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Small dolomite marble lenses and bands occur in the vast Caledonian migmatite and gneiss area of NW Spitsbergen (Svalbard archipelago). The fine-banded marbles contain numerous assemblages of minerals: calcite, dolomite, olivine, clinohumite, diopside, amphibole, chlorite, spinel and phlogopite. The coexistence of calcite + dolomite + olivine + chlorite + spinel over the entire area indicates metamorphic temperatures of 600 to 680° at an estimated pressure of 4 kilobars. A temperature of near 600°C for the peak of metamorphism is suggested by mineral assemblages at the southernmost locality, Jäderinfjellet. Calcite–dolomite geothermometry indicated 595°C at the same locality. The spatial distribution of the marble assemblages suggests that metamorphism occurred under nearly isothermal conditions over an area of at least 25 by 30 kilometres.

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In the summer of 1978 the Swiss Spitsbergen Expedition visited NW Spitsbergen, and as a member of this expedition I was given the opportunity to carry out geological field work, the results of which are presented in this paper.

The studied area is located north of 79°30′ north and west of 12° east and includes Magdalenenfjorden, Vasahalvöja and the central part of Hornemantoppen and Aurevilliusfjellet.

The geology of this Caledonian migmatite and gneiss area has been systematically studied by a number of expeditions from the polar institute of Norway, and a compilation of the available data has been given by Hjelle & Ohta (1974).

Granites, migmatitic gneisses and metapelitic gneisses form the bulk of the rocks of the area, but a large number of marble lenses and bands occur within the gneisses and granites. The petrology of these marbles is largely unknown. The primary purpose of this study is to describe the mineralogy of the marble occurrences and to estimate the conditions of metamorphism.

Geological setting

The investigated marble occurrences are located within an area termed the central and northern gneiss and migmatite area of NW Spitsbergen (Hjelle 1978). It is characterized by the predominance of various banded gneisses and granitic migmatites. Calcsilicate marbles, dolomitic marbles, amphibolites, hornblende gneisses and quartzites occur as small lenses and bands within the migmatitic gneisses. This metasedimentary rock sequence represents a part of the lower Hekla Hoek formation of Precambrian age (Ohta 1974). In the central part of the area a large post-tectonic hornblende-biotite granodiorite pluton intruded the gneisses and migmatites.

The complex deformational history has been worked out by Hjelle & Ohta (1974). Three main phases of folding can be distinguished. The general trend of the axes of major folds is from north to south. Metamorphism reached the upper amphibolite facies during the main phase of Caledonian deformation. Metamorphism of lower amphibolite facies followed the high grade recrystallization and may be correlated with later deformational phases (Ohta 1974).

Field aspects

The distribution of marble occurrences is given in Fig. 1. The lenses and bands of carbonate rocks occur within specific levels of the metasedimentary pile. The lenses form traceable north–south trending horizons and may be linked together with the large marble occurrences further south in the Kongsfjorden area (Gee & Hjelle 1966). The correlation of the individual

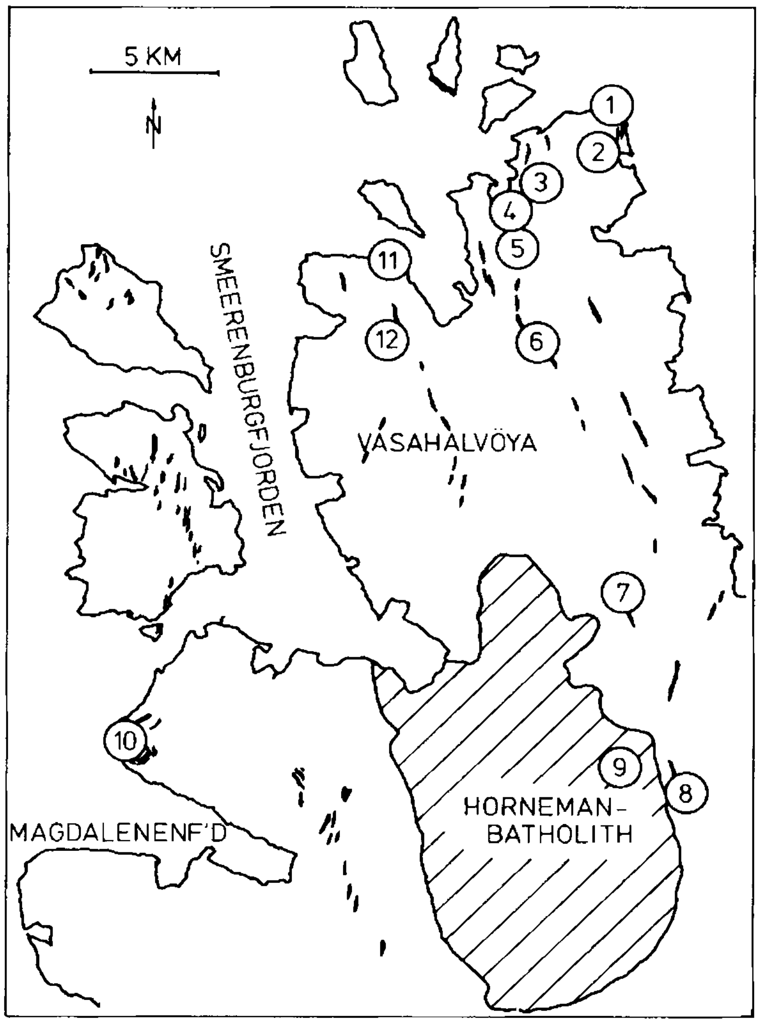

Fig. 1. Map of sample localities. Locality numbers correspond to those in Table 1. Geology: migmatitic gneisses and granites (white); post-tectonic, hornblende-biotite granodiorite intrusion (dashed); and marble lenses and horizons are shown in black.

