Pressure- and stress-induced fabric transition in olivine from peridotites in the Western Gneiss Region (Norway): implications for mantle seismic anisotropy

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ABSTRACT The effects of pressure, water and differential stress on the crystallographic preferred orientation (CPO) of olivine were investigated by an integrated study on 13 peridotite samples from four areas in the Western Gneiss Region (WGR) of the Norwegian Caledonides. The highly depleted dunites are mantle residues after Archean melt extraction, while the garnet peridotites were formed by refertilization of the dunites via melt percolation in the Proterozoic. These orogenic peridotites were tectonically emplaced into Proterozoic gneisses and metasedimentary rocks of the WGR and were recrystallized under high-pressure (HP) to ultrahigh-pressure (UHP) conditions when the Baltic Shield was subducted beneath Laurentia during the 420–400 Ma Scandian orogeny. The CPOs of olivine, enstatite and diopside were measured using the electron backscatter diffraction technique. The weakly deformed garnet wehrlites and dunites from the HP central WGR (the Gurskøy, Almklovdaalen and Tafjord areas) show the A-type olivine fabric defined by the [100] axis subparallel to the stretching lineation and the (010) plane subparallel to the foliation, which may be a relict fabric formed at high temperature and low strain rate in the mantle wedge prior to subduction. The [001](010) fabric (B-type) is observed in strongly sheared HP garnet peridotites and dunites from the Almklovdaalen and Tafjord areas, suggesting the dominant activation of [001](010) slip system at high stress and high strain rate. Recrystallized fine olivine grains may develop a fabric different from porphyroclasts and record a gradual fabric transition. The olivine CPO in garnet lherzolites from Otrøy in the northernmost WGR is characterized by the concentration of [001] axes parallel to the stretching lineation and [100] axes normal to the foliation, indicating a prevailing [001](100) slip (C-type fabric) at P – T conditions of >6 GPa and 850–950 °C. Despite very different deformation microstructures, Fourier transform infrared analysis reveals very low water contents (<13 ppm H₂O by the Paterson calibration) in olivine for both coarse porphyroclasts and recrystallized small grains, which is consistent with the high-degree partial melting of the peridotites during the Archean. Therefore, a combination of UHP and low temperature plays a more important role than water in promoting the C-type olivine fabric in a dry, cold and deeply subducted continental slab. With increasing subduction depths, the C-type olivine fabric will predominate over the A-type fabric and make the maximum P-wave velocity and shear wave splitting of peridotites normal to the foliation. However, the stress-induced fabric transition in olivine from the A-type to the B-type may be localized in shear zones and not distinguishable in seismic anisotropy observations.

Key words: crystallographic preferred orientation; olivine; seismic anisotropy; subduction zone; water.

INTRODUCTION

The relationship between plastic deformation and seismic anisotropy of peridotites is critical for the interpretation of seismic anisotropy in the upper mantle. Since the 1960s, deformation experiments on mantle rocks and olivine aggregates have revealed a predominant crystallographic preferred orientation

(CPO) of olivine, which is characterized by the olivine [100] axis and (010) plane parallel to the shear direction and the shear plane, respectively (A-type fabric; e.g. Raleigh, 1968; Carter & Avé Lallemant, 1970; Zhang *et al.*, 2000). The fabric analysis of naturally deformed peridotites (Ben Ismaïl & Mainprice, 1998) and numerical modelling of olivine alignment (Blackman *et al.*, 2000; Tommasi *et al.*, 2000) have confirmed that

olivine deforms essentially by dislocation creep with the [100](010) slip system under upper mantle conditions. Therefore, the olivine A-type fabric has been widely used to link the seismic anisotropy of the upper mantle with plate dynamics (e.g. Savage, 1999; Park & Levin, 2002).

However, the critical shear stress for activation of certain glide systems during deformation may depend on pressure, temperature, differential stress, strain rate and fluid activity. Recent experiments found that water (in the form of hydrogen dissolved in lattice defects; Jung & Karato, 2001; Katayama *et al.*, 2004; Jung *et al.*, 2006) and UHP (Couvry *et al.*, 2004; Durinck *et al.*, 2005; Mainprice *et al.*, 2005; Raterron *et al.*, 2007; Jung *et al.*, 2009; Ohuchi *et al.*, 2011) can change the easiest slip direction in olivine from [100] to [001] and lead to different CPOs. Although it is still debated whether high water content or UHP/low temperature is the key parameter for the fabric transition in olivine (Ji *et al.*, 2007; Karato *et al.*, 2008), it is noteworthy that some orogenic garnet peridotite bodies from UHP metamorphic terranes display either [001](010) (B-type) or [001](100) (C-type) olivine fabric, for example, Cima di Gagnone in the central Alps (Frese *et al.*, 2003; Skemer *et al.*, 2006), the Western Gneiss Region (WGR) of the Norwegian Caledonides (Katayama *et al.*, 2005), and the Sulu terrane in China (Xu *et al.*, 2006). Despite their different origins and water contents, all these orogenic peridotites were subducted to depths of 80–200 km and exhumed rapidly along with the surrounding gneisses. If they developed the A-type fabric of olivine prior to subduction, the fabric transition in olivine under different thermal–mechanical conditions will produce characteristic change in the seismic anisotropy of the upper mantle (e.g. Katayama & Karato, 2006; Long & Becker, 2010).

The peridotites in the WGR represent Archean mantle fragments embedded in the Proterozoic Baltic continental crust (Beyer *et al.*, 2004, 2006; Lapen *et al.*, 2009; Brueckner *et al.*, 2010). They experienced deformation and eclogite facies metamorphism during the Late Silurian–Early Devonian collision between Baltica and Laurentia (Carswell & Cuthbert, 2003 and references therein; Scambelluri *et al.*, 2008). Based on an integrated study of geochemistry, petrofabrics, seismic anisotropy and water contents for dunites and garnet peridotites from the WGR, we address three main questions: (i) Can Archean and Proterozoic mantle fabrics be distinguished from later orogenic fabrics in the WGR peridotites? (ii) What is the role of pressure and water in the fabric development of olivine in continental subduction zones, where fluid activity is very limited compared with oceanic subduction zones? (iii) What are the tectonic and geophysical implications of different olivine fabric types? Answers to these questions will not only improve understanding of orogenic peridotites but also give new insights into deformation and the seismic anisotropy in subduction zones.

GEOLOGICAL SETTING

The WGR is 300 km long and 150 km wide, stretching along the western coast of Norway from Bergen in the south to Trondheim in the north (Fig. 1). It represents the structurally lowest unit in the southern Scandinavian Caledonides and is predominantly composed of amphibolite to granulite facies orthogneisses and paragneisses, with widespread pods and lenses of eclogites and peridotites (Brueckner & Medaris, 2000; Carswell & Cuthbert, 2003). The protolith ages of tonalitic to granodioritic orthogneisses are mostly between *c.* 1750–1500 Ma (Gothian orogeny) and 1250–900 Ma (Sveconorwegian orogeny) (Austreim *et al.*, 2003; Skår & Pedersen, 2003; Beyer *et al.*, 2012). The mantle-derived peridotite bodies include garnet-free Archean dunites with extremely depleted compositions, and Mg–Cr type garnet peridotites produced by refertilization of the dunites during Proterozoic time (Brueckner & Medaris, 2000; Beyer *et al.*, 2004, 2006; Spengler *et al.*, 2006; Lapen *et al.*, 2009; Brueckner *et al.*, 2010).

