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# Polyphase structural, intrusive and metamorphic evolution of the Bockfjorden area, NW Spitsbergen

by Martin Wyss<sup>1,2</sup>, Jörg Hermann<sup>1</sup>, Othmar Müntener<sup>1</sup> and Liane Benning<sup>1,3</sup>

## Abstract

Structures, intrusive contacts and metamorphic mineral assemblages reveal a polyphase tectonothermal evolution for the Caledonian basement rocks of the Bockfjorden area, NW Spitsbergen. The oldest deformation  $D_1$  is documented by isoclinal folds  $F_1$  in biotite schist.  $F_1$  folds are crosscut by an intrusion  $I_1$  of tonalitic to monzogranitic composition. Both,  $F_1$  folds and  $I_1$  are overprinted by  $D_2$  structures, that are considered to be related to the Silurian Caledonian continental collision.  $D_1$  and  $I_1$  are thus regarded as the record of a complex pre-Silurian evolution of the basement rocks. The Caledonian continental collision that is represented by the isoclinal folding  $F_2$  and by the main schistosity  $S_2$  was simple shear dominated and associated to S–N thrusting in the studied area. During  $D_2$  the  $I_1$  granitoid rocks were transformed to orthogneiss. The related metamorphism  $M_2$  reached upper amphibolite facies conditions. During or after late stage  $D_2$  deformation the orthogneiss provides evidence for incipient partial melting. The resulting migmatites and  $S_2$  were subsequently crosscut by the granodiorite and monzogranite of the intrusive event  $I_2$ , that display partly a peraluminous composition, pointing to partial melting of crustal rocks as the magma source. Subsequently, cordierite formed in all Al-rich rock types including  $I_1$  and  $I_2$  rocks. Cordierite growth was caused by a high T–low P metamorphism at conditions of 630–700 °C and 0.3–0.4 GPa, the geotherm of which was about 50°/km. The transition from migmatite formation to granite emplacement followed by a high T–low P metamorphism indicates near isothermal decompression under upper amphibolite facies conditions. This evolution reflects a continuous exhumation of mid-crustal rocks that is considered as the consequence of crustal extension during the collapse of Caledonian thickened crust.

**Keywords:** metamorphic rocks, structural geology, tectonothermal evolution, Caledonian basement, NW Spitsbergen.

## Introduction

The Caledonian convergence in Spitsbergen can be subdivided into a Middle Ordovician subduction and a later Middle Silurian continental collision (OHTA et al., 1984; DALLMEYER et al., 1990). Evidence for subduction is given by eclogites and blueschists integrated in the pre-Devonian basement rocks. However, most of the features recorded in the basement rocks were caused by continental collision including several generations of deformation, high grade metamorphism, formation of migmatites and intrusion of syn- and post-tectonic granites (HJELLE, 1979; HJELLE and LAURITZEN, 1982). Recent age determinations indi-

cate that magmatism within the pre-Devonian basement is not restricted to the Late Caledonian (PEUCAT et al., 1989; GEE et al., 1992; GEE et al., 1994; OHTA, 1992; OHTA, 1994). This provides evidence for a long and complex history of the basement rocks.

In this study a detailed investigation of the pre-Devonian basement rocks in the Friedrich-breen area in Bockfjorden, NW Spitsbergen is presented. The first part comprises a geological map and detailed petrographic descriptions of the rock types. In the second part new bulk- and trace element data of the intrusive rocks are presented and in the third part we describe intrusive relationships, overprinting structures and metamor-

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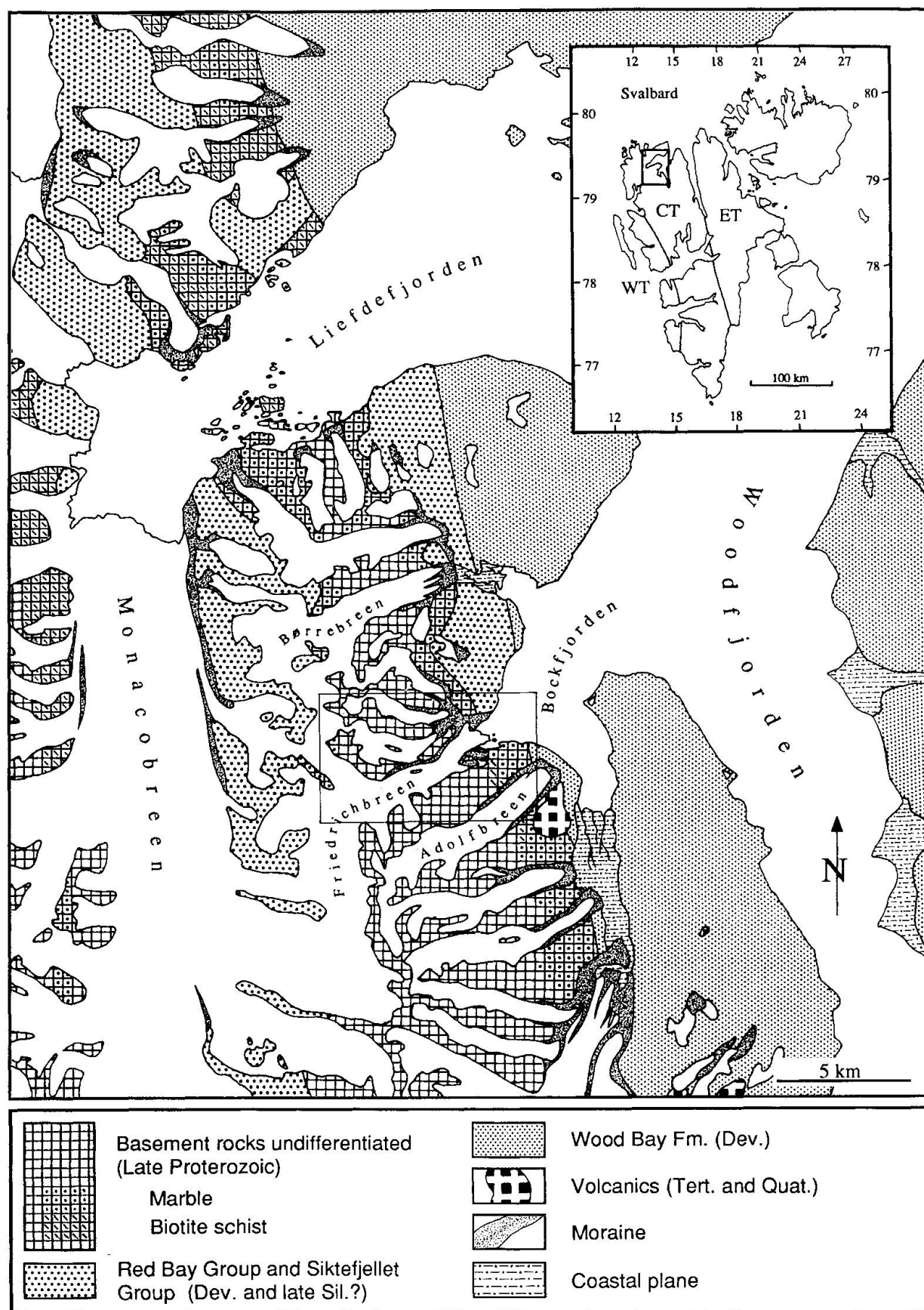


Fig. 1 Map of the Woodfjorden-Liefdefjorden region, Northwestern Spitsbergen, Svalbard. Inset: Subdivision of Svalbard in three terranes: WT = Western Terrane, CT = Central Terrane, ET = Eastern Terrane. Frame: geological map of the Smørstabben-Friedrichbreen-Krona region, figure 2.

phism, on the basis of which we subdivide the complex evolution of the pre-Devonian basement rocks into distinct events. Particular emphasis will be placed on the first deformation  $D_1$  and the first magmatic event  $I_1$  predating the Silurian collision. We will also underline the subdivision of the late Caledonian orogeny into four tectonothermal events, that allow a detailed reconstruction of the thermal history postdating crustal thickening. Finally, the significance of simple shear dominated structures will be discussed in relation to continental collision.

### Geological setting

The metamorphic rocks examined in the present investigation are part of the basement ridge between Woodfjorden and the northern part of the Monacobreen (Fig. 1). HOLTEDAHL (1914) was the

first to mention these rocks as Hecla Hoek rocks in this area. Later, GEE and MOODY-STUART (1966), GJELSVIK (1979), HJELLE and LAURITZEN (1982) and PIEPJOHN et al. (1992) described the so called lower Hecla Hoek rocks in detail. HARLAND and WRIGHT (1979) subdivided the pre Devonian basement of Svalbard into three terranes (Fig. 1), the Bockfjorden area belonging to the Central Terrane. According to GJELSVIK (1979), the lower Hecla Hoek succession is mainly composed of metamorphic carbonates and pelites, as well as of various amounts of granite, gneiss and migmatites. In the present investigation, the metasediments and essentially the granites, gneiss and migmatites are described in detail. Quaternary volcanism in the Bockfjorden region occurred along Devonian faults and has been described in detail by AMUNDSEN (1987) and by TUCHSCHMID and SPILLMANN (1992).

