EXAMENSARBETE I GEOLOGI VID LUNDS UNIVERSITET

Mineralogi och petrologi

Structures and PT determination of the Caledonian metamorphism of the lower part of the Planetfjella Group in the area around Mosseldalen, northern Ny Friesland, Svalbard

Magnus Friberg

Lund 1994 Examensarbete, 20 p Nr 59
Geologiska Institutionen, Lunds Universitet

Errata list to Magnus Fribergs Master thesis, Structures and PT determination of the Caledonian metamorphism of the lowerpart of the Planetfjella Group in the area around Mosseldalen, northern Ny Friesland, Svalbard (1994).

1. Abstract, 9th line: Inteprentated should be interprented.
2. Abstract, 24th line: Adeqate should be adequate.
3. Contents: Pages should be swapped.
4. Page 4, in the text below Fig3: Gee in press should be Gee and Page in press.
5. Page 19: To the text below Fig 10 the following should be added; " The picture is taken in an optical microscope in crossed polars and the area is c. 3×5 mm."
6. Page 20: To the text below Fig 11, " The picture is a backscatter image from an an electrone microscope and the area is 2×3 mm."
7. Page 23 Table 3: "From Fig 11" should be "From Fig 20" and

F92-27

Garnet	Si	Al	Ti	Mg	Fe	Mn	Ca	Xal	Xpy	Xgr	Xsp	Mg/Mg+Fe
Rim	3.05	2.04	0.00	0.36	2.16	0.05	0.24	0.77	0.13	0.09	0.02	0.86
Transient	3.00	2.02	0.00	0.27	2.25	0.05	0.41	0.76	0.09	0.14	0.02	0.89
Core	2.99	1.98	0.01	0.16	2.13	0.10	0.65	0.70	0.05	0.21	0.03	0.93

Should be

F92-27

Garnet	Si	Al	Ti	Mg	Fe	Mn	Ca	Xal	Xpy	Xgr	Xsp	Mg/Mg+Fe
Rim	3.05	2.04	0.00	0.36	2.16	0.05	0.24	0.77	0.13	0.09	0.02	0.14
Outer core	3.00	2.02	0.00	0.27	2.25	0.05	0.41	0.76	0.09	0.14	0.02	0.11
Inner core	3.01	2.01	0.00	0.15	2.10	0.09	0.63	0.71	0.05	0.21	0.03	0.07

and "From Fig 15" should be "From Fig 18".

8. Page 26, Fig 18: To the text the following should be added; " The pictures are backscatter images and the area in the right picture is c. 0.2×0.2mm"
9. Page 29, Fig 20: To the text the following should be added; " The picture is a backscatter image and the area is c. 0.2×0.2mm"

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Abstract

The archipelago of Svalbard is a key area for understanding the North Atlantic Caledonides. The pre-Devonian rocks of Svalbard are an assemblage of different terranes, probably juxtaposed by transpression during the Caledonidian orogenesis. Svalbard´s Eastern Terrane consists of a thick (c. 18 km) succession, of Paleoproterozoic to Ordovician age, referred to as the Hecla Hoek sequence, and is divided into three parts; Lower, Middle and Upper.

Within the upper part of the Lower Hecla Hoek lies the Planetfjella Group. It is intepretated to be sequence of marine sediments, including turbidites. In northern Ny Friesland, in the area of Mosseldalen, the contacts between the Planetfjella Group and the underlying Harkerbreen and overlying Veteranen G roups are tectonic. The importance of these faults has been disputed.

The pressure and temperature of metemorphism of impure pelites from near the base of the Planetfjella Group, have been calculated to 575-700°C and 8-11kbar, using the Hodges and Spear (1982) garnet-biotite thermometer and the Hodges and Crowley (1985) geobarometer. These results are supported by petrographic studies.

The Planetfjella Group (c. 4km thick) has been described to be overlain by c. 8 km of younger strata of Neoproterozoic and Early Paleozoic age. At the time of metamorphism (c. 420 Ma) the analysed specimens should therefore have been at a maximum of c. 12km depth. The P-T data presented here indicate that this succession is not adeqate to account for the metamorphism; about another 10km are needed.

The rocks overlying the Planetfjella Group in the northern Ny Friesland, are not metamorphosed above lowermost greenschist facies, which corresponds to a stratigraphic overburden that cannot have exceeded 15km. This implies that at least 5km is missing between the base of the Planetfjella Group and the overlying Veteranen Group. The thinning is thought to be partly concentrated to a 100 m wide zone at the top of the Planetfjella Group, but also to be distributed within the latter.

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1 Introduction

Presented here is a study of the Planetfjella Group of the Hecla Hoek Succession in northern Ny Friesland, Svalbard (79° 50' N and 16° 30' E). The Planetfjella Group is a c. 4 km thick sequence of low to medium grade, largely metasedimentary rocks.

The work focuses on the lower part of the group, the contact relationships to the underlying rocks and the pressure and temperature of Caledonian metamorphism. This investigation is an attempt to establish the relationships, tectonic or sedimentary, between the Planetfjella Group and overlying and underlying Hecla Hoek rocks.

An area southeast of Mosseldalen has been remapped and samples collected from Planetfjella rocks both south and north of Mosseldalen for thermobarometric studies.

1.1 Geological setting

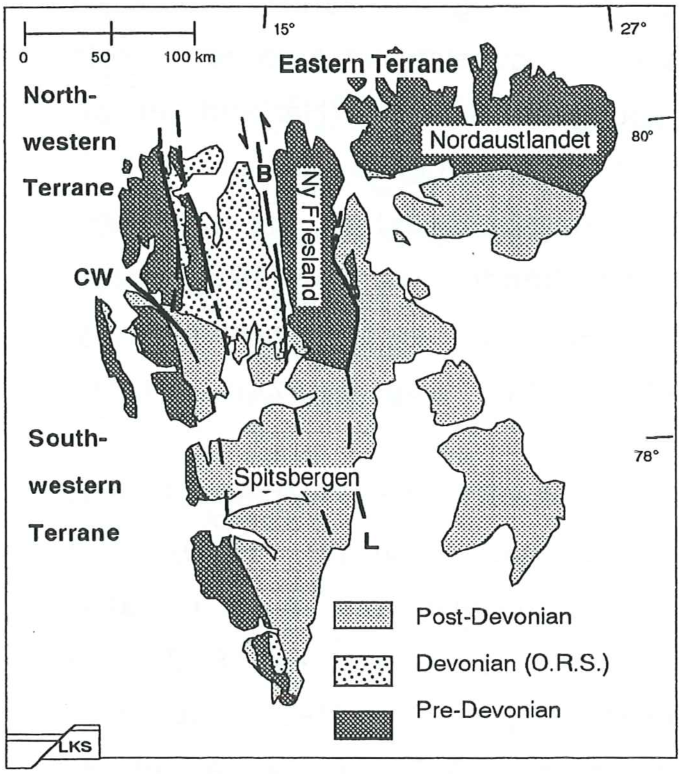

Fig 1.
Svalbards Caledonian terranes (from Gee, et al. 1991)
CW Central Western Faultzone
B Billefjorden Faultzone
L Lomfjorden Fault

1.1.1 Svalbard

The bedrock of the Svalbard archipelago is composed of Caledonian and older rocks, affected by Early to Mid Paleozoic orogeny and overlain by Devonian Old Red Sandstones and younger sequences (Fig. 1). The pre-Devonian rocks of Svalbard form three tectonic terranes separated by large strike-slip fault zones (Harland, 1985; Ohta, et al. 1989). These terranes have been named: Eastern, Central and Western (Harland, 1985). Most metamorphic ages of the pre-Devonian rocks range from 450 Ma to 350 Ma (Harland, 1985). However, in all three terranes there is some isotope evidence of pre-Caledonian metamorphism and/or igneous activity.

The largest of the major faults, separating the provinces, is the Billefjorden Fault zone (BF). It separates the Precambrian to Ordovician Hecla Hoek rocks of Ny Friesland from the Devonian rocks of Andréeland. The BF runs along Widjefjorden; it is thought by some authors to have a displacement of more than 1000 km and to be largely of Late Devonian age (Harland, 1971; Harland, et al. 1974). Others dispute the large displacement (Birkenmayer, 1981; Lamar, et al. 1986).

Harland and Wright (1979) mention another major fault, the Central Western Fault zone (CW). This fault is not as distinct as the BF and is influenced by Tertiary thrusting. It separates the Southwestern from the Northwestern terrane and is considered to be Devonian in age.

The Southwestern terrane is located along the central coast of Spitsbergen and Prins Karls Forland. It consists of Neoproterozoic and Early Paleozoic rocks as young as Silurian (Harland, et al. 1979). Early Ordovician blueschists and eclogites are present in this province (Ohta, et al. 1989). In southwestern areas around Hornsund, Birkenmayer (1981) and Craddock et. al. (1985) have described a folded, Mesoproterozoic volcano-sedimentary succession, unconformably overlain by Neoproterozoic strata, including Vendian tillites.

The Northwestern Terrane is largely covered by Devonian Old Red Sandstones and younger rocks (Harland & Wright, 1979). The Caledonian rocks are exposed in the northwestern area. Locally, they reach eclogite facies (Gee & Hjelle, 1966; Gee, 1972) The rocks of the Northwestern Terrane are partly of Mesoproterozoic age, with granite and gabbro dated to c. 960 Ma (Peucat, et al. 1989). They have yielded both Caledonian and latest Proterozoic ages of metamorphism (Peucat, et al. 1989).

The Eastern Terrane is composed of the Precambrian to Ordovician rocks of Ny Friesland and Nordaustlandet (Table 1 and Fig 2). The upper units of Neoproterozoic and Early Paleozoic age, have been correlated with successions of the same age in East Greenland (Harland & Wright, 1979). The general structure of this province is dominated by a major synclinorium in Hinlopenstretet, flanked to the east and west by major antiforms (Fig 2 and 3).

Table 1. Stratigraphy of the pre-Devonian rocks of Ny Frisland (Harland, et al. 1992 and Gee, et al. 1994).

HINLOPENSTRETET SUPERGROUP		Oslobreen Group Ordovician Carbonates (c. 1100 m)	UPPER HECLA HOEK
		Polarbreen Group Carbonates, shales and Tillites (c. 700m)	
		unconformity	
LOMFJORDEN SUPERGROUP		Akademikerbreen Group Dolomite and limestone (c. 2000 m)	MIDDLE HECLA HOEK
		Veteranen Group Sandstone and subord. shales (c. 3800 m,)	
		major fault ?	
STUBENDORFFBREEN SUPERGROUP		Planetfjella = Mossel Group Phyllites, schists, psammites and subord. marbles (c. 4 km)	LOWER HECLA HOEK
		major fault ?	
	ATOMFJELLA COMPLEX	Harkerbreen Group quartzite, metaarkos and amphibolites, 1750 Ma granit e(Bangenhuk) and dolomite (3.5-4.0 km)	
		thrust	
		Finnlandsveggen Group Calcerous schists, pelites and psammites (Smutsbreen)	
		unconformity ?	
		Metaarkoses, granites, migmatites and amphibolites (Eskolabreen)	

1.1.2 Caledonidian rocks of Ny Friesland

In Ny Friesland, low grade Lower Paleozoic and Neoproterozoic strata, largely quartzites, carbonates, shales and greywackes, in eastern areas (in the Hinlopenstretet synclinorium) overlie higher grade units in the west. The latter are mostly composed of amphibolite facies schists, gneisses and amphibolites.

Western Ny Friesland is dominated by the Atomfjella Antiform, a major upright fold with north-south axis (Harland 1959; Krasil'scikov 1973), and the Planetfjella Group occurs in the east-dipping, eastern limb of this structure.

The Hecla Hoek succession is divided into the Hinlopenstretet, Lomfjorden and Stubendorffbreen Supergroups, informally referred to as the Upper, Middle and Lower Hecla Hoek respectively (Harland, et al. 1966; Harland, et al. 1992). These are further subdivided into groups and formations (Table 1).

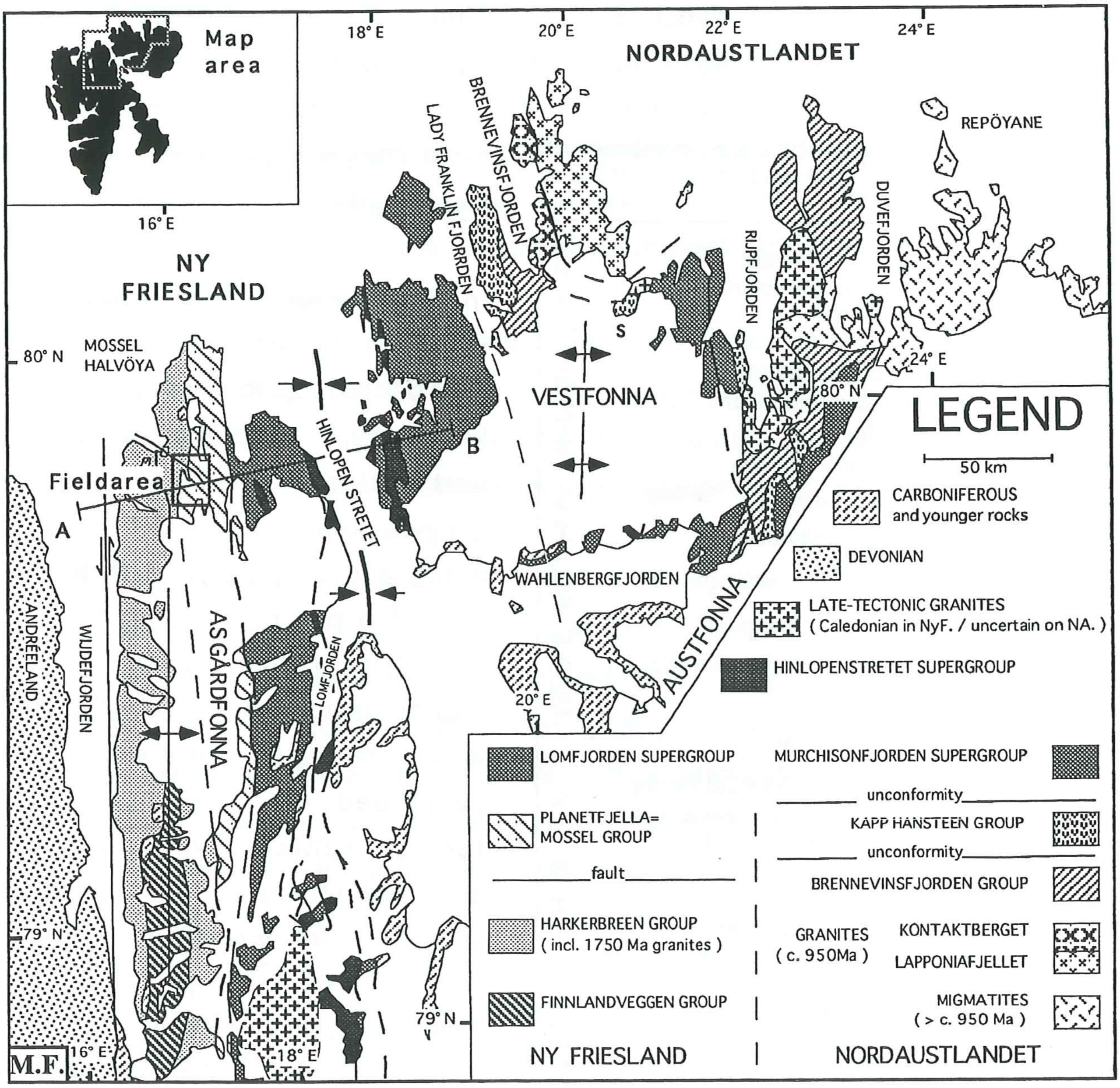

Fig 2.
Geological map over Ny Friesland and Nordaustlandet with field area marked (From Gee in press). Line from A to B marks cross section in Fig 3.