During the Late Silurian–Early Devonian collision between Baltica and Laurentia (Scandian orogeny), the Proterozoic Baltic crust was subducted northwestward beneath the Laurentian plate and collected peridotites from the overlying mantle wedge (Torsvik, 1998; Terry & Robinson, 2004; Brueckner *et al.*, 2010; Beyer *et al.*, 2012). These rocks were subjected to HP–UHP metamorphism at 1.8–3.6 GPa and 600–800 °C between 420 and 400 Ma (Dobrzynetska *et al.*, 1995; Van Roermund *et al.*, 2002; Vrijmoed *et al.*, 2006). However, majoritic (i.e. high silica) garnet in garnet peridotites and websterites from the Nordøyane UHP domain records a pressure of 6–6.5 GPa during the Scandian event, suggesting a much deeper subduction depth for the Nordøyane UHP domain than for the southern WGR (Scambelluri *et al.*, 2008). Subsequently, the WGR was exhumed nearly isothermally to depths of 15–20 km and subjected to an overprint of amphibolite facies retrogression at 0.5–1.5 GPa and 650–850 °C between 400 and 380 Ma (Terry & Robinson, 2003; Hacker *et al.*, 2010). The antiformal structures of the Nordfjord–Stadlandet and Sorøyane UHP domains were formed at amphibolite facies conditions during exhumation of the WGR to the middle crust (Root *et al.*, 2005; Hacker, 2007).

SAMPLE LOCALITIES AND PETROGRAPHY

Hundreds of peridotite bodies are widely distributed across the WGR as tectonic lenses with dimension of metres to kilometres. Small volumes of garnet peridotite occur locally as discrete zones within large bodies of garnet-free, chromite-bearing Archean dunites and harzburgites. The garnet peridotites are usually associated with garnet pyroxenites and probably were fertilized by interactions of the dunites with the pyroxenite melts in Proterozoic time (Brueckner &

Fig. 1. Distribution of orogenic peridotite bodies and ultrahigh-pressure (UHP) eclogites in the Western Gneiss Region, Norway (modified after Beyer *et al.*, 2004 and Root *et al.*, 2005). Boundaries of the three UHP domains, muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ age contours and the fold axes are after Root *et al.* (2005) and Hacker (2007). The thick blue lines delineate the high pressure (HP)–UHP transition zone with mixed UHP (coesite-stable) and HP (quartz-stable) eclogites (Carswell & Cuthbert, 2003), which can be extended eastward using the eclogite isobar of 2.4 GPa by Hacker *et al.* (2010). The thin green lines show northwestward-increasing peak metamorphic temperature (Kylander-Clark *et al.*, 2008).

Medaris, 2000; Beyer *et al.*, 2006; Lapen *et al.*, 2009; Brueckner *et al.*, 2010). In order to cover the different metamorphic and deformation conditions in subduction zones, 13 peridotite samples were selected from four areas: Almkløvdaalen in the Nordfjord–Stadlandet HP/UHP transition zone, Otrøy in the Nordøyane UHP domain, the Gurskøy HP area between the Nordfjord–Stadlandet and Sorøyane UHP domains, and the Tafjord HP area in the eastern WGR (Fig. 1). Thin sections were cut parallel to the structural XZ -plane (X – parallel to the lineation, Y – parallel to foliation and normal to lineation, Z – normal to foliation). The modal compositions are based on optical observations under microscope and electron backscatter diffraction (EBSD) analysis on thin sections (Table 1).

Peridotites from Almkløvdaalen

The Almkløvdaalen peridotite body is located ~10 km north of Nordfjord in the southern WGR (Fig. 1). It

occurs as a bowl-shaped inclined synform extending several kilometres to the southeast below the surrounding gneisses (Cordellier *et al.*, 1981). The dunites are locally chloritized and show well-developed foliation and lineation. The foliation and garnet pyroxenite layers were intensely deformed by several fold generations, with geometries, hinges and axial surfaces parallel to folds in the enclosing gneisses (Medaris, 1980; Cordellier *et al.*, 1981). Three garnet lherzolite samples N97-5, N97-14 and N97-18 are characterized by porphyroclastic texture, with large porphyroclasts (up to 1 cm) of garnet, pyroxene and olivine in a fine-grained (<0.5 mm) matrix of recrystallized olivine and pyroxene. Porphyroclasts of pyroxene and olivine show strong undulose extinction, and in some instances, kink bands (Fig. 2a). Kelyphite rims on garnet are variably developed and may be surrounded by partial collars of coarse-grained amphibole and spinel (Fig. 2b), which were interpreted as recrystallization of kelyphite by Carswell (1968). In mylonitic sample N97-5 from the Raudkleivane peridotite body,

Table 1. Sample locality, modal composition and microstructure of the Western Gneiss Region peridotites.

Sample	Lithology	Locality	Modal composition (vol%)	Microstructure
N97-5	Garnet lherzolite	Raudkleivane, Almklovdaalen	5 Grt, 84 Ol, 2 Opx, 6 Cpx, 2 Amp, 1 Chr	Porphyroclastic, strongly sheared mylonite
N97-14	Garnet lherzolite	Helgehornsvatn, Almklovdaalen	4 Grt, 65 Ol, 4 Opx, 9 Cpx, 2 Amp, 15 Srp, 1 Chr	Porphyroclastic, moderately serpentinized
N97-18	Garnet lherzolite	Helgehornsvatn, Almklovdaalen	5 Grt, 57 Ol, 10 Opx, 20 Cpx, 3 Amp, 4 Chl, 1 Chr	Porphyroclastic
N97-8	Dunite	Raudkleivane, Almklovdaalen	90 Ol, 5 Opx, 1 Amp, 3 Chl, 1 Phl, 1 Chr	Shape-preferred orientation and sigmoidal olivine
N97-9	Dunite	Raudkleivane, Almklovdaalen	90 Ol, 1 Opx, 2 Cpx, 1 Amp, 5 Chl, 1 Chr	Shape-preferred orientation and sigmoidal olivine
N97-13	Dunite	Raudkleivane, Almklovdaalen	92 Ol, 3 Opx, 1 Amp, 3 Chl, 1 Chr	Shape-preferred orientation of olivine
N97-40	Garnet harzburgite	Ugelvik, Otrøy	10 Grt, 40 Ol, 10 Opx, 7 Cpx, 30 Srp, 2 Amp, 1 Chr	Porphyroclastic, serpentinized
N97-41	Garnet harzburgite	Ugelvik, Otrøy	8 Grt, 38 Ol, 11 Opx, 5 Cpx, 35 Srp, 2 Amp, 1 Chr	Porphyroclastic, serpentinized
GBWG	Garnet wehrlite	Gurskebotn, Gurskøy	20 Grt, 40 Ol, 15 Opx, 24 Cpx, 1 Chr	Porphyroclastic, protomylonite
N97-30	Garnet wehrlite	Gurskebotn, Gurskøy	10 Grt, 74 Ol, 5 Opx, 10 Cpx, 1 Chr	Porphyroclastic, protomylonite
TO	Dunite	Kallskaret, Tafjord	99 Ol, 1 Chr + Tre + Chr	Granoblastic, weakly sheared
K-i-I	Dunite	Kallskaret, Tafjord	92 Ol, 2 Opx, 4 Chl, 1 Amp, 1 Chr	Porphyroclastic, strongly sheared mylonite
I-A	Dunite	Kaldhusseter, Tafjord	97 Ol, 1 Opx, 1 Chl, 1 Cpx, <1 Chr + Tlc	Porphyroclastic, strongly sheared mylonite

the foliation and stretching lineation are defined by elongated olivine and pyroxene and trails of garnet porphyroclasts. Sample N97-14 from the Helgehornsvatn (Lien) locality has serpentine veins that crosscut porphyroclasts as well as the kelyphite rims, suggesting that serpentinization postdates deformation and recrystallization of the reaction coronas.

In contrast to the garnet peridotites, dunite samples N97-8, N97-9 and N97-13 from Raudkleivane contain >90% olivine with minor orthopyroxene, clinopyroxene, chlorite, amphibole and chromite. Olivine is either equigranular or elongated, with the grain size varying from 0.1 to 3 mm. The foliation and lineation are defined by elongated olivine grains and discrete flakes or ribbons of chlorite (Fig. 2c). In addition, recrystallized olivine and orthopyroxene aggregates can form sigmoidal (Fig. 2d).