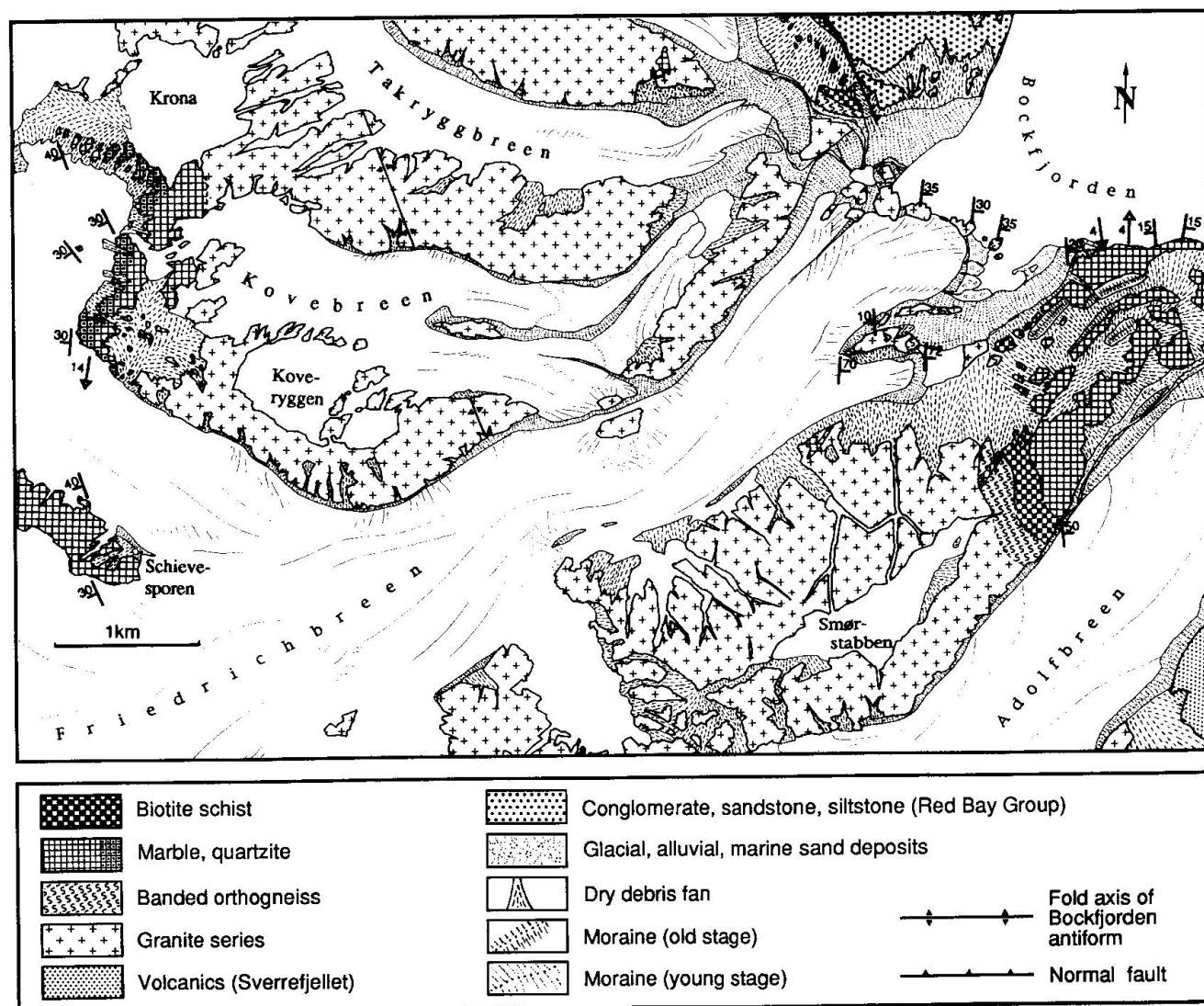


Fig. 2 Geological map of the Smørstabben-Friedrichbreen-Krona region. Arrows: stretching lineations with dip angle indicated; dip-symbols: strike and dip of  $B_0$  and  $S_2$  with dip angle indicated.



**Tab. 1** Mineral assemblages related to the different metamorphic and igneous stages discussed in the text. Ab = albite, Bt = biotite, Cal = calcite, Chl = chlorite, Crd = cordierite, Di = diopside, Ep = epidote, Grt = Garnet, Hbl = hornblende, Hu = humite-minerals, Kfs = K-feldspar, Ms = muscovite, Ol = olivine, Phl = phlogopite, Pl = plagioclase, Qtz = quartz, Scp = scapolite, Sil = sillimanite, Spl = spinel, Tr = tremolite, Ves = vesuvianite, Wo = wollastonite, Wm = white mica.

	biotite schist	marble	banded orthogneiss	granodiorite	monzogranite and schlieren granite
D <sub>1</sub> deformation	Bt				
I <sub>1</sub> : First phase of magmatism			Qtz + Kfs + Pl + Bt ± Grt (?) <sup>a)</sup>		
D <sub>2</sub> deformation	Bt + Sil + Qtz	Di + Phl	Bt + Sil + Qtz ± Grt		
M <sub>2</sub> metamorphism		b)			
I <sub>2</sub> : second phase of magmatism				Qtz + Pl + Kfs + Bt ± Grt (?) <sup>a)</sup>	Qtz + Pl + Kfs + Bt <sup>a)</sup>
High T-low P metamorphism	Bt + Kfs + Pl + Qtz + Crd ± Sil <sup>c)</sup>	Cal + Qtz + Pl + Scp + Di + Phl Ol + Spl + Cal ± Chl ± Hbl	Bt + Kfs + Pl + Qtz + Crd ± Sil <sup>d)</sup>	Bt + Kfs + Pl + Qtz + Crd ± Sil <sup>d)</sup> ± Grt <sup>d)</sup>	Qtz + Pl + Kfs + Bt
Retrograde metamorphism <sup>e)</sup>	Chl + Wm + Ab + Qtz	Tr + Chl + Cal ± Dol	Chl + Wm + Ab + Qtz	Chl + Wm + Ab + Qtz	

<sup>a)</sup> assumed magmatic paragenesis based on norm calculations

<sup>b)</sup> parageneses developed during contact metamorphism: Cal + Qtz + Wo + Di; Grt + Ves + Ep + Chl; Di + Qtz + Kfs + Cal; Phl + Hu + Di + Cal

<sup>c)</sup> in more mafic layers: pyroxene + amphibole

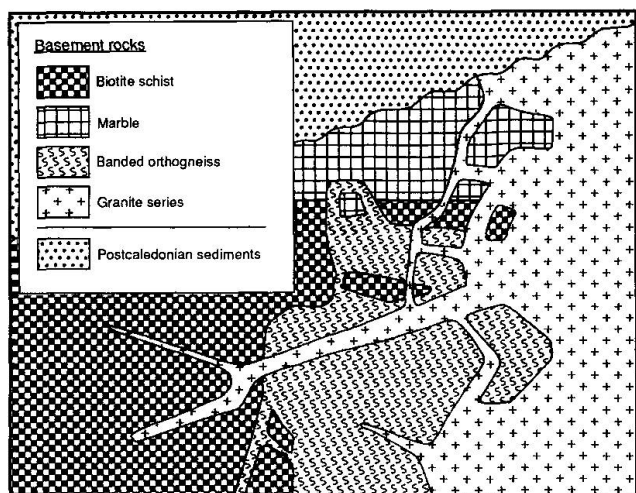
<sup>d)</sup> as inclusions in plagioclase and cordierite

<sup>e)</sup> pinitization and formation of myrmekites in all rock types (except in the marbles)

## Petrography

In the investigated area rocks of the pre-Devonian basement have been mapped. The basement rocks are subdivided into metasediments, the banded orthogneiss and the granite series, from oldest to youngest (Figs 2, 3).

The metamorphic mineral assemblages that occur in these rock types are summarized in table 1.



**Fig. 3** Stratigraphic relationships of the lithologies in the Bockfjorden area; not to scale.

## METASEDIMENTS

### Biotite schist

The biotite schist occurs in the eastern part of the studied area with a maximal thickness of about 100 meters (Fig. 2). It is characterized by a compositional banding of most probably sedimentary origin. Occasionally, it is interlayered with gneiss and/or quartzite and crosscut by discordant pegmatites.

The biotite schist is composed of various amounts of porphyroblastic biotite, quartz, K-feldspar and plagioclase. It also contains cordierite, relic garnet and rare sillimanite, the occurrence of which is bound to distinct layers, depending on the primary sedimentary composition of the rocks. Locally, clinopyroxene, hornblende and titanite are observed. Retrograde crystallization includes pinitization of cordierite, crystallization of white mica, transformation of biotite to chlorite and myrmekite growth in K-feldspar.

### Marbles and associated rocks

Most of the carbonate rocks encountered in the area are impure, coarse-grained, grey-yellow calcite marbles. The most characteristic feature of

these rocks are intercalated, intensely folded and/or boudinaged sedimentary layers of metapelitic to metabasic composition. At the western slope of Koveryggen (Fig. 2), huge lenses of fine-grained quartzite are interbedded with the marble. In general, two different types of marbles are distinguished:

1) A silica saturated calcite marble containing the mineral assemblage calcite + diopside + plagioclase + scapolite + phlogopite + quartz. Accessories are apatite, titanite, hematite and magnetite.

2) A silica undersaturated marble with olivine + spinel + chlorite + calcite + dolomite  $\pm$  humite minerals  $\pm$  pargasitic amphibole  $\pm$  phlogopite.

The metapelitic to metabasic layers contain various amounts of biotite, hornblende, white mica, rutile and rarely sillimanite. The quartzite contains biotite and sillimanite. Minor amounts of plagioclase and K-feldspar as well as accessory tourmaline and apatite occur.

Retrograde crystallization of tremolite + calcite + chlorite is widespread. In the silica undersaturated marble tremolite and dolomite grew at the expense of olivine + calcite. Locally, retrograde Mg-chlorite and serpentine overgrew spinel and olivine, respectively.

At the eastern slope of Schievesporen (Fig. 2), the high-grade marble is overprinted by an intense mylonitic foliation. This led to grain size reduction and to a retrograde crystallization of tremolite + calcite  $\pm$  dolomite  $\pm$  white mica  $\pm$  serpentine.

Marble xenoliths within the intrusive rocks north of Takryggreen display different mineral assemblages (Tab. 1). They are up to several tens of meters thick and display coarse-grained (up to 1 cm) polygonal textures.

#### BANDED ORTHOGNEISS (INTRUSIVE EVENT I<sub>1</sub>)

The occurrence of the grey to dark grey banded orthogneiss is limited to narrow zones between the metasediments (biotite schist and marbles/quartzite) and the granodiorite (granite series) in the eastern part and between the metasediments and the monzogranite (granite series) in the western part, respectively (Fig. 2). It is partly discordant towards the biotite schist and towards the marbles and it is crosscut by the granodiorite and monzogranite of the granite series. The banded orthogneiss is characterized by a strong schistosity and by a compositional banding, consisting of leucocratic and melanocratic layers (Fig. 4a). Both, biotite schist and marbles/

quartzite appear as xenoliths in the banded orthogneiss. Cm- to dm-scale quartz nodules contain occasionally prismatic andalusite intergrown with acicular sillimanite/fibrolite.

The normative magmatic mineral assemblage ranges between monzogranitic and tonalitic compositions. Melanocratic layers contain biotite, oligoclase, cordierite and minor quartz and K-feldspar. Leucocratic layers are characterized by abundant quartz, K-feldspar and cordierite with minor biotite. Biotite is partly intergrown with acicular sillimanite. Staurolite and garnet are restricted to a few samples from melanocratic layers. K-feldspar grains contain rounded quartz- and biotite inclusions; occasionally, they show transformation to myrmekites along grain boundaries. Cordierite generally displays inclusions of rounded quartz and biotite (Fig. 4b) and of acicular sillimanite (Fig. 4c). Oligoclase displays inclusions of acicular sillimanite, too (Fig. 4c). Retrograde alteration of the previous minerals includes pinitization, chloritization and/or coarse muscovite overgrowth on cordierite (Fig. 4b), saussuritization of plagioclase and replacement of biotite by chlorite.

