12.1	13.3	16.9	16.2
Zn	57	63	130	87	100
Zr	60	21	32	80	66
La	0.63	0.53	0.72	9.19	7.76
Ce	1.89	0.94	2.20	20.1	21.8
Pr	0.33	0.27	0.40	2.7	3.1
Nd	1.96	1.89	2.43	12.4	14.9
Sm	0.93	1.3	1.2	3.4	4.3
Eu	0.48	0.45	0.54	1.2	1.1
Gd	1.77	1.83	1.76	3.33	3.94
Tb	0.40	0.33	0.33	0.53	0.58
Dy	2.86	2.15	2.15	3.24	3.26
Ho	0.63	0.44	0.45	0.65	0.63
Er	1.73	1.12	1.27	1.73	1.61
Tm	0.24	0.16	0.19	0.24	0.23
Yb	1.5	0.94	1.3	1.4	1.4
Lu	0.22	0.14	0.20	0.22	0.21

[a]Analysis performed by inductively coupled plasma mass spectrometry (Cs, Ta, U, and REE) or X-ray florescence (remaining elements) at the Geoanalytical Lab at Washington State University. Data reduction followed Knaak and Hooper ((1994) and Johnson et al. (1999) for ICPMS and XRF, respectively.
[b]For sample names and locations, see Fig. 1.

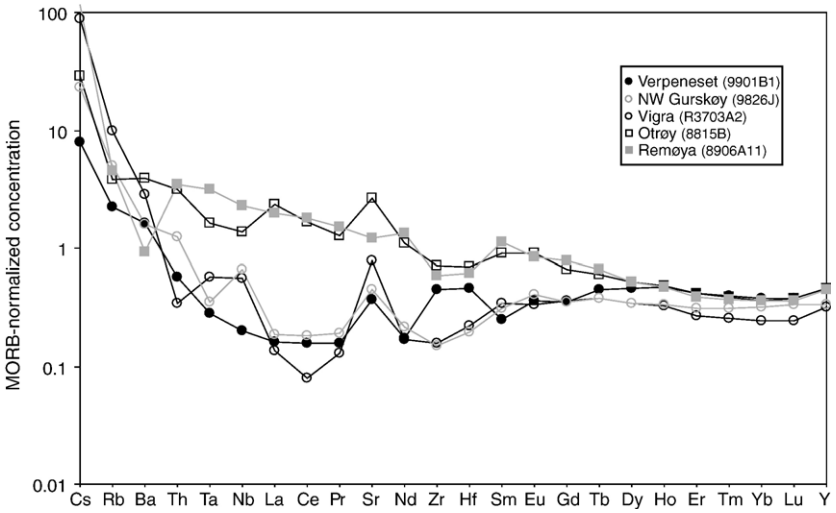


Fig. 5. MORB-normalized spider diagram (Hofmann and Welin, 1988) of the studied eclogites shows that, with the exception of Verpeneset, the 'younger' and 'older' eclogites comprise distinct groups whose members have similar trace-element concentrations.

studied reflect a variety of protoliths. Below we discuss the whole-rock chemical and isotopic data and then the Sm–Nd and Lu–Hf geochronological data. Two samples in this study can be distinguished from the others based on similar trace-element compositions, isotopic signatures, and younger ages. It is therefore convenient to divide the samples from the study into two different groups: the two that yield relatively young ages, or the 'younger' eclogites, and the three that yield relatively older ages, or the 'older' eclogites.

5.1. Whole-rock elemental and isotopic data

Samples 9901B1 (Verpeneset), 9826J (NW Gurskøy), and 8815B (Otrøy) have Al_2O_3 and MgO contents of 15.5–18.5 wt.% and 10.0–12.2 wt.% respectively (Table 2), suggesting that these samples most closely match compositions expected for basaltic magmas. This interpretation is consistent with FeO and CaO contents, as well as moderate Cr and Ni contents of 93–221 ppm and 103–234 ppm, respectively (Table 3). Samples 9901B1 and 9826J contain very low LREE and incompatible element contents (Fig. 5), suggesting derivation from a depleted mantle source and/or the effects of crystal accumulation. In contrast, sample 8815B, has significantly higher LREE contents that are closer to those expected for basaltic magmas that are moderately enriched relative to MORB (Fig. 5).

