Fluid inclusions in granulites and eclogites from the Bergen Arcs, Caledonides of W. Norway

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Abstract

The Grenvillian granulite-facies complex on Holsnøy island, Bergen Arcs, W. Norway, has been metamorphosed at eclogite-facies conditions during the Caledonian orogeny (ca. 425 Ma). The granulite–eclogite facies transition takes place along shear zones and fluid pathways. Mineral thermobarometry indicates PT conditions of 800–900 °C and 8–10 kbar for the Proterozoic granulite facies metamorphism and 700–800 °C and 16–19 kbar for the eclogite-forming event. Quartz in the granulite facies complex contains CO_2 fluid inclusions with less than 2.5 mole percent N_2; the molar volumes are compatible with the PT conditions of the Proterozoic granulite metamorphism. Quartz in pegmatitic quartz + omphacite and quartz + phengite/paragonite veins coeval with shear-zone eclogites contain $N_2 \pm CO_2$ fluid inclusions. Combined laser Raman microanalysis and microthermometry show that the least disturbed inclusions have $X_{CO_2} = 0.1$–0.3, and molar volumes less than 40 cm³/mole, which may agree with the PT conditions during Caledonian high-pressure metamorphism. Younger, low-density N_2 and N_2–H_2O fluid inclusions are the results of decrepitation and redistribution of early inclusions during the retrograde PT evolution of the eclogites.

KEYWORDS: granulite, eclogite, fluid inclusions, carbon dioxide, nitrogen, Bergen Arcs, Norway.

Introduction

ECLOGITE-FACIES conditions are met in the deeper parts of subduction zones and in the root zones of mountain chains. Conditions estimated for the eclogite-facies are typically 550–800 °C at pressures above 12 kbar (e.g. Ringwood, 1975). Garnet and omphacitic pyroxene are essential minerals in eclogites; minerals such as quartz, rutile, clinozoisite, amphibole, white micas (paragonite, phengite) and apatite can also be stable at eclogite-facies PT conditions, depending on whole-rock composition and volatile fugacities (Holland, 1979).

Granulites typically contain water-deficient fluid inclusions, consisting of CO_2, concentrated brines or solidified carbonate melts, (see, for example, Touret, 1981, 1985). Such fluids with low water activity may be instrumental for the

formation of 'dry' granulite-facies mineral assemblages (e.g. Newton, 1986). Although less fluid inclusion work has been done on eclogites, several authors have discussed the composition and importance of a free fluid phase in eclogite-facies metamorphism.

Following the thermodynamical analysis of Holland (1979), a water-dominated fluid phase has been assumed by some students of eclogite metamorphism (e.g. Lappin and Smith, 1981). Fluid inclusion data in support of this hypothesis have also been presented (e.g. Holland, 1983; Klemd, 1989). Other fluid inclusion studies of eclogites have, however, suggested that a CO_2-dominated fluid phase has been present at some stage of the metamorphic history of some eclogites (Luckscheiter and Morteani, 1980a,b; Touret et al., 1982; Kechid, 1984). Other fluid inclusion compositions which have been reported from eclogites include pure or nearly pure N_2 and CH_4, as well as saline aqueous solutions and
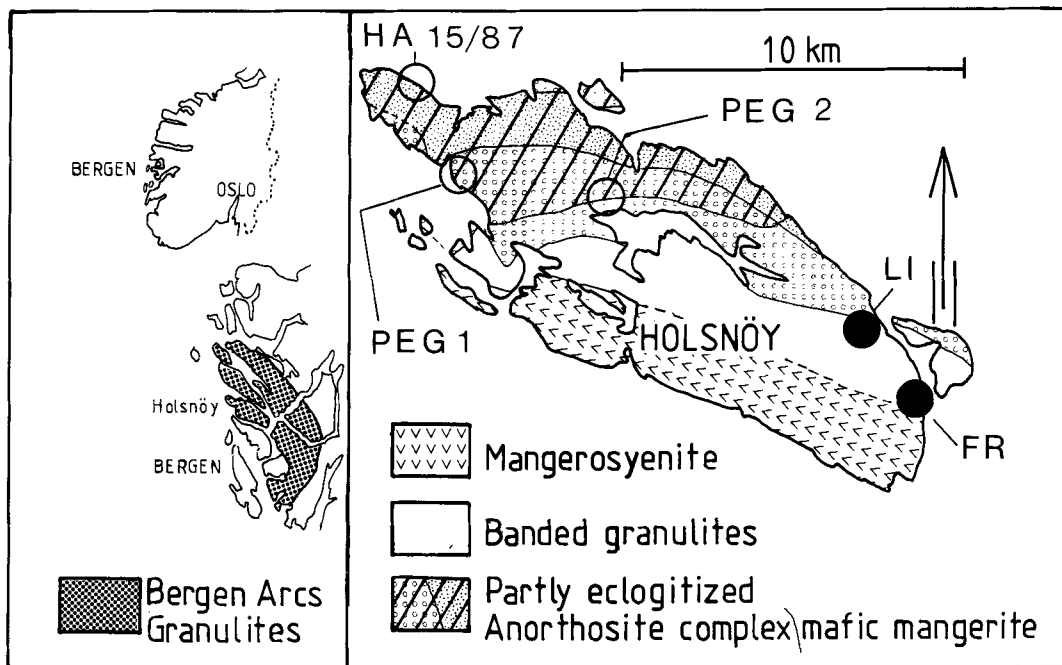
FIG. 1. Geological map of Holsnøy. Sample localities: Filled circles: granulite samples. Open circles: eclogite vein samples.

complex $H_2O-CO_2-N_2-CO-CH_4 \pm$ salt mixtures (Kastrykina and Firsova, 1982; Tomilenko and Chupin, 1983; Shatsky *et al.*, 1985; Sobolev *et al.*, 1985, 1986).

In a recent study, we have presented fluid inclusion data from 'country rock eclogites' in the Western Gneiss Region (henceforth abbreviated WGR) of the Norwegian Caledonides, showing that those eclogites interacted with a N_2-bearing aqueous fluid phase at peak eclogite-facies conditions, or during the earliest phase of their retrograde history (Andersen *et al.*, 1989). Those elogites interacted with a CO_2-rich fluid phase, but only during the later stages of their retrograde history, at pressures significantly below the stability field of eclogite mineral assemblages. These data appear to support the theoretical predictions of a water-dominated fluid phase, but also point to nitrogen as a significant component in eclogite fluids, as was earlier suggested by Tomilenko and Chupin (1983). The country-rock eclogites in the WGR are preserved as partly retrogressed pods and lenses within amphibolite-facies retrogressed gneisses, and therefore usually do not allow the protolith–eclogite relationships to be studied. Locally, it can be shown that eclogites in the WGR

formed from dolerite protoliths (e.g. Mørk, 1985).

At Holsnøy island, W. Norway (Fig. 1), evidence of *in-situ* eclogitization of a granulite-facies complex has been described by Austrheim and Griffin (1985) and Austrheim and Mørk (1988). The eclogite mineral assemblages have formed in and adjacent to shear-zones and fluid pathways (Austrheim, 1987). These rocks represent a unique case, where the fluid regime before, during and after eclogite-facies metamorphism can be studied in detail from fluid inclusions in minerals.