Garnet harzburgites from Otrøy

The occurrence of majoritic garnet demonstrates that the Ugelvik garnet peridotite body on Otrøy in the Nordøyane UHP domain was exhumed from >185 km depth (Scambelluri *et al.*, 2008). Samples N97-40 and N97-41 are moderately serpentinized garnet harzburgites. Despite a network of serpentine veins, large porphyroclasts of garnet, olivine and orthopyroxene can be recognized and a stretching lineation is defined by elongated olivine and pyroxene (Fig. 2e,f). The aspect ratios of elongated olivine porphyroclasts are up to 6:1, implying significant strain of these samples under UHP. A similar case has been observed in garnet peridotites from the Sulu UHP terrane (China), with the aspect ratios of elongated olivine grains up to 10:1 (Xu *et al.*, 2006). In addition, fresh, small euhedral orthopyroxene grains (~0.3 mm) are observed in the matrix (Fig. 2e).

Garnet wehrlites from Gurskøy

The Gurskebotn peridotite body on the island of Gurskøy is located between the Nordfjord–Stadlandet and the Sorøyane UHP domains and was subjected to HP metamorphism and deformation during the Scan-

dian orogeny (Jamtveit, 1984; Lapen *et al.*, 2009). Two fresh garnet wehrlite protomylonites, GBWG and N97-30, show porphyroclastic texture. Large porphyroclasts of garnet have kelyphite rims and may contain rounded clinopyroxene. In some cases, garnet is totally replaced by chlorite. Olivine and pyroxene either occur as porphyroclasts of 1–5 mm size with intensive undulose extinction and kink bands or occur as thin lensoid shear zones with grain sizes of 0.01–0.1 mm (Fig. 2g,h). Grain boundaries of both porphyroclasts and recrystallized fine grains are strongly curved and interlobate in response to grain boundary migration. The mechanical twinning in clinopyroxene porphyroclasts can be attributed to deformation under low temperature and high strain rate (e.g. Godard & Van Roermund, 1995).

Dunites from Tafjord

As the easternmost exposure of garnet-bearing ultramafic rocks in the WGR, two large ultramafic masses in the Tafjord area occur within recumbent folds near Kaldhusseter and Kallskaret, respectively. The Kaldhusseter peridotite body is ~1300 m long and ~100 m wide, while at Kallskaret, numerous peridotite lenses, some as long as 600 m, are distributed over an area of 1.5 km². The ultramafic rocks display a schistosity defined by flattened olivine grains and alignment of chlorite flakes, and a primary lineation defined by alignment of tremolite, enstatite, elongated olivine and trails of olivine and chromite. The orientation of the schistosity and lineation of peridotites is parallel to those of the surrounding almandine–amphibolite facies schists and amphibolites. Furthermore, fourfold generations in the peridotites are also present in the gneisses with identical orientations. Thus, the peridotites and gneisses were subjected to the Caledonian deformation and metamorphism together (Brueckner, 1969, 1977). A similar suggestion has been made for the Almklovdaalen peridotites and the enclosing gneisses (Medaris, 1980).

The dunite sample TO from Kallskaret is very fresh, characterized by 99% olivine with a few grains of chromite. The granoblastic fabric of relatively coarse-

Fig. 2. Photomicrographs showing microstructures and mineral assemblages of the Western Gneiss Region peridotites: (a) Ol porphyroclast in recrystallized Ol and Pyx, and (b) σ -type porphyroclast of Grt and its kelyphite rim in Grt lherzolite N97-5 from Raudkleivane in Almklovdalen; (c) elongated olivine grains and discrete flakes or ribbons of chlorite, and (d) sigmoid of Ol and Opx aggregates in dunite N97-9 from Raudkleivane in Almklovdalen; (e) an elongated Ol grain cut by serpentine veins and fresh recrystallized small Opx grains in garnet harzburgite N97-40 from Ugelvik, Otrøy; (f) a network of serpentine veins in garnet harzburgite N97-41 from Ugelvik, Otrøy; (g) porphyroclasts of Pyx and Ol with undulose extinction and kink bands in Grt wehrlite GBWG from Gurskøy; (h) deformation twin of Cpx porphyroclast and subgrains of Ol in Grt wehrlite N97-30 from Gurskebotn in Gurskøy; (i) granoblastic fabric and weak foliation in dunite TO from Kallskaret in Tafjord; (j, k) σ -type Ol porphyroclasts in chlorite dunite K-i-I from Kallskaret in Tafjord. (l) Shape-preferred orientation of flattened olivine in dunite I-A from Kaldhusseter in Tafjord. Except (g) and (h), all images are taken from *XZ* sections with *X* parallel to the horizontal edge. Abbreviations of mineral names are after Whitney & Evans (2010).

grained olivine (0.2–1 mm) appears to record static recrystallization under mantle conditions (Fig. 2i). A weak lineation is defined by slightly elongated olivine grains. Chromite generally appears as small interstitial grains between polygonal olivine crystals, but occasionally as large grains including rounded olivine. Sample K-i-I is a strongly deformed chlorite dunite from the highly sheared upper level of the Kallskaret body. The stretching lineation is defined by elongated

olivine and pyroxene, ribbons of platy chlorite and associated chromite (Fig. 2j), and is parallel to the lineation of the surrounding gneisses. A huge σ -type olivine porphyroclast up to 1 cm in size occurs within a matrix of elongated olivine and orthopyroxene, and ribbons of chlorite (Fig. 2k).

In contrast, sample I-A is a slightly chloritized, sheared dunite from Kaldhusseter, composed of 95% olivine, minor orthopyroxene, chlorite, tremolite and

very few chromite and clinopyroxene grains. The shape-preferred orientation of olivine grains and discrete chlorite flakes define the lineation (Fig. 2l), which is parallel to the lineation in the surrounding gneisses. Old olivine grains appear as large porphyroclasts (~5 mm in average long axis) with undulose extinction.

MAJOR-ELEMENT COMPOSITION

Analytical methods are outlined in Appendix S1. Table S1 lists the whole-rock major-element contents of the WGR peridotite samples. The Mg#, CaO and Al_2O_3 values of our samples, the primitive mantle (McDonough & Sun, 1995), and the mean Archean and Proterozoic lithospheric mantle (Griffin *et al.*, 2003) are plotted in Fig. 3. The Mg# for the WGR garnet peridotites varies from 90.5 to 92.9, indicating that the garnet-bearing rocks are moderately to weakly refractory relative to the primitive mantle. This feature is consistent with their relatively low contents of Al_2O_3 and CaO. Most garnet-bearing samples fall between and around the mean estimates of the Archean and Proterozoic mantle, that is, 'Archon' and 'Proton' of Griffin *et al.* (2003). Except for garnet lherzolite N97-5, Na_2O contents of the garnet peridotites and dunites are lower than the primitive mantle, consistent with their Cpx/amphibole-poor modal compositions. In contrast to the garnet peridotites, the five dunite samples from the Almklovdaalen and Tafjord areas are strongly depleted with Mg# of 92.4–93.8 and low Al_2O_3 and CaO contents, which can be explained by >90 vol% of olivine and the lack of Ca–Al-bearing phases such as garnet.

Mg# values of olivine range 90.5–90.8 for garnet lherzolites from Almklovdaalen, 91.9–93.2 for garnet wehrlites from Gurskebotn, and 91.9–92.3 for garnet harzburgites from Ugelvik (Table S2). Except for garnet wehrlite GBWG, the garnet peridotites and dunites follow a positive correlation between the olivine Mg# and the whole-rock Mg# (Fig. 4). Sample GBWG is characterized by an extremely high olivine Mg# of 93.2, relatively high contents of Al_2O_3 and CaO, and abundant garnet and clinopyroxene, implying that it experienced significant metasomatism after primary high-degree partial melting.