The low Al_2O_3 and high MgO contents of samples R3703A2 (Vigra) and 8906A11 (Otrøy), at 7.9–8.1 wt.% and 18.3 and 19.7 wt.%, respectively (Table 2), indicate that these samples have a strong cumulate component. This interpretation is supported by exceptionally high Cr and Ni contents of 1262–5734 ppm and 554–819 ppm, respectively (Table 3). These characteristics are similar to other orthopyroxene-bearing eclogites from the WGR (Carswell and Harvey, 1985; Austrheim et al., 2003). Austrheim et al. (2003) postulated that the protoliths of such orthopyroxene eclogites were similar to the pyroxenite in the Hustad igneous complex, a cumulate of mantle-derived melts. However, they have remarkably distinct trace-element contents (Fig. 5) and $\varepsilon_{Nd(0)}$ and $\varepsilon_{Hf(0)}$ values (Fig. 6) that could reflect variable degrees of metasomatism during metamorphism.

Present-day whole-rock Nd and Hf isotope compositions of the samples vary greatly: $\varepsilon_{Nd(0)}$ varies from 11.2 to −8.6, and $\varepsilon_{Hf(0)}$ varies from 13.0 to −13.2 (Tables 4 and 5). Because it is difficult to know the protolith ages,

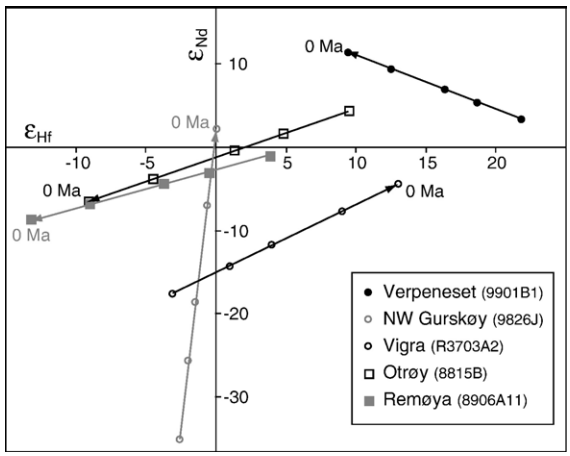


Fig. 6. ε_{Nd} and ε_{Hf} data for samples from this study. Trend lines connect ε_{Nd} and ε_{Hf} at times 1600, 1200, 900, 400, and 0 Ma.

Table 4
Lutetium–Hafnium isotope data for eclogites from the Western Gneiss Region, Norway

Sample	Concentration (ppm)		$^{176}Lu/^{177}Hf$	$^{176}Hf/^{177}Hf$	Age	$\varepsilon_{Hf(0)}$[a]
	Lu	Hf			(Ma)	
9901B1 (Verpeneset)						
grt[b]	0.57	0.27	0.2955	0.285196±17		
grt[c]	0.57	0.65	0.1246	0.283868±7		
cpx	0.01	0.80	0.0012	0.282895±7		
wr	0.23	1.46	0.0220	0.283041±3	419.5±4.3	9.5
9826J (NW Gurskøy)						
grt[b]	0.28	0.15	0.2686	0.284580±17		
cpx	0.01	0.30	0.0025	0.282537±5		
wr	0.15	0.54	0.0384	0.282796±4		
wr	0.15	0.58	0.0359	0.282774±4	412.0±4.7	0.1
R3703A2 (Vigra)						
grt[b]	0.68	0.23	0.4164	0.285975±5		
cpx	0.01	0.68	0.0023	0.282748±5		
wr	0.20	0.63	0.0445	0.283129±4	411.5±4.1[d]	
wr	0.19	0.57	0.0484	0.283140±8	416.3±3.7[e]	13.0
8815B (Otrøy)						
grt[b]	0.40	0.52	0.1072	0.283164±5		
grt[c]	0.39	1.04	0.0537	0.282793±3		
wr	0.23	1.99	0.0161	0.282514±4	380±14	−9.1
8906A11 (Remøya)						
grt[b]	0.65	0.99	0.0930	0.282915±4		
grt[c]	0.66	1.18	0.0797	0.282830±4		
cpx	0.01	1.61	0.0010	0.282282±4		
wr	0.21	1.70	0.0175	0.282398±3	369±11	−13.2

Analysis accomplished by isotope dilution multi-collector plasma mass spectrometry at University of Wisconsin, Madison. Decay constant used for ^{176}Lu is 1.865×10^{-11} yr^{-1} Scherer et al., 2001). Errors in Hf isotope ratios are expressed as 2SE from internal measurements and refer to least significant digits. Isochron ages were calculated using Isoplot v. 3.0. Errors calculated for ages are based solely on external reproducibility of spiked standards and whole-rock samples (errors for individual analyses are negligible): $^{176}Lu/^{177}Hf=0.2\%$, $^{176}Hf/^{177}Hf=0.005\%$.
[a]$\varepsilon_{Hf(0)}$ was calculated using present-day ratios of $^{176}Hf/^{177}Hf=0.282772$ and $^{176}Lu/^{177}Hf=0.0334$ for CHUR (Blichert-Toft and Albarède, 1997).
[b]Purer garnet separate.
[c]Less pure garnet separate.
[d]gt–wr age.
[e]gt–cpx age.

