Preservation of granulite in a partially eclogitized terrane: Metastable phenomena or local pressure variations?

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Abstract

Granulite is preserved over large areas of partially eclogitized and hydrated rocks on Holsnøy, Bergen Arcs, Norway. The interfaces between granulite and eclogite are sharp on a hand-specimen scale and contain microstructural and compositional evidence for the mechanism of eclogitization. The interface studied here is undeformed with a continuous foliation from granulite through an eclogite 'finger' that protrudes into the granulite. Diopside in the granulite evolves continuously to omphacite in eclogite by increasing jadeite composition at a well-defined sequence of microstructures that involve pyroxene-amphibole intergrowths and symplectites. Plagioclase in the granulite develops a high density of zoisite and kyanite inclusions that increase in abundance prior to plagioclase breakdown in eclogite. The transition between granulite and eclogite is interpreted as indicating a pressure gradient. The observation that granulite is preserved adjacent to eclogite although it shows sufficient evidence of hydration such that metastability may not be a factor, suggests that eclogitization involves the generation of increased pressure due to reaction and rock weakening. The pyroxene and feldspar microstructures in the transition zone between granulite and eclogite are very similar to the transition zones between granulite and amphibolite elsewhere in the Bergen Arcs. Localized variation in pressure could be an explanation for concurrent eclogitization and amphibolitization of granulite at the same crustal level during orogenesis.

1. Introduction.

Eclogitization of dry, low-permeability and mechanically strong lower crustal rocks during continental collision and subduction is accompanied by a significant density increase and rheological weakening and hence plays a major role in determining the dynamics of the lithosphere (Ahrens and Schubert, 1975a,b; Austrheim, 1991, 1998; Jackson et al., 2004; Jamtveit and Austrheim, 2010; John and Schenk, 2006; Jolivet et al., 2005; Krystopowicz and Currie, 2013; Malvoisin et al., 2020). The initiation of eclogite formation within the granulitic lower crust is associated with fluid infiltration along fractures and localised shear zones which are generated by earthquakes and their aftershocks (Austrheim, 1987; Hetényi et al., 2007; Jamtveit et al., 2018a; Miller, 2013). The feedbacks between fracturing, fluid-infiltration, metamorphic reaction, deformation and permeability are currently topics of major interest in metamorphic petrology and tectonics and are being investigated through theoretical modelling, observations of natural rock textures and microstructures on a range of spatial scales as well as in laboratory experiments (Beinlich et al., 2020; Chu et al., 2017; Gerya, 2015; Kaatz et al., 2021; Putnis et al., 2017; Richter et al., 2016; Schorn and Diener, 2017; Smit et al., 2020; Taetz et al., 2018).

Understanding the formation of eclogite is central to the current debate challenging the conventional view that metamorphic reactions take place at near-lithostatic pressure and hence that pressures, determined from thermodynamic models of mineral assemblages, can be related to depth in the crust (Li et al., 2010; Moulas et al., 2013; Schmalholz and Podladchikov, 2014) . The general agreement that eclogitization of granulite requires fluid infiltration (Austrheim 1987; Jamtveit et al., 1990), combined with the common observation that fluid infiltration and hence rock strength are spatially heterogeneous, results in a situation where significant pressure differences could exist during deformation (Jamtveit et al., 2018b; Mancktelow, 1993, 1995, 2008; Moulas et al., 2019; Petrini and Podladchikov, 2000; Reuber et al., 2016; Schmalholz and Podladchikov, 2013; Schmalholz and Duretz, 2015; Vrijmoed et al., 2009). However, the currently more widely-accepted explanation for the persistence of granulite in an eclogitized terrain is that while both the granulite and eclogite experienced the same Pressure/Temperature (P,T) conditions during subduction, the granulite did not react because it remained dry. This could be termed the "metastability

hypothesis" (Austrheim, 1987; Jamtveit et al., 2016). On the other hand, recent studies have concluded that local pressure variations provide a more consistent interpretation of the spatial juxtaposition of rocks with widely differing metamorphic grade. Such a "local equilibrium hypothesis" due to pressure variations has been proposed to explain the formation of Caledonian high-pressure rocks in the Western Gneiss Region of western Norway (Vrijmoed et al., 2009) and Caledonian eclogites within the Proterozoic granulites in the Bergen Arcs (Jamtveit et al. 2018b). Chu et al. (2017) have also invoked overpressure generated by local melting in a confined volume (Vrijmoed et al., 2009) to account for eclogitization in New England, USA. Pressure gradients due to reaction-induced stress have been calculated to explain the existence of high pressure whiteschists within an undeformed metagranite in the Monte Rosa nappe, Western Alps (Luisier et al., 2019). The difference between the "metastability" and the "local equilibrium (i.e pressure variation)" hypotheses is not trivial and challenges the fundamental assumptions in the tectonic interpretation of the evolution of the lithosphere that equate regional pressure to depth in the crust.

Within this general context, the aim of this paper is to describe the microstructures and reaction pathways associated with a specific example of eclogitization of granulite on Holsnøy in the Bergen Arcs, western Norway. The Bergen Arcs, a much-studied region (Andersen et al., 1991; Austrheim, 1987; Bhowany et al., 2018; Centrella, 2018; Glodny et al., 2008; Putnis et al., 2017) provides many examples of eclogite ocurrences within granulite facies anorthosites. Eclogitization is spatially heterogeneous and interfaces between eclogite and granulite facies rocks are common, although local dynamic settings are quite variable, as eclogite can be found associated with shear zones but can also occur in undeformed settings as fingers that penetrate the granulite, preserving the granulite fabric at the outcrop scale (Austrheim 1987; Bjørnerud et al., 2002; Jamtveit et al., 2000; Zertani et al., 2019). These different eclogite occurrences are interpreted to be genetically related, possibly representing various stages of fluid infiltration, eclogitization and perturbations of the local stress field (Jamtveit et al., 2000; 2018b).

To determine the reaction pathways from granulite to eclogite we have investigated the initial stages of eclogitization across an interface between the granulite and eclogite that is

sharp in outcrop, allowing a clear macroscopic separation between the two rock types with a transition zone extending over approximately 5 cm. The chosen sample site is the tip of an eclogite 'finger' protruding into the granulite and preserving the granulite foliation across the reaction interface, similar to that described in Jamtveit et al., (2000). This suggests that the eclogitization postdated the formation of the regional scale fabric and proceeded in the absence of additional deformation, i.e. solely driven by fluid infiltration. This field relationship between deformation and replacement textures is different to eclogite facies shear zones also on Holsnøy, and thus provides insight into the microstructural evolution linked only to fluid-rock interaction. The aim is to describe the evolution of the microstructure and local chemical compositions that have taken place sequentially across the transition from granulite to eclogite in an attempt to determine whether the microstructures can be used to discriminate between interpretations based on metastability or local equilibrium due to pressure variations. We have therefore also used thermodynamic modelling to determine whether the observed evolution of the mineral assemblages across the granulite to eclogite reaction zone could be explained by variations in water activity without invoking a pressure gradient.

2. Geological background and sample description

The relevant geological history of the Bergen Arcs can be divided into two major orogenic events – the Proterozoic Grenvillian and the Paleozoic Caledonian orogenies, respectively. The geology of this part of western Norway has been described in considerable detail in many of the original publications of the area (Austrheim and Griffin, 1985; Cohen et al., 1988; Sturt et al., 1975) as well as in more recent papers (e.g. Jamtveit et al., 2018b, 2021; Putnis et al., 2017) and only a short summary is given below.

