EXAMENSARBETE I GEOLOGI VID
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Mineralogi och petrologi

Retrograded eclogites of the Richarddalen Complex, NW Svalbard - Petrology and P/T-conditions

Ros-Mari Hesbøl

Lund 1996 Examensarbete, 20 p Nr 71
Geologiska Institutionen, Lunds Universitet

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Abstract

At least three terranes have been identified in the Svalbard Caledonides, each one having independent structures and tectonothermal evolution. On Biskayerhalvöya in the Northwestern Terrane, eclogites, located within deformed igneous basement rocks, have been dated by the U-Pb zircon method to c. 625 Ma. This study, using the garnet-clinopyroxene Fe/Mg exchange geothermometer, has established the crystallization temperature of these eclogites to be between 640 and 700 °C at estimated pressures from 12 to 18 kbars. The eclogites occur in hornblendic gneisses, associated with marbles, calc-silicate bearing psammites and amphibolites; together with the thermobarometric data, this indicates that these high P/T rocks where formed in a continental collision setting within tectonically thickened crust. The petrographical investigation verified that the eclogites at a later stage have undergone extensive retrograde alteration processes where secondary minerals such as hornblende, chlorite, epidote and sphene were formed at the expense of the primary eclogite minerals, omphacite, garnet, quartz and rutile. $^{40}Ar/^{39}Ar$ and K/Ar isotope studies of the secondary hornblende in the retrograded eclogites indicate that this metamorphism occurred at c. 540 Ma prior to Caledonian deformation and amphibolitefacies metamorphism.

Contents

1. INTRODUCTION

Svalbard is the collective name of a group of islands located in the Arctic Ocean some 1000 km from the North Pole between latitudes 74 ° and 81 ° N. Altogether the islands comprise an area of 62 000 km², of which Spitsbergen is the largest followed by Nordaustlandet, Edgeöya, Barentsöya, Kvitöya, Prins Karls Forland, Kong Karls Land and Björnöya. The islands are to a large extent covered by glaciers and small ice caps, leaving only one third of the land free of permanent ice. The morphology of Svalbard varies, the northwest being very rugged, with steep mountains separated by glacier-filled valleys. The northeast has a more rounded relief whilst the southwest is characterized by flat plateau mountains.

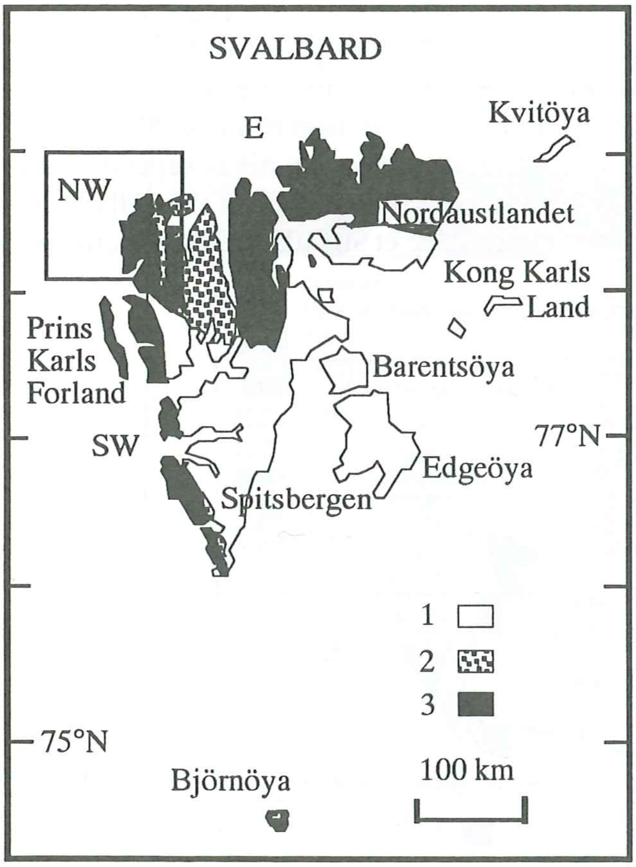
Caledonian rocks compose much of Svalbard's bedrock. In the northwestern part of the Spitsbergen Caledonides, high pressure rocks occur within the Richarddalen Complex, located on Biskayerhalvöya, just east of Raudfjorden. Eclogites occur as lenses in strongly deformed host rocks, which consist of various orthogneisses and metasediments.

The origin of eclogites has been a controversial matter for many decades, particularly since the classical studies of Eskola (1921) in western Norway. Eclogites are the product of metamorphism of rocks of basaltic composition; their formation is thought to involve solid state reactions in rocks with a low partial pressure of water. The mineralogy, dominated by garnet (almandine-pyrope) and omphacite (jadeitic clinopyroxene), requires very high pressure of crystallization, pressures that only exist in and below the lower part of the crust. Their specific gravity, 3.5 g/cm³ (3.0 g/cm³ for normal gabbroic rocks), also speaks for elevated pressures. Rocks associated with eclogites, frequently of acid composition, seldom provide evidence of similar high pressure metamorphism. Therefore there are various opinions concerning the mechanisms by which the eclogite have come to be exposed at the surface. One hypothesis explains the existence of the high pressure minerals by the fact that they were first formed in the mantle and then tectonically intercalated into their present environment (O'Hara et al., 1971; Lappin and Smith, 1978). Another hypothesis favors subduction of oceanic or continental crust to depths great enough for crystallization of eclogites to occur (Gjelsvik, 1953; Bryhni et al., 1977; Cuthbert et al., 1983). Today most authors prefer the latter hypothesis.

The objective of this work is to describe the petrography of the eclogites on Biskayerhalvöya, northwest Spitsbergen, infer possible protoliths and estimate the P/T-conditions of their crystallization.

2. GEOLOGY OF SVALBARD

The bedrock geology of Svalbard can be divided into three sequences:



1. Post-Devonian rocks (Carboniferous and younger)
2. Devonian rocks (Old Red Sandstone-successions)
3. Pre-Devonian rocks (Caledonides)

Fig. 1 Bedrock geology of Svalbard. Square shows the Northwestern Terrane.

2.1 Svalbard Caledonides

The Svalbard Caledonides are divided into separate terranes with different stratigraphies and tectonothermal histories (Harland, 1985). These terranes are commonly referred to as the Eastern, Northwestern and the Southwestern terranes (Gee, 1986) and are separated by major high angle N-trending faults and Old Red Sandstone (ORS) basins (see Fig. 1). The pre-ORS rocks, influenced by the Caledonian orogeny, are by most authors referred to as the Hecla Hoek Complex.

2.1.1 The Eastern Terrane

The Hecla Hoek Complex (HH) of Svalbard's Eastern Terrane (Fig.2) has for a long time been described as a continuous stratigraphic sequence exposing various sedimentary rocks of which the upper units are late Proterozoic and Cambro-Ordovician in age. The lower part of the Hecla Hoek (LHH) differs from the overlying low grade strata as it has been thoroughly metamorphosed and deformed under the conditions of amphibolite facies. Only the uppermost part of the LHH is lower grade(greenschist facies) and, since there is no evident stratigraphic break between the Middle (MHH) and Lower Hecla Hoek, it has been assumed that the metamorphic grade increases continuously downwards towards the latter (Harland, 1985). Recent work (Manby and Lyberis, 1991), however, indicates that there is indeed a structural break separating the LHH from the overlying MHH and Upper Hecla Hoek (UHH) and that the LHH contains Palaeoprotorozoic granitic basement units (Gee et al., 1992,1994; Johansson et al., 1995).

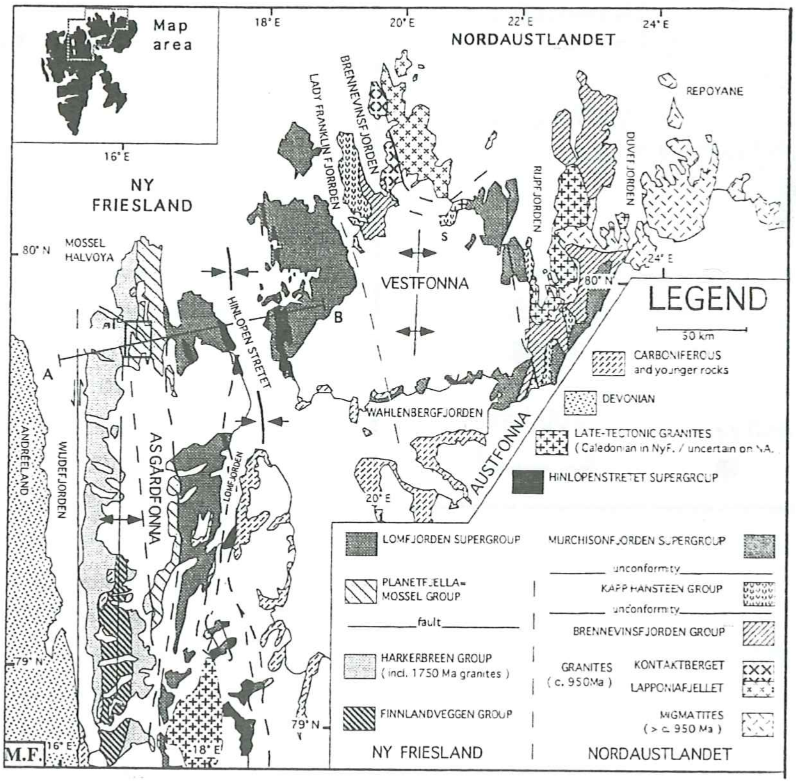


Fig.2 The Eastern Terrane (taken from Gee et al., 1995)

The structure of the Eastern Terrane is dominated by a major synclinorium, with the axis located between Ny Friesland and Nordaustlandet, containing sediments of the MHH and the UHH (Harland, 1959; Flood et al., 1969). To the west (Ny Friesland) and east (Nordaustlandet) the synclinorium is flanked by major antiforms, within which LHH rocks occur that have different stratigraphies and tectonothermal histories.

Ny Friesland: Table 1 shows the stratigraphically continuous UHH and MHH with its various sandstones, shales and carbonates. The MHH is separated from the underlying Planetfjella Group by a N-trending fault. The dominant structure of western Ny Friesland is that of the Atomfjella Antiform and it is within this fold that the rocks of the Stubendorffbreen Supergroup occur. The contact between the metasediments of the Planetfjella Group and the underlying rocks in the Atomfjella Antiform is a fault which is exposed in the eastern limb of the antiform (Fig.3).

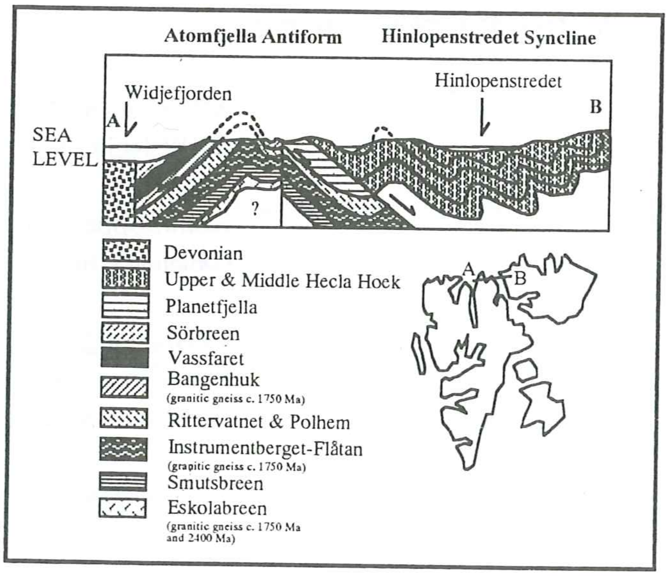


Fig.3 Section through Ny Friesland, modified after Gee et al. (1994)

The Stubendorffbreen Supergroup consists of metasedimentary and metaigneous rocks. Evidence put forward by Gee et al., (1994) and expanded by Johansson et al., (1995) shows that "the Stubendorffbreen Supergroup is a tectonostratigraphic succession with thrust intercalation of basement and cover rocks". This revises the previous interpretation that the Hecla Hoek succession is an uninterrupted geosynclinal assemblage (Harland et al., 1966, Harland et al., 1992).