the whole-rock Nd and Hf isotope compositions are plotted as temporal evolution lines in Fig. 6. Evolution lines for eclogites 8815B and 8906A11 (Otrøy and Remøya, respectively) are similar (Fig. 6), suggesting that at any given time, the Nd and Hf isotope compositions were similar. In contrast, the Nd–Hf temporal evolution trends for the three other eclogites are all distinct (Fig. 6), indicating that, regardless of the uncertainty in protolith ages, their Nd and Hf isotope compositions did not overlap.

5.2. Geochronology

All three 'older' eclogite samples gave high-precision Lu–Hf ages and two of them gave high-precision Sm–Nd ages. The high precision of ±4 to 6 Ma (Tables 4 and 5) reflects the generally high Lu/Hf and Sm/Nd ratios that characterize the 'older' eclogite suite (Fig. 5). Parent/daughter enrichments for garnet relative to the whole rock, expressed as $(Lu/Hf)_{gt}/(Lu/Hf)_{wr}$ and $(Sm/Nd)_{gt}/(Sm/Nd)_{wr}$, ranged from 7.2 to 13.4 and 0.7 to 5.7, respectively, indicating a stronger relative enrichment in Lu/Hf ratio for the garnet relative to Sm/Nd, as expected based on partition coefficients. The sample from Vigra is the only one that yielded a high MSWD (10.7) for all fractions. We prefer the grt–cpx age (416.3±3.7 Ma), as it dates the eclogite-defining assemblage; it may be older than the grt–wr rock age (411.5±4.1 Ma) solely because its pyroxene separate contained numerous rutile inclusions, although the grt–cpx age lies within error of

Table 5
Samarium–neodymium isotope data for eclogites from the Western Gneiss Region, Norway

Sample	Concentration (ppm)		$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Age	$\varepsilon_{Nd(0)}$[a]
	Sm	Nd			(Ma)	
9901B1 (Verpeneset)						
grt[b]	0.16	0.53	0.259	0.513206±9		
wr	0.87	2.25	0.378	0.513214±9		11.2
9826J (NW Gurskøy)						
grt[b]	1.24	0.53	1.409	0.515458±6		
cpx	1.42	3.62	0.237	0.512415±5		
wr	1.30	2.09	0.378	0.512749±5	398.3±5.5	2.2
R3703A2 (Vigra)						
grt[b]	1.24	0.51	1.478	0.515622±8		
wr	1.11	2.59	0.261	0.512411±11	402.7±4.6	−4.4
8815B (Otrøy)						
grt[b]	1.15	1.11	0.628	0.513534±8		
cpx	3.25	11.50	0.171	0.512368±5		
wr	3.27	13.79	0.144	0.512306±5	388±10	−6.5
8906A11 (Remøya)						
grt[b]	1.29	1.04	0.753	0.513673±8		
cpx	4.76	14.25	0.202	0.512275±5		
wr	4.18	15.80	0.160	0.512197±4	384±11	−8.6

Analysis accomplished by isotope dilution multi-collector plasma mass spectrometry at University of Wisconsin, Madison. Decay constant used for ^{147}Sm is 6.54×10^{-12} yr^{-1}. Errors in Nd isotope ratios are expressed as 2SE and refer to least significant digits. Isochron ages were calculated using Isoplot v. 3.0. Errors calculated for ages are based solely on external reproducibility of spiked standards and whole-rock samples (errors for individual analyses are negligible): $^{147}Sm/^{144}Nd=0.5\%$, $^{143}Nd/^{144}Nd=0.005\%$.
[a]$\varepsilon_{Nd(0)}$ was calculated using present-day ratios of $^{146}Nd/^{144}Nd=0.7219$ and $^{143}Nd/^{144}Nd=0.512638$ for CHUR.
[b]Purer garnet separate.

the grt–wr age. Because the rutile occurs as inclusions within the omphacite, it should be older, even though it, like the omphacite, grew during an increase in pressure. Nevertheless, either age supports our conclusions below. For all samples in which we obtained more than one garnet separate based on variable purity (see above), the highest purity separates contained a lower concentration of Hf and a higher Lu/Hf ratio than the less pure separate, suggesting that the less-pure fractions contained inclusions that had relatively high Hf concentrations; such inclusions would most likely be rutile or zircon.

