Blue schists from Motalafjella, Western Spitsbergen

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Abstract

The occurrence of Caledonian glaucophane schists and eclogitic rocks in the Vestgötabreen area, south of St. Jonsfjorden, western part of Spitsbergen, has been studied in detail, and the metamorphic conditions are discussed based on new chemical analyses of 30 bulk rocks and 25 constituent minerals. The rocks occur as a thin thrust schuppen, lying between the lower grade metamorphic and meta-sedimentary rocks of lower Paleozoic age. The original rocks of the glaucophane schists are considered to be argillaceous quartzite and mixtures of argillaceous sediments and basic volcanic rocks. The metamorphic conditions of the schists are similar to those of the Type IV glaucophane schists of California, and the formation conditions of the eclogitic rocks have been calculated to 9.7 kb and 540–570°C from the Fe/Mg partitioning between clinopyroxene and garnet. The metamorphism of these rocks is a transitional facies series between the blue schist type and the intermediate P/T type of metamorphic facies series. The metamorphism of Hecla Hoek rocks of western Spitsbergen is the intermediate P/T facies series. These metamorphic facies series are considered to be developed from the eugeosynclinal Torellian basin of pre-Cambrian time. The possibility of two sets of paired metamorphic zones during the Caledonian period and of a pre-Cambrian metamorphism of the intermediate P/T facies series in Svalbard are discussed.

I. Introduction

An occurrence of glaucophane schists and eclogitic rocks in the Vestgötabreen and Eidembreen areas, south of St. Jonsfjorden, has been known since 1957 among British geologists studying Svalbard. The extension of the occurrence, the outline of mineral assemblages, and bulk rock chemistry were reported by HORSFIELD in 1972, with five K–A ages. Although the area including this locality has been affected by the Tertiary deformation, these particular rocks are considered to be formed during the Caledonian Orogeny, as indicated by the radiometric ages more than 410 m.y. old. Thus, this is one of the oldest in the world among the glaucophane schists hitherto reported, only revealable is the Ballantrae complex in Ayrshire, Scotland.

This area was mapped in detail by the present author in the summers of 1973 and 1975, and all rock varieties of this particular rock formation have been collected. Details of the field occurrence and chemical properties of the rocks and constituent minerals are presented in this paper, and some comparative considerations are made between these rocks and other metamorphic rocks in Svalbard.

II. Geological setting

The distribution of blue schists and their associated rocks is shown in Fig. 1. HORSFIELD (1972) distinguished the following rocks in his geological map: (1) Bulltinden Formation: conglomerate, sandstone and shale; (2) marbles; (3) mica schists, mylonites and breccias; (4) epidote-actinolite greenstones; and (5) glaucophane-bearing rocks. Coarse-grained glaucophane, garnet and muscovite schists were referred by him to the Vestgötabreen suite. Rocks with abundant chloritoid, serpentinite, and others having sodic clinopyroxene, i.e. eclogite type rocks and pyroxenite pods, are also described by him from this rock suite.

HORSFIELD's map has been modified a little north of Skipperbreen and in the southern half of Motalafjella, based on new mapping by the present author. He found a fragment of a badly preserved brachiopod from a scree block of limestone in the middle-north of Motalafjella. This block came no doubt from the limestone lying above the conglomerate of the Bulltinden Formation which has a fossiliferous limestone lens of lower Paleozoic age. For this reason, this limestone (the (2) marbles of HORSFIELD) is included in Bulltinden Formation in this paper.

The rocks of (3), (4), and (5) of HORSFIELD, occur as a narrow zone less than a few hundred metres thick and closely associated for more than 10 km along the strike. The development of cleavage and the degree of recrystallization of these rocks are strikingly different from those of the Bulltinden Formation. Therefore, all these rocks are tentatively grouped as the Vestgötabreen Formation in the present paper.

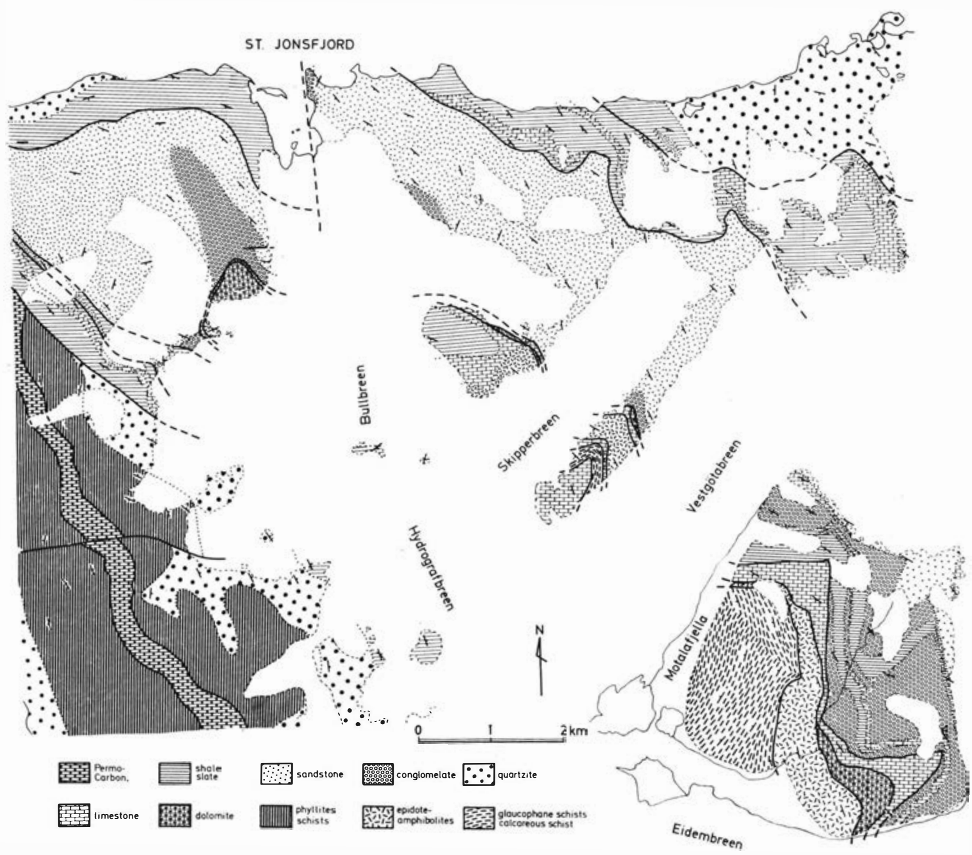


Fig. 1. *Geological map of the area from St. Jonsfjorden to Motalafjella.*

The Bulltinden Formation is composed of (1) coarse-grained sandstone (often conglomeratic) and shale alternations more than 1,000 m thick, (2) boulder conglomerate 500 m thick, (3) fine-grained sandstone-shale alternations 300 m thick, and (4) banded grey limestone less than 50 m thick, in ascending order. A conglomeratic limestone bed 20 m thick occurs in the boulder conglomerate and includes many fossils which suggest upper Ordovician — lower Silurian age (the fossils will be described in a separate paper).

Both the lower and upper sides of the Vestgötabreen Formation are in low angle fault contact with the grey limestone of the Bulltinden Formation.

The rocks of the Vestgötabreen Formation can be divided into two members: (1) the epidote actinolite greenstones, black phyllite, dolomite and serpentinite in the lower part and (2) the glaucophane-bearing rocks, eclogitic rocks, calcareous schists and dolomite in the upper part. The distribution and thickness of each rock type differ very much from place to place (Figs. 1 and 2) and the lower and upper members are separated by a subordinate low angle, probably reverse fault, locally intercalating the grey limestone layers of the

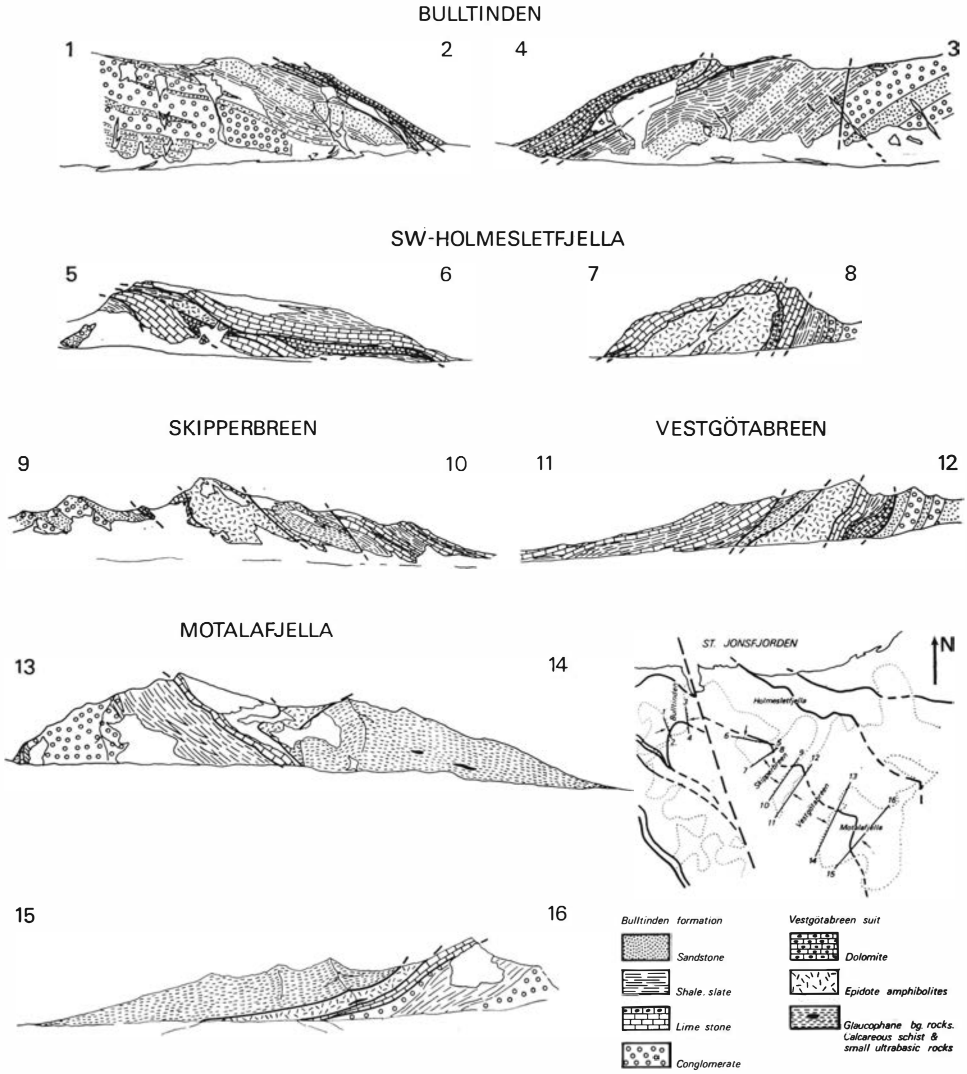


Fig. 2. *Occurrences of the Vestgötabreen Formation.*

Bulltinden Formation as a schuppen. The upper member is lacking north of Skipperbreen and Bulltinden.

Short notes on the lithology of the rocks of the Vestgötabreen Formation are given below.

A distinct yellow dolomite follows along the basal thrust fault of the Vestgötabreen Formation. It is a dense, massive rock, partly gneissose and marked by fresh green chlorite and occurs as large lenses hundreds of metres long with a thickness of up to 150 m. The epidote-actinolite greenstone occurs in sharp concordant contact with the dolomite and limestone, and often shows strong schistosity. A large stock-like body is exposed on the southern face of the ridge between Vestgötabreen and Skipperbreen (Fig. 2, profile 7–8). In Motalafjella, this rock is well banded greenschist, having small garnet grains in some layers, and is interlayered with black phyllite. Small lenses of schistose serpentinite occur concordantly in the greenstone. No gradational change from the greenstones to the overlying glaucophane-bearing rocks has been observed and the border is a subordinate thrust fault.

The upper member of the Vestgötabreen Formation shows frequent alternation of muscovite-quartz schist, glaucophane schist and calcareous schist, and the last-named rock makes up nearly half the volume. The calcareous schist has thin layers of muscovite, chlorite, and garnet with a small amount of glaucophane in medium-grained banded marble. The muscovite-quartz schists show strong diaphtolitic cleavages undulated by large garnet porphyroblasts and scattered prisms of chloritoid. The compositional banding, several cm thick, is defined by the layers of different ratios of the constituent minerals. Glaucophane occurs in these rocks as idiomorphic prisms without linear arrangement on the cleavage surfaces. The glaucophane schist shows dark blue shiny cleavage and has many large garnet grains up to 3 cm across. The groundmass of the rock is often composed of pure glaucophane aggregate.

The eclogitic rocks occur as concordant lenses, from several dm to ten metres thick, in the muscovite-quartz schists and calcareous schists, and have idiomorphic glaucophane around the margins and cracks.

A thick grey limestone and slate occur above the Vestgötabreen Formation on the ridge north of Skipperbreen (Fig. 2, profile 5–6). These rocks can be correlated with the grey limestone and shale of the Bulltinden Formation.

III. Bulk chemical composition of the rocks

In order to evaluate the nature of the original rocks and to study metamorphic mineral parageneses, 30 rocks were analysed for major elements by the following methods: Si, Al, Ti, total Fe, Mn, Mg, Ca, and P by X-ray fluorescence analysis, FeO by titration, Na and K by the atomic absorption method, and gas+water by the penfield-tube ignition method.