Table 1 The Hecla Hoek stratigraphies of Ny Friesland and Nordaustlandet (after Gee et al., 1994)

Ny Friesland	**Nordaustlandet**
UPPER HECLA HOEK	
Oslobreen Gp (Limestones, dolomites)	
Polarisbreen Group (Tillites)	Sveanor Formation (Tillites)
MIDDLE HECLA HOEK	
LOMFJORDEN SUPERGROUP	MURCHISONFJRDN SUPERGROUP
Akademikerbreen Gp 2 km (Dolomites, limestones)	Roaldtoppen Gp 1.4 km (Dolomites, limestones)
Veteranen Gp 3.8 km (Sandstones & subord. shales)	Celsiusberget Gp & Franklinsundet Gp 4 km (Sandstones & subord.shales)
Major fault	*Unconformity*
LOWER HECLA HOEK	
STUBENDORFFBREEN SUPERGROUP	Kapp Hansteen Gp>1km (Volcanic & volcaniclastic rocks)
Planetfjella Gp 4.8 km (Phyllites, schists, psammites & subord. marbles)	
	Unconformity
Major fault	Brennevinsfjorden Gp > 1.5 km (Shales & psammites)
Harkerbreen Gp 4.1 km (Quartzites, meta-arkoses, amphibolites & granite, c. 1750 Ma)	**intruded by** Granite (c. 950 Ma) & older migmatite complex
Major fault	
Finnlandveggen Gp 2.7 km (Semipelite, marble, metased., amphibolite & granite, c. 1750 Ma	

Table 2 Stratigraphy of the Northwestern Terrane (after Harland, 1985)

WESTERN AREA	**RAUDFJORDEN GRABEN**	**EASTERN AREA**
	OLD RED SANDSTONE	
	Andrée Land Gp 5 km	
	Red Bay Gp 0.2 km (Sandstone, conglomerate)	
	Unconformity	
	Siktefjellet Gp 1.6 km (Sandstone, conglomerate)	
	Unconformity	
Hornemanntoppen Post-tectonic Batholith (Quartz monzonite)		
Syntectonic Granites (Granite, granodiorites, aplites, pegmatites)		
Krossfjorden Gp 7-7.5 km		Liefdefjorden Gp 1.2-1.5 km (Marbles, pelites)
Generalfjella Fm (Marbles)		
		Biskayerfonna Gp 4.5-5.5 km
Signehamna Fm (Pelites, psammites)		*Biskayerhuken Fm* (Pelitic & psammitic schists)
Nissenfjella Fm (Pelites, subord. amph.		*Montblanc Fm* (Semipelites, amph,. psammites, marbles)
Svitjodbreen migmatite Complex (Migmatization of Krossfjorden Gp; may contain older basement units)		*Fault*
		Richarddalen Complex (Amph., gneisses, eclogites, marbles, granites and gabbros c. 950 Ma)

Nordaustlandet: The UHH and MHH show a similar stratigraphy to that of Ny Friesland (Table 1). The MHH is unconformably underlain by a volcanic suite, the Kapp Hansteen Group, which represents the upper part of the LHH of Nordaustlandet. The basal conglomerate of the Kapp Hansteen Group unconformably overlies the Brennevinsfjorden Group which is a metasedimentary unit intruded by granites, the latter yielding ages of about 950 Ma. The granite contains migmatite xenoliths at deeper structural levels and the palaeosome of the latter is of sedimentary origin. Whether this palaeosome represents an older unit on top of which the Brennevinsfjorden sediments were deposited, or was derived from the Brennevinsfjorden itself is unclear (Gee et al., 1995). The presence of igneous rocks of Grenvillian age indicates that the LHH represents a basement complex on top of which overlying Neoproterozoic successions rest with major unconformity.

2.1.2 The Northwestern Terrane

Between the Northwestern and the Eastern Terranes there is a graben filled with early to middle Devonian molasse. The Caledonian rocks of the Northwestern Terrane occur in two outcrop areas, separated by a major fault and a subordinate ORS basin, the Raudfjorden Graben (Fig.1). The eastern outcrop area reaches from Biskayerhalvöya southwards to Holtedahlfonna, and the ORS succession unconformably overlies metamorphic rocks of the Biskayerhuken- and Liefdefjorden Groups and Richarddalen Complex. The lithologies and metamorphic history of these units will be discussed in more detail below.

Table 2 and Fig.4 also show the different rock units occurring west of the Raudfjorden Graben. Marbles belonging to the Krossfjorden Group are exposed in the southern part of the terrane. To the north, lower stratigraphic levels are exposed; the sediments here are dominated by pelites. Underneath the pelites are migmatites which dominate the northwestern terrane, being exposed in the north and along its eastern margin. The migmatites in the east have been thrust over the marbles of the Krossfjorden Group along an E-dipping fault. Various granitic intrusions cut through the migmatite, the largest being the Hornemann Batholith; it is exposed in the area south of Smeerenburgfjorden and was reported by Hjelle (1979) to have a Rb-Sr age of 414 Ma. K/Ar ages for the various migmatites and gneisses in this area range between 375 and 450 Ma (Gayer et al., 1966).

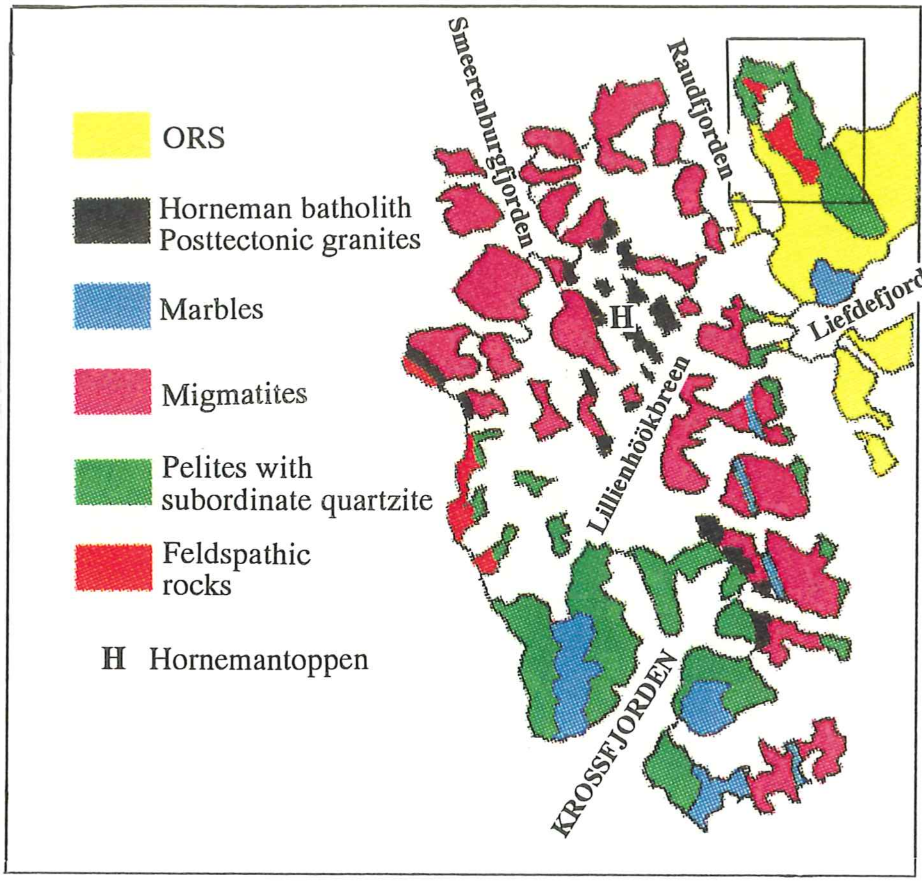


Fig.4 Geological map of Northwestern Terrane, Square showing Biskayerhalvöya (modified after Gee and Hjelle, 1966).

2.1.3 The Southwestern Terrane

Further south, along the west coast of Spitsbergen, there is an early Ordovician blueschist-eclogite complex with metabasic rocks showing oceanic trace element characteristics, thus suggesting the existence of an oceanic subduction complex (Ohta et al., 1986). The blueschists and eclogites are unconformably overlain by late Ordovician through early Silurian limestones and turbidites. Late Proterozoic successions, including tillites, are also present in this terrane. Due to Tertiary folding and thrusting it has been difficult to establish the Caledonian stratigraphy of this area. Devonian molasse overlies the older units unconformably.

2.2 Carboniferous and younger formations

Early Carboniferous sediments unconformably overlie the Hecla Hoek and the ORS-successions. Unstable platform conditions as recorded in the occurrence of several unconformities, prevailed during late Permian through to Cretaceous. In the Tertiary, Svalbard was subject to strong Alpine deformation, referred to as the "West Spitsbergen Orogeny" by Harland, (1969) and the "Spitsbergenian Phase" by Birkenmajer, (1972). A summary of the lithologies and depositional environments af the post-Devonian rocks is given by Birkenmajer (1981).

3. GEOLOGY OF BISKAYERHALVÖYA

3.1 Lithologies

Biskayerhalvöya is located in northern Haakon VII land, on the eastern side of Raudfjorden (Fig.4).

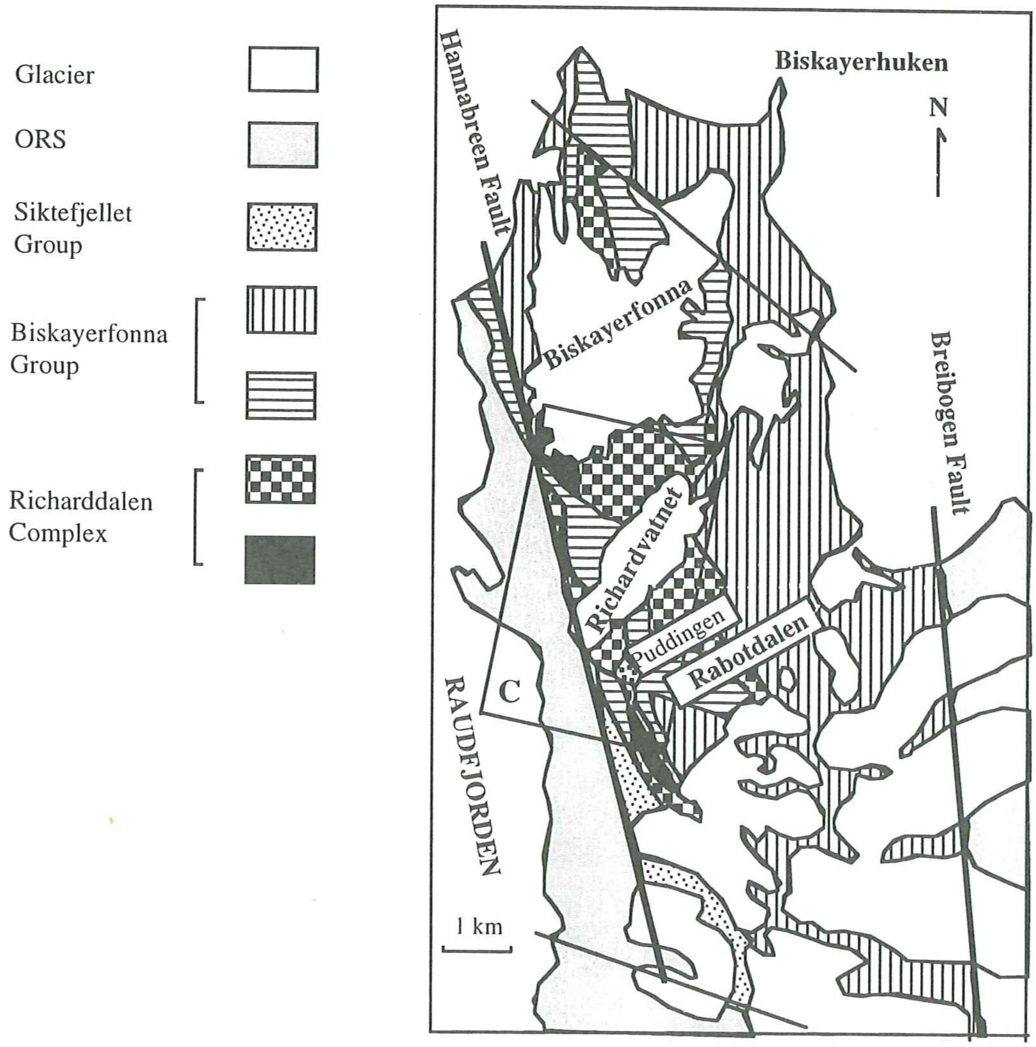


Fig.5 Geological map of Biskayerhalvöya (modified after Gee 1966a). (C) shows the study area.

The ORS-successions of Raudfjorden are underlain by igneous and metamorphic rocks which have been divided into two units, the Biskayerfonna Group and Richarddalen Complex (Gee, 1966a, 1972; Peucat et al., 1989). These two units are exposed on Biskayerhalvöya between two NNW-trending high angle dislocations, the Hannabreen Fault and the Breibogen Fault (Fig.5). The Biskayerfonna Group overlies the Richarddalen Complex, the contact between the two being tectonic (Gee, 1966a, 1972).

3.1.1 ORS-successions

ORS-successions are exposed west of the Hannabreen Fault (Red Bay Gp) and east of the Breibogen Fault (Wood Bay Fm of the Andrée Land Gp); in addition, some conglomerates and sandstones belonging to the Siktefjellet Gp, are exposed along the eastern margin of the Hannabreen Fault in the area from Rabotdalen to Liefdefjorden (Fig.5). The conglomerates of the Siktefjellet Gp contain boulders from the underlying high grade metamorphic rocks (Gee and Moody-Stuart, 1966) and are considered to be the basal conglomerate of the ORS-succession. Diagnostic fossils have not been found and the age of the Siktefjellet Gp is thought to be Late Silurian or Early Devonian. The lower part of the overlying Red Bay Gp conglomerate is mainly made up of marble boulders. At higher levels, conglomerates contain more varied clasts, such as quartz-mica schist and quartzites. The shales and sandstones contain fish faunas of Early Devonian age.

3.1.2 Biskayerfonna Group

The Biskayerfonna Group is mainly made up of metasedimentary rocks. Prograde mineral assemblages in the metasediments of the Biskayerhuken Formation, containing kyanite and staurolite, show that the metamorphic grade reached amphibolite facies. The underlying Montblanc Formation contains feldspathic semipelites, amphibolites and psammites. Occasional bands of marble occur interbanded with the schists. Virtually all lithologies contain garnet.

3.1.3 Richarddalen Complex

The lithologies of the Richarddalen Complex include metagranites, metabasic rocks such as coronagabbro and eclogites, pods of marble and skarn and a variety of gneisses, mainly hornblendic. In contrast to the overlying Biskayerfonna Group, the Richarddalen Complex has undergone high pressure metamorphism, as shown by the retrograded eclogites which occur as lenses in the gneisses.