Orthopyroxene has compositions of $\text{En}_{91.2}$ to $\text{En}_{91.4}$ in the garnet peridotites from Almklovdaalen, and $\text{En}_{92.4}$ to $\text{En}_{92.7}$ in garnet harzburgites N97-40 and N97-41 from Ugelvik (Table S3). Garnet wehrlite GBWG has orthopyroxene of $\text{En}_{93.2}$, which is similar to values of $\text{En}_{93.1}$ and $\text{En}_{92.7}$ in dunites N97-8 and N97-13, respectively, underlining the highly depleted nature of GBWG. Clinopyroxene in garnet peridotites N97-14, N97-18, GBWG and N97-30 display diopside compositions of $\text{En}_{47-50}\text{Fs}_{1.9-3.4}\text{Wo}_{48-51}$ (Table S4). Diopside in sample GBWG has higher contents of Al_2O_3 , TiO_2 and Na_2O , but is less rich in Cr_2O_3 and CaO than the other three samples.

Fig. 3. Correlation of whole-rock Al_2O_3 and CaO abundances with Mg# of the peridotites. The compositions of the primitive mantle are from McDonough & Sun (1995), and mean Archon and Proton subcontinental lithospheric mantle from Griffin *et al.* (2003).

CRYSTALLOGRAPHIC PREFERRED ORIENTATION

CPO of olivine

Our peridotite samples show very different microstructures, ranging from granoblastic, porphyroclastic to mylonitic. To compare the olivine fabrics of bulk

Fig. 4. The whole-rock Mg# v. olivine Mg# in the peridotites.

samples, porphyroclasts and recrystallized grains, a different step size was used in the EBSD analysis and derived subsets of (i) one point per grain; (ii) coarse grains only; and (iii) small grains only from the complete data set. The technical details for EBSD analysis are given in Appendix S1. Except for garnet wehrlite N97-30 and dunite K-i-I, the pole figures of olivine from the complete data set are consistent with those from different subsets (Table 2, Figs 5 & 6, S1 & S2). In addition, fabrics of locally recrystallized small grains were studied using a step size of 10 μm (Fig. S1). The local CPO of recrystallized grains may be strongly influenced by the crystallographic orientation of the host grains, as indicated by core-and-mantle structures in mylonite K-i-I and protomylonite GBWG. Such a phenomenon has been observed in the Balmuccia peridotite complex from the Western Alps (Matysiak & Trepman, 2012) and in deformation and recrystallization experiments on natural peridotites (Druiventak *et al.*, 2012).

The garnet lherzolites and dunites in Almklovdaalen show three types of olivine CPO (Fig. 5). Garnet lherzolites N97-5 and N97-18, and dunite N97-9 developed [001](010) fabric (B-type) characterized by the concentration of [001] axes subparallel to the lineation and [010] axes normal to the foliation. Dunites N97-8 and N97-13 show a preferential alignment of [100] axes of olivine parallel to the lineation and [010] axes normal to the foliation, which is the most common [100](010) fabric (A-type) of olivine in the upper mantle (Ben Ismaïl & Mainprice, 1998). However, garnet lherzolite N97-14 has the E-type fabric defined by the point maxima of [100] axes subparallel to the lineation and [001] axes normal to the foliation.

As shown in Fig. 6, olivine in garnet harzburgites N97-40 and N97-41 from Ugelvik forms the [001](100)

Table 2. Olivine fabrics and calculated seismic properties of the peridotites in the Western Gneiss Region.

Locality	Almklovdaalen										Tafjord												
	Raudkleivane		Helgehornsvatn				Raudkleivane				Ugelvik, Orrøy				Gurskebotn, Gurskøy				Kallskaret		Kaldhusseter		
	Garnet lherzolite	N97-5	Garnet lherzolite	N97-14	Garnet lherzolite	N97-18	Dunite	N97-8	Dunite	N97-9	Dunite	N97-13	Garnet harzburgite	N97-41	Garnet harzburgite	GBWG	Garnet wehrlite	N97-30	Dunite	TO	Dunite	K-I-I	Dunite
Lithology	B	E	B	B	B	A	B	A	C	C	A	A to B	A	C	C	A	A to B	A	B to C	A	B	B to C	B
	50	50	50	50	50	50	50	50	30	30	30	50	30	30	30	50	50	250	200	200	200	200	
	[001](010)	[100](001)	[001](010)	[100](001)	[001](010)	[001](010)	[100](010)	[100](010)	[001](100)	[001](100)	[001](010)	[100](010)	[001](100)	[001](100)	[001](100)	[100](010)	[001](010)	[100](010)	[100](010)	[100](010)	[001](010)	[001](010)	
Sample	One point per grain																						
	Coarse grains																						
	Small grains																						
Step size (µm)	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	
	Local small grains																						
	Manually indexed																						
V_{pmax} (km s ⁻¹)	8.44	8.38	8.40	8.40	8.54	8.52	8.59	8.54	8.54	8.55	8.55	8.54	8.55	8.55	8.55	8.46	8.54	8.45	8.45	8.45	8.44	8.44	
	8.17	8.21	8.15	8.15	8.10	8.07	8.09	8.14	8.14	8.10	8.10	8.14	8.10	8.10	8.10	8.01	7.99	8.17	8.25	8.25	8.25	8.25	
	8.31	8.30	8.28	8.28	8.32	8.30	8.34	8.34	8.34	8.33	8.33	8.34	8.33	8.33	8.33	8.24	8.27	8.34	8.36	8.36	8.35	8.35	
$A(V_p)$ (%)	3.20	2.00	3.00	3.00	5.30	5.40	6.00	4.80	4.80	5.30	5.30	6.00	5.30	5.30	5.50	6.60	6.60	4.40	2.70	2.70	2.40	2.40	
	4.90	4.87	4.86	4.86	4.91	4.94	4.93	4.90	4.90	4.86	4.91	4.88	4.91	4.88	4.90	4.97	4.97	4.92	4.92	4.92	4.90	4.90	
	$A(V_s)$ (%)	2.98	1.81	1.89	1.89	3.80	3.72	4.46	3.24	3.24	4.23	4.23	4.54	5.14	5.14	2.16	3.52	3.52	2.50	2.50	2.50	2.50	2.50

Fig. 5. Electron backscatter diffraction-measured crystallographic preferred orientation of olivine using the complete data set (area weighted) for the peridotites from Almklovdalen. Equal-area projection, lower hemisphere. The contours at multiples of a uniform distribution are plotted and an inverse log grey scale is used to emphasize high densities. Structural directions X , Y and Z are defined in the text. N , number of data points; pfJ, texture index.

Fig. 6 Electron backscatter diffraction-measured crystallographic preferred orientation of olivine for the peridotites from Gurskøy, Otøy and the Tafjord area. Description is same as in Fig. 5.

fabric (C-type), which is defined by the concentration of [001] axes parallel to the lineation and [100] axes normal to the foliation. For garnet wehrlites from Gurskebotn, the complete data sets of olivine yield the typical [100](010) fabric in GBWG, but [001](010) fabric in N97-30. In addition, the pole figures of sample N97-30 reveal [001](010) fabric for the subsets of one point per grain, small grains ($< 150 \mu\text{m}$) and locally recrystallized small grains, but [100](010) fabric for a subset of coarse grains ($> 300 \mu\text{m}$; Fig. S2). Combined with the porphyroclastic texture in thin section, protomylonite N97-30 may record a gradual transition from the A-type fabric in porphyroclasts to the B-type fabric in recrystallized grains during shearing.

For the two dunites from Kallskaret in the Tafjord area, sample TO with granoblastic texture displays a very weak A-type fabric. The dunite mylonite K-i-I contains a large σ -type olivine porphyroclast in thin section (Fig. 2k). Hence, the area-weighted olivine CPO using the complete data set is controlled by the orientation of the large porphyroclast (Fig. S3). However, the subsets of small olivine grains ($< 300 \mu\text{m}$) and one-point-per-grain extracted from the complete data set reveal that the maximum concentration of [001] axes is parallel to the lineation, while [100] and [010] axes form a girdle normal to the lineation with the maximum concentration near the Z direction, implying the activation of both [001](100) and [001](010) slip systems. Manually indexed individual olivine points yield a clear [001](100) fabric. Therefore, the recrystallized olivine grains in mylonite K-i-I were subjected to a fabric transition from the B-type to the C-type. In contrast, olivine in the dunite mylonite I-A from Kaldhusseter shows a typical [001](010) fabric, as do samples N97-5 and N97-9 from the Almklovdalen area.

