

Inhomogeneous deformation in deeply buried continental crust, an example from the eclogite-facies province of the Western Gneiss Region, Norway

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Mesoproterozoic protoliths and Scandian eclogites with coronitic textures were preserved in low-strain domains during burial and exhumation in the Sunnfjord Region of western Norway. In domains with moderate deformation, eclogites were flattened, and form lenses occurring both as massive and LS-tectonites. Highly strained eclogites occur in shear zones with thicknesses from the cm scale up to 20 m. PT estimates on kyanite and phengite-bearing eclogites give P of 2.3 GPa and T up to 635 °C for the eclogites in the Dalsfjorden area. Microfabric analyses of eclogite mylonites show that both intracrystalline and diffusional deformation mechanisms were active at the estimated temperature above 600 °C. EBSD measurements of omphacite from an eclogite mylonite show that {001} reveals a well-defined maximum parallel to the stretching lineation while {010} defines a girdle approximately normal to the foliation. The EBSD measurements are in accordance with microfabric observations suggesting dislocation creep of omphacite. The deep-crustal, eclogite-facies, inhomogeneous deformation is assumed to be the result of compositional, mineralogical and structural variations in the protolith and access to a fluid phase. This caused variations in rock strength leading to local strain partitioning and variation in accumulated strain, in addition to changes in the regional stress regime. In contrast, the subsequent amphibolite-facies deformation resulted in the development of a pervasive, regional, E-W-trending foliation fabric evolved during the late-Scandian exhumation. Based on textural evidence, large parts of the mafic complex south of Dalsfjorden in Sunnfjord are interpreted to have been a former eclogite, representing one of the largest eclogite bodies in the Western Gneiss Region. Based on regional mapping of the area, about 95% of the crust exposed is estimated to have been transformed to amphibolites during the late-Scandian exhumation.

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Introduction

Research on eclogite-facies provinces during the last decades has focused on the ultrahigh-pressure metamorphic state and mechanisms for exhuming rocks from extreme pressure conditions. The Western Gneiss Region (WGR) in western Norway is one of the world's largest eclogite-facies provinces and experienced high-pressure (HP) to ultrahigh-pressure (UHP) metamorphism during Caledonian continent-continent collision in Late Silurian to Early Devonian time (Smith 1984, Griffin et al. 1985, Dobrzhinetskaya et al. 1995, Wain 1997), generally referred to as the Scandian orogeny (Gee 1975). The WGR is interpreted to represent the exhumed parts of the root zone of the Scandian orogen (e.g., Griffin et al. 1985, Andersen et al. 1991, Roberts 2003, Tucker et al. 2004, Hacker & Gans 2005). A number of publications have suggested regional models to explain exhumation of the HP terrane (e.g., Dewey et al. 1993, Krabbendam & Dewey 1998, Labrousse et al. 2002, Hacker et al. 2003, Brueckner & van Roermund 2004, Walsh & Hacker 2004). Several detailed structural studies of eclogite-facies fabrics in the WGR focus on the structural evolution in the deep crust and its relation to the burial and

exhumation history (e.g., Andersen et al. 1994, Engvik et al. 2000, Engvik & Andersen 2000, Terry & Robinson 2004, Foreman et al. 2005, Terry & Heidelbach 2006).

This paper concentrates on the structural and metamorphic heterogeneity which must have prevailed in large parts of the southern WGR at peak metamorphic conditions. In this area, fluid- and deformation-limited metamorphism during burial allowed partial preservation of the original mineralogy and structures (Engvik et al. 2000, 2001, Røhr et al. 2004), similar to the pattern described by Austrheim and coworkers from the Bergen Arcs (Austrheim 1987, Boundy et al. 1992, Erambert & Austrheim 1993). The Mesoproterozoic crust (Skår et al. 1994, Røhr et al. 2004, Austrheim et al. 2003, Glodny et al. in press) underwent partial eclogitisation and, subsequently, partial amphibolitisation during the Scandian orogeny. Strain shadows preserved at both eclogite- and amphibolite-facies conditions provide an opportunity to study protoliths and the various stages of structural modification which occurred at eclogite-facies conditions. This paper documents the mineralogical and structural evolution of a large Mesoproterozoic layered gabbro complex south of Dalsfjorden (Fig. 1) during its eclogiti-

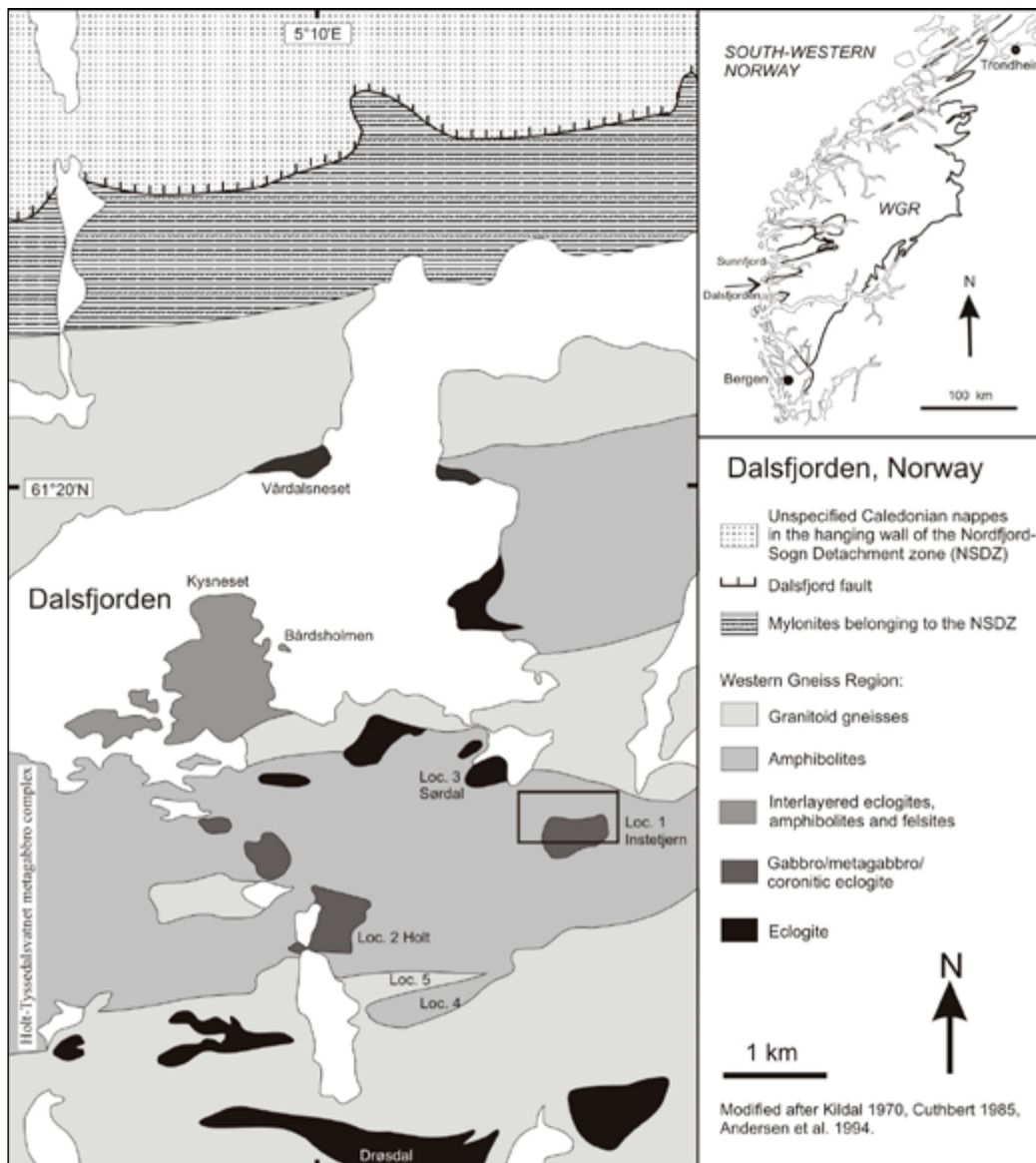


Fig. 1. Geological map of the Dalsfjorden area, West Norway.

sation and amphibolitisation. The amount of transformation during burial and exhumation is evaluated, and it will be shown that a large part of the amphibolites, which are exposed in the southern part of the WGR, were previously eclogite. Petrographic descriptions and microfabric analyses are used to evaluate the deformation mechanisms that operated in the deep crust. Mechanisms that led to the accumulation and localisation of strain will be discussed. In contrast to the heterogeneous state at eclogite-facies conditions, the amphibolite-facies deformation caused a regional homogeneous fabric to evolve during the late-Scandian exhumation in the early to middle Devonian.

Geological setting

The WGR of the Dalsfjorden area is situated below the upper plate allochthonous Caledonian units and Devonian sedimentary basins of Kvamshesten and Solund

(Andersen et al. 1998, Osmundsen et al. 1998, Hacker et al. 2003). The upper plate units are separated from the WGR by mylonites of the Nordfjord-Sogn Detachment Zone (NSDZ). This major detachment was formed during penetrative, top-to-W normal-sense motion (Swenson & Andersen 1991, Hacker et al. 2003, Johnston et al., in press) with subsequent brittle reactivation in Late-Palaeozoic to Mesozoic time (Torsvik et al. 1992). The main movement on the detachment and associated high-level normal faults occurred in the Early to Middle Devonian (Andersen 1998, Osmundsen et al. 1998, Hacker et al. 2003) and caused rapid decompression of the HP rocks to amphibolite-facies conditions. The WGR of Dalsfjorden (Fig. 1) comprises gneisses of granitic to granodioritic composition, and amphibolites containing lenses of metagabbros and eclogites, chlorite-harzburgites, pyroxenites and granulites. The granodioritic gneisses are folded and foliated together with the amphibolites, commonly expressed as interbanded gneiss horizons with the amphibolites. Eclogite bodies vary in size from less than

a metre up to more than a kilometre in length, and only the largest are shown in Fig. 1. The eclogite facies metamorphism of the WGR is dated at c. 415-400 Ma (Mørk & Mearns 1986, Terry et al. 2000, Root et al. 2005, Glodny et al. in press), and the southern parts of the WGR were exhumed to upper crustal levels 390-400 Ma ago within less than 5-10 Myrs (Eide et al. 1999, Andersen 1998, Walsh et al. 2007). In spite of deep burial at eclogite-facies conditions, some of the Precambrian rocks have preserved their pre-Caledonian mineralogies, textures and primary structures. Granulites in Sunnfjord are dated by U-Pb on zircons at 955 ± 3 Ma (Glodny et al. in press) and 949 ± 3 Ma by U-Pb monazite geochronology (Røhr et al. 2004). Skjerlie & Pringle (1978) provided a Rb/Sr whole-rock isochron of 1625 ± 75 Ma for gneisses in Sunnfjord, and more recently Skår et al. (1994) dated a mylonitized quartz-diorite in the NSDZ at 1641 ± 2 Ma. In this study, we present detailed observations within the Precambrian, layered, mafic intrusive complex, referred to as the Holt-Tyssedalsvatnet complex by Engvik et al. (2001). The complex forms an E-W-trending mafic body dominated by amphibolites, and can be correlated with the Flekke unit described by Cuthbert (1985). Gabbro, metagabbro and eclogite occur throughout the unit with, in addition, thinner layers of pyroxenite and chlorite schist. The protolith age of gabbroic rocks from the mafic complex was dated by Skår (1997) to 1522 ± 55 Ma, defined by a combined whole-rock and Sm-Nd mineral isochron.