3.2 Previous work in the area

Early work was carried out by Holtedhal (1926) who mapped the main lithologies occurring in the area. He emphasized that there were similarities between northwestern Spitsbergen and northern Scotland, drawing parallels between the Raudfjorden Fault and the Great Glen Fault.

In 1960, Harland correlated the Liefdefjorden series with Lower Hecla Hoek of Ny Friesland (Eastern Terrane) and Hornsund (Southwestern Terrane).

An investigation dealing with the structure, stratigraphy and metamorphism of the Biskayerhalvöya area was made by Gee (1966a and b). Gee argued for the probability of late Precambrian orogenic deformation in northwestern Svalbard during the deposition of the MHH and UHH in the eastern areas. This Precambrian orogeny was referred to as the Biskayerian Orogeny, being based on age determinations by the K/Ar-method on hornblende from retrograded eclogites; these gave ages of about 535 Ma. Some argon loss was inferred and the high pressure event was argued to be somewhat earlier (c. 600 Ma).

In 1989, U-Pb, Rb-Sr and Sm/Nd age determinations by Peucat et al. confirmed that the lower lithological units of Biskayerhalvöya had indeed been subject to pre-Caledonian high grade metamorphism. Zircons extracted from retrograded eclogites yielded U-Pb ages of $625\pm^{2}/_{5}$ Ma, giving the time of probable metamorphic crystallization. Metagranite and coronagabbro of the Richarddalen Complex gave U-Pb zircon ages of 965 ± 1 Ma and 955 ± 1 Ma respectively, indicating the influence of a Grenvillian tectonothermal event.

Dallmeyer et al. (1990) presented $^{40}Ar/^{39}Ar$ and Rb-Sr mineral ages from rocks in the Biskayerfonna Gp and Richarddalen Complex. Amphibole from retrograde eclogite records $^{40}Ar/^{39}Ar$ isotope correlation ages which confirmed that the Richarddalen Complex was subject to pre-Caledonian high amphibolite facies metamorphic event, perhaps occurring between 500 and 542 Ma; it may have started somewhat earlier, based on the zircon ages of c. 625 Ma. $^{40}Ar/^{39}Ar$ ages from amphibole within the Biskayerfonna Gp coincide with the Rb-Sr mineral ages of about 430 Ma recorded by muscovite and biotite from both Richarddalen Complex and Biskayerfonna Group; these correspond to the time of the Caledonian metamorphic event.

4. FIELD WORK AND SAMPLING OF ECLOGITES

The sampling for this study was mainly carried out in the area between Biskayerfonna and Richardvatnet, where the eclogites are most abundant. In addition, one locality lies just south of Richardvatnet and another is located in Rabotdalen. The localities (Fig.6) were found using the geological map of Gee (1966a). The rocks in the area are extremely deformed and the eclogites appear as lenses, or boudins. The contacts between the eclogite bodies and host rock are extensively sheared. The degree of retrograde metamorphism in the eclogites varies not only among the different localities, but also within one and the same body. Several specimens from each locality were sampled, the relative degree of retrograde metamorphism being estimated directly in the field; thereafter, in the laboratory, the least retrograded specimens were selected for further investigation. Other mafic rocks in the area were sampled as well; these include corona gabbros, amphibolites and a newly discovered layered mafic intrusion. The amount and size of each specimen was restricted to c. 1/2 kg due to the fact that everything had to be carried in a backpack over large distances.

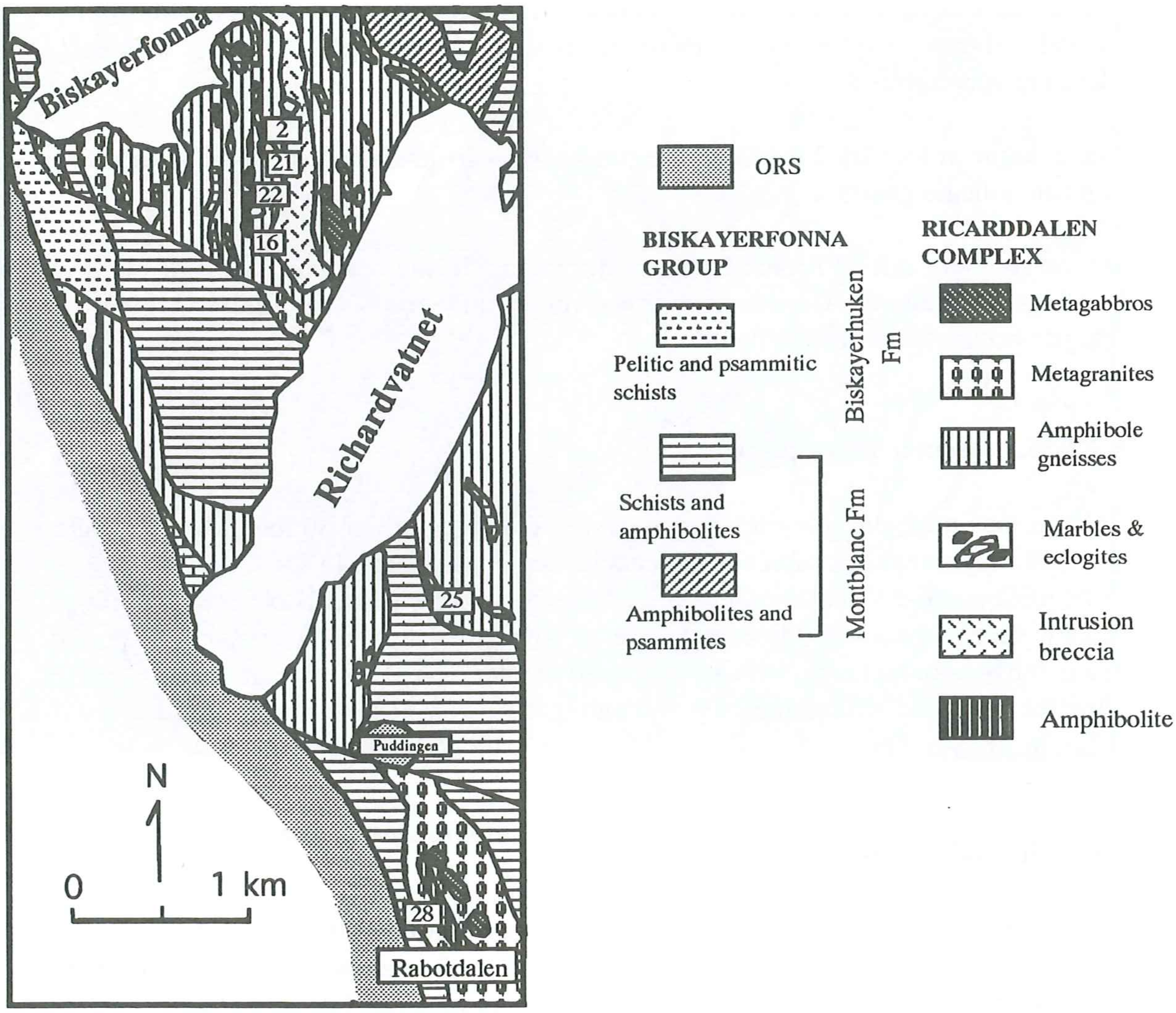


Fig.6 Geological map (after Gee, 1966a) of the study area showing sampling localities.

5. PETROLOGICAL DESCRIPTION OF ECLOGITES AND OTHER SAMPLED ROCKS

Of the samples collected, only a few were selected for further investigation. A first selection was made by choosing the best preserved mineralogies in the hand specimens and a second on the basis of thin section studies.

For every locality, several thin sections have been examined. In the following description, the main characters of every locality are described, based on studies of several thin sections from each locality.

5.1 Eclogites

Of the eclogites found between Biskayerfonna and Richardvatnet, the lenticular outcrop of locality 16 was thought to contain the best preserved specimens. Marbles and calc-silicate gneiss rich in diopside surround the eclogite lens. Contacts with host rocks are very sheared.

The eclogite at locality 2 forms an irregular mass, surrounded by garnet- and diopside-rich calc-silicate gneiss.

On the southern side of Richardvatnet, eclogites are located on a hill north of Puddingen, locality 25. Corona gabbro was found at the top of the hill, whereas the eclogite occurs a few metres below.

5.1.1 Macroscopic description

In hand specimen, the eclogites are massive and contain brownish red garnet and pale green clinopyroxene. Hornblende appears in varying amounts. In some specimens, white mica is quite abundant. Generally, no preferred orientation is observed, although in some specimens a slight lineation is defined by larger amphibole crystals. The grain size is fairly homogeneous with an average diameter of 2.5 mm, though locally coarser eclogites are found with garnets up to 6 mm in diameter. In some specimens, tiny veins of calcite are visible.

5.1.2 Microscopic description

The eclogites are made up of two major components, garnet (40-50%) and omphacite (35-45%). Quartz is usually present in small amounts. Sometimes white mica (probably phengite) can be seen. Rutile is a common accessory mineral. The retrograde mineralogy includes amphibole (5-15%), mostly green hornblende, but also small amounts of bluish actinolitic hornblende, chlorite, epidote, calcite and sphene.

Omphacitic clinopyroxene is evenly distributed as variously cracked, but mostly unfragmented, slightly elongated grains. No zoning has been observed. Beautiful examples of clinopyroxene/plagioclase symplectite were found in some of the samples other than those selected for microprobe analysis, as is illustrated in Photo 2.

Various amounts of green hornblende are found unevenly distributed around the edges or along cleavages of omphacite grains. Many of the hornblendes are poikiloblastic with quartz inclusions.

Garnet grains are fractured and usually contain inclusions of quartz and epidote. Garnet aggregates are frequent, some of the grains exhibiting idioblastic features, others being rounded. Quartz, epidote, white mica and calcite are often found in pressure shadows, with granoblastic texture, among the garnet aggregates. In some cases when next to garnet, clinopyroxene and/or hornblende exhibit a thin rim of blue-green amphibole in the garnet contact zone.

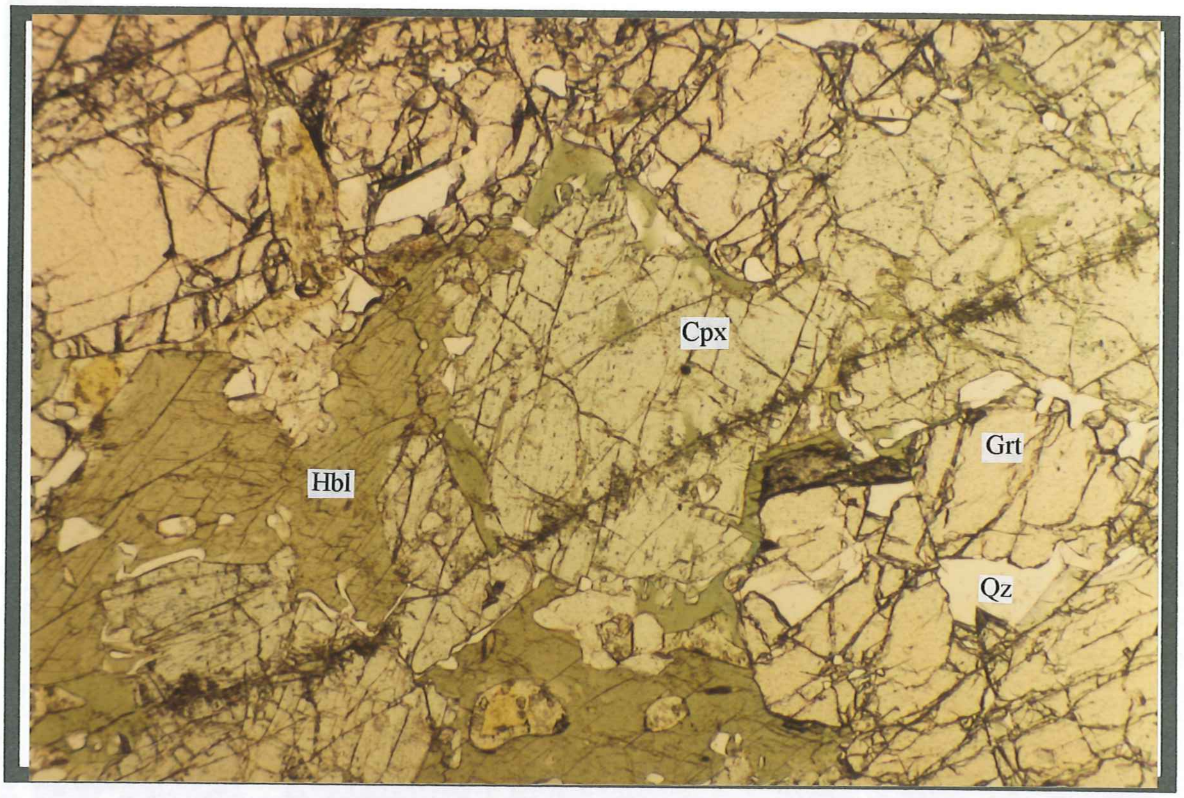


Photo 1 Amphibolitization along cleavages and as patches within clinopyroxene (sample 16)