CPO of enstatite

The pole figures of enstatite are shown in Figs S4 & S5. Enstatite in garnet lherzolite N97-5 and dunites TO and I-A exhibits nearly random orientation due to the small number of data points; therefore, they are not discussed further. For all the other samples, the CPO of enstatite is characterized by the concentration of [001] axes subparallel to the lineation and [100] axes normal to the foliation, suggesting the dominant slip system of [001](100) as observed in previous studies (e.g. Mercier, 1985). In Opx-rich rocks N97-40, N97-41, GBWG and N97-30, the CPO pattern of enstatite is consistent in fine-grained ($< 150 \mu\text{m}$) and coarse-grained ($> 300 \mu\text{m}$) subsets.

CPO of diopside

Due to smaller Burgers vectors in clinopyroxene, there are more active slip systems in clinopyroxene than in orthopyroxene. Diopside from seven garnet peridotite samples displays different fabrics (Fig. S6). In samples

N97-18, GBWG and N97-40, the CPO of diopside is defined by a strong concentration of [001] axes subparallel to the lineation and (010)-poles subnormal to the foliation, which can be explained by activation of multiple dislocation glide on $1/2 < 110 > \{110\}$, [001]{110} and [001](100) slip systems (Godard & Van Roermund, 1995; Bascou *et al.*, 2002). However, diopside in garnet lherzolite N97-14 develops the [100](010) fabric, which is very rare in peridotites. Compared with the strong fabrics of olivine, the CPO of diopside in samples N97-5, N97-30 and N97-41 is very weak.

SEISMIC ANISOTROPY

Ignoring minor minerals, such as garnet, chlorite, serpentine and chromite, the seismic velocities and anisotropy of the WGR peridotite were calculated from the CPOs of major minerals using the Hill average and re-adjusted modal compositions, which allow us to investigate the relationships between the CPO, the volume fraction of each constituent mineral, and the overall seismic velocities and anisotropy of poly-phase rocks. The complete EBSD mapping data are used in the calculation to give area-weighted physical properties of the bulk samples. The single crystal elastic constants and density are taken from studies on olivine (Abramson *et al.*, 1997), enstatite (Chai *et al.*, 1997) and diopside (Collins & Brown, 1998). The seismic properties of olivine, enstatite and diopside are provided in Fig. S7. Due to its high seismic velocities and weak anisotropy, garnet will increase the seismic velocities and decrease the seismic anisotropy of rocks, but will not affect the seismic anisotropy pattern (Mainprice *et al.*, 2004; Wang *et al.*, 2009). The alteration minerals such as serpentine, chlorite, tremolite and phlogopite were formed during exhumation of the peridotites to the middle and upper crust; therefore, they can be ignored when modelling the in-situ composition.

Figures 7 and 8 present the P- and S-wave velocities, anisotropy and shear wave splitting of 13 peridotite samples. The V_p anisotropy, $A(V_p)$, is defined as $A(V_p) = (V_{p\text{max}} - V_{p\text{min}})/(V_{p\text{max}} + V_{p\text{min}}) \times 2 \times 100\%$, where $V_{p\text{max}}$ and $V_{p\text{min}}$ are the fastest and slowest velocity of the sample, respectively. Thus, $A(V_p)$ is direction independent and only reflects the relative difference between $V_{p\text{max}}$ and $V_{p\text{min}}$. The values of $A(V_p)$ in our samples vary between 2.2 and 6.6%, with the mean V_p between 8.24 and 8.36 km s^{-1} (Table 2). Shear wave splitting will occur in an anisotropic solid. The V_s anisotropy along the propagation direction in question, $A(V_s)$, is defined as $(V_{s1} - V_{s2})/(V_{s1} + V_{s2}) \times 2 \times 100\%$, where V_{s1} and V_{s2} are the fast and slow S-wave velocities with mutually orthogonal polarizations. So $A(V_s)$ is a directional parameter and relates with the shear wave splitting ($V_{s1} - V_{s2}$). The values of the maximum $A(V_s)$ for our samples are in the range of 1.8–5.1% (Table 2).

Fig. 7. Calculated P- and S-wave seismic properties of the Almklovdaalen peridotites. Equal-area projection, lower hemisphere. Structural directions X , Y and Z are defined in the text.

Olivine has an orthorhombic symmetry with $V_{p\max}$ and $V_{p\min}$ propagating along the $[100]$ and $[010]$ axis, respectively, and the maximum V_{s1} along the $[101]$

direction (Fig. S7a). Because olivine is volumetrically dominant, $V_{p\max}$ and $V_{p\min}$ of peridotites are controlled by the orientation of olivine $[100]$ and $[010]$

Fig. 8. Calculated P- and S-wave seismic properties of peridotites from Gurskøy, Otrøy, and the Tafjord area. Description is same as in Fig. 7.

axes, respectively. The seismic anisotropy of our samples shows a good correlation with olivine fabrics. The stronger the fabric strength of olivine, as indicated by the p_f values in Figs 5 & 6, the higher the anisotropy. However, because enstatite has a similar seismic anisotropy pattern to olivine (Fig. S7b) and generally develops [001](100) fabric (Figs S4 & S5), if olivine does not form the same fabric (C-type), the enstatite CPO will decrease the value of seismic anisotropy, and even change the propagation direction of $V_{p_{\max}}$, $V_{p_{\min}}$ and V_{s1} in Opx-rich rocks.

Four samples N97-8, N97-13, GBWG and TO show $V_{p_{\max}}$ subparallel to the lineation and $V_{p_{\min}}$ normal to the foliation, and the polarization plane of the fastest S-wave subparallel to the foliation, which is consistent with their [100](010) olivine fabric. The maximum shear wave splitting is parallel to the Y structural direction in dunites N97-8 and N97-13, but becomes normal to the foliation in samples GBWG and TO.

Five samples with the B-type olivine fabric (N97-5, N97-18, N97-9, N97-30 & I-A) are strongly sheared garnet lherzolites and dunites. Except for garnet lherzolite N97-18, the polarization plane of the fastest S-wave is subparallel to the foliation. For samples N97-18, N97-30 and I-A, $V_{p_{\max}}$ is subparallel to the Y direction and $V_{p_{\min}}$ is subnormal to the foliation, consistent with their [001](010) olivine fabric. However, samples N97-5 and N97-9 show $V_{p_{\max}}$ subparallel to the lineation and $V_{p_{\min}}$ normal to the foliation, which is similar to the seismic anisotropy of peridotites with the A-type olivine fabric. The calculated seismic properties of 100% olivine aggregates using the olivine CPO of samples N97-5 and N97-9 indicate that this discrepancy is caused by the preferred orientation of olivine [100] axes (Fig. S8), which forms a girdle subparallel to the foliation instead of a point maximum along the Y direction. Therefore, the transition from the A-type to the B-type olivine fabric may be not recognizable in seismic anisotropy observations.