The analysed rocks are listed in Table 1. Three analyses of Horsfield (1972) from the Vestgötabreen area and four metabasites of Hjelle (1962, and unpublished) from Nordenskiöldkysten are discussed together. The amphibolites from Hornsund (Birkenmajer and Narebski 1960, and

Table 1

Chemical analyses of the rocks

	1	2	3	4	5	6	7	8
SiO_2	48.49	48.80	49.66	46.77	47.00	47.31	47.91	47.75
TiO_2	1.43	1.58	1.01	2.19	1.30	1.29	0.51	1.41
Al_2O_3	15.66	14.30	13.51	14.27	14.78	15.84	13.41	11.93
Fe_2O_3	3.30	8.20	4.39	5.95	9.23	3.50	14.64	6.86
FeO	9.81	4.02	8.69	10.74	3.74	11.28		6.47
MnO	0.25	0.14	0.18	0.15	0.15	0.21	0.23	0.28
MgO	10.54	9.71	11.30	9.02	10.58	9.48	7.73	8.02
CaO	2.22	3.07	2.11	2.11	1.99	2.75	5.86	10.31
K_2O	1.73	1.88	0.78	1.69	3.02	1.66	1.40	0.19
Na_2O	3.10	4.44	4.40	3.17	3.85	2.03	0.85	4.34
P_2O_5	0.05	0.16	0.04	0.06	0.19	0.10	0.88	0.01
$H_2O\pm$	3.60	3.82	3.60	3.39	3.62	4.77	5.64	2.71
Total	100.18	100.12	99.67	99.51	99.45	100.22	99.06	100.28

	9	10	11	12	13	14	15	16
SiO_2	53.78	46.06	44.39	42.52	48.33	45.85	48.71	47.62
TiO_2	0.81	1.79	1.84	2.38	1.02	1.80	1.52	1.36
Al_2O_3	9.88	13.90	13.78	13.33	14.32	14.58	15.84	14.25
Fe_2O_3	5.13	6.98	4.05	4.35	12.08	5.49	2.28	4.71
FeO	3.37	6.47	9.66	11.35		8.87	8.84	6.00
MnO	0.12	0.22	0.22	0.21	0.19	0.29	0.21	0.18
MgO	8.54	7.19	7.76	8.23	7.65	9.16	7.38	7.95
CaO	10.65	11.31	11.00	7.30	10.28	4.58	6.73	12.54
K_2O	0.06	0.76	0.78	0.01	0.40	1.41	1.50	0.23
Na_2O	6.75	1.70	1.92	2.23	2.50	2.08	3.37	1.89
P_2O_5	0.03	0.14	0.15	0.21	0.01	0.16	0.18	0.13
$H_2O\pm$	0.62	3.56	3.86	7.55	5.01	5.15	3.69	2.87
Total	99.74	100.08	99.41	99.72	101.79	99.42	100.25	99.73

	17	18	19	20	21	22	23	24
SiO_2	47.95	47.43	51.32	46.98	53.89	41.42	46.91	43.80
TiO_2	1.55	1.98	1.94	2.84	1.78	2.66	1.50	3.17
Al_2O_3	15.26	11.51	15.22	15.51	16.95	7.28	14.46	13.17
Fe_2O_3	2.13	5.19	1.94	2.88	2.16	2.13	3.25	0.92
FeO	9.05	7.69	6.79	6.97	6.18	12.04	9.05	9.50
MnO	0.20	0.26	0.14	0.13	0.15	0.19	0.19	0.23
MgO	6.34	7.33	6.22	6.98	3.13	18.84	8.08	8.78
CaO	8.58	9.85	6.13	9.17	3.37	8.93	9.54	9.89
K_2O	1.27	0.82	1.66	0.83	3.46	0.68	0.27	1.56
Na_2O	3.48	3.97	4.55	3.43	6.40	0.35	3.25	2.65
P_2O_5	0.18	0.20	0.52	0.45	0.47	0.41	0.11	0.35
$H_2O\pm$	3.78	3.29	3.28	3.42	2.18	5.22	3.55	6.17
Total	99.77	99.52	99.71	99.59	100.12	100.15	100.16	100.19

Table 1 cont.

	25	26	27	28	29	30	31	32
SiO_2	38.47	46.72	50.50	56.01	51.19	67.94	71.79	49.25
TiO_2	1.63	3.28	1.87	1.80	1.60	0.39	0.18	1.14
Al_2O_3	6.54	11.98	14.16	13.23	21.21	12.13	13.32	24.15
Fe_2O_3	4.53	1.85	1.52	3.30	4.11	1.89	1.51	16.80
FeO	7.60	12.46	10.88	12.43	7.51	2.80	1.19	
MnO	0.20	0.24	0.13	0.10	0.12	0.04	0.05	0.23
MgO	26.25	7.67	6.79	6.46	3.66	4.13	2.58	1.98
CaO	6.06	9.41	6.93	1.41	0.55	1.65	0.62	0.00
K_2O	0.57	0.05	0.02	1.85	4.34	4.29	2.87	0.70
Na_2O	0.24	2.74	4.35	0.40	2.08	1.76	3.79	2.60
P_2O_5	0.15	0.22	0.10	0.15	0.23	0.05	0.02	0.05
$H_2O\pm$	7.96	3.45	2.89	2.64	3.21	2.70	1.60	3.04
Total	100.20	100.07	100.14	99.78	99.81	99.77	99.52	99.94

	33	34	35	36	AK0232
SiO_2	58.80	74.40	70.96	58.70	45.08
TiO_2	0.82	0.60	0.28	0.96	3.23
Al_2O_3	16.56	12.41	13.80	20.98	12.24
Fe_2O_3	3.07	1.00	0.86	2.17	4.08
FeO	4.60	3.63	1.98	5.14	11.96
MnO	0.20	0.28	0.03	0.17	0.31
MgO	3.65	2.52	2.98	3.13	5.99
CaO	1.32	0.62	0.21	0.36	8.80
K_2O	1.70	1.36	3.30	2.86	1.13
Na_2O	5.95	1.05	3.12	0.77	2.65
P_2O_5	0.08	0.13	0.04	0.19	1.06
$H_2O\pm$	3.18	1.99	1.98	4.18	3.07
Total	99.93	99.99	99.54	99.61	99.60

Explanation to Table 1

Analysed samples (including four analyses by HJELLE 1962 and three by HORSFIELD 1972).

Glaucophane schists from the Vestgötabreen Formation (○):

1. Garnet-glaucophane schist with muscovite and chlorite.
2. Garnet-muscovite-glaucophane schist.
3. Banded garnet-muscovite-glaucophane schist.
4. Garnet-glaucophane schist.
5. Garnet-muscovite-glaucophane schist.
6. Garnet-muscovite-glaucophane schist.
7. Garnet-epidote-muscovite-glaucophane schist (Analyst: HORSFIELD (E1022)).

Eclogitic rocks from the Vestgötabreen Formation (⊙):

8. Schistose glaucophane-garnet-omphacite eclogite.
9. Glaucophane-garnet-omphacite eclogite with more than 90% omphacite.

Epidote amphibolites from the Vestgötabreen Formation (●):

10. Actinolite-epidote-sericite-chlorite-plagioclase-quartz schist.
11. Actinolite-epidote-chlorite-plagioclase schist with calcite veins.
12. Banded epidote-actinolite-chlorite schist.
13. Epidote-calcite-chlorite-actinolite-plagioclase greenstone (Analyst: HORSFIELD (B3023)).

Garnet-bearing epidote amphibolite from the Vestgötabreen Formation (x):

14. Garnet-epidote-actinolite-chlorite meta-diabase.
15. Garnet-epidote-sericite-actinolite schist.
16. Dense actinolite-epidote-chlorite-sericite-plagioclase schist.
17. Garnet-actinolite-epidote-chlorite-sericite schist.
18. Garnet-chlorite-sericite-plagioclase-quartz meta-gabbro.

Meta-basites from Holmsletfjella, south of St. Jonsfjorden (●):

19. Chlorite-plagioclase meta-diabase.
20. Hornblende-actinolite-epidote-chlorite-plagioclase meta-hornblende gabbro.

Meta-basites from the northern side of St. Jonsfjorden (●):

21. Coarse-grained meta-hornblende gabbro.
22. Hornblende porphyrite.
23. Meta-diabase.

Meta-basites from the Bellsund area, all by HJELLE (●):

24. Meta-basite. Recherchebreen, S Bellsund, unpublished.
25. Ultrabasic rock. Recherchebreen, unpublished.
26. Amphibolite. Diabasodden, N Bellsund (HJELLE 1962, Table 3.3).
27. Amphibolite. 4 km SE of Orustosen, N Bellsund (HJELLE 1962, Table 3.3).

Glaucophane-muscovite-quartz schists from the Vestgötabreen Formation (△):

28. Glaucophane-garnet-chlorite-muscovite-quartz schist.
29. Glaucophane-garnet-chlorite-muscovite-quartz schist.
30. Glaucophane-garnet-muscovite-quartz feather schist.
31. Glaucophane-hematite-muscovite-quartz schist.

Muscovite-quartz schists from the Vestgötabreen Formation (▲):

32. Garnet-chloritoid-muscovite-quartz schist. (Analyst: HORSFIELD (E1020))
33. Cataclastic chlorite-plagioclase-quartz schist.
34. Chloritoid-garnet-muscovite-quartz schist.
35. Chloritoid-muscovite-quartz schist.
36. Chloritoid-chlorite-muscovite-quartz schist.

A meta-gabbro from northern Hornsund, collected by ORVIN (AK0232), has been analysed and is included in the data of the Hornsund amphibolites in the figures.
Symbols in parentheses refer to Figs. 3a, 4a, 5, 6, 7, 8, 16, 17 and 18.

SMULIKOWSKI 1968) are summarized separately and compared with the present data. Hereafter, the epidote-actinolite greenstones and metabasites will be called the epidote amphibolites.

In the AFM diagram (Fig. 3a), the glaucophane schists cannot be distinguished from the other amphibolites. Most of the rocks project in the field of calc-alkaline and alkali basalt. Four plots are slightly off from the border curve of this field, but the border curve itself is rather arbitrary in this part of the

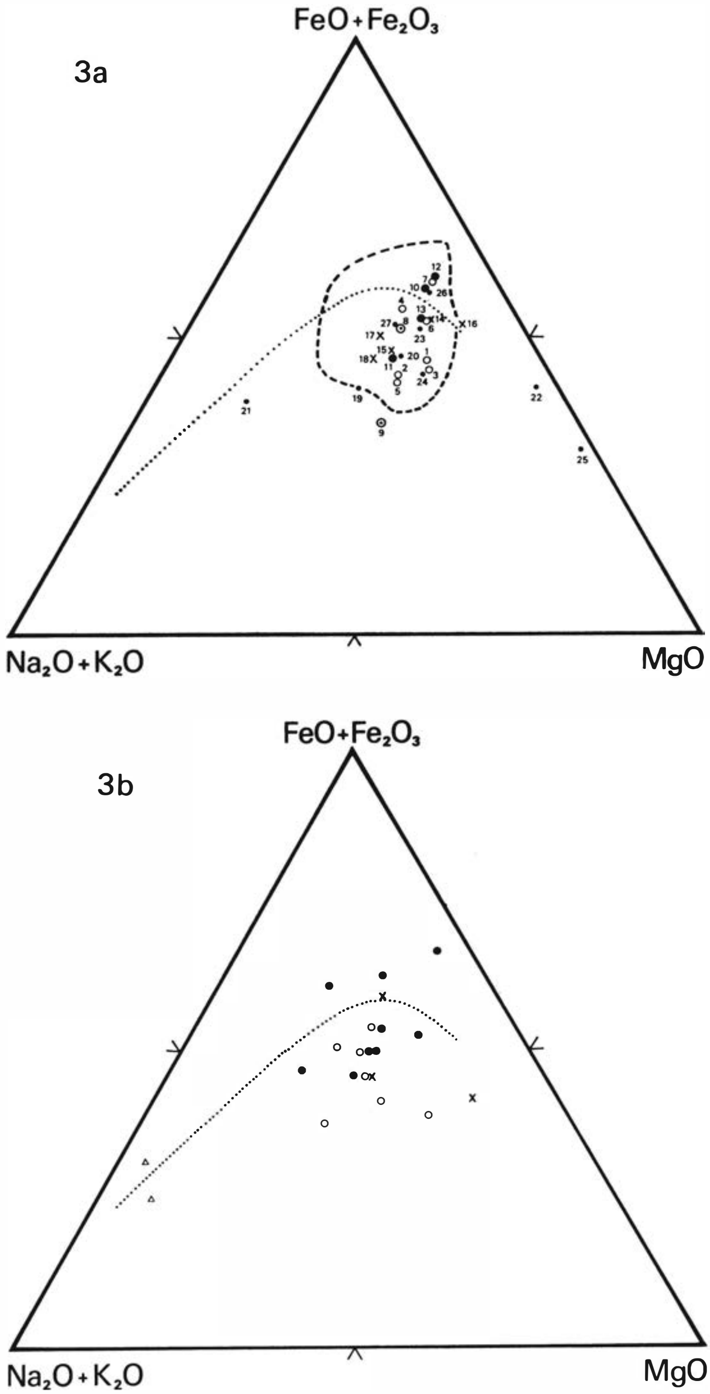


Fig. 3. *Bulk rock compositions on the MgO—$FeO+Fe_2O_3$—Na_2O+K_2O diagram.* (*The symbols and suffixed numbers refer to Table 1.*)

a. *The rocks of the Vestgötabreen Formation, with some greenrocks from St. Jonsfjorden and the Bellsund area. Dotted curve: border of the tholeitiic and alkalic rock series, Hawaii* (KUNO et al. 1957); *broken curve: glaucophane schists fo California* (COLEMAN and LEE 1963).

b. *The rocks of the Hornsund area* (SMULIKOWSKI 1968). *Dots: fine-grained amphibolites; open circles: coarse-grained amphibolites; crosses: schistose amphibolites; triangles: acidic volcanic rocks; dotted curve: same as in Fig. 3a.*

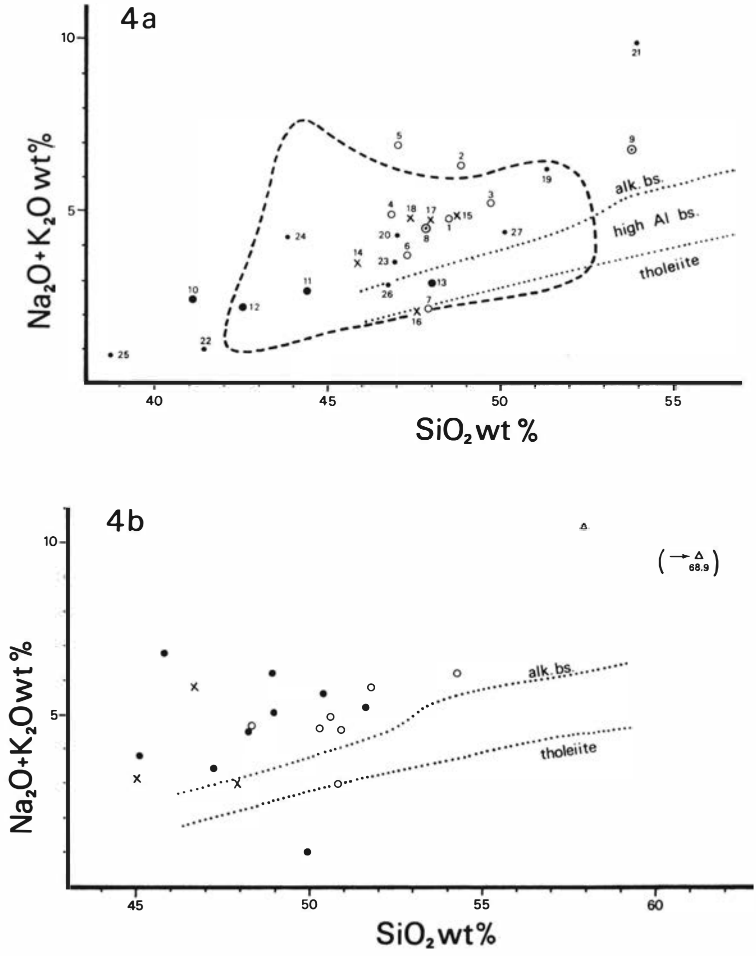


Fig. 4. *Alkali-SiO_2 diagram.*
a. *The rocks of the Vestgötabreen Formation with some amphibolites from western Spitsbergen, excluding those from Hornsund. The symbols are the same as in Fig. 3a, refer to Table 1.*
b. *The rocks from Hornsund. The symbols are the same as in Fig. 3b.*

diagram (KUNO 1957). In the SiO_2-alkalis diagram (Fig. 4a), there are no points in the field of tholeiitic basalt. The basic rocks of the Hornsund area show similar characteristics in the same diagrams (Figs. 3b and 4b). No definite calc-alkaline rock has been found in the Vestgötabreen Formation.

