Metamorphic history in the Bergen Arcs, Norway, as determined from amphibole chemistry

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Electron microprobe analyses of amphiboles and other metamorphic minerals give new information about the metamorphic development in the Major and Minor Bergen Arcs in the Scandinavian Caledonides. The composition of metamorphic amphiboles in Ashgillian–Llandoverian metasediments indicates that the Caledonian metamorphism in the two arcs reached its peak of upper greenschist close to lower amphibolite facies during the main Caledonian (Scandian) event (M2). This result is supported by high Al_2O_3/$FeO + Fe_2O_3$ ratios in white micas and by almandine-rich garnets. Medium pressures are indicated for this event. Old, unstable amphibole porphyroclasts are actinolites to actinolitic hornblendes, and indicate a pre-Ashgillian event (M1) of lower metamorphic grade.

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In 1981 Laird & Albee carried out a detailed work relating mineral chemistry to metamorphic facies in mafic rocks in the Vermont area. These are intercalated with pelites with index minerals which clearly demonstrate the local metamorphic grades. Laird & Albee (1981) made formula-proportion variation diagrams for amphiboles grown under different metamorphic conditions. Such diagrams may be used for examining the metamorphic grade of areas dominated by mafic rocks where metamorphic index minerals like Al_2SiO_5 polymorphs, staurolite, cordierite and chloritoid are scarce or absent. This method has been applied on mafic rocks from the Major and Minor Bergen Arcs.

Geologic setting

The Bergen Arc System (Kolderup & Kolderup 1940) surrounding Bergen, Norway, is a series of arcuate allochthonous rock units bounded to the northeast by the Western Gneiss Region, to the east by the Bergsdalen Nappes, and to the west by the North Sea (Fig. 1). Of the rock units within the Bergen Arc System, the Øygarden Gneiss Complex, the Ulriken Gneiss Complex and the Anorthosite Complex are Precambrian rock complexes which have undergone profound Caledonian deformation and metamorphism. The Øygarden Gneiss Complex (Bering 1985) is a heterogeneous Precambrian migmatite complex which experienced pervasive deformation and lower amphibolite facies metamorphism during

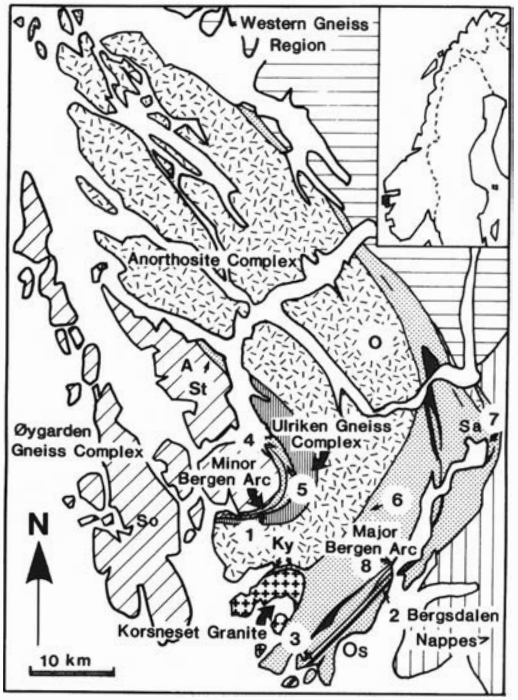


Fig. 1. Geology of the Bergen Arc System. Sample localities chosen for electron microprobe investigation are shown. The Ashgillian–Silurian sedimentary cover sequence to the ophiolitic rocks is shown in black. A = Askøy, O = Osterøy, Sa = Samnanger, So = Sotra, St = staurolite, Ky = kyanite. The Gulfjellet Ophiolite is situated in the Major Bergen Arc.

a pre-Scandian event of thrusting to the west (Rykkelid & Fossen in prep.) and a later Scandian thrusting to the east. The Scandian event in the Bergen Arcs is bracketed by the deposition of lower Llandoverian metasediments of the Major Bergen Arc (below) and the deposition of the assumed mid-Devonian clastics to the north of the Bergen Arc System (Kolderup & Kolderup 1940). The Ulriken Gneiss Complex (Fossen 1986, 1988) is a Precambrian migmatite complex with a greenschist facies sedimentary cover of possible late Precambrian age. Both basement and cover are strongly sheared during the Scandian event. The Anorthosite Complex (Kolderup & Kolderup 1940; Austrheim 1978) mainly comprises Precambrian anorthositic rocks, mangerites and granulites, and represents part of the lower crust that was involved in Caledonian subduction and, later, Scandian thrusting. Caledonian eclogite shear zones (Austrheim & Griffin 1985; Austrheim 1987) indicate that high pressure shearing preceded later-stage Caledonian retrogressive movements.

Lower Paleozoic rocks occur among tectonic slices of Precambrian gneisses and metasediments of unknown age; they form two arcs, the Major Bergen Arc (MaBA) and the Minor Bergen Arc (MiBA) (Fig. 1). Large parts of the MiBA and MaBA have been interpreted as dismembered ophiolite fragments (Furnes et al. 1980), e.g. the Gulfjellet Ophiolite Complex (Thon 1985) and its associated caprocks (cherts, pelites, basic and acidic dykes/lavas) (Ingdahl 1985; Thon 1985; Fossen 1986). A plagiogranite differentiate of the Gulfjellet Ophiolite Complex has been dated at 489 ± 3 Ma (U/Pb zircon age) (Dunning & Pedersen 1988). The ophiolitic rocks were intruded and overlain by magmatic rocks of island-arc and possible back-arc affinity (Ingdahl 1985), and an early tonalitic island-arc type intrusion is dated at 481 ± 3 Ma (Dunning & Pedersen 1988). The Gulfjellet Ophiolite Complex is now interpreted as having formed within a subduction zone environment rather than within a major ocean basin or arc remote basin (Pedersen et al. in press).

Unconformably overlying the ophiolitic rocks in the MaBA occur conglomerates and graywackes (the Moberg Formation), limestones, pelites and quartzites of the Holdhus and Ulven Groups in the Os–Samnanger area (Fig. 1) (Ryan & Skevington 1976; Færseth et al. 1977; Ingdahl 1985). Fossil evidence shows the sediments to range in age from Ashgill to at least middle Llandovery (Reusch 1882; Ryan & Skevington 1976). A similar clastic sequence in the MiBA (the Storetveit Group, Fossen 1986) has been correlated with the lower part of the Holdhus Group (Kolderup & Kolderup 1940; Fossen 1986). Intrusive into rocks of the MaBA is the Krossnes Granite (Fossen & Ingdahl 1987), which has been dated at 430 ± 6 Ma (Fossen & Austrheim 1988). All rocks of the MaBA and MiBA were strongly but heterogeneously deformed and metamorphosed in post-lower Silurian times.

The early Caledonian event

Indications of early (pre-late Ordovician) deformation and metamorphism have been found, though generally obscured by the intense Scandian event. One such indication is the presence of ductile fabrics in granitoid pebbles within the conglomeratic Moberg Formation, where the pebble foliations make angles to the matrix foliation (Kvale 1960). A change in orientation of the foliation at the sheared unconformity between the tonalitic island-arc intrusion and the conglomerate has also been taken as evidence for a tectono-metamorphic break (Sturt & Thon 1976). These angular relationships may, however, also be formed by cleavage refraction and rotation of foliations during the Scandian event, as claimed by Ingdahl (1985, 1986 and in prep.).

A study of the igneous layering and the geochemical trend of the Liafjell Gabbro (Gulfjellet Ophiolite) indicates inversion of the gabbro prior to deposition of the adjacent Holdhus Group (Inderhaug 1975). Somewhat ambiguous structures in pillow lavas may also indicate inversion of the ophiolitic rocks prior to deposition of the Holdhus Group (Sturt & Thon 1976).

Recent work from the western part of the MaBA shows that the Krossnes Granite intrudes ductilely deformed rocks of the MaBA (Fossen & Ingdahl 1987). The 430 ± 6 Ma date of the granite (Fossen & Austrheim 1988) indicates an Ordovician age for this deformation.

Færseth et al. (1977) separated the poorly preserved M1 minerals from the M2 minerals in the MaBA by using textural interpretations. Porphyroblasts (-clasts) with inclusion trails oblique to the matrix foliation were interpreted as M1 minerals, but may also be synkinematic M2 minerals (see discussion below). Plagioclase grains in

Table 1. Amphibole analysis from the MaBA and MiBA. See Table 2 for sample locations.