Main rock types and their structural state: Protolith layered gabbro

Gabbro and metagabbro occur as lenses up to 1 km² and are interpreted as the protolith for eclogites and the enveloping amphibolites. Gabbro with an original magmatic mineralogy and texture is preserved near Instetjern (Loc. 1, Figs. 1 & 2). The gabbro, however, is mostly overprinted by an eclogite- and amphibolite-facies mineralogy, whereas the magmatic layering can commonly be identified through the static overprint (Fig. 3a). The original magmatic layering of the metagabbro is defined by grading from pyroxenite (Fig. 3b) and olivine gabbro through 2-px-ol-gabbro to anorthosite on a scale varying from dm to tens of metres. The metagabbro at locality 1 displays a N-S-oriented magmatic layering, discordant to the foliation of the amphibolites (Fig. 4a).

Gabbro with relict magmatic mineralogy has subophitic textures and cumulative layering. The gabbro is equigranular, medium- to coarse-grained and composed of plagioclase (An₅₉₋₆₃), olivine (Fo₆₉₋₇₈), enstatite (En₇₄₋₇₈), diopside (En₃₈₋₄₃Fo₆₋₁₀Wo₅₁₋₅₂) and smaller amounts of fine-grained spinel (hercynite). Plagioclase is the dominant mineral and appears as subhedral and lath-shaped crystals defining a weak laminar orientation. The pyroxenes and olivine occur as interstitial aggregates between plagioclase crystals, the olivine appearing as rounded grains usually enclosed in enstatite (Fig. 5a). Both plagioclase and diopside are polysynthetically twinned, the diopside being crowded with exsolution lamellae of Ti-bearing magnetite on cleavage planes. Hercynite appears

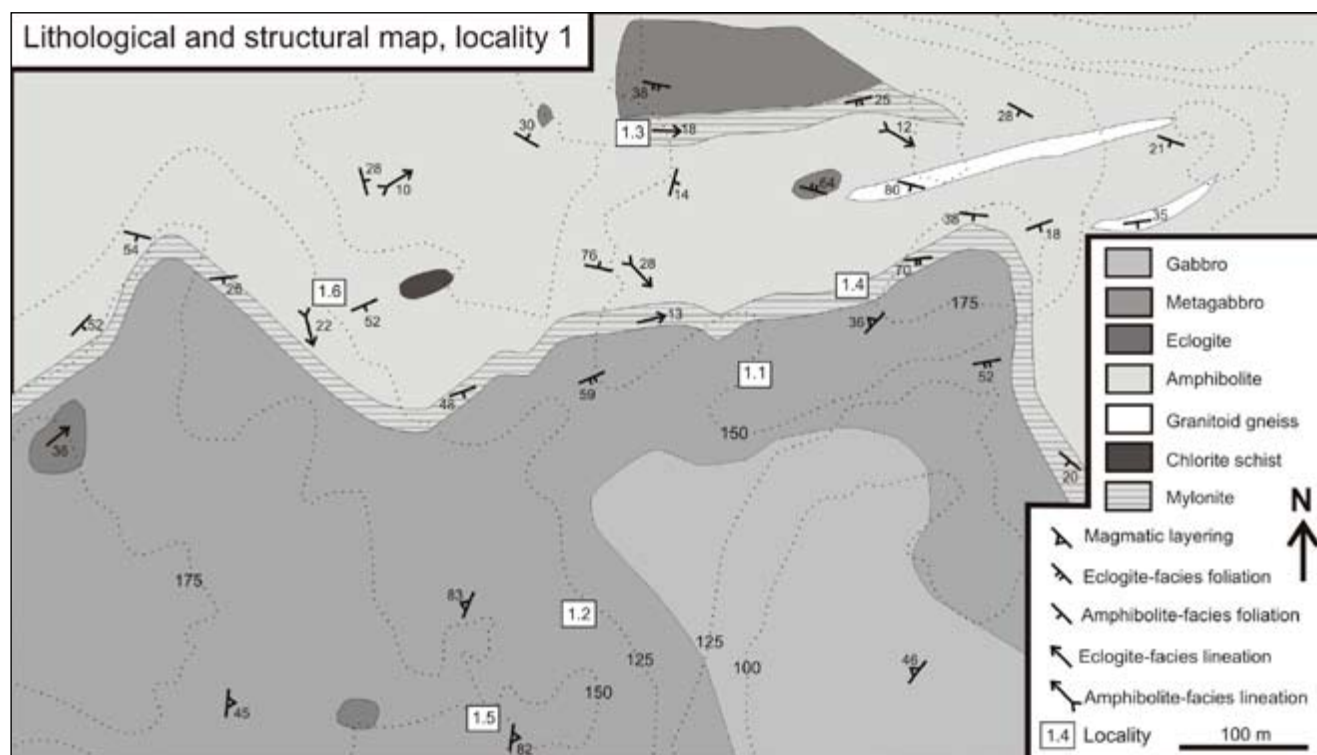


Fig. 2. Structural and lithological map of locality 1, Instetjern (see Fig. 1 for location).

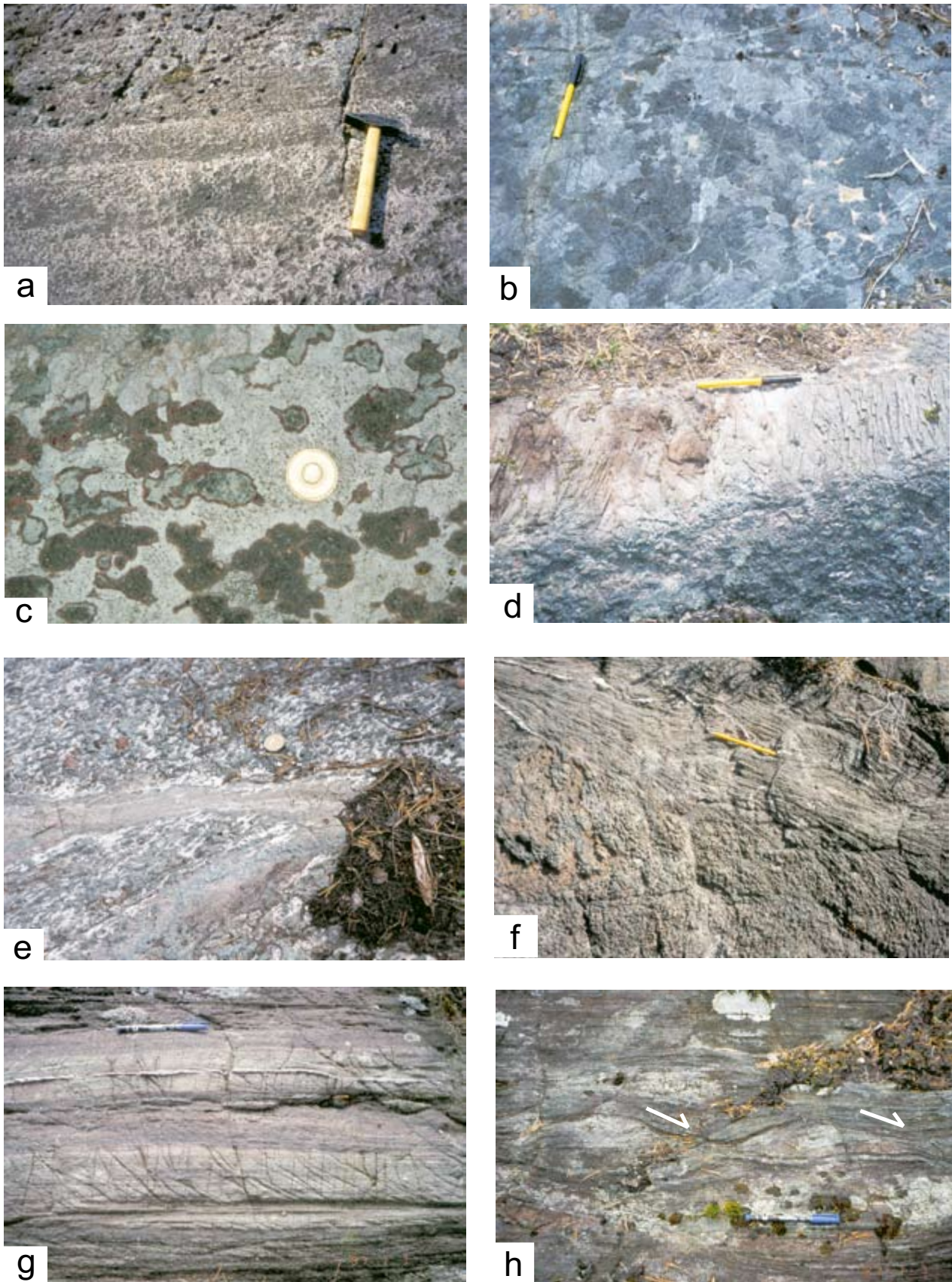


Fig. 3. a) Original magmatic layering preserved in the layered gabbro complex (Loc. 1.1). b) Coarse-grained pyroxenite (Loc. 2). c) Textures of the coronitic eclogite (Loc. 2): Coronas of red garnet surround dark amphibole and pale omphacite. The light matrix represents pseudomorphs after plagioclase. (Coin for scale is 2.5 cm in diameter). d) Fine-grained eclogitised dyke cutting coronitic eclogite (Loc. 2). e) Thin, fine-grained eclogite-facies shear zone cutting coronitic eclogite (Loc. 1.2, coin for scale is 2.5 cm in diameter). f) Transition from coronitic eclogite (lower) to eclogite mylonite (upper). The corona textures are gradually destroyed as the strong, planar, mylonitic fabric developed (Loc. 1.3). g) The penetrative planar fabric of the eclogite mylonite (Loc. 1.3). h) Dextral shear bands forming rotated lenses in eclogite mylonite (Loc. 1.4).

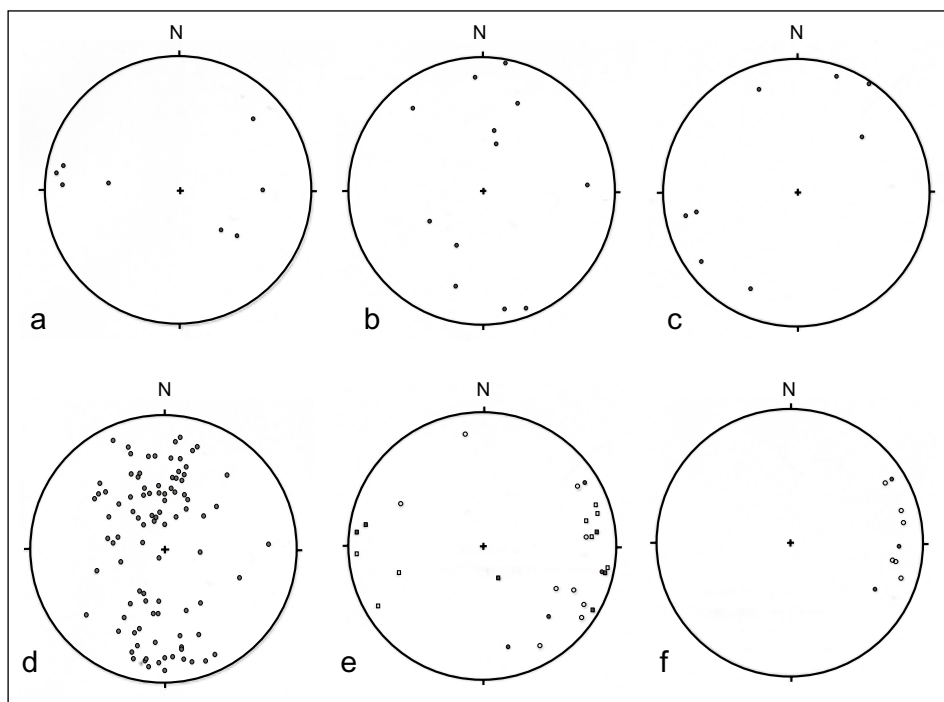


Fig. 4. Structural data for the area south of Dalsfjorden in Fig. 1. Stereonets plotted as lower hemisphere equal-area projections: a) Poles to magmatic layering in gabbro/metagabbro. b) Poles to the eclogite-facies foliation. c) Eclogite-facies lineations from eclogite lenses including L-component. d) Poles to amphibolite-facies foliation in amphibolites and gneisses. e) Amphibolite-facies lineations (filled) and fold axes (open) in amphibolites and gneisses. f) Lineations (filled) and fold axes (open) in shear zone, locality 1.

anhedral, either connected to the mafic aggregates or in symplectitic intergrowth with enstatite. The textural relations between the minerals indicate the initial order of magmatic crystallisation to be plagioclase, followed by olivine, enstatite and diopside.

