Polarforschung 48 (1/2): 92—102, 1978

Aspects of Caledonian Metamorphism in Central Western Svalbard with Particualr Reference to the Glaucophane Schists of Oscar II Land *

By G. M. Manby **

Abstract: The glaucophane schists of Oscar II Land, it has been suggested, originated in a compressive plate boundary — subduction zone environment. An alternative hypothesis is presented here linking the metamorphism of these schists with that of the surrounding pre-Carboniferous rocks. It has been estimated from mineralogical and textural relationships that at the time of metamorphism these rocks exceeded 30 km in thickness. Similarly, an ambient geothermal gradient of 15° C/km has been calculated for the now exposed succession. Pressures of sufficient magnitude would be realised near the base of this geosynclinal pile to produce eclogite from rocks of basic composition. Subsequent synmetamorphic penetrative deformation would give rise to glaucophane and greenschist facies assemblages.

Zusammenfassung: Die Entstehung der Glaukophan-Schiefer des Oscar-II-Landes wird mit einer kompressiven Plattengrenze und Subduktionszone in Zusammenhang gebracht. Es wird eine alternative Hypothese vorgestellt, die die Metamorphose dieser Schiefer mit jener der umgebenden Gesteine verknüpft. Aus mineralogischen und texturellen Beziehungen kann geschlossen werden, daß zur Zeit der Metamorphose diese Gesteine eine Mächtigkeit von über 30 km besaßen. Ähnlich kann ein geothermischer Gradient von 15° C/km für die jetzt aufgeschlossene Folge berechnet werden. Drucke entsprechender Größe mögen nahe der Basis dieses geosynklinalen Komplexes geherrscht haben, um Eklogite aus Gesteinen basischer Zusammensetzung entstehen zu lassen. Eine nachfolgende synmetamorphe durchdringende Deformation verursachte die Vergesellschaftung der Glaukophan- und Grünschiefer-Fazies.

1. INTRODUCTION

The mid-Palaeozoic metamorphism and deformation of the pre-Carboniferous rocks of Spitsbergen is believed to be genetically related to that of other Caledonide belts of the North Atlantic-Arctic Ocean region (HARLAND & GAYER, 1972).

Central Western Svalbard consists of the two areas Prins Karls Forland and Oscar II Land (Fig. 1), in which the metamorphic pre-Carboniferous rocks exhibit, in general, greenschist facies mineral assemblages. However within this highly deformed and metamorphosed succession is found a narrow belt of eclogitic-glaucophane schists.

In this paper those aspects of the mid-Palaeozoic metamorphism in Central Western Svalbard which relate to the origins of the eclogitic-glaucophane schists are briefly examined and a new model is proposed.

2. STRATIGRAPHY

The pre-Carboniferous rocks of Prins Karls Forland and Oscar II Land are referred to as the Forland and Western Complexes respectively. The two nearly continuous successions can be correlated on their common tillite horizons (HARLAND et al., in press). The Forland Complex consists of approximately 6.7 km of strata younger than, the Western Complex of 6 km of strata older than the tillites (Fig. 1), and a total thickness in excess of 12 km is estimated. Flyschoid sequences dominate the upper part of the Forland Complex; slates, limestones, sandstones and minor volcanics constitute the lower part. Below the tillites the Western Complex consists largely of limestones and marbles with psammites to pelitic schists and volcanics.

* Paper presented at the "Conference on Geophysics, Geology, Geomorphology and Geodesy of Spitsbergen", held by the German Society of Polar Research in Hamburg, October 2—3, 1978.

** Dr. G. M. Manby, Geology Department, University of London, Goldsmiths' College, New Cross, London SE14 6NW (England).

The eclogitic glaucophane schists and associated rocks are referred to as the Vestgötabreen formation.