#### GRANITE SERIES (INTRUSIVE EVENT I<sub>2</sub>)

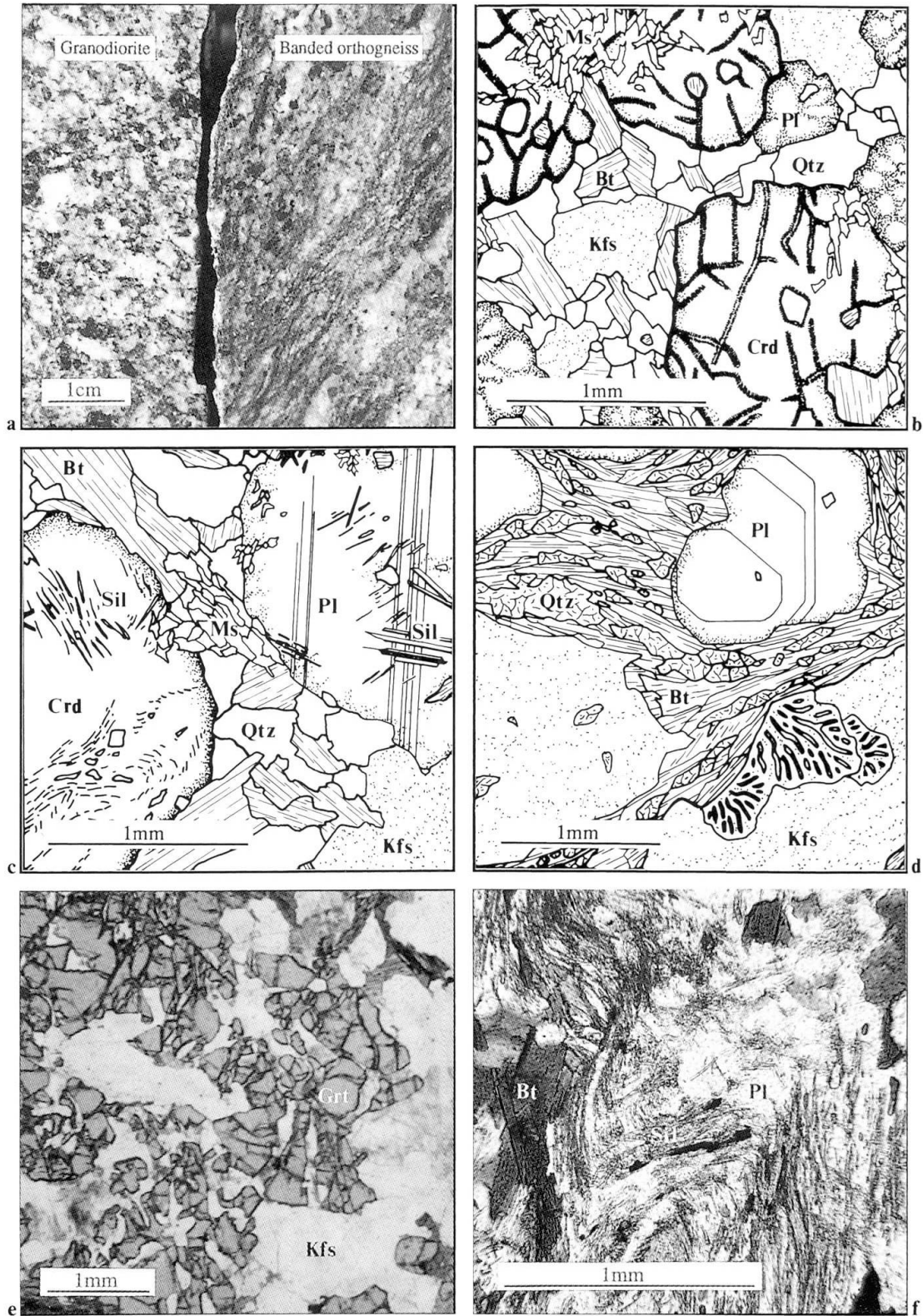
In the granite series, rocks of granodioritic and of monzogranitic composition can be distinguished. The monzogranites are subdivided into monzogranites ss. and monzogranitic schlieren granites. Sharp, mappable boundaries between these rock types do not exist in the Bockfjorden area except for dikes.

#### Granodiorite

The granodiorite occurs as a large intrusive body which includes xenoliths of banded orthogneiss and of metasediments. Rare dikes of granodiorite crosscut the country rocks. Xenoliths of fine-grained massive biotite fels have been found. The contact to the banded orthogneiss is either sharp or diffuse.

The granodiorite is light grey to grey and generally homogeneous. Towards its borders it is weakly foliated. Locally, nearly round, cm- to dm-scale quartz-feldspar nodules occur.

The normative magmatic mineral assemblage ranges between granitic and granodioritic compositions. Main metamorphic minerals are quartz, plagioclase, cordierite, K-feldspar and biotite. Plagioclase is often zoned (An<sub>15-30</sub>) and contains rare inclusions of acicular sillimanite and/or garnet.



*Fig. 4* (a) Polished hand specimens of granodiorite (left) and of banded orthogneiss (right). Most of the dark grains are cordierite. (b) Banded orthogneiss: cordierite is marginally pinitized and displays rounded inclusions of quartz and biotite (drawing after photomicrograph). (c) Banded orthogneiss: cordierite and plagioclase contain inclusions of acicular sillimanite (drawing after photomicrograph). (d) Monzogranite: K-feldspar displays myrmekites, plagioclase is slightly zoned (drawing after photomicrograph). (e) Garnet-bearing aplite: poikiloblastic garnet (photomicrograph). (f) Xenolith of biotite schist: inclusions of F<sub>3</sub>-folded acicular sillimanite in plagioclase (photomicrograph). Abbreviations are: Bt = biotite, Crd = cordierite; Kfs = K-feldspar; Ms = muscovite, Pl = plagioclase; Qtz = quartz; Sil = sillimanite.

Cordierite crystals contain rounded inclusions of quartz and biotite as well as acicular sillimanite and/or rare garnet. Retrograde chloritization and pinitization vary strongly in intensity. K-feldspar commonly displays myrmekite growth and retrogression to muscovite along grain boundaries. In some samples, biotite is intergrown with rutile and/or altered to chlorite.

### Monzogranite

The monzogranite is characterized by a dark grey color and a granoblastic texture. It mainly occurs on Koveryggen (Fig. 2), where it is in direct contact with metasediments. It contains xenoliths of orthogneiss and of metasediments.

The monzogranite consists of porphyroblasts of K-feldspar and oligoclase which are surrounded by a very fine-grained matrix of quartz, plagioclase, K-feldspar and biotite (Fig. 4d). Sometimes, plagioclase exhibits a magmatic zonation, ranging from andesine cores to oligoclase rims. Occasionally, plagioclase contains inclusions of sillimanite fibres. Retrograde crystallization includes myrmekite growth on the grain boundaries of K-feldspar (Fig. 4d), saussuritization of plagioclase and the development of quartz subgrains.

### Schlieren granite

This granite crops out on Koveryggen. It has never been found in contact to metasediments. The schlieren granite is always massive and of a light grey color. It is characterized by nebulous inhomogeneities of magmatic origin caused by differences in mineral ratios (BATES and JACKSON, 1987).

The medium-grained schlieren granite is of monzogranitic composition, consisting of K-feldspar, oligoclase, quartz and biotite. K-feldspar as well as oligoclase show rounded inclusions of quartz. Some plagioclase is slightly zoned. Myrmekite growth along the grain boundaries of K-feldspar and subgrain formation in quartz are common.

### Dikes

The dikes are mostly observed inside the granite series, they rarely occur outside. No contact phenomena in the surrounding rocks such as contact-metamorphosed or metasomatized rims have been observed. Aplites and pegmatites are of a planar shape, the garnet-bearing aplites are mostly of an irregular shape.

*Aplites:* The aplites are undeformed and sharply crosscut the granodiorite. Their normative mineral assemblage is of syenogranitic composition. Main metamorphic components are fine-grained K-feldspar, quartz, plagioclase, rare cordierite and biotite. K-feldspar and plagioclase crystals are interspersed with rounded quartz inclusions, K-feldspar displays myrmekite formation at the grain boundaries and plagioclase shows strong sericitization. Cordierite is often pinitized and/or overgrown by chlorite. Biotite is generally altered to chlorite.

*Garnet-bearing aplites:* The garnet-bearing aplites are of a very irregular shape and crosscut the granodiorite and the monzogranite (Fig. 5, loc. 1 and 2). Their contacts to the granodiorite and monzogranite can be both sharp or indistinct.

The syenogranitic, medium-grained mineral assemblage consists of K-feldspar, quartz, plagioclase, biotite and some poikilitic garnet of up to 1 cm in diameter (Fig. 4e). Some plagioclases are slightly zoned, biotite occasionally displays inclusions of sillimanite. Retrograde crystallization includes alteration of biotite to chlorite and the decomposition of garnet to biotite, plagioclase, hematite and chlorite along cracks. Allanite is a rare accessory mineral.

*Pegmatites:* Pegmatites contain variable amounts of plagioclase, K-feldspar, quartz and often diopside. K-feldspar is commonly overgrown by myrmekite, plagioclase is saussuritized and diopside is converted to green hornblende and biotite. Calcite is a frequent accessory mineral.

## CORRELATION OF ROCK TYPES

The association of rock types in the Bockfjorden area is similar to the one reported from the lower Hecla Hoek of NW Spitsbergen east of Monacobreen (GEE and HJELLE, 1966; HJELLE, 1979; GJELSVIK, 1979). The granite series may correspond to the late tectonic grey granitic rocks of HJELLE (1979), that are closely associated with layered gneisses and migmatites (HJELLE and OHTA, 1974; HJELLE, 1979). These layered gneisses and migmatites partly show the same features as the banded orthogneiss in the studied area.

GEE and HJELLE (1966) defined the Generalfjella Formation in which marbles are widespread. It has been suggested that the marbles in the Bockfjorden area also belong to this formation (GJELSVIK, 1979). However, there is an uncertainty in this correlation as it is not clear if both rock associations underwent a similar structural evolution and as no detailed age determinations exist.