The lowest unit in the Stubendorffbreen Supergroup is the Finnlandveggen Group, found in the core of the Atomfjella Antiform. It is only exposed in southern Ny Friesland and consists of schists and marbles (Smutsbreen Formation) underlain by felsic gneisses, quartzites and amphibolites (Eskolabreen Formation)

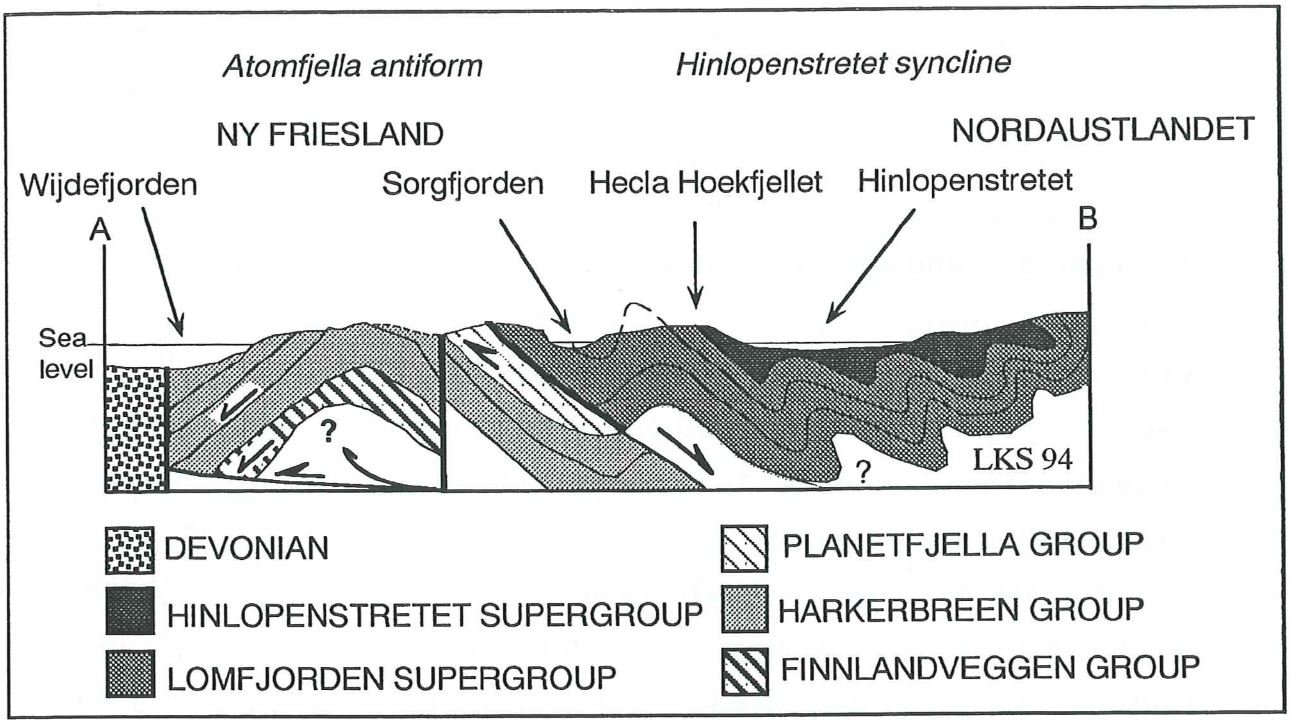

Fig 3.
Geological cross section through the Hecla Hoek succesion in northern Ny Friesland and easternmost Nordaustlandet. See text and Fig 2 for details.
(from Gee, et al. 1994). See text and Fig 1 for details.

The contact to the overlying Harkerbreen Group is considered to be either sedimentary and transitional (Harland, et al. 1966; Manby, 1990 and Harland, et al. 1992) or a major thrust (Gee, et al. 1992 and 1994). The Harkerbreen Group is made up of metasedimentary rocks, mainly quartzites and schists, with felspathic gneisses and amphibolites (Gayer & Wallis, 1966; Harland, et al. 1966). A major unit, the Bangenhuk Formation, largely composed of felsic gneisses, contains granites (Gayer 1969) , dated to c.1750 Ma (Gee, et al. 1992).

The Harkerbreen and Finnlandveggen Groups are referred to as the Atomfjella Complex by Krasil'scikov (1973) and, together with overlying metasedimentary rocks of the Planetfjella Group, described further below, are included in the Stubendorfbreen Supergroup (Lower Hecla Hoek).

Above the Stubendorfbreen Supergroup are the sandstones, shales, dolomites and limestones of the Lomfjorden Supergroup (Middle Hecla Hoek). These are, in turn, overlain by the Hinlopenstretet Supergroup, mostly made up of limestones and dolomites with subordinated shales and sandstones. In the lower part of this supergroup, Vendian tillite formations occur (Harland & Wilson, 1956).

The contact between Lower and Middle Hecla Hoek is a fault, of disputed importance. Most authors (Harland, et al. 1966; Wallis, 1969 and Harland, et al. 1992) interpreted it to be a deformed stratigraphic relationship. However, Nathorst (1910) and more recently Manby (1990) considered it to be a major fault; Manby emphasized the rapid change in metamorphism across the contact. Harland, et al. (1992) claim that the biotite-chlorite isograd crosses the Planetfjella-Veteranen contact.

Most authors have interpreted the Hecla Hoek succession to be one coherent, thick (c. 18km) mainly sedimentary sequence, containing no major depositional breaks or significant faults (Harland & Wilson, 1956; Harland, 1959; Gayer & Wallis, 1966; Gayer, 1969; Wallis, 1969; Krasil'scikov, 1973 and 1979; Harland, 1985 and Harland, et. al. 1992).However, this hypothesis was questioned by Gee et. al. (1992 and 1994), partly because the Bangenhuk Formation has been shown to contain granites, dated to c.1750 Ma (Gee, et al. 1992). This and other evidence has led to the interpretation that the Lower Hecla Hoek is a pile of thrust sheets, involving Paleoproterozoic basement rocks.

The new age data on the Bangenhuk Formation also supports the old view of Blomstrand (1864) and Nordenskiöld (1863) as well as the modern Russian view (Krasil'scikov, 1973 and 1979). These authors interpreted all of the Lower Hecla Hoek to be Paleo- to Mezoproterozoic in age. Their conclusions being largely based on comparisons of the Hecla Hoek sequence with similar rock complexes elsewhere in the Arctic.

1.1.3 Northwestern Ny Friesland

The dominating structural feature in northwestern Ny Friesland is the Atomfjella Antiform. The latter is superimposed on earlier structures in the Harkerbreen Group, including boundinage and two phases of isoclinal and tight folding (Gayer, 1969).

In the eastern limb of the Atomfjella Antiform, the structures become less complex and folding is gentler than in the core of the structure. Isoclinal folding occurs in the Planetfjella Group, but is absent in Middle and Upper Hecla Hoek. In the area of inner Mosseldalen, the Hecla Hoek succession occurs in the eastern limb of the Atomfjella Antiform. The oldest rocks exposed are the Harkerbreen Group, here containing meta-arkoses, schists, carbonates, conglomerates, amphibolites and feldspathic gneisses (Blomstrand, 1864; Harland & Wilson, 1956 and Gayer & Wallis, 1966). The contact between Harkerbreen and Planetfjella Groups, in the area south of Mosseldalen, has been mapped by Gayer (1969) as a thrust. Harland et. al. (1992) have concluded that this is not a major tectonic contact.

In the Hecla Hoek succession there is an increase in metamorphic grade down-section. The Atomfjella Complex shows migmatitic segregation and Barrovian type of metamorphism with a peak in the upper amphibolite facies (Harland, 1959 Wallis, 1969 and Manby, 1990;). In the Planetfjella, the metamorphic grade changes from amphibolite near the base to greenschist at the top. The overlying basal Lomfjorden Supergroup sediments are in low- to sub greenschist grade (Harland & Wilson, 1956; Harland, 1959; Sokolov, et al. 1968; Wallis, 1969 and Manby, 1990). The peak metamorphic conditions of the Middle and Upper Hecla Hoek in northern Ny Friesland never reaches greenschist facies (Harland & Wilson, 1956; Butterfield, Knoll et al. 1988; Manby, 1990; Harland, 1992;).

1.1.4 Planetfjella Group stratigraphy

The Planetfjella Group outcrops from Verlegenhuken in northern Ny Friesland to Billefjorden in the south, a distance of 150 km. In the north, it is limited by the sea and, in the south, it disappears under Carboniferous strata. The best exposed areas of Planetfjella rocks occur on Mosselhalvøya, where the type formations have been described (Wallis 1969). For this reason, Russian authors prefer to call the Planetfjella Group by the name Mossel Group.

Wallis (1969) divided the Planetfjella exposures into four sectors; Northern, Central, Veteranen and Southern. He also subdivided the Planetfjella Group into two mappable units, the Flåen and Vildadalen Formations (Fig 4 and Table 2) and his descriptions are summarized below:

The Vildadalen Formation is the upper unit (c. 3000 m thick) and consists of feldspathic psammites, quartz psammites and subpelites, thought to be derived from turbidites, together with subordinate quartzites and marbles, interpreted to be shallow water sediments.

Wallis (1969) placed the biotite/chlorite isograd 1400 m below the contact to the Middle Hecla Hoek. Above this isograd, the subpelites have quartz, sericite, chlorite and sometimes rare tourmaline and/or plagioclase assemblages. Below the isograd, biotite and muscovite replaces chlorite. Here, occasional feldspathic psammites with megacrystic potassic feldspars occur as lenses and layers in the subpelites.

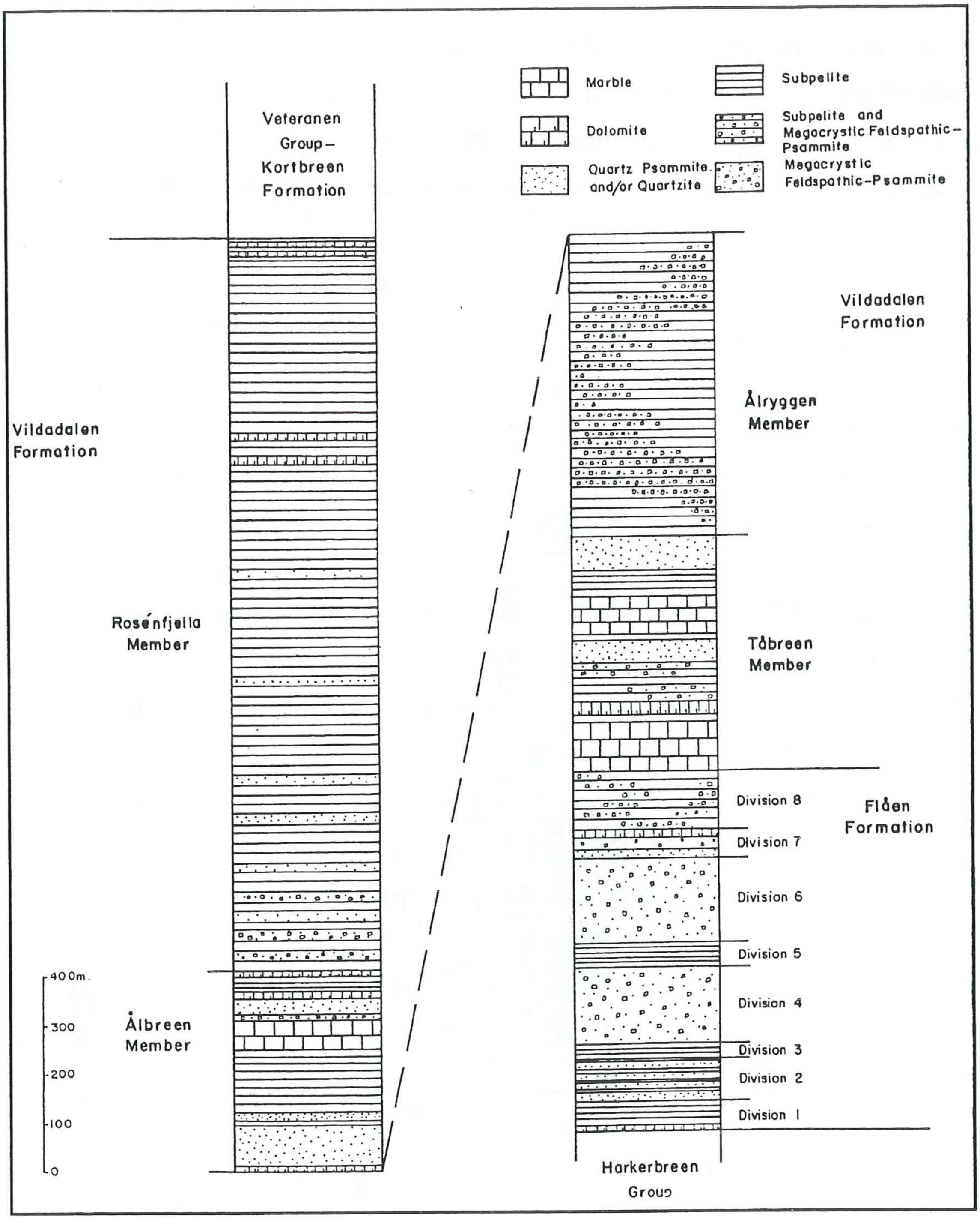

Table 2.
Diagrammatic lithostratigraphy of the Planetfjella Group in the northern sector (from Wallis 1969).