Geological setting

One of the Caledonian nappes of the Bergen Arcs consists of granulite-facies anorthosite, gabbroic anorthosite, norite, mangerite and charnockite (Fig. 1). This complex formed by igeneous intrusion during the Grenvillian orogeny (Cohen *et al.*, 1988) and was equilibrated at this time under granulite-facies $P-T$ conditions ($P = 8–10$ kbar, $T = 800–900\,°C$; Austrheim and Griffin, 1985). Corona structures, interpreted to have formed during cooling, link the granulite-

facies mineralogy to the primary magmatic phases olivine and plagioclase (Griffin, 1972).

The granulite-facies complex is transected by a series of shear zones, varying in thickness from centimetres to more than 100 metres. Over most of the $1000 \, km^2$ or so of granulite-facies rocks of the Bergen Arcs, these shear zones contain amphibolite- and greenschist-facies mineralogies. However, in an area on NW Holsnøy eclogite-facies parageneses (Omphacite + garnet + rutile ± amphibole ± kyanite ± quartz ± phengite ± paragonite ± clinozoisite) have formed. Small-scale development of eclogite assemblages is also seen along millimetre- to centimetre-wide fractures and pegmatitic quartz–paragonite/phengite veins. These features suggest that shearing and facturing combined with fluid fluxing are responsible for the development of eclogite mineral assemblages (Austrheim and Griffin, 1985; Austrheim, 1987). Irregular veins consisting of euhedral, pegmatitic omphacite set in a fine- to medium grained, completely recrystallized quartz matrix are found at some localities within the major eclogite zones.

Three samples were chosen for investigation from a larger collection, because they have fluid inclusions of sufficient size and abundance to allow a detailed study. These samples (Fig. 1) comprise one quartz-omphacite vein (PEG-1) and one quartz–paragonite/phengite vein (PEG-2) from an area with eclogitized anorthosite, as well as a quartz–paragonite/phengite vein (HA 15/87) from an area with eclogitized mafic mangerite (jotunite).

Eclogites containing kyanite + paragonite + quartz + dolomite are well suited to thermodynamic modelling of fluid composition from mineral equilibria. Using this approach, Holland (1979) showed that kyanite–paragonite eclogites from the Tauern window, Austrian Alps, equilibrated with a water-dominated fluid phase. The mineralogy of the present quartz-paragonite/phengite veins is similar to the Tauern window eclogites, and a thermodynamic analysis accordingly suggests a water-dominated fluid composition (Jamtveit et al., 1989).

Sm–Nd and Rb–Sr mineral ages (Cohen et al., 1988) verify the Grenvillian age of the granulite-facies events and demonstrate that the eclogite event took place ca. 500 Ma later, during the Caledonian orogeny.

Fluid inclusions

Granulites. The granulites at the Frekhaug (FR) and Lillebergen (LI) localities (Fig. 1) contain quartz in the matrix, as well as in veins and in segregations. In unaltered granulite, the quartz has a distinct blue colour, which is lost on incipient secondary hydration of the rock. Fluid inclusions are moderately abundant in all quartz occurrences. All inclusions are bound to secondary healed fracture trials. Two generations of trails can be distinguished (Table 1): 'Early secondary inclusions' (GES: Granulite Early Secondary), which form strongly transposed trails, cut by quartz grain boundaries (Fig. 2a), and 'late secondary trails' (GLS: Granulite Late Secondary), which are less transposed and cutting the quartz grain fabric (Fig. 2b). It should be noted that this chronology has only local significance, it is not possible to equate GES or GLS inclusions in one sample with those of another without further data (microthermometry, Raman microanalysis).

Most of the fluid inclusions in granulite quartz contain a single fluid phase at room temperature (T_r), only few inclusions with a vapour bubble have been observed.

Ecolgite. The minerals of the 'massive' ecologite (garnet, omphacite, clinozoisite) do not contain fluid inclusions. In the quartz from quartz-omphacite (PEG-1) and quartz–paragonite/phengite veins (PEG-2, HA 15/87), fluid inclusions occur in moderate numbers.

The quartz matrix of these veins has a fine-grained, equigranular mosaic microfabric, with larger euhedral omphacite or mica crystals. In the quartz–paragonite/phengite veins somewhat larger, subhedral quartz grains are associated with 'nests' of mica crystals (Fig. 3a). These grains appear to be relics of a texture predating the matrix grain mosaic, protected from late (retrograde ?) deformation and recrystallization by the ability of the mica to absorb small-scale deformation.

The relict quartz grains contain two generations of fluid inclusions (Table 1): Possibly primary inclusions (P?) which occur isolated or scattered in groups and clusters (Fig. 3b). These inclusions are not bound to healed fracture trails; groups and clusters, however, are often cut by trails (Fig. 3b), which in turn are cut by the matrix grain boundaries (EES: Eclogite Early Secondary generation). The P? fluid inclusions are either single phase at T_r, or they contain a birefringent solid of variable relative size in addition to the fluid (Fig. 3b). The EES inclusions are always single phase at T_r.

Trails of secondary inclusions cutting the matrix microfabric have been observed in PEG 1 and PEG 2. In PEG 1, such inclusions are the only ones found (Fig. 3c). From textural criteria, they represent at later feature than the P? and EES

Table 1

Fluid evolution chronology at Holsnøy, based on fluid inclusions

Metamorphic event	Inclusion generation	Setting	Dominant volatile component(s)
Granulite facies: (900 Ma)	GES	Transposed trails	High density CO_2
	GLS	Trails cutting the rock fabric	Lower density CO_2
Eclogite facies: (425 Ma)	P?	Scattered in protected grains	High density N_2-CO_2
	EES	Trails cut by grain boundaries	Pure N_2 and CO_2 with minor N_2
	ELS	Trails cutting grain boundaries	N_2, N_2 + H_2O

GES= Granulite early secondary fluid inclusions. GLS= Granulite late secondary fluid inclusions. P?= Possibly primary fluid inclusions in eclogite. EES=Eclogite early secondary fluid inclusions. ELS= Eclogite late secondary fluid inclusions.
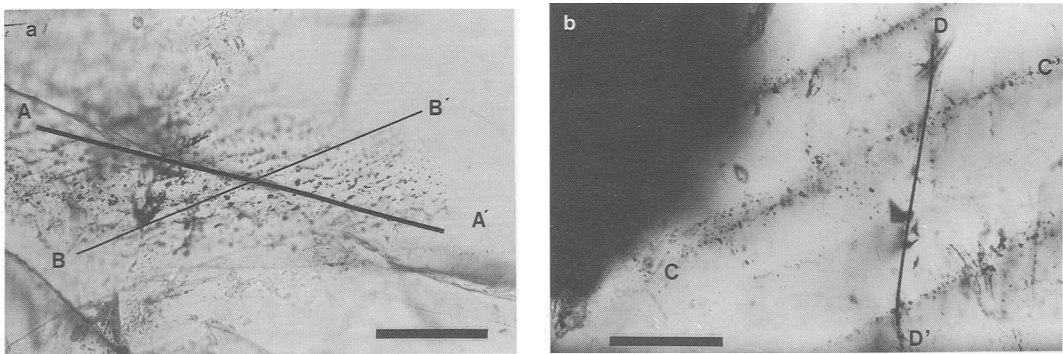