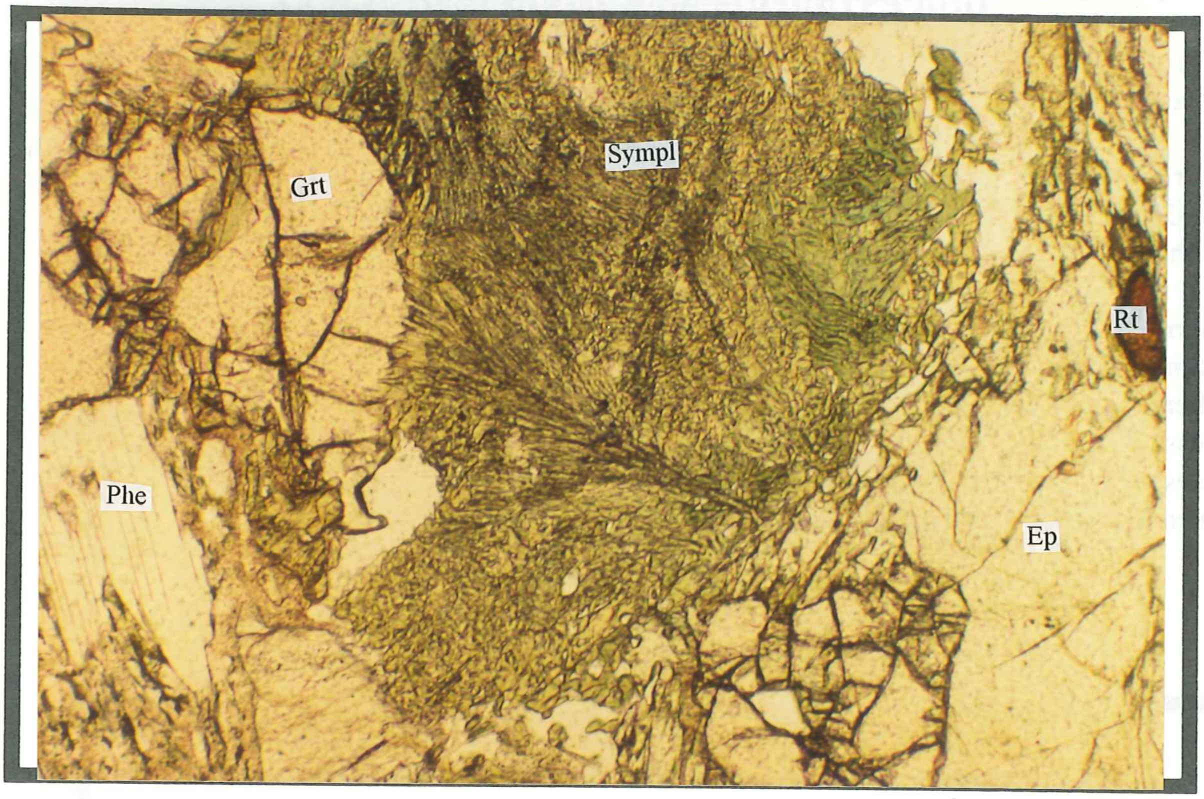


Photo 2 Symplectite textures (sample 18D).

Minor chlorite is associated with amphibole in all samples. At locality 25, small amounts of the chlorite are also associated with garnet. At locality 16, chlorite is seen intergrown with white mica, the grain boundaries of which are very irregular. Granoblastic epidote and brownish, very cloudy, plagioclase are associated with the white mica/chlorite assemblage.

Within chlorite, grains of epidote are observed; this is very clearly illustrated at locality 2 (Photos 3 and 4). The majority of the epidote grains present in the eclogites are found in randomly distributed, equigranular clusters of varying size and shape. At locality 25, small amounts of white mica are seen together with some of the epidote. This white mica is normally surrounded by colourless and turbid minerals, including plagioclase.

Minor quartz is seen unevenly distibuted as small rounded grains or as larger grains concentrated in scattered domains. Rutile and sphene are found, randomly distributed and in small amounts. Occasionally the rutile is mantled by sphene.

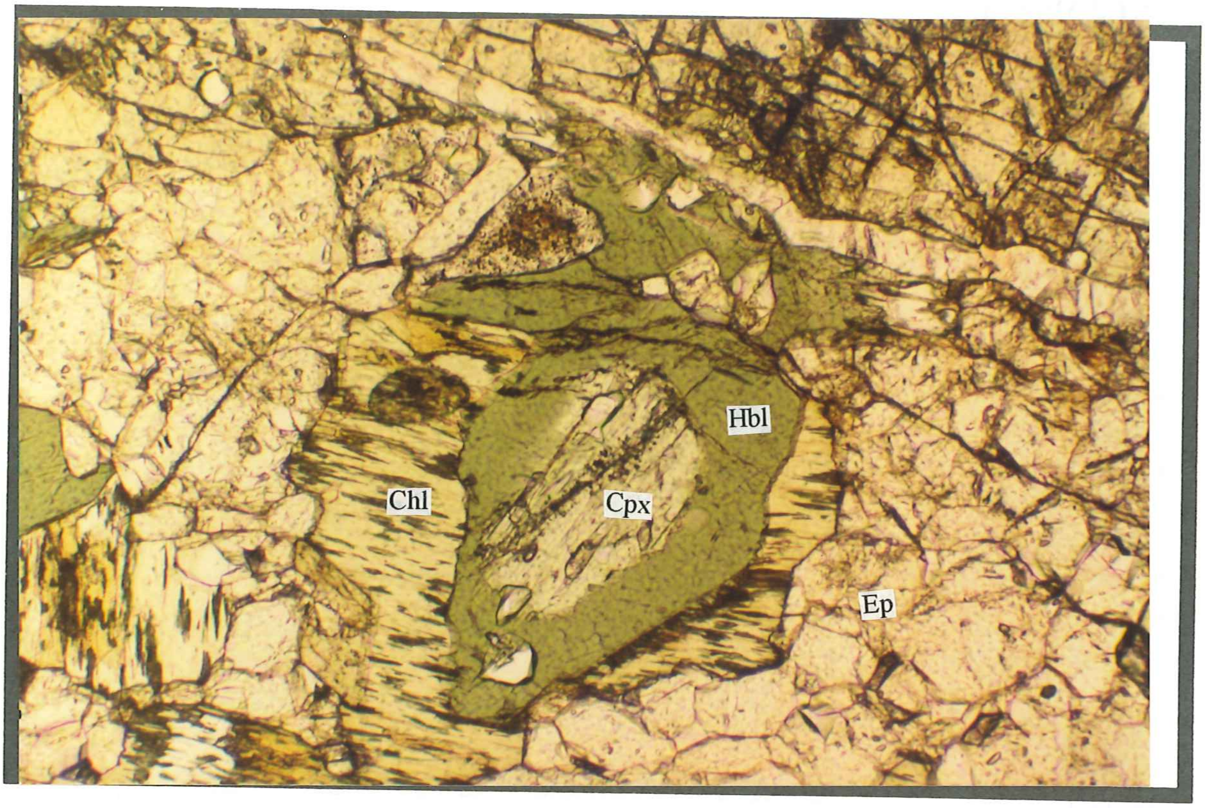


Photo 3 Hornblende with a clinopyroxene core, surrounded by chlorite with epidote (locality 2)

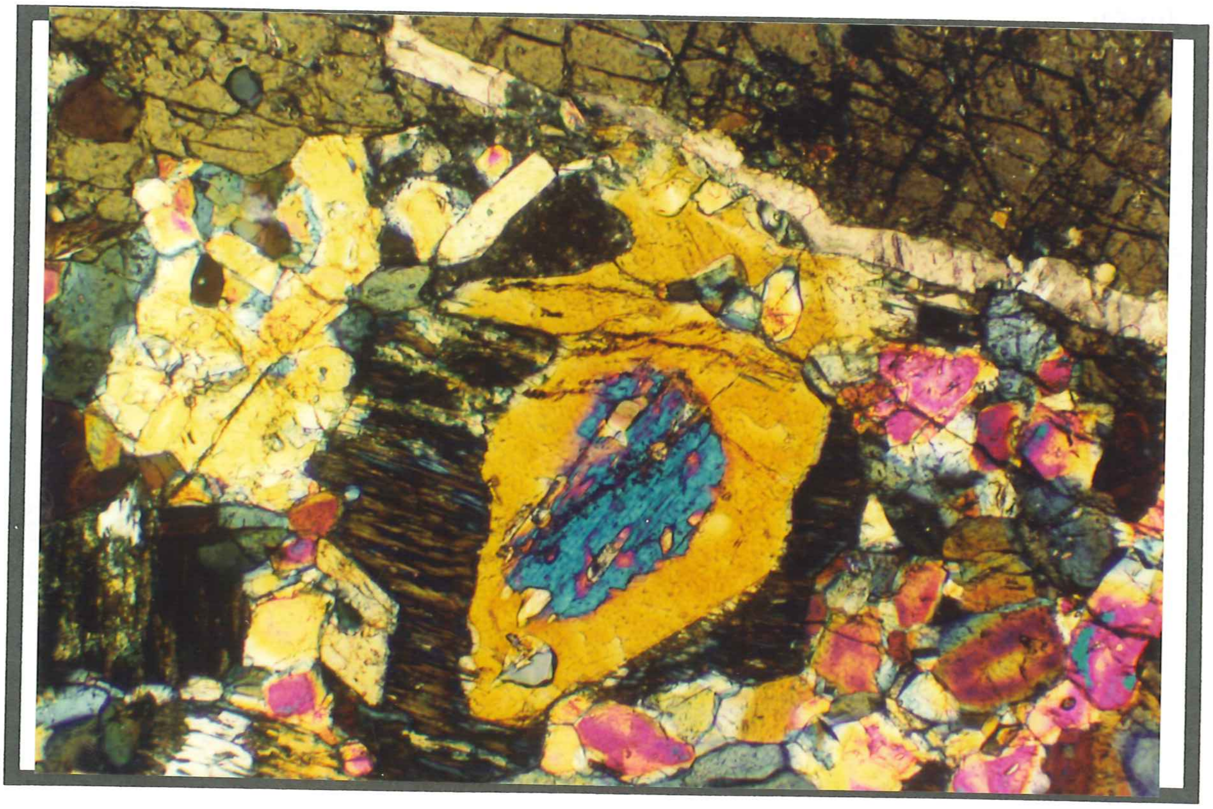


Photo 4 Hornblende with a clinopyroxene core, surrounded by chlorite with epidote (locality 2)

5.1.3 Mineral composition

The mineral compositions of garnet and clinopyroxene of localities 25, 16 and 2 are listed in Tables 3 and 4. No significant zonation of the minerals was detected apart from a slight increase in Mn/Mg ratio in the garnets towards the center in localities 2 and 25 (Fig.8). The values listed in Table 3 are representative compositions, taken from one of the analysis points (marked in Figs.7 and 8). Two mineral pairs were selected and analysed from locality 2 and samples 16C and 16G. Only one mineral pair was analysed from locality 25. Care was taken to find inclusion-free mineral pairs with clear regular contacts and unfractured surfaces, and point analyses were made along a line from near the center of the clinopyroxene grain moving across the contact and continuing towards the center of the garnet. The anomalously high and low values in the diagrams come from unavoidable cracks and inclusions. None of the traverses go all the way across the grain. The length as well as the number of points along each line had to be varied in respect to grain size differences. A small clinopyroxene grain lying next to a big garnet has fewer analysed points over a shorter distance than the corresponding garnet.

Table 3 Representative values of microprobe analyses of garnet and clinopyroxene. Analyses carried out at Uppsala University using a Cameca SX 50 (WDS) microprobe

Loc-alities:	**2**		**16C**		**16G**		**25**	
	Cpx	Grt	Cpx	Grt	Cpx	Grt	Cpx	Grt
(wt %)								
SiO_2	52.40	38.67	53.09	38.15	52.97	38.42	51.69	37.58
TiO_2	0.11	0.01	0.21	0	0.09	0.08	0.13	0
Al_2O_3	5.01	21.25	6.48	20.78	5.31	21.34	5.38	20.81
FeO	4.39	21.47	6.07	25.14	4.39	21.34	3.98	19.81
Fe_2O_3	2.28	1.39	3.33	1.06	2.49	1.59	4.63	2.93
MnO	0	0.66	0	0.28	0	0.36	0.10	0.92
MgO	12.21	6.37	8.99	5.04	11.70	6.57	10.51	4.27
CaO	20.95	10.02	16.55	8.80	19.53	9.93	19.51	12.95
Na_2O	2.11	0	4.40	0	2.84	0	3.05	0.03
Sum	99.72	99.97	99.50	99.39	99.61	99.75	99.52	99.57