Garnet harzburgites N97-40 and N97-41 from Ugelvik yield the C-type olivine fabric. As a result, $V_{p_{\max}}$ is normal to the foliation and $V_{p_{\min}}$ is parallel to the Y direction, with $A(V_p)$ of 4.8–5.3%. The V_{s1} polarization plane is generally normal to the foliation. In dunite K-i-I, a large olivine porphyroclast obscured the fabric of recrystallized grains (Fig. S3), and the area-weighted seismic anisotropy of the bulk sample is controlled by the orientation of the porphyroclast. Compared with samples N97-40 and N97-41, garnet lherzolite N97-14 with the E-type fabric exhibits a similar seismic anisotropy pattern but much lower $A(V_p)$. The calculated seismic properties of 100% olivine and 100% enstatite aggregates using the CPO data of sample N97-14 indicate that the olivine [100](001) fabric will produce $V_{p_{\max}}$ parallel to the lineation and $V_{p_{\min}}$ parallel to the Y direction, while the enstatite [001](100) fabric will result in $V_{p_{\max}}$ normal to the foliation and $V_{p_{\min}}$ parallel to the Y direction (Fig. S8). Thus, the seismic anisotropy of

sample N97-14 is characterized by $V_{p_{\max}}$ normal to the foliation, and $V_{p_{\min}}$ parallel to Y direction. Clearly, more attention is needed to distinguish the C- and E-type fabrics of olivine from seismic anisotropy, especially for pyroxene-rich rocks.

WATER CONTENTS OF OLIVINE

Water contents of coarse-grained and fine-grained olivine were measured by Fourier transform infrared (FTIR) analysis (Appendix S1). Figure 9 shows typical unpolarized FTIR spectra of olivine. The absorption bands in the range of 3500–3570 cm^{-1} represent structural hydroxyl species in olivine, while peaks near 3690 and 3645 cm^{-1} correspond to the OH stretching bands of serpentine, and a broad absorption near 3410 cm^{-1} may reflect submicroscopic fluid inclusions in olivine (e.g. Miller *et al.*, 1987; Khisina *et al.*, 2001; Kovacs *et al.*, 2008). The characteristic peaks of serpentine at 3690 and 3645 cm^{-1} are common in most samples, which can be attributed to serpentine along microcracks in olivine. In the moderately serpentinized sample N97-40, all the analysed grains display characteristic peaks of serpentine, which hampered estimation of its OH concentration. Excluding the altered grains with serpentine and fluid inclusions, no peak of structural hydroxyl species was observed in dunite TO, suggesting that its OH concentration is less than the detection limit of the FTIR spectroscopy (~ 1 ppm H_2O). Only the spectra with the dominant peak near 3570 cm^{-1} were selected for the calculation of water contents using a recent calibration (Bell *et al.*, 2003). Our results are ~ 3.5 times the values derived from the Paterson (1982) calibration, which has been widely used in water content analysis of olivine (e.g. Katayama *et al.*, 2005; Xu *et al.*, 2006; Wang, 2010). In order to compare with previous studies, our data were divided by a factor of 3.5 (Table 3).

Our FTIR analysis demonstrates that both porphyroclasts and recrystallized grains of olivine are very dry. The average water contents of olivine are in the

Fig. 9. Typical unpolarized Fourier transform infrared spectra of olivine in the garnet peridotites and dunites.

Table 3. Mg number, fabrics and water contents of olivine from peridotites in the Western Gneiss Region.

Locality	Almklovdalen												Tafjord											
	Raudkleivane		Helgehornvatn		Raudkleivane		Ugelvik, Otrøy		Gurskebotn, Gurskøy		Kalliskaret		Kaldhusseter											
	Garnet lherzolite	N97-5	Garnet lherzolite	N97-14	Garnet lherzolite	N97-18	Dunite	N97-8	Dunite	N97-9	Dunite	N97-13	Garnet harzburgite	N97-40	Garnet harzburgite	N97-41	GBWG	Garnet wehrlite	N97-30	Dunite	TO	Dunite	K-i-I	Dunite
Mg#	90.8	90.8	90.8	90.5	93.0	93.2	92.8	91.9	92.3	93.2	93.5	92.1	92.3	93.2	93.2	93.2	93.2	91.9	91.9	93.5	92.1	92.3	92.1	92.3
Fabric type	B	E	B	B	A	B	A	C	C	B	A	A	B	A	A	A	A	A to B	A to B	A	B to C	B	B	B
OH content of coarse grains (beam size 100 × 100 µm) using the calibration of Bell <i>et al.</i> (2003)	8	14	4	4	3	13	5	18	9	8.8	8.8	2.0	5.4	21.6	21.6	21.6	21.6	6	6	8	15	14	14	14
Analyses	27.6	25.8	33.2	33.2	26.4	37.2	2.9	37.2	9	37.2	37.2	2.9	5.4	21.6	21.6	21.6	21.6	5.4	5.4	8	15	14	14	14
Max (ppm H ₂ O)	3.6	1.8	10.8	10.8	1.9	0.4	0.5	0.4	0.9	0.9	0.9	0.5	0.5	1.8	1.8	1.8	1.8	0.5	0.5					
Min (ppm H ₂ O)	18.5	13.7	24.5	24.5	17.1	25	1.6	17.1	4.8	4.8	4.8	2	2	13.2	13.2	13.2	13.2	2	2	Dry	Altered	Altered	Altered	Altered
Average (ppm H ₂ O)	5.3	3.9	7.0	7.0	4.9	7.1	0.5	4.9	1.4	1.4	1.4	0.6	0.6	3.8	3.8	3.8	3.8	0.6	0.6	Dry	Altered	Altered	Altered	Altered
OH content using the Paterson (1982) calibration	86	64	114	114	79	115	7	79	22	22	22	9	9	61	61	61	61	9	9	Dry	Altered	Altered	Altered	Altered
Average C _{OH} (H 10 ⁻⁶ Si)	9	10	11	11	11	11	11	11	11	11	11	12	12	63.6	63.6	63.6	63.6	9	9	Dry	Altered	Altered	Altered	Altered
OH content of small grains (beam size 25 × 25 µm) using the calibration of Bell <i>et al.</i> (2003)	13	37.8	7.1	7.1	7.1	57.6	7.8	57.6	7.8	57.6	57.6	23	23	43.8	43.8	43.8	43.8	7.8	7.8					
Analyses	2.5	20.3	2	2	2	24.9	2.3	24.9	2.3	24.9	24.9	2.3	2.3	12.5	12.5	12.5	12.5	2.3	2.3					
Min (ppm H ₂ O)	5.9	26.9	4	4	4	38.4	5.2	38.4	5.2	38.4	38.4	5.2	5.2	203	203	203	203	5.2	5.2					
Average (ppm H ₂ O)	1.7	7.7	1.1	1.1	1.1	11.0	1.5	11.0	1.5	11.0	11.0	1.5	1.5	203	203	203	203	1.5	1.5					
OH content using the Paterson (1982) calibration	27	125	19	19	19	177	24	177	24	177	177	24	24	203	203	203	203	24	24					
Average (ppm H ₂ O)																								
Average C _{OH} (H 10 ⁻⁶ Si)																								

range of <1–13 ppm H₂O using the Paterson (1982) calibration. Coarse olivine grains from dunites N97-13 and TO, and garnet wehrlites GBWG and N97-30 are extremely dry (<1 ppm H₂O). The maximum value of 13 ppm H₂O is obtained in small grains of dunite mylonite K-i-I, implying a relatively high water fugacity during recrystallization. Given the uncertainty (<30%) in the FTIR analysis and the heterogeneous water distribution of water in thin sections, there is no difference between recrystallized and porphyroclastic olivine in sample N97-41. The small differences between the recrystallized olivine grains and olivine porphyroclasts in samples N97-5, N97-14, N97-18 and N97-9 are also negligible.

DISCUSSION

In situ water contents in olivine

Katayama *et al.* (2005) found the C-type fabric in a massive peridotite and the A-type fabric in a layered peridotite with compositional banding of Cr-diopside and garnet from Otrøy. Olivine in both samples is 'wet' (700–800 H 10⁻⁶Si) and shows a dominant slip system of [100](001) (E-type) in dislocation observations. The authors did not provide FTIR spectra of olivine, but claimed that the water contents of these rocks have been modified by extensive hydration and overprinting at amphibolite facies conditions during exhumation. They attributed the C-type olivine fabric to deformation at high water content, low stress (~10 MPa), HP (~6 GPa) and modest temperature (~1300 K), and the E-type dislocation microstructures in the two rocks to later deformation at a higher stress level with a moderate water content.