Sample: B-216

Na_2O	2.36	2.13	1.93	1.97	2.13	1.63	2.11	2.03	2.05
MgO	9.73	9.93	10.01	10.30	10.23	10.82	9.91	10.30	10.81
Al_2O_3	15.23	15.09	14.91	13.77	14.25	13.42	14.81	14.01	13.91
SiO_2	43.08	43.69	43.31	44.09	44.01	44.21	43.13	43.90	44.18
K_2O	0.37	0.38	0.40	0.33	0.36	0.37	0.40	0.32	0.37
CaO	9.43	9.46	9.26	9.45	8.72	9.71	9.67	9.39	9.80
TiO_2	0.41	0.44	0.36	0.28	0.34	0.40	0.48	0.45	0.33
MnO	0.34	0.22	0.30	0.23	0.30	0.28	0.37	0.26	0.29
FeO	15.46	15.33	15.36	15.41	15.13	15.23	15.54	15.23	14.89
Total	96.40	96.66	95.83	95.82	95.47	96.06	96.42	95.88	96.62

Sample: B-216

Na_2O	2.33	2.48	2.56	2.29	3.00	1.52	1.83	1.90	1.58
MgO	10.04	10.43	9.85	10.40	10.54	12.14	11.08	11.42	11.46
Al_2O_3	14.62	13.92	14.62	14.16	11.83	12.08	13.43	13.22	12.82
SiO_2	40.19	40.97	38.73	39.01	45.11	44.43	44.11	44.17	44.87
K_2O	0.36	0.38	0.40	0.38	0.29	0.29	0.39	0.38	0.34
CaO	9.61	9.53	9.58	9.51	10.83	10.52	10.60	10.08	10.47
TiO_2	0.35	0.45	0.55	0.43	0.35	0.40	0.31	0.37	0.43
MnO	0.27	0.28	0.20	0.18	0.13	0.21	0.27	0.30	0.27
FeO	15.71	15.17	15.21	15.20	14.74	15.25	15.31	15.26	15.43
Total	93.48	93.61	91.70	91.56	96.81	96.84	97.32	97.09	97.68

Sample: 0-26

Na_2O	1.96	1.98	2.28	2.40	2.15	1.91	1.98	0.69	1.84	1.46
MgO	9.78	8.71	8.83	8.45	9.17	10.58	9.34	14.29	10.82	12.51
Al_2O_3	10.18	10.35	12.67	12.77	10.70	7.53	11.48	2.53	8.17	5.53
SiO_2	45.93	44.69	43.51	43.66	45.79	48.51	43.36	52.25	47.15	50.51
K_2O	0.26	0.36	0.36	0.50	0.36	0.26	0.33	0.09	0.33	0.16
CaO	10.30	9.74	10.43	9.97	10.21	9.71	11.02	11.10	9.74	10.11
TiO_2	0.20	0.24	0.38	0.35	0.29	0.16	0.36	0.02	0.17	0.13
MnO	0.27	0.34	0.35	0.35	0.50	0.45	0.26	0.34	0.26	0.35
FeO	17.95	17.47	18.49	18.63	18.34	17.40	17.20	14.13	17.12	16.18
Total	96.91	94.89	98.37	97.10	97.58	96.59	95.40	95.62	95.70	97.03

Sample: GU-1

Na_2O	0.68	0.69	1.69	1.51	1.77	1.74	1.46	1.56	0.88	1.53
MgO	16.52	16.75	12.39	12.75	12.37	12.65	12.43	12.40	11.60	12.93
Al_2O_3	4.03	3.86	10.27	9.34	11.40	10.72	9.69	9.23	6.67	9.63
SiO_2	52.80	52.94	45.67	46.19	42.47	43.18	42.00	41.42	43.23	42.09
K_2O	0.08	0.04	0.16	0.19	0.16	0.08	0.18	0.20	0.08	0.08
CaO	11.74	11.68	11.36	10.99	10.73	11.06	19.72	11.14	13.11	10.41
TiO_2	0.12	0.07	2.23	2.30	0.33	0.41	2.32	3.99	3.75	2.06
MnO	0.13	0.37	0.28	0.30	0.35	0.07	0.21	0.21	0.15	0.16
FeO	09.53	09.55	12.21	13.02	12.32	11.55	12.08	11.70	11.23	11.76
Total	95.82	96.10	96.36	96.72	91.89	91.51	91.14	91.97	90.71	90.68

Table 1 (*contd.*).

Sample: GU-1

	'Old' amphiboles		'New', smaller amphiboles		
Na_2O	1.34	1.72	1.95	1.25	1.88
MgO	12.76	12.13	11.12	9.49	11.49
Al_2O_3	11.19	9.84	12.60	8.65	12.70
SiO_2	39.55	42.55	45.24	56.73	44.59
K_2O	0.10	0.17	0.18	0.17	0.33
CaO	09.41	10.72	10.78	9.10	11.10
TiO_2	1.90	2.68	0.49	0.34	0.36
MnO	0.22	0.26	0.29	0.33	0.09
FeO	11.76	14.09	13.68	10.10	13.55
Total	95.82	96.10	96.59	96.21	96.28

Sample: SA-1

	'Old', large amphiboles				'New', smaller amphiboles					
Na_2O	1.62	1.28	1.63	1.61	1.18	2.04	1.26	1.36	1.08	2.39
MgO	11.20	14.03	12.23	12.11	15.34	11.55	13.80	14.11	12.76	11.93
Al_2O_3	11.73	9.74	12.18	12.12	7.67	12.85	9.75	9.73	11.81	12.97
SiO_2	41.95	45.76	43.19	43.60	47.40	42.77	45.84	45.90	43.83	43.30
K_2O	0.10	0.05	0.14	0.06	0.06	0.09	0.06	0.10	0.03	0.00
CaO	10.18	11.51	11.29	10.90	11.08	10.57	11.04	11.35	10.63	10.99
TiO_2	0.27	0.15	0.37	0.33	0.22	0.33	0.22	0.20	0.39	0.64
MnO	0.22	0.05	0.21	0.19	0.20	0.31	0.28	0.20	0.36	1.20
FeO	12.46	11.03	11.63	11.72	9.57	11.25	10.24	10.33	11.47	12.43
Total	99.74	94.90	92.99	91.95	92.99	91.81	92.63	93.46	92.46	95.80

	Sample: SA-1 'New', smaller amphiboles			B-HIF 'Old', large amphibole						
Na_2O	2.02	1.66	1.63	0.52	0.50	0.21	0.60	0.21	0.27	0.04
MgO	12.09	11.40	12.83	16.21	17.52	18.14	16.58	16.07	16.86	15.42
Al_2O_3	12.38	13.69	10.98	5.77	4.46	2.58	6.69	4.60	4.03	2.19
SiO_2	43.20	42.10	43.73	51.85	51.07	53.68	50.68	49.41	50.20	48.03
K_2O	0.00	0.10	0.10	0.07	0.04	0.01	0.05	0.00	0.06	0.02
CaO	10.99	10.61	11.25	12.25	12.20	12.75	11.79	12.42	12.64	12.89
TiO_2	0.45	0.48	0.51	0.08	0.18	0.09	0.35	0.09	0.27	0.20
MnO	0.20	0.30	0.18	0.21	0.16	0.06	0.19	0.09	0.21	0.31
FeO	12.29	11.28	11.92	9.17	8.98	8.40	9.52	9.52	9.00	10.89
Total	93.74	92.03	93.57	96.15	95.09	95.90	96.45	92.42	93.51	89.98

Sample: B-SVD

	'Old', large amphiboles			'New', smaller amphiboles				
Na_2O	0.97	0.80	1.04	1.86	2.14	1.92	1.09	0.79
MgO	14.16	15.20	15.58	11.94	11.53	11.92	14.76	16.02
Al_2O_3	9.64	6.73	6.57	12.35	13.49	12.71	8.14	6.02
SiO_2	44.10	47.82	47.97	43.36	42.07	42.14	47.88	47.40
K_2O	0.10	0.07	0.06	0.23	0.28	0.21	0.06	0.05
CaO	11.69	11.99	11.77	10.85	11.10	10.53	11.69	11.83
TiO_2	0.14	2.21	0.24	0.42	0.33	0.37	0.35	0.23
MnO	0.20	2.22	0.22	0.23	0.19	0.28	0.20	0.23
FeO	12.33	10.51	10.88	13.35	13.22	13.64	10.75	10.34
Total	93.34	93.56	94.32	94.60	94.35	93.72	94.92	92.90

Table 1 (*contd.*).