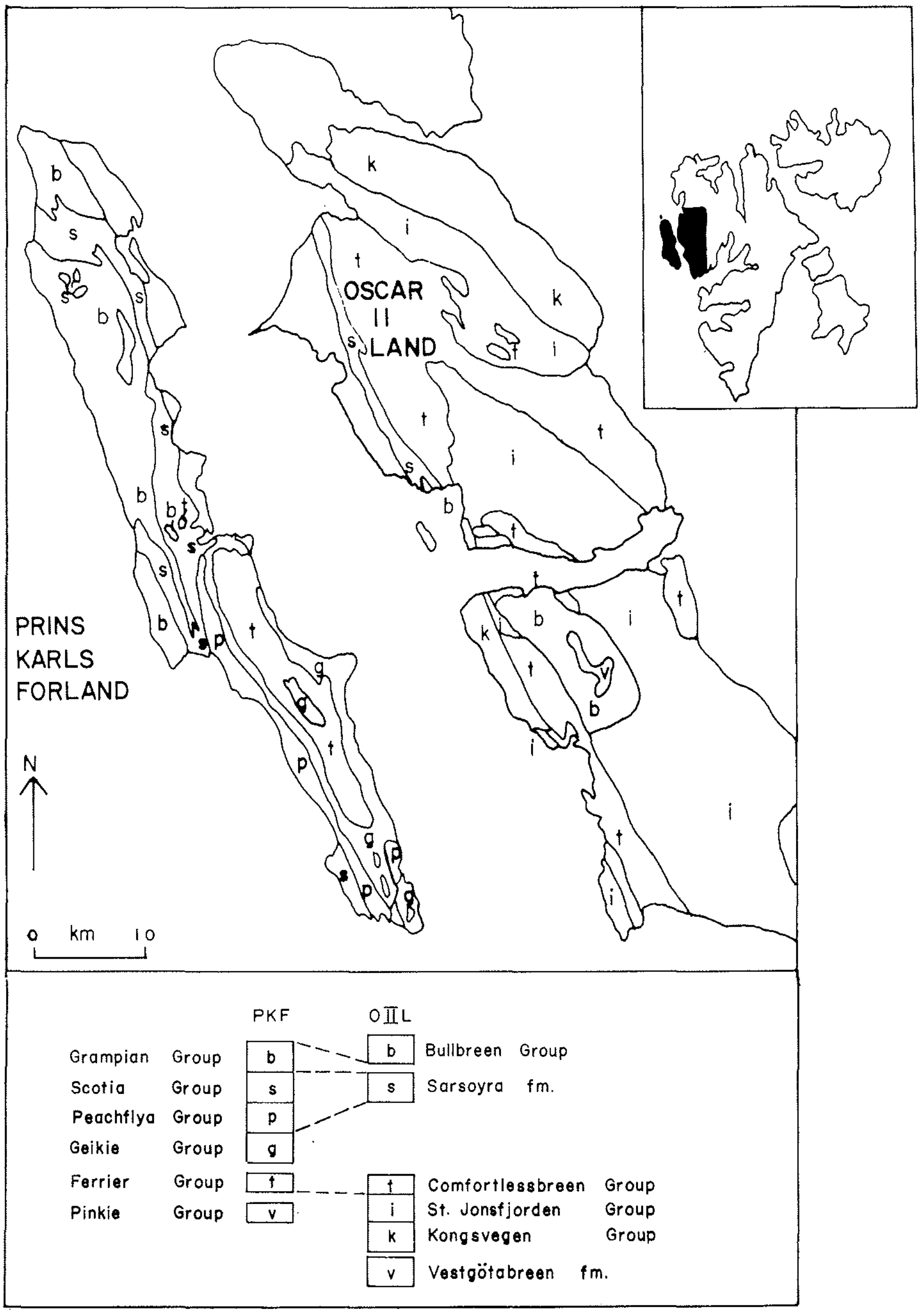

Fig. 1: Lithostratigraphic-structural units of Central Western Svalbard.

Abb. 1: Lithostratigraphisch-strukturelle Einheiten Zentral-Westspitzbergens.

2.1 *Metamorphism-Deformation*

Textural studies have shown that metamorphism of the Forland and Western Complexes occurred as a single thermal event which was initiated prior to and overlapped with the main (D_1) penetrative deformation. Metamorphism appears to have been terminated in the latter stages of the D_1 event as pressure solution fabrics modify the S_1 foliation. In general terms it is found that stratigraphically older rocks and hence more deeply buried rocks during the predeformational history of the geosyncline were metamorphosed to higher grades. This is a phenomenon which has been noted elsewhere in Svalbard (HARLAND, 1969) and is a point on which the Caledonides of Svalbard differ from those in the rest of the North Atlantic-Arctic Ocean Region.