The relatively high alkali contents in the glaucophane schists compared with the epidote amphibolites are due not to Na_2O but to K_2O, as seen in the K_2O—Na_2O diagram (Fig. 5), in which the following zones can be distinguished with increasing K_2O: epidote amphibolites (excluding Nos. 19 and 21) — garnet amphibolites — glaucophane schists — muscovite-quartz schists. Two epidote amphibolites, Nos. 19 and 21, are rich in SiO_2 and have higher Na_2O than the others, somewhat like keratophyre. All other rocks have less than 4.5 wt.% Na_2O, accordingly they are not typically spilitic in com-

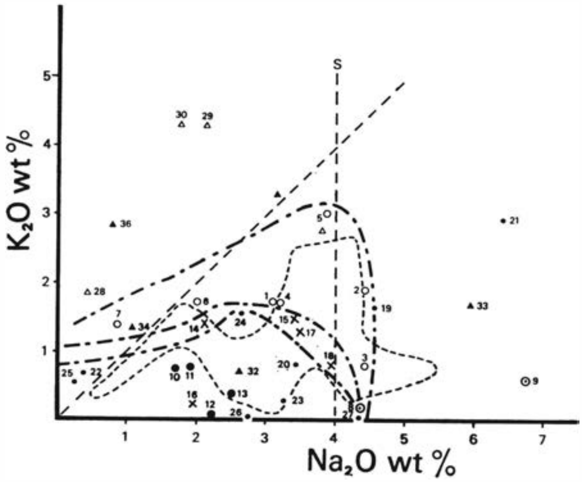


Fig. 5. *K_2O—Na_2O diagram. Thin broken curve: the field of the rocks from Hornsund; thick dash and point curve: see text. The symbols and numbers are the same as in Fig. 3a, refer to Table 1.*

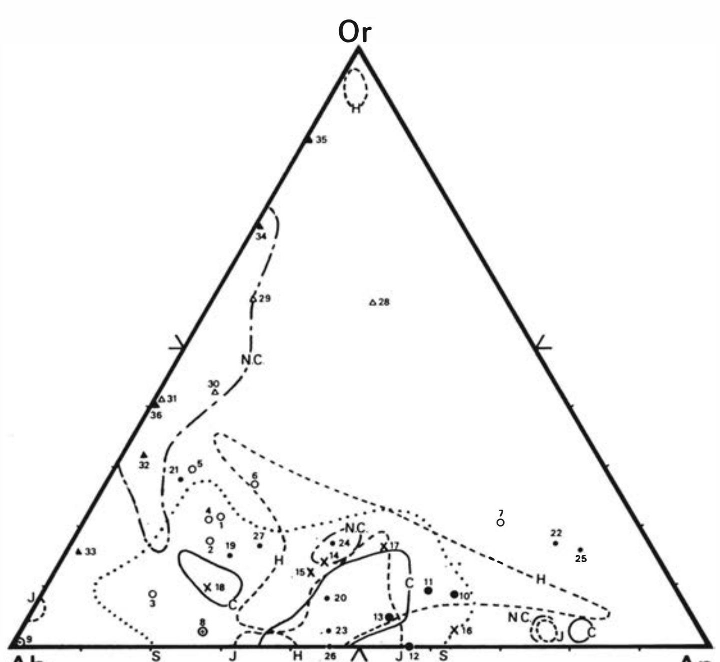


Fig. 6. *Normative Or-Ab-An diagram of the Vestgötabreen Formation rocks. C: Californian glaucophane schists; H: Hornsund rocks; J: Japanese glaucophane schists; NC: New Caledonian glaucophane schists; S: Spilites* (YODER 1967).
The symbols and numbers are the same as in Fig. 3a, refer to Table 1.

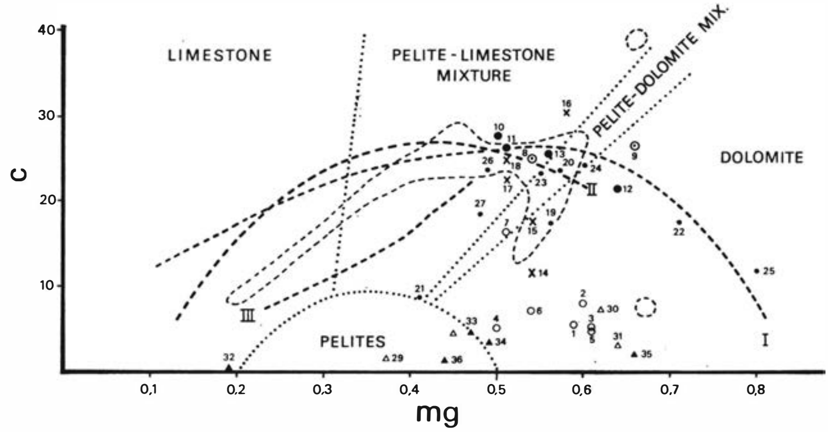


Fig. 7. NIGGLI's *mg-c diagram for estimating the nature of original rock types, after* LEAKE (1963). *I: differentiation trend of Karroo dolerite; II: differentiation trend of Na-rich alkali rock series of Etiopia* (MOHR 1960); *III:* DALY's *average calc alkaline rocks, thin broken curve: field of the rocks from Hornsund.*

The symbols and numbers are the same as in Fig. 3a, refer to Table 1.

position (YODER 1967 and AMSTUTZ 1974). The glaucophane schists project in the field between the epidote amphibolites and the muscovite-quartz schists in this diagram and have relatively high SiO_2 contents, as shown in Fig. 4a. This suggests that the glaucophane schists could be a mixture of basic volcanic rocks and argillaceous quartzitic sediments.

On the Or-Ab-An diagram (Fig. 6), the glaucophane schists, except for No. 7 (HORSFIELD's analysis), project in the field between the epidote amphibolites and the muscovite-quartz schists field. This supports the idea mentioned above. Two keratophyre-like epidote amphibolites, Nos. 19 and 21, plot in the same field as the glaucophane schists; thus they might also be of similar origin.

Figs. 7 and 8 are prepared after LEAKE (1963) and SIMONEN (1953), respectively. Fig. 7 suggests that most epidote amphibolites are originally intermediate differentiates of basaltic magma, and the muscovite-quartz schists without glaucophane are impure argillaceous quartzite. Most glaucophane schists and some muscovite-quartz schists can be considered as mixtures of argillaceous quartzite and early differentiates of basaltic magma. The epidote amphibolites with keratophyre-like composition are suggested to be a mixture of argillaceous quartzite and intermediate differentiates of basaltic magma.

In Fig. 8, some early differentiates of basaltic magma are plotted in the upper left field and this means that the field of volcanogenous sediments extends further up to the left in this diagram. The glaucophane schists project in the field between argillo-siliceous sediments and the early differentiates of basaltic magma in this diagram. This conforms with the conclusions drawn from Figs. 5, 6, and 7.

Excluding probable mixed rocks, classification in terms of bulk chemical composition, was tried on selected basic rocks of basaltic composition with

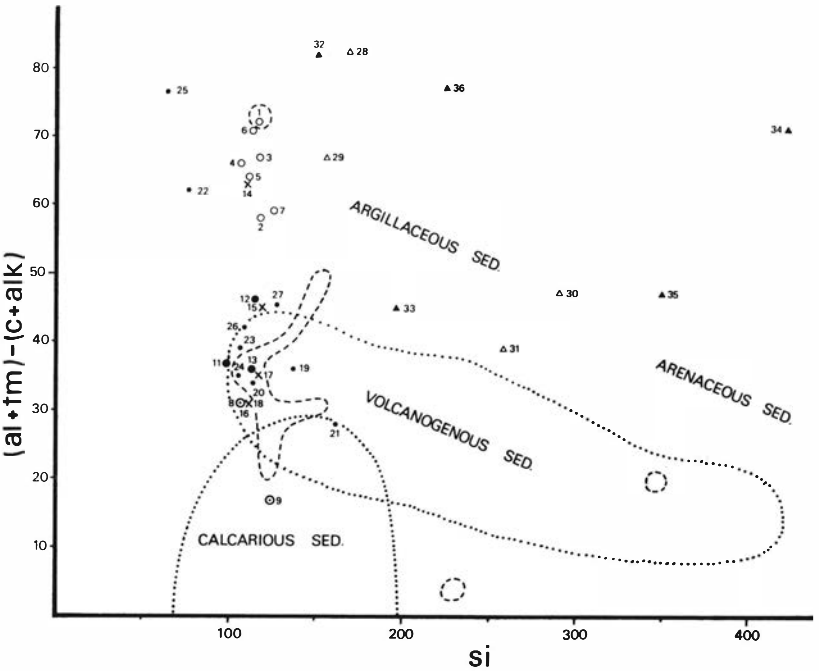


Fig. 8. NIGGLI's *si—"(al+fm)—(c+alk)" diagram to estimate the original rocks, after* SIMONEN (1953). *Thin broken curve: field for the rocks of Hornsund. The symbols and numbers are the same as in Fig. 3a, refer to Table 1.*

44% < SiO_2 < 53.5%, 10 from the present analyses and 17 from Hornsund. Almost all rocks were totally recrystallized and mineralogical and textural information on original rocks has not been preserved at all. Table 2 shows the classification based on the existence of the norm hypersthene and olivine, referring the weight percentages of Al_2O_3 and TiO_2, and was prepared from Figs. 9a, 9b, 9c, and 9d, after the classification suggested by MIDDLEMOST (1975). The sub-alkalic rocks appear as tholeiitic rocks by this classification.

These tables show that the rocks do not show any dominant rock type and have a large variation in their chemical characteristics of major elements, from tholeiite to alkali olivine basalt. The most probable reason for this variation is the fact that the rocks still contain some mixture of terrestrial sedimentary material and modifications of metamorphic differentiation.

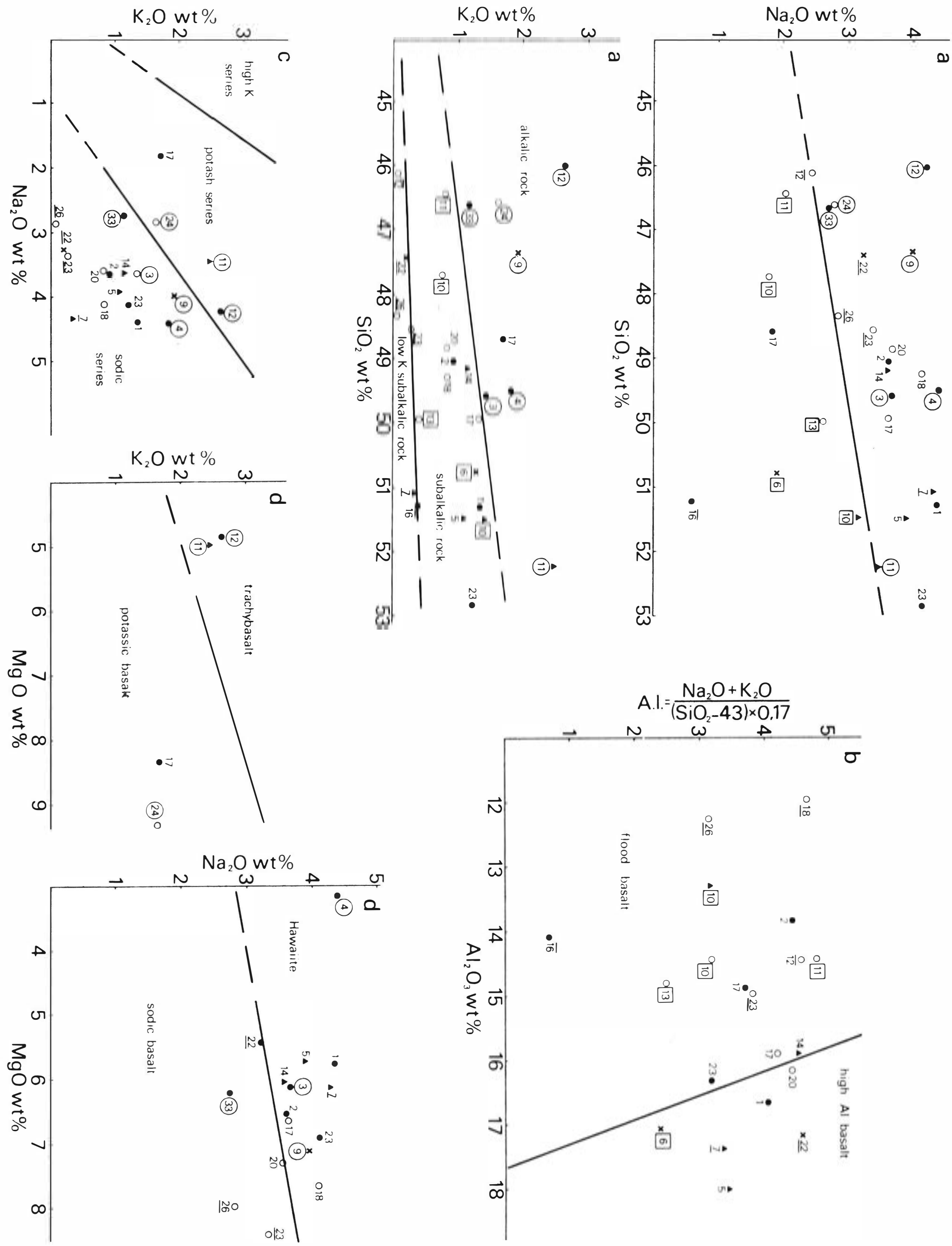
→

Fig. 9. *Classification of the selected basic rocks after* MIDDLEMOST (1975), *recalculated without H_2O.*

a. *The classification of alkalic-subalkalic-low K_2O alkalic rock series.*

b. *Division of the subalkalic and transitional rocks.*

c. and d. *Divisions of the alkalic and transitional rocks. Open circles: basic rocks from the Vestgötabreen Formation, north of St. Jonsfjorden and the Bellsund area, suffixed numbers refer to Table 1. Other symbols are the rocks from the Hornsund area and the suffixed numbers refer to* SMULIKOWSKI 1968; *dots: fine- to medium-grained amphibolites; triangles: coarse-grained amphibolites; crosses: schistose amphibolites. Circled numbers: alkalic rocks; squared numbers: subalkalic rocks; underlined numbers: low K_2O transitional rocks; overlined numbers: low K_2O subalkalic rocks; other numbers: transitional rocks. The alkaline and transitional rocks are plotted together in Fig. 9c, and the subalkaline and transitional rocks are plotted together in Fig. 9d.*



a
Na_2O wt%
SiO_2 wt%
a
K_2O wt%
alkalic rock
subalkalic rock
low K subalkalic rock
SiO_2 wt%
c
K_2O wt%
high K series
potash series
sodic series
Na_2O wt%
b
$A.I. = \frac{Na_2O + K_2O}{(SiO_2 - 43) \times 0.17}$
flood basalt
high Al basalt
Al_2O_3 wt%
d
K_2O wt%
trachybasalt
potassic basalt
MgO wt%
d
Na_2O wt%
Hawaiite
sodic basalt
MgO wt%

Fig. 9.