The Grenvillian Orogeny, dated at between 910 Ma and 930 Ma (Cohen et al., 1988; Bingen et al., 2001), is characterized by extensive magmatic activity, deformation and metamorphism up to granulite grade (P< 10kbar, T=800-900^{0}C). The anhydrous Grenvillian granulites were overprinted by the Caledonian Orogeny during continental collision and subduction at ~400–440 Ma (Austrheim, 1987; Bingen et al., 2004; Boundy et al.,1992; Glodny et al., 2008; Kuhn et al, 2002). The Caledonian overprint is evidenced by reworking

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of the high-grade terrane in apparently contemporaneous shear zones of amphibolite and eclogite grade involving hydration and metasomatism (Andersen et al., 1991, Centrella, 2018; Jamtveit et al., 2018a,b; Moore et al., 2020a; Putnis et al., 2017). The equilibrium $P–T$ conditions for the eclogite facies rocks have been estimated at > 18 kbar, 700^0C (Boundy et al., 1992) and 14.6 kbar, 670 ± 50^0C (Jamtveit et al., 1990) and 21-22 kbar at $670 – 690^0$C (Bhowany et al., 2018).

The interpreted $P–T$ paths from the earlier studies were summarized by Austrheim (1991) to follow a depth–temperature–time trajectory at which the Bergen Arcs complex was recrystallized at granulite facies at the end of the Grenvillian event (c. 900 Ma) at a depth of ~30 km. The later, Caledonian event buried the complex up to a depth of 50–60 km during which the complex was fractured and hydrated. Absence of uplift evidence between the two major events was interpreted as the complex being stable at 30 km depth during which time it must have cooled from 800^0C to ~500^0C given the shield geothermal gradient (Austrheim, 1990; Jamtveit et al., 1990). The subsequent Caledonian event resulted in reheating of the complex up to ~700^0C. Such an interpretation follows from the pressure estimates determined from the thermodynamic properties of the mineral assemblages, and assumes a lithostatic pressure-depth relationship.

The eclogites described in this paper are exposed on the island of Holsnøy, Bergen Arcs, and the sample was taken from the tip of an eclogite finger, similar to that in Figure 1, from the same area that was recently mapped in detail and described by Zertani et al. (2019). The location map is shown in Supplementary Figure S11. Similar eclogite fingers associated with large sheared eclogite blocks have been described by Jamtveit et al., (2000, 2016). The foliation along the eclogite fingers is continuous with that in the granulite with no apparent deformation at the interface. In the field, the eclogite fingers as well as contacts between eclogite and granulite in other locations are often mantled by a paler granulite rock than the granulite further from reaction interface (Fig.1a). Figures 1b,c show part of an eclogite finger showing the foliation direction and the fractures that cut across the eclogite but do not continue into the host granulite.

A 30cm long hand specimen was cut from the tip of a finger across the granulite-eclogite reaction front (Fig.2, location: 60°35'20.87"N, 5°0'10.45"E, Fig. S11). Additional samples were taken from granulite and eclogite facies rocks about a metre from the reaction interface. Thin sections and epoxy mounts were prepared from the samples to investigate the mineral reactions associated with the granulite-eclogite transition.

3. Methods

Polished mounts and thin sections were analyzed using the TESCAN TIMA SEM-EDS system at the John de Laeter Centre, Curtin University, Perth, Australia. TIMA is equipped with four silicon drift energy dispersive (EDS) detectors that are arranged at approximately 90◦ intervals around the electron beam. TESCAN and TIMA software are used to operate the SEM and to acquire and reduce data, respectively. Operating conditions were set at 25 keV, 6 nA, using a spot size of 50 nm and working distance of 15 mm. All samples have been analyzed in 'dot-mapping' mode returning a mineral map of the sample depending on a standard or customized library comparing energy dispersive X-ray (EDX) spectra and relative peak heights with its database. Dot-mapping acquires an EDX spectrum of 1000 counts every 27 μm and discriminates between quantified backscatter electron intensity every 3 μm. In addition to the standard EDX acquisition every new back-scattered electron (BSE) intensity encountered is analysed with EDX. Several areas of interest have been mapped at 1–3 μm 'high-resolution' acquiring an EDX spectrum for each pixel besides analysing the BSE intensity. When settings were different this is mentioned in the text or image caption.

Additional element maps were acquired using the JEOL 8530F electron probe microanalyser (EPMA) in the Institut für Mineralogie, University of Münster. The standard electron probe conditions for mapping were 50 nA and 15 kV. Standards used for quantitative measurement were jadeite (Na), kyanite (Al), sanidine (K), olivine (Mg), hypersthene (Si), diopside (Ca), rhodocrosite (Mn), rutile (Ti), fayalite (Fe), and chromite (Cr).

Quantitative mineral compositions were obtained using a Cameca SX-Five EPMA at the University of Adelaide. This instrument is equipped with 5 adjustable (crystal position) wavelength-dispersive spectrometers. The operating software is PeakSite v6.2 and EPMA

software used is Probe (distributed by Probe Software Inc.) for data acquisition and processing. The instrument operation conditions were set to 20 keV and 20 nA with a defocused beam size of 2 μm. The full list of elements analysed is presented in Table 1. Oxygen was calculated by stoichiometry, assuming that all Fe was Fe^{2+}. Matrix corrections of Armstrong-Love/Scott φ(ρz) (Armstrong, 1988) and Henke MACs were used for data reduction.

Beam damage and alkali element migration in silicate analyses were minimized by using a defocused electron beam. Mean Atomic Number (MAN) background correction (Donovan et al., 2016) was used over traditional 2 point interpolation. This allows single point analysis time to be greatly shortened (from ~3.5 min to ~1.5 min), reducing the effects of beam damage, element migration and their subsequent impact on the quality of analysis. In addition, elements that are particularly mobile (e.g. Na, F, Cl) were analysed first on the detector and then Time Dependent Intensity (TDI) correction feature of Probe for EPMA was utilized. Using this method, the decay of X-ray counts over time is measured and modelled to return to 0 at the intercept, and from this a concentration is calculated.

Electron back scatter diffraction (EBSD) analyses were carried out at the John de Laeter Centre, Perth. Data were acquired using a field emission Tescan MIRA3 SEM, Oxford Instruments Aztec software and EBSD detector. A tilted sample (70◦) was analysed using the electron beam set at 20 keV, beam current of 6 nA, beam size of 70 nm at a working distance of 15 mm. Post-processing was done using Oxford Instruments Channel 5.12 software Tango, applying a wild spike and iterative 8, and 7 nearest neighbour corrections before further analysis.

Thermodynamic modelling using Perple_X_6.9.0 (Connolly, 1990, Connolly, 2009) and the internally consistent thermodynamic dataset and equation of state for H_2O of Holland and Powell (2011) were used to estimate the pressures required to generate eclogite and amphibolite from the granulite at 700^0C with variable water activity . The solution models are for clinopyroxene (cpx; Green *et al.*, 2016), clinoamphibole (amp; Green *et al.*, 2016), epidote (czo; Holland & Powell, 2011), garnet (gt; White *et al.*, 2014), white mica (wmca;

White *et al.*, 2014), ternary feldspar (pl; Holland & Powell, 2003), and tonalitics 'metabasite' melt (L; Green *et al.*, 2016).