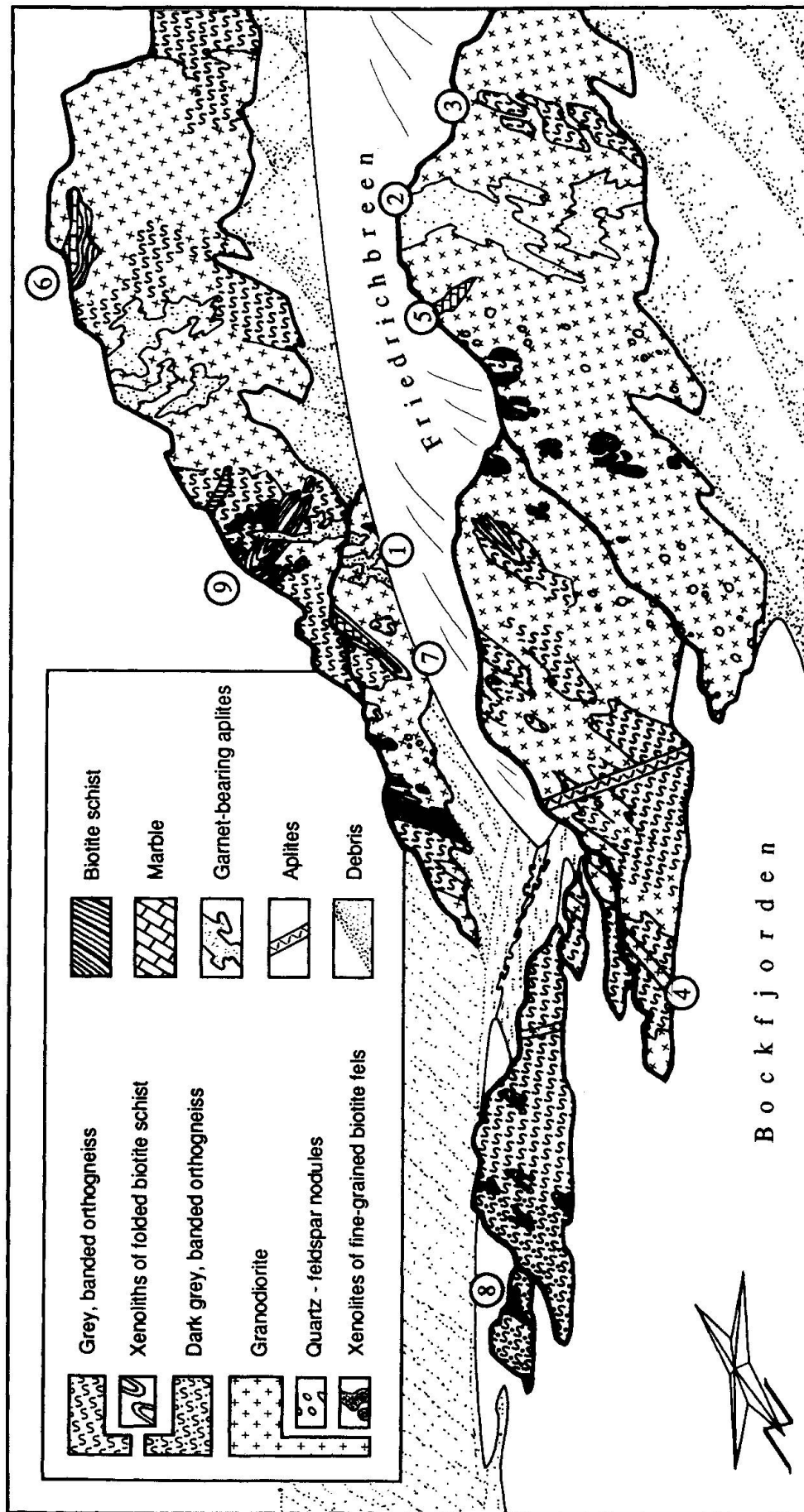


Fig. 5 Intrusive relationships at the eastern border of the granite series, below the glacier tongue of Friedrichsreen. Explanations to localities 1-9 are given in the text. View from north to south. Scale: locality 5: 1 cm = 1.5 m; locality 9: 1 cm = 20 m.



In addition, the thickness of these rock types is quite different. GEE and HJELLE (1966) reported 2000 metres of Generalfjella formation sediments, whereas the biotite schist and marble in the Bockfjorden area have a maximum thickness of about 600 metres.

### Bulk rock chemistry of the intrusive rocks

In the investigated area two intrusive events are distinguished: an older intrusion  $I_1$  of tonalitic to monzogranitic composition and the younger granite series (intrusion  $I_2$ ). The intrusion  $I_1$  is completely transformed to banded orthogneiss by the deformation  $D_2$ . The younger granite series  $I_2$  by contrast crosscut the  $D_2$  structures. Xenoliths of banded orthogneiss are widespread within the granite series. The intrusive contacts are best exposed in front of the glacier tongue of Friedrichbreen (Fig. 2). A detailed overview of this area is given in figure 5, showing the field relationships between the observed rock types.

Bulk rock analyses of biotite schist, of banded orthogneiss and of different rock types of the granite series (Tab. 2) were carried out in order to clarify four problems:

1) *Is there a difference in the chemical composition of the rocks belonging to the two magmatic events  $I_1$  and  $I_2$ ?* The major elements show similar distribution patterns for  $I_1$  and  $I_2$  rocks, an example of which is given in figure 6. The distribution patterns of minor- and trace elements are very similar for the  $I_1$  rocks (pattern 3; Fig. 7 and Tab. 3) and for part of the  $I_2$  rocks (granodiorite, pattern 1; Fig. 7 and Tab. 3). Another part of the  $I_2$  rocks (monzogranite, schlieren granite, garnet-bearing aplite and sample B11 of granodiorite) is characterized by pattern 2 (Fig. 7 and Tab. 3). Therefore, neither major element- nor minor- and

trace element distribution patterns provide arguments for a clear chemical distinction of the rocks of the two magmatic events  $I_1$  and  $I_2$ .

2) *Do the magmas of  $I_1$  and  $I_2$  represent partial melts of the upper mantle or do they represent partial melting of the crust?* In the rocks of  $I_1$  as well as in the rocks of  $I_2$  the  $K_2O$ ,  $FeO_{tot}$ ,  $Al_2O_3$  and  $SiO_2$  content varies strongly (Tab. 2). However, the  $MgO/MgO + FeO_{tot}$ -ratio remains almost constant (Fig. 6). This demonstrates, that the melts of  $I_1$  and  $I_2$  did not undergo large fractionation during their intrusion. By contrast, in differentiated intrusions the mafic index decreases with increasing  $SiO_2$ -content. Therefore, the magmas of  $I_1$  and  $I_2$  do not represent differentiated melts from an upper mantle source. This is supported by the lack of mafic enclaves that crystallized from more primitive melts in differentiated intrusions (CHAPPELL and WHITE, 1974). The mostly peraluminous chemistry (Tabs 2, 3) of the granite series and of the orthogneiss classifies these rocks as

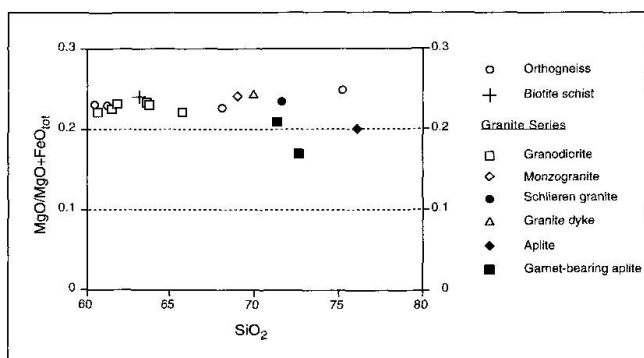


Fig. 6 Major elements plotted in a  $SiO_2$  versus  $MgO/MgO + FeO_{tot}$  diagram. The distribution pattern is representative for  $K_2O$ -,  $FeO_{tot}$ - and  $Al_2O_3$  versus  $MgO/MgO + FeO_{tot}$  diagrams.

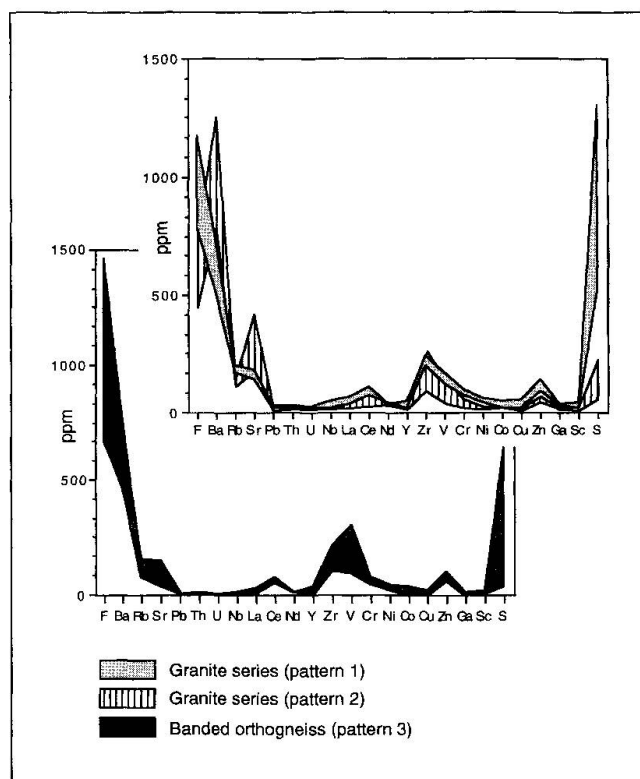


Fig. 7 Diagrams for the minor and trace elements in the banded orthogneiss and in the granite series. Within the granite series, two different minor- and trace element distribution patterns can be distinguished. Pattern 1 displays high F/Ba and F/Rb ratios, high Ba/Rb ratios and low Rb/Sr ratios. Pattern 2 shows F/Ba ratios lower than 1, high Ba/Rb ratios and Rb/Sr ratios lower than 1. The minor and trace element distribution pattern 3 for the banded orthogneiss is similar to pattern 1 of the granite series.

Tab. 2 Bulk chemical composition of  $I_1$  and  $I_2$  rocks from the Bockfjorden area.

The bulk chemical composition was determined by X-ray fluorescence (XRF) analyses with a sequential spectrometer (Philips PW 1404) using natural USGS rock samples for calibration. Rocks were ground in a tungsten carbide mill. Major elements were determined using glass beads which were fused from ignited (at 1050 °C) rocks powders mixed with  $Li_2B_4O_7$  in a 1/5 ratio in gold platinum pans at 1150 °C. The intensities were corrected for instrumental drift, background and matrix effects. The trace elements were determined by XRF analyses of 10g rock powder samples using the synthetic background method for which major elements have to be known (NISBERG et al., 1979).