Table 2

Classification of the selected basic rocks.

Locality	Alkalic basalt			Subalkalic basalt			Transitional basalt			Total
	High-K basalt	K-alkalic basalt	Na-alkalic basalt	Low K-subalk. basalt	Flood basalt	High-Al basalt	Low-K transitional basalt	K-rich transitional basalt	Na-rich transitional basalt	
St. Jonsfj. etc.	0	1	0	1	3	0	2	0	3	10
Hornsund	0	2	4	1	1	1	2	1	5	17
Total	0	3	4	2	4	1	4	1	8	27

<table>
<tr><th rowspan="3">Locality</th><th colspan="5">Alkalic and transitional basalt</th><th colspan="2">Subalkalic and transitional basalt</th></tr>
<tr><th rowspan="2">High-K series</th><th colspan="2">Potash series</th><th colspan="2">Sodic series</th><th rowspan="2">Flood basalt</th><th rowspan="2">High-Al basalt</th></tr>
<tr><th>Trachybasalt</th><th>Potassic basalt</th><th>Hawaiite</th><th>Sodic basalt</th></tr>
<tr><td rowspan="2">St. Jonsfj. etc.</td><td rowspan="2">0</td><td colspan="2">(1)</td><td colspan="2">(5)</td><td rowspan="2">8</td><td rowspan="2">1</td></tr>
<tr><td>0</td><td>1</td><td>2</td><td>3</td></tr>
<tr><td rowspan="2">Hornsund</td><td rowspan="2">0</td><td colspan="2">(3)</td><td colspan="2">(11)</td><td rowspan="2">6</td><td rowspan="2">5</td></tr>
<tr><td>2</td><td>1</td><td>9</td><td>2</td></tr>
<tr><td>Total</td><td>0</td><td>2</td><td>2</td><td>11</td><td>5</td><td>14</td><td>6</td></tr>
</table>

When terrestrial sediments are mixed, rocks tend to be enriched by SiO_2 and K_2O; therefore, some rocks classified as belonging to the potash-alkaline group are suspicious. The coarse-grained rocks from Hornsund might be modified by the granitization (BIRKENMAJER and NAREBSKI 1960; SMULIKOWSKI 1968). The second reason may be found in their occurrence; some of them should not be included in the basaltic rock group. For example, the low potash tholeiite of No. 26 actually occurs in shallow sea sediments as an intrusive vent and may be considered a lamprophyre; accordingly this is not representative of ocean floor basalts. The third possibility implies that these rocks may be from different stratigraphic horizons of the Hecla Hoek succession of western Spitsbergen. This is apparent from the literature (BIRKENMAJER 1975; HJELLE 1962). Thus, more systematic sampling to avoid mixture of foreign material and different stratigraphic horizons and the studies of minor elements are important in the future study of basic rocks in western Spitsbergen.

Summary of the original nature of the Vestgötabreen Formation

1. Most epidote amphibolites were derived from intermediate differentiates of basaltic magma.
2. Some relatively acidic varieties are not later differentiates of basaltic magma, but mixtures of intermediate differentiates and argillo-siliceous sediments.
3. The muscovite-quartz schists with or without glaucophane were formed from impure argillaceous quartzite.
4. The glaucophane schists are mixtures of early differentiates of the basaltic magma and argillo-siliceous sediments.
5. Na enrichment is not prominent in the glaucophane schists and the original rocks were not typically spilitic.
6. The original volcanic rocks of these basic rocks are unknown, and they have large variation presumably by tectonic stirring.

Essential association of volcanic rocks in the Vestgötabreen Formation is alkaline and possibly tholeiitic rocks. This fits well in with what MIYASHIRO (1975) pointed out from the Sanbagawa and Franciscan blue schist zone. The tectonic setting of this volcanic association is problematic.

IV. Mineral chemistry

The main constituent minerals of the epidote amphibolites and glaucophane schists were analysed by an electron probe microanalyser by the courtesy of Dr. M. KOMATSU of Niigata University, Japan, and Prof. H. RAMBERG, Uppsala University, Sweden (Table 3). Natural and synthetic minerals were used as standards and each analysis is the average of five measurements. Physical properties of these minerals have not been fully examined yet, and their chemical nature will be presented here with brief comments on their occurrences.

Table 3

Chemical composition of the constituent minerals (analyses Nos. 1 and 2 of garnet and Nos. 4 and 5 of alkali amphibole by H. RAMBERG, *Uppsala Univ.; all others by* M. KOMATSU, *Niigata Univ. Japan).*

Garnets

	1	2	3	4	5
SiO_2	38.15	37.0	37.93	38.91	38.30
TiO_2	0.8	0.2	0.6	0.2	—
Al_2O_3	20.75	20.8	20.88	21.70	21.85
FeO	30.64	28.1	32.38	25.5	28.12
MnO	2.49	0.7	3.88	0.9	0.88
MgO	2.67	4.8	2.86	7.2	5.52
CaO	6.41	6.7	3.16	6.1	5.59
Total	101.19	98.3	101.14	100.51	101.26

Calcic and sub-alkalic amphiboles

	1	2	3	4	5
SiO_2	54.23	53.20	48.94	50.05	37.84
TiO_2	0.02	0.02	—	—	—
Al_2O_3	1.16	1.17	6.20	7.60	15.49
FeO	13.38	15.60	21.08	16.40	27.96
MnO	0.07	0.20	—	—	—
MgO	15.93	13.13	12.67	13.08	3.58
CaO	11.58	11.31	8.90	8.63	11.54
K_2O	0.03	0.07	—	—	—
Na_2O	1.14	1.25	1.24	2.98	2.01
Total	97.54	96.54	99.03	98.99	99.74

Alkali amphiboles

	1	2	3	4	5	6	7
SiO_2	54.69	55.9	55.62	55.72	55.1	56.73	56.71
TiO_2	—	0.1	—	0.3	0.2	—	0.04
Al_2O_3	9.88	8.8	7.19	7.68	8.4	10.42	9.97
FeO	15.54	15.1	18.57	14.52	15.9	15.20	13.00
MnO	—	0.1	—	0.03	0.1	—	0.08
MgO	8.45	9.5	7.81	10.42	8.8	8.25	9.94
CaO	1.39	1.6	0.54	0.46	1.1	0.35	0.39
K_2O	0.05	0.00	0.00	—	0.00	0.08	0.01
Na_2O	6.31	5.5	7.03	7.15	5.8	6.28	7.03
Total	96.58	96.6	96.76	95.99	95.4	97.30	97.16

(cont. next page.)

(Table 3 cont.)

Chloritoids

	1	2
SiO_2	24.27	25.25
TiO_2	0.15	0.16
Al_2O_3	39.58	40.78
MnO	0.12	0.53
MgO	2.71	4.72
CaO	0.08	0.08
K_2O	0.05	0.04
Na_2O	0.07	0.05
Total	93.90	94.28

White micas

	1	2	3
SiO_2	49.27	49.34	50.41
Al_2O_3	26.90	27.62	25.58
FeO	3.48	3.30	4.61
MgO	2.75	3.01	3.36
K_2O	10.05	9.60	10.16
Na_2O	0.53	1.02	0.65
Total	92.97	93.89	94.77

Epidotes

	1	2
SiO_2	37.71	38.05
Al_2O_3	23.97	24.47
FeO	10.76	10.91
MnO	0.33	0.29
CaO	22.64	22.45
Total	95.42	96.16

Chlorites

	1	2
SiO_2	28.55	25.84
Al_2O_3	18.63	20.49
FeO	25.84	30.34
MgO	17.62	12.70
Total	90.64	89.37

Clinopyroxene

	1
SiO_2	56.20
TiO_2	0.09
Al_2O_3	8.98
FeO	6.05
MnO	0.01
MgO	8.48
CaO	11.56
Na_2O	7.38
Total	98.75

Garnet

Garnet of the epidote amphibolites occurs as small scattered grains in certain compositional layers, while those of the glaucophane schists and muscovite-quartz schists are remarkably large idioblastic crystals up to 3 cm across. Such large garnets are unique among the glaucophane schists from the world. Most garnet grains in the present glaucophane-bearing rocks are weakly fractured and the cracks are filled with chlorite (Plate 2–4). The core parts of the garnets are often homogeneous with a few inclusions of chloritoid and opaque minerals (Plate 2–3). The margins of the garnets are always poikiloblastic and skeletal, including many elongated quartz and glaucophane grains. Chloritoid makes a thin rim around those garnet grains which are almost free from inclusions.

The garnet of eclogitic rocks is scattered in the dense omphacite groundmass and has always many cracks filled with chlorite.

Five garnets from the glaucophane-bearing rocks were analysed and the results were calculated as shown in Table 4 and Figs. 10a and 10b. Their pyralspite components are more than 80%. The first component is always almandine, followed by pyrope, and the third is grossularite, except for No. 1 the second component of which is grossularite and the third pyrope. Comparing with TRÖGER's statistical work on garnet (TRÖGER 1959), the present

Table 4

Molecular contents of the garnet

	1	2	3	4	5
Host rock	Glaucophane schist	Mus-qt schist	Mus-qt schist	Eclogitic rock	Eclogitic rock
Pyrope	10.50	18.93	11.30	27.48	21.04
Almandine	65.83	60.55	71.04	53.77	58.99
Spessartine	5.57	1.58	8.70	1.99	1.91
Grossularite	16.53	16.82	8.13	15.52	16.95
Andradite	1.57	2.11	0.83	1.23	1.12
Pyralspite	81.90	81.07	91.04	83.25	81.93
Ugandite	18.10	18.93	8.96	16.75	18.04
Bulk rock analysis No. (Table 1)	28	30	34	8	9

garnets have compositions similar to those from charnockites (Nos. 3, 4, and 5), pelitic metamorphics (No. 2) and mica schists (No. 1).

Cation percentages in the garnets relative to those of the host rock are shown in Table 5. Samples 1, 2, and 3 show higher CaO and MnO concentrations than the others and the values are comparable to those of the type III glaucophane schists of California (LEE et al. 1963). The high pyrope and low spessartine contents of all present garnets are characteristic for the garnets from the Type IV rocks of California. In general, the present garnets are chemically similar to those of the type IV glaucophane schists of California, and project in the composition field between the garnets from the type III glaucophane schists of California and true eclogites in Figs. 10a and 10b.

Calcic and sub-alkaline amphiboles

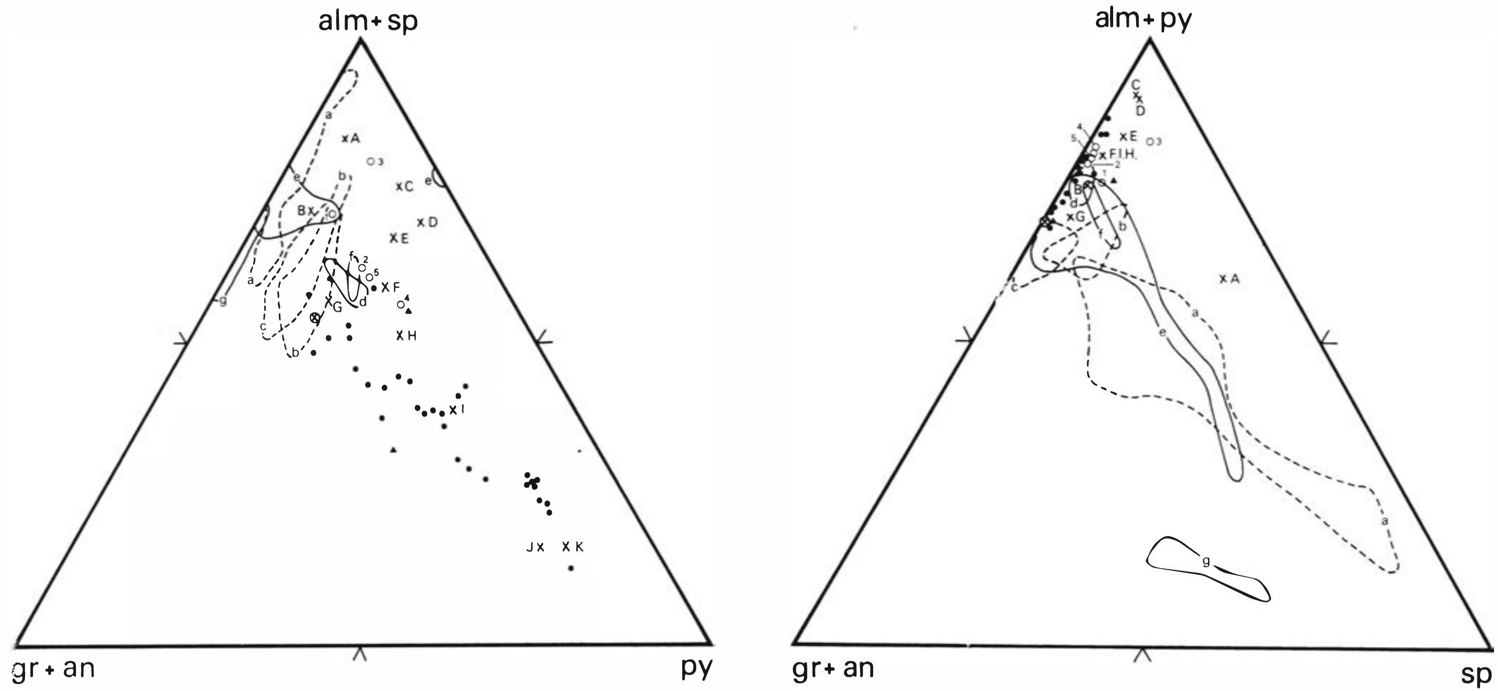
A progressive development of colourless actinolite from chlorite is well observed in the epidote amphibolites (Plate 2–2). Nematoblastic actinolite needles occur at the crests of tight crenulations in chlorite and occasionally show distinct bluish green pleochroism. Similar, but more bluish amphibole was found in an amphibolite from Nordenskiöldkysten (its bulk analysis is No. 26, Table 1), collected by A. HJELLE. Another type of deep bluish green amphibole has been found in the meta-gabbroic rocks from the northern side of St. Jonsfjorden (bulk analyses are Nos. 21 and 23, Table 1) and in some amphibolites from the northern Hornsund area, collected by ORVIN (No. 37, Table 1). The rocks of the latter locality were studied by SMULIKOWSKI (1968) by optic means and the amphibole was found to be hastingsite. These deep bluish green amphiboles show a different mode of occurrence from the nematoblastic actinolite and occur as rims or irregular patches in large relict brown-green hornblendes which are certainly of primary igneous origin.