Sample:	B-H6F			B-19240		B-19239			
Na_2O	1.68	1.59	1.66	1.73	1.29	1.57	1.47	1.41	1.81
MgO	9.27	10.05	9.14	9.33	9.98	11.43	9.02	11.02	8.90
Al_2O_3	16.23	16.05	15.97	14.95	15.29	12.46	15.27	14.05	13.92
SiO_2	43.60	44.02	42.94	44.49	44.40	42.52	40.48	42.46	39.47
K_2O	0.40	0.34	0.38	0.39	0.36	0.30	0.31	0.27	0.40
CaO	10.08	10.13	10.16	9.08	9.85	9.22	10.06	9.99	9.31
TiO_2	0.36	0.42	0.42	0.45	0.38	0.24	0.40	0.35	0.32
MnO	0.22	0.28	0.25	0.12	0.26	0.19	0.12	0.18	0.16
FeO	14.98	15.32	15.14	16.30	15.81	14.85	15.90	13.99	16.39
Total	96.85	98.20	96.05	96.85	97.61	92.80	93.01	93.71	90.67

porphyritic amphibolites commonly show saussuritized cores, which were taken by Færseth et al. (1977) as the indication of lower amphibolite facies metamorphism during M1. The albitic rims were ascribed to retrogression during M2. However, the saussuritization is probably due to retrogression of a primary more calcic plagioclase, and therefore would not provide evidence for the metamorphic condition during M1. Henriksen (1981) suggests a tectono-metamorphic break between the Vestrevatn formation and amphibolites of the Samnanger Complex (MaBA), using much of the same argumentation as Sturt & Thon (1976) and Færseth et al. (1977). The Vestrevatn formation is the name assigned to a lens of metasandstone in amphibolite on northern Osterøy (Fig. 1), and is tentatively correlated with the Holdhus Group by Henriksen (1981).

There are therefore indications of an early Caledonian event in the MaBA, but its importance and metamorphic grade are uncertain. A Finnmarkian age of the early Caledonian event is suggested (Sturt et al. 1978; Sturt 1984), but the new dates from the lower Ordovician Gulfjellet Ophiolite Complex (Dunning & Pedersen 1988) show that the early event occurred after 481 ± 3 Ma and hence is younger than the Finnmarkian as defined by Sturt et al. (1978).

The main Caledonian (Scandian) event

The progressive, polyphasal main Caledonian (Scandian) event was very strong, obliterating most earlier structures (Færseth et al. 1977; Fossen 1986). Metasediments were intensely folded and sheared with pervasive strains of complex shapes and paths, and in many places mylonitic LS-fabrics were established in all of the rock units. Progressive or repeated deformation resulted in repeated folding of this fabric and in strong mineral recrystallization. In the MaBA, only parts of the Gulfjellet Ophiolite Complex were preserved

Table 2. Sample localities and mineral assemblages. St. Gr = Storetveit Group, Mb. Fm. = Moberg Formation, Nor. C. = Nordåsvatn Complex, Sk. Fm. = Skarfjell Formation. Ti = Titanite phase.

Thin section	Shown in Fig.	Coordinates (UTM)	Locality	Mineral assemblage
B–216	2a, 3	983935	1 St. Gr.	Am+pl+ep+bi+qtz+chl+Ti
0–26	4	095824	2 Mb. Fm.	Am+pl+ep+qtz
0–95	2b, 5	007749	3 Mb. Fm.	Am+pl+ep+bi+qtz+carb+chl+Ti
B–19240	11, 12	968930	4 Nor. C.	Am+pl+ep+mu+bi+qtz+carb+chl+gar+Ti
B–19239	12	968930	4 Nor. C.	Am+pl+ep+mu+bi+qtz+carb+chl+gar+Ti
B–134	10	982010	4 Nor. C	Pl+ep+bi+mu+qtz+chl+gar
B–H6F	7	988004	4 Nor. C.	Am+pl+ep+qtz+bi+mu+carb+chl+Ti
B–H1F	6a, 7	983011	4 Nor. C.	Am+pl+ep+carb+Ti
B–SVD	6b, 7	000998	5 Nor. C.	Am+pl+ep+qtz+chl+Ti
GU–1	8	100940	6 GOC	Am+pl+ep+chl+carb+Ti
SA–1	8	150004	7 GOC	Am+pl+ep+qtz+chl+Ti
SK–10	12	098849	8 Sk. Fm.	Qtz+pl+mu+carb+Ti

relatively undeformed between zones of strongly sheared ophiolitic rocks, metasediments and slices of reworked Precambrian gneisses. Heterogeneous deformation and retrogressive metamorphism proceeded after the peak of the M2 metamorphism, and M2 porphyroblasts obtained porphyroclastic appearances.

Metamorphic index minerals and assemblages

Many of the rocks within the two arcs are of mafic composition, and amphibole is the most common group of minerals in the area. In addition, plagioclase, chlorite, garnet, micas and especially kyanite indicate that at least the garnet grade of the greenschist facies was reached.

The green, mafic conglomerates of the Storetveit and Holdhus Groups show a mineral assemblage similar to that of deformed saussurite gabbros, gabbropegmatites and amphibolites of the older, ophiolitic rocks. The assemblage (Table 2) corresponds to Laird & Albee's (1981) 'common assemblage', except for thin section 0–26 and HIF where chlorite is absent. It appears from the results that the local absence of chlorite has little significant influence on the amphibole composition in the study area.

Mafic mica schists from the Nordåsvatnet Complex (Fig. 3) have a somewhat different mineral assemblage: amphibole + garnet + plagioclase + chlorite + quartz + carbonate + biotite + white mica ± opaques. The presence of garnet and abundant white mica in the mica schist seems to have little influence on the amphibole composition (Fig. 3), probably because plagioclase is present in Laird & Albee's (1981) mineral assemblage as an Al-saturating phase.

Amphiboles

Amphiboles in mafic rocks show a marked change in composition slightly below the transition from upper greenschist facies to lower amphibolite

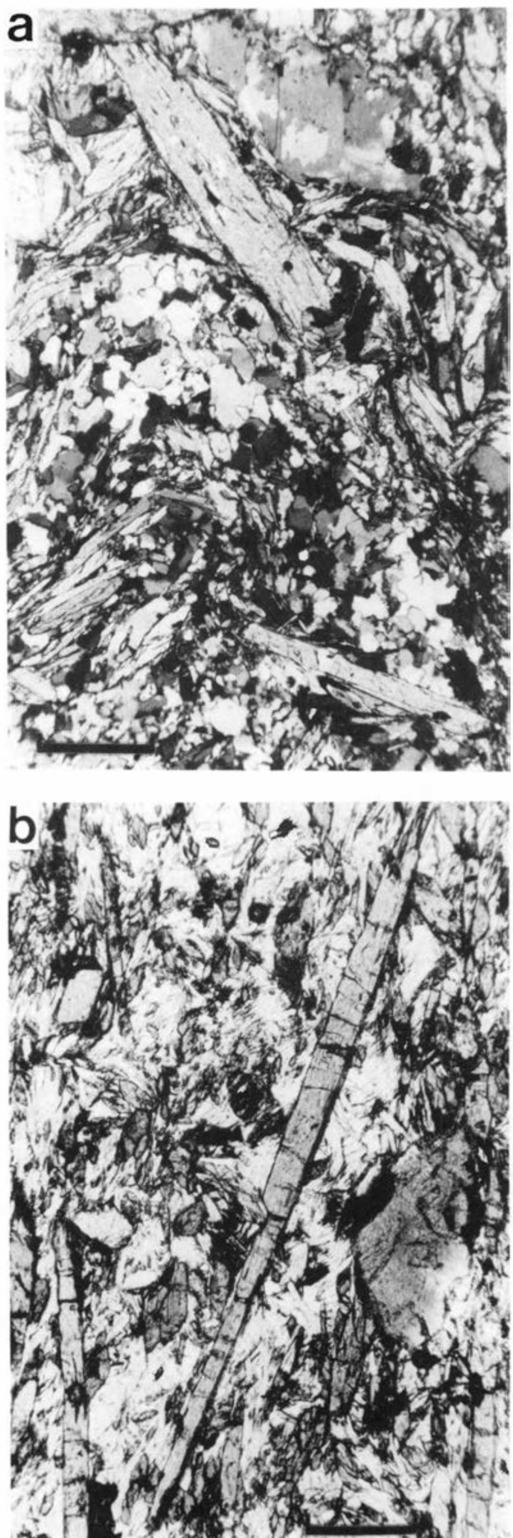
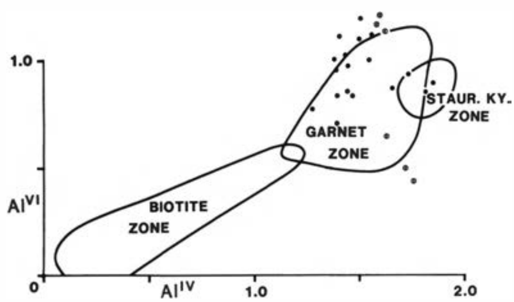