The megacrysts are often euhedral and lie within the foliation; they vary in size from 1cm to 5cm and have been influenced by all known deformations. Sometimes, they constitute as much as 50% of the rock.

1900 m down section from the contact to the Middle Hecla Hoek, small garnets, c. 2mm, start to appear in the subpelites and plagioclase totally replaces sericite. The garnets become more abundant and larger (maximum of 5mm) further down the sequence.

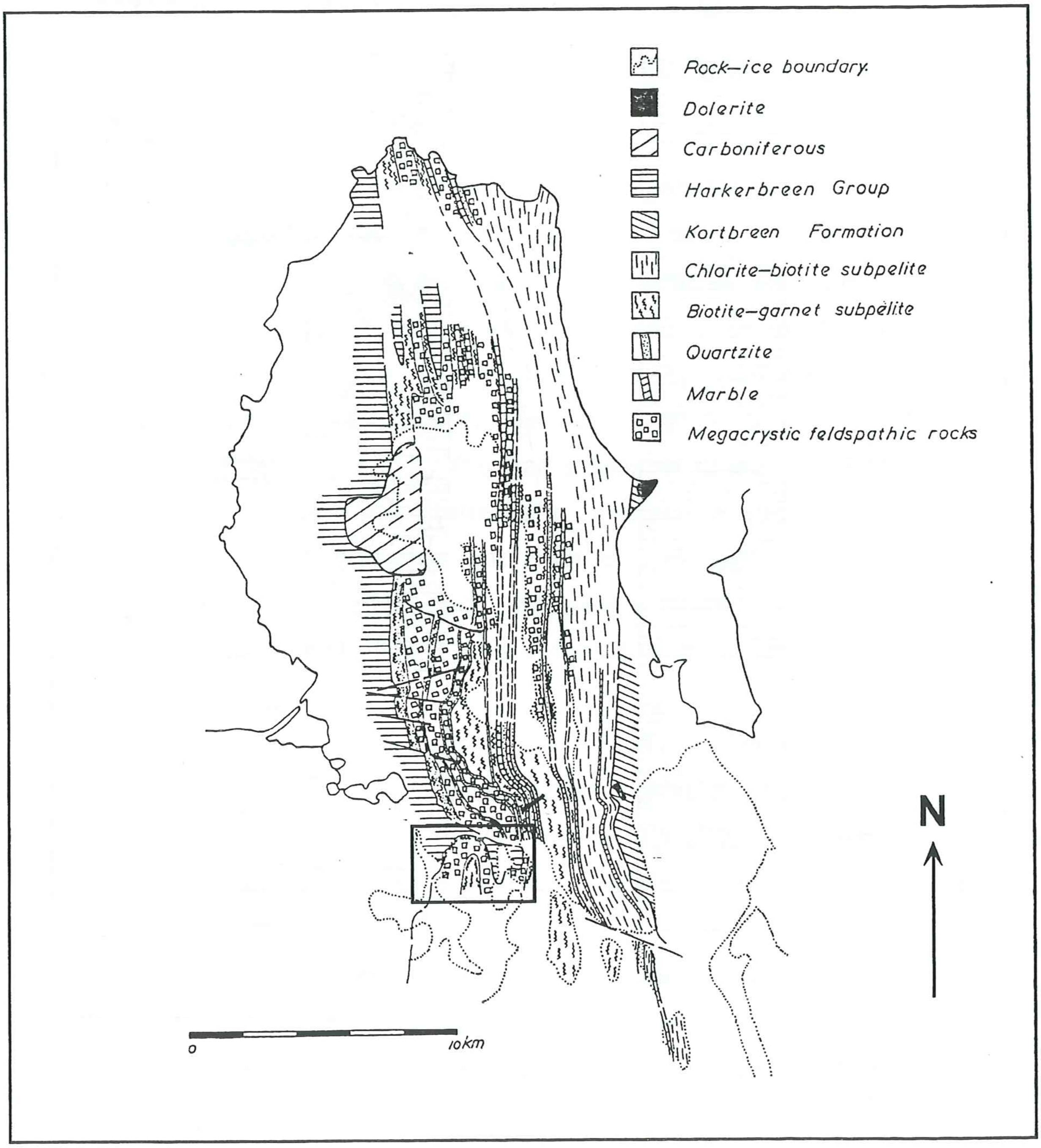

Fig. 4.
Lithological sketch map of the Planetfjella Group in the northern sector (from Wallis 1969), with location of the Mosseldalen area.

The marbles include both calcium and magnesium carbonates. The quartzites are often pure; they can also be muscovitic and are then distinctly foliated. Marbles and quartzites occur as subordinate horizons throughout the Vildadalen sequence.

The underlying Flåen Formation outcrops in the area of Mosseldalen and is c. 700m thick. It differs from Vildadalen Formation by having tens of meters thick units of feldspathic psammites with megacrysts up to 4cm in diameter. The megacrysts are of both plagioclase and orthoclase. The potassium feldspar megacrysts lie in a matrix of quartz ± plagioclase ± biotite. These rocks grade into subpelites, with and without garnets, the latter as large as 5mm in diameter. The subpelites often have quartz lenses in the foliation and in fold hinges.

Subordinate marbles are present, with both calcite and magnesium carbonates, in different levels in the sequence; north of Mosseldalen, the contact to the Harkerbreen Group is a 3m thick marble, that can be mapped for a distance of 8km (Fig 4).

As noted above, the metamorphism of the Planetfjella Group increases downwards, from chlorite grade at the contact to the Middle Hecla Hoek to garnet grade at the base. Gayer (1969) reported staurolite, kyanite and garnet assemblages in the lower subpelite lithologies in the area south of Mosseldalen.

Wallis (1969) suggested that the megacrystic feldspathic psammites to be either derivates from acid pyroclastic rocks, or potassic arkoses derived from acid magmatic rocks. Studies carried out by P. Nilsson in the summer of 1993 (pers comm), indicate that at least some of the feldspathic megacrystic rocks are derived from granites.

Wallis (1969) interpreted the Planetfjella Group to be a sedimentary sequence, conformable with the underlying and overlying Hecla Hoek successions.

2 New work

Only a part of the northern sector of the Planetfjella rocks has been studied in this paper, i.e the area around the Mosseldalen Valley (Fig 5).

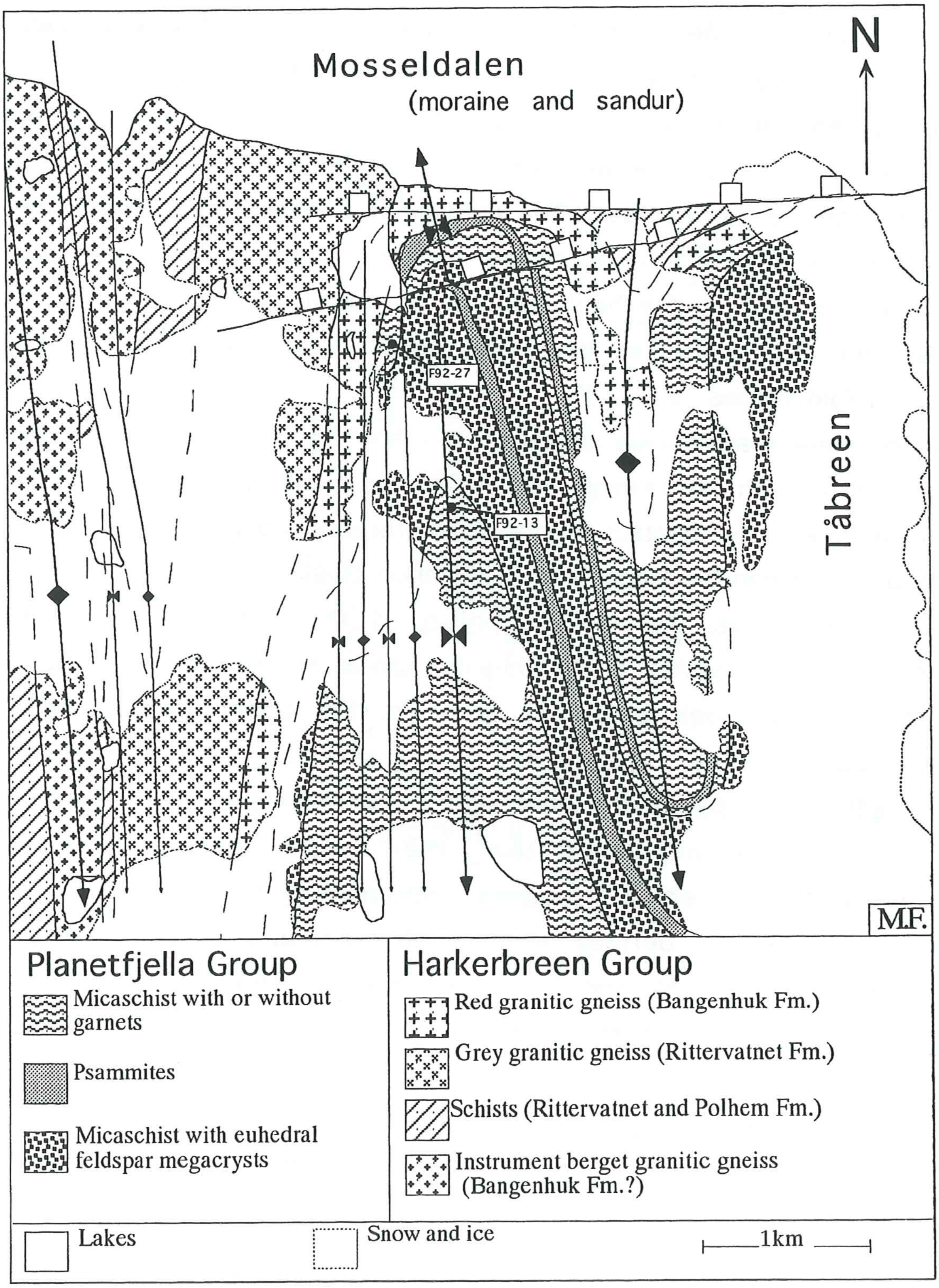

Fig. 5. Map over field area, showing the contact between Planetfjella and Harkerbreen Groups on Ingstadegga, south of Mosseldalen.

The new work focuses on the Flåen Formation in the area south of Mosseldalen, where the Planetfjella Group rests on the Harkerbreen Group.

2.1 Mapping and petrography

A WNW-trending fault occurs in Mosseldalen, separating the successions on each side of the valley. It is a steep, brittle fracture zone, probably with normal movement and downthrow to the north. North of the valley, the Planetfjella Group rests on quartzites and amphibolites of the Polhem Formation (Gayer 1969) or the Sörbreen Formation (Harland et. al. 1992). The strata dip 25°-50°E and the contact is reported to be concordant. Ultramafic lenses occur in this contact zone from Mosseldalen and at least 8 km to the north.

South of Mosseldalen, the lower units of the Planetfjella Group occur in gentle folds. The fold axes plunge c. 5°S. Some brittle deformation zones are found close to the fault in Mosseldalen, oriented subparallel to the latter. They strike N 80°W to S 80°W, are vertical and downthrow to the north (Fig 5).

2.1.1 Lower contact of the Planetfjella Group

To the south of Mosseldalen, on Ingstadegga, the Planetfjella Group occurs in a synform (Gayer 1969), overlying various rocks of the Harkerbreen Group, all of which are intensely deformed. The contact is not exposed anywhere in the area; it is covered either by snow or by moraine.

Directly below the Planetfjella contact lies a red, fine-grained granitic gneiss; though intensely deformed, it has preserved myrmekitic potassium feldspars (Nilsson pers. comm.). It contains frequent amphibolites of unknown origin. This unit is believed to be the same as the feldspathic gneisses of the Bangenhuk Formation (Gayer & Wallis, 1966) (Fig 5).

A lower granitic gneiss, grey, medium to fine grained with megacrystic plagioclase (Fig 6), lies close to, but nowhere at, the contact to the Planetfjella Group. Due to shearing, the gneiss looses its megacrysts and becomes mylonitic close to the contact with Planetfjella (Fig 7).

Fig 6.
Grey granitic gneiss with feldspar augen. The scalebar is 17cm from edge to bend in both directions.

Fig 7.
Same granitic gneiss as in Fig 6; here it is mylonitic. This picture is from a spot close to the Harkerbreen-Planetfjella contact. The hammerhead is 14 × 3.5cm.

It contains two amphibolite horizons, both parallel with the foliation. On Gayer´s (1969) map it is included in the Rittervattnet Formation, but it is not described as a separate unit.

Above this unit and below the red gneiss lies more typical Rittervattnet gneisses, metapelites and quartzites, with interbedded amphibolites (Gayer & Wallis, 1966).

2.1.2 Lower part of the Flåen Formation

The lower part of the Flåen Formation of the Planetfjella Group, as can be seen from the map (Fig 5), is made up of a banded sequence of micaschists and quartzites with a prominent, 10m thick, quartzite unit at the base.

The quartzites are fine grained, white rocks that weather light brown. They show little or no compositional banding, but have a pronounced foliation and lineation. In addition to quartz, which is almost 100%, they contain small amounts of muscovite. The white quartzites occur in two distinct horizons.

Mica schists are by far the most common lithology in the area. They often contain garnet and sometimes feldspar megacrysts. The different varieties form distinct and interlayered horizons. The dominating minerals are biotite, muscovite, plagioclase and quartz in association with epidote, tourmaline, apatite and ilmenite. Staurolite, calcite, graphite, titanite, kyanite, andalusite and garnet may also be present. Chlorite exists as a relict mineral as well as a product of retrograde reactions. In all outcrops, quartz forms lenses within the foliation, up to 20cm in length. The lenses are commonly folded together with the foliation planes.