Eclogites

Eclogites occur within amphibolite and felsic lithologies. The eclogites are heterogeneous in terms of structure, mineralogy and chemistry. Below, we describe different types of eclogite grouped as being I) statically eclogitised or II) dynamically recrystallised. Coronitic eclogite and massive eclogite dykes represent statically metamorphosed equivalents of gabbro and mafic dykes, respectively. Dynamically recrystallised eclogites are found 1) with a foliation overprinting the coronitic eclogite, 2) as highly strained layers in shear zones and mylonites, and 3) as lenses of various LS-tectonites. Despite the obliteration of the previous texture and structure of the rock, coronitic eclogites can be recognised as the starting point for many eclogite tectonites in the complex.

Statically eclogitised lithologies

Coronitic eclogite

The lenses mapped as metagabbro are dominated by coronitic eclogite. This eclogite has mafic domains with medium-grained, randomly oriented minerals surrounded by garnet coronas and very fine-grained pseudomorphs after plagioclase (Fig. 3c). The mafic aggregates are composed of omphacite ($Jd_{49-63}Ae_{0-5}Q_{36-48}$), barrosite, tremolite and talc. These minerals are formed by the replacement of the primary phases olivine, enstatite, diopside and Fe-Ti-oxides. Accessory rutile and Cl-rich

apatite are present both in the mafic domains and in the plagioclase pseudomorphs. Garnet constitutes 1-5 mm thick coronas around the mafic aggregates and has euhedral crystal faces towards the matrix (Fig. 5b). The matrix, which is interpreted to represent pseudomorphs after plagioclase, comprises randomly oriented fine-grained clinzoisite, kyanite, omphacite ($Jd_{66-68}Ae_{<1}Q_{32-34}$), quartz and some larger crystals of paragonite and euhedral garnet. Garnet also occurs along fractures in the coronitic eclogites, constituting up to 1 cm-thick veins with cores of amphibole and minor omphacite, rutile and micas. The garnets of both the coronas and the veins were studied in detail by Engvik et al. (2001). They showed a complex petrographic and chemical zoning ($Alm_{46-58}Grs_{9-27}Prp_{13-40}Sps_{13-40}$), and were interpreted to have formed during fluid infiltration at deep crustal levels, a process that initiated the eclogitisation of the gabbro protolith.

Fine-grained eclogite dykes

Fine-grained eclogitic dykes, up to 6 m wide, commonly cut the metagabbros (Fig. 3d), and are also observed in gneisses throughout the Dalsfjorden area. The fine-grained eclogite is dominated by garnet ($Alm_{51-53}Prp_{25-27}Grs_{20-24}Sps_1$), omphacite ($Jd_{47}Ae_{<1}Q_{26-27}$), amphibole with minor white mica, and rutile, apatite and zircon as very fine-grained accessory minerals. The contacts between the metagabbro and the dykes are usually straight and sharp, and the eclogitic dykes are interpreted to be metamorphosed equivalents of former mafic/doleritic dykes cutting the original layered magmatic complex. Disrupted dykes are also present in the amphibolites as massive, fine-grained lenses of eclogite up to 10 m in size, always surrounded and enclosed by the amphibolite-facies foliation.

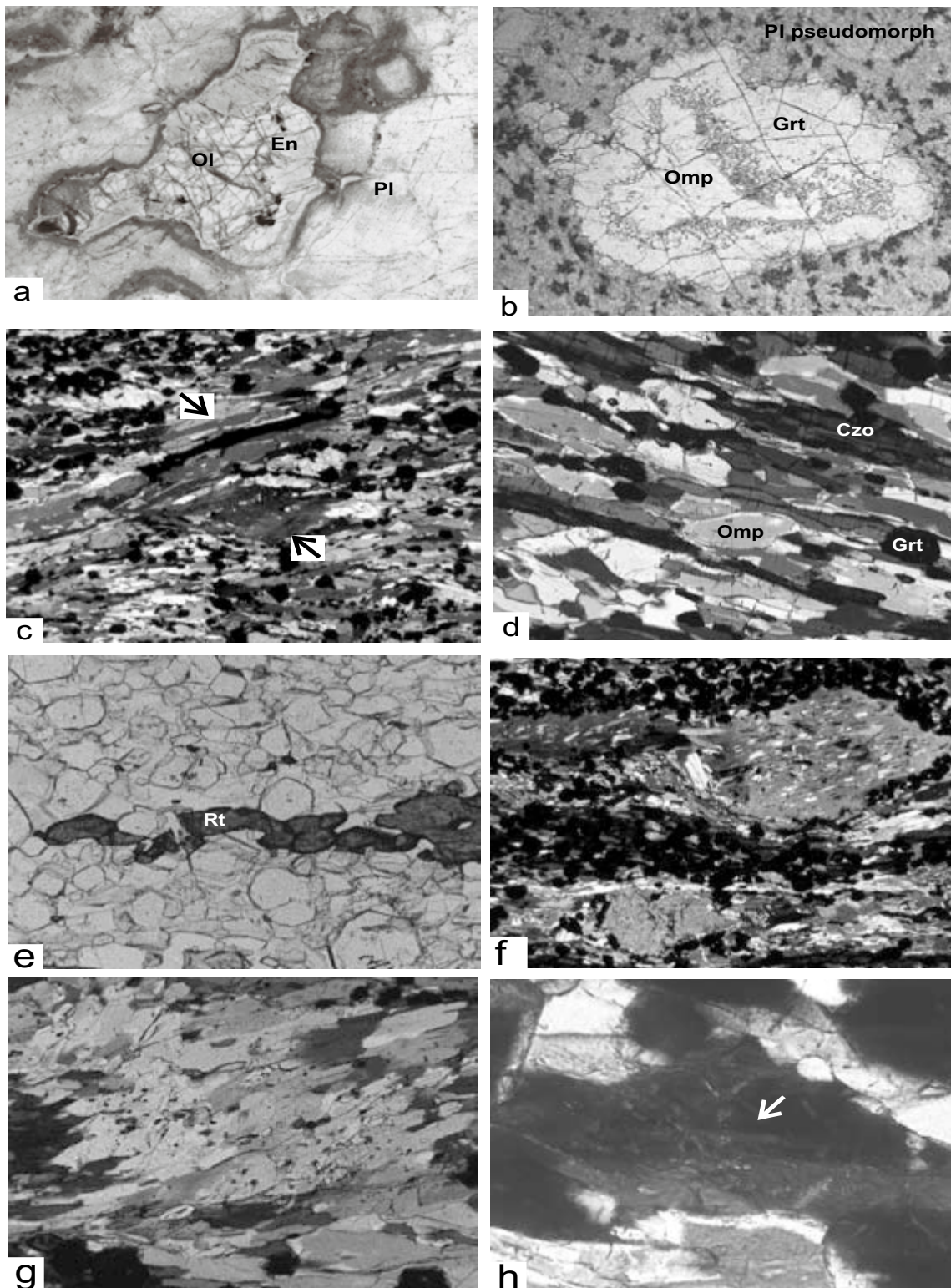


Fig. 5. a) Anhedronal olivine grain surrounded by enstatite in gabbro. Sample SF55, picture width 4.40 mm. b) Omphacite surrounded by garnet corona in plagioclase pseudomorph. Coronitic eclogite, sample FJ22A, picture width 2.98 mm. c) Shear band foliation (upper arrow) and porphyroclast (lower arrow) in eclogite mylonite. Sample SF54C, crossed polarizers, picture width 5.40 mm. d) Clinzoisite and omphacite shape-preferred oriented minerals in eclogite mylonite. Sample FJ2D, crossed polars, picture width 1.49 mm. e) Rutile strings stretched along foliation in eclogite mylonite. Sample SF54C, picture width 1.49 mm. f) Rotated omphacite porphyroclasts filled with inclusions oriented at a high angle to the main foliation in eclogite mylonite. The orientation of the inclusions indicates varying degrees of porphyroclast rotation. The porphyroclasts have pressure shadows and matrix foliation is deflected around the porphyroclasts. Sample SF54C, crossed polarizers, picture width 5.40 mm. g) Development of subgrains in strained porphyroclast. Sample SF54C, crossed polarizers, picture width 1.49 mm. h) Local variation in extinction along distinct zones in omphacite (arrow) interpreted as deformation bands. Sample SF54C, crossed polarizers, picture width 0.376 mm.

Dynamically recrystallised eclogites

Foliated eclogite horizons

The coronitic eclogite shows locally transitions to deformed equivalents with varying foliation intensity representing alternating layers and flattened domains inherited from the coronitic eclogite textures: Domains and layers of red garnet are remnants after flattened garnet corona structures; domains and layers of dark amphiboles are remnants after the mafic aggregates in the core of the corona structures; and the very fine-grained omphacite + clinozoisite + white mica + kyanite rock represents the light-coloured plagioclase pseudomorphs. Both the amphiboles from the interior of the coronas and the very fine-grained aggregates formed from plagioclase show a preferred orientation. Locally, garnet with a pattern inherited from the corona structure is preserved in the foliated eclogites. A high density of small inclusions occurs in garnet adjacent to the fine-grained plagioclase pseudomorphs, whereas garnet in contact with coarse amphibole contains few inclusions. The eclogite-facies foliation trends east-west throughout the area (Fig. 4b).

Eclogite-facies shear zones and mylonites

Eclogitic shear zones vary in thickness from a few cms up to 20 m and truncate the coronitic eclogites (Fig. 3e-h). At locality 1, a 10 to 20 m-thick mylonite zone occurs at the border between the coronitic metagabbro and foliated green amphibolites (Fig. 2). The mylonite zone comprises layers of intensely foliated eclogite (Fig. 3g) alternating with thinner horizons of mylonitic pale-grey amphibolite. The eclogite-facies foliation of the shear zones is oriented east-west, consistent with the eclogite-facies foliation mapped throughout the area (Fig. 4b). The foliation is locally deformed in tight to isoclinal intrafolial folds. Shear bands producing asymmetric lenses of foliated eclogite (Fig. 3h) are enclosed in the eclogitic mylonite, indicating both dextral and sinistral motions.

The planar mylonitic fabric was apparently formed by progressive deformation of the coronitic eclogite (Fig. 3e-f). The large garnet coronas are disrupted and the garnet recrystallised to small euhedral grains. The mafic minerals that previously formed the interior of the garnet coronas are reduced in grain size down to 10 µm during the recrystallisation, whereas the very fine-grained eclogite-facies pseudomorphs comprising omphacite + clinozoisite + paragonite + kyanite after igneous plagioclase coarsened in grain size. The mylonitic eclogite became mostly equigranular, with euhedral garnet in a matrix of well oriented omphacite, barroisite, clinozoisite, paragonite, kyanite, rutile and minor quartz. Grain size varies from fine- to medium-grained (10-100 µm). Clinozoisite, kyanite and paragonite are usually concentrated in layers which show intense deformation and commonly localize shear bands (Fig. 5c). Omphacite, clinozoisite and kyanite have a pronounced shape-preferred orientation (SPO), which gives the mylonite a mineral lineation (Fig. 5d). Euhedral garnet is evenly distributed throughout the

rock. Rutile is deformed and occurs as strings (Fig. 5e) with the long axes of individual crystals parallel to the SPO. Rotated porphyroclasts of omphacite, amphibole and garnet up to 1 cm in size occur locally (Fig. 5f), and are interpreted as remnants after minerals in the mafic domains inside the garnet coronas. Omphacite porphyroclasts are in many cases crowded with inclusions of rutile, quartz, micas and garnet. The inclusions are oriented along lamellae, and show varying degrees of rotation and orientation with respect to the mylonitic foliation. The kinematics deduced from porphyroclasts, shear bands and asymmetric lenses show both east and west vergence, indicating a bulk non-rotational deformation in the mylonite zone.