FIG. 2. Fluid inclusion textures in granulite quartz. Length of scale-bars: 0.1 mm. (a) 'Early secondary' (GES) fluid inclusions in blue quartz segregation; sample FR-A2 from Frekhaug, Holsnøy (locality FR in Fig. 1). The orientation of the original inclusion trail was along the line A-A' (where it wedged out). During transposition, inclusion arrays have been re-aligned along B-B'. The inclusions consist of CO_2 with minor N_2 and high density (Table 2). (b) 'Late secondary' fluid inclusion trails in blue granulite quartz, sample LI-1. The inclusion trails (C-C') crosscut a sub-grain boundary marked by the line D-D'.

fluid inclusion generations, and they are accordingly classified as a separate group: ELS (*E*clogite *L*ate *S*econdary). Most ELS inclusions contain a single fluid phase at T_r (Fig. 3d); liquid H_2O, however, has been observed in a few inclusion trails in PEG 1.

In coarse-grained quartz segregations in PEG 2, EES inclusions form strongly transposed trails,

which are cut by large, flat and irregular ELS inclusions, some of which contain water (Fig. 4a,b).

Microthermometry

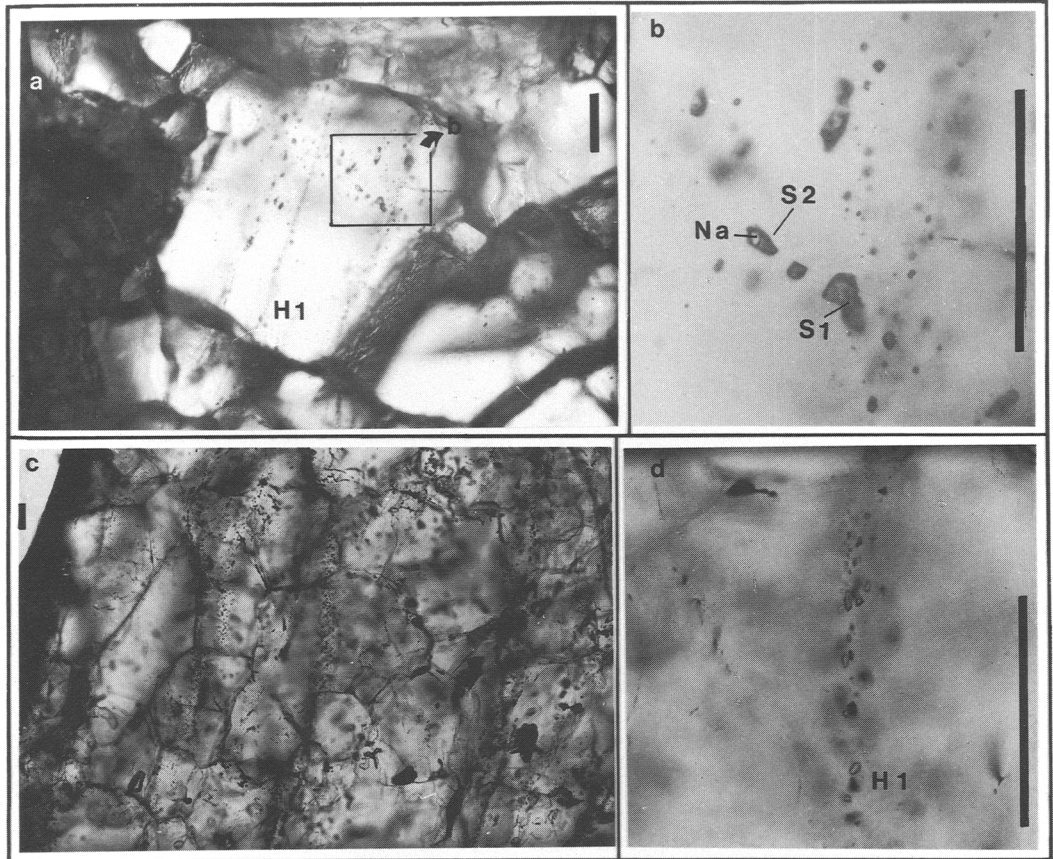Microthermometry measurements were made in the laboratories of the Mineralogical-Geologi-

FIG. 3. Fluid inclusion textures in eclogite veins. Microthermometric behaviour annotated S1, S2, H1 according to Van den Kerkhof (1988b) is indicated, see explanation in the text. Length of scale bars: 0.1 mm. (a) Fluid inclusions in relict grains in sample HA 15/87. 'Early secondary' (EES) inclusions along trails show H1 behaviour. (b) Close-up of part of a (frame), showing the relationship between possibly primary (P?) inclusions with S1/S2 behaviour and EES-trails. The solid (Na) has been identified as nahcolite ($NaHCO_3$) by laser-Raman microprobe analysis. (c) Matrix texture of PEG-1, showing late secondary (ELS) fluid inclusion trails. (d) Magnified detail of PEG-1 matrix, single-phase ELS fluid inclusions showing H1-behaviour cut the matrix grain boundaries.

cal Museum, Oslo, Norway, and of the Institute of Earth Sciences, Free University of Amsterdam, The Netherlands, which both have Chaixmeca and Linkam THM 600 heating/freezing stages, with nitrogen as the cooling medium. The minimum temperature obtained with the Linkam THM 600 instrument in Oslo was $-193\,°C$. The stages were calibrated with a series of pure synthetic substances with known melting points, as well as with pure CO_2 in natural fluid inclusions (see, for example, Roedder, 1984). The accuracy and precision of measurements are $\pm0.2\,°C$ at the CO_2 meling points, and $\pm1.0\,°C$ at T_h.