In the garnet-mica schist, the garnets are abundant as porphyroclasts (Fig 8) and vary in size from 2mm to 1.5cm in diameter. The foliation always wraps around the garnets.

Mica schist, containing feldspar megacrysts have a similar mineralogy to the other mica schists; they sometimes have occasional garnets, 2-5mm in diameter and subhedral plagioclase with a maximum length of 10cm. The megacrysts of plagioclase often lie in quartz lenses and they weather to a light yellow colour (Fig 9).

Fig 8. Garnet mica schist, as it appears in outcrop. Sample F92-27 is from this spot. The scale bar is 17 cm from the top to the bend.

Fig 9. Mica schist containing euheadral feldspar megacrysts as it appears in outcrop. The scale bar is 17 cm from the top to the bend.

Mica schists without garnet and feldspar megacrysts, are often deeply weathered. They vary from light greenish or brownish grey to greenish black, and always with a silvery appearance; fresh surfaces are dark grey. At one location, close to the lower contact, a horizon containing a kyanite and andalusite intergrowth has been found (Gee pers. comm.).

Marble is only found in one c. 1 m thick horizon in the field area south of Mosseldalen and only in very small outcrops. It is impure, grey and with a vague internal foliation.

2.1.3 Upper contact of the Planetfjella Group

The author has only briefly studied the upper contact at exposures in Vildadalen. The conclusions drawn from the observations made there, agree better with the results of Manby (1990), than those of Wallis (1969).

The contact between Lomfjorden and Stubendorffbreen Supergroups in the northern Ny Friesland is located c. 4 km east of Mosseldalen. It is a distinct N-trending lineament that is easily seen on air-photos.

At the contact, over a distance of 100-200m, the Planetfjella Group schists are altered to phyllites and the carbonates are mylonitic. Away from the contact, c 1km into the Planetfjella Group, there are zones where the micaschists have been altered in the same way as at the upper contact.

The rocks above the contact are more calcic, with limestones and dolomites together with quartzites and shales. The structures of these rocks are less complex then those of the Planetfjella Group, with bedding well preserved and a conspicuous cleavage.

2.2 Mineralogical investigations

In the field the ambition was to sample all different lithologies. From the 40 samples collected in field, eight were selected to make polished thin sections.

2.2.1 Methods

The mineral composition in the different samples was determined using the Department of Geology at the University of Lund´s JEOL electron microscope, coupled with a Link EDS-equipment. The samples were studied with the SEM using both backscatter and reflected images to find suitable mineral grains for analysis. A spot was considered suitable if it had no cracks close to it, the thin section was without irregularities and the SEI detector did not display any charges on the coating.

During the time when this part of the work was carried out, there was a problem with the EDX detector. Unfortunately, there was neither time nor money to do the analyses somewhere else.

Analyses of garnet were considered to be accurate when the oxides summed to 8± 0.2 by stoichiometry and the cations analysed for constituted more than 99%. For biotite, the oxide only had to reach close to 16 by stoichiometry and the cations should constitute 93.5%. The limits for plagioclase were 5±0.10 cations and 97.5%. The fit index values were not allowed to pass beyond 4 for any analysis.

Using these criteria, 1 out of 3 analyses were acceptable when everything was running smoothly; at other times 1 out of 10.

2.2.2 Selection of samples for geothermobarometry

From the polished thin sections, two samples were discarded. One of these is deeply weathered and therefore not suitable for analysis. The second sample contained large quantities of staurolite; because of the uncertainty as to how this effects equilibrium in the system, this sample was also excluded.

After studies of the six remaining samples under the electron microscope, two, F92-13 and F92-27, were selected for detailed work. They seem to have very few retrograde reactions; most of the biotite and garnet grains are euhedral to subhedral, the latter showing signs of zoning; almost all grain boundaries are sharp and distinct.

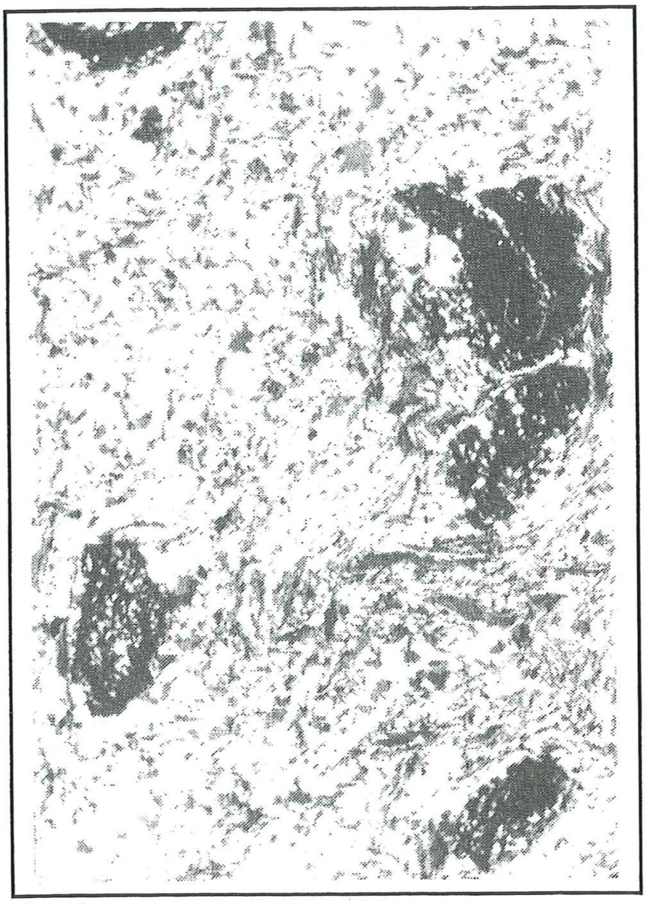

Fig 10.
Sample F92-13.Cracked garnets, the fragments are offset due to shearing. The schistosity is chaotic between the garnet fragments.

2.2.3 Results

The petrology and mineral chemistry are presented below

Sample F92-13 contains quartz, biotite, muscovite and plagioclase as main matrix minerals, together with garnet. Accessory minerals are apatite, tourmaline, chlorite and opaques, mainly ilmenite.

The matrix micas are crenelated and have developed two foliation planes— distinct S_1-surfaces and weak S_2-surfaces. Between the garnets, the micas display chaotic structures (Fig 10).

Fig 11.
The foliation in the matrix can be traced as inclusions within large garnets.
The arrow marks the the area in Fig 20.

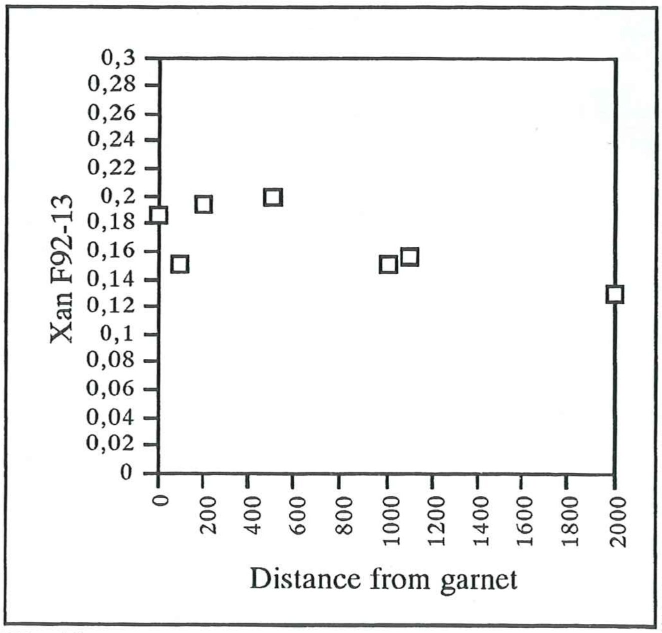

Fig 12.
Plagioclase compositions in sample F92-13, plotted in relation to distance from garnets.

Some of the garnets are cracked and show evidence of shearing after crystallization. Often, the foliation sweeps around isolated fragments of garnets. In the uncracked crystals the S_1-planes can be traced into the rim, for a distance of about half the radius of the garnets (Fig 11). The inclusions are plagioclase, quartz, ilmenite and rarely chlorite. In the core of the garnets, inclusions are too few to indicate any preferred orientation. The garnets continued to grow after fragmentation, causing idiomorphic garnet surfaces to develop on the cracked planes.

There are no obvious reaction textures other than recrystallisation of biotite and muscovite to form the S_2-surfaces.

Anorthite in plagioclase ranges irregularly from 0.13 to 0.20 (Fig 12 and Table 3).

The Mg/(Mg+Fe) ratio in the biotites is 0.44-0.45 (Fig 13 and Table 3), and in the garnets, it increases from core to rim.

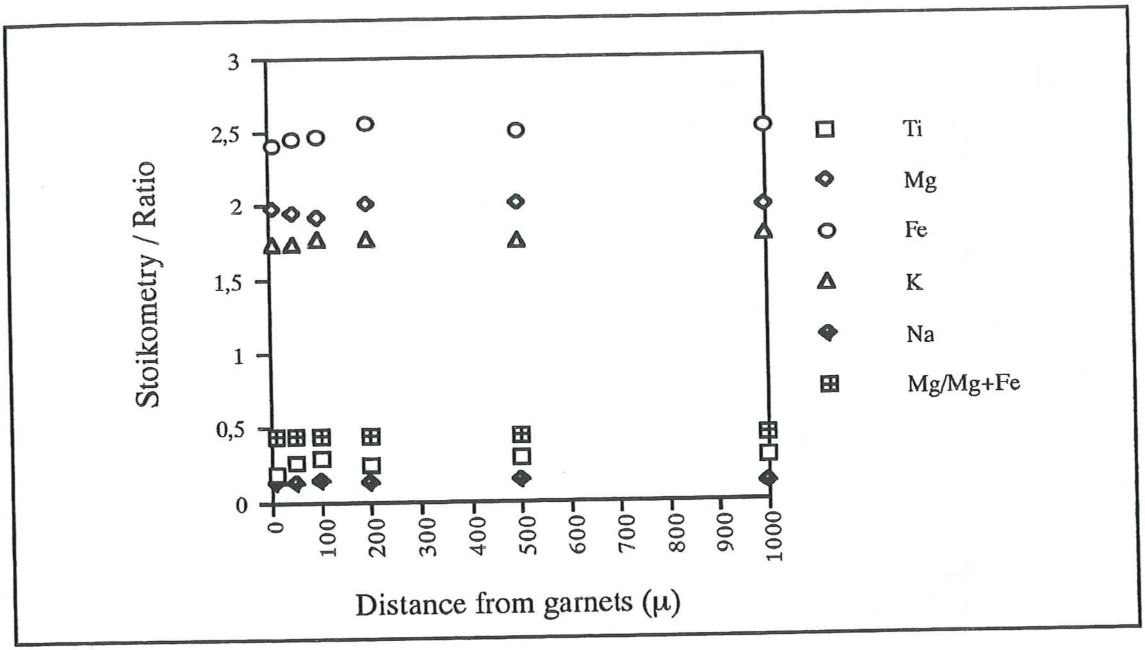

Fig 13a.
Biotite compositions i sample F92-13, plotted in relation to distance from garnets. 0 represents contact with garnet.

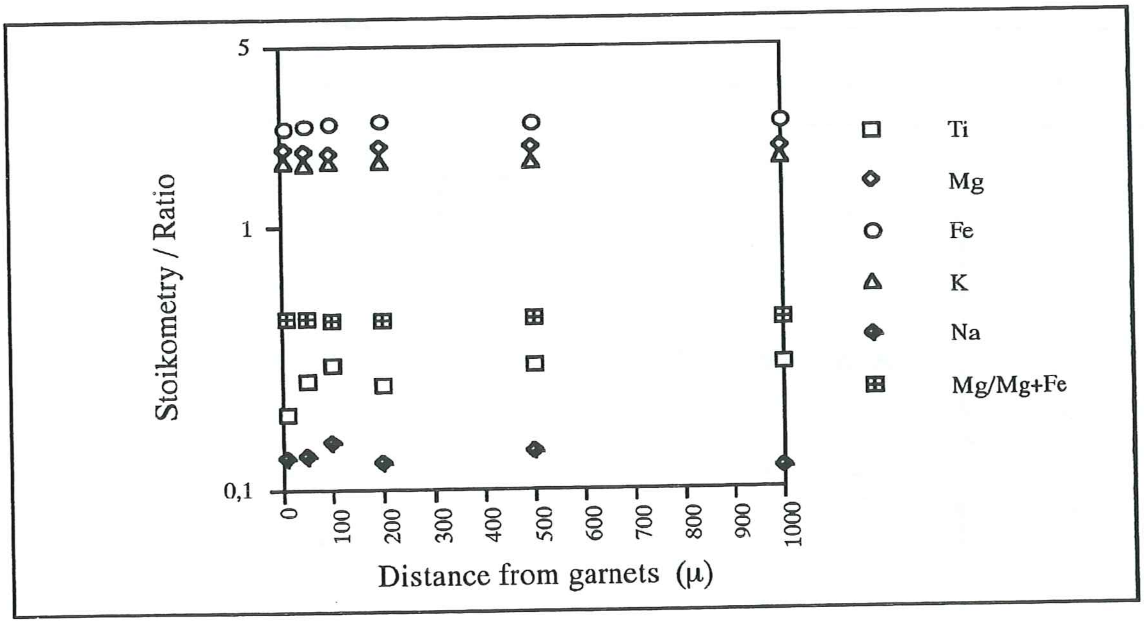

Fig 13b.
Biotite compositions i sample F92-13, plotted in relation to distance from garnets. 0 represents contact with garnet. Note that the Y-axis is logarithmic.

Close to the rim, where garnet is in contact with quartz, the Mg/(Mg+Fe) ratio jumps from 0.08 to 0.12 over a distance of c. 100 µ. Where the garnet is in contact with biotite, the jump is slightly less.(Fig 14 and Table 3).