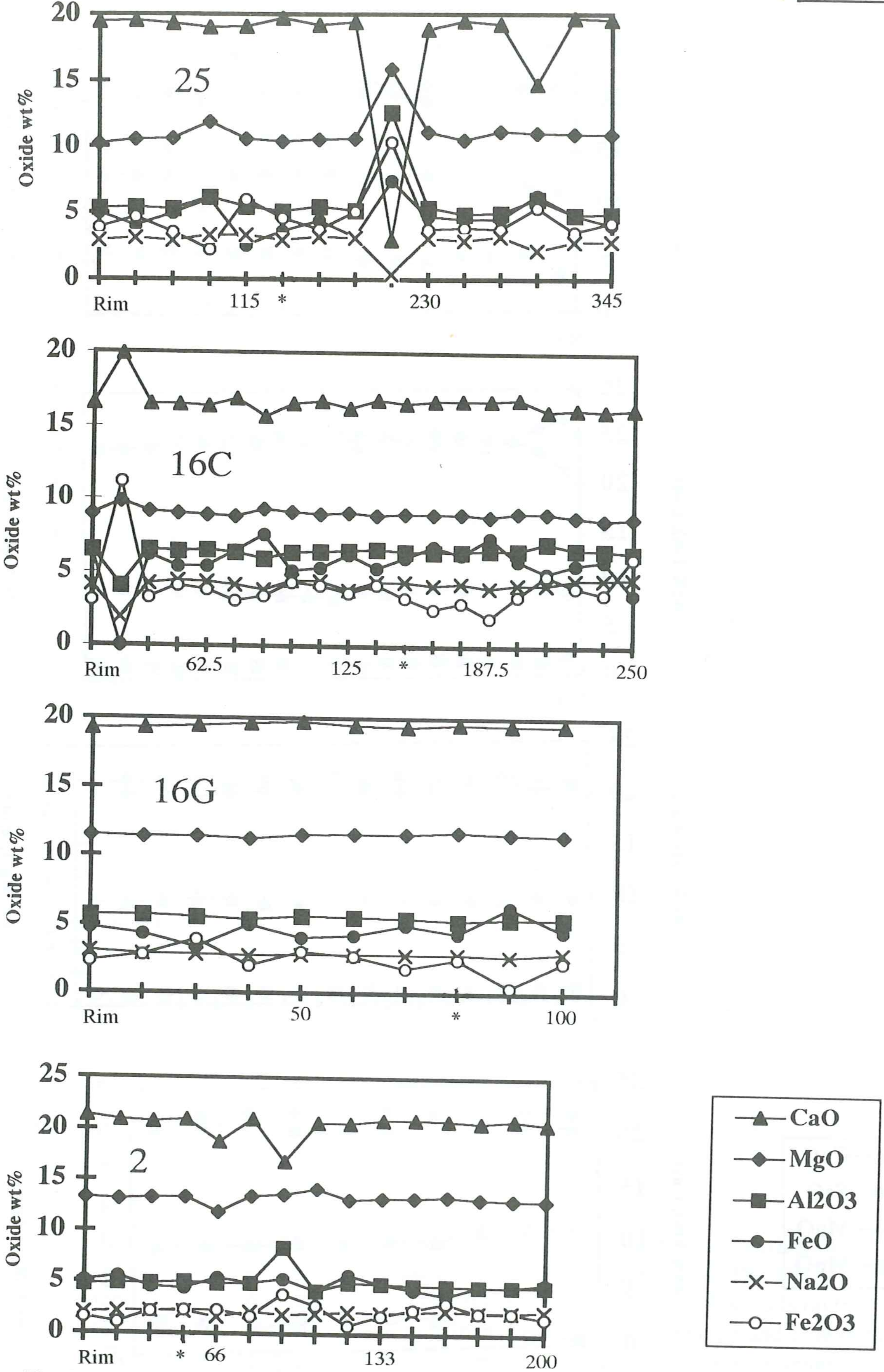


Fig.7 Compositional variation within clinopyroxenes of localities 25, 16C, 16G and 2. Distances are shown in microns (x10^{-6} m) from the garnet contact (Rim). Values for corresponding garnets are shown in Fig.8. (*) indicates the values found in Table 3

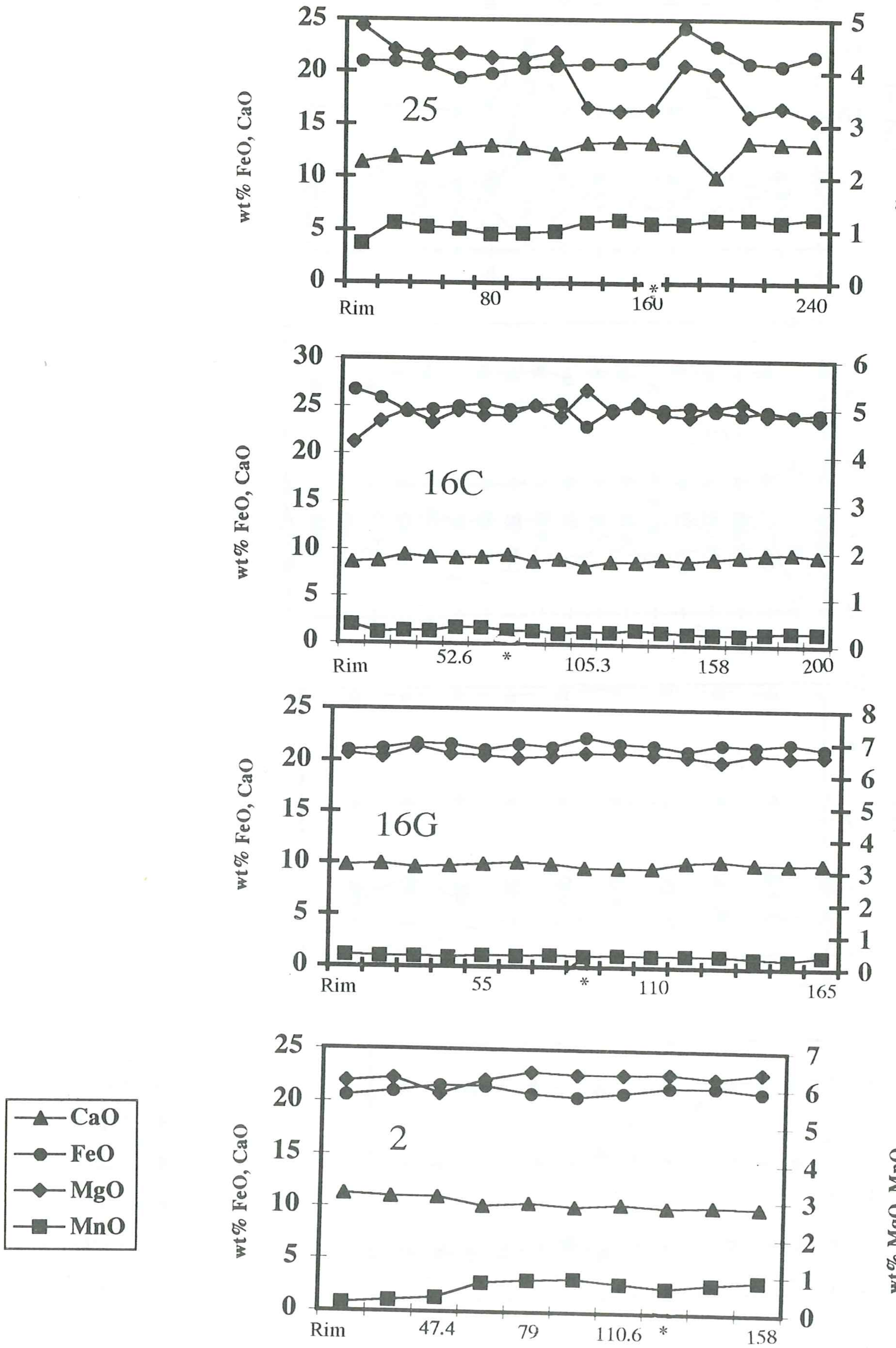


Fig.8 Compositional variation within the garnets of localities 25, 16C, 16G and 2. Distances are shown in microns (x10^{-6} m) from the contact (Rim) to the clinopyroxene (see Fig.7). (*) indicates the values found in Table 3

Table 4 Mineralogical composition of sampling localities

	2		16C		16G		25	
By stoichiometry:	Cpx	Grt	Cpx	Grt	Cpx	Grt	Cpx	Grt
Si	1.93	2.99	1.96	3.00	1.95	2.96	1.92	2.95
Al^{IV}	0.07	0.01	0.04	-	0.05	-	0.08	0.05
Ti	-	-	-	-	-	0.08	-	-
Al	0.15	1.93	0.24	1.93	0.17	1.95	0.16	1.88
Fe^{3+}	0.06	0.08	0.09	0.06	0.07	0.09	0.13	0.17
Fe^{2+}	0.13	1.38	0.19	1.65	0.13	1.38	0.12	1.29
Mn	-	0.04	-	0.02	-	0.02	-	0.06
Mg	0.67	0.73	0.50	0.59	0.64	0.75	0.58	0.50
Ca	0.83	0.83	0.66	0.74	0.77	0.82	0.78	1.09
Na	0.15	-	0.32	-	0.20	-	0.22	-
Total	3.99	7.99	4.00	7.99	3.98	8.05	3.99	7.99

End-members by stoichiometry:	Cpx	Cpx	Cpx	Cpx
Acm	0.06	0.09	0.07	0.13
Jd	0.07	0.23	0.13	0.09
Ts	0.06	0.01	0.05	0.07
Di+Hd	0.68	0.65	0.72	0.70
Fs	0.03	0.04	0.05	-

End-members by percentage:	Grt	Grt	Grt	Grt
Alm	46.31	55.00	46.46	43.87
Prp	24.50	19.67	25.25	17.01
Grs	27.85	24.67	27.61	37.07
Sps	1.34	0.67	0.67	2.04

The values of the analysed clinopyroxene data have been plotted in a classification scheme, (Essene and Fyfe, 1967), for sodic pyroxenes. In Fig.9 the Ts-, Di-, Hd- and Fs-components are included under augite. Only the pyroxene of locality 16C falls on the borderline of the true omphacite field. Pyroxenes from localities 16G, 25 and 2 lie in the field of sodic augite. These pyroxene compositions agree with those for pyroxenes found in the group B eclogites of Coleman et al. (1965)

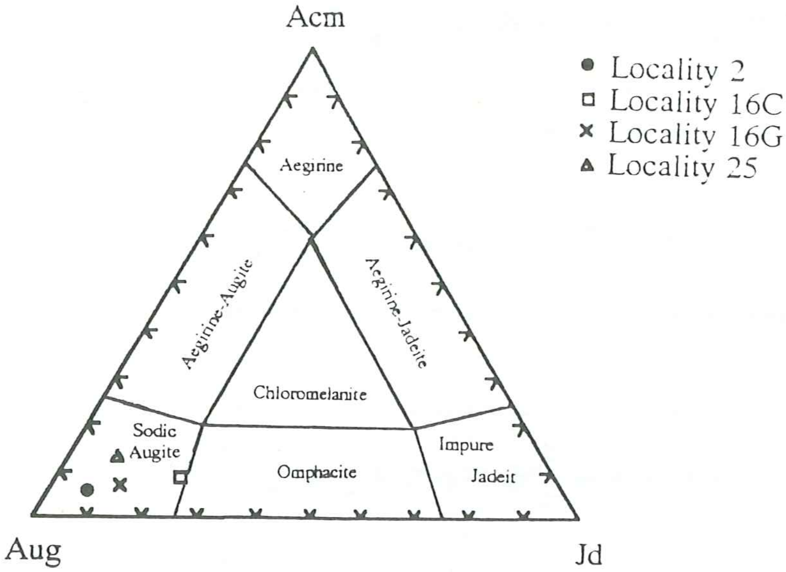


Fig.9 Clinopyroxene classification scheme after Essene and Fyfe (1967)

In the garnets, the variation in almandine/pyrope component ranges from $Alm_{55\text{-}59}$ $Prp_{20\text{-}27}$ to $Alm_{46\text{-}48}$ $Prp_{25\text{-}26}$ wheras the grossularite component ranges between 25-32 % except at locality 25 where the percentage of grossularite component is as high as 34-44 %.

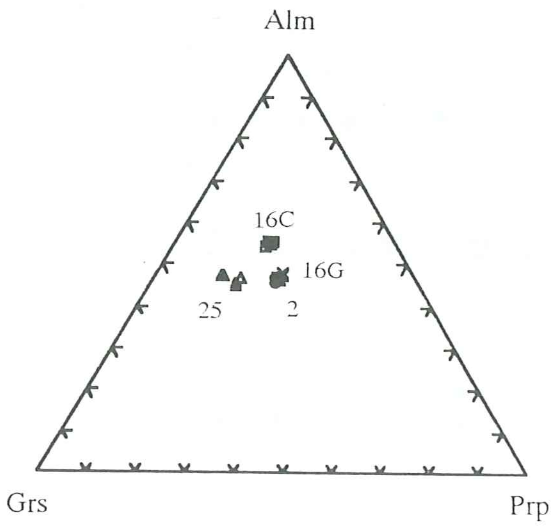


Fig.10 Composition of the garnets in the eclogites from localities 2,16 and 25, five values from each locality.

As can be seen in Table 3 and Fig.9, sample 16C has the highest sodic content, and was also considered the best preserved of the clinopyroxenes analysed. Modal analysis (Table 5) performed on samples 16C and 16G confirmed that the sodic content of the clinopyroxene is higher when alteration to amphibole is more restricted.

Table 5 Modal analysis of samples 16C and 16G.

	16C	16G
Sodic content: (oxide wt%)	4.40	2.84
Number of points:	500	500
(vol%)		
Grt	46.4	44.2
Cpx	40.8	27.8
Amp	5	16.4
Qz	3.2	6.4
Rt	4.6	3.2
Cal	-	2
Sum	100	100

5.2 Corona gabbro

The samples from locality 21 were collected on the plateau north of Richardvatnet, a few tens of metres from western margin of the igneous breccia that runs through that area (Fig.6). Sample 21 was collected a few metres away from specimens 21A and 21C, but belongs to the same locality. Specimens 21A and 21C come from a spot where the gabbro was intruded by a mafic dyke. In these last two specimens only the parts where the corona gabbro occurs have been studied.

5.2.1 Macroscopic description

In hand specimen the rock has a medium to coarse grained igneous texture. It is light coloured as it contains c. 70 % leucocratic materials. Pale green amphibole is evenly distributed and has an outer ring of black amphibole; it is normally separated from the light material by brownish red garnets which form coronas around the amphiboles. Gaps in this corona exist and some amphiboles lack coronas. The size of the amphibole, including the garnet corona, is about 2-4 mm in diameter, but amphiboles up to 8 mm in diameter exist. The shapes of these garnet/amphibole areas are rather irregular.