4. Results

The focus in this paper is on the transition from the granulite to the eclogite by describing the microstructures and compositions along a transect from the granulite to the eclogite across the reaction interface (Fig.2). The labels A-D in Figure 2 relate to the major mineral assemblages along this transect and their compositions determined from electron probe micro-analyses (Table 1).

4.1. The "dry" granulite.

The granulite consists of plagioclase (45 vol%), garnet (35 vol%) and aluminous diopside (20 vol%) (Fig. 3a), and minor scapolite, corundum and spinel. The major phases are euhedral to subhedral with a grain size between 0.1 – 2.5 mm. In anhydrous granulite samples taken several metres from the eclogite interface the plagioclase is clear, pinkish in colour with the composition $An_{47}Ab_{52}$ (Table 1; abbreviations after Whitney and Evans, 2010) and generally in the smaller size range (0.1 – 1.8 mm). The plagioclase is multiply twinned with sharp, parallel or tapering twin boundaries that are initiated at grain boundaries. Nearer to the eclogite the plagioclase shows signs of reaction with the growth of acicular clinozoisite forming along plagioclase-plagioclase grain boundaries (10-20 μm thick) as well as minor fine-grained clinozoisite and kyanite needles protruding into the plagioclase grains (Fig. 3a). Plagioclase-garnet grain boundaries (20-40 μm thick) also contain acicular clinozoisite and kyanite, visible around the garnet grain in Figure 3a.

The garnet in the granulite is Mg-rich ($Prp_{55}Alm+Sps_{26}Grs_{19}$) and is free of inclusions. Clinpyroxene is composed of clear dark-green aluminous diopside ($Di+Hd_{66}Ts_{25}Jd_1Aeg+NAT_8$). Emanating from fractures within the clinopyroxene, fine amphibole lamellae form along the cleavage planes (arrow in Fig.3a). The clinopyroxene contact with plagioclase is sharp with straight or curved grain boundaries.

4.2   The transitional zone between granulite and eclogite

Nearer to the transition to eclogite the plagioclase develops a milky white appearance (Fig. 2) and contains dense inclusions of clinozoisite with minor kyanite (Fig.3b). The twinning in the plagioclase is gradually obliterated by the high density of inclusions until it is entirely absent. Where microprobe analysis can be made in areas free from inclusions, the plagioclase is significantly enriched in albite component ($An_{17}Ab_{83}$) and reduced K_2O composition (0.07 wt% compared to 0.22 wt% in the granulite). The plagioclase grain boundaries are all occupied by a fine mat of acicular clinozoisite, with minor kyanite (Fig. 3b). Potassium in the grain boundaries can be detected in microprobe spectra and element maps (Supplemental Figure S12).

In the same part of the transect the clinopyroxenes are yellow in transmitted light and contain a high density of fine amphibole lamellae throughout the grains along the pyroxene cleavage planes (Fig. 3c). Further towards the core of the eclogite finger amphibole lamellae within the pyroxene are coarser and coalesce (Fig. 3d) allowing electron probe analysis. Compared to clinopyroxene in the granulite, the clinopyroxene in the granulite-eclogite transition zone is richer in the jadeite component ($Di+Hd_{74}Ts_{14}Jd_{11}Aeg+NAT_1$) and contains more amphibole. The amphibole lamellae, where wide enough to analyse are also sodic with 2.2 wt% Na_2O compared to the amphibole lamellae around fractures in the granulite (1.23 wt% Na_2O). EBSD also confirms the lamellae to be amphibole. The pyroxene-amphibole intergrowth in the transitional zone (Fig.3c,d) is representative of recurring texture type 1 (T1) and designated as Zone 1 in the description of the spatial compositional and textural changes towards the eclogite that follows.

Garnet is clear, free of inclusions, and displays two dominant fracture orientations approximately perpendicular to each other throughout the thin sections. A fine intergrowth of phengite, amphibole and quartz formed in open fractures. Fracture and grain rims are generally Fe-enriched except when in contact with clinopyroxene. We interpret linear, Fe-enriched domains within the garnet interiors as healed fractures. Garnet–clinopyroxene grain boundaries are serrated with small indentations that are filled with amphibole (Amp 2 in Table 1, Assemblage B). Garnet–plagioclase grain boundaries are wider (80 – 100 μm

thick) and contain a fine-grained assemblage of phengite + clinozoisite + quartz + omphacite ± kyanite ± albite.

4.3 Textural evolution of pyroxene across the granulite-eclogite transition

At the granulite–eclogite interface the clinopyroxene with texture Type 1 (T1) is replaced by a symplectite-textured intergrowth of Na-rich clinopyroxene and pargasitic amphibole, designated as Zone 2 and texture Type 2 (T2) (Fig. 4). The clinopyroxene in both T1 ($Di+Hd_{71}Ts_{13}Jd_{15}Aeg+NAT_1$) and T2 ($Di+Hd_{68}Ts_7Jd_{23}Aeg+NAT_1$) are both more jadeititic than the pyroxene in the transitional zone, further from the eclogite. The leading edge of the symplectite is free from amphibole and is richer in Na than in the symplectite intergrowth (Fig. 4b). The interface between texture T1 and texture T2 clinopyroxene is sharp at the SEM scale. There is some variability in the Na-content of the clinopyroxene in the symplectite which is also evident in element maps (Supplemental figure S13) .

In the next stage and further towards the eclogite, the pyroxene-amphibole symplectite (texture T2) is replaced at a sharp interface by jadeite-rich clinopyroxene ($Di+Hd_{65-66}Ts_3Jd_{29-30}Aeg+NAT_1$) with relics of the amphibole symplectite whose texture suggests that the pargasite in the symplectite texture has reacted out. This is termed Zone 3 and texture T3 (Fig. 5). Texture T3 invariably contains open pores sometimes filled with Mg-rich calcite or dolomite. BSE image brightness variations are related to variability of the Na content (Supplemental Fig. S13). At the point in the thin section where texture T2 is replaced by texture T3, the granulitic plagioclase is pseudomorphically replaced by a fine-grained intergrowth of phengite + omphacite ± kyanite. Fe-enriched rims in garnet are wider and fractures are filled with amphibole + phengite ± kyanite.

In the final stage of pyroxene replacement, a further sharp interface separates Zone 3 from a zone of clinopyroxene with few inclusions and a composition closer to ideal omphacite. This is termed Zone 4 (texture T4) in Figure 5 and the pyroxene composition is ~$Di+Hd_{54}Ts_3Jd_{41}Aeg_1$. At the interface with the eclogite and within the eclogite some clinopyroxene grains show all 4 zones and texture types, always concentrically arranged from T1 in the core to T4 at the rims (Fig. 5). Texture T2 always separates texture T3 from T1

and texture T4 is never in direct contact with texture T1. Texture types 1-4 pseudomorph the original clinopyroxene grains in the granulite i.e. texture T4 forms from the outer rim of the original grain.

Elsewhere in the same thin section Fe-enriched garnet rims are wider and their fractures filled with amphibole, phengite ± kyanite. New euhedral omphacite grains also mantle garnet grains along former garnet-plagioclase grain boundaries.