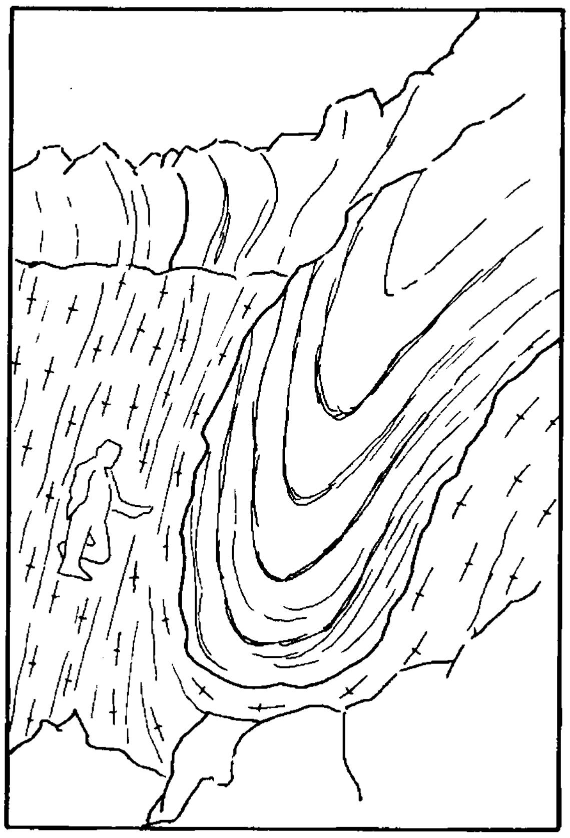

Fig. 2. Isoclinally folded marble in migmatitic gneisses at Byttane (locality 7).

lenses and bands is complicated by the isoclinal folding (F2 folds, Ohta 1974) of the area and tectonic repetitions may be expected to be common. Due to this complication, it is unclear how many distinct marble horizons occur within the lower Hecla Hoek formation of NW Spitsbergen. The marble bands rarely exceed thicknesses of 20 to 30 metres. The marbles of the eastern part of the area are typically associated with metasedimentary rocks such as quartzites and metapelites. This is the most complete marble unit and forms a continuous layer from Holmiabukta in the north to Larssentopen in the south. A less complete sequence is found to the west and may be traced from Drottenfjellet to Jäderinfjellet. Further to the west, thin marble lenses occur as small dismembered masses within the vast migmatites. The carbonate rocks found in the eastern area contrast very sharply with those in the west. The carbonate rocks in the eastern part of the study area are predominantly fine-banded dolomitic marbles. Calcsilicate marbles were not found. In the west, along Magdalenenfjorden, on Reuschhalvöya and on Danskӧya (Hjelle 1974), numerous lenses and bands of calcsilicate marbles are enclosed by the gneisses. No dolomitic marbles were found. This observation suggests that the marbles belong to different levels in the stratigraphic sequence.

The marble lenses are strongly banded on the cm to dm scale. The compositional banding is rather irregular, continuous compositional transition zones are common, and strongly symmetrical mineralogical zonations across the bands are absent. The banding is therefore believed to represent a primary sedimentary layering. In some outcrops the marbles are strongly isoclinally folded (Fig. 2). Axial planes dip steeply to the east, with fold axes gently dipping in a southerly direction. At Byttane, the sedimentary bedding is discordantly cut by granitic rocks (Fig. 3). Metasomatic exchange zones (skarns; stippled area in Fig. 3) are usually thin (a few cm) compared with the total volume of the marble lenses. The marbles do not show any compositional and mineralogical zonation parallel to the contact surface between the marble and the granite. This is in contrast to other reported marble occurrences of high grade metamorphic

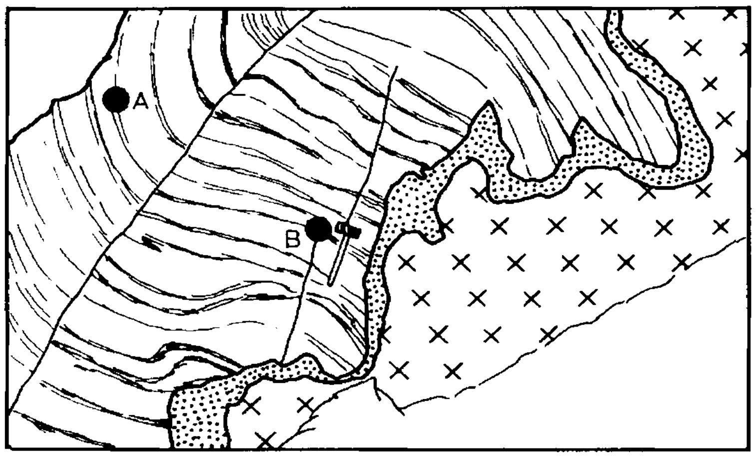

Fig. 3. Banded dolomitic marble inclusion in granite (crosses). Remarkably small metasomatic skarn zone (stippled). See text for further explanation.

terrains (e.g. Glassley 1975). At Bytanne (Fig. 3), for instance, two specimens of banded marble were collected at sites A and B and showed identical mineral assemblages. In both samples the observed assemblages are characteristic of the composition of the different bands, but show no relation to the distance from the contact. At other localities (i.e. Rubinfjellet, Jäderinfjellet) a metasedimentary sequence a few 100 m in thickness, including several marble bands of some metres thickness, is well preserved.

The calcsilicate marbles

Numerous lenses and bands of calcsilicate marble occur in the western part of the study area. Hjelle & Ohta (1974) reported grossular, diopside, vesuvianite, wollastonite, scapolite, epidote, plagioclase and amphibole from calcite marbles of the Magdalenenfjord and Smeerenburgfjord area. Marbles from Knatten (locality 10) are composed of various assemblages of the minerals reported by Hjelle & Ohta (1974). Characteristic assemblages are:

calcite + quartz + diopside + plagioclase
calcite + quartz + grossular + diopside
calcite + wollastonite + diopside + grossular + vesuvianite.

In some samples epidote and clinozoisite replace grossular and diopside. Overgrowth of grossular on diopside has been observed. In a number of samples the critical assemblage quartz + grossular has been identified. The isochemical assemblage anorthite + wollastonite was not found.