2.2 *Mineral Assemblages*

Biotite bearing assemblages are found in calcareous metagreywackes belonging to the uppermost Grampian Group rocks. However, biotite is rare in pelitic rocks in this group and its appearance represents some arbitrary stage in the expansion of the phengite + chlorite field (cf. MATHER, 1970). The occurrence of biotite in the calcareous metagreywackes is thought to be due to the reaction

$$1\,Mu + 8\,Dm + 3\,Qt + 9\,H_2O \rightleftharpoons 1\,Bi + 8\,Ct + 1\,Ch + 8\,CO_2$$

(after CHATTERJEE, 1970) as both products and reactants are found in these rocks. Biotite becomes increasingly abundant in the Peachflya to Ferrier/Comfortlessbreen Groups occurring in a wider range of rock types. Pelitic rocks in the St. Jonsfjorden and Kongsvegen Groups contain garnet + oligoclase + biotite assemblages and metabasic rocks contain more hornblendic amphiboles and oligoclase. The oligoclase in both rock types does not exceed An_{23}. Throughout the Forland and Western Complexes Mu + Ch + Qt and Ctd + Qt assemblages remain stable in pelitic rocks. Staurolite and kyanite have not been found. In metabasic rocks Act + Ch + Ep remain stable throughout.

2.3 *PT Conditions of metamorphism*

From the mineral assemblages found in the Forland and Western Complexes it is evident that conditions of metamorphism did not exceed those of the greenschist facies. The appearance of biotite in the Grampian Group rocks is indicative of temperatures in the 380°—400° C range. That maximum temperatures approached but did not exceed 550° C is indicated by the hornblendic character of the amphiboles coexisting with oligoclase (An_{23}).

The temperature difference during metamorphism of the 12+ km of pre-Carboniferous rocks represents therefore a geothermal gradient of c. 15° C/km, a figure suggestive of a stable crustal region or of rapid accumulation of strata.

Since the Grampian Group rocks belong to the biotite grade and assuming the geothermal gradient can be extrapolated to the surface then it appears that something like 15—20 km of strata have been removed from the succession. The total thickness of rocks accumulated in the Holtedahl geosyncline (HARLAND et al., in press) must have been in excess of 30 km. Following this line of reasoning pressures in the Grampian Group could have approached 5 kb whilst those in the Kongsvegen Group were in the order of 8 kb during metamorphism.

It is in the light of these considerations that the possible origins of the Vestgötabreen formation eclogitic glaucophane schists and associated greenstones can be examined.

3. THE VESTGÖTABREEN FORMATION

HORSFIELD (1972) who was the first to isolate this formation described it as a sequence of quartz-mica mylonites, greenstones and glaucophane schists with occasional pyroxenite pods and serpentinites. He notes in particular the lateral transition from glaucophane schists into the greenstones.

3.1 *Field occurrence*

The distribution of the Vestgötabreen formation is illustrated in Fig. 2. The rocks are restricted to a narrow strip running between Motalafjella and Bulltinden. They are described by HORSFIELD (1970 and 1972) as being thrust into the Bullbreen Group, the youngest rocks of the Western Complex.