4.3.1. Pyroxene compositions across the reaction interface from granulite to eclogite

Electron microprobe point analyses of clinopyroxene from regions in Zone 1 to Zone 4 (Figs. 4 and 5) show a gradually increasing jadeite component (Fig. 6). The compositions correlate well with the texture types so that increased coarsening of the symplectite (clinopyroxene + amphibole) corresponds with increasing jadeite component. At the Zone 1–2 interface the clinopyroxene is generally free from amphibole and has a higher jadeite content than in the intergrowth that forms the rest of texture T2 (Fig. 4). Similarly, at the Zone 2–3 interface the pyroxene of texture T3 has a higher Na content at the interface than further from it. Generally, each textural change along the granulite to eclogite transition is accompanied by an abrupt increase in the jadeite component of clinopyroxene (Supplemental Figure S13).

The pargasitic amphiboles within the symplectite intergrowth in texture T2 have composition $Na_{0.6}Ca_{2.1}Mg_{3.1}Fe^{2+}_{0.8}Si_{6.5}Al_{2.2}O_{22}(OH)_2$ and also show the presence of potassium in element maps (Fig.4).

The same spatial sequence of texture types within clinopyroxenes has been recognized in other samples taken from granulite-eclogite contact zones on Holsnøy (e.g. in Putnis and Austrheim, 2010) and can be regarded as a common feature. Texture T1 is distinctive for the granulite assemblage proximal to eclogite and is in contact with plagioclase, garnet or with a fibrous clinozoisite–kyanite infill at plagioclase or garnet grain boundaries.

4.3.2. Electron backscatter diffraction (EBSD) imaging

The sequence of replacement of the diopside from texture T1 through to T4 pseudomorphically replaces the original diopside grains. However, at each successive replacement step, EBSD also shows a step change in orientation of the pyroxene phase in the symplectite (Fig. 7). The EBSD data confirm that the lamellae in the clinopyroxene are composed of amphibole, and within each texture type the amphibole orientation maintains its crystallographic relationship to the clinopyroxene with a-, b- and c-axes of both phase coincident.

4.4. Within the eclogite finger

In the core of the eclogite finger the mineral assemblage consists of omphacite + garnet + clinozoisite + kyanite + phengite + quartz + amphibole. Here, euhedral, near-stoichiometric omphacite forms a corona, fringing the garnet grains, by a direct reaction between garnet and the fine phengite + omphacite ± kyanite assemblage that replaced the plagioclase. The breakdown of the plagioclase coincides spatially with widening of the corona and the growth of omphacite by a mechanism that is texturally separate from the omphacite developed through Zones 1-4 from the diopside nearer to the granulite interface. The omphacite corona around garnet is further bordered by euhedral to subhedral kyanite + clinozoisite + phengite and subhedral quartz. Garnet grains have a Mg-rich core and rim of almandine (Table 1) and have not fully equilibrated to eclogite compositions. Amphibole is present in minor amounts at garnet grain boundaries and within its fractures. Clinopyroxene grains showing textures T1 to T4 similar to the sequence shown in Figure 5 are occasionally preserved within the eclogite. Some clinopyroxene grains retain the texture T1 with no compositional development towards texture types T2-T4, even adjacent to the newly-formed stoichiometric omphacite that fringes the garnet.

Superimposed on the granulite to eclogite sequence described above, the grain boundaries between omphacite grains within the coronas are generally fiilled with a very fine symplectite containing albite-amphibole-clinopyroxene (Fig. 8 and Supplemental Figure S14).

4.4.1 Fractures associated with the eclogite finger.

Fractures across the eclogite finger such as shown in the field photograph in Figure 1 are common in relatively undeformed eclogite and typically disappear in the surrounding granulite. They have often been noted (e.g. Austrheim et al., 1997) and ascribed to the volume reduction during eclogitization. On an optical microscope scale, fracturing of grains occurs as intragranular cracks in garnet and clinopyroxene. Fractures along most of the thin section are generally closed with no obvious evidence of reaction (Fig. 9a). However, a prominent parallel fracture set along a zone approximately 1mm wide occurs in the transition part of the sample (within region B Fig. 2). This fracture is open in garnet and includes an infill of mainly amphibole + minor phengite and kyanite (Fig. 9b). The amphibole within the fractures contains chlorine (Fig. 9 c,d). Along the fractures the garnet is enriched in iron. Adjacent to this brittle fracture zone the fractures in the garnets are closed.

Fractures through clinopyroxene are associated with coarsening of the amphibole lamellae in texture T1. Fractures are not obvious in plagioclase but are interpreted to have existed due to the dense occurrence of clinozoisite extending linearly from fractures through garnet–clinopyroxene. Where a fracture intersects a grain boundary it is generally filled with dense aggregates of clinozoisite + phengite + kyanite + amphibole ± omphacite ± quartz ± plagioclase (Ab-rich).

4.5. Eclogite within the shear zone

The eclogite finger sampled here penetrates into the granulite and is associated with a larger sheared eclogite body, similar to those shown in the mapping of Zertani et al. (2019). Shear-zone eclogite consists of bottle green omphacite matrix ($Di+Hd_{48}Ts_5Jd_{39}Aeg+NAT_8$), dotted with bright red almandine garnet ($Prp_{28}Alm+Sps_{45}Grs_{27}$), with additional kyanite, clinozoisite, phengite, quartz, plagioclase (An_{11-19}), and accessory rutile. The major phases are euhedral to tabular ranging in size between 0.2 and 2.0 mm. The breakdown of omphacite to a very fine albite + amphibole ± clinopyroxene along grain boundaries is also developed to varying extents in the shear zone.

4.6 Thermodynamic modelling

The aim of the thermodynamic modelling was to determine whether the mineral assemblage in the eclogite and in the adjacent hydrated granulite could be formed at the same pressure but with variable water activity. The P-α_{H2O} pseudosection (Fig. 10) was computed at a fixed temperature of 700°C using an anorthositic granulite composition reported by Kühn (2002). In the outcrop described by Kühn (2002) and Centrella (2014) the granulite is statically hydrated to both eclogite and amphibolite-facies assemblages but records only minor mass changes in the major oxide components across both transitions (see also Centrella, 2014). The lack of significant mass changes provides an ideal scenario for modelling the conditions of transformation to both metamorphic facies. Further, the used bulk composition exhibits a granulite-facies assemblage of plagioclase, garnet, clinopyroxene, scapolite, and spinel, consistent with that reported here. The reported eclogite assemblage of omphacite, garnet, quartz, kyanite, phengite, clinozoisite and rutile and the amphibolite assemblage of amphibole, plagioclase, chlorite, phengite, clinozoisite, margarite and rutile are also consistent.

In addition to bulk composition, quantitative garnet and phengite compositions are reported by Kühn (2002) for the eclogite and the amphibolite. In the eclogite the reported garnet X_{Alm} (0.46-0.49) and phengite X_{Na} (0.20-0.26) may be used to constrain the P-α_{H2O} conditions further, while in the amphibolite, garnet is absent and thus only the phengite X_{Na} (0.16-0.18) component is used. For the amphibolite, phengite composition and the assemblage are consistent with conditions of 1.36-1.48 GPa and an α_{H2O} of 0.85-0.92 at 700°C (Fig. 10). Phengite and garnet mineral compositions for the eclogite are consistent with conditions 1.75-1.9 GPa and an α_{H2O} of 0.8-1 at 700°C, however, the modelled eclogite assemblage at this α_{H2O} contains a significant proportion of amphibole (25-30 modal%). Alternatively, if the eclogite mineral compositions are taken to be not representative of the equilibrium compositions and eclogite assemblage (without amphibole) is used alone than the resulting conditions for eclogite facies metamorphism are >1.64 GPa and an α_{H2O} of ca. 0.28-0.8.