The behaviour of CO_2–N_2 fluid inclusions during low-temperature microthermometry is a func-

tion of temperature and density (molar volume). Van den Kerkhof (1988a,b) has suggested a classification of fluid inclusion behaviour based on the number of phase transitions between -193 and $+31\,°C$, and on the nature of the final transition (liquid–vapour homogenization: H-types, or sublimation of solid CO_2: S-types). Among the several possible types of microthermometric behaviour, four have relevance to the present study. *H1* inclusions show only one phase transition, homogenization of N_2 at $T_h \leqslant -147\,°C$. *H3* inclusions have three phase transitions: First and final melting of CO_2 (at T_i and T_m, respectively) and, finally, homogenization to vapour or liquid (at T_h). In *S1* inclusions, only sublimation of solid
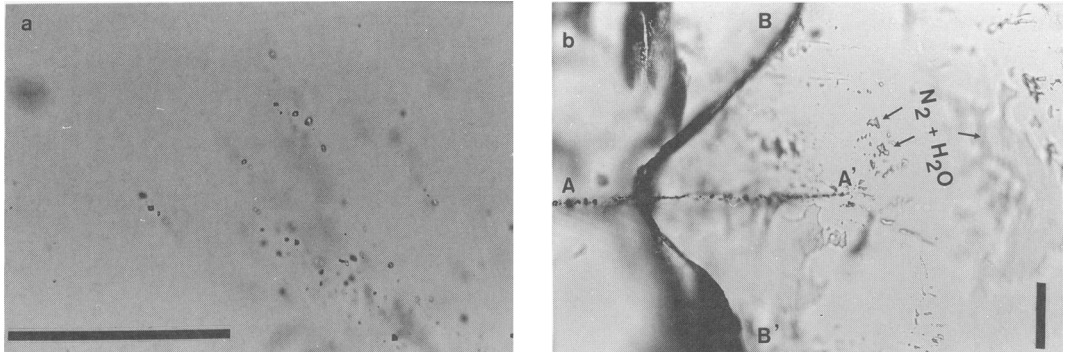
FIG. 4. Fluid inclusion textures in a quartz–paragonite/phengite vein, PEG-2. Length of scale bars: 0.1 mm. (a) 'Eearly secondary', strongly transposed trails with CO_2 inclusions (EES-generation). (d) 'Late secondary' water-nitrogen inclusions (ELS-generation). The trail A-A' crosscuts the grain boundary B-B' and consists of low-density N_2 inclusions.

CO_2 can be observed, at a temperature (T_s) below −56.6 °C; in S2 inclusions, the sublimation event is preceeded by partial homogenization, i.e. N_2 liquid and vapour homogenize to a single fluid phase in the presence of solid CO_2 (at $T_{hs} \leqslant$ −147 °C). H1-behaviour is characteristic of 'pure' N_2 inclusions; S1 and S2 for different intermediate compositions, and H3 for pure or nearly pure CO_2 inclusions (Van den Kerkhof, 1988b). It should be noted that partial homogenization may be difficult to observe if the inclusions are small, if the amount of liquid formed by condensation is small, or if T_{hs} is close to the low-temperature limit of the freezing stage used. Failure to observe T_{hs} leads to misidentification of S2 inclusions as S1.

Results

Granulites. The fluid inclusions in granulite quartz show H3 behaviour, with $T_i = T_m$ close to the triple point of pure CO_2. A minor melting-point depression relative to −56.6 °C is observed in some inclusions (Table 2). The inclusions homogenized to liquid with T_h^L at −50 to +30 °C. Within this wide temperature range, there are several distinct histogram maxima, each of which representing a single sample' (Fig. 5a). The fluid inclusions in bleached quartz fall within the low-density part of the range of the inclusions in blue quartz. Generally, the GES inclusions have lower T_h^L than the GLS inclusions.

Eclogite veins. The ELS inclusions in the quartz–omphacite vein (PEG 1) show H1 behaviour, homogenizing to vapour $(T_h^V \leqslant$ −147 °C). Fluid inclusions in the quartz–paragonite/phengite veins show more complex behaviour. The quartz in sample PEG-2 contains H3 (EES) and H1 (ELS) inclusions only, whereas HA 15/87 is characterized by P? inclusions showing S1, S2 and H1 behaviour, in addition to H1 EES inclusions. The majority of H1 incusions have low densities, homogenizing to vapour. A subordinate number homogenize to liquid with T_h^L in the range −147 to −158 °C (Fig. 5b). Such inclusions have been sought systematically for, and they are thus over-represented in Fig. 5. relative to their true abundance.

SI and S2 inclusions are found only among the P? and EES inclusions in sample HA 15/87. In the S2 inclusions, partial homogenization to liquid (T_{hs}^L) or at the critical point of nitrogen (T_{hs}^C) can be clearly observed below −147 C; in the S1 inclusions this phase transition is not observed above the minimum temperature limit obtainable with the freezing stages used. The final phase transition in both types is sublimation of CO_2, at T_s below the triple point of CO_2 at −56.6 °C. No second fluid phase formed at the sublimation temperature.

H3 inclusions in PEG-2 show distinct melting intervals and depression of the final melting temperature $(T_i \approx$ −58.8 °C, $T_m =$ −58.2 °C). These inclusions homogenize to liquid at $T_h^L =$ −15 to −20 °C.

Raman microanalysis

The purpose of Raman microanalysis in this study has been (1) to make quantitative analyses of volatile components in selected fluid inclusions, and (2) to identify solids *in situ* in some fluid inclusions. Analyses have been made with a Dilor Microdil-28 multichannel laser Raman microprobe in the Institute of Earth Sciences, Free

Table 2. Quantitative data on selected fluid inclusions from granulites and eclogites, Holsnøy island, Bergen Arcs

Sample	Incl. no.	Setting	Other phases at T_r	Microthermometry						Raman		N_2 peak position cm^{-1}	Molar volume cm^3	Isochore P_{700} kbar
				Type	T_{hs}	T_s	T_i	T_m	T_h	CO_2	N_2			
										Mole percent				
Granulite quartz														
LI-1	Ib-1	GLS		H3				-57.0	-30.5 L	97.5	2.5	2326.8	41	6.75
FR-A-2	Ia-3	GES		H3				-56.5	-50.0 L	99.45	0.55		39	8.29
	Ic-1	GES		H3					-54.0 L	>99	<<1		37.6	9.82
Eclogite quartz														
HA-15/87	4b-1	P?		S1/2			-73			10.1	89.9	2327.7	≤ 37	≥ 7.93
	4b-2	P?		S2		-148 V	-61			24.1	75.9	2327.7	110	0.94
	4b-3	P?	Na	H1		-148 L				-	+		65	2.04
	4b-4	P?		S1/2						27.6	72.4	2327.0	≤ 35	≥10.62
	3-1	P?		H1		-165 V				-	+		512	0.17
	3-7	P?	Cc	H1		-161 V				-	+		394	0.22
	1-1	P?		H1		-170 V				-	+		714	0.12
	1-5	P?		H1		-155 V				-	+		261	0.34
	6-1	EES		H1		-153 L				-	+		53	2.97
	6-5	P?		S1			-60.3			20.7	79.3	2327.0	≤ 36	≥ 9.13
	6-7	P?	Na	S2		-148 C	-65			14.7	85.3	2327.0	81	1.44
	6-10	P?		S1			-65			9.8	90.2	2327.7	≤ 38	≥ 7.19
	6-12	P?		S1			-57.5			18.5	81.5	2327.0	≤ 36	≥ 9.07
PEG 1	I-3	ELS	w	H1		-158 V					+	2329.7	322	≥ 0.27
	XI-2	ELS		H1		-155 V					+		261	0.34
PEG 2	I-3	EES		H3					-15.7 L	88.0	12.0	2326.4	46	4.57
	II-9	EES		H3				-58.8	-58.2	-19.7 L	91.5	8.5	2326.0	44	5.24
	X-1	EES		H3						95.1	4.9	2326.0		
	IV-5	ELS	w	H1		-152 V				-	+		208	0.44

Setting: **ES**= "Early secondary" (see text), **LS**= "Late secondary" (see text), **P?**= Possibly primary. *Other phases at T_r:* **Na**= Nahcolite (NaHCO$_3$), **Cc**= Calcite, **w**= liquid water. *Microthermometry:* **H1, H3, S1, S2**= Types of phase behaviour (Van den Kerkhof, 1988a,b), **L**= Homogenization to liquid, **V**= to vapour, **Ths**= Partial (or nitrogen) homogenization, **Ts**= CO$_2$ Sublimation. **Ti**= Initial CO$_2$-melting, **Tm**= Final CO$_2$ melting, **Th**= CO$_2$ homogenization. *Raman:* -= Not detected by laser Raman microprobe analysis, +=Present in quantities above detection limit for laser Raman microprobe.