Orthogneiss				Granodiorite								Monzo- Schlieren granite				Aplite				Garnet-bearing aplite			
Sample	B1	B7	B7/1	A7	B10	B11	B12	B13	B17	B21	K9	K13	B9	B16	E4	detection limit							
Major Elements (wt%)																							
SiO <sub>2</sub>	68.12	60.44	61.21	65.8	61.33	70.12	61.75	63.57	63.72	60.65	69.15	71.48	75.64	71.3	72.81								
TiO <sub>2</sub>	0.75	1.04	1.1	0.75	0.97	0.41	1.03	0.89	0.74	1.02	0.78	0.21	0.05	0.24	0.22								
Al <sub>2</sub> O <sub>3</sub>	15.25	17.7	17.26	15.5	18.14	16.25	17.62	17.04	16.56	18.8	15.9	15.36	13.93	14.46	14.66								
Fe <sub>2</sub> O <sub>3</sub> <sup>1</sup>	6.25	8.4	8.98	5.86	8.09	3.89	8.49	7.46	6.89	8.91	5.22	1.54	0.52	1.89	2.5								
MnO	0.04	0.1	0.11	0.09	0.09	0.06	0.1	0.1	0.04	0.08	0.07	0.01	0.01	0.02	0.11								
MgO	1.83	2.51	2.66	1.66	2.38	1.26	2.56	2.26	2.06	2.53	1.7	0.47	0.13	0.51	0.5								
CaO	1.29	1.34	1.26	1.6	1.51	0.82	1.29	1.49	1.74	0.86	2.85	2.18	0.66	1.3	1.33								
Na <sub>2</sub> O	1.56	1.92	1.64	1.85	2.1	1.48	1.77	2.3	2.14	1.48	2.78	3.33	2.76	2.19	2.25								
K <sub>2</sub> O	3.04	4.45	3.69	3.43	3.65	4.88	3.67	3.45	3.28	4.13	2.42	3.54	5.82	5.84	4.98								
P <sub>2</sub> O <sub>5</sub>	0.26	0.15	0.09	0.13	0.13	0.12	0.1	0.14	0.07	0.12	0.12	0.05	0.04	0.09	0.11								
Cr <sub>2</sub> O <sub>3</sub>	0.01	0.01	0.02	0.01	0.01	0	0.02	0.01	0.01	0.02	0	0	0	0	0								
volatiles	1.63	1.5	1.54	1.68	1.52	1.24	1.76	1.43	2.08	2.65	0.66	0.47	0.47	0.6	0.31								
Σ	100.03	99.56	99.56	98.4	99.92	100.53	100.16	100.14	99.33	101.25	100.65	98.64	100.03	98.44	99.78								
Trace Elements (ppm) <sup>2</sup>																							
F	743	1191	1104	816	759	479	1221	886	1179	1129	817	341	327	494	434								
Ba	570	797	480	726	592	1252	519	570	497	595	1132	817	119	1173	851								
Rb	119	163	159	155	146	123	166	142	174	194	107	138	257	151	131								
Sr	121	157	127	178	161	168	127	135	163	123	309	463	45	216	204								
Pb	<5	13	<5	<5	7	13	10	<5	<5	11	<5	7	11	13	14								
Nb	<4	6	6	<4	10	<4	9	8	29	9	<4	<4	<20	<4	<4								
La	21	27	26	35	41	<20	25	39	40	25	41	<20	<20	72	35								
Ce	49	66	63	79	73	17	63	68	84	56	86	<15	<15	122	106								
Nd	<25	<25	27	<25	<25	<25	27	<25	<25	<25	<25	<25	<25	41	33								
Y	27	30	28	27	34	17	35	30	8	33	19	<3	22	24	33								
Zr	151	206	226	195	199	82	227	182	199	191	233	91	41	240	241								
V	99	156	161	99	149	34	153	144	120	135	135	14	<10	22	24								
Cr	53	75	81	55	86	21	76	77	70	79	48	<6	<6	7	24								
Ni	29	41	49	24	29	12	42	28	28	44	20	5	<3	<3	<3								
Co	19	<4	<4	16	23	13	<4	22	21	5	18	7	8	11	6								
Cu	5	15	27	9	43	<3	25	21	24	31	<3	<3	<3	<3	<3								
Zn	86	109	115	74	104	45	117	100	121	120	63	18	7	18	12								
Ga	14	18	19	16	19	9	21	18	20	21	14	15	15	9	8								
Sc	18	27	28	16	25	8	26	23	10	26	17	2	2	6	9								
S	134	343	676	<50	1285	<50	640	510	903	1192	<50	<50	<50	<50	137								

<sup>1</sup> Fe<sub>2</sub>O<sub>3</sub> is total iron<sup>2</sup> Th < 5, U < 10

Tab. 3 Excess of  $Al_2O_3$ , trace element patterns (according to Fig. 7) and occurrence of the Al-bearing minerals sillimanite, cordierite and garnet for 15 rock samples from the Bockfjorden area. Crd = cordierite; Grt = Garnet; Sil = sillimanite.

Calculation scheme of  $Al_2O_3$  excess: Rocks were normalized to CIPW norm. As biotite does not occur in CIPW norm, it was calculated according to the reaction orthopyroxene + K-feldspar + corundum  $\rightarrow$  biotite + quartz. Orthopyroxene was completely consumed, therefore some corundum (expressed as excess  $Al_2O_3$ ) remained.

Rock type	Sample	$Al_2O_3$ excess oxide %	Trace element pattern (according to Fig. 7)	Al - minerals
Orthogneiss	B1	5.5	3	Crd, Sil
	B7	5	3	Crd, Sil
	B7/1	5.6	3	Crd, Sil
Granodiorite	A7	4.3	1	Crd, Sil
	B10	5.6	1	Crd, Sil
	B11	5.8	2	Crd, Sil
	B12	5.8	1	Crd, Sil
	B13	4.6	1	Crd, Sil
	B17	4.2	1	Crd, Sil
	B21	7.8	1	Crd, Sil
Monzogranite	K9	1.9	2	rare Sil
Schlieren granite	K13	1.6	2	—
Aplite	B9	1.7	—	rare Crd
Grt-bearing aplites	B16	1.8	2	rare Grt
	E4	2.6	2	rare Grt

S-type granitoids (CHAPPELL and WHITE, 1974), indicating that their origin was related to partial melting of crustal rocks.

3) *Is the overall presence of sillimanite and cordierite in the banded orthogneiss, in granodiorite and in aplites and their scarcity or even absence in the monzogranite and in schlieren granite a function of chemical composition?* Table 3 shows that all cordierite- and sillimanite-rich samples from the banded orthogneiss and from the granodiorite display large excess of  $Al_2O_3$ . The presence of sillimanite and cordierite has therefore to be considered as a function of bulk rock composition.

4) *Were the rocks with minor  $Al_2O_3$  and the rocks with large excess of  $Al_2O_3$  derived from different protoliths?* Rocks with large excess of  $Al_2O_3$  are generally characterized by the trace element patterns 1 and 3, whereas rocks with low  $Al_2O_3$  display pattern 2 (Tab. 3, Fig. 7). However, sample B11, characterized by trace element pattern 2, displays large excess of  $Al_2O_3$ . Therefore, a different origin for high-Al rocks and for low-Al rocks is unlikely.

### Magmatic events, structures and metamorphism

Intrusive contacts and their relations to structures and metamorphism were mainly observed on key-

outcrops below the tongue of Friedrichbreen (Fig. 5) and on Koveryggen. Observations from these outcrops permit to deduce a detailed sequence of events (Tab. 4, I–IX) for the Bockfjorden area.

#### I) $D_1$ DEFORMATION: ISOCLINAL FOLDING OF THE BIOTITE SCHIST

The oldest structure preserved in the studied area is the isoclinal folding  $F_1$  of the banding  $B_0$  in the biotite schist, that is associated to the formation of an axial surface schistosity  $S_1$  (Fig. 8). No  $F_1$  folds have been observed in the marbles. A pre- $D_1$  set of pegmatite dikes of unknown origin was boudinaged during the  $D_1$  deformation (Fig. 5, loc. 9).

The degree of the accompanying metamorphism is difficult to determine, since these rocks were subsequently affected by the  $M_2$  metamorphism and by a high T-low P metamorphism (VII).

#### II) $I_1$ : FIRST PHASE OF MAGMATISM; THE INTRUSION OF THE PROTOLITH GRANITOIDS OF THE ORTHOGNEISS

The banded orthogneiss is considered as the granitoid of a first phase of magmatism  $I_1$ , that intruded the metasediments after  $D_1$ . Evidence for this

Tab. 4 Sequence of events from the Bockfjorden area, compared to the tectonometamorphic evolution of NW Spitsbergen after HJELLE (1979).

Event	Features	Interpretation	Comparison to Hjelle (1979)
<b>I D<sub>1</sub> deformation</b>	Isoclinal folding of the biotite schist, schistosity S <sub>1</sub> <i>Amphibolite facies</i>	a) Early Caledonian phase? b) Grenvillian deformation?	a) F <sub>1</sub> : Isoclinal folding, development of cleavage <i>Upper amphibolite facies</i>
<b>II I<sub>1</sub>: First phase of magmatism</b>	Intrusion of granitoids with a monzogranitic to tonalitic composition, crosscutting D <sub>1</sub> structures Formation of xenoliths of biotite schist and marble	a) Magmatism related to subduction? b) Late Grenvillian intrusions?	
<b>III D<sub>2</sub> deformation M<sub>2</sub> metamorphism</b>	Isoclinal folding F <sub>2</sub> in biotite schist and marble, main schistosity S <sub>2</sub> , lineation L <sub>2</sub> , shear sense top-to-the N Transformation of the I <sub>1</sub> granitoids to orthogneiss <i>Amphibolite facies, High T, medium P</i>	Main Caledonian deformation	F <sub>2</sub> : Main recrystallization, isoclinal folding, development of layering and gneissosity <i>Upper to lower amphibolite facies</i>
<b>IV Migmatite formation</b>	Segregation of leucocratic layers in the orthogneiss → banded orthogneiss	Incipient partial melting of the orthogneiss due to crustal extension	F <sub>3</sub> : Migmatite formation, emplacement of syntectonic grey granite; weak open folding, initiation of main anticlinorium
<b>V D<sub>3</sub> disharmonic folding</b>	Disharmonic folding F <sub>3</sub>	Deformation due to ballooning during the intrusion of I <sub>2</sub> ?	<i>Lower amphibolite facies</i> (Local development of <i>lowermost granulite facies</i> east of Smeerenburgfjorden)
<b>VI I<sub>2</sub>: Second phase of magmatism; the granite series</b>	Intrusion of granodiorite and monzogranite with aplites and pegmatites, crosscutting biotite schist, marble and I <sub>1</sub> banded orthogneiss Formation of xenoliths of biotite schist, marble and banded orthogneiss <i>Contact metamorphism</i>	Emplacement of magmas derived from partial melting of crustal rocks due to extension of the crust	
<b>VII High T–low P metamorphism</b>	Annealing of previous fabrics; formation of cordierite in biotite schist, banded orthogneiss and granodiorite; geotherm of 50°/km <i>High T, low p metamorphism</i>	Continuous decompression due to extension of the crust	
<b>VIII D<sub>4</sub> deformation</b>	E-vergent folding F <sub>4</sub> , local thrust faults <i>Upper greenschist facies</i>	E–W compression, E-vergent thrusting	
<b>IX D<sub>5</sub> deformation Bockfjorden antiform</b>	Open, large scale folding F <sub>5</sub> with subvertical, N–S trending axial surfaces	E–W compression	

sequence is given by enclaves of marble (Fig. 5, loc. 7) and of biotite schist (Fig. 5, loc. 8) that are enclosed by the banded orthogneiss. These enclaves display sharp contacts towards the banded orthogneiss. In addition, they are occasionally rimmed by metamorphic contact zones: The biotite schist enclaves display hornfels rims, whereas wollastonite-bearing mineral assemblages are

observed in the marble enclaves. Both, sharp contacts and contact metamorphic rims label them as xenoliths. The isoclinal F<sub>1</sub> folds are documented in the biotite schist xenoliths only, in the banded orthogneiss by contrast, they are not recorded (Fig. 8). This indicates that the biotite schist was intruded by the protolith granitoids of the banded orthogneiss after D<sub>1</sub>.

### III AND IV) D<sub>2</sub> DEFORMATION, M<sub>2</sub> METAMORPHISM AND MIGMATITE FORMATION

The deformation D<sub>2</sub> is characterized by the isoclinal folding F<sub>2</sub>, that is associated to the penetrative schistosity S<sub>2</sub> in the biotite schist and in the marbles. S<sub>2</sub> is the main schistosity in the studied area. The I<sub>1</sub> granitoids were transformed to orthogneiss by D<sub>2</sub> (Fig. 8). In the biotite schist and in the marbles a N-S-trending stretching lineation L<sub>2</sub> was formed on the schistosity S<sub>2</sub> (Fig. 2). In the marbles and associated rocks, a strong difference in competence between the metapelitic/metabasic layers and the marble lead to dismembering and to rotation of the metapelitic/metabasic layers during D<sub>2</sub> deformation. Figure 9 shows a dismembered and rotated metapelitic layer. Rotation as well as the asymmetric tails of the boudin point to a simple shear dominant deformation. Some rare asymmetric clasts within the marble indicate a top-to-the N sense of shear. The fold axis of the F<sub>2</sub> isoclinal folds are oriented parallel to L<sub>2</sub>. This may be explained by rotation of the fold axis due to strong D<sub>2</sub> simple shearing.