5. Discussion

Petrographic observations along a transect from the relatively unaltered granulite into the eclogite finger have been used here to relate the reaction microstructures to the pathways to eclogitization. The microstructures are consistent with the generally accepted idea that in the Bergen Arcs eclogitization was induced by the influx of aqueous fluids along fractures and shear zones that are likely to have been seismically generated (Austrheim, 1991, 1998; Austrheim et al., 1997; Jamtveit et al., 2019; Petley-Ragan et al., 2018). The subsequent feedbacks between fracturing, fluid infiltration, reaction, rock weakening and deformation and changes in fluid pressure have been discussed at some length in the literature (Austrheim, 2013; Jamtveit et al., 2018a,b; Jolivet et al., 2005; Lund and Austrheim, 2003; Malvoisin et al., 2015, 2020; Miller and Nur, 2000; Moulas et al., 2019; Schmalholz and Duretz, 2015; Schmalholz and Podladchikov, 2013; Vrijmoed et al., 2009).

Eclogitization at Holsnøy is associated with shear zones from which eclogite fingers may protrude into the relatively unaltered granulite along its pre-existing granulite foliation. Eclogitization along these fingers is static i.e. no observable deformation. Jamtveit et al., (2000) have described these fingers as due to reaction-induced perturbations in the local stress field and that the anisotropy of the external stress field controls the morphology of the reaction front. As the fingers are invariably along the granulite foliation they also likely represent fluid injection pathways along planes of weakness in the rock. The tip of the finger would then indicate the furthest extent of fluid transport during the eclogitisation phase. The source of fluid at the tip of the finger is assumed to be from the shear zone and to have migrated along the length of the finger.

Beyond the extent of the eclogite finger the granulite is also partly hydrated, however it has not reacted to eclogite. This is a critical observation in our interpretation and is discussed in more detail below. The plagioclase in the granulite adjacent to the eclogite is milky white in hand specimen, shows faint or no twinning and contains abundant clinozoisite inclusions, whereas the granulite farther away from the eclogite has clear and lilac coloured plagioclase crystals with sharp twin planes and only few inclusions. There is a gradual increase in the number of clinozoisite inclusions in the plagioclase with distance towards the eclogite,

suggesting increasing hydration (from a microstructure such as in Figure 3a to Figure 3b). An increasing abundance of clinozoisite and kyanite inclusions in plagioclase has also been described for the granulite to amphibolite transition zones of the Bergen Arcs (e.g. Moore et al., 2020a,b; Mukai et al., 2014; Putnis et al., 2017).

The presence of locally hydrated granulite at the eclogite-granulite interface suggests that eclogite formation and granulite hydration are linked. This is consistent with the systematic microtextural change from pristine granulite, through the transition zone, into the eclogite finger, reflecting different snapshots along the reaction sequence from unreacted to fully reacted. In the granulite, incipient reaction is reflected by the presence of amphibole lamellae emanating from fractures in diopside (Figure 3a) and invariably forming along pyroxene cleavage planes. Toward the eclogite, fine lamellae of amphibole (not necessarily related to any visible fractures) become abundant and are homogeneously distributed and crystallographically oriented throughout entire pyroxene crystals (Fig 3 c, d; referred to as texture T1 of Zone 1). This is contemporary with alteration products decorating grain boundaries of garnet and pyroxene while clinozoisite inclusions also increase in the plagioclase (Fig. 3b). As stated above, similar reaction sequences are observed across the granulite to amphibolite transitions elsewhere in the Bergen Arcs, and lead to a continuous evolution of the interface hydration assemblage into the amphibolite shear zones (Mukai et al., 2014; Moore et al., 2020a,b). The similarity between the transition zones and the absence of any clear overprinting relationships of amphibolite and eclogite assemblages in the field or in thin sections (Centrella, 2018; Putnis et al., 2017; Zertani et al., 2019; Moore et al., 2019) make it increasingly difficult to establish a sensible P,T,t path involving separate stages for either metamorphic assemblage.

The question of the origin of the amphibole lamellae, although obviously due to hydration, bears on the wider question whether oriented lamellae in minerals always have a classical exsolution origin (i.e. phase separation from an initial solid solution). Coherent amphibole lamellae along the (010) cleavage planes of pyroxene are not unusual and the mechanism of formation has been discussed by Veblen and Buseck (1980) in terms of fluid infiltration and reaction. Mellini et al., (1983) described amphibole lamellae in pyroxenes from the Bergen Arcs and suggested the formation of a high temperature "solid solution" with hydroxyls

bonded to silicate chains and vacant M sites as the precursor to "exsolution". Proyer et al. (2009, 2013) have generalized the problem of oriented precipitates of non-compatible phases in minerals as "open system precipitation" that also first involves a solid-state diffusion mechanism to form a precursor solid solution from which exsolution occurs. These arguments are based on the fact that crystallographic relationships between lamellae and host are invariably those expected from solid state exsolution. The various alternative explanations for oriented intergrowths have been discussed by Hwang et al. (2013) as well as Axler and Ague (2015) and Keller and Ague (2020). In cases where fluid-mineral interactions are demonstrably responsible for lamellar formation, it has been shown that recrystallisation of the parent phase by coupled dissolution-precipitation can also result in a two-phase product with a crystallographic relationship between the phases (e.g. monazite lamellae in apatite, Harlov et al.,2005; exsolution in the bornite-digenite solid solution, Zhao et al., 2017).

Some further light is cast on this problem from the observations of the coarsening of the lamellar amphibole-pyroxene intergrowth in Zone 1 (texture T1). Electron microprobe analysis shows that both the pyroxene and amphibole contain increasing amounts of Na as the texture coarsens. The amphibole also contains K (Fig.4) which is consistent with hydration by a saline solution. The replacement of the lamellar amphibole-pyroxene intergrowth in Zone 1 (texture T1) by the Zone 2 symplectite (texture T2) further increases the Na content of both phases at a sharp interface. The Na-enriched leading edge also suggests influx of Na-rich fluid that becomes depleted through reaction with the pre-existing pyroxene with a subsequent drop in Na content of the pyroxene within the pyroxene-amphibole symplectite. Given that the bulk compositions of the granulite and eclogite differ only by the addition of water and minor CO_2, (Jamtveit et al., 2000; Rockow et al., 1997) the source of the increased K and Na is most likely due to the breakdown of plagioclase within the eclogite further into the finger and fluid transport towards the eclogite-granulite interface. This textural evolution through zones 1 to 4 is consistent with successive pulses of fluid infiltration rather than any mechanism that involves repeated solid-state diffusion to explain the intergrowth of Zones and their interfaces. The amphibole-pyroxene crystallographic relationship is retained throughout.

A similar issue arises when explaining the origin of the clinozoisite inclusions within the plagioclase. The progressive increase in the abundance of the clinozoisite needles, initiated from grain boundaries but finally throughout whole plagioclase grains, the consequent obliteration of the twinning, as well as the increased Na content of the plagioclase associated with clinozoisite formation points to a pervasive recrystallization reaction of the plagioclase with the fluid. We suggest that a similar process of recrystallisation that results in the formation of the clinozoisite inclusions also operated to form the amphibole lamellae in the pyroxene.