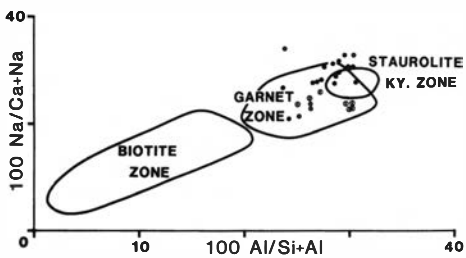
Fig. 2. (a) Metamorphic amphiboles overgrowing the folded and recrystallized foliation in the matrix of strongly deformed polymict conglomerate of the Paradis Fm., Storetveit Group, Minor Bergen Arc. Locality 1. Scale bar: 1 mm.

Fig. 2. (b) Hornblende overgrowing chlorite-rich metamorphic matrix in the Moberg Fm. Locality 3. Scale bar: 1 mm.

Fig. 3. Composition of syn- to post-tectonic amphiboles in the mafic conglomerate of the Storetveit Group (filled symbols) and from mafic mica schist, Nordåsvatn Complex (open symbols), plotted in formula proportion variation diagrams. The division into metamorphic zones in diagrams (a) to (d) is based on analyses of amphiboles in mafic schists from Vermont (Laird & Albee 1981), where intercalated pelitic rocks give good control of the metamorphic conditions. Bar = barrosite, Ed = edenite, Pgs = pargasite, Act = actinolite, Tsch = tschermakite. Locality 1.



a)



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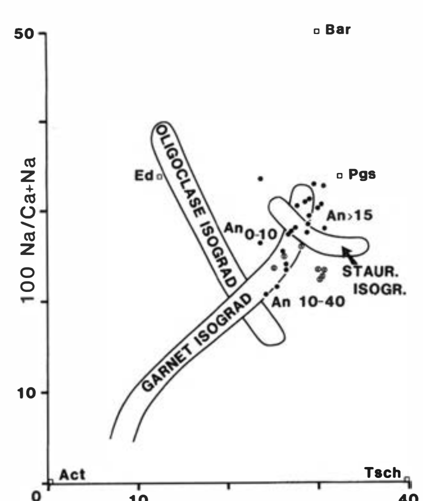

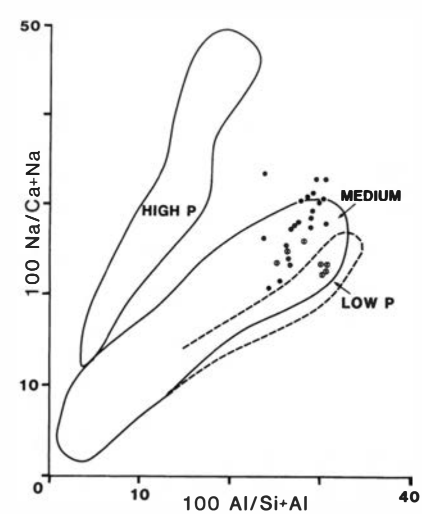

d)

facies (epidote-amphibolite facies) (Miyashiro 1973; Winkler 1979; Moody et al. 1983; Raase et al. 1986). Hence, for upper greenschist to lower amphibolite facies mafic rocks, amphibole compositions may give valuable information about the metamorphic grade.

Scandian amphiboles

In order to deduce the metamorphic conditions during the Scandian event, metamorphic amphiboles in the metasedimentary Holdhus Group (MaBA) and in the Storetveit Group (MiBA) have been examined.

The amphiboles which are analysed are unequivocally metamorphic grains (Fig. 2a, b) which overgrow the marked, locally mylonitic, foliation in the mafic conglomerates and grits of the Holdhus and Storetveit Groups. The amphibole analyses from the Storetveit Group (Fig. 3) plot close to the oligoclase isograd and both below and above the staurolite isograd. Compared with analyses from other metamorphic areas where this type of data is available, the amphiboles indicate medium pressure conditions (Fig. 3d) in uppermost greenschist facies and locally lowermost amphibolite facies (Fig. 3a, b). Most amphibole analyses from the Holdhus Group show similar compositions, but some of the metamorphic grains show a chemical variation from the rim to the core (Figs. 4, 5). The rims have compositions similar to the amphiboles from the Storetveit Group,while some cores indicate early growth during lower metamorphic conditions (Figs. 4, 5a–c). This is interpreted as growth during a prograde metamorphic event which reached its maximum close to the staurolite isograd (Figs. 3c, 4c, 5c).

The upper part of the medium pressure area is indicated (Figs. 3d, 4d, 5d), and the fact that no analyses plot above the staurolite isograd indicates a slightly higher metamorphic grade in the Storetveit Group than in the Holdhus Group. The prograde development is not seen in the Minor Bergen Arc, perhaps because the rocks of the Storetveit Group were more intensely recrystallized during the metamorphic peak.

Pre-Scandian amphiboles

Due to intense recrystallization during the Scandian orogenic event the pre-Scandian mineralogy is normally difficult to distinguish. Parts of the Gulfjellet Ophiolite Complex, however, escaped most Scandian deformation and metamorphism. Pre-Scandian deformation has not been clearly recognized in these parts, but most pyroxenes in gabbros and gabbro pegmatites are altered to amphiboles. Towards the Scandian shear zones, large amphiboles in gabbro pegmatites and saussurite gabbros become unstable, and a new generation of amphiboles appears defining the Scandian fabric (Fig. 6a, b). The new-grown amphiboles occur also as post-tectonic grains. Both generations have been analysed by electron microprobe (Figs. 7, 8). The newer grains have compositions similar to Scandian amphiboles in the younger metasediments, while the larger porphyroclasts have more actinolitic compositions. These actinolitic amphiboles appear to indicate lower metamorphic conditions on a regional scale, as they are found in the pre-Ashgillian rocks of both the MiBA (the Nordåsvatn Complex) and the MaBA (Gulfjellet Ophiolite Complex).

Based on textural criteria, the large porphyroclasts are the oldest amphiboles found in the rocks. They dominate the less-deformed parts of the Gulfjellet Ophiolite Complex, and similar amphiboles are interpreted as clastic grains in the Vestrevatn formation, Osterøy (Henriksen 1981). Their composition indicates an earlier metamorphism (M1) of lower grade than the later and stronger Scandian event. Figs. 7a–b and 8a–b indicate that this early metamorphism was of the biotite to possibly garnet grade of the greenschist facies.

Garnets

The appearance of almandine-rich garnets occurs within the upper part of the greenschist facies, giving rise to Barrow's 'garnet zone' (Barrow 1912). Chemically, garnets are expected to be enriched in FeO relative to MnO by rising temperature (e.g. Miyashiro 1973).