Generally, only relics of the mineral assemblages related to the metamorphism M<sub>2</sub> are preserved except diopside, phlogopite and biotite, that represent the schistosity S<sub>2</sub> in the marbles and in the biotite schist, respectively. This is due to the later high T-low P metamorphism (VII), that lead to an annealing of the fabrics. A biotite schist xenolith displays relics of sillimanite on S<sub>2</sub> that are overprinted by folds of the subsequent deformation D<sub>3</sub> (Fig. 4f). In the orthogneiss oriented silli-

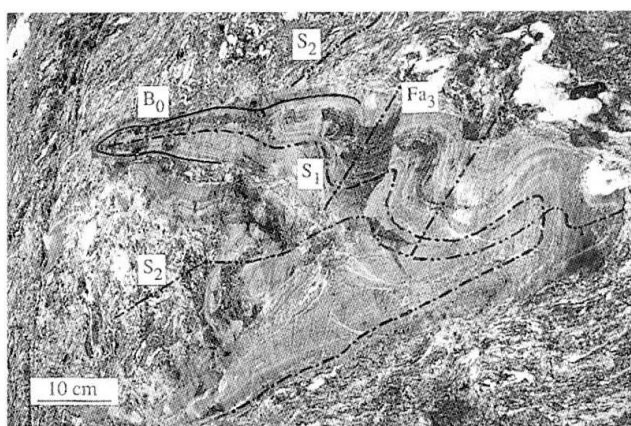


Fig. 8 Xenolith of biotite schist in the banded orthogneiss (see Fig. 5, loc. 8). The xenolith is isoclinally folded by F<sub>2</sub>, the axial surface cleavage of which corresponds to the main schistosity S<sub>2</sub> in the orthogneiss. F<sub>2</sub> deforms the axial surface schistosity S<sub>1</sub> in the biotite schist, that is related to the isoclinal fold F<sub>1</sub>, affecting the primary banding B<sub>0</sub>. The main schistosity S<sub>2</sub> is crenulated by F<sub>3</sub> (Fa<sub>3</sub> = fold axis of F<sub>3</sub>) in the orthogneiss and in the biotite schist.

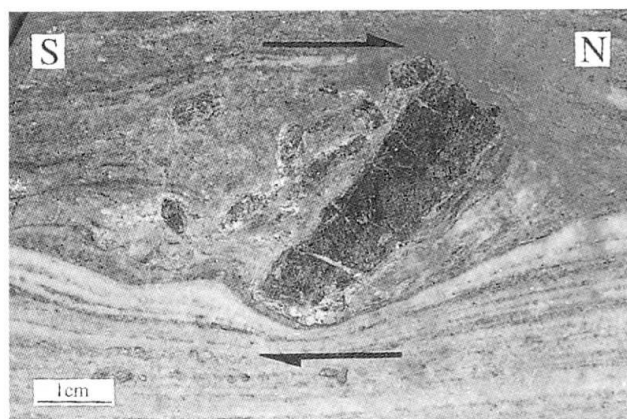


Fig. 9 Rotated boudin of a competent metapelitic layer with asymmetric tails in the marble, indicating a top-to-the N sense of shear.

manite is included in cordierite and in plagioclase (Fig. 4c). Other inclusions are rounded quartz and biotite (Fig. 4b) as well as rare garnet that are considered to be grown during D<sub>2</sub>. The mineral assemblages related to D<sub>2</sub> are summarized in table 1 for all rock types, indicating upper amphibolite facies conditions for M<sub>2</sub>.

The banded orthogneiss is characterized by a metamorphic differentiation in melanocratic and leucocratic layers that blurs the schistosity S<sub>2</sub> (Figs 4a, 8, 10). However, leucosomes crosscutting D<sub>2</sub> have not been observed. This feature is interpreted as incipient partial melting of the orthogneiss during late stage- or post-D<sub>2</sub> deformation. The M<sub>2</sub> upper amphibolite facies metamorphism thus reached its thermal peak conditions during late D<sub>2</sub> migmatite formation.

### V) D<sub>3</sub> DISHARMONIC FOLDING

Near the contact to the granite series rocks the orthogneiss is overprinted by the disharmonic folding F<sub>3</sub> (Figs 8, 10). Neither F<sub>3</sub> fold axis nor axial surfaces display a systematic orientation. These chaotically oriented structural elements suggest a plastic behavior of the orthogneiss during D<sub>3</sub>. The folding F<sub>3</sub> may have occurred during or after migmatite formation. It may be related to a ballooning effect of the granite series intrusion (VI) into the weak migmatites, indicating that the granite series intruded into still hot country rocks.

### VI) I<sub>2</sub>: SECOND PHASE OF MAGMATISM; THE INTRUSION OF THE GRANITE SERIES

Xenoliths of strongly foliated biotite schist, marble and banded orthogneiss occur in undeformed



Tab. 5 Mineral compositions representative for the  $M_2$  mineral assemblage in orthogneiss (a), for the mineral assemblage of the high P–low P metamorphism in orthogneiss (b) and for the garnet-bearing aplite (c). Mineral compositions were analyzed using a Cameca SX-50 microprobe, equipped with five crystal spectrometers. Samples were coated with 200 Å of carbon. Operating parameters include an acceleration potential of 15 kV, a beam current of 20 nA and a beam size of 10 Å. Data collection time was 20 s. Natural and synthetic oxides and silicates were used as standards. A ZAF type correction procedure was applied to the data.

	a) Inclusions in cordierite (orthogneiss, sample B1)		b) Equilibrium paragenesis in orthogneiss (sample B1)				c) Garnet-bearing aplite (sample E4)					av. relative error (2 $\sigma$ ) in %
weight %	Gar	Bio	Kfs	Plag	Bio	Crd	Gar (core)	Gar (rim)	Bio	Kfs	Plag	
SiO <sub>2</sub>	35.8	32.7	64.0	61.0	33.4	46.6	37.5	36.8	34.1	64.5	61.0	1.4 (at 40% level)
TiO <sub>2</sub>	< 0.03	4.15	< 0.03	< 0.03	3.46	< 0.03	< 0.03	< 0.03	3.72	< 0.03	< 0.03	3.2 (at 4.0% level)
Al <sub>2</sub> O <sub>3</sub>	20.7	17.8	19.3	23.8	18.2	31.8	21.7	21.7	19.7	19.0	24.3	1.6 (at 20% level)
Fe <sub>2</sub> O <sub>3</sub> <sup>1</sup>	1.93	6.05			1.64		2.38	2.97	3.25		0.12	
FeO	34.5	17.7	< 0.05	< 0.05	20.0	11.2	34.7	32.2	19.6	< 0.05		2.2 (at 20% level)
MnO	4.02	0.10	< 0.03	< 0.03	0.14	0.30	3.18	6.99	0.23	< 0.03	0.07	12.0 (at 0.5% level)
MgO	1.65	6.90	< 0.04	< 0.04	6.79	6.36	3.10	2.18	6.82	< 0.04	< 0.04	1.4 (at 7% level)
CaO	0.81	0.12	0.10	5.50	< 0.02	< 0.02	1.02	0.61	0.04	0.04	5.35	2.4 (at 5% level)
Na <sub>2</sub> O	na	0.19	2.04	8.29	0.24	0.35	na	na	0.19	1.59	8.59	10.2 (at 0.2% level)
K <sub>2</sub> O	na	8.54	13.8	0.62	9.24	< 0.02	na	na	8.64	14.1	0.39	2.2 (at 9% level)
Cl	na	0.28	na	na	0.30	< 0.02	na	na	0.10	na	na	10.0 (at 0.2% level)
H <sub>2</sub> O <sub>calc</sub>		3.77			3.74				3.91			
$\Sigma$	99.6	98.5	99.3	99.3	98.1	96.7	103.6	103.4	100.3	99.3	99.8	
Ions calculated on the basis of 8 cations (garnet), 5 cations (feldspars), 3 cations (sillimanite), 18 oxygens (cordierite) and 11 oxygens and cations-Na-K = 7-Ti (biotite)												
Si	2.94	2.56	2.95	2.73	2.63	4.97	2.93	2.90	2.59	2.98	2.71	
Ti	0.00	0.24	0.00	0.00	0.20	0.00	0.00	0.00	0.21	0.00	0.00	
Al	2.01	1.64	1.04	1.26	1.68	3.99	1.99	2.02	1.76	1.04	0.00	
Fe <sub>3</sub>	0.12	0.36	0.00	0.00	0.10	0.00	0.14	0.18	0.19	0.00	1.27	
Fe <sub>2</sub>	2.37	1.15	0.00	0.00	1.37	1.00	2.27	2.13	1.25	0.00	0.00	
Mn	0.28	0.01	0.00	0.00	0.01	0.03	0.21	0.47	0.01	0.00	0.00	
Mg	0.20	0.80	0.00	0.00	0.80	1.01	0.36	0.26	0.77	0.00	0.00	
Ca	0.07	0.01	0.01	0.26	0.00	0.00	0.09	0.05	0.00	0.00	0.25	
Na	0.00	0.03	0.18	0.72	0.04	0.07	0.00	0.00	0.03	0.14	0.74	
K	0.00	0.85	0.81	0.04	0.93	0.00	0.00	0.00	0.84	0.83	0.02	
Cl	0.00	0.04	0.00	0.00	0.04	0.00	0.00	0.00	0.01	0.00	0.00	
OH	0.00	1.96	0.00	0.00	1.96	0.00	0.00	0.00	1.99	0.00	0.00	

<sup>1</sup> calculated assuming stoichiometry, na: not analysed

or only weakly foliated granodiorite and monzogranite of the granite series (Fig. 5, locs 3, 5 and 6). Figure 5 (loc. 3) and figure 10 show a weakly foliated granodiorite with a xenolith of banded orthogneiss, that displays the schistosity  $S_2$  and disharmonic folds  $F_3$ . This demonstrates that  $D_2$  and  $D_3$  occurred prior to the granite series intrusion. Further evidence for this sequence is given by undeformed granodiorite dikes crosscutting the orthogneiss (Fig. 5, loc. 4). The granite series is thus considered to represent the youngest intrusive rocks in the Bockfjorden area.

Marble xenoliths enclosed in granite series rocks (Fig. 5, loc. 5 and loc. 6) display a mineral assemblage that is different from the assemblages observed in the marbles that are not in contact with the granite series intrusion (Tab. 1). This is interpreted as the result of a contact metamorphism in the xenoliths.