Two of the 'older' eclogites yielded Sm–Nd ages that are younger than the Lu–Hf ages obtained on the exact same dissolved mineral separates (Tables 4 and 5). In contrast, the Sm–Nd and Lu–Hf ages for the two 'younger' eclogite samples overlap (Tables 4 and 5). The Sm–Nd and Lu–Hf ages for the 'younger' eclogites range from 388 to 369 Ma, compared to those of the 'older' eclogites at 420 to 398 Ma, and the 'younger' eclogites have ages that are much younger than those determined by U–Pb geochronology from the same area (Terry et al., 2000; Carswell et al., 2003b; Krogh et al., 2004). The age uncertainties are higher for the two 'younger' eclogites because the Lu/Hf and Sm/Nd ratios for garnet are lower (Tables 4 and 5), reflecting the lower ratios in the whole rocks (Table 3). $(Lu/Hf)_{gt}/(Lu/Hf)_{wr}=5.3$ and 6.7 for the two 'younger' eclogites, and both samples have $(Sm/Nd)_{gt}/(Sm/Nd)_{wr}=3.7$. The spread in Sm/Nd ratios for sample 9901B1 (Verpeneset) was insufficient to obtain a meaningful Sm–Nd isochron.

6. Discussion

Consideration of distribution coefficients (Green et al., 2000) indicates that eclogites that have not been subjected to significant heating above the Lu–Hf and Sm–Nd blocking temperatures will have garnet in which the Lu/Hf ratios are highest in the core and Sm/Nd ratios are relatively constant from core to rim, assuming equilibrium garnet-matrix element partitioning during garnet growth. The contrast in core-to-rim zonation in Lu/Hf and Sm/Nd ratios for garnet is even more extreme under conditions