Garnets commonly occur in mica-bearing lithologies in the study area, mainly in the older mica schists of the Gulfjellet Ophiolite Complex and the Nordåsvatnet Complex, but locally also in the Ashgillian-Llandoverian Holdhus Group (Ingdahl 1985). As the Scandian deformation was of a polyphasal, progressive character (Ingdahl 1985; Fossen 1986) most garnets are enveloped by the main foliation, and their age is, from a textural point of view, not always easy to

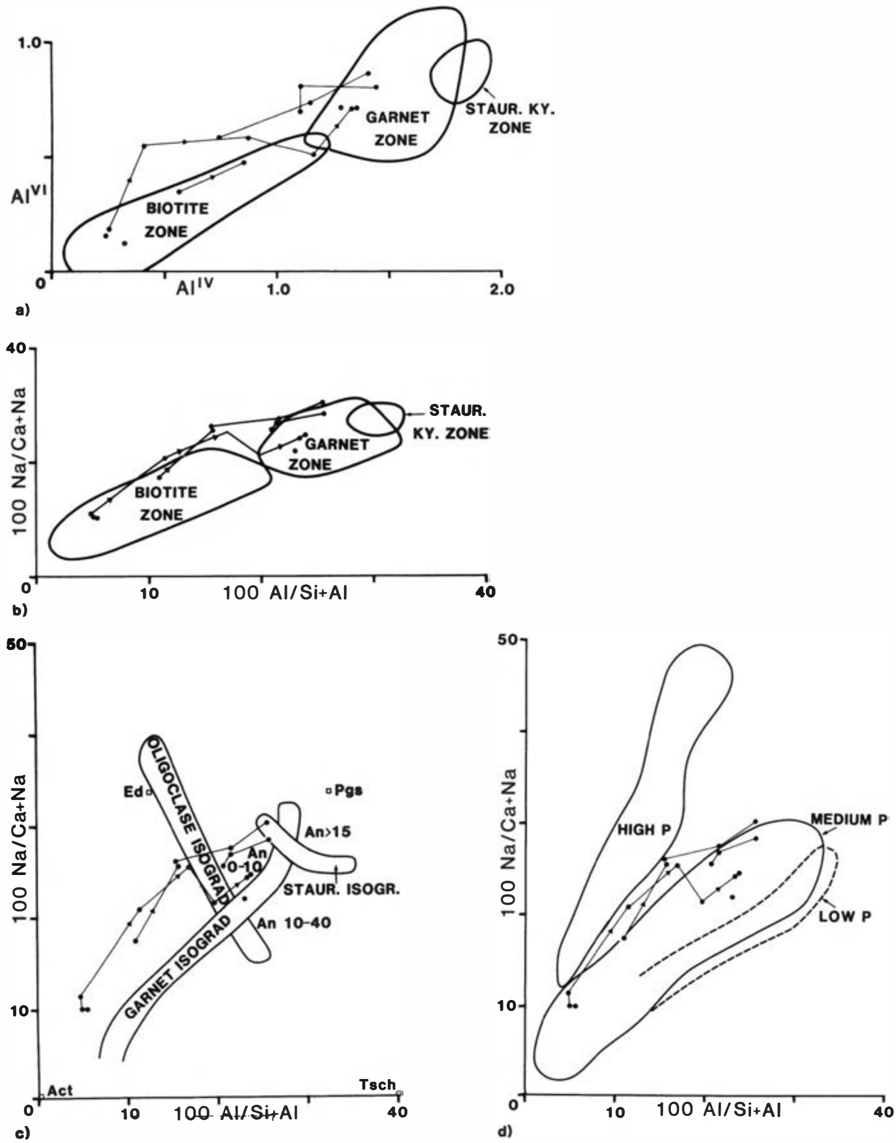

Fig. 4. Composition of syn- to post-tectonic amphiboles in the Moberg Fm., Holdhus Group. Analyses of the same metamorphic grain are linked, and arrows show the trend from the core towards the rim. Locality 2. One of the amphiboles is shown in Fig. 2b. See also text to Fig. 3.

ascertain. Færseth et al. (1977) interpreted garnets which are enveloped by the main foliation, and which have inclusion patterns at angles to it, as pre-Ashgillian porphyroblasts in the MaBA. If the inclusions were more fine-grained than the matrix, this was another indication of M1 porphyroblasts. However, similar structures may have evolved during the main Caledonian event, as illustrated in Fig. 9. The amphibole compositions show that the metamorphic grade was above the garnet isograd during the Scandian event, and since most amphiboles recrystallized during this event the garnets probably grew as well.

There are, however, garnets with clear textural zoning, as shown in Fig. 10. A fine-grained inclusion fabric may or may not be folded prior to being overgrown by one or several rims of

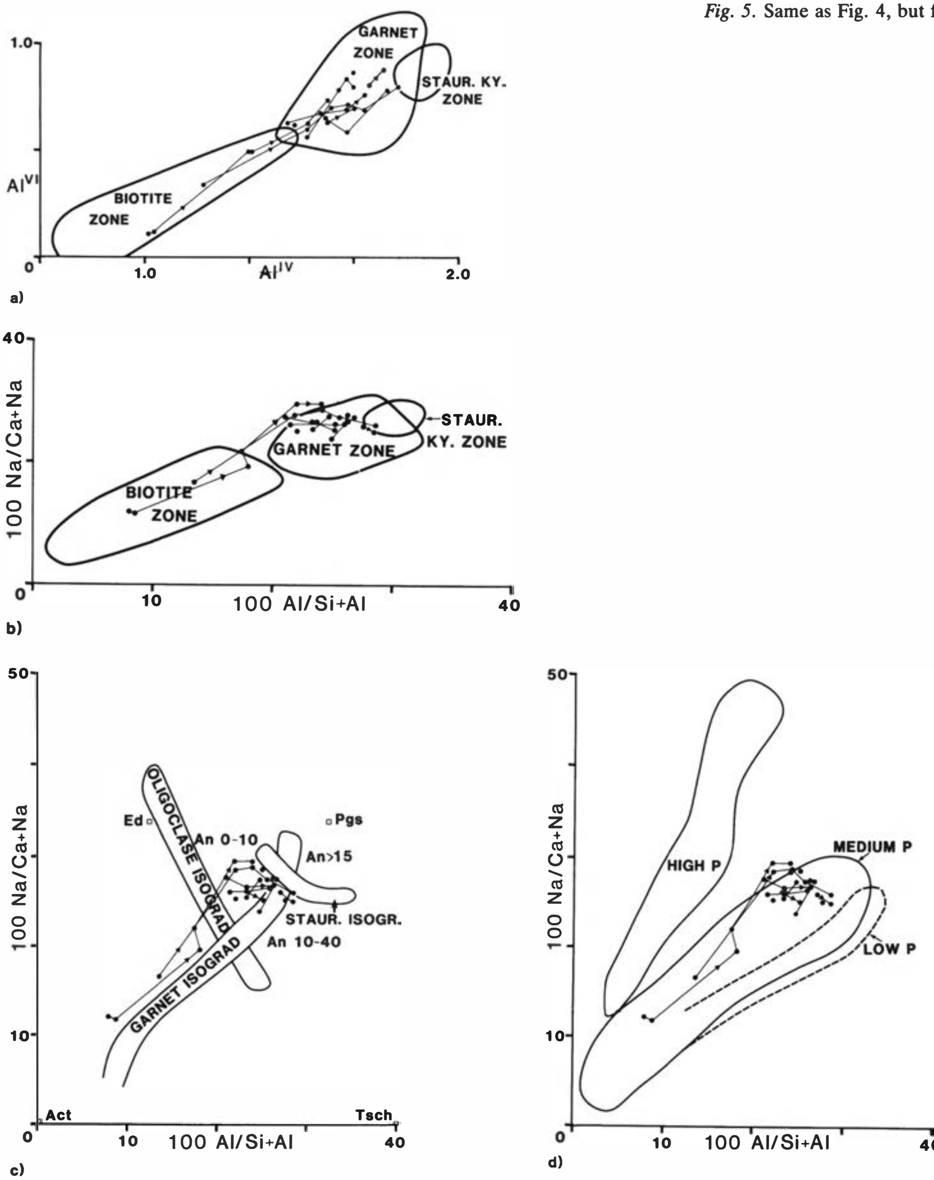

Fig. 5. Same as Fig. 4, but from locality 3.

homogeneous garnet or by garnet with more coarse-grained inclusions. A sharp textural break may occur between the zones. A few such garnets from the MiBA have been analysed, and the textural break marks a compositional change (Fig. 11). The core may have grown during an early metamorphism, and the outer rim during the Scandian metamorphism. The Mn-rich core may correspond to the lower-grade, early metamorphism indicated by the amphibole analyses, and the almandine-rich rim to the Scandian. Alternatively, the zoning may be a result of the polyphasal Scandian event, and no evidence has been found to resolve this uncertainty. However, if Henriksen's (1981) interpretation of clastic garnets in the Vestrevatn formation is correct, garnet growth clearly occurred during M1 as well as M2.