The dolomitic marbles

Dolomitic marbles predominate in the eastern part of the study area (localities 1 through 9). Table 1 gives the observed mineral assemblages of dolomitic marbles. Minerals found in the marbles include: dolomite, calcite, olivine, clinohumite, amphibole, diopside, chlorite, spinel, phlogopite, Fe-Ti oxides and serpentine. At each locality numerous assemblages of these minerals are found due to variations in the chemical compositions of the different layers in the fine-banded marbles. The field observations (see discussion above) preclude the possibility of different assemblages observed at each locality reflecting different bulk compositions due to metasomatism.

In general, the minerals show coarse mosaic textures. Post-crystallization deformation phenomena are rare. Calcite occurs as large, occasionally somewhat deformed grains. At some localities small exsolution patches of dolomite are common. Colourless olivine grains may measure several millimetres in diameter. At most localities, olivine is weakly fractured and may be strongly serpentinized. Pseudomorphs of serpentine after olivine are frequently observed in some sections. In some samples dolomite is believed to be the product of the retrograde reaction 2 forsterite + calcite + CO_2 + $2H_2O$ = serpentine + dolomite. Spinel occurs as euhedral, colourless crystals. In most samples with strongly serpentinized olivine, spinel shows no late alteration to chlorite. In one sample, spinel was clearly zoned with an iron-rich, green core and a magnesium-rich, colourless rim. Chlorite occurs as isolated, large, undeformed fresh flakes or in coexistence with spinel. In most samples chlorite appears to be in textural equilibrium with dolomite and spinel. Occasionally the textures clearly indicate retrograde chlorite replacing spinel. Small fresh flakes of phlogopite are present in most samples. Chlorite-phlogopite intergrowths were observed in one sample only. Twinned, colourless, or strongly yellow, pleochroic clinohumite was found to be widespread in the marbles. Serpentine plus ilmenite pseudomorphs after clinohumite were present in samples with serpentinized olivines. Magnetite and ilmenite are common constituents of the

Table 1. Mineral assemblages of NW Spitsbergen dolomites.

Locality No. Name	Sample No.	Cc	Do	Fo	Hu	Tr	Di	Chl	Sp	Phl
1 Flatkukfjellet	37	×	×	×	×			×	×	×
	38	×	×	×	×			×	×	
	39	×	×	×	×			×	×	
2 Makarovbreen	35	×	×	×	×			×	×	×
3 Birgerfjellet	54	×		×		×	×			
4 Holmiafjellet	51	×	×	×		×				×
	52	×	×	×				×	×	
	53	×		×		×				×
5 Bjelbofjellet	50	×	×	×				×	×	×
6 Rubinfjellet	25	×	×	×				×	×	×
	26	×		×						×
	27	×	×	×					×	×
	28	×	×	×				×	×	×
	29	×	×	×				×	×	
	30	×	×	×	×			×	×	×
	31	×	×	×						×
	32	×		×			×	×		×
	33	×		×			×			×
7 Byttane	40	×	×	×					×	×
	41	×	×	×				×	×	
	42	×	×	×				×	×	
	43	×	×	×	×	×		×	×	×
	44	×	×	×				×	×	
	45	×		×		×	×			×
	46	×		×		×	×			×
8 Jäderinfjellet	10	×	×	×	×	×		×	×	×
	11	×		×	×	×	×			×
	12	×	×	×	×				×	
	13	×	×	×		×	×			×
	14	×	×	×		×				×
	16	×	×	×	×	×		×	×	
	17	×	×	×	×	×		×	×	
	18	×		×		×	×			
	19	×	×	×						×
	20	×	×	×				×	×	×
	19a	×	×	×		×		×	×	×
	21	×	×	×				×	×	
	22	×			×					×
	23	×					×			
9 Aurivilliusfjellet	24	×	×	×					×	
10 Lestrisfjellet (Hjelle & Ohta 1974)		×	×	×	×		×		×	×

Hu: Clinohumite, Phl: Phlogopite. All other mineral symbols in Table 5.

marbles. Small grains of colourless diopsidic clinopyroxene were found in samples from most localities. Amphiboles are present in two generations, as indicated by microtextures. Al-rich amphibole coexists in textural equilibrium with spinel + dolomite + chlorite + olivine + calcite. Fine needle-shaped tremolite is texturally related to forsterite and may have grown at the expense of the latter, according to the reaction 13 calcite + 8 olivine + 9 CO_2 + H_2O = tremolite + 11 dolomite. In several samples, textures involving amphibole are difficult to interpret: Extremely poikilitic crystals of the amphibole may represent either dissolution or a growth phenomenon.

Mineral chemistry

For this study some 70 rock samples were examined microscopically. Calcite was optically distinguished from dolomite by the staining technique of Friedman (1959). Mineral compositions were determined on carbon coated polished sections using the ARL SEMQ electron microprobe with an energy dispersive system (Tracor Northern) at the University

Table 2. Microprobe analyses of clinohumite, chlorite, spinel, olivine and phlogopite.

	Clinohumite		Chlorite		Spinel		Olivine		Phlogopite
	SPI 17	SPI 39	SPI 17	SPI 39	SPI 17	SPI 39	SPI 17	SPI 39	SPI 17
SiO_2	38.82	39.04	30.78	30.88	–	–	42.91	41.99	40.35
TiO_2	1.21	0.15	–	–	0.20	tr.	–	–	0.88
Al_2O_3	–	–	21.91	24.44	71.17	71.38	–	–	16.16
FeO *	0.88	1.71	0.40	0.79	1.43	2.67	1.28	2.15	0.32
MgO	56.39	56.56	33.89	33.91	27.32	26.52	55.79	55.54	26.43
K_2O	–	–	–	–	–	–	–	–	10.68
F	3.45	3.15	tr.	tr.	–	–	–	–	1.63
H_2O **	1.22	1.40	12.50	12.50	–	–	–	–	3.5
Total ***	100.55	100.71	99.48	98.52	100.12	100.71	99.98	99.68	99.26
Anions	18	18	36	36	4	4	4	4	24
Si	4.02	4.04	5.46	5.83	–	–	1.01	1.00	5.65
Ti	0.09	0.01	–	–	0.004	–	–	–	0.09
Al	–	–	4.82	4.55	2.00	2.00	–	–	2.67
Fe	0.08	0.15	0.06	0.12	0.03	0.05	0.03	0.04	0.04
Mg	8.71	8.74	9.43	9.54	0.97	0.94	1.96	1.96	5.52
K	–	–	–	–	–	–	–	–	1.91
F	1.13	1.03	–	–	–	–	–	–	0.72
H	0.65	0.97	15.57	15.73	–	–	–	–	3.27
O	0.19	–	–	–	–	–	–	–	–
X_{Mg}	0.991	0.983	0.993	0.987	0.972	0.946	0.987	0.978	0.993
X_F	0.638	0.516	–	–	–	–	–	–	0.181