The garnet and omphacite of the eclogite mylonite are unzoned with mineral chemistries comprising $\text{Alm}_{50}\text{Grs}_{26-28}\text{Prp}_{21-23}\text{Sps}_1$ and $\text{Jd}_{58-59}\text{Ae}_3\text{Q}_{38-39}$, respectively. This is in contrast to the coronitic eclogite which shows disequilibrium in the mineral chemistry of garnet and omphacite, expressed as a strong zonation of garnet and a large variation in the chemistry of the omphacite inside the coronas in comparison with the omphacite of the plagioclase pseudomorphs (see above). During recrystallisation, the mineral chemistries of garnet and omphacite homogenised resulting in mineral chemical equilibrium.

Massive and LS-tectonite eclogite lenses

Lenses of eclogites up to 1 km² in size occur within both the amphibolites and the gneissic lithologies in the Dalsfjorden area. The eclogite fabric in the lenses grades from massive to S and LS-tectonites. The mineral lineation measured in LS-tectonite eclogite lenses throughout the area shows spreading around a subhorizontal NE-SW orientation (Fig. 4c).

The smaller lenses are usually fine-grained, commonly foliated and with a preferred lineation defined by omphacite. The lenses are interpreted to represent former mafic dykes or layers, metamorphosed, disrupted and with a competence contrast to the surrounding lithologies.

Large lenses of LS eclogite occur within the Holt-Tyssedalsvatnet complex at locality 1 and at Sørdal (Loc. 3). The eclogites are relatively dark coloured, enriched in Fe-Ti oxides, dominated by garnet ($\text{Alm}_{64-53}\text{Grs}_{27-22}\text{Prp}_{9-25}\text{Sps}_1$), omphacite ($\text{Jd}_{48-53}\text{Ae}_{7-14}\text{Q}_{37-39}$) and barroisite with minor epidote, phengite, paragonite and accessory rutile, carbonate and opaque minerals. The Sørdal eclogite is relatively heterogeneous with lighter layers rich in epidote and white mica. Grain size is medium to coarse (0.1-1 cm). Larger garnets are euhedral and usually packed with inclusions of omphacite, barroisite, pargasite, epidote, paragonite, phengite, ilmenite, rutile, apatite, quartz and plagioclase. The garnet shows a zonation with a decreasing FeO/(FeO+MgO) ratio from core to rim, which is typical for many eclogites from both the Dalsfjorden area (Cuthbert 1985, Engvik & Andersen 2000) and for the non-UHP eclogites of the WGR in general (e.g., Krogh

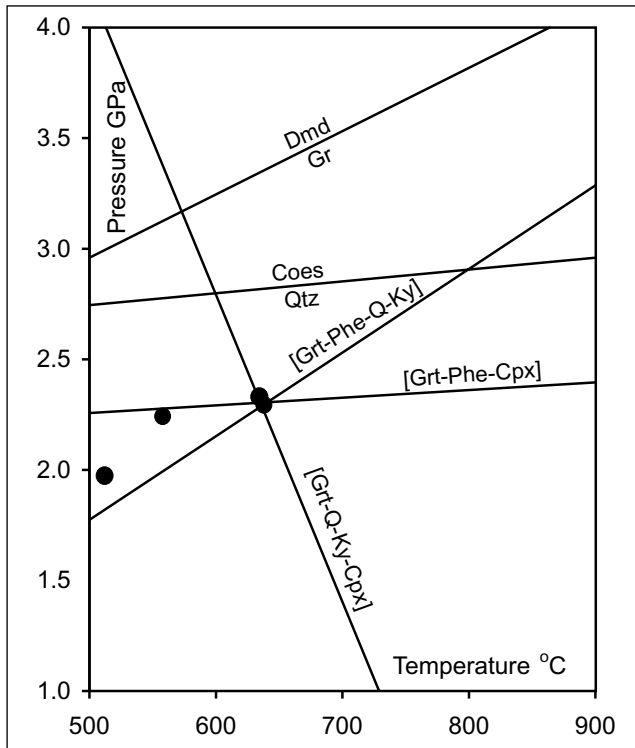


Fig. 6. PT diagram showing the results of the thermobarometric calculation on Ky- and phengite-bearing eclogites of the Dalsfjorden area, by using the thermobarometer after Ravna & Terry (2004). The dots show estimates of the eclogites presented in Table 4. K_{eq} -lines are drawn for the Grt+Omp+Ky+phengite+Qtz-assemblage of the Vårdalsneset eclogite, achieving a well-constrained estimate of $T=635^{\circ}\text{C}$ and $P=2.30\text{ GPa}$.

1982). The lineation in the eclogite lenses is defined by the preferred orientation of omphacite, barroisite and epidote, while the S-element comprises white micas and garnet+amphibole or mica+epidote-rich layers.

Amphibolites

The Holt-Tyssedalsvatnet complex is dominated by amphibolites with an E-W-trending foliation and with a variable dip towards both north and south (Fig. 4d). The regionally pervasive amphibolite-facies foliation wraps around the eclogites, and its formation is therefore interpreted to post-date the eclogite-facies fabrics. The variation in dip indicates folding along E-W-trending and slightly east-plunging fold axes ($\sim 100/10^{\circ}$). Measurements of amphibolite-facies lineations and fold axes show east-west orientations (Fig. 4e). Up to 10 m-thick layers of granodioritic gneiss occur interfolded with the amphibolites. Shear bands and asymmetrical boudins are common in the foliated amphibolites and gneisses throughout the mapped area. The shear bands show both sinistral and dextral shear-senses, indicating bulk coaxial shortening across the amphibolite-facies foliation.

Contacts between the metagabbro and the amphibolites are transitional on a metre-scale with respect to textures,



Fig. 7. a) Static amphibolite facies retrogression of coronitic eclogite (Loc. 1.5). b) Alternating and undulating light and green bands and lenses in amphibolite, with textures after deformed coronitic eclogite (Loc. 4). c) Small boudin of eclogite (arrow) in granodioritic gneiss (Loc. 5).

mineralogy and structures. Locally, the coronitic eclogite is statically overprinted by amphibolite-facies assemblages (Fig. 7a), and garnet coronas are partly replaced by amphibole and chlorite (Fig. 8a) along fractures and resorbed rims. Matrix omphacite is replaced by a symplectitic intergrowth of plagioclase and amphibole (Fig. 8a) and the metagabbro has acquired a greenish-grey colour. These textures and mineralogies document a retrogression of the coronitic eclogite to amphibolite-facies conditions.

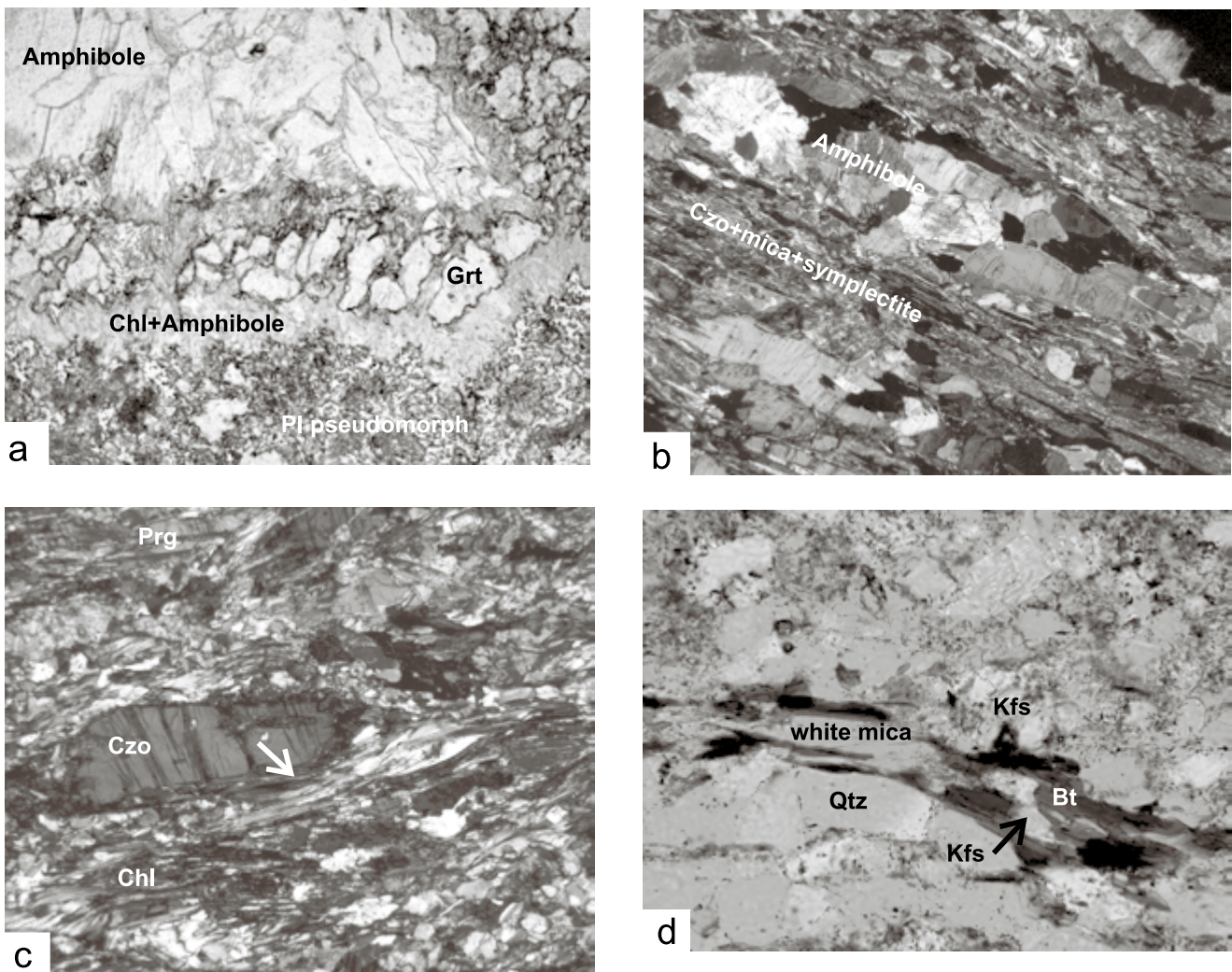


Fig. 8. Photomicrographs: a) Breakdown textures in coronitic eclogite. Remnants of garnet surrounded by chlorite and amphibole. Omphacite in the plagioclase pseudomorph has broken down to a symplectitic intergrowth of plagioclase and amphibole. Sample SF29II, picture width 2.98 mm. b) Layers of medium-grained amphiboles alternating with clinozoisite+white mica+symplectites of plagioclase and amphibole representing, respectively, dark and light layers in the amphibolite. Sample 1.031I, crossed polarizers, picture width 5.40 mm. c) High-strain amphibolite in the lower part of the mylonite zone at Loc. 1. Shear bands developed in chlorite horizons. Sample FJ1, crossed polarizers, picture width 5.40 mm. d) Symplectite of K-feldspar and biotite including a preserved grain of white mica. From gneiss, sample FJ15, picture width 0.7 mm.