Four nematoblastic amphiboles (Nos. 1 to 4) from the epidote amphibolites of the Vestgötabreen Formation, and one deep bluish green amphibole (No. 5)

Table 5

Cation percentages in the garnets relative to those of the host rock.

		California III			California IV		Zermatt			Western Spitsbergen					Knockormal	
		27-CZ-59	59-CZ-59	58RGC-58C	50-CZ-60	62-GC-58	PUB878	PUB891	PUB941	1	2	3	4	5	A	B
MgO	Rock	0.43	0.16	3.10	5.15	5.40	4.5	4.6	3.5	6.46	4.13	2.52	8.02	8.54	6.45	7.91
	Garnet	0.70	0.08	0.44	2.10	1.70	3.3	4.68	5.54	2.67	4.7	2.86	7.2	5.52	—	11.44
	G/R	1.63	0.50	0.14	0.41	0.32	0.73	1.00	1.57	0.41	1.14	1.14	0.90	0.65	—	1.45
FeO	Rock	2.00	3.50	10.80	6.64	9.10	6.8	5.9	4.9	12.43	2.80	3.63	6.47	3.37	10.12	7.04
	Garnet	15.60	13.8	24.6	25.3	27.6	26.8	25.2	26.1	29.92	28.08	32.01	24.64	27.60	21.00	13.45
	G/R	7.80	3.94	2.28	3.81	3.03	3.94	4.27	5.33	2.41	10.03	8.82	3.81	8.20	2.08	1.91
CaO	Rock	3.2	0.22	2.1	16.14	11.0	6.4	9.1	8.3	1.41	1.65	0.62	10.31	10.65	8.61	13.01
	Garnet	7.1	6.3	6.4	11.1	9.5	8.2	7.6	7.2	6.41	6.70	3.16	6.10	6.59	—	9.11
	G/R	2.22	28.64	3.05	0.69	0.86	1.28	0.84	0.87	4.55	4.06	5.10	0.59	0.62	—	0.70
MnO	Rock	2.3	0.65	2.8	0.33	0.23	0.2	0.2	0.2	0.10	0.04	0.28	0.28	0.12	0.25	0.18
	Garnet	17.6	21.3	10.8	1.6	1.3	1.6	0.6	1.0	2.49	0.70	3.88	0.90	0.88	4.04	0.64
	G/R	7.65	32.77	3.86	4.85	5.65	8.00	3.00	5.00	24.9	17.5	13.86	3.21	7.33	16.16	3.56
		LEE, COLEMAN and ERD (1963)					BEARTH (1973)			present paper					BLOXAM and ALLEN (1959)	



a b

Fig. 10. *Garnets from the glaucophane-bearing rocks.*

a. *Pyrope-Almandine+Spessartine-Andradite+Grossularite diagram. Open circles 1–5: garnets from the rocks of this area, see Table 3; open circle with cross inside: garnet of the eclogite, from Biskayerhuken, NW Spitsbergen; solid triangles: garnet from the glaucophane schists of Knockermal, Scotland; dots: garnets from eclogites of the world; crosses:* TROGER's *averages of garnets from various rocks: A: from pelitic metamorphic rocks (average of 31); B: from mica schists (3); C: mica schists and hornfels (33); D: paragneisses (19); E. granodiorites and pegmatites (10); F: charnockites (15); G: amphibolites (21); H: meta-gabbros (8); I: eclogites (14); J: kimberlites; K: ultrabasites. Broken curves: a: garnets from the Type III glaucophane schists of California; b: from the Type IV glaucophane schists of California; c: from the eclogites in the glaucophane schists; solid line curves: d: from glaucophane eclogites of Zermatt; e: from the glaucophane schists of Japan; f: from New Caledonia; g: from the green schists of New Zealand.*

b. *Almandine+Pyrope-Spessartine-Andradite+Glossularite diagram. The symbols are the same as in Fig. 10a.*

Table 6

Calcic and sub-alkaline amphiboles

	Al^{IV}	Na+K	100 Mg / Mg+ total Fe+Mn	100 (Na+K) / Ca+Na+K	Chemical formula
1 Na actinolite	0.159	0.327	67.7	15.4	$(NaK)_{0.327}(Fe''Mn)_{1.627}Mg_{3.433}(TiAl)_{0.141}(AlSi)_8O_{22}$
2 Na actinolite	0.143	0.369	59.7	17.1	$(NaK)_{0.369}Ca_{1.790}(Fe''Mn)_{1.953}Mg_{2.891}(TiAl)_{0.168}(AlSi)_8O_{22}$
3 Common hornblende	0.799	0.355	51.0	20.2	$(NaK)_{0.355}Ca_{1.405}Fe''_{2.598}Mg_{2.783}Al_{0.277}(AlSi)_8O_{22}$
4 Edenite	0.762	0.884	58.0	37.8	$(NaK)_{0.884}Ca_{1.337}Fe''_{1.983}Mg_{2.819}Al_{0.533}(AlSi)_8O_{22}$
5 Ferro hastingsite	2.076	0.876	15.1	31.2	$(NaK)_{0.876}Ca_{1.935}Fe''_{3.442}Mg_{0.834}(Fe''Al)_{1.0}(AlSi)_8O_{22}$

1, 2 and 3 are from the same rock: No. 11 of Table 1. Total FeO = FeO, except for No. 5.

from a meta-gabbro of the Hornsund area (from ORVIN's collection), have been analysed (Table 3), and their chemical formulae and classification are shown in Table 6 and Fig. 11.

Two nematoblastic bluish green amphiboles are Na-actinolite and the other two are common hornblende and edenite. They seem to have a composition range from common hornblende to sub-alkaline amphibole, with a little amount of tschermakite component. These amphibole compositions are common in green schists from the blue schist metamorphic zones of the world.

The deep bluish green amphibole from Hornsund (No. 5) is pargasite or ferro-hastingsite and is a typical sub-alkaline variety. This agrees with the optic studies of SMULIKOWSKI (1968), and the mode of occurrence of these amphiboles indicates a type of metasomatic change associated with the introduction of quartz and biotite into various kinds of gabbroic rocks. Thus, the metamorphism of the Hornsund amphibolites can be distinguished from the amphibolites of the Vestgötabreen Formation.

Alkali amphiboles

Blue amphiboles show various modes of occurrence; the dense granoblastic groundmass of the glaucophane schists, scattered large idioblasts (Plates 3–1 and 3–2) and vein-like monomineralic mass in the eclogitic rocks, and thin long crystals showing feather-amphibolite texture in the muscovite-quartz schists (Plates 1–1 and 1–2). The idiomorphic and vein-like varieties may have crystals up to 4–5 cm long. Typical glaucophane schist is composed of more than 90% blue amphibole, with subordinate garnet, epidote, muscovite and some secondary chlorite. Idioblastic blue amphiboles are often poikiloblastic

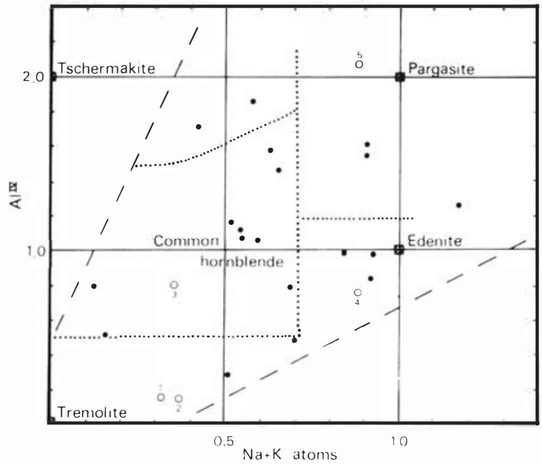


Fig. 11. *Calcic and sub-alkaline amphiboles. Open circles: amphiboles from the present area, see Table 4; dots: amphiboles from Japanese glaucophane schists.*

with inclusions of quartz in the muscovite-quartz schists and of clinopyroxene in the eclogitic rocks (Plates 3–2 and 3–4). They often show distinct zonal structure with a zone of strong pleochroism around the margins (Plates 3–1 and 3–2) and sometimes along cracks (Plate 3–3). The blue amphibole in the vein-like mass occurs as long prismatic crystals, perpendicular to the wall of the vein, and sometimes represents remarkable radial aggregates, and the core of vein is often occupied by quartz. Some blue amphibole grains are included in the marginal poikiloblastic parts of the garnet.

Table 7

Alkali amphiboles

	Al^{IV}	$\frac{100Fe'''}{Fe'''+Al^{VI}+Ti}$	$\frac{100Fe''+Mn}{Fe''+Mg+Mn}$	$\frac{100(Na+K)}{Ca+Na+K}$	Host rock (Nos refer to Table 1)
1 Glaucophane	0.130	23.1	43.7	89.2	fine grained, banded ga-gl-mus-chl schist
2 Glaucophane	—	27.0	42.3	89.4	gl-ga-mus-qt schist (No. 30)
3 Crossite	—	38.5	46.8	75.8	ga-gl schist with mus crots (No. 2)
4 Crossite	—	35.0	31.8	96.6	mus-ga-gl schist (No. 28)
5 Glaucophane	0.001	26.1	38.7	84.7	gl-ga-cpx eclogite (No. 8)
6 Glaucophane	0.014	14.3	46.5	97.1	gl-ga-cpx eclogite
7 Glaucophane	0.004	20.2	34.9	97.0	gl-ga-cpx eclogite (No. 9)

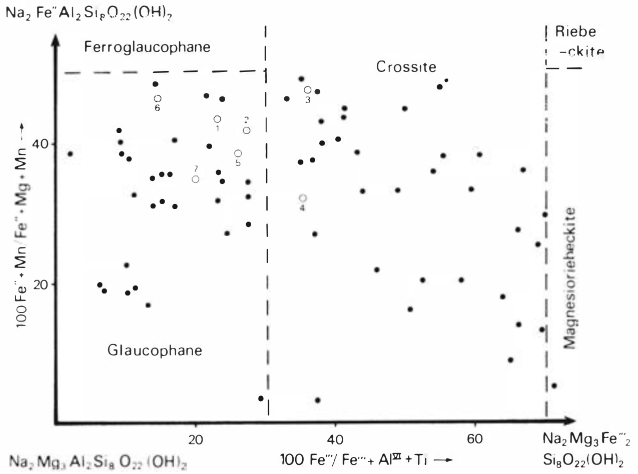


Fig. 12. *Alkaline amphiboles. Open circles: from the present area, see Table 5; dots: glaucophane and crossite from the world* (Deer et al 1962, Koctrok 1970).

Seven blue amphiboles were analysed (Table 7, Fig. 12). Five are glaucophane and two are crossite. No systematic difference of composition has been found among those from different host rocks. The crossite makes up the deep pleochroic marginal zone and narrow zones along cracks of the idiomorphic glaucophane crystals. The $Fe'''/Fe'''+Al^{VI}+Ti$ ratios vary in the range of 14–38% from glaucophane to crossite, and the transitions are gradational in most zoned crystals, but some show sharp borders (Plate 3–2).

The radial occurrence of glaucophane suggests they might be formed along open cracks in the host eclogitic rock. The idioblastic texture of this mineral is suggestive of an origin later than the main recrystallization phase of the host rock and some segregation or circulation of materials may be expected. For example, addition of Fe and subtraction of Ca from omphacite to make glaucophane in the eclogitic rocks, and concentration of Fe, Mg and Na and subtraction of Al and K in the muscovite-quartz schists might have occurred even though there is no positive evidence to suggest Na-metasomatism in the study of the bulk chemical compositions.

Chloritoid

This mineral occurs in the muscovite-quartz schist as prismatic crystals up to 3.5 cm long. Most chloritoid grains are in the quartz-rich groundmass and some are concordantly enclosed by undulated muscovite. Chloritoid is a dominant inclusion in the core parts of large garnets. All chloritoid grains show polysynthetic twin lamellae and abnormal birefringence colours. They show no secondary alteration.

Two chemical analyses of chloritoid are shown in Fig. 13: (1). from garnet-muscovite-quartz schist, and (2). from inclusion in the garnet of typical glaucophane schist. The data have been given on the anhydrous base of $0 = 12$ and total iron as FeO; therefore, the projections may move towards the $Al+Fe'''+Ti$ direction on the figure when Fe''' is detected.

The chloritoid (2) included in garnet has less Mg and projects in the composition field similar to those from the rocks of green schist facies, i.e., the Mn-rich low grade schists from the NW Rheine schist area (Kramm 1973), but the latter have a large amount of Mn instead of Fe″. The chloritoid (1) from the garnet-muscovite-quartz schist has a little higher Mg than (2), but still less Mg than those from the glaucophane eclogite of Zermatt (Bearth 1973).

White micas

White mica is a main constituent mineral of the muscovite-quartz schists, up to about 25% in volume, and is always found in all other schistose rocks of the Vestgötabreen Formation. It occurs as large flakes and defines the strong diaphtolitic cleavage. The flakes show no trace of alteration and have no inclusions of other minerals.

Three chemical analyses of white mica show that all of them are phengite with less than 44% trioctahedral Fe″ (Table 8). They project in the same field as the phengites from other glaucophane schists of the world (Fig. 14). The glaucophane schists from Bessi, Japan (Banno 1964) and the glaucophane eclogites from Zermatt (Bearth 1973) have white micas of paragonite composition, however, the paragonite contents of the present ones are less than 14%.