## VII) HIGH T–LOW P METAMORPHISM

Generally, the high T–low P metamorphism is not associated to deformation. Locally however, it is related to a schistosity at the boundaries of the granite series in the granodiorite and in the monzogranite. As the high T–low P metamorphism annealed the fabrics of all previous events in the metasediments as well as in the banded orthogneiss and in some granite series rocks, it is considered to represent the latest stage of metamorphic crystallization leading to equigranular, polygonal fabrics (Fig. 4a). The schistosity  $S_2$ , however, was not blurred by the high T–low P metamorphism, it is preserved either by diopside and phlogopite in the marbles or by biotite in the biotite schist and in the banded orthogneiss.

The high T–low P metamorphism is characterized by the crystallization of cordierite together

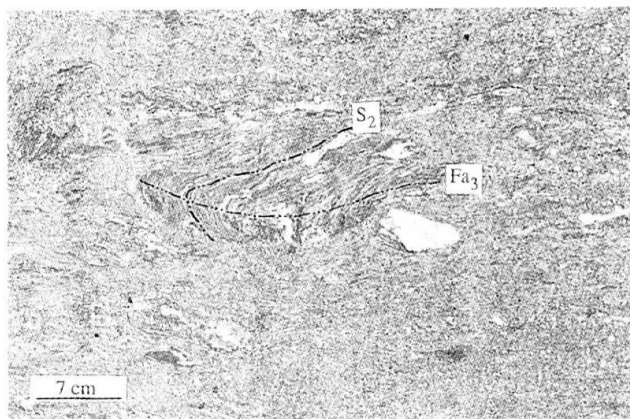


Fig. 10 Granodiorite with xenolith of banded orthogneiss that was folded by  $F_3$  (see Fig. 5, loc. 3). The granodiorite is bare of  $F_3$  folds.  $S_2$  = main schistosity;  $Fa_3$  = fold axis of  $F_3$ .

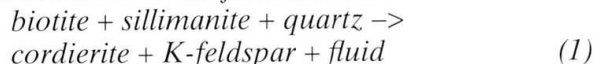
with quartz, plagioclase, K-feldspar and biotite in the biotite schist, in the banded orthogneiss and in the granodiorite of the granite series (Tab. 1, Figs 4a–c). Biotite is intergrown with sillimanite. In K-feldspar and cordierite, rounded biotite and quartz inclusions are common as relics of the  $M_2$  mineral assemblage (Fig. 4b). In the granodiorite  $M_2$ -sillimanite and rare garnet are additional inclusions in cordierite. This demonstrates, that cordierite has a metamorphic and not a magmatic origin in the  $I_2$  rocks.

It is noteworthy that the high T–low P metamorphism did not cause crystallisation of cordierite in all rocks of the granite series. Calculated norms based on whole rock chemistry indicate that the occurrence of abundant cordierite is restricted to rocks with a large excess of  $Al_2O_3$  that occurs especially in the granodiorite (Tab. 3). The garnet-bearing schlieren aplites display also excess of  $Al_2O_3$ , which is documented by magmatic garnet (Tab. 3, Fig. 4e).

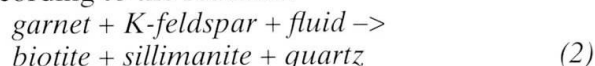
The mineral chemistry of three assemblages, that are representative a) for the  $M_2$  mineral assemblage (relics of garnet, biotite and sillimanite as inclusions in cordierite, sample B1 in Tab. 5), b) for the mineral assemblage of the high T–low P metamorphism in an orthogneiss (sample B1 in Tab. 5) and c) for the garnet-bearing aplite (sample E4 in Tab. 5) corresponds well with analyses from a gneiss-migmatite complex about 45 kms WNW of the studied area (KLAPER, 1986). Klaper calculated temperatures of 650 °C and 0.5–0.6 GPa for the mineral assemblage biotite + cordierite + plagioclase + K-feldspar + garnet + sillimanite + quartz.

As garnet is very rare in the cordierite- and aluminosilicate-bearing rocks of the studied area,

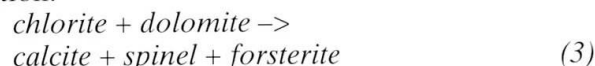
but biotite, quartz and sillimanite occur frequently as inclusions within cordierite and K-feldspar, the following cordierite forming reaction is proposed for the Bockfjorden area:



However, biotite and sillimanite included in cordierite are unlikely to represent magmatic minerals. In many peraluminous granites garnet is a primary magmatic phase. The relative scarcity of garnet and the frequent occurrence of sillimanite and biotite might indicate that primary magmatic garnet was decomposed to biotite and sillimanite, according to the reaction:



In the silica undersaturated marble, the mineral assemblage dolomite + calcite + spinel + forsterite ( $\pm$  chlorite) (Tab. 1) is formed by the reaction:



BUCHER-NURMINEN (1981) described this reaction in rocks from a region near the area studied by KLAPER (1986), calculating temperatures of 610–680 °C for assumed pressures of 0.4 GPa.

In the phase diagram of HOLDAWAY (1971) and HOLDAWAY and LEE (1977) (Fig. 11), minimum conditions of 630 °C and 0.3 GPa are indicated for the reaction *biotite + sillimanite + quartz*  $\rightarrow$  *K-feldspar + cordierite + fluid* by the absence of

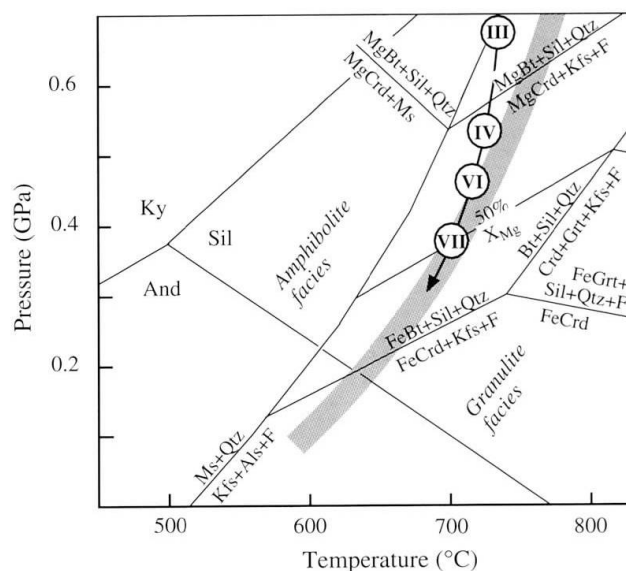


Fig. 11 Phase diagram after HOLDAWAY (1971) and HOLDAWAY and LEE (1977). The roman ciphers refer to the events in table 3: III: Metamorphism  $M_2$ , IV: Migmatite formation, VI: Second phase of magmatism  $I_2$ , VII: High T–low P metamorphism. Facies boundary (in grey) after SPEAR (1993).

white mica and by the measured  $X_{Mg}$  of 0.5 in cordierite. The lack of granulite facies mineral assemblages indicate that the metamorphic conditions did not exceed uppermost amphibolite facies. This is consistent with temperatures of 630–700 °C and pressures of 0.3–0.4 GPa for an  $X_{Mg}$  of 0.5 in cordierite. High temperature–low pressure conditions are thus derived for this stage of metamorphism from metapelitic rocks as well as from metacarbonates. On the basis of these data it is suggested that cordierite formed during near isothermal decompression within upper amphibolite facies.

#### VIII) $D_4$ DEFORMATION: EAST-VERGENT FOLDING

An east-vergent, open to isoclinal folding  $F_4$  overprints the schistosity  $S_2$ , the intensity of which increases to thrust folding on Kovergygen. In isoclinal  $F_4$  fold hinges the mineral assemblage of the high T–low P metamorphism breaks down to an upper greenschist facies mineral assemblage (see Tab. 1; "retrograde metamorphism"). In the marble for example, tremolite crystallizes parallel to the  $F_4$  axial surface, whereas quartz and calcite underwent ductile deformation. This indicates that  $D_4$  postdates the high T–low P metamorphism

and therefore also the  $I_2$  intrusion of the granite series.

#### IX) $D_5$ DEFORMATION: THE OPEN BOCKFJORDEN ANTIFORM

In the eastern part of the studied area the schistosity  $S_2$  dips to the E and in the western part, it dips to the W (Fig. 2) forming a regional antiform referred to as the Bockfjorden antiform. This antiform structure was described by GJELSVIK (1979). It is, however, not coincident with the east-vergent folding  $F_4$  (Fig. 12): On the eastern side of the Bockfjorden Antiform the  $F_4$  small scale folds are verging towards east. This demonstrates that they cannot be considered as second order folds to the Bockfjorden antiform. In addition, E of Smørstabben the axial surfaces of  $F_4$  folds are overprinted by very open folds of 10 to 500 meters wavelength, that are related to the Bockfjorden antiform. This indicates that the Bockfjorden antiform was formed posterior to  $D_4$ .

#### Discussion

The pre-Devonian basement rocks of the Bockfjorden area were affected by nine tectonothermal events. The features and interpretations of

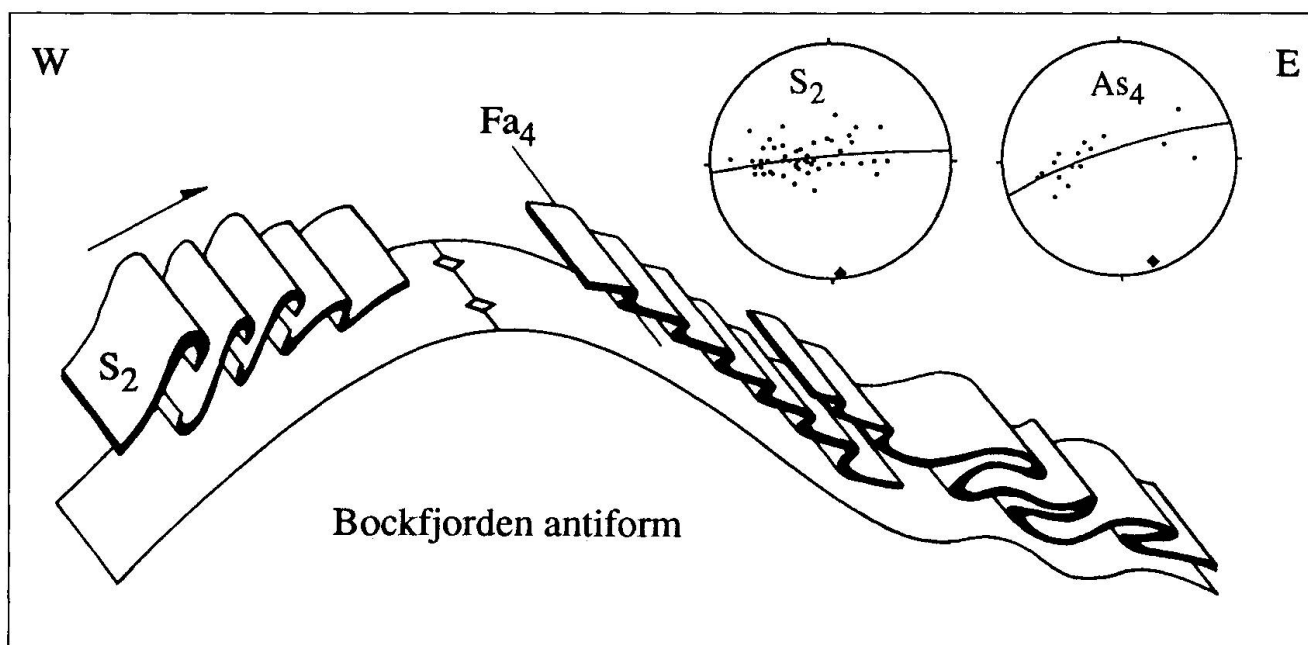


Fig. 12 Schematic structural sketch showing the relation between east-vergent folding  $F_4$  and the Bockfjorden antiform  $F_5$ .  $S_2$  = schistosity related to  $D_2$ ,  $Fa_4$  = fold axis of  $F_4$ .  $As_4$  = axial surface of  $F_4$ . The sketch is not to scale; the Bockfjorden antiform is about 8 km wide, the small scale folds of  $F_4$  are of a dm scale. The poles of  $S_2$  as well as of  $As_4$  scatter along a great circle due to subsequent deformation of  $D_2$  and  $D_4$  structures by the  $F_5$  Bockfjorden Antiform. The constructed axis of the Bockfjorden Antiform is subhorizontal and trends approximately in a N–S direction.