The amphibolites have a foliation characterised by alternating and undulating green and lighter coloured bands of mm up to cm thickness (Fig. 7b), showing textures interpreted to represent the retrogression and alteration of minerals in the coronitic eclogites. Typical alteration textures are:

- 1) Remnants of anhedral garnets surrounded by chlorite.
- 2) Very fine-grained plagioclase+green amphibole symplectites occurring as typical replacement textures after omphacite. The symplectites appear commonly together with fine- to medium-grained clinozoisite and white mica in the light bands of the amphibolite (Fig. 8b).
- 3) Medium-grained pleochroic green amphibole, which locally shows an inner colourless core interpreted as a remnant of the former amphibole inside the garnet coronas. The medium-grained amphibole occurs in layered aggregates of euhedral crystals paralleling the layering of the amphibolites (Fig. 8b).

- 4) Chlorite occurring in pockets or along the medium-grained amphibole aggregates, indicating retrograde replacement of garnet coronas.
- 5) Rutile with coronas of ilmenite.

The textures listed above indicate that the green, amphibole-dominated layers in the amphibolites represent flattened replacements after the corona structures in the metagabbro, whereas the light coloured layers are remnants of the original plagioclase domains. The green domains locally define a lineation in the amphibolites where it is seen as a LS-tectonite.

Alteration textures in the gneisses suggest breakdown of phengitic white mica to biotite and orthoclase. In these cases, white mica is rimmed by biotite, or replaced by a symplectite of biotite+orthoclase (Fig. 8d). This reaction releases water, and has been reported by Heinrich (1982) as a retrograde reaction of phengite which is stable under high-pressure conditions.

Parts of the amphibolites in the Holt-Tyssedalsvatnet metagabbro complex have a strong foliation. The amphibolite is composed of green amphibole (pargasite), plagioclase (An_{18}), Mg-Fe chlorite, epidote, minor quartz, locally garnet ($Alm_{51}Grs_{22-23}Prp_{25-26}Sps_1$) and rutile with ilmenite coronas. The foliation is defined by fine bands dominated by chlorite, amphibole and plagioclase+epidote, respectively. The minerals are fine-grained and show a preferred orientation, but very fine-grained plagioclase+amphibole-symplectites are also locally preserved. The differences in the amphibolite appearance, structure and texture are mostly caused by variations in strain intensity. The lower part of the shear zone, along the border between the metagabbro and the amphibolites at locality 1, is composed of highly strained amphibolite. On the microscale, shear bands are usually defined by chlorite (Fig. 8c), and show both dextral and sinistral senses of shear.

The textures described above are all typical of amphibolitisation of eclogite-facies parageneses (Bryhni 1966, Mysen & Heier 1972, Krogh 1980, Griffin 1987, Engvik et al. 2000), and together with the preserved eclogite lenses, are taken as evidence that the amphibolites of the Holt-Tyssedalsvatnet metagabbro complex were formed from eclogites. This suggests that the area was pervasively

eclogitised during the Scandian orogeny, and the complex must have represented one of the largest eclogites in the WGR at peak pressure conditions.

Thermobarometry

Quantitative PT determinations were performed on four kyanite- and phengite-bearing eclogite samples using the thermobarometer calibrated by Ravna & Terry (2004). Quantitative microanalyses of minerals were performed by using a Cameca Camebax electron microprobe at the Mineralogical-Geological Museum, University of Oslo. Data reduction was done with Cameca PAP software package. Accelerating voltage was 15 kV and counting time 10 s, increased for minor elements. Point analyses of garnet and pyroxene were done at 20 nA, mica was analysed with defocussed beam at 10nA. Synthetic and natural minerals and oxides were used for standards. The mineral chemical analyses used for thermobarometry are presented in Table 1-3, and the thermobarometric results presented in Table 4 and Fig. 6. PT estimates of the eclogites in the Dalsfjorden area give $T = 512-635^{\circ}C$

Table 1: Chemical analyses of garnet

Locality	Loc. 1	Loc. 3	Bårdsholmen	Vårdalsnes
Sample	FJ2BI	FJ10	B8	V5B
Analysis no.	1.2	2.1b	1.1	2
SiO ₂	38.79	38.64	38.27	39.98
TiO ₂	0.23	0.09	0.01	0.01
Al ₂ O ₃	21.19	21.4	21.01	21.84
FeO	23.35	24.31	26.96	22.62
MnO	0.56	0.32	0.6	0.35
MgO	5.96	6.37	4.39	9.26
CaO	9.38	8.4	8.71	6.48
	99.46	99.53	99.95	100.54
Structural formula based on 8 cations				
Si	3.017	3.001	3.003	3.026
Al VI	1.942	1.958	1.943	1.948
Ti	0.013	0.005	0.001	0.001
Fe ²⁺	1.518	1.579	1.769	1.432
Mn	0.037	0.021	0.040	0.022
Mg	0.691	0.737	0.513	1.045
Ca	0.782	0.699	0.732	0.526
O	12.001	11.985	11.974	12.001
Alm	50.2	52.0	57.9	47.3
Prp	22.8	24.3	16.8	34.5
Grs	25.8	23.0	24.0	17.4
Sps	1.2	0.7	1.3	0.7
$\frac{FeO}{FeO+MgO}$	0.687	0.682	0.775	0.578

Table 1: Chemical analyses of garnet used for thermobarometry.

Table 2: Chemical analyses of omphacite

Locality	Loc. 1	Loc. 3	Bårdsholmen	Vårdalsnes
Sample	FJ2BI	FJ10	B8	V5B
Analysis no.	1.1b	3.4	2.1	1.2
SiO ₂	56.36	56.47	56.43	57.27
TiO ₂	0.06	0.06	0.06	0.03
Al ₂ O ₃	10.02	10.77	10.99	11.59
Cr ₂ O ₃	0.04	-	0.02	0.04
FeO	4.13	4.14	6.85	2.78
MnO	0.07	0	0.03	0.01
MgO	8.8	8.34	6.35	8.54
CaO	13.68	13.25	11.15	13.29
Na ₂ O	6.66	7.16	8.52	7.25
	99.82	100.19	100.4	100.8
Structural formula based on 4 cations				
Si	2.005	1.996	1.995	2.003
Al IV	0.000	0.004	0.005	0.000
Al VI	0.425	0.444	0.453	0.481
Ti	0.002	0.002	0.002	0.001
Cr	0.001	0.000	0.001	0.001
Fe ³⁺	0.025	0.047	0.132	0.004
Fe ²⁺	0.098	0.075	0.071	0.077
Mn	0.002	0.000	0.001	0.000
Mg	0.467	0.439	0.335	0.445
Ca	0.521	0.502	0.422	0.498
Na	0.459	0.491	0.584	0.492
Jd	58.5	59.1	57.3	64.7
Aegerine	3.4	6.3	16.7	0.6
Aug	38.1	34.6	26.0	34.7
$\frac{FeO}{FeO+MgO}$	0.319	0.332	0.519	0.246

Table 2: Chemical analyses of omphacite used for thermobarometry.

Locality	Loc. 3	Bårdsholmen	Vårdalsnes
Sample	FJ10	B8	V5B
Analysis no.	3.3	2.7	2
SiO ₂	49.54	49.75	50.15
Al ₂ O ₃	27.79	28.8	28.68
TiO ₂	0.37	0.46	0.26
Cr ₂ O ₃	0	0.07	0.05
FeO	1.87	2.6	1.18
MnO	0.02	0	0.02
MgO	2.95	2.94	3.36
CaO	0.05	0	0.01
BaO	0	0.28	0.44
Na ₂ O	1.07	1.11	0.94
K ₂ O	9.3	10.19	10.23
	92.96	96.2	95.32
Structural formula based on 22 O			
Si	6.737	6.616	6.683
Al	4.454	4.514	4.505
Ti	0.038	0.046	0.026
Cr	0.000	0.007	0.005
Fe	0.213	0.289	0.132
Mn	0.002	0.000	0.002
Mg	0.598	0.583	0.668
Ca	0.007	0.000	0.001
Ba	0.000	0.015	0.023
Na	0.282	0.286	0.243
K	1.613	1.729	1.739
SUM kat	13.945	14.085	14.027
$\frac{\text{FeO}}{\text{FeO}+\text{MgO}}$	0.388	0.469	0.260

Table 3: Chemical analyses of phengite used for thermobarometry.

and $P = 1.98\text{--}2.33$ GPa. The best constrained estimate is from the Vårdalsneset eclogite, which is based on the mineral assemblage of Grt + Omp + Ky + phengite + Qtz, achieving peak conditions of $T=635^\circ\text{C}$ and $P=2.30$ GPa, with uncertainties of $\pm 65^\circ\text{C}$ and 0.32 GPa (after Ravna & Terry 2004, uncertainty calculations based on THERMOCALC). The eclogite mylonite of Loc. 1 shows similar PT conditions estimated to 629°C and 2.33 GPa,

this estimate has a larger uncertainty as it is based on the Grt-Cpx-Ky-Qtz curve which has a relatively steep negative slope. The estimates are in accordance with results by Foreman et al. (2005) and Hacker et al. (2003) from other eclogites in the Sunnfjord area.

Microfabric analyses and deformation mechanism in high-strain zones

Omphacite is one of the major mineral phases in mafic eclogites and determines their bulk rheological behaviour (Godard & van Roermund 1995, Jin et al. 2001). As described above, the omphacite grains of the eclogite mylonite show strong, shape-preferred orientations (SPO). Photomicrographs of the eclogite mylonite illustrating the textures are shown in Fig. 5c-h. Omphacite crystallographic preferred orientation (CPO) was determined by electron backscatter diffraction (EBSD). The EBSD patterns were acquired using a scanning electron microscope (SEM) LEO 1530, operated at an accelerating voltage of 20 kV, with the section tilted by 70° to the incident beam at a working distance of 25 mm. The EBSD patterns were automatically indexed with the HKL software CHANNEL 5. A marked CPO is defined by omphacite within the mylonite zone. Poles to the crystal planes of $\{001\}$, $\{010\}$ and $\{100\}$ are shown in Fig. 9. Poles to $\{001\}$ reveal a well-defined maximum parallel to the omphacite stretching lineation. Poles to $\{010\}$ define a girdle approximately perpendicular to the eclogite-facies foliation, with maxima varying between 10° and 70° with reference to the foliation plane. This crystallographic pattern is typical for L- and LS-tectonites. The crystallographic preferred orientations measured by EBSD in the mylonite zone fit to the microfabric observations, suggesting that deformation of omphacite took place in the dislocation creep regime, dominated by dislocation gliding and accompanied by dynamic recrystallisation (Fig. 5c-d). According to Bascou et al. (2002) and Ulrich & Mainprice (2005), the main control on omphacite CPO comes from the activity of the slip systems $[100](010)$, and, in our case, $[001](100)$, and $[001](010)$. Our observation is in accordance with previous studies on omphacite microfabrics (e.g., Buatier et al. 1991, Godard & van

Locality	Sample no.	Mineral assemblage	P (GPa)	T ($^\circ\text{C}$)
Vårdalsneset	V5B	Grt-Omp-Ky-phengite-Qtz	2.30	635
Loc. 1 - Instetjern	FJ2BI	Grt-Omp-Ky-Qtz	2.33	629
Loc. 3 - Sördal	FJ10	Grt-Omp-phengite-Qtz	2.25	556
Bårdsholmen	B8	Grt-Omp-phengite-Qtz	1.98	512

Table 4: Result of thermobarometry on eclogites from the Dalsfjorden area, based on the Grt-Omp-Ky-Phengite-Qtz thermobarometer by Ravna & Terry (2004). Calculations based on the full Grt-Omp-Ky-Phengite-Qtz-assemblage have uncertainties of $\pm 65^\circ\text{C}$ and 0.32 GPa. Calculations based on Grt-Omp-Ky-Qtz- and Grt-Omp-Phengite-Qtz-assemblages have a larger uncertainty. Results of samples V5B and B8 are recalculated after Engvik & Andersen (2000) and Engvik et al. (2000).