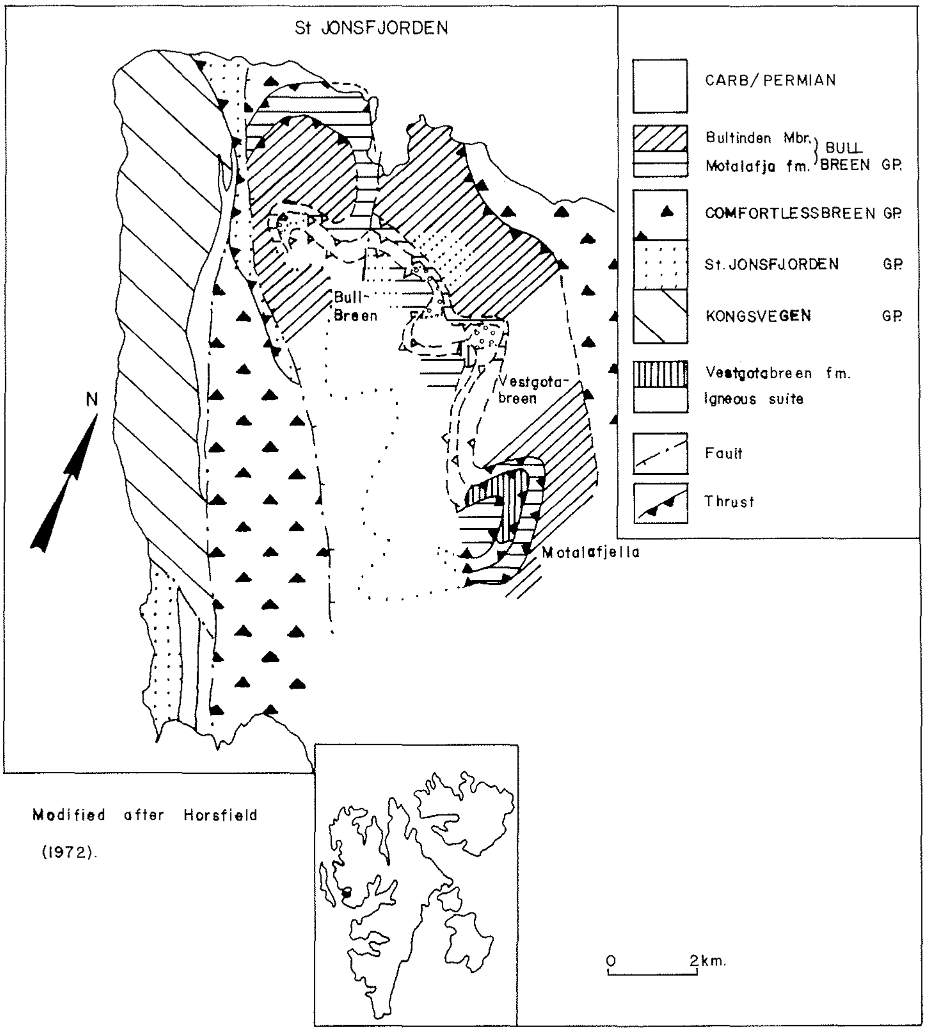

Fig. 2: Distribution of Vestgötabreen formation, Oscar II Land (modified after HORSFIELD, 1972).
Abb. 2: Verbreitung der Vestgötabreen-Formation, Oscar-II-Land.

3.2 *Mineral assemblages*

The mineralogical and textural variety of the eclogitic glaucophane schists are illustrated in Fig. 3, A to D. Simple bimineralic, garnet + omphacite assemblages are not found, usually the omphacite is degenerate and is being replaced by epidote and glaucophane. In weakly foliated coarser grained varieties phengite + glaucophane and garnet assemblages are found with epidote, calcite and rutile as less abundant phases (Fig. 3, C). Occasionally the garnets are found to contain inclusions of quartz and chloritoid.

3.3 *Chemistry of major phases*

All of the major phases of the eclogitic glaucophane schists have been analysed using the Cambridge E. D. S. electron probe microanalyser and the results are presented in table 1.

	GARNETS												
SiO_2	39.46	39.60	39.35	38.54	38.21	38.71	39.40	40.34	39.68	40.12	38.59	39.23	39.41
TiO_2	—	—	—	—	—	—	—	—	—	—	—	—	—
Al_2O_3	22.31	22.79	21.98	21.43	21.50	21.43	22.33	23.31	22.38	22.77	22.22	29.87	22.41
FeO	26.65	30.65	29.42	28.88	30.06	27.88	29.26	28.54	28.52	27.63	30.43	26.50	28.45
MnO	0.75	0.78	0.83	0.73	0.50	0.60	2.12	0.26	0.44	0.51	0.68	0.69	0.98
MgO	6.59	3.60	3.96	3.39	3.31	4.31	4.26	8.76	4.83	6.60	3.43	5.23	4.20
CaO	5.98	7.38	6.51	7.85	7.49	7.70	6.14	2.89	7.23	6.33	6.72	7.81	7.11
K_2O	—	—	—	—	—	—	—	—	—	—	—	—	—
Na_2O	—	—	—	—	—	—	—	—	—	—	—	—	—
Total	102.24	104.80	102.10	100.83	101.05	100.63	103.54	104.11	103.17	103.95	102.70	101.31	102.56