White mica

The Si : Al ratio in white micas is dependent on the metamorphic grade under which the mica

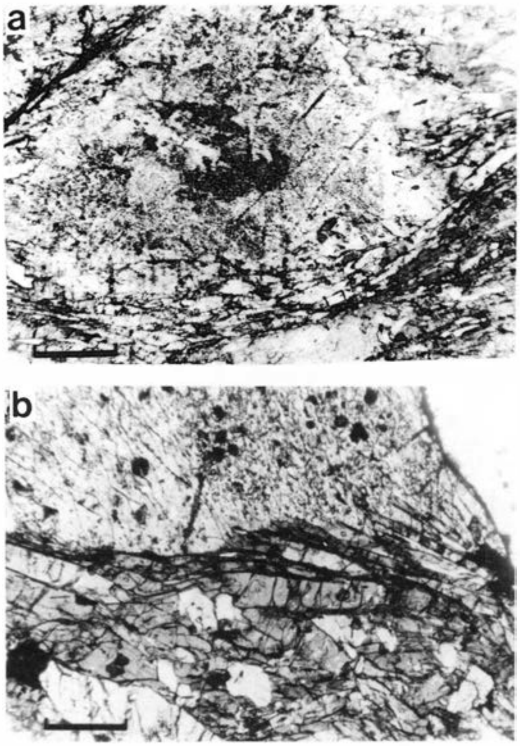

Fig. 6. (a) Amphibole porphyroclast recrystallizing to smaller amphiboles along the margins. A chemical variation between the porphyroclast and the newer grains along the margins is shown in Fig. 7. Protomylonitic gabbro, Nordåsvatn Complex, MiBA. Similar porphyroblasts occur in ophiolitic rocks in the MaBA. Locality 4. Scale bar: 1 mm. (b) Close-up of the edge of a large, relict amphibole porphyroclast in strongly deformed gabbro-pegmatite, Nordåsvatn Complex. A preferred orientation of the new-formed amphiboles indicates stress-related (syn-tectonic) growth. For chemical compositions, see Fig. 7. Locality 5. Scale bar: 1 mm.

formed (Velde 1967), and the ideal muscovite composition is attained only in some magmatic rocks and by high-grade metamorphism. Most metamorphic white micas are solid solutions between idealized muscovite and celadonite, and those enriched in the celadonite component are termed phengite (Si : Al $< 3:1$).

White micas have been analysed on the electron microprobe from mica schists of the Nordåsvatn Complex, MiBA (Fossen 1986) and the Ulven and Holdhus Groups, MaBA. Micas from both areas indicate uppermost greenschist facies close to the staurolite zone (Fig. 12). This is the same result as is indicated by the amphibole analyses above.

Plagioclase

A change in the plagioclase composition from An < 10 to An > 15 has traditionally been considered to take place at or slightly below the greenschist to amphibolite facies transition (e.g. Winkler 1979). The work of Laird & Albee (1981) also indicates that this transition is dependent on pressure. The coexistence of albite and oligoclase is considered by Turner (1981) to be a general phenomenon that immediately precedes the full development of the amphibolite facies mineralogy.

Plagioclase compositions in rocks of the MiBA vary from An_{01} to An_{40} (Fossen 1986) in both the Storetveit Group and the older Nordåsvatn Complex. The amphibole analyses (Fig. 8c) indicate that the metamorphic conditions were close to the oligoclase isograd where albite and more calcic plagioclase are expected to coexist.

From the Major Bergen Arc, Ingdahl (1985) reported the common metamorphic plagioclase to be albite in the Os area (Fig. 1), although oligoclase occurs. An explanation of this difference from the MiBA may be found by comparing Figs. 3c, 4c and 5c. These plots indicate that the metamorphic conditions in the Os (Fig. 1) area are generally above the oligoclase isograd (An_{0-10}), while the conditions within the Minor Bergen Arc are both below and above this isograd. One reason for this may be the slightly higher pressures in the Major Bergen Arc. However, near the Anorthosite Complex in the western part of the MaBA, the metamorphic grade appears to be above the staurolite isograd, and An_{10-40} is common.

Kyanite

Kyanite is the high-pressure Al_2SiO_5 polymorph, and indicates that the pressure has been intermediate or higher.

Kyanite is found in a limited area in the westernmost extension of the MaBA (Fig. 1). Kolderup & Kolderup (1940) described kyanite from the MiBA on Askøy too (Fig. 1). The local presence of relatively late Caledonian porphyroblasts of kyanite indicates at least medium pressures consistent with the amphibole compositions (Figs. 3d, 4d, 5d, 7d, 8d). Preliminary pressure–temperature estimates from this area by the methods of Ferry & Spear (1978), Newton & Haselton

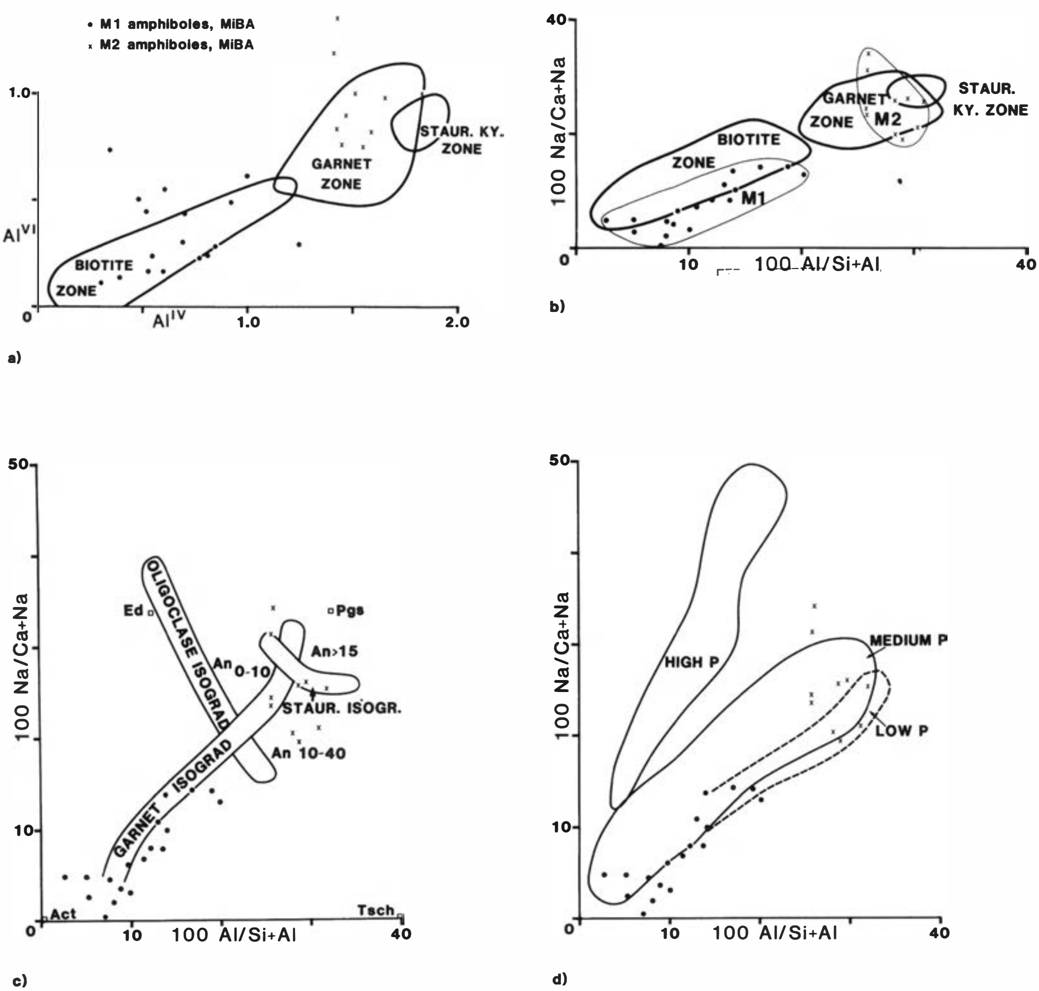

Fig. 7. Electron microprobe analysis of old, large, unstable porphyroclasts (filled symbols) and newer, smaller amphiboles (crosses) which have crystallized along the margins as shown in Fig. 6a–b. Deformed gabbro(pegmatites), Nordåsvatn Complex. Locality 5.