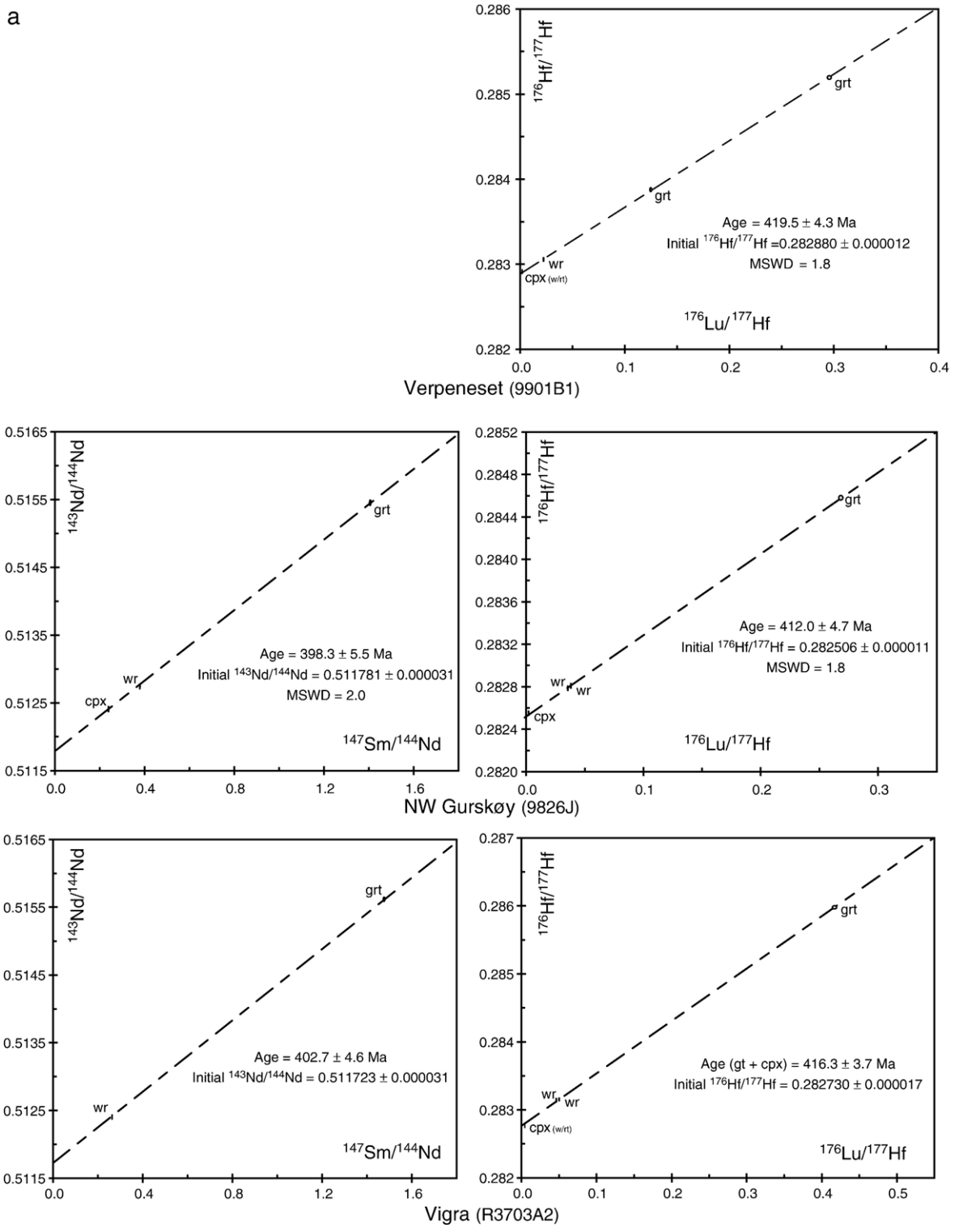


Fig. 7. Lu–Hf and Sm–Nd isochrons from three ‘older’ (a) and two ‘younger’ (b) eclogites.

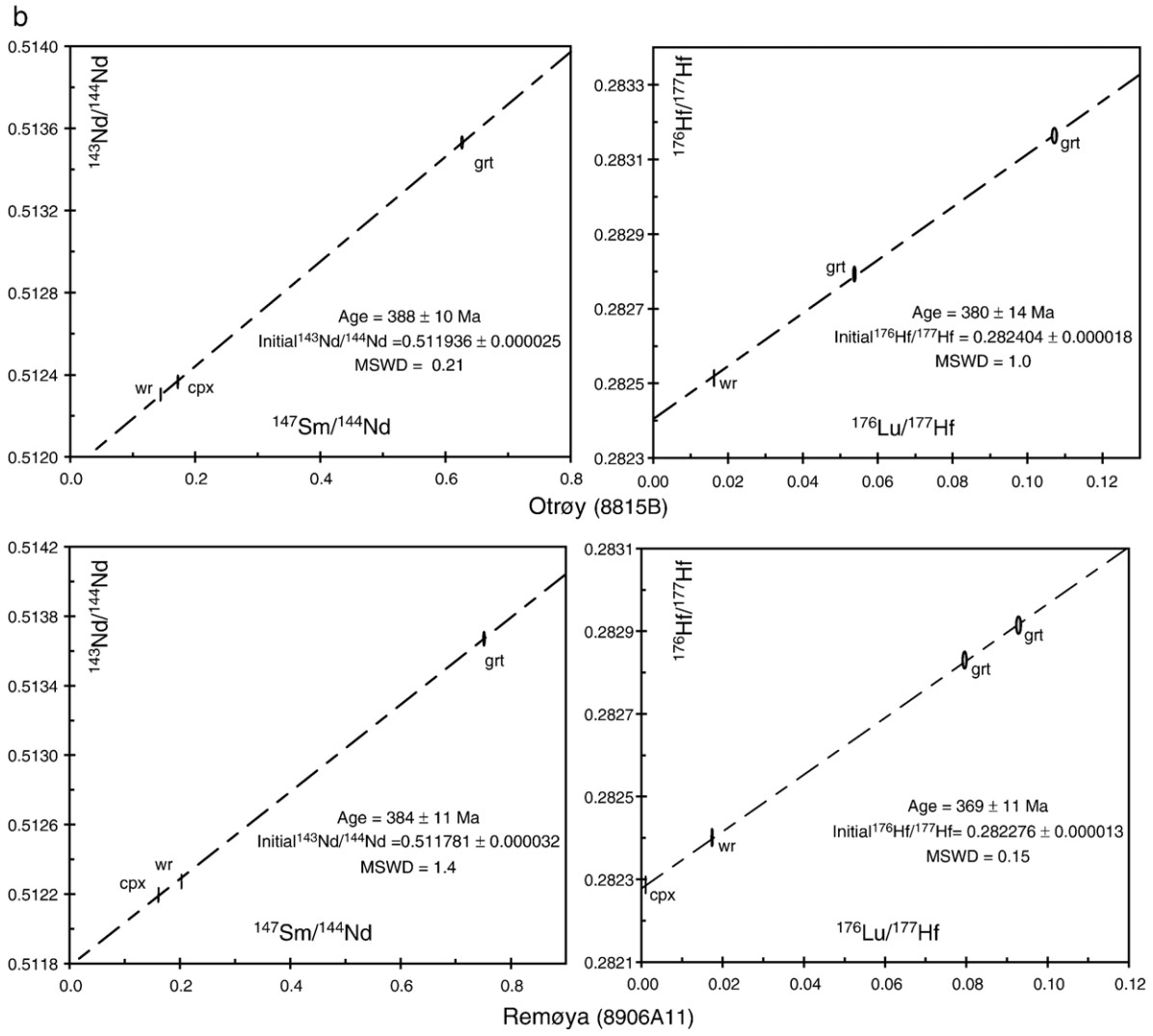


Fig. 7 (*continued*).