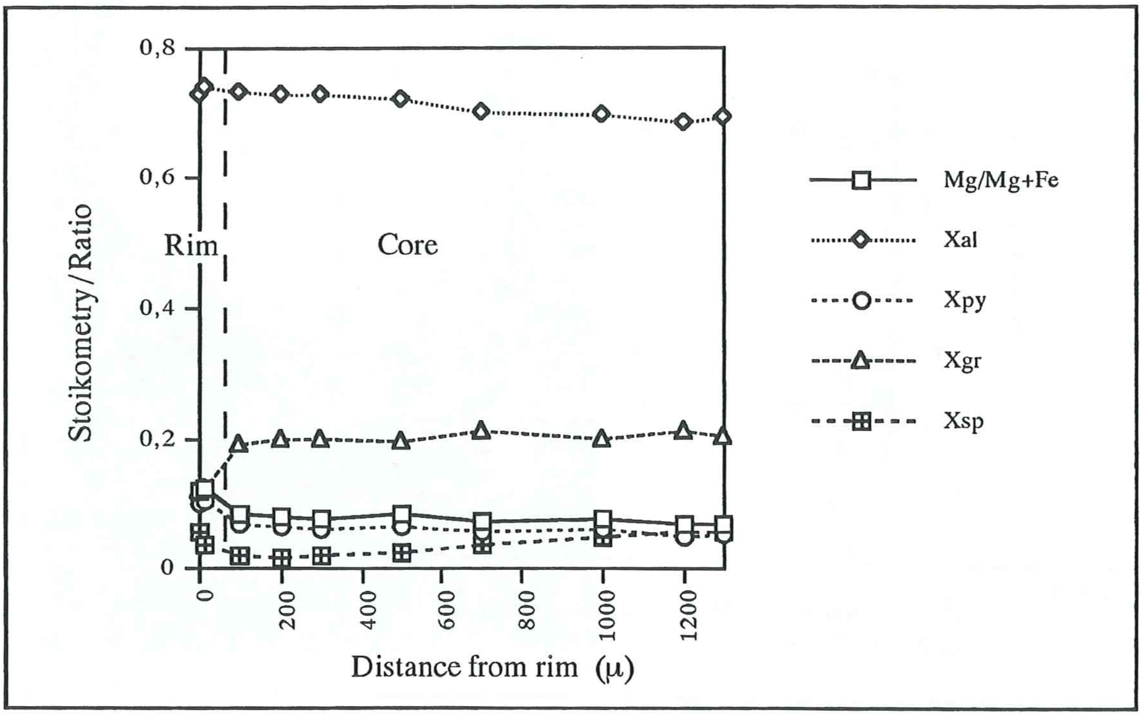

Fig 14a.
Profile across garnet radius in sample F92-13. 0 is at the edge and 1300 is in the center.

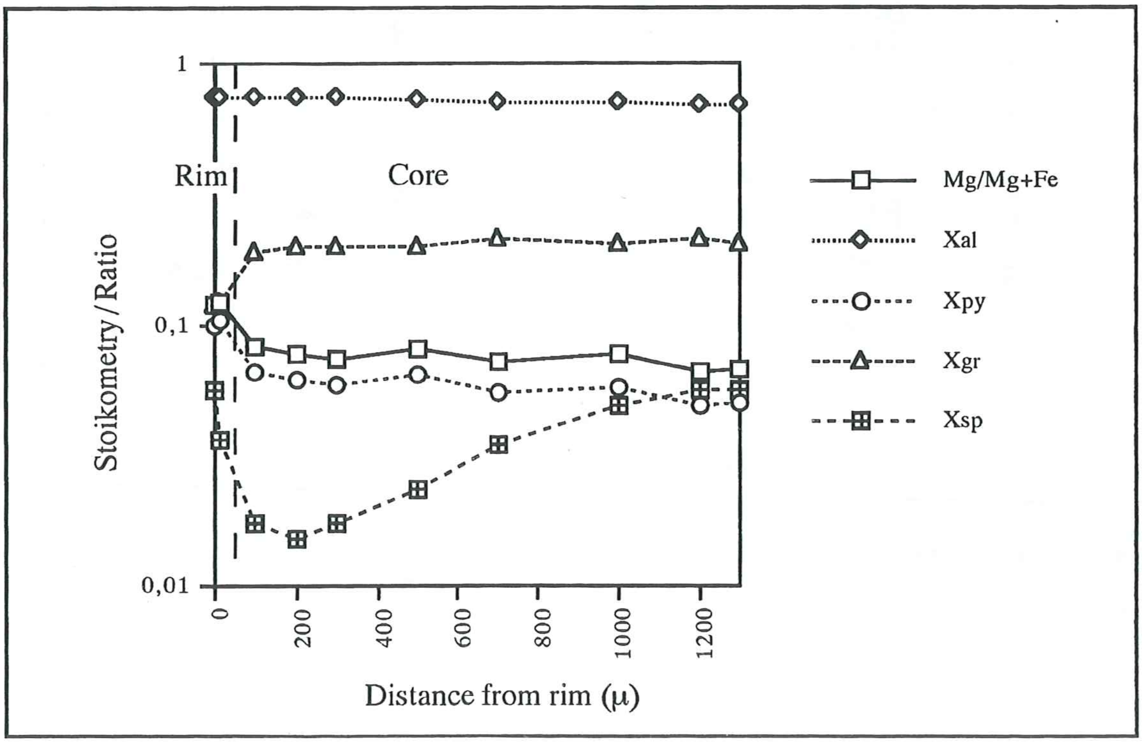

Fig 14 b.
Profile across garnet radii in sample F92-13. 0 is at the edge and 1300 is in the center.
Note that the Y-axis is logarithmic.

Table 3. Some representative analyses from samples F92-13 and F92-27.

F92-13

Garnet	Si	Al	Ti	Mg	Fe	Mn	Ca	Xal	Xpy	Xgr	Xsp	Mg/Mg+Fe
Rim	2.98	2.01	0.01	0.31	2.22	0.11	0.37	0.74	0.10	0.12	0.04	0.12
Outer core	2.99	1.99	0.01	0.18	2.20	0.05	0.59	0.73	0.06	0.20	0.02	0.08
Inner core	2.99	1.99	0.01	0.17	2.11	0.15	0.61	0.70	0.06	0.20	0.05	0.08

Biotite	Si	Al	Ti	Mg	Fe	Mn	Ca	Na	K	Mg/Mg+Fe
From Fig 11	5.40	3.67	0.19	1.97	2.40	0.01	0.01	0.13	1.74	0.45
Matrix	5.39	3.46	0.25	2.01	2.56	0.01	0.00	0.13	1.76	0.44

Plagioclase	Si	Al	Fe	Ca	Na	K	Xan	Xab
From Fig 11	2.81	1.20	0.02	0.18	0.77	0.00	0.19	0.81
Matrix min An	2.88	1.13	0.01	0.12	0.81	0.01	0.13	0.86
Matrix max An	2.81	1.20	0.00	0.19	0.76	0.01	0.20	0.79

F92-27

Garnet	Si	Al	Ti	Mg	Fe	Mn	Ca	Xal	Xpy	Xgr	Xsp	Mg/Mg+Fe
Rim	3.05	2.04	0.00	0.36	2.16	0.05	0.24	0.77	0.13	0.09	0.02	0.86
Transient	3.00	2.02	0.00	0.27	2.25	0.05	0.41	0.76	0.09	0.14	0.02	0.89
Core	2.99	1.98	0.01	0.16	2.13	0.10	0.65	0.70	0.05	0.21	0.03	0.93

Biotite	Si	Al	Ti	Mg	Fe	Mn	Ca	Na	K	Mg/Mg+Fe
From Fig 15	5.51	3.50	0.17	2.04	2.45	0.01	0.00	0.13	1.63	0.45
Matrix	5.47	3.46	0.22	2.15	2.38	0.00	0.00	0.13	1.62	0.48

Plagioclase	Si	Al	Fe	Ca	Na	K	Xan	Xab
From Fig 15	2.78	1.23	0.01	0.18	0.81	0.00	0.18	0.82
Matrix	2.86	1.15	0.00	0.12	0.88	0.01	0.11	0.88

Sample F92-27 has the same mineralogy as F92-13, but quartz, feldspars and garnets are more abundant, at the expense of mica. The garnets are 0.5-2cm in diameter and have inclusions, mostly of quartz, but also of biotite, ilmenite and, occasionally, chlorite. The inclusion patterns form an S within many garnets. In these garnets the rim inclusions are parallel with the matrix foliation .In other garnets, the rim inclusions are scarce and randomly orientated. Garnets are not cracked in this sample.

The S_2-surfaces are better developed here than in sample F92-13, but the crenulation is less pronounced, probably due to there being less mica.

The composition of the matrix biotites deviates from those closer to the garnets (Fig 15 and Table 3). The analysed biotites far from the garnets have a Mg/(Mg+Fe) ratio of nearly 0.48, while biotites closer to the garnet display more heterogeneous and slightly lower ratios— between 0.45 and 0.47. The difference is probably insignificantly small, except in the case of the 0.45 biotite that is in direct contact with the garnet.

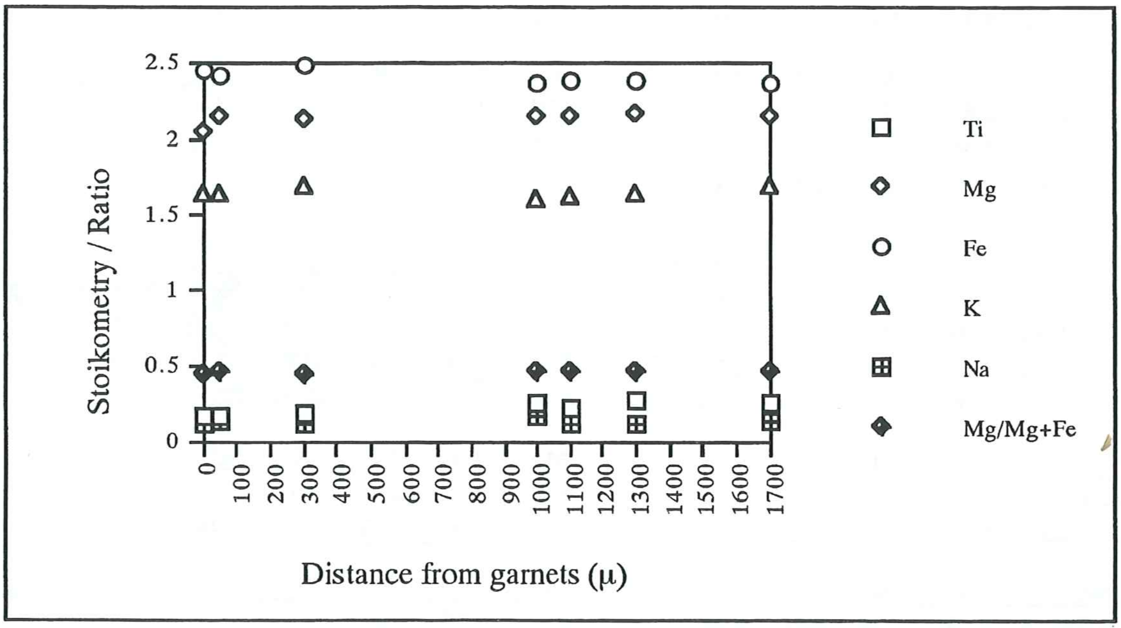

Fig 15a.
Biotite compositions i sample F92-27, plotted in relation to distance from garnets.
0 represents contact with garnet.

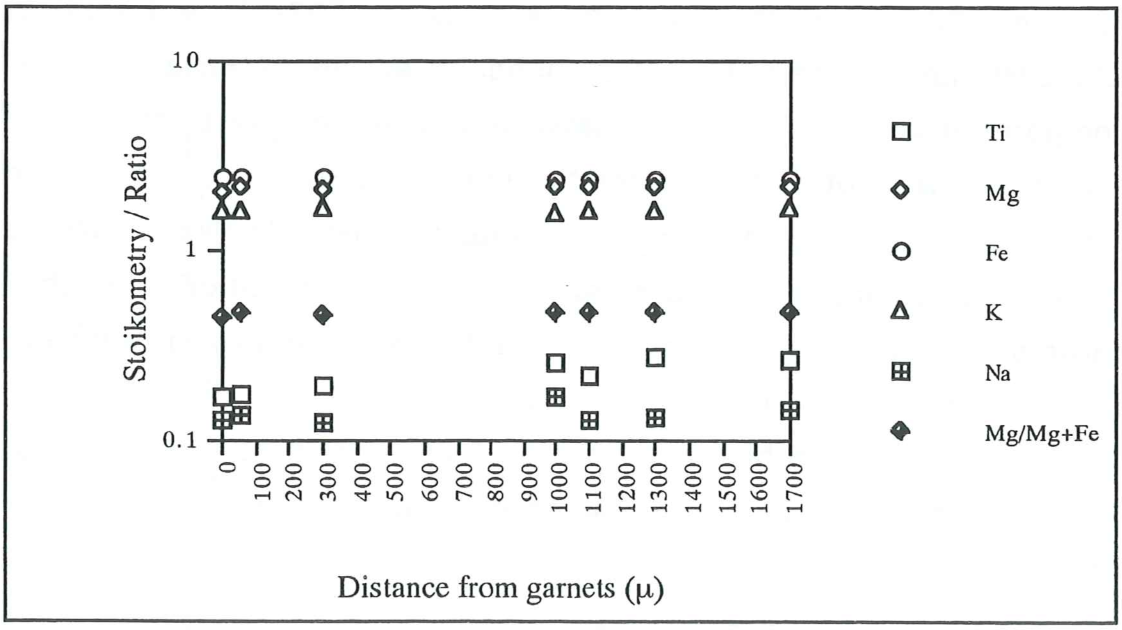

Fig 15b.
Biotite compositions i sample F92-27, plotted in relation to distance from garnets.
0 represents contact with garnet. Note that the Y-axis is logarithmic.

The garnets are compositionally zoned (Fig 16 and Table 3). In the core (up to 2/3 of the radius) the Mg/(Mg+Fe) ratio is c. 0.06. Outside the core it gradually increases and reaches a maximum of 0.14 at the very rim. This change is mostly due a greater increase of magnesium than of iron. The increase in Mg/(Mg+Fe) ratio is typical for a growth zonation. It is accompanied by decrease in the grossular and spessartine components.