	GARNETS			OMPHACITES			WHITE MICAS				
SiO_2	39.93	39.47	39.85	57.22	57.90	48.07	47.61	51.85	51.27	50.08	50.56
TiO_2	—	—	—	0.12	—	—	0.31	0.31	0.38	0.39	0.16
Al_2O_3	22.72	21.84	22.47	9.34	11.63	13.80	27.21	29.02	29.08	27.95	26.80
FeO	27.45	27.87	27.92	9.79	7.67	11.37	2.90	2.97	1.60	3.38	3.53
MnO	0.25	1.28	0.70	—	—	—	—	—	—	—	—
MgO	10.19	5.28	6.50	6.11	5.89	15.77	2.85	2.86	3.20	3.19	2.60
CaO	2.12	5.79	5.46	10.56	9.80	0.36	0.08	—	—	—	—
K_2O	—	—	—	—	—	—	9.28	9.75	9.68	9.58	9.50
Na_2O	—	—	—	9.05	8.97	4.63	0.30	0.44	0.39	0.39	—
Total	102.67	101.53	102.91	102.20	101.87	'94.00'	90.54	97.19	95.59	94.95	93.15

	GLAUCOPHANES								
SiO_2	58.22	59.24	57.93	59.38	59.44	59.15	57.41	56.84	56.20
TiO_2	—	—	—	—	—	—	—	—	—
Al_2O_3	8.46	9.87	9.72	10.32	10.19	9.62	9.89	9.44	9.11
FeO	12.87	11.75	12.93	10.20	9.97	13.86	10.43	10.15	14.47
MnO	—	—	—	—	—	—	—	—	—
MgO	10.46	9.79	8.94	11.68	11.57	9.25	10.16	11.40	8.88
CaO	2.34	0.21	0.12	0.95	1.01	0.20	0.47	1.94	0.46
K_2O	0.77	—	—	—	—	—	—	—	—
Na_2O	5.66	7.49	7.53	7.17	7.21	7.88	7.05	6.75	6.88
Total	98.08	98.36	97.36	99.70	99.38	100.00	95.39	96.50	96.12

	EPIDOTES				
SiO_2	36.36	38.16	38.64	31.46	38.46
TiO_2	—	—	—	—	—
Al_2O_3	23.13	26.04	24.85	19.65	26.59
FeO	10.75	9.77	11.64	9.35	8.77
MnO	0.11	0.13	—	—	—
MgO	—	—	—	0.38	—
CaO	25.88	22.72	23.05	28.14	22.67
K_2O	—	—	—	—	—
Na_2O	—	—	—	—	—
Total	96.23	96.83	98.18	'88.18'	96.67

Tab. 1: Analyses of major phases in Vestgötabreen formation schists.

Tab. 1: Analysen wichtiger Gemengteile in Schiefern der Vestgötabreen-Schiefer (Garnets = Granate, Omphacites = Omphazit-Pyroxene, White Micas = Muskowite, helle Glimmer, Glaukophanes = Glaukophan-Hornblenden, Epidotes = Epidote).

Garnets

Analyses of the Vestgötabreen formation garnets have been recalculated in terms of the major end members and plotted in Fig. 4. These garnets show distinct affinities with those of groups II and III eclogitic garnets of SMULIKOWSKI (1968) or groups C and B of COLEMAN et al. (1965).

The garnets are commonly optically homogenous, although chemically all show a progressive depletion in FeO toward the rims which is parallelled by an increase in MgO + CaO contents.