of diffusion-limited growth. Lu/Hf ratios are very high in the core, but rapidly decrease toward the rim under diffusion-limited growth, whereas the similar diffusion coefficients for Sm and Nd produce low Sm/Nd ratios from core to rim that are approximately equal to those of the matrix (Skora et al., 2006). These patterns lead to the prediction that the Lu–Hf ages will be older than Sm–Nd ages, especially under relatively cool and dry conditions where trace-element transport is likely to be diffusion limited (Skora et al., 2006). The contrast in Lu–Hf and Sm–Nd ages, therefore, provides insight into the time-scales of prograde garnet growth (Lapen et al., 2003). The prograde history of garnet growth determined through comparative Lu–Hf and Sm–Nd geochronology may, however, be lost if temperatures during metamorphism exceed the Lu–Hf and Sm–Nd blocking temperatures for a period of time sufficient to re-equilibrate the parent and/or daughter isotopes with their surroundings. In such cases, the ages would reflect cooling. Below we discuss the contrasting geochronology for the 'older' and 'younger' eclogites in this interpretive framework, and conclude with a discussion of the results in the context of the tectonothermal history of the (U)HP terrane of the WGR.

6.1. 'Older' eclogites

The peak metamorphic temperatures for the three 'older' eclogite are likely to have been below the closure temperature of the Lu–Hf and Sm–Nd systems. The closure temperature of the Sm–Nd system for garnet in

slowly cooled terranes (<10 °C/m.y.) may be ~730 °C (Ganguly and Tirone, 1999; Van Orman et al., 2002). In the rapidly cooled WGR (~20–30 °C/m.y.; Carswell et al, 2003b; Root et al., 2004, 2005), the Sm–Nd closure temperatures for garnet were likely higher, perhaps by as much as several hundred degrees (Van Orman et al., 2002). Lu–Hf closure temperatures for garnet-bearing rocks appear to be hotter than for Sm–Nd (Scherer et al., 2000). One possible interpretation, therefore, is that the consistent 14 m.y. age difference between the Lu–Hf and Sm–Nd ages for samples R3703A2 (Vigra) and 9826J (NW Gurskøy) reflects a differential record of the two isotope systems in terms of prograde garnet growth, as proposed by Lapen et al. (2003). In this case the blocking temperature for both Lu–Hf and Sm–Nd would be higher than the hottest 'older' eclogite (Vigra), i.e. 750–850 °C. A second possibility is that the Lu–Hf ages of the 'older' eclogites are prograde ages and that the younger Sm–Nd ages reflect cooling through the blocking temperature of Sm–Nd. In this case, the blocking temperature of Lu–Hf must have been higher than 750–850 °C (Vigra) and that of Sm–Nd lower than ~740–780 °C (NW Gurskøy). Unfortunately, most of the other Sm–Nd ages of eclogites from the WGR (Fig. 1) are either two-point isochrons and/or overlap both the Lu–Hf and Sm–Nd ages of the 'older' eclogites from this study, thus providing little insight into understanding the blocking temperature of Sm–Nd in eclogites from the WGR. Many U–Pb zircon ages, however, precisely date (U)HP metamorphism in eclogites at ~405–400 Ma implying metamorphic-mineral growth at those times; this is consistent with the former interpretation which suggests that the Lu–Hf and Sm–Nd ages represent prograde garnet growth, where Lu–Hf ages should be older than Sm–Nd ages.

In either case, the initiation of garnet growth during prograde metamorphism must have predated the Lu–Hf age; we suggest that garnet growth (upper blueschist or lower eclogite facies) in the 'older' eclogites began during the early stages of continental subduction, between ~425 and ~420 Ma, as suggested by Hacker and Gans (2005). The two Sm–Nd ages place constraints on the latest time at which eclogite was stable. If the temperature never exceeded the blocking temperature for Sm–Nd, garnet growth likely continued beyond the time recorded by the Sm–Nd age (Lapen et al., 2003), and that age is a maximum estimate for the end of eclogite stability. Otherwise, the age likely represents the beginning stages of cooling, and hence exhumation, from HP depths.