(1981) and Gangelu & Saxena (1984) indicate a pressure of about 9 ± 2 kb and a temperature of 600 ± 50°C.

Kyanite occurring close to the Anorthosite Complex in the Major Bergen Arc (Fig. 1) may indicate a different chemical composition of the rocks or an increase in pressure towards this complex. If the latter is the case, it is of particular interest that very high pressures are estimated from Caledonian mineral paragenesis within anorthositic rocks in the northern part of the Anorthosite Complex (Austrheim & Griffin 1985), and kyanites are common as small needles in Caledonian shear zones in the southern part of the Anorthosite Complex not far from the Major and Minor Bergen Arcs. This may or may not indicate that the Caledonian high-pressure metamorphism in the Anorthosite Complex is related to the main Caledonian event in the Major and Minor Bergen Arcs. As kyanite is found along the contact between these complexes, the post-Llandoverian juxtaposition of the rocks probably occurred at medium to high pressures near the transition between greenschist–amphibolite facies.

Radiometric age determinations from eclogites

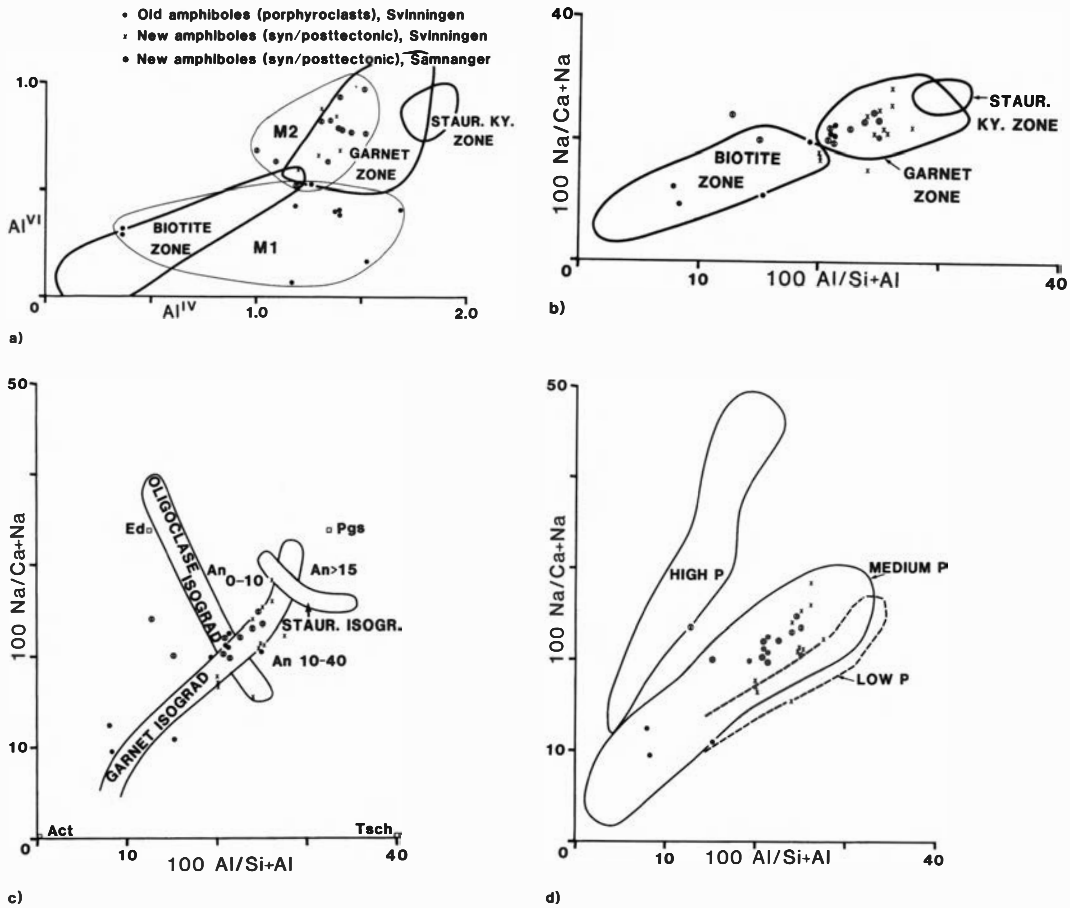

Fig. 8. Same as Fig. 7 but from the Gulfjellet Ophiolite Complex, MaBA. Localities 6 and 7.

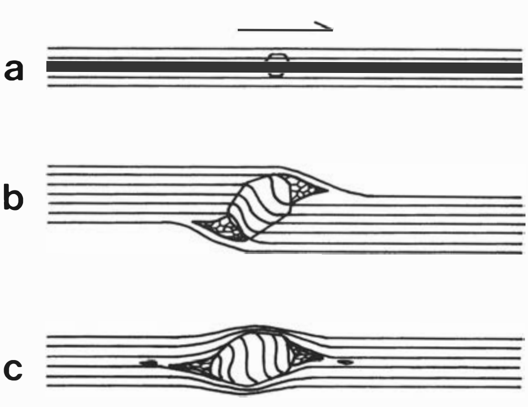

Fig. 9. Schematic illustration of a syn-kinematic porphyroblast which obtains the features of a porphyroclast as shearing proceeds. The result is a porphyroclast with an internal foliation oblique to the external due to material rotation during growth.

in the Anorthosite Complex (Austrheim & Råheim 1981) and several other locations in Western Norway (Griffin et al. 1985) strongly indicate a Caledonian age for the high pressure event.

Staurolite

Staurolite is found in a small zone of mica schist of unknown age within the Øygarden Gneiss Complex at Askøy close to rocks of the MiBA (Fig. 1) (R. Duncamb, unpublished data). The mica schist shares the same Scandian fabric as rocks of the MiBA. The growth of staurolite is synkinematic to the Scandian event and gives support to the interpretation that the staurolite isograd was exceeded, at least locally, in the MiBA (e.g. Fig. 3c).

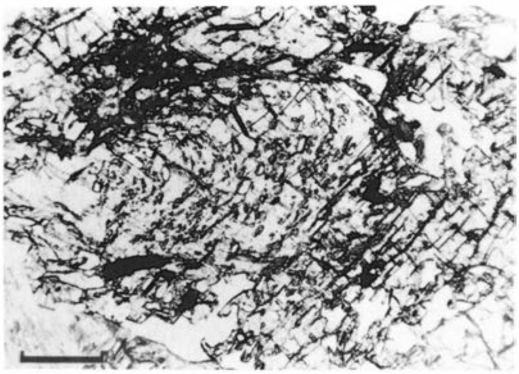

Fig. 10. Garnet from micaschist of the Nordåsvatn Complex, MiBA, showing an inner core with fine-grained inclusions defining a curved foliation, and an outer rim with more randomly oriented, coarser inclusions. Locality 4. Scale bar: 1 mm.

Discussion and conclusions

All rock units within the MiBA and MaBA underwent prograde metamorphism close to the upper greenschist–lower amphibolite facies transition, and probably locally reached the lower amphibolite facies at the peak of the metamorphism. The metamorphism occurred after the deposition of the Storetveit, Holdhus and Ulven Groups, as shown by the microchemical examination of unequivocal metamorphic minerals within these younger (Upper Ordovician–Lower Silurian) rocks in the arcs.

The structural and metamorphic fabric seen in the younger rocks also dominates the older Lower Palaeozoic rocks as the strong Scandian deformation has commonly obliterated any earlier metamorphic mineralogy. However, middle greenschist facies mineralogy is locally preserved in old porphyroclasts, and dominates little-deformed domains of the Gulfjellet Ophiolite.

Earlier workers (Sturt & Thon 1976; Færseth et al. 1977; Henriksen 1981) interpreted the pre-Ashgillian metamorphism to be of lower amphibolite facies, and the later, Scandian, metamorphism to be of middle to upper greenschist facies, increasing towards the north. Mineral compositions, however, suggest a metamorphic development in the MaBA and MiBA which is at variance with the earlier interpretation, i.e. the main Caldeonian (Scandian) metamorphism is the stronger and of the higher grade, while the pre-Ashgillian is poorly preserved and of lower grade (Fig. 13).