The change in texture Zone 1 to Zone 4 also suggests a sequence of recrystallisation reactions in the pyroxene. Both dissolution and precipitation are fast and efficient reequilibration mechanisms in rocks infiltrated by aqueous solutions (Altree-Williams et al., 2015; Beinlich et al., 2020; Carmichael, 1969; John et al., 2012; Putnis and Austrheim, 2010; Putnis and Putnis, 2007; Rubie 1986; Taetz et al., 2018; Wood and Walther, 1983) and recrystallisation of both pyroxene and plagioclase in the presence of an aqueous solution would result in an intergrowth of an altered composition of the anhydrous phases (in this case with increasing Na composition) together with a hydrated phase (amphibole and clinozoisite respectively.)

The simultaneous recrystallization of a single phase (in this case diopside) to form a two-phase intergrowth (Na-enriched clinopyroxene + amphibole) and its subsequent coarsening typically results in a symplectite microstructure, such as texture T2. Symplectites have been recognized in a wide variety of recrystallizing materials as well as differing geological settings, involving many different pairs of phases and the existence of symplectites cannot be simply ascribed to any specific set of conditions. Symplectites due to fluid-rock reactions have also been produced experimentally (e.g. Spruzeniece et al., 2017) where successive pairs of symplectite intergrowths were induced by the evolving fluid composition.

Further into the eclogite finger the plagioclase breaks down to a fine-grained intergrowth of phengite + omphacite ± kyanite. At this point, near-stoichiometric omphacite is formed directly at grain boundaries between garnet and the former plagioclase and forms mm-wide coronas around the garnet grains (Fig. 8). This second route to omphacite formation

operates concurrently with the replacement of Zone 1 by Zone 2 in the clinopyroxene. For convenience in this discussion we will refer to the progressive formation of omphacite via Zones 1-4 as Route 1 and the direct formation of near-stoichiometric omphacite as Route 2. Before the breakdown of plagioclase, omphacite formation by Route 2 is minimal at plagioclase – garnet grain boundaries but becomes the dominant omphacite-forming reaction within the eclogite finger. This suggests that before the transitional zone the conditions for eclogitisation were not yet reached although the rock was hydrated. Reaction was limited to that observed in Zones 1-4 in the pyroxene and the growth of clinozoisite and kyanite inclusions in the plagioclase.

The hydration, recrystallisation and coarsening sequence and the progressive increase in the Na content of the pyroxene establishes the direct connection between the hydration of the granulite and eclogitization. We propose that the initial hydration of the granulite and formation of amphibole lamellae in the pyroxene (Zone 1 T1) is part of the same process that leads to eclogitization. The difference is a matter of reaction progress, with the core of the eclogite finger having reached a stage that approximates to "eclogite" although equilibrium has not yet been achieved. The garnet cores mainly retain their granulite composition and the pyroxene textures described as Zones 1-4 (Route 1) are still present together with stoichiometric omphacite formed by the Route 2 reaction between garnet and the breakdown products of plagioclase.

The change in the composition of the aluminous pyroxene in the granulite to the near-stoichiometric omphacite (Zones 1-4) within the eclogite appears continuous in Figure 6 although at each successive interface there is a discontinuity in the jadeite component. In the diopside-omphacite phase diagram the solid solution is complete above about 650^0C – $700 \,^0$C depending on the Fe-content and the model for cation order used (Carpenter, 1983; Green et al., 2007; Vinograd, 2002). The estimated eclogitization conditions at Holsnøy are at about 670–690 °C (Bhowany et al., 2018) and therefore the range of pyroxene compositions in the texture Types 1-4 was mostly formed within the disordered C2/c solid solution except at the compositions near to stoichiometric omphacite that could have grown directly with the ordered P2/n structure. During cooling, all but the compositions near the diopside endmember would undergo ordering and exsolution in the C2/c + P2/n

miscibility gap, so that the intermediate pyroxene compositions in Figure 6 may represent two-phase intergrowths. However, the low solvus temperature means that such intergrowths are on a scale that requires transmission electron microscopy (TEM) and such a study was not part of this paper.

The final microstructure that forms part of the history of the sample is the fine grained symplectite composed of albitic plagioclase + amphibole ± clinopyroxene that forms along some grain boundaries of the Route 2 omphacite around the garnet (Fig.8 and Supplementary Fig. S14). This symplectite forms by the breakdown of omphacite at a reduced pressure where plagioclase is again a stable phase. The heterogeneous development of the symplectite with some grain boundaries free of reaction while others attain a width of ~40 μm and the formation of amphibole indicate that fluid infiltration is also implicated in the breakdown of omphacite. Such symplectites are widespread in eclogite terrains in western Norway (Martin et al., 2018) and ascribed to decompression.

Interpretation of the reaction pathway

During eclogite formation, the eclogite and the host granulite were at the same structural level in the crust. The field relations suggest influx of fluid along the eclogitized finger with the reaction interface defined by the eclogite – granulite boundary. The sharp interfaces and the discontinuous compositions between Zones 1-4 suggest fluid pulses that may also drive sporadic advances of the reaction interface further into the granulite. Fluid pulses during eclogitization have been related to seismic aftershocks (Jamtveit et al., 2018a) as well as periodic fluid release from subducting rocks (John et al., 2012; Taetz et al., 2018). Seismic aftershocks are driven by high-pressure fluids (Miller et al., 2004; Miller, 2013, 2020) that in turn create permeability through hydraulic fracturing (Miller and Nur, 2000).

Estimates of the fluid-rock reaction rates in such a situation predict virtually "instantaneous" propagation of reaction fronts, at up to 10 cms per year (Beinlich et al., 2020) in a metamorphosed ophiolite sequence in northern Norway, through rocks whose permeability is enhanced through fracturing and dissolution-precipitation reactions. Also using lithium diffusion modelling, John et al. (2012) calculated similar rates for eclogitisation

reactions in ths Tianshan Mountains, China along selvages due to pulses of high pore-fluid pressure along conduits linked to seismicity. Conventional radiogenic isotope geochronology cannot normally capture such short-lived events but using high-precision Lu-Hf dating, Schmidt et al. (2008) were able to constrain the period of eclogitisation over a region of ~100km to within several million years in the Dabi-Sulu UHP terrane in eatern China, suggesting that mineral growth in such a relatively short-lived and widespread event may have been due to influx of fluid. The growth of the eclogite fingers in Holsnøy could follow the same pattern of rapid advancement with every fluid pulse that creates reactions and permeability, while remaining dormant between pulses.

Within the eclogite finger the reactions reduce the strength of the rock creating a situation where a weaker zone is formed within the stronger, stressed granulite host (Jamtveit et al., 2016; Malvoisin et al., 2020). Thermomechanical modelling and force-balance arguments predict that under such circumstances a significant increase in pressure is inevitable, depending on the relative mechanical properties of the eclogite and the granulite host and the orientation of the differential stress relative to the reaction interface (e.g. Luisier et al., 2019; Mancktelow 1995, 2008; Moulas et al., 2014, 2019; Schmalholz and Podladchikov, 2013). Depending on the state of stress in the granulite, the thermomechanical models predict that overpressure associated with hydration and rock-weakening on eclogitisation can raise the ambient pressure in the granulite to eclogite facies conditions by at least 0.5 GPa and therefore without the necessity for deeper subduction. This has been a key argument in the hypothesis that the generated overpressure could have formed eclogite at shallower depths than if the pressure was lithostatic (Jamtveit et al., 2018b). The duration over which such overpressure can be maintained (Dabrowski et al., 2015) also exceeds the time-scales for eclogitisation to take place.