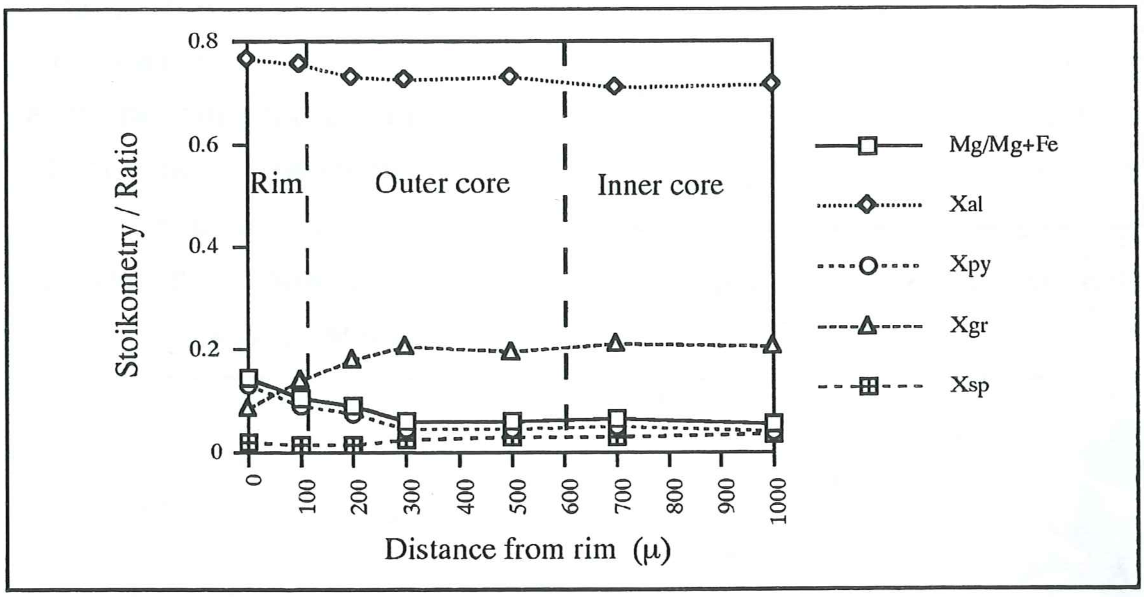

Fig 16a.
Profile across garnet radius in sample F92-27. 0 is at the edge and 1000 is in the center.

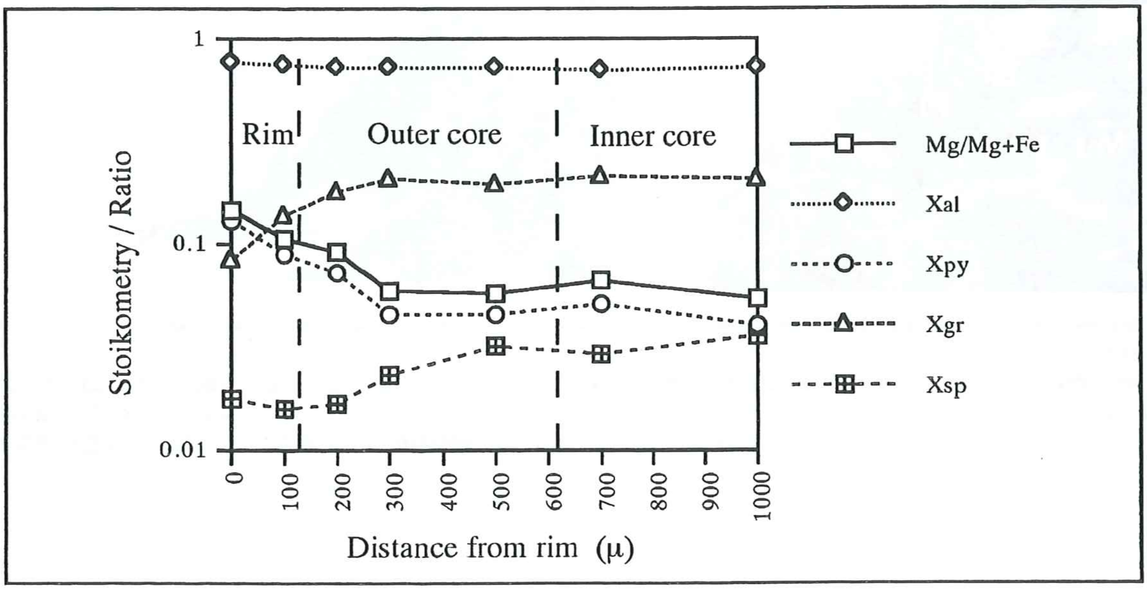

Fig 16b.
Profile across garnet radius in sample F92-27. 0 is at the edge and 1000 is in the center. Note that Y-axis is logarithmic.

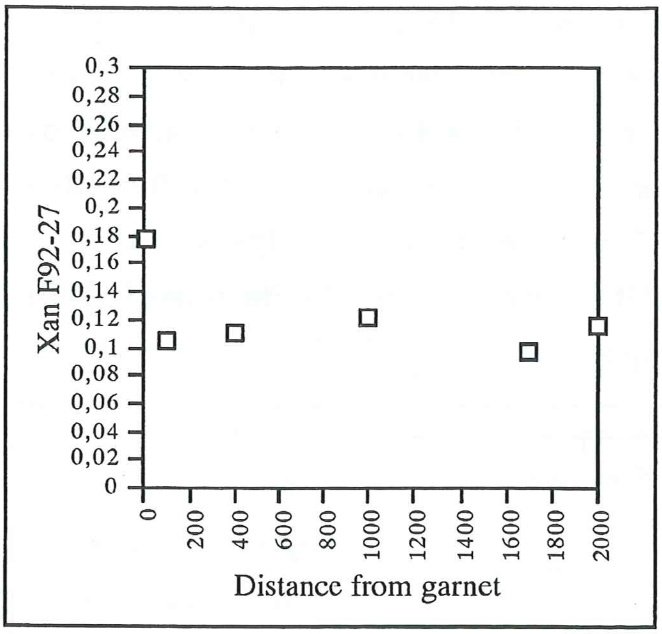

Fig 17.
Plagioclase compositions in sample F92-27, plotted in relation to distance from garnets.

In the matrix, the anorthite content of the plagioclase is c. 0.10, based on 10 analyses. From spots close to garnet and biotite, the analyses gave Xanorthite 0.18, (Fig 17, Fig 18 and Table 3); this is interpreted as a different and later equilibrium, as discussed below in chapter 2.3.4.

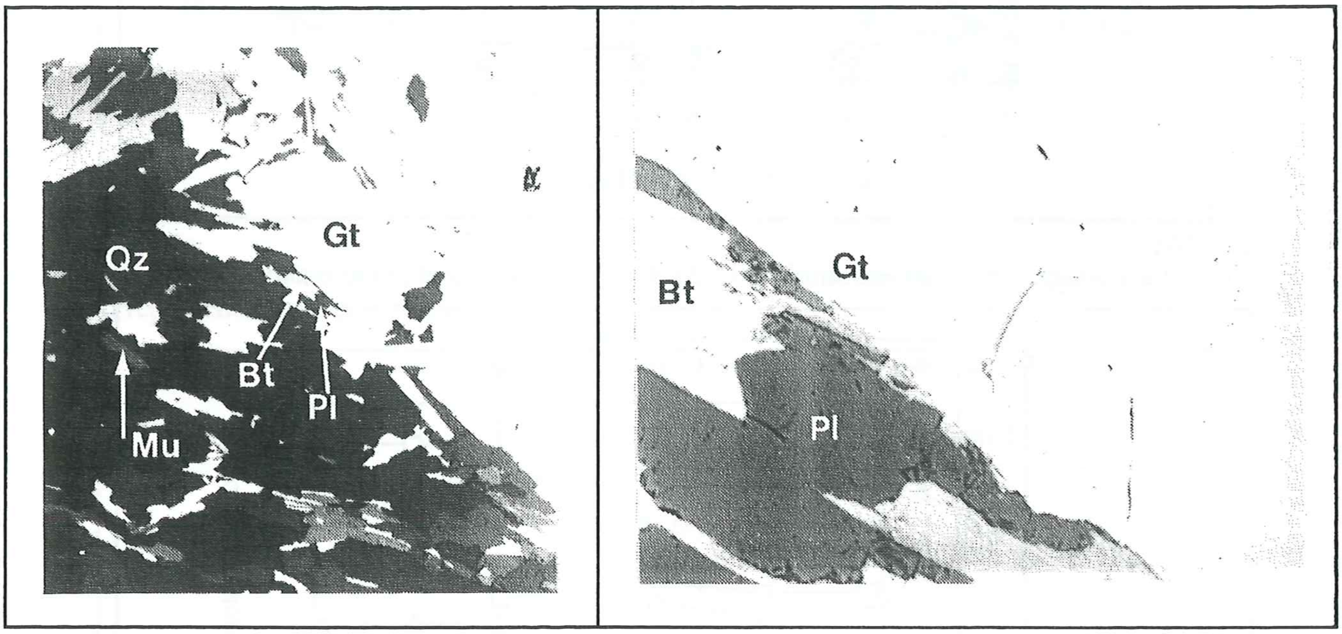

Fig 18. Sample F92-27
The area in which the matrix minerals display different composition than the rest of the matrix.The right picture is an enlargement of the garnet, plagioclase and biotite domain in the left picture. The PT-calculation resulting in the highest temperature together with a reasonable pressure, are based on analyses from these grains.

2.3 Geothermobarometry

2.3.1 Geothermometer

A widely used calibration of the garnet-biotite thermometer is that of Hodges and Spear (1982); it has been used in this paper. It assumes ideal Fe-Mg solid solution in biotite. This model is suitable for samples with not too much titanium in the biotites. Hodges and Spear (1982) used biotites with a TiO_2 content of 1.25% to 1.43%. In sample, F92-13 varies from 1.69% to 2.58% and in sample F92-27 from 1.49% to 2.43%, which thus are somewhat greater. Even so, TiO_2 is not a major component, and the Hodges and Spear (1982) calibration is considered to be applicable on the selected samples.

The Hodges and Spear (1982) geothermometer considers all mixing parameters as ideal, except the one for calcium-magnesium. They presented the following equation

$$K=\frac{(a_{py})^3(a_{ann})^3}{(a_{ph})^3(a_{al})^3}=\frac{(X_{py})^3(X_{ann})^3}{(X_{ph})^3(X_{al})^3}\cdot\frac{(\gamma_{py})^3}{(\gamma_{al})^3} \quad \text{where;}$$

$$\frac{\gamma_{py}}{\gamma_{al}}=e^{\left(\frac{(3300-1.5T(K))(X_{gr}^2+X_{al}X_{gr}+X_{gr}X_{sp}+X_{py}X_{gr}+W_{MgMn}(X_{sp}^2+X_{gr}X_{sp}+X_{al}X_{sp}+X_{py}X_{sp})}{RT(K)}\right)}$$

2.3.2 Geobarometer

The lack of aluminium silicates in the collected samples limits the options for good geobarometry, leaving only one suitable paragenesis: Garnet-plagioclase-muscovite-biotite (Ghent & Stout, 1981). This gives two net transfer reactions:

(1) pyrope+grossular+muscovite = 3 anorthite+phlogopite

(2) almandine+grossular+muscovite = 3 anorthite+annite

They can be written as;

$$(Fe,Mg)_3Al_2(SiO_4)_3+Ca_3Al_2(SiO_4)_3+KAl_2AlSi_3O_{10}(OH,F)_2$$
$$\leftrightarrow 3CaAl_2Si_2O_8+K(Mg,Fe)_2AlSi_3O_{10}(OH,F)_2$$

Both reactions change the coordination of aluminium from six in the garnet to four in the plagioclase. Magnesium and iron change from eight in garnet to six in biotite. The iron end member reaction is not used in this paper, because it requires an estimation of the amount of iron participating as Fe^{3+}. This is difficult to do with sufficient accuracy.

The garnet-muscovite-plagioclase-biotite geobarometer is usable for intermediate plagioclase compositions, anorthite from 0.14 to 0.60 (Kohn, 1989). Hodges and Silverberg (1988) have shown that the equilibrium depends very little on the composition of the muscovite and, as it is a difficult phase to analyse, it is therefore considered to be ideal. I have chosen to use the model by Hodges and Crowley (1985). In this model, biotite is considered ideal and muscovite is not. Therefore, I have tested it against the model by Hoisch (1989).

The two models treat the activity of garnet in the same way, the only difference is in two constants of the Margules parameters (Appendix 7.2). Hoisch (1990) treats the composition of muscovite and both end members of biotite as ideal, but considers the activity of anorthite to be non-linear in relation to the composition of the plagioclase (Appendix 7.2). In both models, the Margules parameter of anorthite only depends on temperature, a being proportional to exp(1/T).

The difference between the models is less than 0.2kbar for the Mg end-member reaction in this investigation.

2.3.3 Applications

Sample F92-13 yields, using the Hodges and Spear (1982) thermometer and the Hodges and Crowley (1985) barometer (Fig 19), a temperature of 575-600°C and a pressure of c. 11kbar for the parageneses shown in Fig 20 (Biotite, plagoiclase and rim garnet in Table 3).