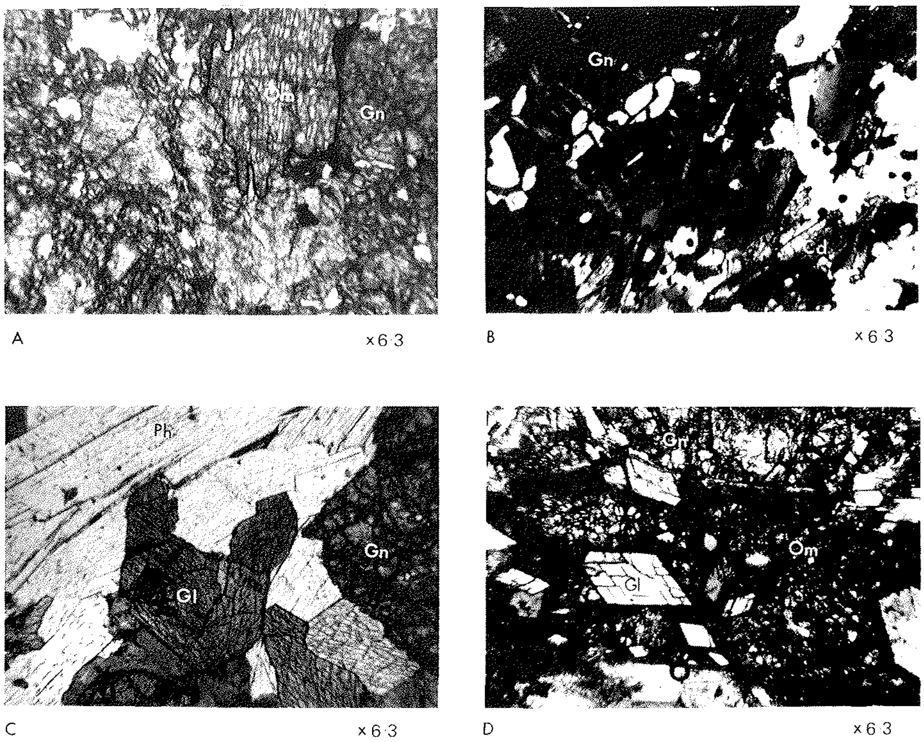

Fig. 3: Vestgötabreen formation eclogitic-glaucophane schists. A. Intergrowth of garnet and omphacite. B. Garnet with chloritoid and quartz inclusions defining 'S' trail. C. Coarse grained garnet, glaucophane and phengite, foliation weakly developed. D. Garnet, omphacite and glaucophane. Glaucophanes are zoned and are later than the omphacite which is degenerate.

Abb. 3: Eklogit-Glaukophan-Schiefer der Vestagötabreen-Formation. A. Verwachsungen von Granat und Omphazit. B. Granat mit Chloritoid und Quarzeinschlüssen bilden ein s-Flächen-Gefüge ab. C. Grobkristalliner Granat, Glaukophan und Adphengit; Kristallisationsschieferung ist schwach entwickelt. D. Granat, Omphazit und Glaukophan. Die Glaukophane sind zonar und später als der Omphazit gewachsen, der angegriffen wird.

Glaucophanes

Glaucophanes, unlike the garnets show marked optical zoning with concommitant chemical zoning. Interestingly the chemical zoning is the reverse of that exhibited by the garnets. The chemical variations (Fe and Mg) in adjacent garnet-glaucophanes are illustrated in Fig. 5. How far this reverse relationship can be interpreted as being indicative of synchronous growth or of partial re-equilibration of the garnet during glaucophane growth is uncertain.

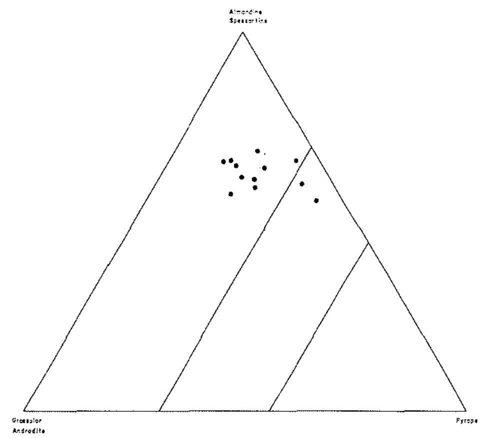

Fig. 4: Composition of garnets from the Vestgötabreen formation as end members (after COLEMAN et al., 1965; SMULIKOWSKI, 1968).

Abb. 4: Zusammensetzung der Granate der Vestgötabreen-Formation (dargestellt als Endglieder der Mischungsreihen). (Nach COLEMAN et al. 1965 und SMULIKOWSKI 1968).

White micas

All of the micas analysed contain proportions of the phengite component with Si:Al ratios in excess of 3:1 and with some Al^{VI} replacement by Fe and Mg (Fig. 6). White micas from other Western Complex rocks are not nearly so phengitic and they are nearer the ideal muscovite composition. The increased phengite content in the Vestgötabreen schists is attributed to the higher pressure conditions during metamorphism than obtained for the rest of the Western Complex. Some replacement of K^+ by Na^+ is apparent in many micas although no definite pattern emerges.