Epidotes

Epidote is granular and is abundant in the epidote amphibolites. It is also common in the glaucophane schists, eclogitic rocks, calcareous schists and muscovite-quartz schists, and is in secondary appearance to some extent, dusty granular alignments along schistosity. Clinozoisite is often associated with epidote.

Two epidotes, from the epidote amphibolite (1) and typical glaucophane schist (2), have very small piedmontite contents (2.58% and 2.99%, respectively) and their zoisite contents are 26.2% and 31.3%, respectively. Thus, they are classified as Al-epidote (Fig. 15).

Table 8

White micas

	Paragonite ratio $\frac{100\,Na}{Na+K}$	Di-octahedral degree $\frac{100\,Al^{VI}}{Al^{VI}+Fe+Mg}$	Ferri-phengite comp. $\frac{100\,Fe'''}{Al^{VI}+Fe'''}$	Ferro ratio in triocth. $\frac{100\,Fe''}{Fe''+Mg}$	Host rock (Nos. refer to Table 1)
1 Phengite	7.36	12.14	—	41.54	chd-ga-mus-qt schist (No. 34)
2 Phengite	13.83	18.24	—	38.03	gl-ga schist+ mus.crots (No. 2)
3 Phengite	8.90	—	2.00	43.52	gl-ga-mus-qt schist (No. 28)

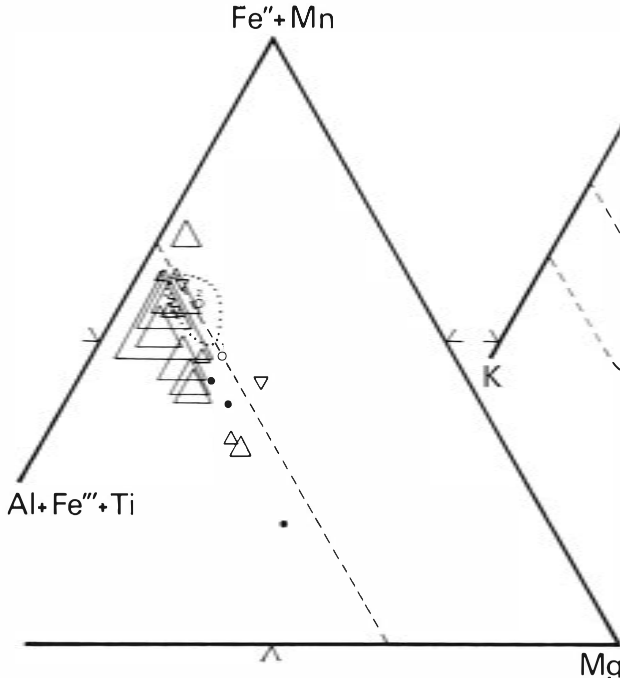


Fig. 13.

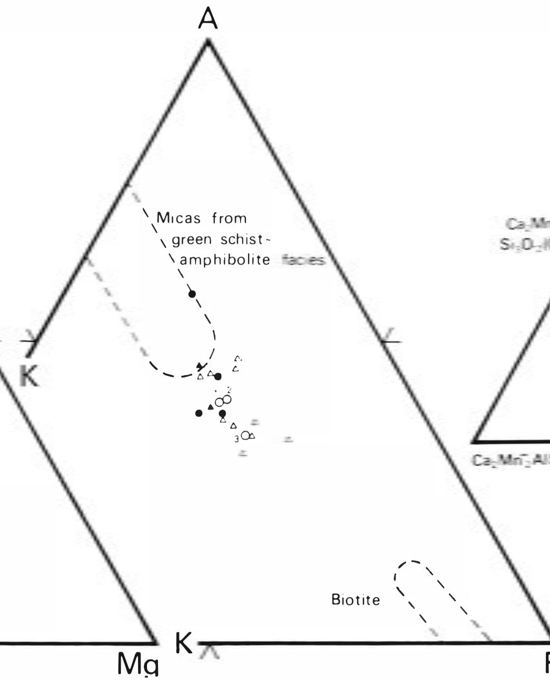


Fig. 14.

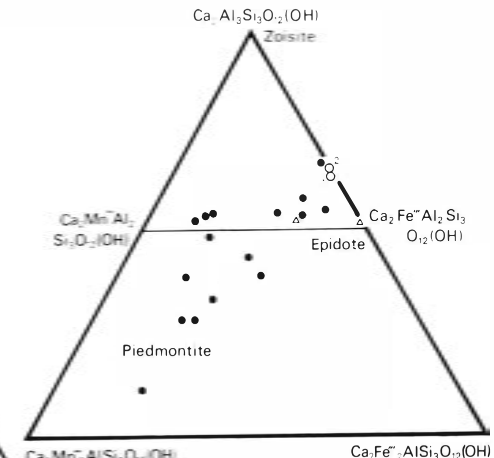


Fig. 15.

Fig. 13. *Chloritoids. Open circles: from the present area, see text; dots: from the glaucophane eclogites of Zermatt; triangles: from various metamorphic rocks in the world* (DEER et al. 1962). *Dotted curve: from the schists of Venn Stavetet, northwest Rheineschiefergebiet* (KRAMM 1973).

Fig. 14. *White micas. Open circles: from the present area, see Table 6; dots: from Japanese glaucophane schists; open triangles: from California; solid triangles: from New Caledonia.*

Fig. 15. *Epidotes. Open circles: from the present area, see text; open triangles: from Japanese glaucophane schists; dots; from various metamorphic rocks of the world* (DEER et al. 1962).

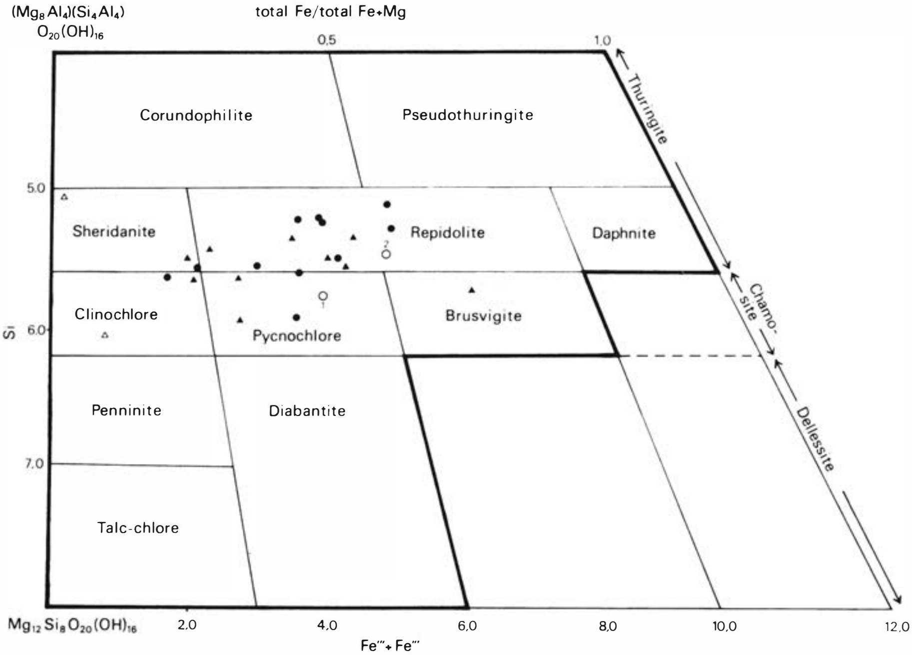


Fig. 16. *Chlorites. Open circles: from the present area, see text; dots: from Japanese glaucophane schists; solid triangles: from chlorite schists of the world; open triangles: from serpentine schists of the world. The diagram after* Hey (1954).

Chlorites

Chlorite is one of the main constituents of the epidote amphibolites and is always a secondary alteration product filling cracks in the garnets of the glaucophane-bearing rocks.

Two chlorites, from the glaucophane-epidote-actinolite-chlorite schist (1) and garnet-glaucophane schist (2), were analysed. Both have similar Si/Al ratios, but their Fe/Mg ratios are somewhat different. The (1) chlorite is pycnochlorite and the (2) is repidolite (Fig. 16); the latter occurs in the cracks of garnet. All chlorites filling the cracks of garnet in various rocks show almost the same pleochroism and birefringence as the analysed repidolite, while the chlorites from the epidote amphibolites may have a certain compositional variation judging from the difference of the birefringence.

Clinopyroxene

Clinopyroxene is an essential constituent of the eclogitic rocks, most of which have some amount of glaucophane. The host rock of the analysed clinopyroxene is a small lens, 10–15 cm thick, in the glaucophane-garnet-muscovite-quartz schist, composed of more than 95% of slightly dusty, dense clinopyroxene aggregate and less than 5% medium grained garnet which is often cracked and chloritized.

The molecular components of the analysed clinopyroxene are: Jd = 38.4%, Ac = 13.6%, Di = 45.0%, and $(Fe,Mg)Si_2O_6$ = 3.06%. This composition

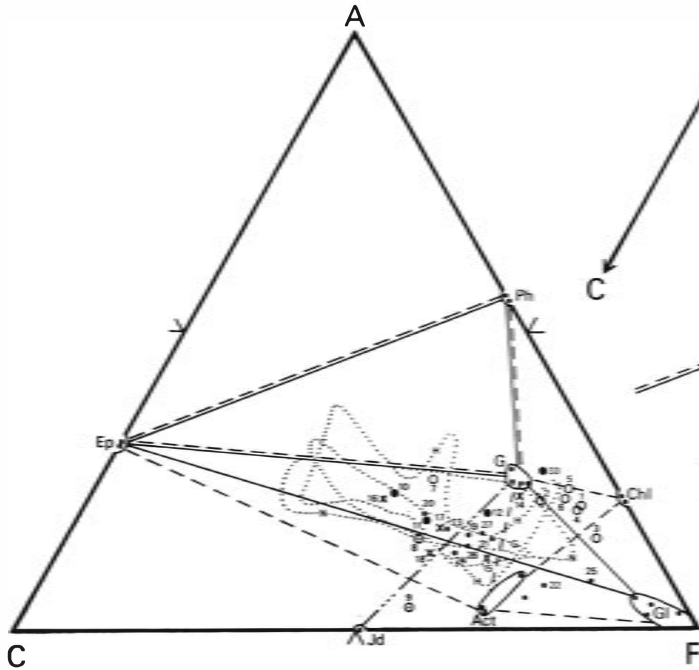


Fig. 17a.

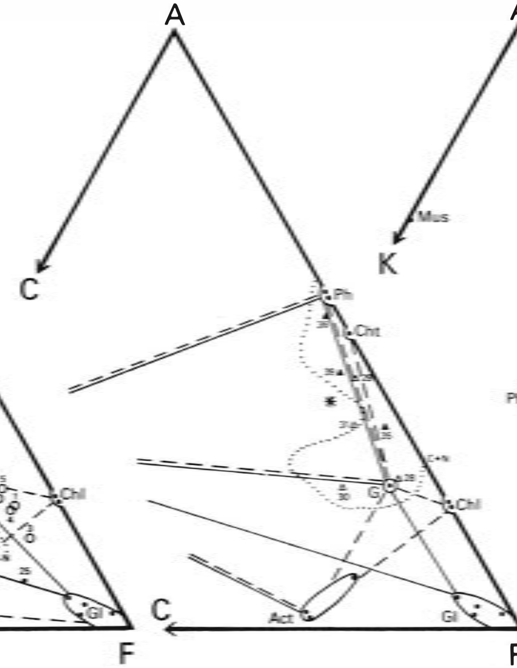


Fig. 17b.

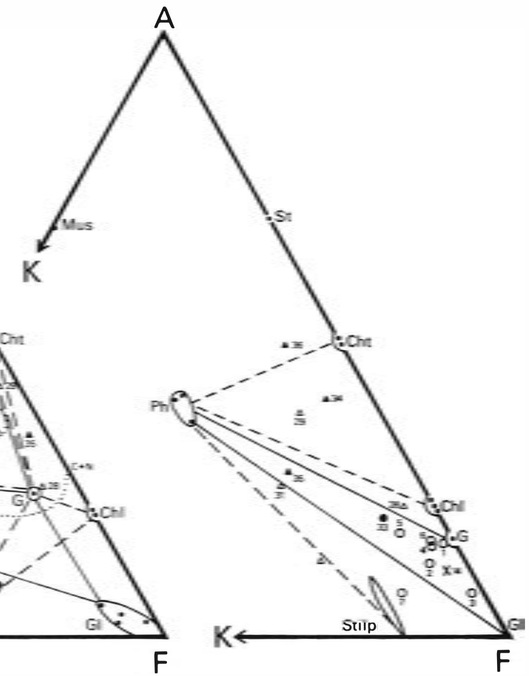


Fig. 18.

Fig. 17. *A-C-F diagrams of the rocks from the Vestgötabreen Formation.*

a. *Meta-basic rocks. Broken tie lines: assemblages from the rocks without glaucophane; solid tie lines: assemblages with glaucophane; dash and point tie line: assemblage of the eclogitic rocks. Dotted curves: C, the field of Californian glaucophane schists; H, the field of Hornsund amphibolites; N, the field of New Caledonian glaucophane schists; small dots without No.: analysed minerals. Other symbols and numbers are the same as in Fig. 3a and Table 1.*

b. *Meta-sediments. Legends are the same as in Fig. 17a.*

Fig. 18. *A-K-F diagram. The tie lines are the same as in Fig. 17 and the symbols and numbers are the same as in Figs. 3b and 17, refer to Table 1.*

is in the middle of the omphacite field of the pyroxene diagram (ESSENE and FYFE 1967), and is similar to those found in the metamorphic rocks of blue schist facies and in eclogite from different parts of the world.

V. Metamorphism

To map successive metamorphic zones in the Vestgötabreen Formation in the field is almost impossible because most lithologic units are separated by faults. However, petrographic observations suggest some sequences of metamorphic reactions in these rocks.

(A). Medium grained hornblende-plagioclase rocks are rarely observed as domains of relictic texture (not original igneous texture) in the epidote amphibolites with weak schistosity. In the schistose rocks, all mafic constituents were converted to a chlorite-epidote-sphene-opaque assemblage and plagioclase decomposed into sericite-epidote-carbonate-albite-quartz assemblages. Actinolite occurs at the crests of tightly crenulated chlorite (Plate 2–2), and small garnet grains are scattered. Thus, the reactions chlorite→actinolite and chlorite→garnet are characteristic in these rocks, and indicate the metamorphic condition of the epidote-actinolite subfacies of greenschist facies. No definite indicator of high pressure metamorphic facies series, such as pumpellyite, lawsonite and jadite-quartz assemblage, has been found, except for stilpnomelane (Plate 2–1).