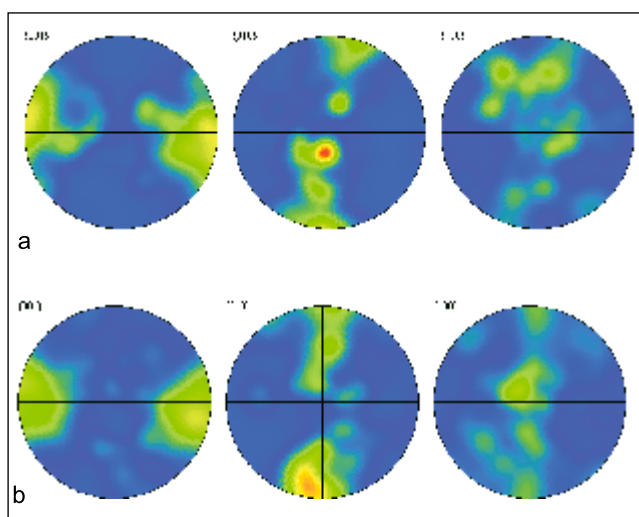


Fig. 9. EBSD measurements of omphacite in eclogite mylonite (Loc. 1), using a set-up for jadeite. Stereographic projections of poles to the crystal planes {001}, {010} and {100}, lower hemispheres. Pole to foliation is top and lineation is horizontal. a) Sample SF54C, 4952 data points, densities (mud): Min=0.00, Max=8.88. b) Sample SF54CII, 4220 data points, densities (mud): Min=0.00, Max=8.81.

Roermund 1995, Piepenbreier & Stöckhert 2001, Terry & Heidelberg 2006), which infer that crystal-plastic deformation may affect omphacite. Our T estimate, above 600°C, is also in accordance with earlier high- T observations on the plastic behaviour of omphacite (Buatier et al. 1991, Philippot & van Roermund 1992, Terry & Heidelberg 2006).

From the pronounced CPO and SPO, it is obvious that the eclogitic mylonite formed by dynamic recrystallisation in the deeply subducted Baltican crust. There is a sharp transition on the dm-scale between the low-strained coronitic eclogite and the intensely deformed mylonite. The compositional variations in the mylonite can be explained by original petrographic differences caused by the corona texture. The petrographic descriptions also show that both grain coarsening and grain-size reduction mechanisms were operating. The variations in angles of inclusion trails in porphyroclasts compared to the main foliation indicate rotation of the porphyroclasts during deformation. The less common, large omphacite, amphibole and garnet grains are interpreted as porphyroclasts due to the presence of pressure-shadows and deflection of the main foliation around the grains. Undulose and discontinuous extinction in rotated omphacite porphyroclasts indicates deformation of the crystal lattice, and formation of subgrains (Fig. 5g) which contributed to recrystallisation and reduction of the grain size, in line with observations by Buatier et al. (1991). In contrast, the matrix omphacite, clinozoisite and white mica show smaller and more uniform grain sizes. Local undulose extinction in matrix omphacite is restricted to distinct zones with a low angle to the main foliation. These zones are suggested as deformation bands (Fig. 5h), which resulted from dislocation accumulation due

to dislocation gliding. The occurrence of rutile as strings with SPO long axes parallel to the foliation (Fig. 5e) can be interpreted as mineral grains stretched in the foliation during deformation, contemporaneous with crystal growth (Mauler et al. 2001), suggesting that also diffusion creep may have been a deformation mechanism in the eclogite high-strain zone. The euhedral garnet behaves as rigid inclusions in the dynamically recrystallised matrix. A combination of grain boundary and intracrystalline deformation mechanisms in high-pressure shear zones has also been reported from eclogite shear zones in northern parts of the WGR by Terry & Heidelberg (2006) who described diffusion creep and grain boundary sliding in garnet while dislocation creep was active in omphacite, plagioclase, ilmenite and magnetite.

Discussion

In Figure 10, a three-stage evolution of the rocks in the southern part of the WGR is suggested: 1) The Mesoproterozoic protolith stage, 2) the main Caledonian (Scandian) eclogite-facies stage, and 3) a late-Scandian (Devonian) amphibolite-facies stage. The sketch illustrates the structural, compositional and metamorphic inhomogeneity of the Mesoproterozoic and Early Palaeozoic deep crust. In contrast to the early heterogeneity, a regional homogeneous fabric evolved during the late-Scandian exhumation and pervasively overprinted the earlier structures, leaving only relics of the previous heterogeneous character.

The Mesoproterozoic crust

The descriptions above show that a mostly anhydrous, layered, mafic magmatic complex constituted a major part of the study area in the Mesoproterozoic. The mafic complex was hosted in granitoid gneisses which, in part, occur as banded leucocratic and mafic granulites (Engvik et al. 2000, Røhr et al. 2004). These gneisses also hosted and were cut by a number of minor mafic bodies presently found as layers in the granulites or as doleritic dykes cutting pre-Caledonian structures. The mafic dykes and layers are interpreted to be protoliths of widespread, smaller, eclogite lenses occurring in the amphibolites and gneisses. The banded leucocratic and mafic granulites in Dalsfjorden and Sognefjorden (Røhr et al. 2004) document the former presence of a regional, pre-Caledonian granulite-facies terrane dated around 950 Ma (Røhr et al. 2004, Glodny et al. in press). It is important to note, however, that the older Mesoproterozoic gabbro in the Holt-Tyssedalsvatnet complex was apparently not completely equilibrated during the granulite-facies metamorphism. These observations show that the Proterozoic gneiss complex was inhomogeneous in terms of composition, structure and metamorphic grade prior to the Caledonian orogeny, and contained significant volumes of anhydrous rocks.

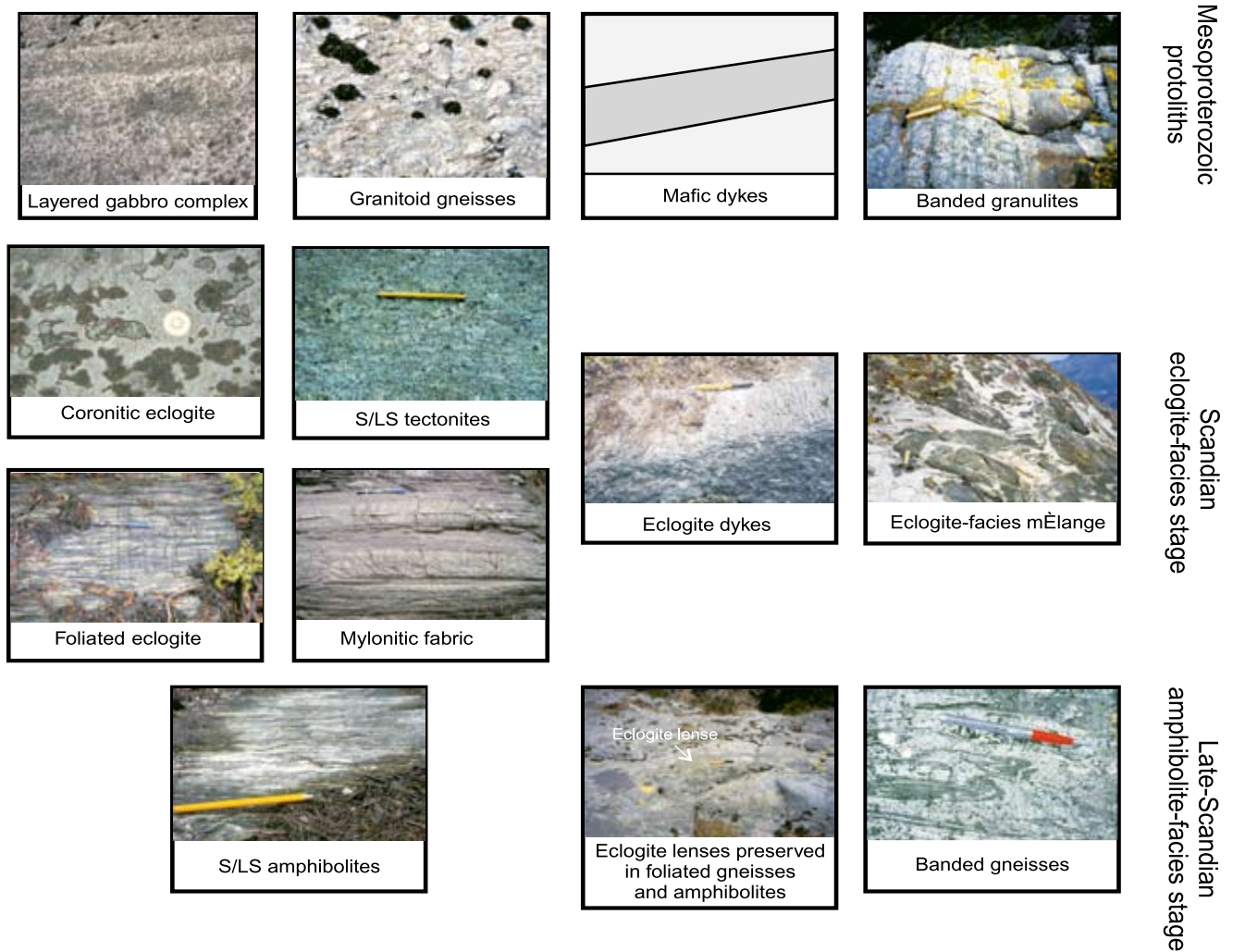


Fig. 10. A three-stage evolution concept for the rocks in the southern part of the WGR: 1) The Mesoproterozoic protolith stage, 2) Scandian eclogite-facies stage and 3) late-Scandian (Devonian) amphibolite-facies stage. The sketch illustrates the inhomogeneity of the deep crust in Mesoproterozoic and Early Palaeozoic time. In contrast to the early heterogeneity, a regional homogeneous fabric evolved during late-Scandian exhumation pervasively overprinting the earlier structures.

Caledonian deep crustal heterogeneity

As documented above, the eclogites in the Holt-Tysedalsvatnet complex are highly variable in structure, ranging from coronitic eclogite and eclogitised dykes to high-strain shear zones and mylonites, foliated eclogite horizons and lenses of massive to LS eclogites, all formed from the same Proterozoic layered mafic complex (Fig. 10). In addition, eclogite-facies, mélange-like lithologies, with lenses of eclogite seen floating in felsic material, formed from the Mesoproterozoic banded granulite complex, as documented by Engvik et al. (2000). These structures reflect heterogeneous deformation with the development of low-, intermediate- and high-strain domains during maximum burial. Statically eclogitised rocks in low-strain domains were formed without preferred orientation of the eclogite-facies minerals and widespread coronitic replacement textures. Eclogite tectonites formed by dynamic recrystallisation resulted in the development of foliated eclogite horizons and lenses of LS-tectonites in intermediate strained domains, and of eclogite mylonites

in highly strained zones. Strain partitioning at high-pressure conditions with the evolution of eclogite-facies shear zones has also been described from northern parts of the WGR (Krabbendam et al. 2000, Terry & Robinson 2004), the Bergen Arcs (Austrheim 1987, Boundy et al. 1992), and from other orogenic belts (Pennacchioni 1996, Suo et al. 2001). While the coronitic eclogite and horizons of flattened coronitic eclogite show textural relationships with their precursors, mylonites formed under more intense deformation would be difficult to trace back to the metagabbro protolith without preservation of the contact showing the gradual increase in strain.