* All Fe as FeO; ** Stoichiometric H_2O; *** Total, minus O for F.

Table 3. Microprobe analyses of carbonate minerals.

	Calcite		Dolomite	
	SPI 17	SPI 39	SPI 17	SPI 39
CaO	51.81	52.85	30.77	31.10
MgO	2.42	2.73	21.55	21.19
FeO	0.06	0.12	0.21	0.38
Total	54.29	55.70	52.54	52.67
Carbonate equivalents in mol%				
$CaCO_3$	93.81	93.05	50.51	51.07
$MgCO_3$	6.10	6.69	49.21	48.40
$FeCO_3$	0.09	0.17	0.27	0.48
X_{Mg}	0.985	0.975	0.995	0.990

of Basel. Analysed natural and synthetic compounds were used as standards. Data reduction was performed with a theoretical ZAF correction procedure. For most minerals the content of oxide components is given in the form of the arithmetic mean from about 10 point analyses.

Microprobe analyses of calcite, dolomite, olivine, clinohumite, chlorite, spinel, phlogopite and amphibole from two selected samples are given in Tables 2, 3 and 4. The analyses show that the marbles are very pure. The minor elements manganese, nickel, chromium, zinc and vanadium could not be detected in any of the minerals. Titanium is enriched in phlogopite and clinohumite. These two minerals also contain a substantial amount of fluorine. The iron content of all minerals is found to be extremely low. Even in spinels (where iron is preferably accommodated), the hercynite component does not exceed 5.3 mol%. Olivine typically contains 98–99 mol% forsterite component.

Over the small compositional range represented by the marble samples the order of Fe preference relative to magnesium is: spinel > calcite > olivine > clinohumite > phlogopite > chlorite > dolomite (Fig. 4). The order of fluorine preference relative to hydroxyl is: clinohumite > phlogopite. The zoned amphibole of sample SPI 17 showed X_{Mg} values above those of the coexisting chlorite. This is in agreement with the Fe–Mg partitioning among marble minerals found by Rice (1977) and Bucher (1977). The consistent Fe–Mg partitioning between coexisting minerals indicates that chemical exchange equilibrium was attained.

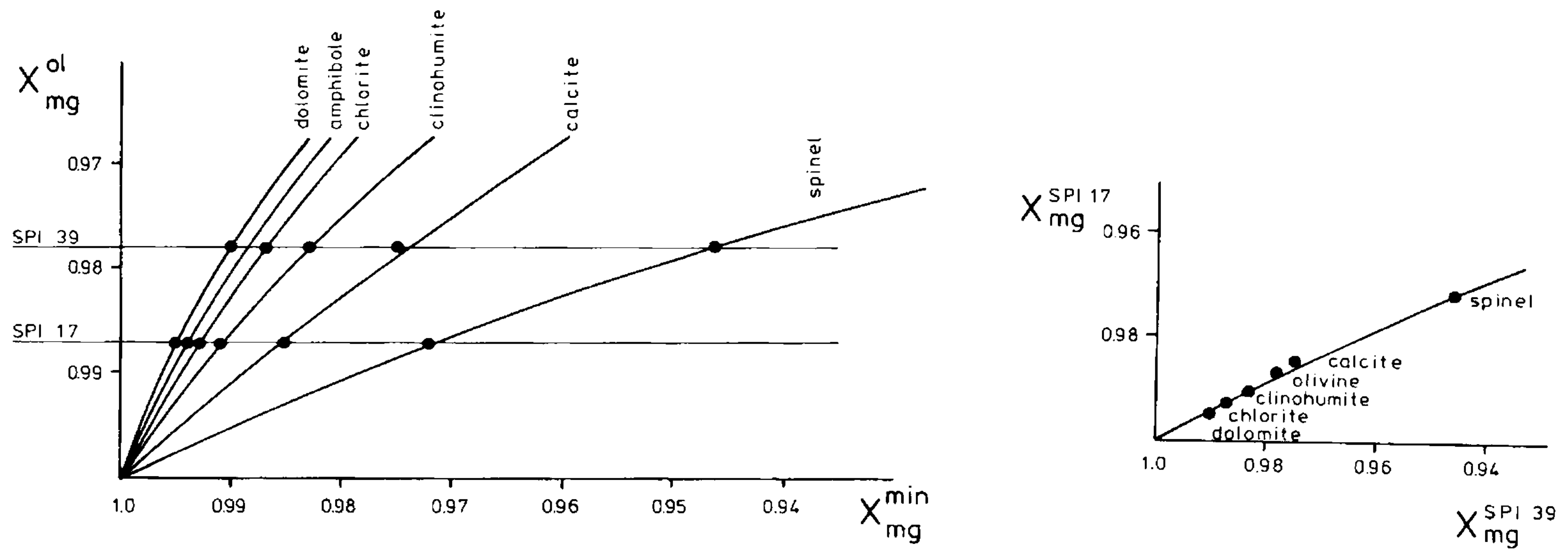

Fig. 4. Iron–magnesium partitioning among the analysed minerals of SPI 17 and SPI 39. X_{Mg} = Mg/Mg + Fe (atoms per formula unit; Tables 2, 3 and 4).