University of Amsterdam, The Netherlands (Burke and Lustenhouwer, 1987).

Fluid inclusions

Granulites. The analyses of fluid inclusions in granulite quartzes confirm the high CO$_2$ content as indicated by microthermometry (Fig. 6, Table 2). The maximum N$_2$ content encountered was 2.5 mole %, which caused a 0.4 °C melting point depression (Table 2). Other CO$_2$ inclusions only showed N$_2$ signals close to the detection limit of the Raman microprobe which can be estimated to less than 0.5 mole % (Fig. 7).

Eclogites. The pattern of fluid inclusion compositions in the eclogite veins is somewhat more complex. As expected, the H1 type inclusions give good N$_2$-peaks (Fig. 7), but no signals from CO$_2$ or CH$_4$. The H3 inclusions (EES generation in PEG 2) show a dominance of CO$_2$, with N$_2$ contents in the range *ca.* 5–12 mole %, far more than in any of the CO$_2$ inclusions in the granulites. The S1 and S2 inclusions in HA 15/87 (P? and EES generations) are dominated by N$_2$, but have 10–30 mole % CO$_2$.

Density, Raman intensity and frequency

The intensity of the Raman signal is a function of several factors, including size and depth of the fluid inclusion, density of the gas phase and concentration and Raman yield of the component in question (Burke and Lustenhouwer, 1987). Other things equal, a dense inclusion gives a higher Raman intensity than a less dense inclusion.
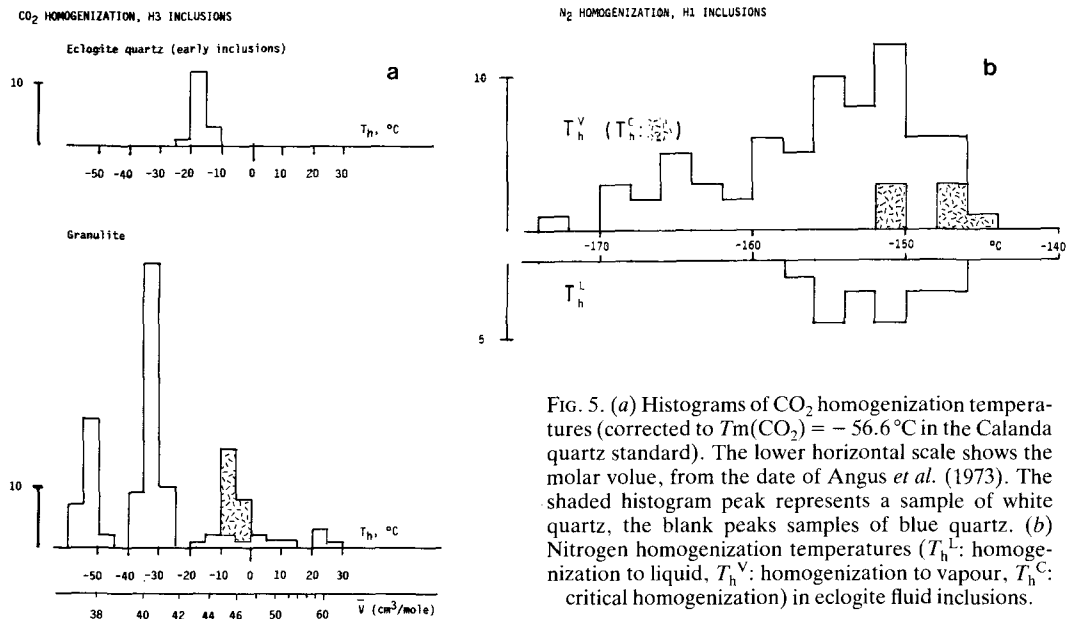
The vibration frequency of a gas molecule

CO2 HOMOGENIZATION, H3 INCLUSIONS

Eclogite quartz (early inclusions)

N2 HOMOGENIZATION, H1 INCLUSIONS

Granulite

FIG. 5. (*a*) Histograms of CO_2 homogenization temperatures (corrected to $Tm(CO_2) = -56.6\,°C$ in the Calanda quartz standard). The lower horizontal scale shows the molar volue, from the date of Angus *et al.* (1973). The shaded histogram peak represents a sample of white quartz, the blank peaks samples of blue quartz. (*b*) Nitrogen homogenization temperatures (T_h^L: homogenization to liquid, T_h^V: homogenization to vapour, T_h^C: critical homogenization) in eclogite fluid inclusions.

depends upon pressure; lines are shifted towards lower Raman wave numbers with increasing pressure (or density) of a fluid inclusion. At $P = 1\,atm$, the single Raman line of N_2 is positioned at $2331\,cm^{-1}$ (Schrötter and Klöckner, 1979). In fluid inclusions, peak positions lower than $2330\,cm^{-1}$ are commonly encountered, even below 2329 cm^{-1} for N_2 and N_2–CO_2 inclusions with $\bar{V} < 80\,cm^3/mole$ (Van den Kerkhof, 1988*b*). The position of the N_2 Raman peak in S_1 inclusions is thus a qualitative guide to their density.

In Table 2, N_2 Raman peak positions are indicated for some of the inclusions measured. The S1 and S2 inclusions are characterized by the N_2-peak at $<2328\,cm^{-1}$, values above $2328\,cm^{-1}$ have only been recorded in H1 inclusions homogenizing to vapour.

Identification of solids

The Raman microprobe has been used to identify solids which occur in some N_2-dominated fluid inclusions. The birefringent crystals found in some S1 inclusions in HA 15/87 (Fig. 4*b*) show a characteristic peak at $1047\,cm^{-1}$, identifying it as nahcolite ($NaHCO_3$; White, 1974). In comparison, the strong Raman peak of $KHCO_3$ is located at $1029\,cm^{-1}$ (White, 1974), a difference more than sufficient to allow distinction with the instrument used (Burke and Lustenhouwer, 1987). Other H1 inclusions in the same sample carry small birefringent crystals with a Raman peak at $1085\,cm^{-1}$, characteristic for calcite (White,

1974). The carbonate crystals are not universally present in fluid inclusions in this sample, and they have variable relative sizes. This suggests that they have originated as accidentally trapped solids, rather than as daughter minerals (e.g. Roedder, 1984). Fluid inclusions with carbonate crystals show nitrogen homogenization temperatures indistinguishable from inclusions without crystals, implying identical density of the N_2 or N_2–CO_2 fluid in the inclusions. This is also an indication that the carbonate were trapped together with the fluid, and not formed by consumption of components contained in the inclusion fluid after trapping, which would have led to a reduction of density. Both calcite and nahcoite also occur as accidentally trapped solids in fluid inclusions in eclogites from several localities in the Western Gneiss Region (Andersen *et al.*, 1989).