The limited presence or introduction of fluids at various stages under different strain regimes may be one of several important factors explaining the different structural states of eclogites (Austrheim et al. 1997). In contrast to the anhydrous mineralogy found in the preserved Mesoproterozoic protoliths, the eclogites contain hydrous minerals including epidote, clinozoisite, micas, amphi-

boles and talc. The eclogitisation described by Engvik et al. (2000, 2001) was initiated by fluid infiltration along fractures under eclogite-facies conditions, succeeded by a more pervasive eclogitisation. Limited availability of fluid and its subsequent consumption appear to be the principal reasons for the preservation of pristine Mesoproterozoic crust (Austrheim 1987, Wayte et al. 1989, Rubie 1990, Walther 1994). The timing of fluid introduction thereby controls the timing of metamorphic transformations of the anhydrous rocks (Austrheim et al. 1997). In contrast, the chemical zonation and inclusion patterns from core to rim in eclogite garnets have been ascribed to continuous growth during prograde conditions from amphibolite facies (e.g., Krogh 1982, Cuthbert & Carswell 1991). This type of mineral transformation and growth following coherent temperature evolution will only occur if enough fluid is present in the protolith. This seems to have been the case for the larger lenses of LS-tectonite described above, which have undergone a complete transformation to eclogite. A high fluid pressure in some of the eclogite lenses is also indicated by the presence of numerous and spectacular kyanite + omphacite + quartz- and amphibole-filled veins (Engvik & Andersen 2000, Foreman et al. 2005).

Compositional, mineralogical and structural variations in the protolith influence the structural state of the product due to variations in rock strength (e.g. Jin et al. 2001). In the eclogite-facies *mélange* lithology, where eclogite lenses are floating in felsic rocks, rheological heterogeneity appears to be strongly influenced by the lithological variations of the protolith resulting in a disruption of mafic layers into lenses. Variations in the volume proportion of garnet compared to omphacite in eclogites also lead to large variations in rheology due to differences in the mineral strength of garnet which is much higher than that of omphacite (Stöckhert & Renner 1998, Jin et al. 2001). The variation in mineral strength between different phases in the eclogite mylonites is reflected at grain-scale by the operation of different deformation mechanisms as described above (see also Mauler et al. 2001, Terry & Heidelbach 2006). Variation in rock strength at map scale, outcrop scale and down to grain scale causes strain partitioning and variations in accumulated strain (e.g., Mancktelow 1993, Jin et al. 2001, Terry & Heidelbach 2006). This helps to explain boudinage of the competent, fine-grained, garnet-rich eclogite dykes/layers preserved in the amphibolites.

Regional changes in fabric evolution with time have been documented in the WGR (Andersen et al. 1994, Terry & Robinson 2004). As indicated in Figure 10, the coronitic eclogite is related to an initial eclogitisation and the LS fabric preserved in eclogite lenses and boudins to a prograde eclogite stage. The fabrics of foliated and mylonitic eclogites are in harmony with the regional foliation, and can be related to an early stage of the exhumation which started under eclogite facies conditions and continued

into the amphibolite-facies crustal regime (Engvik & Andersen 2000, Foreman et al. 2005).

Regional homogeneous deformation during exhumation

The layered gabbro is interpreted to have been the protolith for the regionally mapped amphibolite-dominated complex on the south side of Dalsfjorden. It has been shown that the foliated amphibolites formed by retrogression of eclogites. Hydration of eclogite to amphibolite facies mineral assemblages is evident as garnet is replaced by chlorite- and amphibole-bearing assemblages, and omphacite is replaced by amphibole. The breakdown of phengitic mica to biotite and orthoclase (Fig. 8d) in the gneisses releases water (Heinrich 1982), and this process can have acted as the source of water for amphibolitisation during decompression from eclogite facies. Areas that escaped deformation and hydration were therefore favourable sites for the preservation of eclogites and their protoliths. Because of the almost pervasive amphibolitisation, it is not possible to give a precise estimate as to how much of the Proterozoic crust was eclogitised. However, based on petrography, it is evident that a significant part of the mafic complex south of Dalsfjorden was eclogitic, and consequently this must have been one of the largest eclogite bodies in the deeply-buried Baltic crust. Approximately 95% of the crust at the present exposed level was transformed to amphibolite during the late-Scandian exhumation.

Figure 10 shows the contrast between the heterogeneous eclogite-facies structures and the homogeneous amphibolite-facies fabric. The E-W-trending amphibolite-facies foliation is the dominant fabric in mafic and felsic lithologies. Proterozoic protoliths and different types of eclogite are preserved as lenses up to km-size within the regional foliation. Smaller eclogite lenses (m-size) are widespread in the gneisses and foliated amphibolites. The amphibolite facies fabric originated during a stage of vertical shortening and shear bands with both top-to-E and top-to-W vergence indicate that the deformation was coaxial at mid-crustal levels during exhumation. Local L-tectonite horizons indicate a component of constriction and E-W-oriented stretching. This is in accordance with Foreman et al. (2005) who concluded that mafic bodies in the Sunnfjord area were modified by eclogite- to amphibolite-facies transformation and E-W-directed stretching, which gave rise to boudin-like lenses at different scales from cm to km. The observations also support the exhumation model proposed for the southern part of the WGR, involving lower-crustal coaxial vertical shortening overprinted by top-west non-coaxial shear in the NSDZ (Andersen & Jamtveit 1990, Dewey et al. 1993, Hacker et al. 2003). The structural homogeneity in the amphibolite facies can be explained by an interaction of differential stresses during vertical shortening, fluid recycling and rheological softening, in accordance with the conclusions reached by Engvik et al. (2000).

Conclusions

This paper describes the structural and metamorphic heterogeneity of the deep crust which occurred in large parts of the southern WGR during Scandian metamorphism. Mesoproterozoic crust underwent partial eclogitisation and, subsequently, partial amphibolitisation during the Scandian orogeny. Rocks preserved in strain shadows at both eclogite- and amphibolite-facies conditions provide an opportunity to study protoliths and transitions of these which occurred under eclogite-facies conditions at various stages of structural modification. The paper documents the inhomogeneity of the Mesoproterozoic and Early Palaeozoic deep crust. In contrast to the early heterogeneity, a regional homogeneous foliation fabric formed during the late-Scandian exhumation and pervasively overprinted the earlier structures. This work documents that:

- Mesoproterozoic protoliths and Scandian eclogites with coronitic textures were preserved in low-strain domains during burial and exhumation. In domains with intermediate deformation coronitic eclogite structures are flattened, and eclogite lenses occur as both massive and LS-tectonites. Highly strained eclogites occur in shear zones with thicknesses from the cm scale up to 20 m.
- Microfabric analyses of eclogite mylonites show that both intracrystalline and diffusional deformation mechanisms were active at estimated temperature conditions above 600°C and pressures of about 2.3 GPa. Both grain-coarsening and grain-size reduction mechanisms were operative. EBSD measurements of omphacite show that {001} reveals a well-defined maximum parallel to the stretching lineation while {010} defines a girdle approximately normal to the foliation, consistent with dynamic recrystallisation and dislocation glide in omphacite.
- In the eclogite-facies, inhomogeneous deformation is assumed to be the result of compositional, mineralogical and structural variations in the protolith and the availability of a fluid phase. This caused variations in rock strength leading to local strain partitioning and variations in accumulated strain, in addition to changes in the regional stress regime.
- The structural homogeneity in the amphibolite facies lithologies can be explained by an interaction of regional vertical shortening, fluid recycling and rheological softening.
- Large parts of the mafic complex south of Dalsfjorden are interpreted to have been formerly eclogite, representing one of the largest eclogite bodies in the deeply subducted Baltic crust. During the late-Scandian exhumation, about 95% of the exposed crust is estimated to have been transformed to amphibolites.

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References

- Andersen, T.B. 1998: Extensional tectonics in southern Norway: An overview. *Tectonophysics* 273, 129-153.
- Andersen, T.B., Berry, H.N., Lux, D.R. & Andresen A. 1998: The tectonic significance of Ar⁴⁰/Ar³⁹ phengite cooling ages in the Caledonides of western Norway. *Journal of the Geological Society London* 155, 297-309.
- Andersen, T.B. & Jamtveit, B. 1990: Uplift of deep crust during orogenic extensional collapse: Model based on field studies in the Sogn-Sunnfjord region of Western Norway. *Tectonics* 9, 1097-1111.
- Andersen, T.B., Jamtveit, B., Dewey, J.F. & Swensson, E. 1991: Subduction and exhumation of continental crust: major mechanisms during continent-continent collision and orogenic extensional collapse, a model based on the south Caledonides. *Terra Nova* 3, 303-310.
- Andersen, T.B., Jolivet, L. & Osmundsen, P.T. 1994: Deep crustal fabrics and a model for the extensional collapse of the Southwest Norwegian Caledonides. *Journal of Structural Geology* 16, 1191-1203.
- Austrheim, H. 1987: Eclogitization of the lower crustal granulites by fluid migration through shear zones. *Earth & Planetary Science Letters* 81, 221-232.
- Austrheim, H., Erambert, M. & Engvik, A.K. 1997: Processing of crust in the root zone of the Caledonian continental collision zone: the role of eclogitization. *Tectonophysics* 273, 129-153.
- Austrheim, H., Corfu, F., Bryhni, I. & Andersen, T.B. 2003: The Proterozoic Hustad igneous complex; a low strain enclave with a key to the history of the Western Gneiss Region of Norway. *Precambrian Research* 120, 149-175.
- Bascou, J., Tommasi, A. & Mainprice, D. 2002: Plastic deformation and development of clinopyroxene lattice-preferred orientation in eclogites. *Journal of Structural Geology* 24, 1357-1368.
- Boudry, T.M., Fountain, D.M. & Austrheim, H. 1992: Structural development and petrofabrics of eclogite facies shear zones, Bergen Arcs, western Norway: implication for deep crustal deformational processes. *Journal of Metamorphic Geology* 10, 127-146.
- Brueckner, H.K. & van Roermund, H.L.M. 2004: Dunk tectonics: A multiple subduction/exhumation model for the evolution of the Scandinavian Caledonides. *Tectonics* 23, doi: 10.1029/2003TC001502.
- Bryhni, I. 1966: Reconnaissance studies of Gneisses, Ultrabasites, Eclogites and Anorthosites in Outer Nordfjord, Western Norway. *Norges geologiske undersøkelse* 241, 1-68.
- Buatier, M., van Roermund, H.L.M., Drury, M.R. & Lardeaux, J.M. 1991: Deformation and recrystallisation mechanisms in naturally deformed omphacites from Sesia-Lanzo zone; geophysical consequences. *Tectonophysics* 195, 11-27.
- Cuthbert, S.J. 1985: Petrology and tectonic settings of relative low-temperature eclogites and related rocks in the Dalsfjord area, Sunnfjord, West Norway. Unpublished Ph.D. thesis, University of Sheffield, United Kingdom.
- Cuthbert, S.J. & Carswell, D.A. 1991: Formation and exhumation of medium-temperature eclogites in the Scandinavian Caledonides. In Carswell, D.A. (ed.): *Eclogite facies rocks, 180-203*. Blackie & Son Ltd, Glasgow.
- Dewey, J.F., Ryan, P.D. & Andersen, T.B. 1993: Orogenic uplift and collapse, crustal thickness, fabrics and metamorphic phase changes: the role of eclogites. *Journal of the Geological Society London, Special Publication* 76, 325-343.
- Dobrzynetskaia, L.F., Eide, E.A., Larsen, R.B., Sturt, B.A., Trønnes, R., Smith, D.C., Taylor, W.R. & Posukhova, T.V. 1995: Microdiamond in high-grade metamorphic rocks of the Western Gneiss Region, Norway. *Geology* 7, 597-600.
- Eide, E.A., Torsvik, T.H., Andersen, T.B. & Arnaud, N.O. 1999. Early Carboniferous unroofing in Western Norway: A tale of alkali feldspar thermochronology. *Journal of Geology* 107, 353-374.
- Engvik, A.K. & Andersen, T.B. 2000: Evolution of Caledonian deformation fabrics under eclogite and amphibolite facies at Vårdalsnet, Western Gneiss Region, Norway. *Journal of Metamorphic Geo-*