Table 4. Microprobe analyses of amphibole (SPI 17).

	Grain A		Grain B		
	Rim	Core	Rim		Core
SiO_2	58.98	53.83	58.16	55.50	54.15
TiO_2	0.25	–	0.07	0.01	0.13
Al_2O_3	0.64	7.59	0.80	5.50	7.66
FeO *	0.24	0.35	0.20	0.26	0.32
MgO	24.07	21.72	23.82	22.65	21.80
CaO	13.62	13.50	13.46	13.30	13.60
Na_2O	0.20	0.40	–	0.40	0.30
K_2O	–	–	–	0.18	0.10
F	0.28	–	0.85	0.47	0.17
H_2O **	2.00	2.20	1.90	2.00	2.10
Total	100.15	99.58	98.91	100.06	100.26
Number of atoms per formula unit, based on 24 anions					
Si	7.98	7.34	7.95	7.53	7.34
Ti	0.02	–	0.01	–	0.01
Al	0.10	1.22	0.13	0.88	1.22
Fe	0.03	0.04	0.02	0.03	0.04
Mg	4.85	4.42	4.85	4.58	4.41
Ca	1.97	1.97	1.97	1.93	1.98
Na	0.05	0.11	–	0.11	0.08
K	–	–	–	0.03	0.02
F	0.12	–	0.37	0.20	0.07
H	1.81	2.00	1.73	1.81	1.90
X_{Mg}	0.994	0.991	0.995	0.994	0.992

* All Fe as FeO; ** Stoichiometric H_2O.

Calcite

The composition of calcite coexisting with dolomite is determined by the temperature (and pressure) dependent miscibility gap between these two minerals. Using the equation given by Rice (1977), based on available experimental data on the calcite-dolomite miscibility gap, the two samples indicated temperatures of equilibration of 595°C (measured range 540°C to 595°C), and 590°C (measured range 580°C to 590°C), respectively. The two temperatures coincide within analytical error and are in agreement with the uniform spatial distribution of the marble assemblages over the entire area. However, microscopically, many calcite samples exhibit small exsolution patches of dolomite. Inclusion of exsolved dolomite in the analysis of the host calcite was attempted by using a wide electron beam (~ 15 microns) and measuring a large number of randomly selected spots on each calcite grain. This technique should, at least in part, eliminate erroneously low apparent temperatures due to dolomite exsolution during cooling. It is therefore assumed that the temperatures calculated from the microprobe analyses of calcite indeed reflect the minimum temperature during metamorphism.

Chlorite

The composition of chlorite from both localities shows a considerable deviation from the clinochlore end-member composition (Fig. 5). Tetrahedral aluminium was found to comprise 2.31 and 2.20 atoms per formula unit, respectively. The compositional deviation from end-member clinochlore can be described by a tschermakite type exchange. The exchange component $2AlMg^{-1}Si^{-1}$ is controlled in both samples by the coexistence of spinel and forsterite

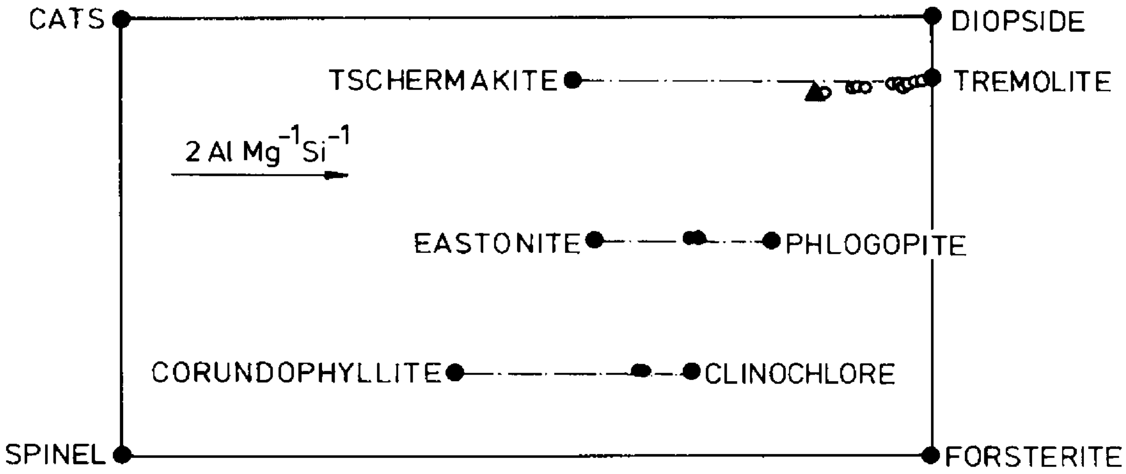

Fig. 5. Chemical composition of minerals projected onto the plane SiO_2–$AlO_{1.5}$–(MgO + FeO), with calcite in excess. CATS = $CaAl_2SiO_6$. The chemical variation of solid-solution minerals occurs mainly along the tschermak exchange vector. Solid triangle = composition of aluminous cores of amphiboles; open circles = tremolitic rims of amphibole.

through the equilibrium $MgAl_2O_4 = Mg_2SiO_4 + 2AlMg^{-1}Si^{-1}$. The composition of chlorite in both samples is in close agreement with the composition of chlorites from other reported occurrences, where the chlorite composition is buffered by the assemblage dolomite + calcite + forsterite + spinel + chlorite (Rice 1977; Bucher 1977).

Phlogopite

The composition of phlogopite differs significantly from end-member phlogopite. Fig. 5 shows that, similar to chlorite, the compositional departure from end-member phlogopite can be described by a tschermakite type exchange controlled by the presence of spinel and forsterite in the rock. The mole fraction X_F of 0.18 (fluorine measured, hydroxyl stoichiometric) can be used to estimate the fugacity of HF in the metamorphic fluid, provided the temperature, pressure and X_{H_2O} are known (Munoz & Ludington 1974). With the estimations of the metamorphic conditions given later in this paper f_{HF} has been calculated to be on the order of 0.01 bars.