Molar volume determination

Molar volumes for pure CO_2 and N_2 inclusions can be determined directly from T_h by use of the compiled data on the two-phase regions of the single components systems by Angus *et al.* (1973, 1979). The molar volume of S2 inclusions, of which both T_{hs} and composition have been measured, can be determined by simple interpolation in a molar volume–composition ($\bar{V}X$) diagram: all CO_2 can be assumed to be in the solid state at T_{hs}, and composition and molar volume of the inclusion must then plot on the tie line connecting
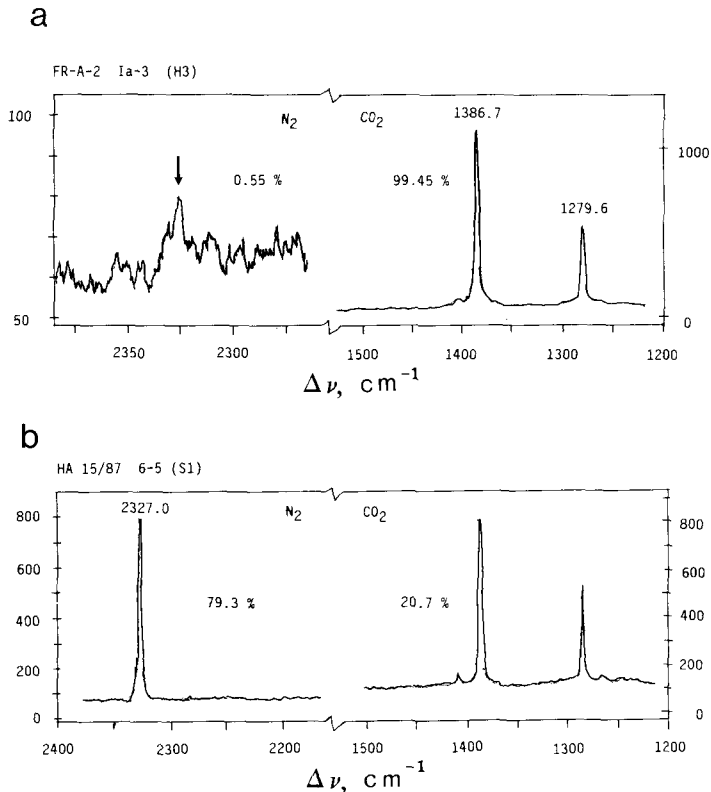
a

FR-A-2 Ia-3 (H3)

b

HA 15/87 6-5 (S1)

FIG. 6. Raman spectra of CO_2-N_2 fluid inclusions. (a) CO_2 inclusion with 0.55 mole % N_2 in granulite sample FR-A-2. The arrow indicates the position of the N_2-peak. (b) S1-type inclusion in HA 15/87. Note the high intensity and the low Raman frequency of N_2.

the CO_2 and N_2 phases at T_{hs} (Van den Kerkhof, 1988b). The S2 inclusions in the present samples have more than 70 mole % N_2, and molar volumes in the range 80–110 cm^3/mole (Table 2).

The molar volume of N_2-containing H3 inclusions, whose composition is known from Raman microanalysis, has been estimated by interpolation in a T_h-contoured VX diagram, as derived by Darimont and Heyen (1988) on the basis of the equation of state of Heyen (e.g. Heyen et al., 1982), the resulting values range from 39 to more than 46 cm^3/mole, at CO_2 concentrations above 85 mole %.

It is not possible to determine the exact molar volume of inclusions showing S1 behaviour, even when their composition is known from Raman microanalysis. S1 behaviour is possible for certain inclusion compositions in the N_2–CO_2 system, when the molar volume is such that the nitrogen homogenization temperature (T_{hs}^L or T_{hs}^V) is outside the range of the microthermometric equip-

ment used, i.e. < -193 °C (Van den Kerkhof, 1988b). S1 behaviour appears to be restricted to low-density inclusions ($T_{hs}^V < -158$ °C, i.e. $\bar{V} > ca.$ 280 cm^3/mole) with 85–90 mole % N_2, and to extremely dense inclusions ($T_{hs}^L < ca.$ -180°C, i.e. $\bar{V} < 40$cm^3/mole) with a wide range of compositions (Fig. 5.17 in Van den Kerkhof, 1988b).

The present S1 fluid inclusions have compositions with 10–30 mole % CO_2, many of which fall outside the comosition range expected for low-density S1 inclusions (Van den Kerkhof, 1988b). These inclusions also show higher Raman intensities than any of the low density inclusions (Figs. 7b), and the N_2 Raman frequency is displaced to <2328 cm^{-1}, characteristic for dense N_2–CO_2 mixtures ($\bar{V} < 80$ cm^3/mole, Van den Kerkhof, 1988b). The present S1 inclusions must therefore have molar volumes within the high-density S1 field, i.e. below the maximum limit defined by the tie-line connecting the molar volume of solid CO_2 and nitrogen with
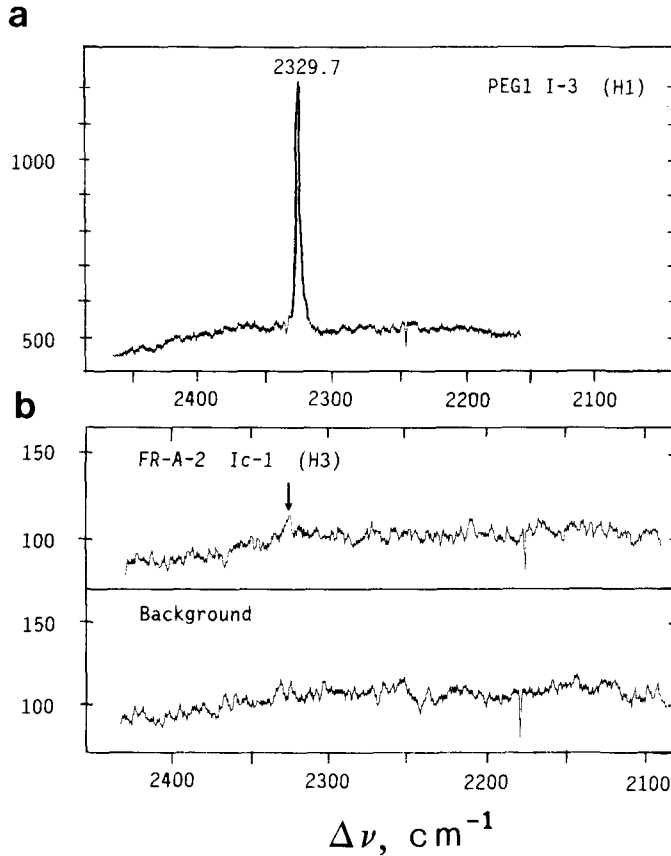
a

b

$$\Delta \nu, \ cm^{-1}$$

FIG. 7. Raman spectra of N_2 in fluid inclusions. (*a*) Nitrogen peak from low density (H1) ELS water-nitrogen inclusion in sample PEG-1. Compare the peak position with that in Fig. 6*b*. (*b*) Nitrogen signal from granulite CO_2 inclusion with far less than 1 mole percent N_2, compared to a background spectrum recorded by illuminating the quartz matrix next to the inclusion.