The most dominant rock in the Vestgötabreen Formation is the calcareous schists with muscovite, epidote, clinozoisite, and garnet. There is no mineral indicating higher metamorphic grade than the epidote amphibolite facies. Glaucophane occurs as idiomorphic prisms or flaky aggregates in the muscovite-rich layers of these rocks.

(B). The muscovite-quartz schist, with or without garnet and chloritoid, is one of the dominant rocks in this formation. Staurolite has never been observed. The mineral assemblages observed in these rocks, including (A), are shown by the broken tie lines in Figs. 17a, 17b, and 18. Judging from the zonal distribution of inclusions in the garnet, the chloritoid-bearing assemblages may be earlier than the formation of glaucophane.

The co-existence of chloritoid and Al-silicate polymorphs is suggested to be stable under the condition of 500–570°C and 3.5–5.5 Kb. from experimental studies (NEWTON 1966; RICHARDSON, BELL and GILBERT 1969; and GANGULY 1969). Since no Al-silicates have co-existed with chloritoid even in strongly micaceous layers, for example No. 36, Fig. 17, in the present rocks, it is suggested that they were formed outside the above mentioned condition. Occurrence of stilpnomelane and a slightly higher Mg content in the chloritoid, may indicate relatively high pressure (CHINNER and DIXON 1973). This condition corresponds to the lower amphibolite facies of the intermediate P/T facies series.

(C). The eclogitic rocks occur as isolated bodies and are concordantly enclosed by the chloritoid-garnet-muscovite-quartz schist. Strong diaphtolitic cleavages of the enclosing schist never penetrate into the eclogite. Direct contact between the eclogite and the calcareous schists has not been found and the eclogite does not occur in the epidote amphibolites. Thus, primary occurrence and the time relation of the eclogite in relation to various schists and amphibolites are unknown.

However, from petrographic observations, the primary bimineralic eclogite constituents are evidently older than the formation of glaucophane. This assemblage is shown by the dash-point tie line in Fig. 17a.

Based on the Fe″/Mg partitioning between co-existing omphacite and garnet (Table 3, No. 5) in the eclogite (an almost glaucophane-free part was selected), the formation conditions of the eclogite was estimated as suggested by BANNO and MATSUI (1965). Since total iron was given as FeO by the electron microprobe, Fe″ was calculated by the formulae proposed by RYBURN et al. (1976).

$$K_{G}^{Fe''-Mg} = 2.706, \quad K_{cpx}^{Fe''-Mg} = 0.205, \quad K_{G-cpx}^{Fe''-Mg} = 13.21$$

$$\text{Jd content of cpx} = 38.4\%$$

The P–T condition was estimated referring the diagrams of GREEN and RINGWOOD (1967 and 1972) and RÅHEIM and GREEN (1975), K_D and Jd content as functions of pressure and temperature:

$$\text{minimum pressure} = 9.7 \text{ kb (without co-existence of albite)}$$

$$\text{temperature} = 540\text{–}570°\text{C}$$

These data give a first approximation to the formation conditions of the eclogite from the present area.

The same estimation was attempted for the eclogite from Biskayerhuken, northwest Spitsbergen, reported by GEE (1966).

$$K_{G}^{Fe''-Mg} = 3.196, \quad K_{cpx}^{Fe''-Mg} = 0.285 \text{ (Fe'' by chemical analyses)},$$

$$K_{G-cpx}^{Fe''-Mg} = 11.18, \quad \text{Jd content of cpx} = 20,$$

$$\text{minimum pressure} = 4 \text{ kb}, \quad \text{temperature} = 550\text{–}620°\text{C}$$

The low pressure of the Biskayerhuken eclogite can be explained by secondary modification under the conditions to form extensive amphibole-plagioclase symplectite which has not been observed in the eclogite of the present area.

(D). The glaucophane-bearing assemblages are younger than all others and are similar to the type IV glaucophane schist of California (the solid tie lines in Figs. 17a, 17b, and 18). The formation conditions of the latter have been studied by the Oxygen isotope method by TAYLOR and COLEMAN (1968) and are given as 400–500°C. The phengites (Fig. 14) from the glaucophane-bearing rocks have the Si^{+4} value = 3.39 in average, based on the assumption of O_{10} per unit formula. Taking the estimated maximum temperature from the Californian type IV rocks, the maximum pressure for the present glaucophane schists can be assumed to be about 8 kb from the diagram of VELDE (1967) for the estimate of P–T conditions from the Si^{+4} value of natural phengites. These conditions may be not far from the present case.

All estimated physical conditions for different types of rocks from the Vestgötabreen Formation are shown on the phase diagram (Fig. 19) as A, B, C, and D with the same divisions as discussed above. The P–T conditions of B. C, and D are in the similar temperature range, while the pressure differs to some extent. If the estimates made above are near the truth, the rocks of the Vestgötabreen Formation represent a transitional facies series between the blueschist type and the intermediate P/T type metamorphic facies series. This corresponds to the high-temperature glaucophane schist facies of WINKLER (1967) and TAYLOR and COLEMAN (1968). This conclusion agrees with the lack of typical high pressure minerals in the lower grade rocks and also with the mode of occurrence of glaucophane in vein-like and radial aggregates.

VI. Metamorphic facies series of the western Spitsbergen Hecla Hoek rocks

Epidote amphibolites similar to those of the present area are known from several places along the west coast of Spitsbergen: the north and south sides of St. Jonsfjorden, the southern half of Nordenskiöldkysten, west of Recherchebreen, and the northern entrance of Hornsund. All these rocks have mineral assemblages of the epidote-actinolite subfacies of greenschist facies in general, but an important characteristic is the association of stilpnomelane and bluish green sub-alkaline amphiboles.

Many thin, green phyllite horizons occur in Prins Karls Forland and everywhere along the west coast of Spitsbergen, and their essential mineral assemblages are chlorite-sericite-epidote with occasional chloritoid, for example in Prins Karls Forland (ATKINSON 1956).

All these basic rocks are stratigraphically lower than the possibly Vendian tilloid formation; the Hornsund amphibolites are of the Eimfjellet Group of the Torellbreen Supergroup (BIRKENMAJER 1975), while those of the Bellsund area cut the lower calcareous successions of the Sofiebogen Group and are found as pebbles of tillitic conglomerate (HJELLE 1962). The amphibolites from St. Jonsfjorden and Prins Karls Forland are not correlated with certainty yet, but may be lower than the tilloid formation.

A staurolite-biotite assemblage was reported by ATKINSON (1956) from Prins Karls Forland, and the garnet-sillimanite and staurolite-garnet assemblages have been found by the present author in the pelitic metamorphic rocks from Prins Karls Forland and Sørkapp Land, respectively. Garnet-biotite gneisses occur north of Hornsund, and similar garnet-biotite schists are distributed in Svartfjellstranda on the east coast of Forlandsundet. All these high grade rocks

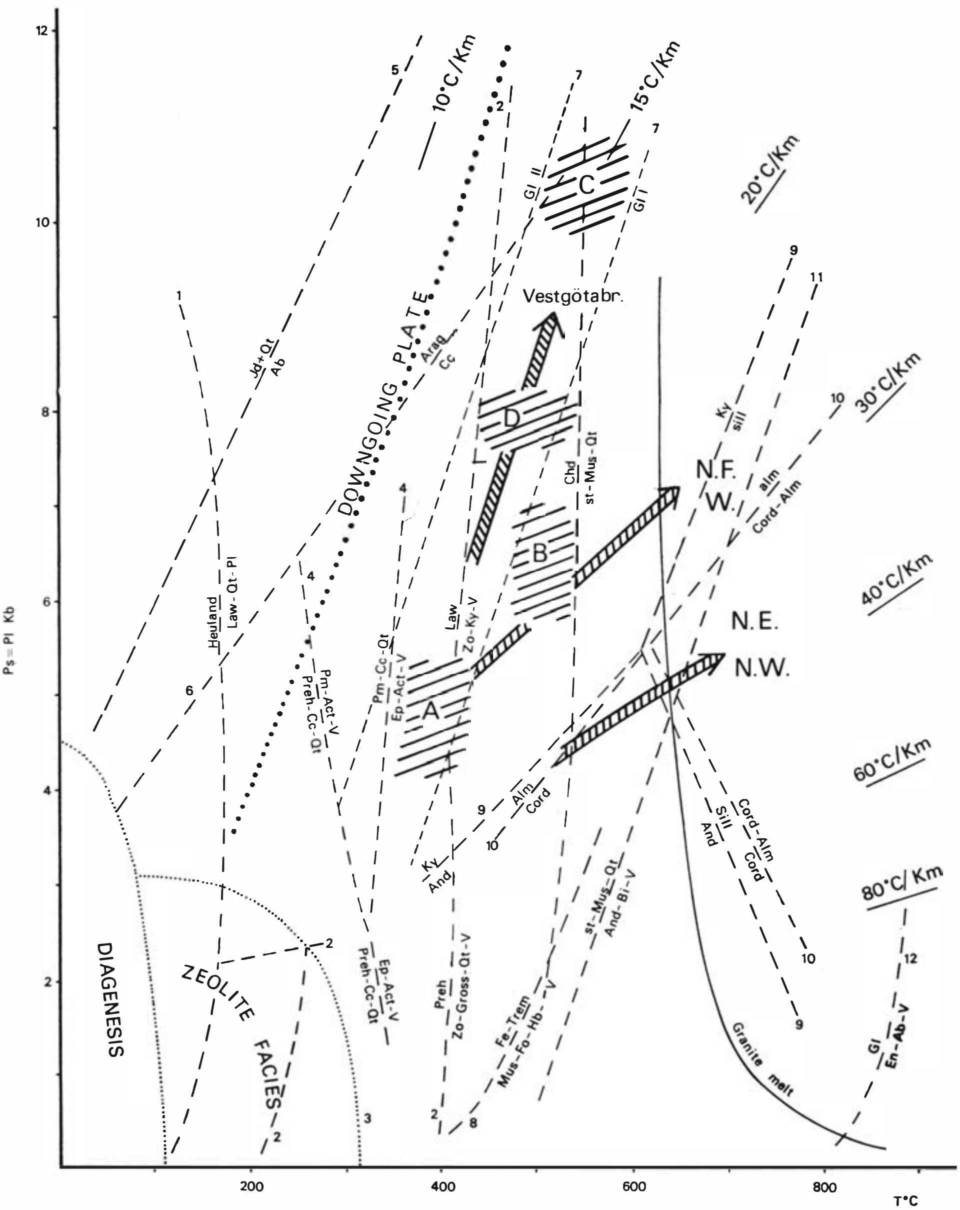


Fig. 19. *Metamorphic facies series.*

A: epidote-actinolite-greenstones; B: chloritoid-muscovite-quartz schists; C: eclogitic rocks; D: glaucophane schists. Thick arrows: the metamorphic facies series of: N.A., Nordaustlandet zone; N.F., Ny Friesland zone; N.W., Northwestern Spitsbergen; W, West Spitsbergen metamorphic zone. (1) NITSCH 1968, (2) LIUS 1971, (3) SEKI 1973, (4) NITSCH 1971, (5) NEUTON and SMITH 1967, (6) CLARK 1957, (7) ERNST 1963, (8) ERNST 1966, (9) RICHARDSON 1969, (10) HIRSCHBERG 1968, (11) HOCHAK 1969, (12) ERNST 1961.

can be grouped as Bjørnhamna Group of the Torellbreen Supergroup and are the deepest rocks so far observed in western Spitsbergen.

The mineral parageneses of these rocks indicate that the metamorphism of this area belongs to the intermediate P/T type metamorphic facies series.

It is said that the type of metamorphism in a certain metamorphic zone is restricted to one metamorphic facies series, and may extend into types intermediate to the neighbouring facies series (MIYASHIRO 1961; ZWART et al. 1967). The occurrence of high-temperature glaucophane schist facies in the intermediate P/T type western Spitsbergen zone does not contradict to this statement. A similar example has been reported from the Betic orogenic zone, southern Spain (KAMPSCHUUR 1975).

The occurrence of idioblastic large crystals of glaucophane in the Vestgötabreen Formation indicates that this mineral was formed later than the muscovite-quartz schists and eclogitic rocks. This suggests a polyphasial metamorphism.

A peculiar chemical composition with a large amount of Na-rich pyroxene in the eclogitic rocks, might have played an important role in the formation of the glaucophane schists of the Vestgötabreen Formation. Recent studies of eclogite amphiboles (MOTTANE and EDGAR 1970) show that much glaucophane, Ca-glaucophane and barroisite were formed in the symplectite amphiboles after the omphacite of eclogites, and this suggests a retrogressive formation of the glaucophane schists from eclogites.

VII. A Caledonian subduction zone?

HORSFIELD (1972) mentioned that the lithologic characteristics of the Vestgötabreen rock suite (in his definition) suggest a possible subduction zone, involving oceanic crust, during the Caledonian period: Indeed, some young blueschist metamorphic zones elsewhere in the world can be explained by a subduction-zone model (ERNST 1972 and 1975; MIYASHIRO 1972), but there are still many problems to be solved when this idea is going to be applied far back into geologic time (MIYASHIRO 1975).

Although the Vestgötabreen Formation is an isolated thrust schuppen, it probably had not travelled a long distance into the present area. From what we know of the metamorphic grade, these rocks are comparable to those of the upper Isbjørnhamna Group or younger, the most possible correlation to the epidote amphibolites being to the Sofiebogen Group of the Bellsund area.

BIRKENMAJER (1975) proposed two-fold geosynclinal cycles in the pre-Cambrian of western Spitsbergen based on the stratigraphic breaks in the Hecla Hoek successions: the older Torellian eugeosynclinal cycle and the younger Jarlsbergian miogeosynclinal cycle.

The observed thickness of the Torellian eugeosynclinal succession is about 11 km. The metamorphic condition of the chloritoid-staurolite-bearing rocks of the Isbjørnhamna Group is supposed to be 5–7 kb and 500–700°C (Fig. 19); this is a depth of about 15–20 km. This condition is not impossible by large lateral shortening in a folded belt and some introduction of heat from the depth brought up by granitic intrusion, such as in the northern Hornsund area. The general eugeosynclinal characteristics of the Torellbreen Supergroup (BIRKENMAJER 1975) are in harmony with the development of an intermediate P/T type metamorphic facies series, and there is no need to introduce the idea of a subduction zone.

The K–A ages of the glaucophane schists are mostly in the range of 402 ± 14–$475 \pm$m.y. (muscovite and whole rock), indicating a main Caledonian phase, and one is 621 ± 12 m.y. (whole rock) (HORSFIELD 1972). The older one may be correlated to the 556 ± 24 and 584 ± 25 m.y. biotite ages of the garnet-biotite schist from Hornsund (GAYER et al. 1966), which suggest the middle Cambrian event similar to the west-Finnmark event in North Norway (STUART and MILLER 1967) and the Grampian event of Scotland (DEWEY and PANKHURST 1969).