Amphibole

The analysed amphiboles from sample SPI 17 (Table 3) are strongly zoned. The compositional variation ranges from pure tremolitic rims to amphibole rich in tschermakite component found in the core zones. The chemical variation again is parallel to the tschermakite vector of Fig. 5. Amphibole rich in aluminium, however, contains small amounts of alkalies and some variation in chemical composition may be ascribed to an edenite type of exchange.

The aluminous cores of the zoned amphiboles had 0.66 tetrahedral sites and 0.56 octahedral sites occupied by aluminium. The sum of the alkali atoms per formula unit was found to be close to 0.1. Consequently, the amphibole composition in terms of end-member components is 62% tremolite, 28% tschermakite and 10% edenite. Narrow rims of tremolitic amphibole are found on aluminous cores. This tremolite overgrowth is clearly of retrograde origin and it may have formed according to the reaction: 8 forsterite + 13 calcite + 9 CO_2 + 1 $H_2O \rightarrow$ 1 tremolite + 11 dolomite. However, the aluminium-rich amphiboles are considered to have coexisted in equilibrium with the assemblage calcite + dolomite + forsterite + chlorite + spinel.

Clinohumite

The clinohumite analysed in both samples contained substantial amounts of titanium and fluorine. In sample SPI 17, where the f_{HF} has been estimated to be about 0.01 bars, an X_F in clinohumite of 0.57 has been calculated.

Conditions of metamorphism

A model for the regional metamorphism of impure dolomites

A quantitative model for equilibrium phase relations of aluminous siliceous dolomites is presented in Fig. 6. The equilibrium conditions of the thirteen reactions relevant to the chemical space and the phases considered were calculated using an independent set of four equilibria based on experimental work (Skippen 1974; Widmark 1980). Reaction stoichiometries and equilibrium data are given in Tables 6 and 7. X_{CO_2} solutions of the equation

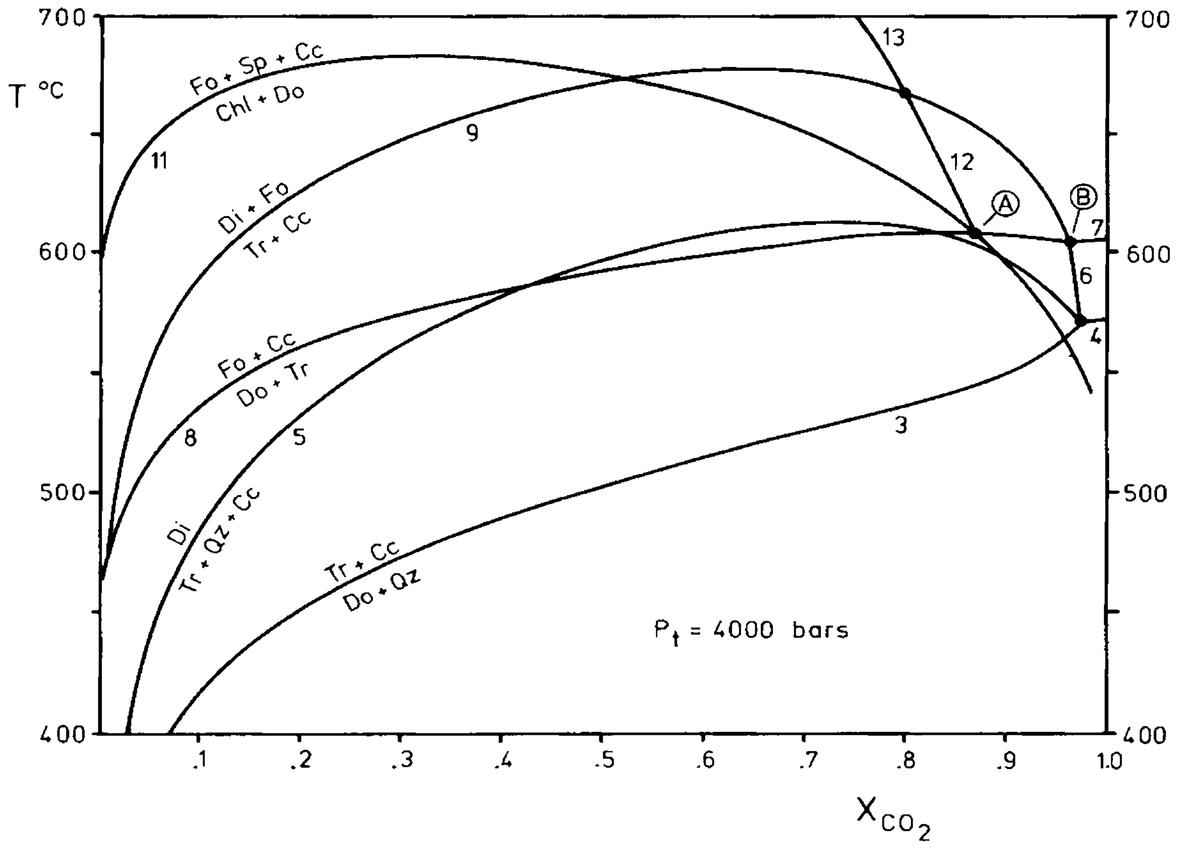

Fig. 6. Isobaric (4 kb) temperature versus X_{CO_2} diagram based on the compositions given in Table 5, the reaction stoichiometries of Table 6 and the equilibrium data given in Table 7.

Table 5. Composition of phases.