5.2.2 Microscopic description

The leucocratic minerals in the corona gabbro are zoisite, plagioclase (albite or oligoclase), white mica, sericite and epidote. The most common amphibole in the coronagabbro is actinolite, very occasionally with cores of relic clinopyroxene. Biotite is associated with the actinolite as well as small amounts of chlorite. Garnet is located between the areas containing leucocratic minerals and those containing amphibole, forming the coronas around the amphibole. Other minerals are hornblende, quartz, rutile, carbonate and opaques.

Zoisite needles are abundant in the corona gabbro. Sometimes larger grains of zoisite are found, unevenly distributed, close to the garnet coronas. These larger zoisites are sometimes accompanied by grains of epidote. Larger flakes of white mica and grains of quartz are evenly distributed among the zoisite needles. The plagioclase has been identified as oligoclase. In samples 21A and C sericite is added to the mineral assemblage.

The garnets are generally inclusion free, exhibiting idioblastic outlines facing the leucocratic assemblage. In sample 21 some gaps and cracks between garnets are filled with small amounts of fibrous chlorite.

In sample 21 the amphibole is made up of actinolite and bluish actinolitic hornblende. The actinolite contains many small unidentified inclusions and is often accompanied by brownish carbonaceous material. Occasional clear grains of actinolite can be seen, always being fibrous and inclusion-rich towards the edges. Towards the garnet interface the amphibole is more intact, consisting of blue green hornblende intergrown with quartz.

In sample 21A, garnets enclose biotite, amphibole and rutile. The biotite occurs as bent and deformed single flakes or associated with amphibole. Garnet enclosed trains of rutile are found scattered among the leucocratic minerals.

Photo 5 Fibrous actinolitic amphibole with preserved cores of clinopyroxene. Between the plagioclase with zoisite and the amphibole is a garnet corona (sample 21C) .

Within some of the fibrous amphibole of sample 21C, clinopyroxene cores are preserved. Biotite as well as opaques accompany the actinolite. A 0.05 mm thick rim of quartz grains is found between the amphibole and the surrounding garnet coronas. Small amounts of chlorite are unevenly distributed and associated with the actinolite. Carbonaceous material is associated with grains where actinolite and chlorite grow together.

5.3 Layered mafic body within eclogite

One eclogite association (locality 22), found in an isolated outcrop, differs from all the other rocks found in the area by exhibiting layering. Dark bands with pyroxene grains alternate with leucocratic layers. The pyroxene grains are very coarse at the bottom of the sequence and fine upwards (Photo 6). Higher in the section, the layering is highly deformed and pods of bimineralic omphacite/garnet eclogites, extensively amphibolitized, were found. The total thickness of the layered sequence is c. 15 m.

Photo 6 Layered sequence, locality 22

5.3.1 Macroscopic description

In hand specimen, the sequence starts with a very green rock where pyroxene is abundant. Moving up from the base of the layered sequence layers of pyroxene crystals of diminishing size alternate with white leucocratic layers giving the rock a banded appearance. At the top of the exposed sequence, the rock is again coloured green by the abundance of pyroxene.

5.3.2 Microscopic description

The basal part of the exposed section is an eclogite, very rich in pyroxene. Large grains of clinopyroxene, sometimes exhibiting orthopyroxene intergrowth, dominate the rock. Grains of zoisite are found between pyroxenes together with garnet. The garnets are distributed between the clinopyroxene and the zoisite as coronas. Passing upwards into the layered sequence, the amount of pyroxene diminishes but still dominates together with zoisite. A few pyroxenes have small amounts of green hornblende along their edges. Further up, a few large grains of pyroxene persist, the dominating mineral now being zoisite. Green hornblende together with grains of quartz are found among the zoisites. A few poikilitic garnets occur, with inclusions of zoisite. The light bands in the layered sequence exclusively consist of zoisite and white mica; in the darker bands, smaller grains of pyroxene are added to this assemblage. The smaller pyroxenes are poikilitic anhedral. Above the layered part, the eclogite again becomes rich in large pyroxene grains with zoisite and/or zoisite filled garnets in between them. Only small amounts of green hornblende and a few opaques are also present. Some pyroxenes exhibit clinopyroxene/orthopyroxene intergrowth textures (Photo 7). Further up the section, garnet coronas are seen between areas of zoisite and the pyroxene grains and plagioclase appears to be absent.

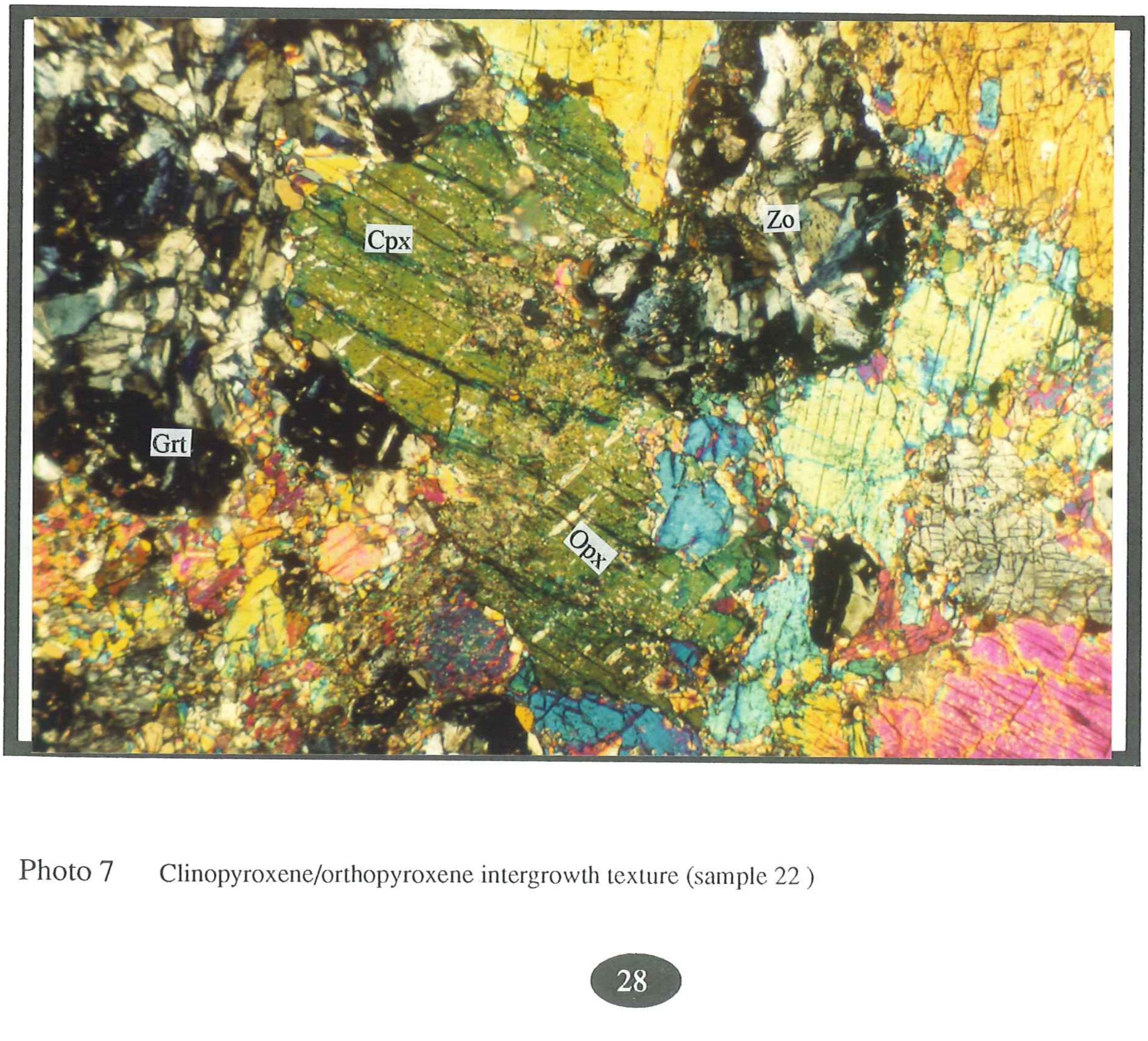


Photo 7 Clinopyroxene/orthopyroxene intergrowth texture (sample 22)

5.4 Amphibolite

Site number 28 is located on the northern slopes of Rabotdalen. It is found as an elongated lens in very deformed augen granite dated previously to 965 Ma (Peucat et al., 1989). The deformation is seen in the amphibolite as well. It is the only amphibolitic lens found in this area.

5.4.1 Macroscopic description

In hand specimen, a lineation is defined by the orientation of amphibole grains and streaks of plagioclase. Small, pale green clinopyroxene grains with rims of black amphibole are seen in some of the samples. In most of the samples though, only black hornblende is present. Garnet grains, 1-2 mm in diameter, are seen evenly distributed among the other minerals.

5.4.2 Microscopic description

The major minerals in the amphibolite are green hornblende (75-80%), garnet (5-10%) and plagioclase (5-10%). Various amounts of chlorite, epidote and rutile mantled by sphene are also present. The amphibolite is poor in quartz even though this mineral is always present. Relics of clinopyroxene are observed in better preserved specimens.

Hornblende is evenly distributed. A slight layering is defined by alternating elongated areas where either amphibole or plagioclase and quartz are more concentrated. The quartz and plagioclase often accompany the hornblende as rounded inclusions. In some samples, grains of clinopyroxene, filled with tiny, unidentified inclusions, occur with hornblende located around their edges.

The plagioclase is brownish and full of very fine grained inclusions. Elongated, tabular grains of epidote appear, in varying amounts, associated with the plagioclase rich areas. Small amounts of chlorite and/or white mica also occur together with the plagioclase/ epidote assemblage. Most of the chlorite is present as bent fibrous flakes associated with garnet, occasionally also with amphibole. Epidote is seen inside some chlorites.

The garnets, around which most of the chlorite is found, are round and rich in inclusions of rutile, sphene, epidote, quartz and plagioclase. In better preserved samples the garnets are small and fragmented and free of inclusions with only small amounts of chlorite.

Rutile and sphene are common, but unevenly distributed. The two minerals are closely associated, and sphene often seen mantling the rutile. Mostly, the amount of rutile exceeds that of sphene. When seen together with chlorite, the rutiles are mantled by sphene and the amount of sphene exceeds that of rutile. Single grains of sphene are always slightly elongated. The rutile is associated with garnet, amphibole and chlorite.

In sample 28A, the relict texture of a corona gabbro is seen (Photo 8) consisting of primary pale green clinopyroxene, fibrous amphibole, chlorite, zoisite, plagioclase, rutile, opaques, garnet and very small amounts of biotite. Large grains of fibrous, light green, amphibole sometimes have rims of yellow-brown amphibole around their edges. Many of the amphiboles have been replaced by chlorite. Very small amounts of biotite are associated with the chlorite and yellow-brown amphibole. In between the amphibole/chlorite grains are zoisite needles growing in a plagioclase groundmass. In some areas garnet coronas separating the amphibole from the plagioclase/zoisite are preserved. Rutile and opaques are common but unevenly distributed.

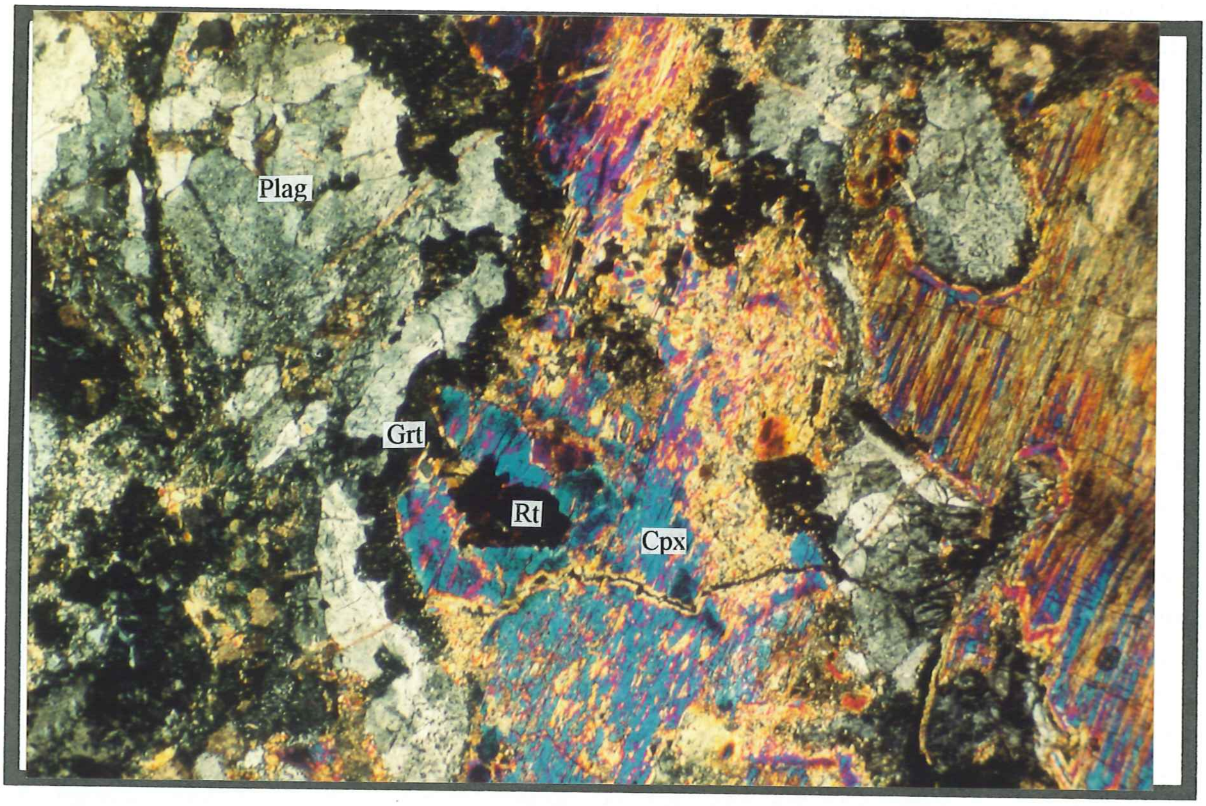


Photo 8 Relict texture in amphibolite (sample 28A)

6 CONDITIONS OF METAMORPHISM

As augite is replaced by sodic pyroxene as a result of the changed P/T-conditions, the elements calcium, magnesium and iron are released and made available for participation in other reactions. One possibility for these elements is to take part in corona forming reactions during the prograde metamorphism. In the eclogite exhibiting the layered sequence all the plagioclase has gone to zoisite. Between the zoisite and the clinopyroxene, garnets have grown in a corona like pattern. The corona gabbro of the Richarddalen Complex may be the result of prograde metamorphic reactions of high P/T character with diffusion of calcium, magnesium and iron from the pyroxene through the outwards expanding corona. At the garnet/plagioclase interface, calcium and aluminum would have been available. The sharp, idioblastic garnets facing the plagioclase indicate the direction of growth. For some reason this corona gabbro escaped eclogitisation; maybe the coronas hindered diffusion to take place and thus prevented the change to eclogite, or the elevated P/T-conditions simply did not last long enough for the change to take place.