$T_{hs}^L = -180\,°C$. This corresponds to molar volumes less than 37 cm³/mole (Fig. 8).

Isochore calculation

Isochores have been calculated from the $\bar{V}X$ data (Table 2) from the MRK equation of Holloway (1981), using a modified version of his computer program. Isochores for selected fluid inclusions are shown in Fig. 9, and isochore pressures at $T = 700\,°C$ are given for individual inclusions in Table 2.

Granulites. The most dense CO_2 inclusions in granulite quartz define isochores corresponding well with the *PT* field of mineral equilibration in these rocks as determined by Austrheim and Griffin (1985) (Fig. 9*a*). Later, less-dense inclusions (GLS) have been trapped or remobilized/re-

equilibrated at later stages of the pre-eclogite (Proterozoic) cooling history of the granulite terrane.

Eclogites. The H1 N_2-fluid inclusions define isochores falling far short of the eclogite *PT* field, as do the corresponding late secondary nitrogen inclusions in eclogites from the WGR (Andersen *et al.*, 1989).

Since only maximum molar volumes have been estimated for the S1 inclusions, only minimum isochore pressures can be calculated (Table 2 and Fig. 9*b*). Fig. 9*b* also includes a model isochore calculated for a hypothetical fluid inclusion with 80 mole % N_2 and $\bar{V} = 34$ cm³/mole, shown as a triangle in Fig. 8.

As calculated, all of the S1 minimum isochores fall below the eclogite *PT* field. It should be noted that *a relatively small decrease in molar volume will induce a marked increase in isochore pressure*
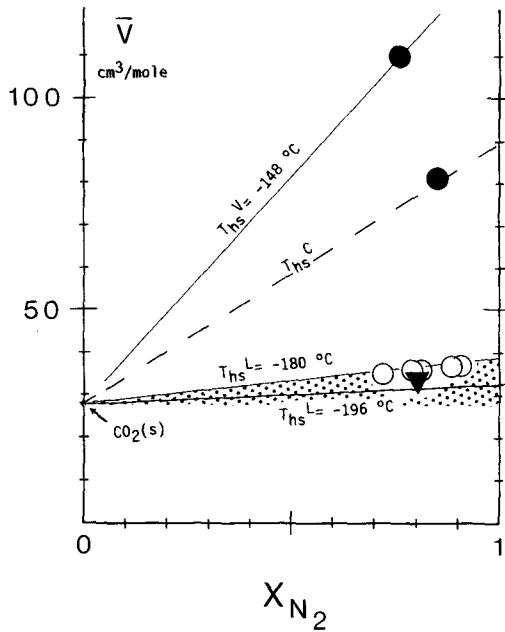
FIG. 8. VX diagram showing molar volumes of S2 inclusions (filled circles) and maximum molar volume estimates for S1 inclusions (open circles) in sample HA 15/87. The filled triangle represents composition and molar volume of a hypothetical fluid inclusion used for the model isochore calculation in Fig. 9b ($\bar{V} = 34\ cm^3$/mole, 80 % N_2).

for a given temperature as shown by the model isochore with $\bar{V} = 34\ cm^3$/mole.

The presence of minor amounts of undetected water in the inclusions would also increase the isochore slope (Touret and Hansteen, 1988). There is no observational evidence for water in any of the early fluid inclusions in the eclogite samples. However, significant quantities of water, at least 10 volume percent, can pass undetected in regularly shaped CO_2- or N_2-rich inclusions, because of its tendency to wet the cavity walls (Roedder, 1984).

Discussion

Fluid evolution chronology

The fluid inclusions in the Holsnøy granulites and eclogites were trapped during metamorphism of the rocks in Grenvillian and Caledonian time, respectively. The granulites and eclogites in the area have characteristic fluid inclusion assemblages, which differ from each other in terms of inclusion composition and density. This allows for the deduction of the fluid evolution chronology of the Holsnøy complex, from observations on fluid inclusions.

The most important features of the fluid evolution history are (Table 1): During the *900 Ma granulite facies event*, the rocks interacted with a CO_2-dominated fluid phase. This fluid contained <2.5 mole % N_2, and less water than can be detected by microscopy and microthermometric methods. There is, furthermore, a change of density, from dense GES inclusions, whose isochores are compatible with peak metamorphic PT conditions, to later, less dense GLS inclusions. The isochores of the GLS inclusions fall short of the pressure expected at peak metamorphic temperatures.

During *Caledonian eclogite metamorphism*, the fluid evolution was somewhat more complex: The earliest fluid retained in P? inclusions consists of high-density N_2–CO_2 mixtures ($X_{N2} \approx 0.8$); no water has been detected. Early secondary inclusions consist of pure N_2 and CO_2 with some N_2 ($X_{N2} \leqslant 10$ mole %); the EES inclusions reflect the fluids present in the system after the peak of eclogite metamorphism. The latest fluid in the eclogites was trapped in ELS inclusions at low pressures during uplift, and consisted of low density N_2 or N_2–H_2O.

Comparison with the Western Gneiss Region eclogites

The presence of significant amounts of nitrogen in the earliest or least disturbed fluid inclusions is a common feature of the Bergen Arc and Western Gneiss Region (WGR) eclogites (Andersen et al., 1989). The complexity of fluid inclusion textures, including a high number of late secondary or remobilized inclusions is also common to the eclogites in both areas.