Name	Symbol	Composition
Quartz	Qz	SiO_2
Calcite	Cc	$CaCO_3$
Dolomite	Do	$CaMg(CO_3)_2$
Tremolite	Tr	$Ca_2Mg_5Si_8O_{22}(OH)_2$
Diopside	Di	$CaMgSi_2O_6$
Forsterite	Fo	Mg_2SiO_4
Chlorite *	Chl	$Mg_{4.90}Al_{2.35}Si_{2.80}O_{10}(OH)_{8.05}$
Spinel	Sp	$MgAl_2O_4$

* Composition of breakdown chlorite (Widmark 1980).

$$\log K_{PT} = \frac{A}{T} + B + \frac{C(P-P^\circ)}{T} =$$
$$= \nu_{CO_2} \log(P_t \gamma_{CO_2} X_{CO_2}) + \nu_{H_2O}(P_t \gamma_{H_2O}(1 - X_{CO_2}))$$

were calculated at various pressures and temperatures using the program FINDX (Flowers 1978), assuming ideal mixing of CO_2 and H_2O. Reference state was chosen as pure solids at the pressure and temperature of interest and pure ideal gas at the temperature of interest and 1 bar pressure. The activities of components $CaCO_3$ and $CaMg(CO_3)_2$ in calcite and dolomite, respectively, are defined by the coexistence of these two carbonate minerals. Reaction 10 (numbers consistent with Rice 1977) has very small A and B constants compared to the other chlorite–spinel reactions. The location of the equilibrium conditions of reaction 10 is therefore very sensitive to experimental error. Taking the constants from Table 7, the curve would have a very steep but positive slope; curve 10 in Fig. 6 has been drawn to be consistent with Rice (1977). The phase diagram of Fig. 6 has been constructed at 4 kb for the following reason: At the Jäderinfjellet locality, mineral assemblages indicating the conditions of points A and B were found in a number of samples. At the same locality calcite–dolomite compositions revealed a minimum temperature of 595°C. At 4 kb, points A and B are close to 605°C and therefore Fig. 6 is consistent with the data from the calcite–dolomite thermometry. However, the 4 kb total pressure deduced by this method does not agree well with Ohta's estimate of 5500 bars for the pressure during metamorphism. Ohta's pressure estimation is based on mineral assemblages of metapelites of the area and depends on the location of the alumosilicate triple point of Richardson et al. (1969). The observed mineral assemblages in metapelites would be consistent with a pressure of 4 kb using the data of Holdaway (1971).

Table 6. Reaction stoichiometries.

Reaction*	Qz	CC	Do	Tr	Di	Fo	Chl	Sp	CO_2	H_2O
3	-8	3	-5	1	–	–	–	–	7	-1
4	-2	–	-1	–	1	–	–	–	2	–
5	-2	-3	–	-1	5	–	–	–	3	1
6	–	-3	1	-1	4	–	–	–	1	1
7	–	4	-3	–	-1	2	–	–	2	–
8	–	13	-11	-1	–	8	–	–	9	1
9	–	-5	–	-3	11	2	–	–	5	3
10	–	-107	79	140	–	–	-40	47	-51	147
11	–	75	-75	–	–	112	-40	47	75	161
12	–	-150	–	75	–	632	-440	517	150	1696
13	–	-75	–	–	75	186	-120	141	75	483

* Numbers correspond to numbers in Rice (1977).

Table 7. Equilibrium data.

Reaction	A*	B*	C*	
3	-33082	63.914	.6401	Rice (1977)
4	-9242	18.305	.2130	Rice (1977)
5	-13311	27.62	.5152	Rice (1977)
6	-4032.4	9.314	.2842	Rice (1977)
7	-20158	30.729	.1339	Rice (1977)
8	-84665	132.23	.8197	Rice (1977)
9	-32254	58.668	.9864	Rice (1977)
10	42930	64.18	8.2442	$\log K_{11}$–14 $\log K_8$
11	-1142380	1915.4	19.72	Widmark (1980)
12	-6216305	11152.2	155.44	11 $\log K_{11}$–75 $\log K_8$
13	-1915290	3441.5	48.118	3 $\log K_{11}$–75 $\log K_7$

* Constants in an equation of the type $\log_{10} K = \frac{A}{T} + B + \frac{C(P-1)}{T}$ (cal, bar).

Effect of the variations in mineral composition on equilibria of the pure model system

The iron–magnesium substitution: Although the compositions of the iron–magnesium minerals were found to be close to the compositions of the respective magnesian end-members, it might be suspected that substantial displacements of the equilibria could have occurred because of Fe substitution in Mg minerals due to the large stoichiometric coefficients, particularly those of the chlorite–spinel reactions. In order to estimate the order of magnitude of this effect, consider the reaction (reaction 11):

40 chlorite + 75 dolomite = 75 calcite + 112 forsterite + 47 spinel + 75 CO_2 + 161 H_2O

The equilibrium constant of the above reaction may be expressed by:

$$K = \frac{a_{CaCO_3}^{75}\ a_{Mg_2SiO_4}^{112}\ a_{MgAl_2O_4}^{47}\ a_{CO_2}^{75}\ a_{H_2O}^{161}}{a_{CaMg(CO_3)_2}^{75}\ a_{Chl}^{40}}$$

Where Chl is the chlorite component as defined in Table 5.

The composition of the carbonate minerals with respect to the calcium–magnesium exchange is given by the miscibility gap between calcite and dolomite. Using the activity composition relations

$$a_{MgAl_2O_4} = X_{Mg}^{Sp};\ a_{Chl} = (X_{Mg}^{Chl})^{4.9};\ a_{Mg_2SiO_4} = (X_{Mg}^{Ol})^2;\ a_{CaMg(CO_3)_2} = X_{Mg}^{Do}$$

and the composition data from sample SPI 39, $\log K^{solids}$ of the expression $\log K = \log K^{solids} + \log K^{gas}$ becomes -1.8531. At 4 kb and 600°C this results in a displacement of the equilibrium curve of reaction 11 in Fig. 6 by only $-1.33°C$. The effect on other equilibria is of the same order and can therefore safely be neglected.

The tschermak substitution: The composition of the analysed chlorite is very close to the composition of the experimental chlorite used to define the reaction conditions for reaction 11 (Widmark 1980). The effect of the tschermak exchange on the reactions involving chlorite is therefore inherent to the locations of the equilibrium curves of Fig. 6 (similar to the Ca–Mg exchange on the carbonate minerals).