A transect from within the eclogite finger to the reaction interface and into the granulite would therefore suggest a pressure gradient. A pressure gradient could also be inferred from the increase in the jadeite component in the clinopyroxene from Zone 1 to Zone 4, given the known pressure dependence of the Na,Al substitution for Ca,Mg in diopside. The volume decrease from diopside to omphacite of approximately 3% across the whole

compositional range can also account for the development of porosity, always present in Zone 3 texture T3 where the composition approaches omphacite.

The forward progress of the finger depends on the supply of fluid and its termination indicates an end of the pulse sequence that drives the fluid along the length of the finger to the reaction interface. A reduction in the availability of fluid would lead to a more localized fluid distribution and overall fluid pressure reduction at the tip of the finger as it is taken up by hydrous phases such as amphibole and clinozoisite. The precipitation of carbonates within the pores in the Zone 3 pyroxene also suggests at least partial desiccation of a CO_2-bearing aqueous solution near the reaction interface.

The fact that the granulite ahead of the eclogite finger is hydrated but did not react to eclogite apart from very minor formation of omphacite at garnet–plagioclase grain boundaries is highly significant. Given that even very small amounts of water can catalyse a reaction (Ahrens and Schubert, 1975b) by providing a dissolution-reprecipitation mechanism (Milke et al.,2013), the question arises why the hydration of the granulite only resulted in a recrystallisation of the plagioclase (to clinozoisite+Na-enriched plagioclase) and pyroxene (to an Na-enriched pyroxene + amphibole), typical in amphibolite terrane on Holsnøy, and not directly to eclogitization. We suggest that in the granulite adjacent to the eclogite the degree of hydration and limited extent of reaction would not have been sufficient to significantly change the rock strength to produce the necessary pressure perturbation. In other words, the granulite may have existed adjacent to the eclogite but at a lower pressure.

Eclogitization results in a density increase and without a significant compositional change should involve a volume reduction. Densification involves a compression within the eclogite finger and generation of porosity. This creates new pathways for fluid transport but is also mechanically unstable and prone to collapse and further seismic aftershock (Malvoisin et al., 2020). The dimensional mismatch between eclogitized and untransformed crust should also lead to a tensional stress at the interface (Hacker, 1996) that could be related to the lower pressure reactions in the transitional zone (i.e. amphibole lamellae in the pyroxene and clinozoisite needles within the plagioclase). The paler coloured mantle in the granulite that

surrounds eclogite fingers is a common feature (see also images of eclogite fingers in Jamtveit et al., 2000, 2016) and represents the hydrated lower-pressure granulite zone. The extent of this hydration in the granulite has not been determined but completely dry granulite is relatively uncommon within a partially eclogitized region. On the outcrop scale the mapping of eclogite domains within granulite shown in Zertani et al. (2019) could be interpreted as mapping pressure distribution. Pressure variations during subduction have also been noted on a global scale. Waveform analysis of seismic data has identified paired stress fields as tensional earthquakes lying 1 km above compressional earthquakes in the subducting Pacific Plate (Nakajima et al., 2013). The tensional stress was attributed to the negative volume change associated with eclogitization.

Centrella (2018) has also explored the spatial associations of the granulite to eclogite and the granulite to amphibolite transitions in the Bergen Arcs from the point of view of the stresses generated due to the volume changes involved in each case and the mass transfer that would alleviate these stresses.

The large fractures cutting across the eclogite finger and terminating at the reaction interface (Fig.1) are interpreted to be associated with the volume change on eclogitization. The reduction in volume of a column of rock that becomes the eclogite finger would result in a greater decrease in length of the finger than in the width, creating extensional stress parallel to the finger and increasing the relative compressive stress normal to the finger. This would result in conjugate sets of high angle fractures across the finger. On a thin-section scale fracture networks associated with eclogitization are most noticeable through the garnets. In Figure 9, the granulite garnets are from the transition zone between the granulite and eclogite. Along an approximately linear set of heavily fractured garnets across a thin section, the fractures are open and filled with mainly amphibole with minor phengite and clinozoisite (Fig.9b-d). Within this part of the transition zone the plagioclase is filled with clinozoisite needles and the diopside has internal texture T1 in Zone 1 (with amphibole lamellae). Further within the eclogite finger the garnet fractures are sealed with eclogite facies minerals – omphacite, kyanite and clinozoisite (Jamtveit et al., 2000). This observation is consistent with an interpretation that a pressure gradient may exist between the tip of the eclogite finger and its interior.

Pressure gradients that can exist on an outcrop scale due to heterogeneous distribution of fluids and consequent rock weakening, can also exist on a grain scale (Tajčmanova et al., 2014, 2015; Wheeler, 1987; Zhong et al., 2017) when fluid pathways may be controlled by grain boundaries and local stresses by the proximity of hard minerals in a softer matrix (Vrijmoed and Podladchikov, 2015). The observation made in the eclogite finger described here, that low pressure granulite pyroxenes (with Type T1 textures of amphibole lamellae in the pyroxenes) are preserved adjacent to high pressure omphacite raises the same problem as to whether this represents metastable retention of a granulite fragment due to limited fluid access or whether the limited fluid access generates a local pressure gradient. Varying fluid pressures on grain boundaries and consequent stresses on adjacent minerals can have dramatic effects on metamorphic reactions, according to Wheeler (2014, 2015) and have been invoked to account for the orientation-dependent reactions described by Moore et al., (2019).

The question remains as to whether the observed sequence of reactions should be interpreted as a metastable sequence, given the overall non-equilibrium situation of fluid infiltration into the stressed dry granulite (Jamtveit et al., 2016) or whether each stage of the sequence represents a local equilibrium defined by the local pressure and temperature.

A key point in our argument is that the granulite adjacent to eclogite is also hydrated, but only altered to amphibolite-facies minerals and that the hydration sequence in the granulitic pyroxene evolves sequentially as an integral feature of the eclogitization process through the texture types T1 to T4. The continuous increase in jadeite component in the pyroxene through this process also indicates a pressure dependence.

The thermodynamic modelling presented here (Fig.10) demonstrates that to produce the assemblages of both the amphibolite and the eclogite these lithologies must have experienced a ca. 0.16-0.5 GPa difference in thermodynamic pressure, regardless of α_{H2O}. If the mineral compositions are representative of equilibrium conditions, then both lithologies should have been near H_2O saturation (α_{H2O} of ca. 0.8-1; Fig. 10) during metamorphism and

the pressure difference required is larger (0.25-0.5 GPa). This pressure difference is similar to that calculated from the thermomechanical modelling (Jamtveit et al., 2018b).

The interpretation that mineral compositions are representative of thermodynamic equilibrium is complicated by the fact that the preserved amphibolite assemblage is consistent with that produced in the P- α_{H2O} model while the modelled eclogite assemblage contains a larger proportion of amphibole than observed. The model suggests that to achieve the observed phengite and garnet mineral compositions in a closed system these minerals should be in equilibrium with amphibole. This suggestion may be supported by our textural observations in which we rarely observe a discrete interface in which diopside reacts straight to omphacite, rather we see a series of amphibole-bearing zones separating the end-member compositions. This interpretation would then require that the omphacite replaces the amphibole via a local dehydration/recrystallization reaction, without significant diffusive exchange with garnet and phengite.