The coldest sample, 9901B1 from Verpeneset, was metamorphosed at ~715 °C and has insufficient spread in Sm/Nd ratios between garnet and whole rock to obtain a Sm–Nd isochron. Root et al. (2004) interpreted U–Pb zircon ages from Verpeneset and elsewhere in the WGR to indicate that eclogite-facies metamorphism occurred at 405–400 Ma. The 419.5±4.3 Ma Lu–Hf age therefore suggests a minimum of 15–20 m.y. of prograde garnet growth—similar to what we propose for the other two 'older' eclogites. That this relatively cold sample did not produce a Sm–Nd isochron may reflect the possibility that garnet growth in cold eclogites is diffusion limited; at such cold temperatures, similar diffusivities for Sm and Nd may produce little enrichment in the Sm/Nd ratio of garnet relative to the matrix despite intrinsically significant distribution coefficients (Skora et al., 2006). Alternatively, the lack of spread in Sm/Nd ratios in sample 9901B1 could have been caused by the presence of LREE-rich inclusions in garnets, mainly zoisite. This sample was the only one to have significant amounts of such minerals.

6.2. 'Younger' eclogites

The Lu–Hf and Sm–Nd ages obtained for the Otrøy (8815B) and Remøya (8906A11) UHP eclogites are the same within analytical error (Fig. 7b). All four Lu–Hf and Sm–Nd ages determined in this study range from 388 to 369 Ma and have errors of ±10 to ±14 Ma. The Lu–Hf and Sm–Nd ages are significantly younger than any other U–Pb zircon or monazite age, or other Sm–Nd ages determined for eclogite-facies rocks from the WGR. They lie within error of $^{40}Ar/^{39}Ar$ ages determined for white mica for UHP rocks from the same area, which range from 384 to 369 Ma and have individual errors of ±3 Ma (Root et al., 2005).

It is surprising that the Lu–Hf and Sm–Nd ages for the two 'younger' eclogites are significantly younger than the ~420 to 400 Ma ages determined elsewhere in the WGR; several possibilities may explain this contrast. One possibility is that these samples record a previously unrecognized UHP event; this would require juxtaposition of separate eclogite terranes of distinct age within the WGR. Sample 8815B (388±10 Ma and 380±14 Ma) lies within 5 km of the majorite locality on Otrøy in the Nordøyane region (van Roermund and Drury, 1998). This region has U–Pb zircon ages of 411.5±1.2 Ma, 410±1 Ma, and 408±1 Ma (Lepsøya and Flemsøya; Krogh et al., 2004), a Sm–Nd age of 410±16 Ma (Flemsøya; Mørk and Mearns, 1986, recalculated by Root et al., 2004), and a prograde U–Pb monazite age of 415±7 Ma Terry et al., 2000). These ages for eclogite-facies metamorphism predate post-peak U–Pb zircon ages of 397±3 Ma and 394.5±2 Ma that are interpreted to reflect amphibolite-facies melting (Krogh et al., 2004). Similar relations exist for the Remøya eclogite with its young ages of 384±

11 Ma and 369±11 Ma, the Remøya eclogite must have been juxtaposed against the 398 Ma Gurskøy eclogite, the 402 Ma Vigra eclogite and the 401.6±1.6 and 412±12 Ma Hareidlandet eclogites (Jamtveit et al., 1991; Carswell et al., 2003b). Such juxtaposition would require post-370 Ma shear zones. No amphibolite-facies or younger shear zones have been identified that could be responsible for the required juxtapositions, in spite of field study intended to identify such features (Root et al., 2005).

A second possibility is that the garnets were not in equilibrium with the matrix minerals, or that unequilibrated inclusions exist in the garnets. If old inclusions with low-parent–daughter ratios and high daughter concentrations exist in garnets, isochron ages will be younger than actual ages (e.g. Prince et al., 2000). The small spread in Lu–Hf and Sm–Nd ratios for the two 'younger' eclogites might be taken to suggest that their garnets host significant inclusions. The Lu/Hf ratios in the 'younger' eclogites are significantly lower than the Sm/Nd ratios, implying that high-Hf inclusions might be the cause for such low Lu–Hf ages. Although the distribution coefficients of Lu, Hf, Sm, and Nd predict higher Lu/Hf ratios in garnet, there are, however, a number of factors that control the budget of these elements in garnet, such as whole-rock element ratios and mineral modes. Nevertheless, inclusions significantly older than the 'younger' eclogites are unlikely to have affected their ages because all four of the Lu–Hf points are isochronous. The Sm–Nd isochrons yield ages within error and are thus also unlikely to be significantly affected by the presence of inclusions.