- logy 18, 241-257.
- Engvik, A.K., Austrheim, H. & Andersen, T.B. 2000: Structural, mineralogical and petrophysical effects on deep crustal rocks of fluid-limited polymetamorphism, Western Gneiss Region, Norway. *Journal of the Geological Society London* 157, 121-134.
- Engvik, A.K., Austrheim, H. & Erambert M. 2001: Interaction between fluid flow, deformation and mineral growth, an example from the Sunnfjord area, Western Gneiss Region, Norway. *Lithos* 57, 111-141.
- Erambert, M. & Austrheim, H. 1993: The effect of fluid and deformation on zoning and inclusion pattern in poly-metamorphic garnets. *Contributions to Mineralogy & Petrology* 115, 204-214.
- Foreman, R., Andersen, T.B. & Wheeler, J. 2005: Eclogite-facies polyphase deformation of the Drøsdal eclogite, Western Gneiss Complex, Norway, and implications for exhumation. *Tectonophysics* 398, 1-32.
- Gee, D. 1975: A tectonic model for the central part of the Scandinavian Caledonides. *American Journal of Science* 275-A, 468-515.
- Glodny, J., Kühn, A. & Austrheim, H. in press: Diffusion versus recrystallisation processes in Rb-Sr geochronology: isotopic relics in eclogite facies rocks, Western Gneiss Region, Norway. *Geochemica and Cosmochemica Acta*.
- Godard, G. & van Roermund, H. 1995: Deformation-induced clinopyroxene fabrics from eclogites. *Journal of Structural Geology* 17, 1425-1443.
- Griffin, W.L. 1987: "On the eclogites of Norway" – 65 years later. *Mineralogical Magazine* 51, 333-343.
- Griffin, W.L., Austrheim, H., Braasted, K., Bryhni, I., Krill, A.G., Krogh, E.J., Mørk, M.B.E., Quale, H. & Tørudbakken, B. 1985: High-pressure metamorphism in the Scandinavian Caledonides. In Gee, D.G. & Sturt, B.A. (eds.): *The Caledonide Orogen - Scandinavia and Related Areas*, 783-802. John Wiley & Sons Ltd, Chichester.
- Hacker, B.R., Andersen, T.B., Root, D.B., Mehl, L., Mattinson, J.M. & Wooden, J.L. 2003: Exhumation of high-pressure rocks beneath the Solund Basin, Western Gneiss Region of Norway. *Journal of Metamorphic Geology* 21, 613-629.
- Hacker, B.R. & Gans, P.B. 2005: Continental collisions and the creation of ultrahigh-pressure terranes: Petrology and thermochronology of nappes in the central Scandinavian Caledonides. *Bulletin of the Geological Society of America* 117, 117-134.
- Heinrich, C.A. 1982: Kyanite-eclogite to amphibolite facies evolution of hydrous mafic and pelitic rocks, Adula Nappe, Central Alps. *Contribution to Mineralogy & Petrology* 81, 30-38.
- Johnston, S.M., Bradley, R.H. & Andersen, T.B. in press: Exhuming Norwegian Ultrahigh-Pressure Rocks: Overprinting Extensional Structures and the Role of the Nordfjord-Sogn Detachment Zone. *Tectonics*.
- Jin, Z.-M., Zhang, J., Green, H.W. & Jin, S. 2001: Eclogite rheology: Implications for subducted lithosphere. *Geology* 29, 667-670.
- Kildal, E.S. 1970: *Geologisk kart over Norge, berggrunnskart. Målestokk 1:250 000*. Norges Geologiske Undersøkelse, Trondheim.
- Krabbendam, M. & Dewey, J.F. 1998: Exhumation of UHP rocks by transtension in the Western Gneiss Region, Scandinavian Caledonides. In Holdsworth, R.E., Strachan, R.A. & Dewey J.F. (eds.): *Continental Transpression and Transtensional Tectonics*, Geological Society London, *Special Publications* 135, 159-181.
- Krabbendam, M., Wain, A. & Andersen, T.B. 2000: Pre-Caledonian granulite and gabbro enclaves in the Western Gneiss Region, Norway: indication of incomplete transition at high pressure. *Geological Magazine* 137, 235-255.
- Krogh, E.J. 1980: Geochemistry and petrology of glaucophane-bearing eclogites and associated rocks from Sunnfjord, western Norway. *Lithos* 13, 355-380.
- Krogh, E.J. 1982: Metamorphic evolution deduced from mineral inclusions and compositional zoning in garnets from Norwegian country-rock eclogites. *Lithos* 15, 305-321.
- Labrousse, L., Jolivet, L., Agard, P., Hébert, R. & Andersen, T.B. 2002: Crustal-scale boudinage and migmatization of gneiss during their exhumation in the UHP Province of Western Norway. *Terra Nova* 14, 263-270.
- Mancktelow, N.S. 1993: Tectonic overpressure in competent mafic layers and the development of isolated eclogites. *Journal of Metamorphic Petrology* 11, 801-812.
- Mauler, A., Godard, G. & Kunze, K. 2001: Crystallographic fabrics of omphacite, rutile and quartz in Vendée eclogites (Armorican Massif, France). Consequences for deformation mechanisms and regimes. *Tectonophysics* 342, 81-112.
- Mysen, B.O. & Heier, K.S. 1972: Petrogenesis of eclogites in high grade metamorphic gneisses exemplified by the Hareidland eclogite, west Norway. *Contributions to Mineralogy & Petrology* 36, 73-94.
- Mørk, M.B.E. & Mearns, E.W. 1986: Sm-Nd isotopic systematics of a gabbro-eclogite transition. *Lithos* 19, 255-267.
- Osmundsen, P.T., Andersen, T.B., Markussen, S. & Svendby, A.K. 1998: Tectonics and sedimentation in the hanging wall of a major extensional detachment: the Devonian Kvalshesten basin, western Norway. *Basin Research* 10, 213-234.
- Pennacchioni, G. 1996: Progressive eclogitization under fluid-present conditions of pre-Alpine mafic granulites in the Austroalpine Mt Emilius Klippe (Italian Western Alps). *Journal of Structural Geology* 18, 549-561.
- Philippot, P. & van Roermund, H.L.M. 1992: Deformation processes in eclogite rocks: evidence for the rheological delamination of the oceanic crust in deeper levels of subduction zones. *Journal of Structural Geology* 14, 1059-1077.
- Piepenbreier, D. & Stöckhert, B. 2001: Plastic flow of omphacite in eclogite at temperatures below 500°C – implications for interplate coupling in subduction zones. *International Earth Sciences* 90, 197-210.
- Ravna, E.J.K. & Terry, M.P. 2004: Geothermobarometry of UHP and HP eclogites and schists – an evaluation of equilibria among garnet-clinopyroxene-kyanite-phengite-coesite/quartz. *Journal of Metamorphic Petrology* 22, 579-592.
- Roberts, D. 2003: The Scandinavian Caledonides: event chronology, palaeogeographic settings and likely modern analogues. *Tectonophysics* 365, 283-299.
- Root, D.B., Hacker, B.R., Mattinson, J.M. & Wooden, J.L. 2005: Zircon geochronology and ca. 400 Ma exhumation of Norwegian ultrahigh-pressure rocks: an ion microprobe and chemical abrasion study. *Earth and Planetary Science Letters* 228, 325-341.
- Rubie, D.C. 1990: Role of kinetics in the formation and preservation of eclogites. In Carswell, D.A. (ed.): *Eclogite facies rocks*, 180-203. Blackie & Son, Glasgow.
- Røhr, T.S., Corfu, F., Austrheim, H. & Andersen, T.B. 2004: Sveconorwegian U-Pb zircon and monazite ages of granulite-facies rocks, Hisarøy, Gulen, Western Gneiss Region, Norway. *Norwegian Journal of Geology* 84, 251-256.
- Skjerlie, F.J. & Pringle, I.R. 1978: A Rb/Sr whole-rock isochron date from the lowermost gneiss complex of Gaular area, west Norway and its regional implications. *Norsk Geologisk Tidsskrift* 58, 259-265.
- Skår, Ø. 1997: Protoliths of the gneisses and mafic rocks in the Hellevik-Flekkje Area in Sunnfjord, Western Norway. *Norges geologiske undersøkelse*, Report 97.077, pp 24.
- Skår, Ø., Furnes, H. & Claesson, S. 1994: Proterozoic orogenic magmatism within the Western Gneiss Region, Sunnfjord, Norway. *Norsk Geologisk Tidsskrift* 74, 114-126.
- Smith, D.C. 1984: Coesite in clinopyroxene in the Caledonides and its implications for geodynamics. *Nature* 310, 641-644.
- Stöckhert, B. & Renner, J. 1998: Rheology of crustal rocks at ultrahigh pressure. In Hacker, B.R. & Liou, J.G. (eds.): *When continents Collide: Geodynamics and Geochemistry of Ultrahigh-Pressure Rocks*, 57-95. Kluwer, Dordrecht.
- Suo, S., Zhong, Z., Zhou, H. & You, Z. 2001: Structural analyses of UHP metamorphic rocks in the Bixiling area, Dabie Mountains, China. *Earth Science Frontiers* 8, 385-394.
- Swensson, E. & Andersen, T.B. 1991: Petrography and basement-cover

- relationships between the Askvoll Group and the Western Gneiss Region, Sunnfjord, W. Norway. *Norsk Geologisk Tidsskrift* 71, 15-27.
- Terry, M.P. & Heidelbach, F. 2006: Deformation-enhanced metamorphic reactions and rheology of high-pressure shear zones, Western Gneiss Region, Norway. *Journal of Metamorphic Geology* 24, 3-18.
- Terry, M.P. & Robinson, P. 2004: Geometry of eclogite-facies structural features: Implications for production and exhumation of ultrahigh-pressure and high-pressure rocks, Western Gneiss Region, Norway. *Tectonics* 23, doi:10.1029/2002TC001401
- Terry, M.P., Robinson, P., Hamilton, M.A. & Jercinovic, M.J. 2000: Monazite geochronology of UHP and HP metamorphism, deformation, and exhumation, Nordøyane, Western Gneiss Region, Norway. *American Mineralogist* 85, 1651-1664.
- Torsvik, T.H., Sturt, B.A., Swensson, E., Andersen, T.B. & Dewey, J.F. 1992: Palaeomagnetic dating of fault rocks: Evidence for Permian and Mesozoic movements along Dalsfjord Fault, Western Norway. *Geophysical Journal* 109, 565-580.
- Tucker, R.D., Robinson, P., Solli, A., Gee, D.G., Thorsnes, T., Krogh, T.E., Nordgulen, Ø. & Bickford, M.E. 2004: Thrusting and extension in the Scandinavian hinterland, Norway: New U-Pb ages and tectonostratigraphic evidence. *American Journal of Science* 304, 477-532.
- Ulrich, S. & Mainprice, D. 2005: Does cation ordering in omphacite influence development of lattice-preferred orientation? *Journal of Structural Geology* 27, 419-431.
- Wain, A.L. 1997: New evidence for coesite in eclogite and gneisses: Defining an ultrahigh-pressure province in the Western Gneiss region of Norway. *Geology* 25, 927-930.
- Walsh, E.O. & Hacker, B.R. 2004: The fate of subducted continental margins: Two-stage exhumation of the high-pressure to ultrahigh-pressure Western Gneiss Region, Norway. *Journal of Metamorphic Geology* 22, 671-687.
- Walsh, E.O., Hacker, B.R., Gans, P.G., Grove, M. & Gehrels, G. 2007: Protolith ages and exhumation histories of (ultra)high-pressure rocks across the Western Gneiss Region, Norway. *GSA Bulletin* 119, 289-301.
- Walther, J.V. 1994: Fluid-rock reactions during metamorphism at mid-crustal conditions. *Journal of Geology* 102, 559-570.
- Wayte, G.J., Worden, R.H., Rubie, D.C. & Droop, G.T.R. 1989: A TEM study of disequilibrium plagioclase breakdown at high pressure: the role of infiltrating fluid. *Contributions to Mineralogy & Petrology* 101, 426-437.