this sequence of events are summarized in table 4 (I–IX) and compared with the tectonometamorphic evolution of the basement rocks of central Northwestern Spitsbergen (HJELLE, 1979). According to HARLAND and WRIGHT (1979) central Northwestern Spitsbergen belongs to the same terrane as the Bockfjorden area (Central Terrane). In general, the sequence of events from the investigated area is consistent with the sequence from Central Northwestern Spitsbergen, where three main phases were distinguished (HJELLE, 1979):  $F_1$  (I in Tab. 4),  $F_2$  (III), and  $F_3$  (VI–VII).

The main results are discussed in the light of the subdivision of the Caledonian orogeny into a middle Ordovician period of accretion and subduction and a later middle Silurian continental collision (OHTA et al., 1984; DALLMEYER et al., 1990): First, the main phase of deformation III ( $D_2$ ) will be treated in relation to the Silurian continental collision. Then, we discuss the significance of the pre  $D_2$  phase II ( $I_1$ ) and attempt to correlate phase I ( $D_1$ ) and phase II ( $I_1$ ) to the regional tectonic evolution. Finally, the phases IV–VII and VIII–IX are discussed.

#### STRUCTURES RELATED TO COLLISION

The  $D_2$  deformation caused the dominant folding  $F_2$  and foliation  $S_2$  in the Bockfjorden area. It is correlated to the folding  $F_2$  of HJELLE (1979). The related stretching lineation  $L_2$  trends in a N–S direction. Strong stretching and rotation of competent boudins in the marbles (Fig. 9) indicate a simple shear dominated deformation during  $D_2$  with a top-to-the-N sense of shear. The  $F_2$  fold axes are parallel to the stretching lineation. It is suggested that the orientation of the fold axes has been rotated during  $D_2$  shearing. As a consequence, they can not be used to deduce the direction of tectonic transport during  $D_2$ . Therefore,  $D_2$  structures are considered to indicate N–S thrusting rather than E–W shortening. However, E–W shortening occurred during the east-vergent folding  $F_4$  and during  $F_5$ , causing the general N–S trend of the lithological boundaries in the basement rocks of Northwest Spitzbergen (see Fig. 1).

#### THE FIRST PHASE OF MAGMATISM $I_1$ : MIGMATITIC FEATURES VERSUS INTRUSIVE RELATIONSHIPS

Enclaves of biotite schist and marble are widespread within the banded orthogneiss. The biotite schist can either be regarded as melanocratic

restites or as metasedimentary xenoliths enclosed by magmatic rocks. Sharp contacts towards the banded orthogneiss demonstrate that they were crosscut by the intrusion of the protolith granitoids of the orthogneiss. They must therefore be considered as xenoliths. Evidence for this is also provided by the sequence of tectonometamorphic phases: The xenoliths were enclosed by the protolith granitoids of the banded orthogneiss prior to the deformation  $D_2$ , that caused the main schistosity  $S_2$ . Migmatite formation by contrast occurred during late stage metamorphism  $M_2$ . The xenoliths therefore must not be regarded as restites of the late to post- $D_2$  migmatite formation. The protolith granitoids of the banded orthogneiss were thus not produced by partial anatexis of the biotite schist. Consequently, we separate the banded orthogneiss from the partly migmatized paraserries of HJELLE (1979) and GJELSVIK (1979) and consider it as an older independent intrusive event.

There is only little evidence for incipient partial melting and migmatite formation during late stage Silurian continental collision. However, as the magmas of the  $I_2$  granite series are inferred to be derived from partial melting of crustal rocks, anatexis must be important in deeper levels of the continental crust at the end of the Caledonian convergence.

#### SIGNIFICANCE OF THE EVENTS $D_1$ AND $I_1$

Intrusive rocks (the first phase of magmatism  $I_1$ ) predating the middle Silurian collision tectonics  $D_2$  were not yet reported from the Bockfjorden area. They permit more insight into the complex evolution of the pre-Devonian basement rocks; their origin, however, remains unclear.

The deformation  $D_1$  and magmatism  $I_1$  predating the middle Silurian deformation  $D_2$  may be interpreted in two distinct ways. (a) They are either related to the middle Ordovician accretion or (b) they represent an older event, probably the Grenvillian orogeny.

(a) The isoclinal folding  $F_1$  in the biotite schist points to strong shortening combined with shearing during  $D_1$ . It may therefore be explained as a deformation related to early Caledonian accretion. If the biotite schist corresponds to the upper Proterozoic Generalfjella group (GJELSVIK, 1979), it could not have been affected by an orogeny older than the Caledonian one. The  $I_1$  intrusion could then be explained as a magmatism related to early Caledonian subduction. However, the peraluminous composition of the  $I_1$  intrusives and the lack of endogene xenoliths point to partial



melting of the crust. These magmas are thus not expected to be related to accretion and subduction processes.

(b) PEUCAT et al. (1989) describe granitic intrusions of 950–960 Ma from Biskayerhalvøya, the melts of which were at least partially derived from crustal anatexis. If the  $I_1$  intrusives corresponds to these granites,  $D_1$  and  $I_1$  could be related to the Grenvillian orogeny. Then, a correlation of the biotite schist to the Generalfjella group is unlikely and the biotite schist has to be considered as older. Preliminary age determinations on the banded orthogneiss from the Bockfjorden area point to a late Grenvillian age for the  $I_1$  intrusion (OHTA, pers. comm., 1997).

#### MIGMATITE FORMATION, MAGMA INTRUSION AND HIGH TEMPERATURE – LOW PRESSURE METAMORPHISM DURING CRUSTAL EXTENSION

On the basis of the observations in the Bockfjorden area, the  $F_3$  event of HJELLE (1979) can be subdivided into the four phases IV–VII (Tab. 4). This allows a reconstruction of the late Caledonian high temperature history (Fig. 11).

(IV) The banding of the orthogneiss is interpreted as late  $D_2$  migmatite formation due to incipient partial melting of  $I_1$  granitoid rocks.

(V and VI) The  $I_2$  granite series intrusion crosscuts the partially molten banded orthogneiss. It originated from partial melting of deep seated crustal rocks. Ballooning effects may have caused  $F_3$  disharmonic folding of the late  $D_2$  banding in the orthogneiss. Large volumes of granitic rocks originating from partial melting of crustal rocks are widespread in the Caledonides.

(VII) The formation of cordierite + K-feldspar at the expense of biotite + sillimanite + quartz in all Al-rich rock types including granodiorite of the  $I_1$  granite series during high T–low P metamorphism documents ongoing decompression after the intrusion of the granite series. In the studied area, the high T–low P metamorphism postdates formation of the migmatites, which is in contrast to HJELLE (1979) and KLAPER (1986). Pressure-temperature estimates for the cordierite formation are of 630–700 °C and of 0.3–0.4 GPa, corresponding to uppermost amphibolite facies conditions. The resulting high geotherm of about 50 °C/km is explained with extension of continental crust during high T–low P metamorphism (FOUNTAIN, 1989; HARLEY, 1989). Isothermal decompression (ITD) as it is documented for the Bockfjorden rocks has also been reported from granulite terranes (HARLEY, 1989). Such gran-

ulites are interpreted to develop in crust, that was previously thickened by collision. According to Harley, ITD paths are generated during thinning related to rapid tectonic exhumation, that cannot solely be explained by erosion, but must also be related to extension. Thus, the transition from migmatite formation to granite emplacement followed by cordierite formation is interpreted as a post-collisional continuous exhumation of the pre-Devonian basement rocks due to crustal extension.

#### THE AGE OF LATE-STAGE COMPRESSION

The east-vergent folding  $F_4$  (VIII) developed under retrograde greenschist facies conditions. The Caledonian retrograde metamorphism has been dated to 400–430 Ma by Rb–Sr and Ar–Ar biotite and muscovite cooling ages (DALLMEYER et al., 1990). Therefore,  $D_4$  is considered to be late Caledonian. It is more difficult to constrain the age of the Bockfjorden Antiform ( $D_5$ , IX). Large open folds have been mapped in the Devonian sediments east of Liefdefjorden (Figs 1, 2) as well as in Triassic sediments south of the Bockfjorden (HJELLE and LAURITZEN, 1982). Therefore it is likely, that  $F_5$  folding developed during Alpine convergence.

#### Conclusions

The complex evolution of the basement rocks in the Bockfjorden area permits the distinction of four different periods.

*Pre-Silurian evolution:* The situation encountered in the Bockfjorden area allows to show that pre-Caledonian igneous rocks form part of the Caledonian basement. These intrusive rocks ( $I_1$ ) cut an older penetrative deformation ( $D_1$ ) which is recorded in the biotite schist. This provides evidence for a complex pre-Silurian evolution of the basement rocks, that is probably related to the Grenvillian orogeny.

*Caledonian continental collision:* The first Caledonian event in this region is recorded by the simple shear dominated deformation  $D_2$ , that causes the main schistosity and that leads to N-directed thrusting in the Bockfjorden area. The metamorphic conditions ( $M_2$ ) reached upper amphibolite facies conditions.

*Post-collisional extension:* After the pressure peak of  $M_2$  a nearly isothermal decompression under upper amphibolite facies conditions led to migmatite formation in the  $I_1$  intrusive rocks. The subsequent emplacement of  $I_2$  S-type granitoid



melts provides evidence for anatexis in deeper levels of the crust. Ongoing decompression led to a high T–low P metamorphic overprint at conditions of 630–700 °C and 0.3–0.4 GPa, that is characterized by the formation of cordierite + K-feldspar at the expense of sillimanite + biotite + quartz. The evolution from partial melting to granite emplacement followed by high T–low P metamorphism related to a geotherm of about 50 °C/km provides evidence for a continuous exhumation of the crust due to crustal extension subsequent to collision. This may be interpreted as a collapse of the Caledonian thickened crust.

*Late stage compression:*  $F_4$  folding corresponds to late Caledonian shortening whereas  $F_5$  may have developed during Alpine convergence.

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