However, the water contents of olivine from our WGR dunites and garnet peridotites, including garnet harzburgites from Otrøy, are very low (<200 H 10⁻⁶ Si) (Table 3). Re-Os dating of peridotites from Nordøyene (Brueckner *et al.*, 2002) and the Almklovdalen and Tafjord areas (Beyer *et al.*, 2004) yielded Archean Re-depletion model ages ($t_{RD} \approx 2.7$ –3.1 Ga) for the dunites, but mixed Archean and Proterozoic whole-rock and sulphide ages for the garnet peridotites. The dunites represent the Archean lithospheric mantle residues after >60% melt extraction at 5–7 GPa, while the garnet peridotites were formed by metasomatic refertilization of the dunites during the Proterozoic (Beyer *et al.*, 2006). Our samples show a similar strong correlation between whole-rock Mg# and Al₂O₃, CaO contents (Fig. 3), suggesting that they underwent similar depletion and refertilization processes. Therefore, the low water contents in olivine are consistent with the high-degree melt extraction as indicated by high Mg# for both olivine and the whole rock.

On the other hand, the Almklovdalen and Tafjord chlorite peridotites experienced pervasive multistage fluid infiltration and retrogression during late Caledonian uplift (Kostenko *et al.*, 2002). The consistent

foliation and lineation defined by chlorite, tremolite and olivine in the chlorite peridotites suggest that olivine was recrystallized at amphibolite facies conditions in the presence of water, which seems contrary to the measured low water contents in olivine. To resolve this paradox, we must evaluate the effect of hydrogen diffusion on the water concentration in olivine during exhumation from the upper mantle to the crust.

The effect of hydrogen diffusion can be quantified by

$$l = \sqrt{D^{\text{eff}} t} \quad (1)$$

where l is the characteristic distance in metres, D^{eff} is the effective diffusion coefficient of olivine in $\text{m}^2 \text{s}^{-1}$, and t is the time in seconds (Crank, 1956). D^{eff} of olivine includes the hydrogen diffusion in the lattice and along grain boundaries and can be described by the Arrhenius law (Demouchy, 2010):

$$D^{\text{eff}} = D^{\text{L}} + (3\delta/d)D^{\text{gb}} \quad (2)$$

where D^{L} is the hydrogen diffusion coefficient along the fastest direction in olivine lattice, that is, the [100] direction for the 'proto-polaron' mechanism (Mackwell & Kohlstedt, 1990), D^{gb} is the hydrogen diffusion coefficient along grain boundaries, d is the grain size, δ is the grain boundary width and is set to be 0.75 nm (two monoatomic layers). At $\geq 900^\circ\text{C}$, the grain boundary term $(3\delta/d)D^{\text{gb}}$ for a grain size of 1 mm is 1–2 orders of magnitude smaller than D^{L} , leading to $D^{\text{eff}} \approx D^{\text{L}}$ (Fig. S9a). Therefore, at upper mantle conditions, hydrogen transport in unsaturated coarse-grained rocks would be controlled by the lattice diffusion, which will yield very limited diffusion distance and ensure the survival of water heterogeneity in the upper mantle (Demouchy, 2010). However, at 600–800 $^\circ\text{C}$, the grain boundary term $(3\delta/d)D^{\text{gb}}$ for a grain size of 0.1 mm is much higher than D^{L} , suggesting significant hydrogen diffusion along grain boundaries in fine-grained peridotites. Therefore, in a cold subducted slab, grain boundaries will behave as an efficient pathway for hydrogen transport before development of fractures. The reduction of grain size by dynamic recrystallization will enhance the hydrogen diffusion along grain boundaries and result in the growth of chlorite and tremolite along grain boundaries of 'dry' olivine in mylonitic peridotites. At $< 500^\circ\text{C}$ (i.e., in the middle to upper crust), the effective hydrogen diffusion is too slow to alter the water concentration of olivine (Fig. S9b). The fluid infiltration was facilitated by fracture networks and pervasive dilation of grain boundaries during uplift (Kostenko *et al.*, 2002).

At 600–850 $^\circ\text{C}$, which is the temperature range of eclogite and amphibolite facies metamorphism across the WGR (Fig. 1), the characteristic diffusion distance using Equations (1) and (2) and grain size of 1 mm yields 5–30 m for 1 Ma, 16–94 m for 10 Ma, and 51–297 m for 100 Ma in olivine-rich rocks

(Fig. S9b). Given the fast exhumation rate of the WGR and the size of peridotite bodies, the effect of hydrogen diffusion on water contents of olivine is very limited during exhumation. Hence, the measured values certainly yield an upper bound for the *in situ* water contents.

Mechanisms for fabric transition in olivine

The water-induced fabric transition in olivine was first reported by Jung & Karato (2001). In their olivine fabric diagram for high-temperature conditions, the dominant slip system will change from the [100](010) (A-type) at low stress or [100]{0kl} (D-type) at high stress in 'dry' olivine ($< 200 \text{ H } 10^{-6}\text{Si}$), to [100](001) (E-type) with moderate water content (200–1000 $\text{H } 10^{-6}\text{Si}$) and low stress, and to either [001](010) (B-type) at high stress or [001](100) (C-type) at low stress in 'wet' olivine ($> 1000 \text{ H } 10^{-6}\text{Si}$) (Jung & Karato, 2001; Katayama *et al.*, 2004). Our samples show very low water contents in olivine; as a result, the A- or the D-type fabric would be expected at low or high stress, respectively. However, the independence of olivine water contents and fabric types (Table 3) indicates that in this case, water is not the key parameter for the fabric transition in olivine.

In fact, olivine samples in laboratory deformation experiments contain much higher water contents than orogenic peridotites from UHP terranes (Wang, 2010), and were subjected to much higher temperatures (typically 1200–1300 $^\circ\text{C}$) than in a subducted slab (650–900 $^\circ\text{C}$; Fig. 1). Early deformation experiments revealed the dominance of [100](010) slip system at high temperature and low strain rate, and a change of slip direction in olivine from [001] to [100] with increasing temperature and decreasing strain rate (Raleigh, 1968; Carter & Avé Lallemant, 1970; Zhang *et al.*, 2000). Recent experiments and theoretical modelling have demonstrated the pressure-induced slip transition from [100](010) to [001](010) in dry olivine at pressures $> 3 \text{ GPa}$ (Couvry *et al.*, 2004; Mainprice *et al.*, 2005; Raterron *et al.*, 2007; Jung *et al.*, 2009; Ohuchi *et al.*, 2011). Therefore, the activation of [001] slip in olivine may result from dislocation creep at conditions of low temperature, HP and/or high strain rate.

The subduction-related P – T gradient across the WGR has not been significantly disrupted by the later exhumation-related, amphibolite facies, protomylonitic fabrics (Hacker *et al.*, 2010), which provides an opportunity to preserve the olivine fabrics formed in earlier episodes. It is interesting to note that the C-type olivine fabric was observed in the highly depleted garnet harzburgites from Otrøy. The multistage generation of majoritic garnet in the Nordøyane UHP domain records a complex evolution history: Archean upwelling and accretion to subcratonic lithosphere (M1), isobaric cooling until the Middle Proterozoic (M2), and subduction to a depth of $\sim 200 \text{ km}$ within

the Baltic continental crust during the Scandian orogeny (M3) in the diamond-eclogite facies (850–950 °C and 5.5–6.5 GPa) (Van Roermund, 2009). Compared with previous deformation experiments, the C-type olivine fabric in garnet harzburgites from Otrøy should be formed under the M3 stage characterized by ultrahigh-pressure, low temperature and low geothermal gradient ($< 5\text{ °C km}^{-1}$), and dry conditions. Our explanation is consistent with the occurrence of microdiamond and majoritic garnet in the peridotites within the deeply subducted continental crust (Brueckner *et al.*, 2002; Spengler *et al.*, 2006; Vrijmoed *et al.*, 2006; Scambelluri *et al.*, 2008), and the north-westward increase in temperature and pressure across the WGR (Fig. 1). A similar case has been recognized in the Zhimaifang garnet peridotites from the Sulu UHP terrane, China (Xu *et al.*, 2006), suggesting that the C-type olivine fabric can be regarded as an indicator of UHP and low geothermal gradient in the upper mantle.