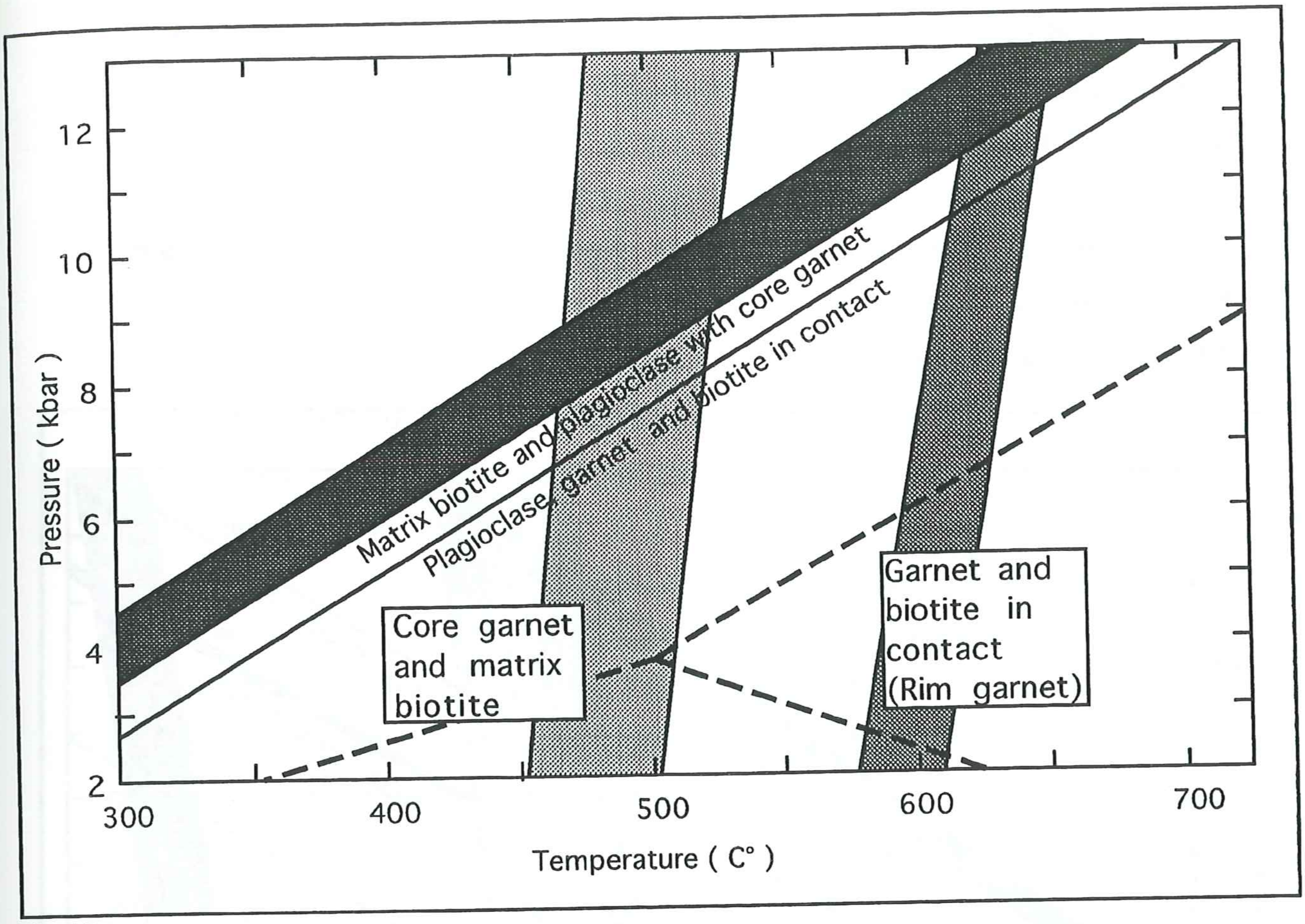

Fig 19.
Results of PT-calculations based on analyses of sample F92-13, using the Hodges and Spear (1982) geothermometer, together with the Hodges and Silverberg (1985) geobarometer. See text for details.

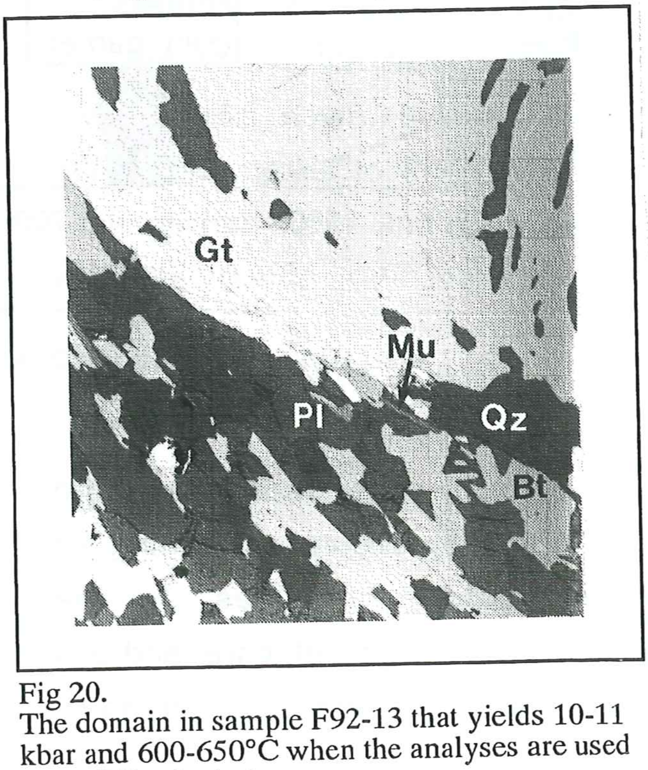

Fig 20.
The domain in sample F92-13 that yields 10-11 kbar and 600-650°C when the analyses are used in the PT-calculations.

The same calculations, using the core garnet composition with matrix biotite and plagioclase compositions (Table 3), gives 465-530°C and 7.2-10.2kbar (Fig 19).

The analyses from sample F92-27 are generally of higher quality than in F92-13. This is seen in the calculations of errors by the ZAF-4 program and by the composition plots of plagioclase and biotite, that do not display the same heterogeneity as in sample F92-13.

The minerals in Fig 18, using the Hodges and Spear (1982) and Hodges and Crowley (1985) methods, yield 670-715°C and 10.3-11.5kbar (Fig 21).

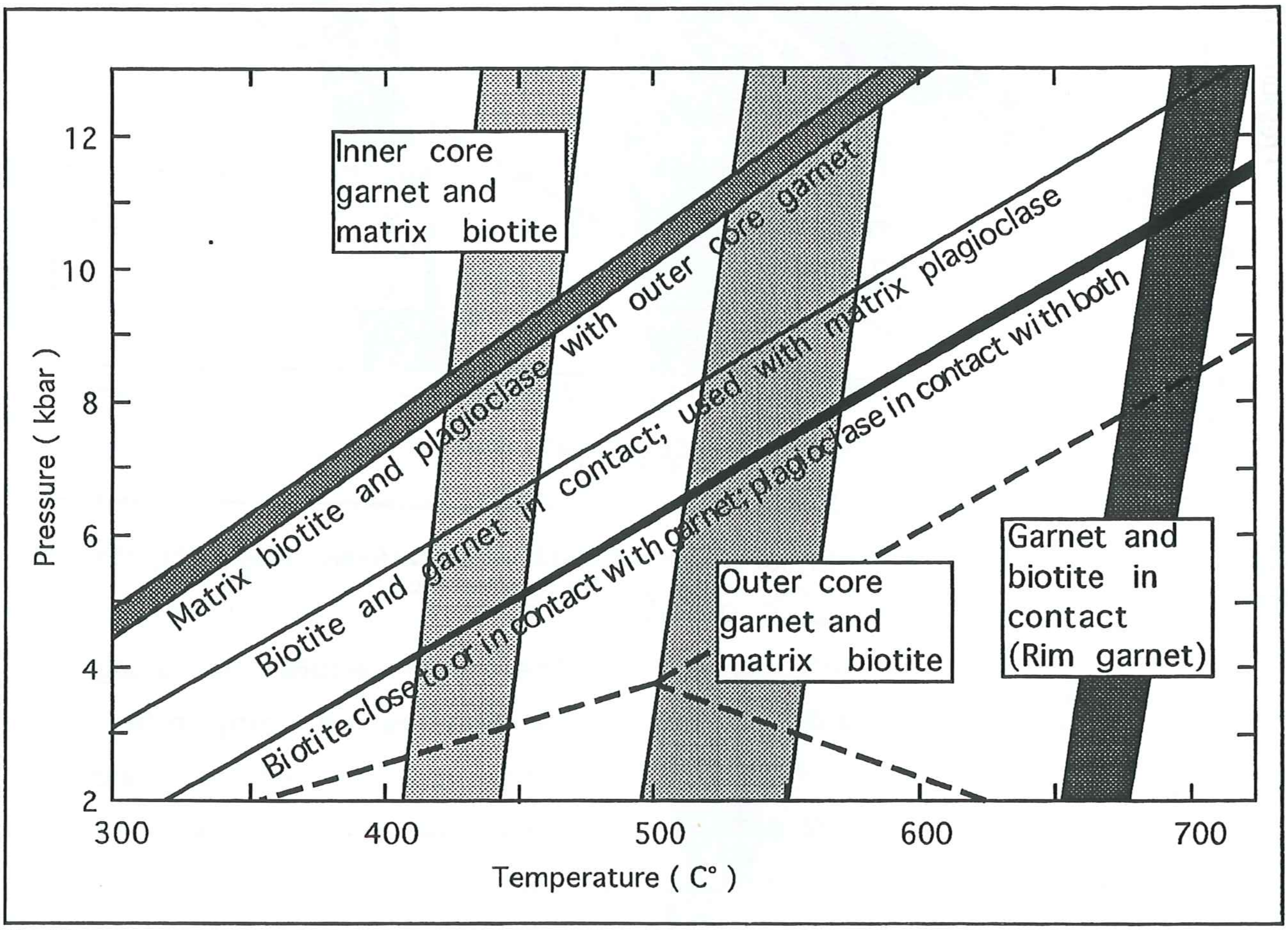

Fig 21.
Results of PT-calculations based on analyses from sample F92-27, using Hodges and Spear (1982) geothermometer, together with Hodges and Silverberg (1985) geobarometer. See text for details.

These temperatures are unreasonably high, when bearing in mind that a temperature as high as 700°C normally results in melting of muscovite, potassium feldspar and quartz in pelites, in the presence of H_2O (Thompson 1982). Using the garnet core and and matrix compositions in the models gives a temperature of 425-500°C and preassure from 8-9.5kbar.

Assuming equilibrium between matrix biotite and plagioclase compositions and garnet rim or outer core compositions, leads to a far higher pressure, 12-14kbar for outer core composition and even more for rim composition.

2.3.4 Interpretation of results

The garnet cores and rims represent different equilibria. The rims are interpreted to be in equilibrium with the matrix close to or in contact with the garnets. These compositions should then reflect peak metamorphic conditions.

The main matrix composition has probably changed since the garnet cores were formed, but not enough to equilibrate with the garnet rims or the the areas close to them. As claimed by Robinson et al. (1982), a change in garnet composition is not likely to bring great changes in the main matrix-mineral compositions. This is because the volume of the matrix is so much larger than that of garnet, that when a garnet rim is formed, the amount of compound required is so small that the transfer will not be noticed in the matrix compositions. On the other hand, during the formation of the garnet core, the matrix probably contained Mg-rich chloritoid. When the latter breaks down, it affects the composition of the matrix biotites. This leads to the conclusion that the PT estimations based on the garnet cores and main matrix minerals could be valid, but should be treated with caution.

2.3.5 Error estimation

Because of the limited number of analyses a normal statistical test of the confidence of the results, as suggested by Hodges and McKenna (1987) is impossible. The analytical data used in the calculations have been chosen from grains whose composition does not vary more than a few percent for each analysed element. The single analysis picked for the calculations should be representative and fill the criteria presented in chapter 2.2 above.
The uncertainty in the calibrations and analyses are estimated by Hodges and McKenna (1987), to be several kbars and more than 100°C. In this study the errors are probably even larger; nevertheless, they provide a basis for discussion of the structural relationships between the Planetfjella Group and overlying and underlying units.

2.3.6 Summary of PT estimations

*The metamorphism is at least a two step event.
*The peak temperature is 575-700°C
*The pressure reached 8kbars and could be as high as 11kbar.
*The most prominent mineral growth occurred at a temperature of 450-530°C and probably at a pressure of 7-10kbar.

3 Discussion

3.1 Geological implications

3.1.1 The origin of the Planetfjella rocks in the area

The mica schists in the Planetfjella Group are most probably derived from impure shales, perhaps from turbidites as suggested by Wallis (1969). The origin of the idiomorphic feldspar megacrysts in the schists was discussed by Wallis (1969), who concluded that they are derived from volcanoclastics. However, the results from the analyses presented here, suggests that the megacrysts could be of migmatitic origin. If the fluid pressure is high enough, pelitic rocks will begin to melt at c. 650°C. The melt will be generated by the reaction;

Albite+potassiumfeldspar+quartz+$H_2 0$ → melt (Luth, et al. 1964).

This kind of melt could easily be mobilised in the foliation planes, and ,on crystallization, form euhedral feldspar megacrysts in quartz veins (Fig 9).

3.1.2 Mapping

The Planetfjella Group, in the area south of Mosseldalen, rests upon a thin sheet of red granitic gneiss similar to the granitic gneisses of the Bangenhuk Formation. The deformation in the Harkerbreen Group clearly increases as the contact to the Planetfjella Group is approached. This is most evident in the grey augen-gneiss that underlies the red granitic gneiss. 500 meters away from the contact, it carries white feldspar augen; at the contact to the red gneiss that underlies the Planetfjella Group it has lost all augens and has changed into an ultramylonite. The significance of this shear zone depends on its regional development, *i.e.* if it occurs along the entire contact between the Harkerbreen and Planetfjella

Groups. If it is, as Gayer (1969) and Wallis (1969) claim, only a local structure, then the contact could be interpreted as sedimentary. But, even so, it could not be a conformable contact, because then the Harkerbreen Group had to be deformed before the Planetfjella rocks were deposited.

The rocks close to the contact on both sides, are approximately of the same metamorphic grade, which indicates that the Harkerbreen and Planetfjella Groups were juxtaposed prior to the peak metamorphism. This is also supported by the fact that Planetfjella rocks, close to the lower contact, display the same metamorphic history as the rocks further up the sequence. The fact that the structures of both groups are similar, though more intense in the Harkerbreen Group, and that the contact is affected by, at least, the latest recorded deformation, leads to the conclusion that they shared the same tectonic history.

The phyllite alterations close to and at the upper contact of the Planetfjella Group, are products of retrograde reactions that occurred during shearing, evidently after peak metamorphism. This later tectonic event probably started in a ductile regime and was penetrative throughout the Planetfjella Group; later, the movements were concentrated to the discrete shear-zones that run parallel with the Planetfjella-Veteranen contact and to the contact itself.

3.1.3 Interpretations of petrography and pressure-temperature estimates

The zoning patterns in the garnets, together with the rotated inclusions, reflect synkinematic growth. The cracked garnets have continued to grow after fragmentation, which implies that cracking of the garnets occurred during prograde metamorphism. The well developed schistosity, or crenelation also developed during this phase. None of the S_2-surfaces in the matrix have their equivalent in the garnet inclusions, and the S_2 fabric is therefore interpreted to have developed after the peak of metamorphism, probably during an early stage of uplift. The chlorite replacement of biotite and garnet in many of the samples and the crystallization of the kyanite-andalusite intergrowth, is supposed also to relate to this event.