The total composition of the earliest fluid inclusions in the Holsnøy eclogites is, however, different from that observed in the WGR. In quartz–orthopyroxene and quartz–biotite eclogites from serveral localities in the WGR, the earliest inclusions have been retained in quartz protected by garnet and clinopyroxene, and have high water contents ($X_{H2O} > 80$ mole %). In contrast, the most primitive inclusions in the Holsnøy eclogite samples contain N_2–CO_2 mixtures without detectable water. Another significant difference is the absence of late (i.e. ELS), low-density CO_2 inclusions from the Holsnøy samples. Such inclusions are abundant in the WGR eclogites (Touret et al., 1982; Kechid, 1984; Andersen et al., 1989), where they can be attributed to volatile influx during a regional retrogression event (Andersen et al., 1989).
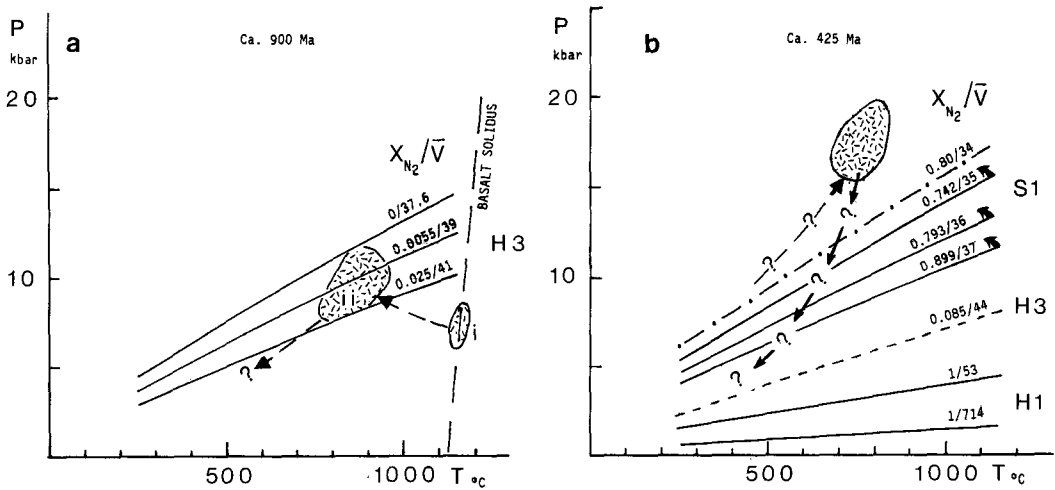
FIG. 9. Isochores calculated from the present microthermometric data (Figs. 5 and 8), using the modified Redlich-Kwong equation of state of Holloway (1981). The isochores are labelled with type of microthermometric behaviour (H1, H3, S1) as defined by Van den Kerkhof (1988*a*), as well as with nitrogen contents and molar volume given as (molar fraction)/(molar volume in cm³/mole). The *PT* fields for granulite-facies and eclogite-facies metamorphism and possible *PT*-paths are based on mineral thermobarometry (Austrheim and Griffin, 1985). (*a*) *Granulites.* *PT* constraints and cooling path for Holsnøy granulites. Field *i* represents igneous crystallization of the anorthosite-mangerite complex, field *ii* represents metamorphic recrystallization in the Grenvillian. (*b*) *Eclogites.* The H1 and H3 isochores represent fluid inclusions whose composition and molar volume are known (Table 2). The S1 isochores are a models for the given compositions and molar volumes. The arrow indicates that the true isochores of any of the S1 inclusions lie to the high pressure side of the lines shown. The prograde *PT* path is taken from Austrheim and Griffin (1985), whereas the retrograde path is based on analogies with other eclogites in Western Norway (e.g. Griffin, 1987).

Evolution of the fluid phase

The apparent absence of water from the S1 fluid inclusions in the present eclogite samples does not necessarily indicate that the fluid phase interacting with the shear-zone eclogites was anhydrous. The presence of white mica in close association with the S1 inclusion-bearing quartz grains suggests a quite elevated water activity (Holland, 1979).

During initial decompression after the peak metamorphic temperature, fluid inclusions may decrepitate due to internal overpressure. If partial decrepitation takes place after an initially homogeneous H_2O–CO_2–N_2 inclusion has exsolved an aqueous phase, water could be lost along microfractures in preference to CO_2, because of greater tendency of water to wet the host mineral (Roedder, 1984; Crawford and Hollister, 1986; Andersen *et al.*, 1989). Some water loss from early inclusions should not be ruled out, even in inclusions which have retained a textural and compositional identity, such as the possibly primary S1 and S2 inclusions in HA 15/87.

The water lost from inclusions by partial decre-

pitation may be consumed locally by a reaction with the jadeite component of omphacite:

$$NaAlSi_2O_6 + Al_2SiO_5 + H_2O =$$
$$NaAl_2AlSi_3O_{10}(OH)_2$$
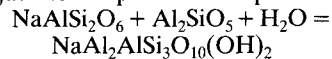
Omphacite$_{ss}$ + kyanite + water = paragonite

during retrograde metamorphism of the eclogite. AT $P <$ 15 kbar and $T <$ 700 °C paragonite can form from omphacite + kyanite, even in the presence of a fluid phase with less than 25% water (Holland, 1979). This reaction will thus be able to 'dry out' an initially water-bearing fluid phase during early retrogression of the eclogite.

Source of the volatile components in the eclogites

CO_2 is the dominant volatile component in the granulite fluid inclusions at Holsnøy, as in many granulite terranes worldwide (e.g. Touret, 1981). The CO_2 inclusions survive only in rock volumes which have not been disturbed by the eclogite-forming shear movement. Some CO_2 must have been liberated to the fluid phase from the granulite-facies protolith in the zones transformed to eclogite. The presence of EES CO_2 inclusions in one of the eclogite vein samples (PEG-2), and

the CO_2-component in the possibly primary S1 inclusions can be attributed to remobilized 'granulite' CO_2 inherited from the protolith.

The provenance of N_2 remains an unsolved question; as discussed in connection with the WGR eclogites (Andersen et al., 1989), N_2 may have an external origin, or it may be inherited from the protolith. If present in the protolith, the nitrogen may have been fixed as NH_4^+-ion in feldspars or other pre-eclogite minerals. The mangeritic rocks, containing antiperthite, would have a greater capacity to fix nitrogen by this mechanism, than would anorthositic rocks. It may therefore be speculated that breakdown of feldspar in the protolith, or more probably, in rocks of similar composition at somewhat greater depth, can account for the N_2-rich early (P?) inclusions in HA 15/87. The Holsnøy eclogites present a case where the possibility of inherited nitrogen can be tested from analysis of protolith minerals; we will return to this problem in a later paper (Austrheim and Andersen, in prep.).

Conclusions

Fluid inclusions in Proterozoic granulite-facies rocks and Caledonian eclogites at Holsnøy in the Bergen Arcs yield evidence of two different fluid regimes connected with two different metamorphic processes: during granulite-facies metamorphism at ca. 900 Ma ($P \approx 8$–10 kbar, $T \approx 800$–900 °C), the rocks interacted with a N_2-'free' CO_2-dominated fluid phase, whereas in eclogite metamorphism at ca. 425 Ma (16–19 kbar, 700–750 °C), the fluid phase contained substantial amounts of N_2 and possibly water in addition to minor CO_2.

The $\bar{V}X$ properties of the early fluid inclusions suggest that they have been somewhat disturbed during the early retrograde history of the eclogites ($P > 10$ kbar), with possible loss of water.

Our data from the Bergen Arc and Western Gneiss Region eclogites, as well as findings reported in Russian literature (e.g. Tomilenko and Chupin, 1983), suggest that the presence of nitrogen-bearing fluids may be a general feature of eclogite metamorphism. CO_2 is, however, present in some of the earliest fluid inclusions in the eclogites. It is suggested that this CO_2 is inherited from fluid inclusions in the granulite-facies protolith, whereas the provenance of N_2 is at present uncertain.

Acknowledgements

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