The strongest metamorphic event is related to post-Llandoverian shearing in the area, and the metamorphic grade is apparently constant throughout the two arcs. Local growth of kyanite may, however, indicate higher pressure close to the Anorthosite Complex. Retrograde high-pressure metamorphism in the Anorthosite Complex and the prograde development in the Major and Minor Bergen Arcs may possibly be explained by juxtaposition under medium or slightly higher pressures in post-Lower Silurian times.

The significance of the early metamorphism is not yet clear. It may be related to a regional orogeny which involved continental crust, as pre-

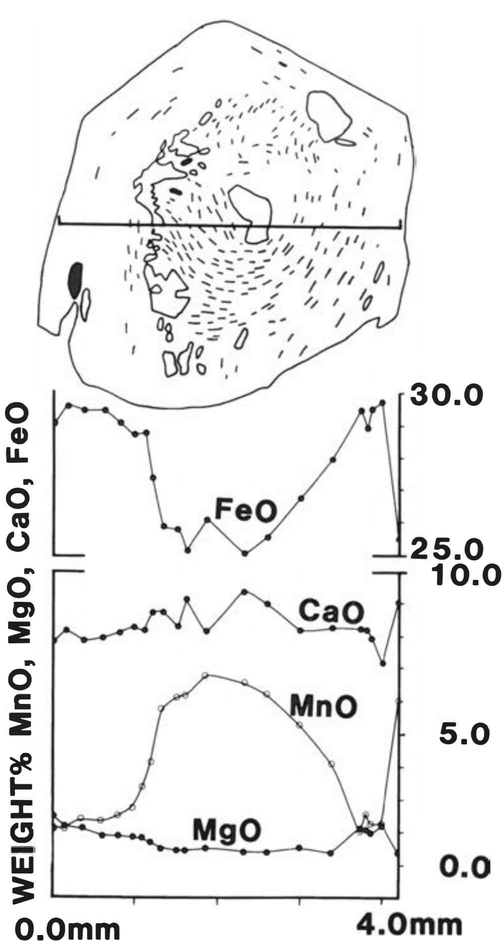

Fig. 11. Typical compositional profile of a texturally zoned garnet from garnet-amphibole micaschist, Nordåsvatn Complex. On the left hand side a textural and chemical break is clear and coinciding. On the right hand side the break appears somewhat less well defined. Near locality 1.

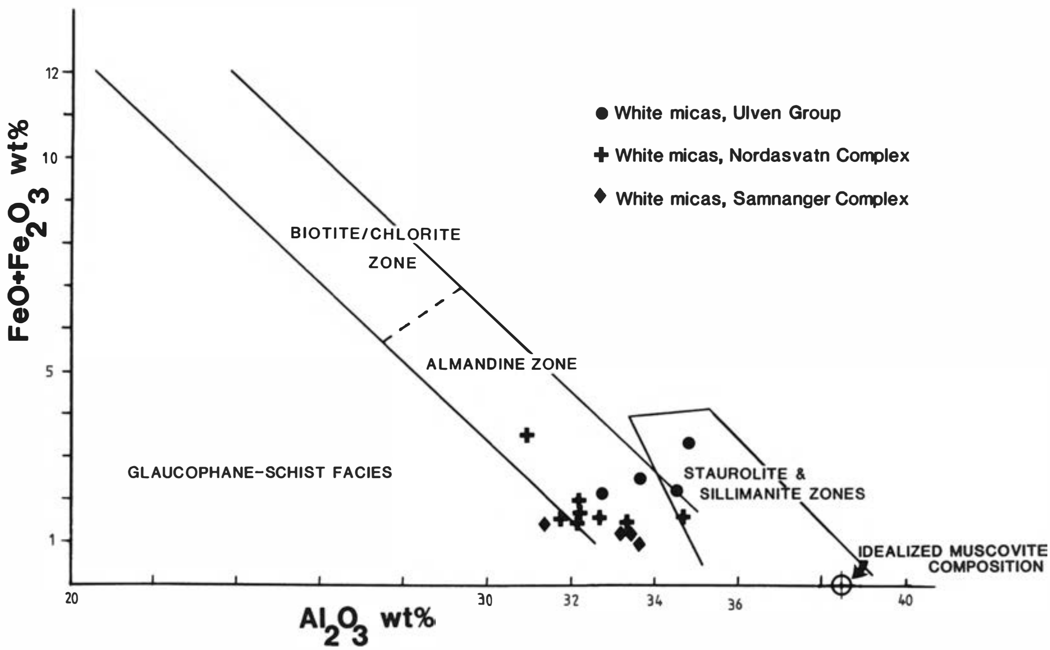

Fig. 12. White micas from quartzite of the Ulven Group (loc. 8) and from garnet–amphibole micaschists of the Nordåsvatn Complex (MiBA, loc. 1) and Samnanger Complex (MaBA) plotted in formula proportion variation diagram composed by Miyashiro (1973).

viously suggested (Sturt & Thon 1976; Sturt et al. 1978), including obduction of the ophiolitic rocks (Thon 1985). Alternatively, it may be related to ocean floor metamorphism, or to local deformation and metamorphism in intraoceanic arc-related environments.

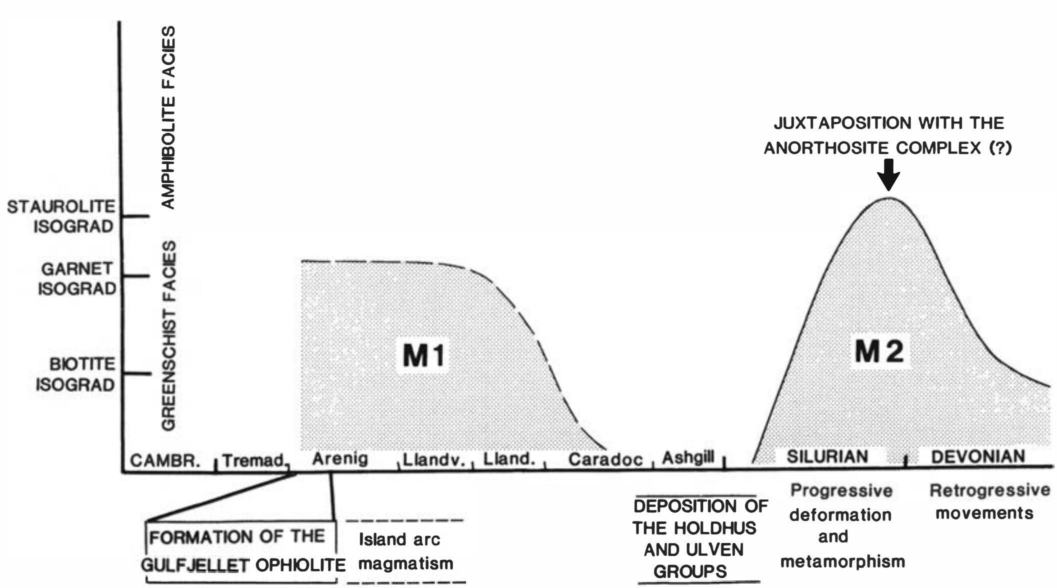

Fig. 13. Schematic illustration of the metamorphic development in the Lower Palaeozoic rocks of the Bergen Arcs, based on the results from this work and from earlier work and interpretations cited in the text.

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APPENDIX: Analytical methods

Mineral analyses of samples B216, B19240, B19239, B134, B-PH6F, and B-SVD were acquired with an ARL 58 (at the University of Bergen during 1985) with an accelerating voltage of 15 kv and a sample current of 10nA. Analyses of samples 0-26, 0-95, Gu-1, SA-1, SK-10 were obtained with a Cameca electron microprobe (wavelength dispersive system) with voltage and current as above. The ZAF matrix correction was used.

Amphibole analyses are normalized by the method of Leake (1978) based on 23 Oxygen. The diagrams by Laird & Albee (1981) were based on analyses normalized to total cations less $(Ca+Na+K)=13$ except those that have $Ca \leq 2$. However, recalculations of some of the analyses have shown that the difference with respect to $Na/(Na+Ca)$, $Al/(Si + Al)$ and Al(IV) is negligible and small for Al(VI).

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