The effect of amphibole composition on equilibria involving tremolite: In contrast to chlorite, the effect of deviation of the measured amphibole compositions from pure tremolite could be quite substantial. Its effect on tremolite involving equilibria can be estimated as follows: Consider reaction 8 (Table 7): 11 dolomite + tremolite = 8 forsterite + 13 calcite + 9 CO_2 + H_2O.

$$K = \frac{a^{13}_{CaCO_3}\ a^{8}_{Mg_2SiO_4}\ a^{9}_{CO_2}\ a_{H_2O}}{a^{11}_{CaMg(CO_3)_2}\ a^{1}_{Ca_2Mg_5Si_8O_{22}(OH)_2}}$$

Assuming ideal site mixing, the activity of the tremolite component in the amphibole solution may be approximated by

$$a_{tr} = (X^{A})\,(X^{M_4}_{Ca})^2\,(X^{M_2}_{Mg})^2\,(X^{M_1+M_3}_{Mg})^3\,(X_{OH})^2$$
$$tr = Ca_2\,Mg_5\,Si_8\,O_{22}\,(OH)_2$$

Because of the preference of the octahedral aluminium for the two M2 sites, all octahedral Al has been assigned to that site. Using the compositional data given in Table 4 for the aluminous amphibole cores, the calculated activity of the tremolite component is 0.39. This value, together with the activities of the remaining components, results in a log $K^{solids} = 0.4348$ for reaction 8 and a corresponding shift of the equilibrium curve for this reaction at 4 kb and 600°C (Fig. 6) of $+4°C$.

From the above analysis, the observed compositional deviations of the Spitsbergen minerals from the ideal mineral compositions used in the construction of Fig. 6 cause only minor shifts in the positions of the equilibrium curves shown in Fig. 6. Therefore, Fig. 6 is generally applicable to the observed mineral assemblages.

Discussion

In silica undersaturated aluminous dolomite marbles, the assemblage chlorite + spinel + dolomite + calcite + forsterite has been observed over the entire area. The coexistence of these minerals requires equilibrium of the reaction dolomite + chlorite = calcite + forsterite spinel + CO_2 + H_2O (reaction 11). At 4 kb this assemblage may be present between 610°C and 680°C. These temperature limits are in close agreement with Ohta's (1974) estimate of 650°C to 700°C for the main phase of Caledonian metamorphism.

In a marble inclusion within the Horneman intrusion (locality 9), only the chlorite absent assemblage calcite + dolomite + spinel + forsterite has been found. This observation indicates that at this particular locality the stability field of the assemblage chlorite + dolomite has been exceeded, either because of a high temperature of metamorphism or because of an external control of the fluid composition by the large mass of hornblende–biotite granodiorite around the small marble inclusions.

The assemblage calcite + tremolite + diopside + forsterite was found in marbles from three different localities (3, 7, 8, Fig. 1). The coexistence of these four minerals requires equilibrium of reaction 9, and indicates temperatures of equilibration between 605°C and 675°C (at 4 kb). This temperature interval is nearly identical to that suggested above for the calcite + dolomite + chlorite + spinel + forsterite assemblage. The assemblage calcite + tremolite + diopside + forsterite has only been observed in marbles lacking both chlorite and spinel, which is in agreement with a prograde formation history in the presence of a CO_2-rich fluid for the above reported assemblages.

Samples from the marble lenses of the west ridge of Jäderinfjellet (locality 8) contain a number of interesting, low-variance mineral assemblages (Table 1). The assemblage calcite + dolomite + forsterite + chlorite + spinel suggests equilibrium conditions of reaction 11, the assemblage calcite + diopside + forsterite + tremolite those of reaction 9, and the coexistence of dolomite + calcite + tremolite + forsterite requires the equilibrium conditions of reaction 8. Furthermore, at this locality apparently prograde aluminous amphibole still coexists with dolomite. In four samples of Jäderinfjellet, the six mineral assemblage calcite + dolomite + forsterite + tremolite + chlorite + spinel has been found.

Under isobaric conditions this assemblage is restricted to the conditions of invariant point A of Fig. 6. At 4 kb the equilibrium temperature of this point is 610°C and the $X_{CO_2} = 0.85$. In one sample the assemblage calcite + dolomite + diopside + tremolite + forsterite has been identified. This assemblage may be present in the rock under the conditions of point B (Fig. 6). At 4 kb the equilibrium temperature is nearly the same as at point A (605°C), but X_{CO_2} equals 0.97. The mineral pair dolomite + diopside indicates a very CO_2-rich metamorphic fluid. Similar to the assemblage calcite + forsterite + diopside + tremolite found at a number of localities (see above), the assemblage calcite + dolomite + tremolite + diopside + forsterite of sample 13 occurs in a rock lacking chlorite and spinel. The absence of chlorite at lower metamorphic grades is required of any rock which reaches point B along a prograde equilibrium path of metamorphism (Fig. 6).

In contrast to locality 8, the amphibole found at Holmiafjellet (locality 4) and Byttane (locality 7) is probably of retrograde origin, as indicated by its texture (fine needle-shaped tremolite overgrowths on large forsterite crystals).

In conclusion, the mineral assemblages found at Jäderinfjellet are consistent with a temperature of equilibration of 600 to 610°C at 4 kb and a CO_2-rich fluid (i.e. near points A and B in Fig. 6). At localities further to the north, amphibole probably does not coexist with dolomite. The two assemblages calcite + dolomite + forsterite + chlorite + spinel and calcite + tremolite + diopside + forsterite are consistent with temperatures during metamorphism between 610°C and 680°C. The temperature of 595°C derived from the calcite–dolomite assemblage at the northernmost locality Flathuken, however, suggests that the temperature of metamorphism did not significantly exceed those deduced for the Jäderinfjellet locality. Thus, nearly isothermal conditions are indicated for metamorphism of the studied area.

The mineral pair grossular + quartz found in calcsilicate rocks at Knatten (locality 10) requires temperatures below 675°C at 4 kb (the equilibrium temperature (at 4 kb) of the reaction grossular + quartz = 2 wollastonite + anorthite according to data of Helgeson et al. (1978)). This is consistent with the metamorphic conditions deduced from the dolomitic marbles to the east.

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