As pressure and temperature drops, the eclogite paragenesis is replaced by minerals such as amphibole, epidote, white mica, chlorite and sphene. Omphacite breaks down to amphibole via pyroxene-plagioclase symplectite. As the conditions change, the Jd-component of the omphacite is expelled, yielding diopside pyroxene and sodic plagioclase. This secondary pyroxene is subsequently replaced by hornblende. Amphibole also forms directly from the omphacite, commencing along the edges of the clinopyroxene grain, then proceeding towards their inner parts. In combination with this, the omphacite can be attacked from within as amphibole forms along cleavages and then spreads out patchily inside the grains.

Rims of blue green hornblende are seen around some garnets in the retrograded eclogites. Rutile is replaced by sphene.

As the retrograde metamorphism proceeded, the secondary hornblende gave way to chlorite, the assemblage chlorite/hornblende being diagnostic for low amphibolite facies. As chlorite forms at the expense of hornblende, calcium is liberated as it has no place in chlorite. The excess calcium allows epidote to form in association with chlorite. The abundance of secondary epidote together with chlorite in some of the samples indicate that retrograde reactions, in some areas, took place under greenschist facies conditions.

Retrograde reactions affecting the corona gabbro are alteration of primary clinopyroxene to pale green actinolitic amphibole followed by its replacement by chlorite. The chlorite replacing the actinolite is accompanied by small amounts of biotite and opaques as well as some brownish carbonaceous material and quartz. Rocks of basic composition that undergo low temperature metamorphism commonly produce actinolite associated with chlorite and/or epidote by reactions, involving chlorite, calcite and quartz, under greenschist facies conditions. Actinolite is also a common product of retrograde metamorphism of basic rocks. Pyroxenes are known to give way to secondary fibrous actinolitic amphibole, a process known as uralitization. Eventually the pyroxene may be totally pseudomorphosed by chlorite. The uralitization reactions are generated by hydrothermal solutions which may be associated with late-stage crystallization of igneous rocks or with either regional, contact or metasomatic metamorphism.

Alteration of plagioclase, as is seen in the corona gabbro, is caused by circulating fluids acting on the rock allowing fine grained zoisite, epidote, sericite and oligiclase to form. The same is true for the formation of sericite from zoisite in the layered sequence

Relict gabbroic textures found in the Rabotdalen amphibolite indicate the protolith. Gee (1966a) found eclogitic rocks in amphibolite sheaths at this locality, but this time no eclogite was found. These observations give support to the idea that the gabbro was first eclogitized; thereafter the eclogites were retrograded in amphibolite facies.

6.1 P-T-estimation

Geobarometry of eclogites is difficult due to the general lack of suitable mineralogy in these rocks. Very high pressure indicators (e.g. coesite and diamonds) have only been found in a few eclogite associations. The absence of plagioclase as well as the presence of garnet and omphacite allows for an estimation of the lower pressure limit of the rock. Thermodynamic considerations based on experiments and investigations of eclogites around the world has established the minimum pressures needed for eclogite formation to be around 12-13 kbar (Fig.11, from Miyashiro, 1994).

In calculating the temperature using the garnet/clinopyroxene exchange thermometer of Ellis & Green (1979), modified by Krogh (1988, equation 1), several values for pressure, ranging from 12 to 18 kbar, were put into the formula in order to see the significance of pressure.

$$T(K) = [-6173(X{Ca}^{Gn})^2 + 6731X{Ca}^{Gn} + 1879 + 10P(\text{kbar})] / (\ln K_D + 1.393) \quad (1)$$

$$K_D = (Fe^{2+} / Mg)^{Gn} / (Fe^{2+} / Mg)^{Cpx} \quad (2)$$

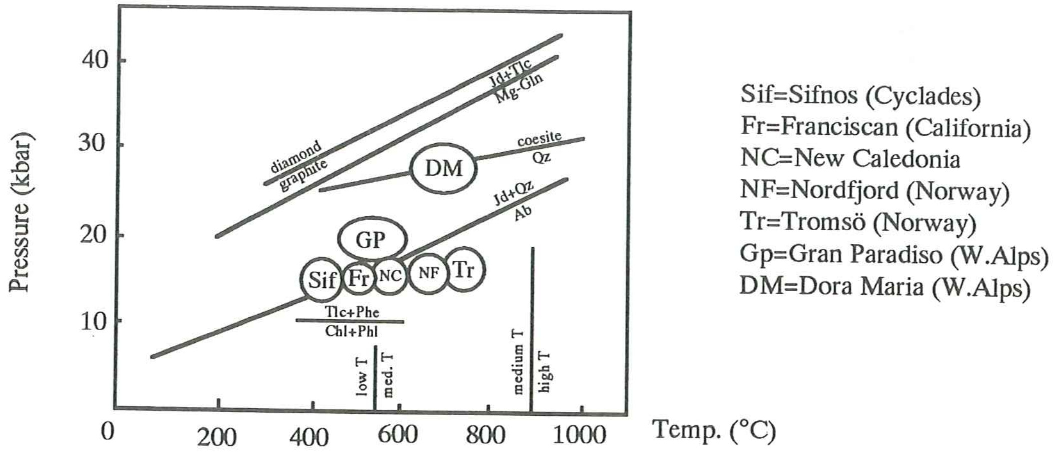


Fig.11 P/T-diagram. Also shown is Carswell's (1990) temp. division of the eclogite facies

The distribution coefficient, K_D, between garnet and clinopyroxene is a function of pressure and temperature. When calculating the temperature, care must be taken in order to find the correct ratio of Fe^{2+}/Fe^{3+} of the minerals. In the microprobe analyses, all iron is put as Fe^{2+} ; thus a correction for Fe^{3+} must be made before the geothermometer can be used. In this paper the Fe^{2+}/Fe^{3+} was estimated according to the procedure described by Droop (1987), before the revised thermometer of Krogh (1988) (equation 1), was used.

Calculation of the temperature was made using data from all samples. The results of the calculations are listed in Table 6.

Table 6 P/T-conditions of the Richarddalen Complex eclogites

	$K_D=(Fe^{2+}/Mg)^{Grt}/(Fe^{2+}/Mg)^{Cpx}$	Temp. at 12 kbar (°C)	Temp. at 14 kbar (°C)	Temp. at 16 kbar (°C)	Temp. at 18 kbar (°C)
2	7.3-11.5	612-740	617-746	622-752	627-758
16C	6.1-9.3	644-765	650-771	655-777	661-784
16G	7.3-10.7	649-735	655-741	660-747	666-753
25	8.8-15.1	591-783	595-789	600-794	605-80

As seen in Table 6, the temperature estimate does not vary much with changing pressure. The temperature difference at lowest pressure versus highest pressure is rather constant at 15°C. The samples from locality 16 exhibit least variation in K_D and hence also in temperature. Locality 2 has a slightly higher variation whereas K_D at locality 25 is very variable. In an attempt to get more precise values of the temperature, the anomalously highest and lowest values were rejected, these being analyses that hit either cracks or inclusions and hence are unsuitable for P/T-estimation. In addition to this, the distribution of the temperature was determined using histograms. In Fig.12 the distribution of the temperature at 12 and 18 kbar of sample 16C is shown. Table 7 shows the revised temperature values of Table 6.

Table 7 Revised temperature values

	Temp. at 12 kbar	Temp. at 14 kbar	Temp. at 16 kbar	Temp. at 18 kbar
2	693-740	699-746	704-752	710-758
16C	645-680	650-686	656-692	661-700
16G	651-712	657-717	662-723	668-729
25	590-620	595-624	600-629	605-634

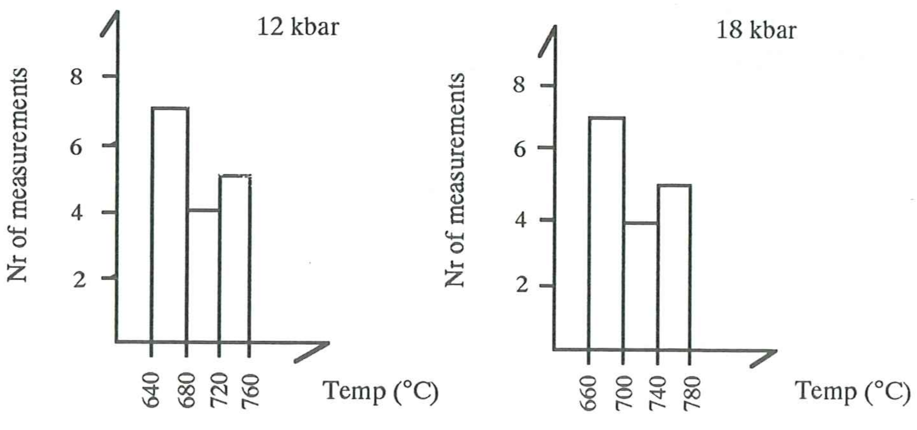


Fig.12 Histograms of temperature distribution in sample 16C

As locality 16 has been shown to be the best preserved, these will be the values used in the eclogite classification scheme, Table 8. The investigated eclogites of the Richarddalen Complex correspond to the medium temperature type in the proposed scheme of Carswell (1990), based on the ideas of Banno (1970), i.e. their likely origin was in tectonically thickened crust.

Table 8 Eclogite classification schemes

Eskola (1921)	**Coleman et al (1965)**	**Carswell (1990)**	
Geological occurrences	Mineral compositions	Equil. temp.;	likely origin
Type 1 Xenoliths in kimberlites etc.	*Group A* Garnet >55 mole% pyrope	High temp.;	Upper mantle
		900 °C	
Type 2 Layers and lenses in alpine-type peridotite bodies		Medium temp.;	
Type 3 Lenses in migmatitic gneiss complexes	*Group B* Garnet 30-55 mole% pyrope		Tectonically thickened continental crust
		550 °C	
Type 4 Blocks in blueschist facies terranes	*Group C* Garnet <30 mole% pyrope	Low temp.;	Subducted oceanic crust and arc sed.

6.2 Estimation of errors in the microprobe data

A microprobe is not able to distinguish between Fe^{3+} and Fe^{2+}; hence all iron is registered as FeO. In order to come to terms with the proper Fe^{2+}/Fe^{3+} relationship in the analysed minerals, the amount of ferric iron is calculated using the stoichiometric data obtained by the microbrobe analysis. Thus the accuracy of the Fe^{3+}-calculation is dependent on the quality of the microprobe analysis. The error when using a microprobe can be estimated to be about 1%. This error will increase as the already incorrect values are added together and then used, in relation to the ideal case, in the Fe^{3+} -calculation. If the Fe^{2+}/Fe^{3+} ratio in the mineral is high to begin with, the new ratio will not have a great effect on the temperature values. If the analytical error of one of the major components is high it will have big effect on the final Fe^{3+} value, and hence also the temperature value, as the value of this major component will be hidden among the other components and make the base for the calculations.

Even though the samples used for the microprobe analyses were carefully selected to provide the best results, the fact remains that all minerals were more or less fractured. The diagrams of locality 25 in Figs.7 & 8 are clearly not as homogeneous as the other samples. Local variations in the diagram come from cracks and inclusions resulting in anomalous values. The negative effect on Fe^{3+} -calculation, K_D and temperature estimation is evident in Tables 6 and 7.

The garnet-clinopyroxene mineral pair of locality 2 gives as good chemistry data as those of the other localities. However, because of grainsize differences and abundance of cracks between the garnet and the clinopyroxene, only a few analytical points over a short distance were made in the pyroxene in relation to the garnet. This made the correlation of the equilibrium chemistries of the two minerals difficult. Because of this, the calculated temperature-values of locality 2 must be considered a bit uncertain.

In order to obtain a correct crystallization temperature using the Fe-Mg exchange reaction thermometer, values corresponding to the original true equilibrium composition are to be used. The eclogites of the Richarddalen Complex have all, to some extent, been affected by retrograde alteration reactions. Some eclogites have been more spared than others, and care was taken to select these for further examination. The composition of the clinopyroxenes in the samples plot in the field of sodic augite in Fig.9, with the exception of sample 16C which is located on the borderline between sodic augite and omphacite. As microscopic examination, microprobe analysis and point counting indicate that this is the best preserved eclogite sample, the temperature (660°±20°C) derived from sample 16C is considered to have the best accuracy.