The rocks involved in the proposed Jarlsbergian and Hornsundian event (BIRKENMAJER 1975) are of miogeosynclinal character and are not likely to produce an intermediate P/T facies series metamorphism. It is reasonable to consider the original rocks of the Vestgötabreen Formation to be of the Torellian eugeosynclinal deposits, probably metamorphosed in the Torellian event and modified during the Caledonian period to renew the K–A ages.

An important piece of geological evidence for the conclusion of a subduction of oceanic crust would be to find out to what extent the rock succession of such metamorphic zones, belongs to the oceanic ophiolite suite. The rock assemblage of the Vestgötabreen Formation is very similar to the classic "ophiolite trinity" of STEINMANN (1927). The original succession of these rocks, phyllarenite — basic volcanics — limestone, suggests a sedimentary condition around the margins of an eugeosynclinal basin, if there is any dominant ophiolite suite associated in the same geologic regime. The percentage of basic rocks in the observed type succession of the Torellian eugeosyncline is about 12%, and is far smaller in the areal distribution. The association of alkalic and tholeiitic volcanic rocks in the Vestgötabreen Formation fits well in with that of the Sanbagawa and Franciscan blueschist zone as summarized by MIYASHIRO (1975). A large amount of sodic alkaline rocks is characteristic for ocean islands of probable hot-spot origin; however, if these rocks were detached from descending ocean plate and implicated in a subduction zone, a large amount of oceanic tholeiite might be associated. The evidences — association of shallow sea sediments and very small amounts of tholeiitic rocks in the Vestgötabreen Formation — are not in favour of a subduction zone. Moreover, some potassic alkaline rocks in the Vestgötabreen Formation and occurrence of granite and potassic rhyorite ($K_2O = 9.40$ and 10.21 wt.%) pebbles in the conglomerate of the Vimsodden Subgroup of Hornsund, suggest the existence of a continental crust during the development of the Torellian eugeosyncline in western Spitsbergen. Thus, the idea of a Caledonian subduction zone is still an open question at the present stage of our knowledge. The idea of a large transcurrent displacement proposed by HARLAND (1969) and others, is beyond the scope of the present paper.

VIII. A discussion on the metamorphic facies series in Svalbard

It is evident that the majority of Hecla Hoek rocks in Svalbard were involved in the Caledonian metamorphism. The radiometric ages already available support this (GAYER et al. 1966). These metamorphic rocks occur around the north and west sides of Svalbard, and three zones of N–S trends are distinguished on the northern coast: the Nordaustlandet (NE) zone, the Ny Friesland (NF) zone, and the Northwestern (NW) zone. Another zone (W zone) occurs along the west coast of Spitsbergen (Fig. 1).

The characteristic mineral parageneses and metamorphic facies series of these zones are shown in Table 9. Although the Vestgötabreen Formation is not a typical high-pressure type metamorphic facies series, the Caledonian metamorphism of Svalbard covers nearly all three varieties of a metamorphic facies series within the width of about 300 km (Figs. 1 and 19). The zones of the high T/P facies series, the NE and the NW zones, are characterized by extensive development of migmatite and granite. The zones of the intermediate P/T facies series, the NF and the W zone, have a little granite intrusions and have some eugeosynclinal sediments in the lower parts of their geosynclinal successions.

These four zones can be considered two sets of paired metamorphic zones (MIYASHIRO 1961 and 1973) if all these zones were formed during the Caledonian period.

Different metamorphic facies series are closely related to different histories of the geosynclinal development. Therefore, the idea of paired metamorphic zones should be justified by the difference in the geosynclinal successions of the Hecla Hoek from these zones. Some differences have already been noticed, but their characteristics are not so contrasting as in the younger paired zones which are typically made up by a pair of a high P type and a high T/P type metamorphic zones.

The present author assumes that these two sets of paired zones, the NE–NF pair and the NW–W pair, are essential geologic units in the pre-Devonian

Table 9

Mineral parageneses and metamorphic facies series of Svalbard (ref. Fig. 1)

Zone	Diagnostic mineral assemblages	Metamorphic facies series
Nordaustlandet zone	Cordierite, almandine, sillimanite (staulorite in the contact zone)	High T/P type facies series (the older unknown)
Ny Friesland zone	Staurolite, almandine, kyanite, sillimanite	Intermediate P/T type
NW zone	Cordierite, almandine, sillimanite (kyanite and staurolite relic)	High T/P type (the older: intermediate P/T type)
W zone	Stilpnomelane, chloritoid, staurolite, sillimanite, sub-alkaline amphiboles, almandine (younger; alkaline amphiboles)	Intermediate P/T type

structures of Svalbard, and they should be considered fundamental tectonic units when any large scale transposition is assumed on the plate tectonics (HARLAND 1969; HARLAND et al. 1974; CHURKIN 1973; BIRKENMAJER 1972).

An alternative interpretation of the difference of pre-Devonian rocks in Svalbard is superposed metamorphism.

Two occurrences of kyanite have been found in the NW zone: Biskayerhuken (GEE 1964) with staurolite, and Danskøya–Amsterdamøya. The kyanite of the latter locality was recently conformed by HJELLE and the present author from HJELLE's collection. The kyanite occurs as small fragmental relics, sericitized along cracks, in the cordierite-sillimanite gneiss.

Pseudomorphs of spinel-corundum clots after presumably staurolite or chloritoid, were reported by the present author (Plates 3 and 4 of HJELLE and OHTA 1974) from the Smeerenburgfjorden area.

These evidences suggest that there was a regional metamorphism prior to the migmatization, having the nature of the intermediate P/T facies series in the NW zone.

Staurolite has been known from Nordaustlandet (FLOOD et al. 1969), but this occurs around a granitic intrusion and does not show any older metamorphic phase. Although Nordaustlandet is completely soaked by migmatization products and it is very difficult to distinguish older phases, a deformation of late pre-Cambrian age, prior to the deposition of Murchisonfjorden Supergroup has been suggested (GEE in FLOOD et al. 1969).

In the W zone, the metamorphism of the intermediate P/T facies series can be considered to be older than the main Caledonian phase as discussed before.

It is worth mentioning that the older phases of both the NW and W zones are the intermediate P/T facies series as in the NF zone (GAYER and WALLIS 1966). One possible conclusion based on this evidence is that the metamorphism of the earlier phase of Caledonian or Torellian (BIRKENMAJER 1975), was of the intermediate P/T facies series over all three zones, and the later main Caledonian high T/P facies series was superimposed intensely in the NE and NW zone.

Existence of continental crust in the basement of the Hecla Hoek geosyncline is suggested by the occurrences of thick acidic volcanic rocks in the Kapp Hansteen Formation of Nordaustlandet and in the Harkerbreen Group of Ny Friesland, potassic rhyorite in the Vimsodden Subgroup of Hornsund, and the granite pebbles from the Vimsodden Subgroup, Rittervatnet Formation of the Harkerbreen Group, and from the Vendian tillitic rocks elsewhere in Svalbard. Without the study of lower Hecla Hoek volcanic rocks, the problem of a proto-Iapetus ocean (HARLAND and GAYER 1972) can not be discussed with any certainty.

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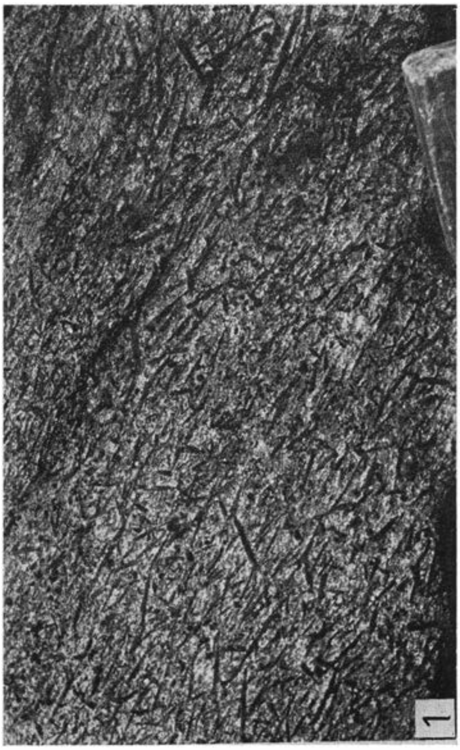
PLATES

PLATE I

Glaucophane-bearing rocks.

1–1. Feather amphibolite texture of glaucophane-muscovite schist.
1–2. Garnet-muscovite-quartz schist with glaucophane needles.
1–3. Garnet-glaucophane schist, the groundmass is pure glaucophane aggregate.
1–4. Garnet-glaucophane schist, idiomorphic large garnet and pure glaucophane groundmass with secondary calcite veins.

PLATE I



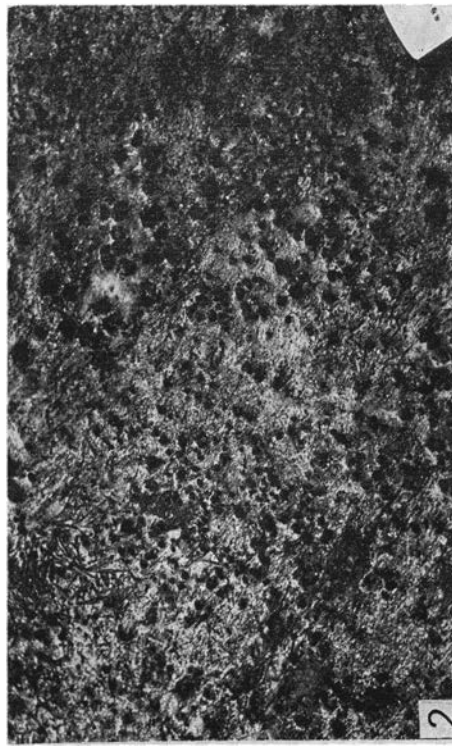


PLATE II

Microphotographs.

2–1. Stilpnomelane in the epidote-chlorite schist. The short side of picture is 0.7 mm.

2–2. Actinolite needles along the border between the chlorite-rich and quartz-rich band of the epidote-chlorite schist. The short side of picture is 0.7 mm.

2–3. Garnet with chloritoid inclusions in the inner part and poikiloblastic texture along the margins. The short side of picture is 2.0 mm.

2–4. Cracked garnet in dense glaucophane groundmass. The short side of picture is 2.0 mm.

PLATE II

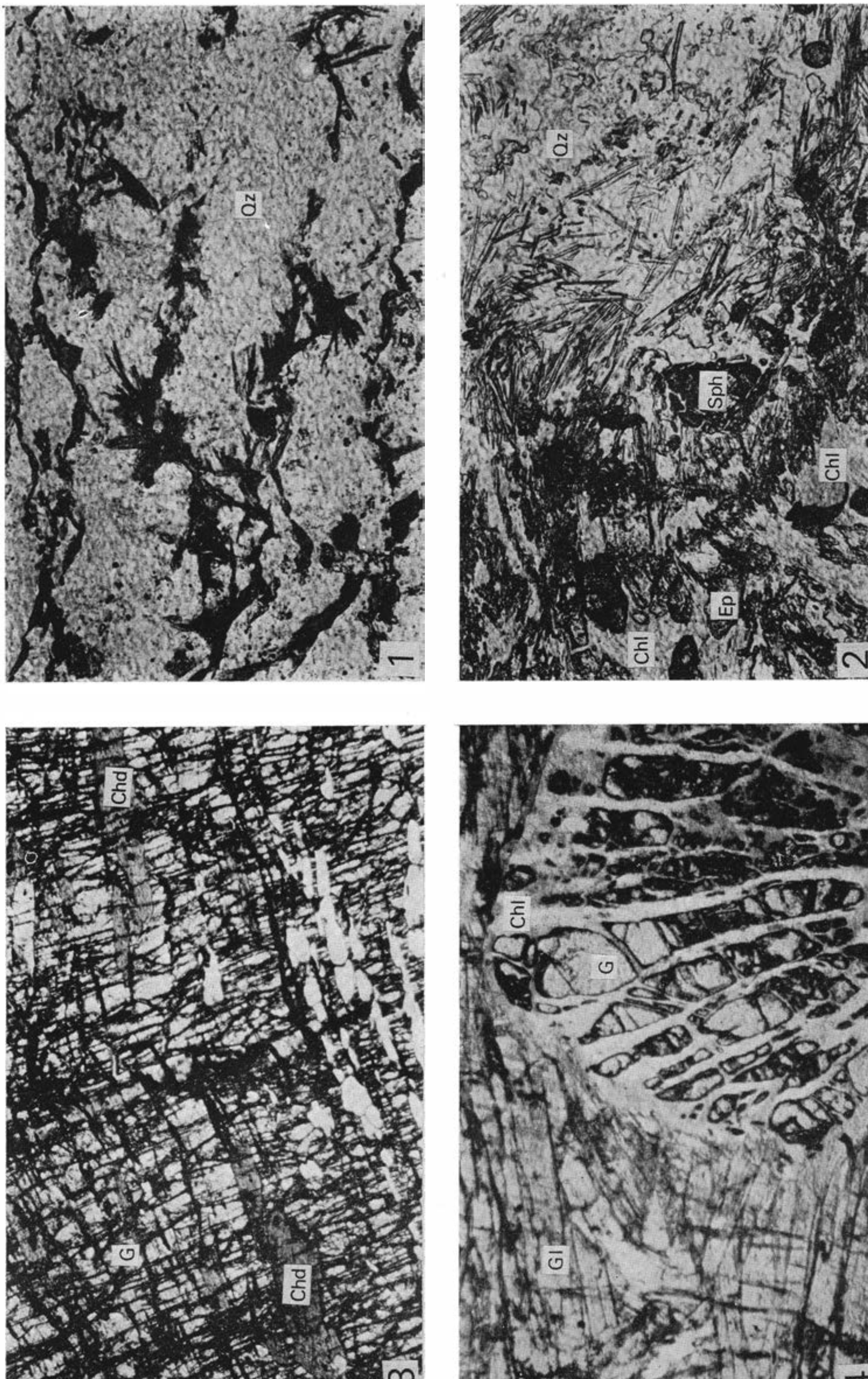


PLATE III

Microphotographs.

3–1. Zoned idiomorphic glaucophane in the calcareous schist. The short side of picture is 2.0 mm.

3–2. Zoned idiomorphic glaucophane in the dusty groundmass of omphacite, eclogitic rock. The short side of picture is 2.0 mm.

3–3. Idiomorphic glaucophane, the dark parts along cracks and cleavages are crossite. The short side of picture is 0.7 mm.

3–4. Omphacite inclusions at the margin of idiomorphic glaucophane in the eclogitic rock. The short side of picture is 0.7 mm.

PLATE III