Bulk-rock composition is unlikely to have played a role in producing discrepant ages for eclogites in this study. Thöni (2002) postulated that the average ages of the Saualpe–Koralpe eo-Alpine gabbroic eclogites were older than the average ages of nearby eclogite-facies pelites because the Mg-rich garnets of the pelitic eclogites were reset at lower temperatures or grew later than the Ca-rich garnets of the gabbroic eclogites. However, neither the garnet compositions nor the major-element bulk-rock compositions of the 'older' and 'younger' eclogites from this study are distinct. Nevertheless, the trace-element and REE compositions of the two groups are distinct. This could point to LREE-enriched late-stage metasomatism that reset the Lu–Hf and Sm–Nd isotope systems.

It is also unlikely that the ages are young because the rocks underwent metasomatism that postdated eclogite-facies metamorphism. Rocks that have undergone significant elemental exchange with their surroundings would likely be retrogressed and would be expected to record lower Fe–Mg exchange temperatures. These features are absent in the rocks studied. Furthermore, metasomatism would likely produce isotopic disequilibrium between garnet, pyroxene, and whole rock. The three- and four-point isochrons for both these samples, plus a remarkable lack of retrogression mineral assemblages, suggest that the isochrons indicate the true age of the 'younger' eclogites.

Our preferred interpretation is that the 'younger' eclogites from Otrøy and Remøya record the final stages of a >20 m.y.-long eclogite-facies metamorphism. The high equilibration temperatures, high Hf contents, and reduced spread in Lu/Hf and Sm/Nd ratios imply that the 'younger' eclogites reached sufficient temperatures for sufficient periods of time to have been open with respect to Hf and Nd. Although thermobarometry implies equally high equilibration temperatures in one of the 'older' eclogites (Vigra), the flat Fe–Mg profiles in the garnets and pyroxenes of these three eclogites imply that the actual temperatures of these eclogites were higher than those indicated by Fe–Mg exchange.

If the two 'younger' eclogites were open with respect to Hf and Nd, the ages signify the time of closure to Hf and Nd diffusion rather than the time of prograde or peak metamorphism. The coincidence of ε_{Nd} and ε_{Hf} and the similar incompatible-element nature of the Otrøy and Remøya eclogites (Figs. 5 and 6) may reflect similar metasomatic events at high temperatures and profound depths. The overlapping Lu–Hf, Sm–Nd, and $^{40}Ar/^{39}Ar$ ages—all relatively young compared to elsewhere in the WGR—reinforce previous interpretations that the UHP rocks of the WGR were exhumed rapidly (Root et al., 2005; Walsh et al., in press).

7. Conclusions

High-pressure and ultrahigh-pressure eclogites from the Western Gneiss Region of Norway record a range of Lu–Hf and Sm–Nd ages that reflect prograde garnet growth or cooling, depending upon the P–T history of the samples. The HP and transitional HP/UHP eclogites have Lu–Hf ages that are up to 20 m.y. older than the time of near-peak metamorphism, as estimated from Sm–Nd ages on the same samples or U–Pb ages previously determined from the same locality. Provided that the samples have not been heated above the closure temperatures of either of these systems, these results confirm the suggestion by Lapen et al. (2003) that the difference in Lu–Hf and Sm–Nd ages constrains the duration of prograde garnet growth. The contrasting Lu–Hf and Sm–Nd ages suggest initiation of prograde garnet growth in upper blueschist/lower eclogite-facies

conditions at ~425–420 Ma, continuing to peak conditions at ~405–400 Ma.

Two ultrahigh-pressure eclogites that crystallized above ~800 °C have indistinguishable Lu–Hf and Sm–Nd ages, and these ages are younger than the ~400 Ma ages that have been thought to mark the end of eclogite-facies metamorphism in the WGR. Lutetium–Hf and Sm–Nd ages for these two UHP samples lie between 388 and 369 Ma, and overlap $^{40}Ar/^{39}Ar$ white mica ages from the same or nearby localities. These results, as well as the enriched nature of the whole-rock trace-element and Nd and Hf isotope compositions suggest that the UHP samples underwent large-scale diffusion during peak conditions, followed by rapid exhumation and cooling. The Lu–Hf and Sm–Nd ages for the 'younger' UHP rocks are interpreted to reflect cooling at eclogite-facies conditions and not prograde garnet growth or peak metamorphic conditions.

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