7. PROTOLITH OF ECLOGITES

In the best preserved eclogite samples, the minerals are almost exclusively made up of omphacite and garnet, with rutile and quartz as accessory minerals. This mineral assemblage is similar to that produced in experiments (Green and Ringwood, 1967) using basic protoliths. Additional phases in eclogites reflect variations in bulk chemistry in the protolith and/or P/T-conditions of metamorphism. In the investigated eclogites of the Richarddalen Complex, additional phases found include zoisite, epidote, white mica, sphene, amphibole, chlorite and calcite. In those samples where zoisite occurs, the mineral may be considered as primary together with garnet, omphacite, rutile and quartz. These minerals can be expected to be found in common eclogites derived from mafic rocks of common gabbro compositions (Carswell, 1990)

The formation of eclogite from pre-existing basic igneous rocks under high P/T-conditions can be expressed by the following equations (Alderman, 1936):

From dolerite:

$$\underset{\text{Augite}}{Ca(Mg,Fe^{2+},Al)(SiAl)_2O_6} + \underset{\text{Plag}}{NaCa(AlSi)_4O_8} + \underset{\text{Ilm}}{FeTiO_3} \longrightarrow$$

$$\underset{\text{Omp}}{CaNa(Mg,Al,Fe^{2+},Fe^{3+})Si_2O_6} + \underset{\text{Garnet}}{(Ca,Mg,Fe^{2+})_3Al_2Si_3O_{12}} + \underset{\text{Qz}}{SiO_2} + \underset{\text{Rt}}{TiO_2} \quad (3)$$

From olivine gabbro:

$$\underset{\text{Lab}}{NaCa\ (AlSi)_4O_8} + \underset{\text{Ol}}{(Mg,Fe^{2+})SiO_4} \longrightarrow$$

$$\underset{\text{Omp}}{CaNa(Mg,Al,Fe^{2+},Fe^{3+})Si_2O_6} + \underset{\text{Garnet}}{(Ca,Mg,Fe^{2+})_3Al_2Si_3O_{12}} + \underset{\text{Qz}}{SiO_2} \quad (4)$$

At the high pressures required for eclogite formation, the access to fluids is probably limited. However, reaction rates in the solid state would be too slow for completion of the eclogite formation; therefore some kind of fluid phase, acting as a catalyst, is likely to be present in order to speed up reaction rates, but playing a minor role during the actual developement of the main anhydrous eclogite minerals.

According to reaction (3), augite is replaced by omphacite by the introduction of sodium and additional aluminum (from plagioclase) in the clinopyroxene structure. Plagioclase is replaced by garnet by processes involving activation of iron and magnesium as well as calcium, aluminum and silica . Titanium does not fit into either of these two minerals, but is left as an accessory mineral in the form of rutile together with remaining quartz.

The formation of additional phases is dependent on the bulk composition of the protolith as is the composition of the primary eclogite minerals. If there is a sodium shortage , the amount of Jd-component in the omphacite will be restricted. Presence of white mica as a primary mineral only occurs in rocks showing aluminum excess and which are enriched in either sodium or potassium. Epidote is retrograde and forms initially as zoisite, then clinozoisite and later epidote. Estimation of rock chemistry based on mode (Blackburn and Dennen, 1988) of sample 16C (Table 9) gives an approximate SiO_2-content of 43 %. Gee (1966b) published some data on the chemistry of the Richardvatnet eclogites also based on modes; a comparison between the data of this investigation and those of Gee (Table 9) reveals that the whole rock chemistries are similar. As these chemical data are only estimations based on optical investigation of the vol% of each mineral present, these values can only be used as guidelines in evaluating the eclogite/protolith relationship.

Table 9 Modal analyses of sample 16C and estimated rock chemistry based on the mode (**A**). Modal analyses of Richardvatnet eclogites (Gee, 1966b) and estimated composition based on mode (**B**). The specific gravity (D) of the minerals have been taken from Deer et al. (1992), yielding the whole rock specific gravity, $D_{wh.r}$ = 3.51 g/cm³. The average mineral composition for hornblende is taken from Deer et al. (1963), values for garnet and clinopyroxene are taken from Table 3.

		MODE			WHOLE ROCK CHEMISTRY	
		A	**B**		**A**	**B**
Nr of points:		500	1000			
	D (g/cm³)	(vol%)	(vol%)		(wt%)	(wt%)
Cpx	3.20	40.8	30.1	SiO_2	43.6	42
Garnet	3.80	46.4	55.3	TiO_2	5.8	2.3
Hornblende	3.15	5.0	6.6	Al_2O_3	13.3	14.9
Quartz	2.65	3.2	0.1	FeO	15.5	16.5
Rutile	4.30	4.6	1.6	Fe_2O_3	2.0	3.1
Sphene		-	3.4	MnO	0.1	0.2
Epidote		-	2.6	MgO	6.5	6.4
Opaques		-	0.1	CaO	11.1	13.7
Carbonate		-	0.2	Na_2O	1.7	0.8
Tot		100	100		99.1	100

In a classification diagram, based on silica content, for igneous rocks the estimated bulk chemistry (43 % SiO_2) of the investigated eclogites would fall in the field of ultrabasic rocks (peridotite). Such rocks were reported to occur locally in northern Rabotdalen by Gee (1966a). However, they are rare and most of the rocks (meta gabbros & dolerites) showing transitions to eclogite are mafic in composition.

In several respects the Richarddalen eclogites are compatible with the eclogites of Norway's western Gneiss Region (WGR). In comparing the estimated bulk composition of the Richarddalen eclogites with the average chemical compositions of eclogites of the WGR (Table 10) a variation in some elements is seen. The differences are greatest for the elements Na, Mg, Al and Fe; this is particularly evident when comparing the clinopyroxene and garnet mineral chemistries separately. The differences are quite normal as these are the major elements of the minerals taking part in the retrograde alteration processes. The difference in SiO_2 -content is not very big. In the SiO_2 classification diagram, the Midöy eclogite has a protolith composition corresponding to a basic rock verging to ultrabasic. The type of eclogites found in the Midöy-area have been recognised in many places elsewhere in the WGR (Griffin and Carswell, 1985). The protoliths of the Midöy-eclogites are doleritic dykes that intruded into the igneous protolith of an augen orthogneiss complex.

The eclogites of the Richarddalen Complex and those of the WGR of Norway show many similarities. For the eclogites in the Midöy-area the following sequence of events led to their formation (Griffin and Carswell, 1985):

- Intrusion of the igneous protolith of the augen gneiss
- Intrusion of dolerite dykes
- Metamorphism (T = 750°C, P = 17-21 kbar) with formation of eclogites, deformation
- Further deformation, retrograde alterations in amphibolite facies

Table 10 Comparison between one of the Richardvatnet eclogites (A) and eclogites of Midöy-area, WGR (B) (In (B) analyses performed by energy-dispersed microprobe techniques (LINK- system, ZAF-4 reduction prgm, ARL-EMX probe. XRF analyses for bulk comp. by Carswell).

	A			B				
	Cpx	Grt	Bulk	Cpx (core)	Cpx (rim)	Grt (core)	Grt (rim)	Bulk
wt%								
SiO_2	51.97	38.10	43.13	51.0	50.9	40.0	39.2	46.65
TiO_2	0.44	0.09	6.28	0.38	0.46	-	-	2.45
Al_2O_3	4.72	20.89	13.19	10.7	5.1	23.0	22.8	12.16
FeO	5.54	24.32	15.42	5.9	7.4	19.6	21.2	9.85
Fe_2O_3	4.54	1.77	1.93	1.9	1.3	-	-	0.45
MnO	0.02	0.33	0.14	0.10	0.15	0.30	0.30	0.18
MgO	10.89	4.27	6.38	9.3	11.0	7.6	6.6	9.81
CaO	19.57	10.53	11.05	17.3	20.1	10.9	10.7	12.98
Na_20	2.82	0	1.68	3.6	1.8	-	-	2.65
K_2O	0.04	0	0.03	-	-	-	-	0.08
P_2O_5			-					0.80
S			-					0.44
H_20^+			0.07					0.45
Sum	100.6	100.3	99.31	100.2	98.22	101.4	100.8	99.03

Radiometric data indicate that the igneous gneiss protolith intruded about 1500 Ma ago and that eclogite formation, deformation and retrograde alterations took place during the Caledonian orogeny, 450-380 Ma ago. The eclogites formed as continental crust was pressed down during Caledonian continent-continent collision. The mineralogy, petrology and estimated P/T-conditions of the eclogites in the Richarddalen Complex as well as their geological setting are similar to the eclogites of WGR. Like the latter, the Richarddalen eclogites are of medium temperature type, formed in tectonically thickened continental crust.

8. DISCUSSION

In the Biskayerhuken area, not all the mafic-ultramafic rocks in the Richarddalen Complex altered into eclogites during the regional high pressure event. The result of the P/T-estimation, made on samples from different localities, indicate that the metamorphic grade in the investigated area was quite uniform. All typical garnet/omphacite eclogites were found in areas that have been subject to strong deformational activity. The discovery of the layered sequence within the Richarddalen Complex, and its association with typical eclogites in deformed parts within the same body, implies that formation of bimineralic garnet/omphacite eclogites has been favored in areas where high pressure metamorphism has been combined with deformation.

No traces of a high P/T-event have been found in the Biskayerfonna Group,comparable with that in the underlying Richarddalen Complex. The eclogite facies metamorphism of the latter is dated to c. 620 Ma (U/Pb-zircon method). A late Caledonian amphibolite facies metamorphic event has been registered by amphiboles of the Biskayerfonna Group, but is not seen in the amphiboles of the underlying Richarddalen Complex. $^{40}Ar/^{39}Ar$ isotope ages of the Biskayerfonna amphibole lies between 437 and 429 Ma. The ages derieved from the Richarddalen Complex are older; 500 and 542 Ma (Dallmeyer et al., 1990). Rb-Sr ages of muscovite and biotite from both the Richarddalen Complex and Biskayerfonna Group coincide at 430 and 410 Ma, representing cooling following the late Caledonian metamorphic event. As the contact between these two units is tectonic, the emplacement possibly occurred during or shortly after the initial phase of this late Caledonian event.

Svalbard's Terranes all exhibit contrasting geological histories. The high pressure metamorphic event (620 Ma) and subsequent amphibolitization (500-540 Ma) recorded in the Richarddalen Complex occurred simultaneously with deposition of the latest Proterozoic and Cambro-Ordovician platform successions in the Eastern Terrane. It seems unlikely that such stable platform conditions should prevail in the east at the same time as a high pressure event, strong enough for eclogite formation, was occurring in the northwest. It can therefore be concluded that the Northwestern and the Eastern Caledonian terranes cannot have been as closely related then as they are now.

Characteristic features of western Spitsbergen Caledonides have been recognised on northern Ellesmere Island, situated northeast of Greenland. The Ordovician blueschist-eclogite complex found in the Southwestern Terrane can be correlated with a pre-upper Ordovician island-arc sequence located on northernmost Ellesmere Island (Trettin, 1987). Ohta et al. (1989) suggested, on the basis of ideas of Trettin et al. (1982), that the island-arc sequence of Ellesmere Island formed as a result of the collision of a small continental plate, now represented in the Biskayerhalvöya lithologies, to the north of Ellesmere Island. As oceanic crust was subducted, the blueschist-eclogite complex now visible in Svalbard's Southwestern Terrane, was formed. Ohta suggested that the eclogites of the Richarddalen Complex on Biskayerhalvöya could have formed in an initial stage of this continent collision (Ohta et al., 1989). The platform successions in the Eastern Terrane of Svalbard have been found to be similar to successions on East Greenland (Harland and Wright, 1979). The Caledonian terranes of Svalbard are separated by N-trending transcurrent faults and it is therefore thought that they came together in Silurian times, possibly as a result of the collision further south between Baltica and Laurentia (Gee and Page, 1994).

9 CONCLUSIONS

* The eclogites of the Richarddalen Complex on Biskayerhalvöya were formed in a continental collision setting at temperatures of c.650-700 °C and pressures ranging from 12 to 18 kbars.

* The protoliths of the eclogites were gabbros and dolerites (in one case a layered gabbro). One corona gabbro has an age of c. 955 Ma (U/Pb-zircon method).

* The eclogites have yielded an age of c. 620 Ma (U/Pb-zircon method). Amphibolite facies metamorphism of the Richarddalen Complex resulted in extensive amphibolitization of the eclogites at 500-540 Ma, perhaps somewhat earlier.

* Caledonian deformation and accompanying metamorphism (c. 430 Ma) in amphibolite facies resulted in the emplacement of the Biskayerfonna Group on the Richarddalen Complex. Retrograde reactions took place well into greenschist facies.

* The high P/T metamorphism that resulted in the eclogite formation was not pervasive; some mafic rocks escaped eclogitization. All examined rocks that escaped eclogitization, but have the right composition to become eclogites, show little penetrative deformation. All eclogite localities were found within very deformed host rocks, their connecting margins being extensively sheared. The reason why some rocks escaped eclogitization may be because of a shortage of fluids needed to speed up the reactions; fluid penetration was promoted by intense deformation.

* The corona gabbros, after formation of the corona, have been affected by the circulation of fluids resulting in extensive alteration of plagioclase. The layered mafic sequence has also been affected by fluids at a later stage.

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