The garnet lherzolites and dunites from the Almklovdaalen and Tafjord areas show very complex microstructures with A-, B- and E-type fabrics of olivine. The Almklovdaalen peridotite body is a sheath fold in the HP/UHP transition with $> 2.4\text{ GPa}$ and 700 °C, and is located in the hinge zone of the Nordfjord–Stadlandet antiform formed under the amphibolite facies conditions (Fig. 1). The ultramafic masses in the Tafjord area occur within recumbent folds, and were also strongly sheared together with the enclosing gneisses under granulite to amphibolite facies conditions. The mantle peridotites could be tectonically emplaced into the crustal slab either during subduction or subsequent exhumation. The lack of prograde metamorphic features in garnet peridotites from Almklovdaalen and Tafjord led Brueckner *et al.* (2010) to propose that these peridotite bodies were transferred from the mantle wedge into the continental crust during exhumation of the WGR in the late stages of the Scandian orogeny. However, Griffin & Qvale (1985) documented that Fe-rich eclogite lenses within the Raudkleivane peridotite body in Almklovdaalen contain prograde-zoned garnet, suggesting that the Raudkleivane peridotite body was captured by the subducting Baltic crust and experienced the Scandian prograde metamorphism from amphibolite to eclogite facies. The lack of garnet growth at UHP conditions may be caused by the incomplete metamorphic transformation during the short-lived UHP event in the southern WGR (Carswell *et al.*, 2003).

At 650–750 °C, [001](010) slip in olivine is dominant at high strain rate, both in the presence and absence of water (Carter & Avé Lallemant, 1970; Couvy *et al.*, 2004). Therefore, the B-type olivine fabric in the Almklovdaalen and Tafjord peridotites was formed under low temperature, high differential stress and high strain rate in shear zones, which is consistent with the strong porphyroclastic to mylonitic textures in these samples. Given the stability field of chlorite and

peridotites, the B-type fabric of these peridotites was probably formed at amphibolite facies conditions (0.5–1.5 GPa and 650–750 °C) during exhumation of the WGR. Systematic EBSD measurements on oriented samples will help to confirm this interpretation. The formation of orogenic fabrics within a crustal package can provide important information on mantle deformation and seismic anisotropy in some cases. For example, the C-type olivine fabric may develop at a depth $> 150\text{ km}$ beneath cratons. The B-type olivine fabric may be dominant in mantle shear zones, such as the interface between the subducted slab and the mantle wedge, the lithosphere–asthenosphere boundary beneath a continental rift, and strain localization associated with water-induced partial melting.

The A-type fabric in the weakly deformed dunites, however, probably represents an original fabric that formed under high temperature and low strain rate in the mantle wedge. This A-type olivine fabric is widely observed in mantle xenoliths and ophiolite complexes (Ben Ismaïl & Mainprice, 1998). Similarly, garnet wehrlites from Gurskebotn in the eclogite facies HP domain also preserve the relict A-type fabric of olivine. The activation of [100](001) slip system in garnet lherzolite N97-14 may be enhanced by the high stress and localized high fluid activity under HP/UHP transition conditions, as suggested by its porphyroclastic texture and relatively high water contents in small recrystallized olivine grains (Table 3).

It is noteworthy that recrystallized olivine grains may develop a fabric different from the coarse porphyroclasts. For example, garnet wehrlite protomylonite N97-30 from Gurskebotn records a gradual transition from the A-type fabric in porphyroclasts to the B-type fabric in recrystallized grains during shearing. The coexistence of both [001](010) and [001](100) slip systems in dunite mylonite K-i-I from Tafjord probably reflects water-enhanced activity of the [001](100) slip system at high strain rate and low temperature, as shown by stronger fabric strength and relatively high water contents in recrystallized small grains, distribution of chlorite and tremolite in grain boundaries, and the consistent foliation and lineation of olivine and the hydrous minerals. The lack of the dominant C-type fabric in the Almklovdaalen, Tafjord and Gurskebotn peridotites suggests that these samples were not subjected to high enough pressures as those in the Nordøyene UHP terrane during the Scandian orogeny.

CONCLUSIONS

An integrated study of geochemistry, microstructures and water contents of garnet peridotites and dunites from four areas of the WGR provides new insights into the fabric transition of olivine in continental subduction zones. The highly depleted dunites represent Archean mantle fragments in Proterozoic crust, while the garnet peridotites resulted from Proterozoic refertil-

ization of the dunites by melt percolation. They were introduced into the subducted Proterozoic Baltic shield and experienced HP to UHP metamorphism and deformation during the Scandian orogeny. The very low water contents of olivine are consistent with the high-degree melt extraction of the peridotites. The hydrogen diffusion on the water contents of olivine during exhumation is very limited due to the relatively low temperature and coarse grain size. The garnet peridotites from Otrøy are comparable with the Zhi-mafang garnet peridotites from the Sulu terrane (China) (Xu *et al.*, 2006) in their high-degree partial melting, the C-type olivine fabric, low water content, and the UHP metamorphism conditions of >6 GPa and 850–950 °C. Therefore, the C-type fabric of olivine can be an indicator of an ultradeep origin for mantle rocks, especially in a dry and cold subducted continental slab. The B-type olivine fabric is observed in strongly sheared HP garnet peridotites and dunites from the Almklovdalen and Tafford areas, suggesting the dominant activation of [001](010) slip system at high stress and high strain rate. The A-type olivine fabric in peridotites from the eclogite facies HP domain preserves the relict fabric in the mantle wedge before they were caught into the subduction zone.

The calculated seismic anisotropy of the peridotites from the WGR shows complex patterns. The pressure-induced fabric transition of olivine from the A- to C-type fabric will result in a characteristic change in P-wave anisotropy and shear wave splitting with increasing depth. The dominance of the olivine C-type fabric will make the maximum V_p and the polarization plane of the fast S-wave normal to the foliation. However, the stress-induced transition from the A- to B-type fabric is probably localized in mantle shear zones and will not be distinguishable in seismic anisotropy observations.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Analytical methods.

Figure S1. Equal-area lower hemisphere projection of olivine crystal axis distribution for recrystallized small grains using a step size of 10 μm in the EBSD analysis.

Figure S2. Equal-area lower hemisphere projection of olivine crystal axis distribution for sample N97-30.

Figure S3. EBSD analysis results of a strongly sheared, porphyroclastic dunite K-i-I.

Figure S4. Equal-area lower hemisphere projection of enstatite crystal axis distribution for the Almklovalen peridotites.

Figure S5. Equal-area lower hemisphere projection of enstatite crystal axis distribution for peridotite samples from Ugelvik, Gurskebotn and Kallskaret.

Figure S6. Equal-area lower hemisphere projection of diopside crystal axis distribution for the WGR peridotites.

Figure S7. Equal-area lower hemisphere projection for seismic properties of olivine, enstatite and diopside.

Figure S8. Calculated seismic properties of 100% olivine and 100% enstatite aggregates using the EBSD-derived CPO data for samples N97-5, N97-9 and N97-14.

Figure S9. (a) Arrhenius diagram of various hydrogen diffusivities and (b) the effective hydrogen diffusion distance of olivine for 1, 10 and 100 Ma using grain size of 1 mm.

Table S1. Whole-rock major-element abundances (wt%) for peridotites from the Western Gneiss Region.

Table S2. Major-element abundances (wt%) of olivine from peridotites in the Western Gneiss Region.

Table S3. Major-element abundances (wt%) of orthopyroxene from peridotites in the Western Gneiss Region.

Table S4. Major-element abundances (wt%) of clinopyroxene from peridotites in the Western Gneiss Region.

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