Finally, the only microstructural feature in our samples that is due to decompression, most likely during exhumation, is the fine albite + amphibole + pyroxene symplectite (Fig. 8 and Supplemental Fig. S14) that results from the breakdown of omphacite along grain boundaries. The spatial and textural relationship between this symplectite and that described as texture T2 in the eclogitisation sequence emphasises the very different reaction pathways that lead to the observed mineral intergrowths. The common assumption that amphibole lamellae formed within granulite facies pyroxene are due to exhumation is not borne out by the observations described here.

6. Conclusion

The eclogitization sequence described here suggests an extension of the concept first proposed by Austrheim (1987) that eclogitisation in the Bergen Arcs was initiated by fluid infiltration and therefore that reequilibration of the granulite was dependent more on the availability of fluids than on changes in P,T conditions. The assumption at that time was that the dry granulite experienced the same P,T conditions as the eclogite but that fluid was

required to provide the mechanism and kinetics for eclogitisation. This concept has influenced the understanding of metamorphism in the Bergen Arcs and beyond.

Here we propose that the fluids that initiate the transformation to eclogite play a much more profound role than merely enhancing the kinetics. The fluids, injected through seismic fractures, shear zones and along pre-existing foliation create a self-sustaining situation where metamorphic reactions weaken the rock creating a heterogeneous distribution of weak zones within strong stressed rock, resulting in variations in the local pressure. At the same time the reactions increase porosity and permeability allowing further ingress of fluids. The pressure difference between reacted and unreacted rock, at the same level in the crust, can create a juxtaposition of different metamorphic facies rocks developed at the same depth and temperature conditions. We further propose that the feedbacks between mechanisms of metamorphic reactions, rock strength and hence deformation, and mass transfer are controlled by the composition of interfacial fluids that also define the local equilibria between the fluid and the precipitating phases.

The microstructural reaction sequence described here lends support to the thermomechanical models that predict local pressure variations due to rock weakening by fluid-enhanced reactions and the conclusion by Jamtveit et al., (2018b) that such pressure perturbations contributed to the formation of eclogites at a shallower depth than suggested from solely lithostatic pressure.

7. References

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Figure Captions

Figure 1. (a) Field photograph of a typical eclogite 'finger' within the anorthositic granulite host. (b) Detail of the eclogite finger from which the NE end of the tip, at the interface with granulite, was sampled. The foliation within the granulite and eclogite is continuous. (c) Interpretation of the foliation and fractures across the finger. Eclogite (green), fractures (red) and foliation (thin black lines in white).

Figure 2. Section through the studied sample (30cm long) of granulite–eclogite reaction interface. The change in mineral assemblage is approximated by the sections A-D. The Texture types refer to the evolution of clinopyroxene across the eclogitization reaction front (see text). Mineral abbreviations after Whitney and Evans (2010).

Figure 3. (a) Optical micrograph (crossed polars) of relatively unaltered granulite. The cpx shows amphibole lamellae parallel emanating from fractures (white arrow). The plagioclase – garnet grain boundaries show signs of incipient reaction. (b) Within the transitional zone the plagioclase is dense with acicular inclusions of clinozoisite ± kyanite. Former grain boundaries with garnet show greater extent of reaction. (c) Clinopyroxene in the granulite with amphibole lamellae along cleavage planes. (d) Towards the transition zone the lamellar microstructure is coarser. This is designated as Zone 1 in the clinopyroxene with texture Tt1.

Figure 4. (a) Back-scatter scanning electron (BSE) micrograph of the interface between Zone 1 and Zone 2 clinopyroxene. Within Zone 2 the symplectite is composed of sodic clinopyroxene (pale) and amphibole. (b) Detail of the area outlined in (a) together with a potassium element map highlighting the amphibole. The darker (K-free) region at the interface is clinopyroxene richer in Na than in the symplectite. This is also imaged as the darker region at the interface between Zones 1 and 2 in (a).

Figure 5. BSE micrograph showing all 4 zones in a sequentially replaced clinopyroxene crystal with texture Types 1-4. The same sequence is repeated in all of the clinopyroxene crystals transforming from diopside in the granulite to omphacite in the eclogite. The lines separating the Zones are drawn as guides for the eye.

Figure 6. Ternary diagram in diopside – hedenbergite - jadeite space of the clinopyroxene compositions from Zones 1 to 4. The black filled circles show the compositions of omphacite formed directly by reaction Route 2 in the eclogite finger.

Figure 7. EBSD maps across Zone 1-3 in the clinopyroxene. (a) Phase map with clinopyroxene (yellow), pargasite (green), dolomite (grey) and pores (black). Change of typical textures can be seen from Zone 1 to Zone 3. (b) All Euler orientation map of clinopyroxene (pargasite

remains grey) and (c) pargasite (clinopyroxene remains grey), with pole figure insets of grain orientation for a, b and c-axis respectively (PF lower hemisphere, colours as those in the maps and are representative of all Euler rotations). The orientations of clinopyroxene and amphibole change in each successive Zone, while the relative orientation between the clinopyroxene and amphibole are retained with a-, b- and c- axes parallel.

Figure 8. BSE images within the eclogite finger. (a) The field of view shows garnet with Fe-enriched rims mantled by near-stoichiometric omphacite. (b) Detail showing the breakdown and replacement of the omphacite by a fine symplectite containing Na-rich plagioclase, amphibole and clinopyroxene along the fracture line. Element maps of this area are shown in Supplemental data Figure S14.

Figure 9. Fracture networks in the garnet from the transition zone at the tip of the eclogite finger. (a) Closed brittle fractures with no reaction along fractures (b) Open fractures along a highly fractured linear zone that mirrors the large fractures across the eclogite finger in the field. (c,d) Detail of the open fractures filled with mainly Cl-bearing amphibole. The Cl map shows the amphibole infill with darker chlorine-poor regions and lighter chlorine-rich regions. (Cl-map with 1μm pixels each consisting of 25000 total EDS counts.)

Figure 10. P-α_{H2O} pseudosection for anorthositic granulite composition of Kühn (2002). Eclogite and amphibolite-facies assemblage stability fields are indicated by bold text. Mineral abbreviations are given in the methods section.

Supplemental Figure S11. Composite outcrop photo outlining the eclogite finger and the adjacent shear zone. The dashed green and white lines show the foliation directions in the eclogite and granulite respectively. The taped crosses mark out m^2 grids for mapping. The inset shows the location within the eclogitized zone on North Holsnøy island, Bergen Arcs.

Supplemental Figure 12. Grain boundary reactions between pyroxene, garnet and plagioclase. The needles in the plagioclase and on grain boundaries are clinozoisite and kyanite. The element maps show additional phengite and minor omphacite along the grain boundaries.

Supplemental Figure 13. Interface between Zone 2 and Zone 3 in the clinopyroxene. The lower left is the Zone 2 symplectite with low Ca in the amphibole. The upper right is the Zone 3 pyroxene with pores (black) and variability in jadeite content. The interface between Zone 3 and Zone 4 can be seen in the Na map as a discontinuity in composition.

Supplemental Figure 14. Detail from Fig.8b showing BSE and element maps of the symplectite formed from the breakdown of omphacite along grain boundaries in the eclogite.