The **minimum** estimates of temperature and pressure for peak metamorphism (575°C and 8kbars) are supported by petrography, *i.e.* mobilization of quartz-feldspar segregates, the total breakdown of chlorite, and the presence of staurolite and occasional kyanite.

3.2 Tectonic implications

Fossils reported by Butterfield et. al. (1988) from the Akademikerbreen Group of the Lomfjorden Supergroup (Table 1), indicate, that this part of the sequence is practically unmetamorphosed. These fossiliferrous strata are c. 5km stratigraphically above the contact between the Planetfjella and Veteranen Group and c. 3.5km from the top of the sequence (Butterfield, et al. 1988 and Harland, et al. 1992). Using these thicknesses, the samples analysed in this paper would come from approximately 12km depth.

The thickness of the Hecla Hoek succession, between the base of the Planetfjella Group and the base of the Veteranen Group, is estimated by Wallis (1969) to c. 4km, for the area around Mosseldalen. The base of the Veteranen Group is in sub-greenschist facies; however, this could, at the most, represent a depth of c. 15 km.

The estimated pressure for the basal Planetfjella rocks corresponds to at least 25km.

The depth for metamorphism obtained from the stratigraphy and from the pressure determinations, leads to the conclusion that at least 5km of sequence is missing between the base of the Planetfjella Group and the base of the Veteranen Group. And as much as 10km of rock is missing between the base of the Planetfjella Group and the top of the Hecla Hoek succession.

Most of the missing rock were probably cut out by the fault along the Planetfjella and Veteranen Groups contact, it is mapped as transcurrent (Harland, et al. 1992) with a dip-slip component (Manby, 1990 and Gee, et al. 1994).

The deformation that postdates the peak metamorphism, i.e. the S_2-surfaces and the phyllite alteration, is interpreted to have formed during the extension. This would imply that the thinning, at an early stage, was within the Planetfjella Group, and the extension was progressively concentrated to the major fault-zones at a later stage. This is supported by the rapid increase in metamorphic grade down section in the Planetfjella Group.

4 Summary and conclusions

* The contact between the Harkerbreen and the Planetfjella Groups in the area represents a major break, probably tectonic.
* The Harkerbreen and Planetfjella Groups were juxtaposed prior to peak metamorphism.
* The peak metamorphism of the Planetfjella Group was in upper amphibolite facies, i.e. 575°C-700°C and 8-11kbar.
* There must have been subsequent thinning in the overlying Hecla Hoek succession after the peak of metamorphism; at least 5 km is missing.
* The extension has to some extent occurred within the Planetfjella Group, but most of the normal-faulting was concentrated to the Planetfjella-Veteranen contact.

5 Acknowledgements

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6 References

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7 Appendix

7.1 Calculations and parameters used in Pt modelling

7.1.1 Hodges and Spear (1982)

Table 4. Morgules parameters and their source.

$W_{FeMg=0}$	(Newton & Haselton, 1981)
$W_{CaMg=3300-1.5T(K)}$	(Newton, et al. 1977)
$W_{MgMn=0}$	(Hodges and Spear 1982)
$W_{CaFe=0}$	(Cressey, et al. 1978)
$W_{CaMn=0}$	(Ganguly & Kennedy, 1974)
$W_{FeMn=0}$	(Ganguly & Kennedy, 1974)

7.1.2 Hodges and Crowley (1985)

Table 5. Activity and composition relationships.(Hodges and Crowley 1985)

$$a_{gr}=\left[X_{gr}\exp\left(\frac{\left(\left(3300-1.5T(K)\right)\left(X_{py}^2+X_{al}X_{gr}+X_{py}X_{sp}\right)\right)}{RT(K)}\right)\right]^3$$

$$a_{ann}=(X_{ann})^3$$

$$a_{ph}=(X_{ph})^3$$

$$a_{an}=X_{an}\exp\left(\frac{610.34}{T\,(K)}-0.3837\right)$$

$$a_{mu}=\left(X_{kmu}X_{almu}^2\right)\exp\left(\frac{\left(\left(X_{namu}X_{almu}^2\right)^2\left(W_{mu}+2X_{kmu}X_{almu}^2\left(W_{pa}-W_{mu}\right)\right)\right)}{RT(K)}\right)$$

Table 5. continued

X_{al}=Fe/(Fe+Mg+Ca+Mn) in garnet
X_{py}=Mg/(Fe+Mg+Ca+Mn) in garnet
X_{gr}=Ca/(Fe+Mg+Ca+Mn) in garnet
X_{sp}=Mg/(Fe+Mg+Ca+Mn) in garnet
X_{an}=Ca/(Ca+Na+K) in plagioclase
X_{femu}=Fe/(Fe+Mg+Mn+Ti+Al^{4+}) in muscovite
X_{almu}=Al^{4+}/(Fe+Mg+Mn+Ti+Al^{4+}) in muscovite
X_{kmu}=K/(Ca+Na+K) in muscovite
X_{namu}=Na/(Ca+Na+K) in muscovite
X_{ph}=Mg/(Fe+Mg+Ti+Al^{4+}) in biotite
X_{ann}=Fe/(Fe+Mg+Ti+Al^{4+}) in biotite
W_{pa}=2923.1 + 0.1590 P(bar) + 0.1698T(K)
W_{mu}=4650.1 + 0.1090 P(bar) + 0.3954T(K)

7.2 Analyses

7.2.1 Sample F92-13

Table 6.Results from microprobe analysis. “Distance” referes distance from the outer margin of garnet, used as an index for each analysis.

Biotite, as %-oxides

Distance (um)	SiO2	Al2O3	TiO2	MgO	FeO	MnO	CaO	Na2O	K2O	Sum
10	35.49	20.45	1.69	8.68	18.89	0.08	0.07	0.44	8.97	94.77
50	35.22	18.37	2.33	8.46	19.58	0.15	0.00	0.42	8.97	93.51
100	35.60	18.78	2.58	8.64	19.30	0.08	0.00	0.51	8.99	94.48
200	35.17	19.16	2.15	8.79	19.98	0.07	0.00	0.42	8.97	94.70
500	35.16	19.01	2.56	8.76	19.44	0.19	0.10	0.46	8.93	94.61
1000	34.93	18.93	2.45	8.55	19.30	0.04	0.02	0.44	8.98	93.63

Biotite, as stoichiometry

Distance (um)	Si	Al	Ti	Mg	Fe	Mn	Ca	Na	K	Mg/Mg+Fe
10	5.40	3.67	0.19	1.97	2.40	0.01	0.01	0.13	1.74	0.45
50	5.50	3.43	0.26	1.95	2.45	0.01	0.00	0.13	1.74	0.44
100	5.55	3.39	0.30	1.91	2.47	0.01	0.00	0.15	1.76	0.44
200	5.39	3.46	0.25	2.01	2.56	0.01	0.00	0.13	1.76	0.44
500	5.39	3.43	0.30	2.00	2.49	0.03	0.02	0.14	1.75	0.45
1000	5.43	3.40	0.30	1.98	2.51	0.01	0.00	0.12	1.78	0.44

Table 6. Continued

Garnet, as %-oxides

Distance (um)	SiO2	Al2O3	TiO2	MgO	FeO	MnO	CaO	Sum
0	36.82	21.06	0.10	2.44	32.24	2.46	4.17	99.29
10	36.90	21.04	0.18	2.59	32.78	1.57	4.23	99.27
100	37.02	20.95	0.08	1.63	32.63	0.73	6.59	99.62
200	36.78	20.82	0.13	1.52	32.36	0.67	6.83	99.11
300	36.49	20.83	0.11	1.45	32.55	0.77	6.98	99.17
500	36.95	20.98	0.09	1.60	32.12	0.99	6.81	99.53
700	36.83	20.65	0.15	1.35	31.37	1.49	7.43	99.26
1000	36.75	20.73	0.11	1.43	31.07	2.13	6.96	99.18
1200	36.69	20.57	0.13	1.22	30.80	2.50	7.42	99.33
1300	36.81	20.87	0.13	1.24	30.44	2.85	7.04	99.37

Garnet, as stoichiometry

Distance (um)	Si	Al	Ti	Mg	Fe	Mn	Ca	Mg/Mg+Fe
0	2.98	2.01	0.01	0.29	2.18	0.17	0.36	0.12
10	2.98	2.01	0.01	0.31	2.22	0.11	0.37	0.12
100	2.99	1.99	0.01	0.20	2.20	0.05	0.57	0.08
200	2.99	1.99	0.01	0.18	2.20	0.05	0.59	0.08
300	2.97	2.00	0.01	0.18	2.22	0.05	0.61	0.07
500	2.99	2.00	0.01	0.19	2.17	0.07	0.59	0.08
700	2.99	1.98	0.01	0.16	2.13	0.10	0.65	0.07
1000	2.99	1.99	0.01	0.17	2.11	0.15	0.61	0.08
1200	2.98	1.97	0.01	0.15	2.09	0.17	0.65	0.07
1300	2.99	2.00	0.01	0.15	2.06	0.17	0.61	0.07

Plagioclase, as %-oxides

Distance (um)	SiO2	Al2O3	FeO	CaO	Na2O	K2O	Sum
10	63.12	22.78	0.48	3.73	8.896	0.08	99.08
100	64.65	22.4	0.15	2.96	9.125	0.09	99.36
200	63.5	23.11	0.05	3.8	8.736	0.1	99.29
500	63.08	22.94	0.11	4.01	8.847	0.15	99.14
1000	64.58	22.2	0.09	3.05	9.344	0.13	99.39
1100	64.47	22.47	0	3.17	9.334	0.21	99.65
2000	65.93	21.99	0.13	2.62	9.589	0.16	100.4

Plagioclase, as stoichiometry

Distance (um)	Si	Al	Fe	Ca	Na	K
10	2.812	1.196	0.02	0.18	0.768	0
100	2.856	1.116	0.01	0.14	0.782	0.01
200	2.814	1.207	0	0.18	0.751	0.01
500	2.807	1.203	0	0.19	0.763	0.01
1000	2.856	1.157	0	0.14	0.801	0.01
1100	2.846	1.169	0	0.15	0.799	0.01
2000	2.881	1.133	0.01	0.12	0.813	0.01

7.2.2 Sample F92-27

Table 7.Results from microprobe analysis. “Distance” referes distance from the outer margin of garnet, used as an index for each analysis. * means that the element is not analysed for.

Biotite, as %-oxides

Distance (um)	SiO2	Al2O3	TiO2	MgO	FeO	MnO	CaO	Na2O	K2O	Sum
10	35.91	19.34	1.49	8.93	19.12	0.05	*	0.443	8.31	93.58
50	36.11	19.25	1.59	9.49	19	0.07	*	0.467	8.41	94.4
300	35.66	19.04	1.68	9.31	19.39	0.06	*	0.422	8.58	94.13
1000	36.14	18.68	2.25	9.42	18.54	0.05	*	0.584	8.18	93.83
1100	35.8	19.18	1.95	9.48	18.62	0.03	*	0.434	8.47	93.95
1300	35.74	18.91	2.44	9.51	18.68	0.03	*	0.457	8.36	94.1
1700	35.63	18.72	2.33	9.34	18.48	0.03	*	0.489	8.56	93.57

Biotite, as stoichiometry

Distance (um)	Si	Al	Ti	Mg	Fe	Mn	Ca	Na	K	Mg/Mg+Fe
0	5.51	3.50	0.17	2.04	2.45	0.01	*	0.13	1.63	0.45
50	5.50	3.45	0.18	2.15	2.42	0.01	*	0.14	1.63	0.47
300	5.47	3.44	0.19	2.13	2.49	0.01	*	0.13	1.68	0.46
400	6.46	3.01	0.16	1.56	1.83	0.01	*	0.42	1.25	0.46
1000	5.52	3.36	0.26	2.15	2.37	0.01	*	0.17	1.59	0.48
1100	5.47	3.46	0.22	2.15	2.38	0.00	*	0.13	1.62	0.48
1300	5.55	3.40	0.28	2.16	2.38	0.00	*	0.14	1.63	0.48
1700	5.47	3.39	0.27	2.14	2.38	0.00	*	0.15	1.68	0.47

Garnet, as %-oxides

Distance (um)	SiO2	Al2O3	TiO2	MgO	FeO	MnO	CaO	Sum
0	37.72	21.40	*	3.26	31.89	0.74	2.76	97.77
100	36.40	20.85	*	2.18	32.62	0.68	4.68	97.4
200	37.73	21.30	*	1.81	32.40	0.74	6.27	100.2
300	37.92	20.80	*	1.12	31.66	1.02	7.13	99.65
500	37.75	21.31	*	1.11	32.27	1.14	6.74	100.3
700	37.59	20.83	*	1.10	31.47	1.54	7.03	99.57
1000	37.98	21.04	*	1.00	31.41	1.55	7.09	100.1

Garnet, as stoichiometry

Distance (um)	Si	Al	Ti	Mg	Fe	Mn	Ca	Mg/Mg+Fe
0	3.05	2.04	*	0.36	2.16	0.05	0.24	0.14
100	3.00	2.02	*	0.27	2.25	0.05	0.41	0.11
200	3.00	2.01	*	0.22	2.16	0.05	0.54	0.09
300	3.05	1.97	*	0.14	2.13	0.07	0.61	0.06
500	3.02	2.01	*	0.13	2.16	0.10	0.58	0.06
700	3.01	2.01	*	0.15	2.10	0.09	0.63	0.07
1000	3.04	1.99	*	0.12	2.10	0.11	0.61	0.05

Plagioclase, as %-oxides

Distance(um)	SiO2	Al2O3	FeO	CaO	Na2O	K2O	Sum
10	61.3	22.9	0.37	3.61	9.223	0.06	97.47
100	64.61	21.88	0.13	2.16	10.2	0.13	99.11
400	63.31	21.75	0.09	2.27	10.02	0.13	97.56
1000	63.6	21.47	0.02	2.34	10.05	0.13	97.6
2000	63.24	21.66	0	2.34	10.07	0.04	97.35

Table 7. continued

Plagioclase, as stoichometry

Distance (um)	Si	Al	Fe	Ca	Na	K
10	2.782	1.225	0.01	0.18	0.812	0
100	2.867	1.114	0.01	0.1	0.878	0.01
400	2.855	1.156	0	0.11	0.877	0.01
1000	2.856	1.153	0	0.12	0.873	0
1700	2.881	1.132	0	0.1	0.881	0
2000	2.858	1.15	0	0.12	0.881	0.01

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