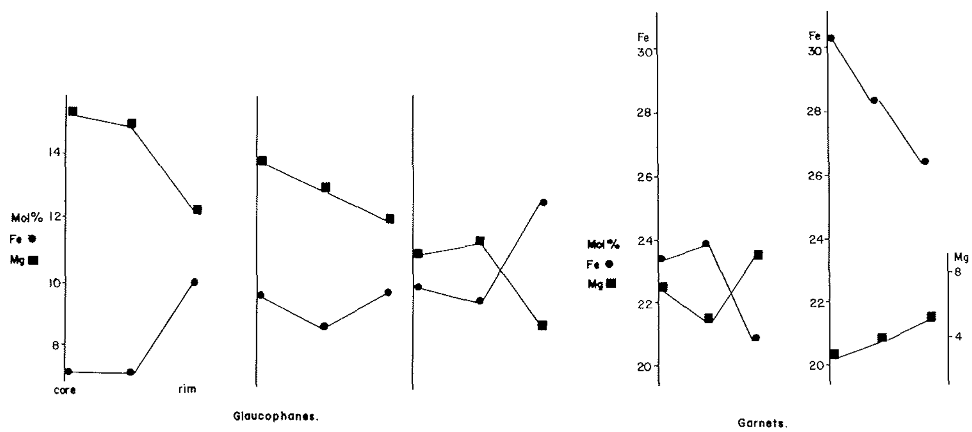

Fig. 5: Partial traverses of adjacent glaucophanes and garnets from the Vestgötabreen formation schists (Fe, Mg variations only).

Abb. 5: Geochemische Teil-Querschnitte durch benachbarte Glaukophan und Granatkristalle aus Schiefern der Vestgötabreen-Formation (nur Eisen- und Magnesium-Verhältnisse).

Epidotes

Two generations of epidotes are found in the Vestgötabreen schists. The earlier generation partially replaces the omphacite and many crystals are optically and chemically zoned with slight depletion in Al, enrichment in Fe and Ca toward the rims (table 1). This generation of epidotes are variably digested and are apparently pre-the glauco-

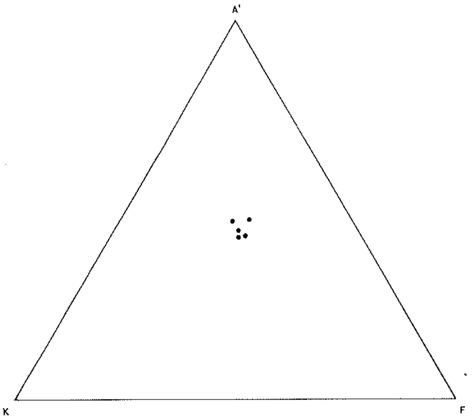

Fig. 6: A'KF plot of white micas (phengites) from the Vestgötabreen formation schists.

Abb. 6: A'KF-Diagramm von Hellglimmer (Phengit) aus Schiefern der Vestgötabreen-Formation.

phanes. The later generation of epidotes are clear, unaltered and unzoned prismatic needles of zoisite apparently coeval with the glaucophanes.

Sodic pyroxenes

In many specimens the sodic pyroxenes are considerably degenerate being replaced by glaucophane and epidote. Where analyses of the pyroxenes proved possible they were found to be variable in their jadeite component. The variations in the jadeite component however are not thought to reflect any temperature differences at the time of formation, rather they are the result of bulk rock chemistry differences.

3.4 *Metamorphism-Deformation*

Relationships between metamorphism and deformation in the Vestgötabreen formation schists do not differ significantly from those deduced for the rest of the Western and Forland Complex rocks. Many of the garnets are markedly idioblastic and are interpreted as being pre-tectonic with respect to the main D_1 deformation. However, some garnets (Fig. 3 B) contain 'S' trails of inclusions and are clearly syntectonic. Occasionally garnets may be found showing an internal region clouded with inclusions and an outer inclusion-free region suggesting some post-teconic growth. In coarser grained, more competent bands the S_1 foliation is only weakly developed. In finer grained rocks the glaucophanes and white micas define the S_1 foliation which is deflected around the garnets (Fig. 7 E). With increasing development of the foliation the garnets become progressively more chloritized (Fig. 7 F) and in some cases both garnets and glaucophanes are completely replaced (pseudomorphed, Fig. 7 G).

4. DISCUSSION

It has been suggested that the glaucophane schists of the Vestgötabreen formation are relics of a compressive plate boundary (HORSFIELD, 1972). However, the total lack of ophiolite associations and the miogeosynclinal aspect of the other pre-Carboniferous rocks of Central Western Svalbard do not support this view. The relationships between

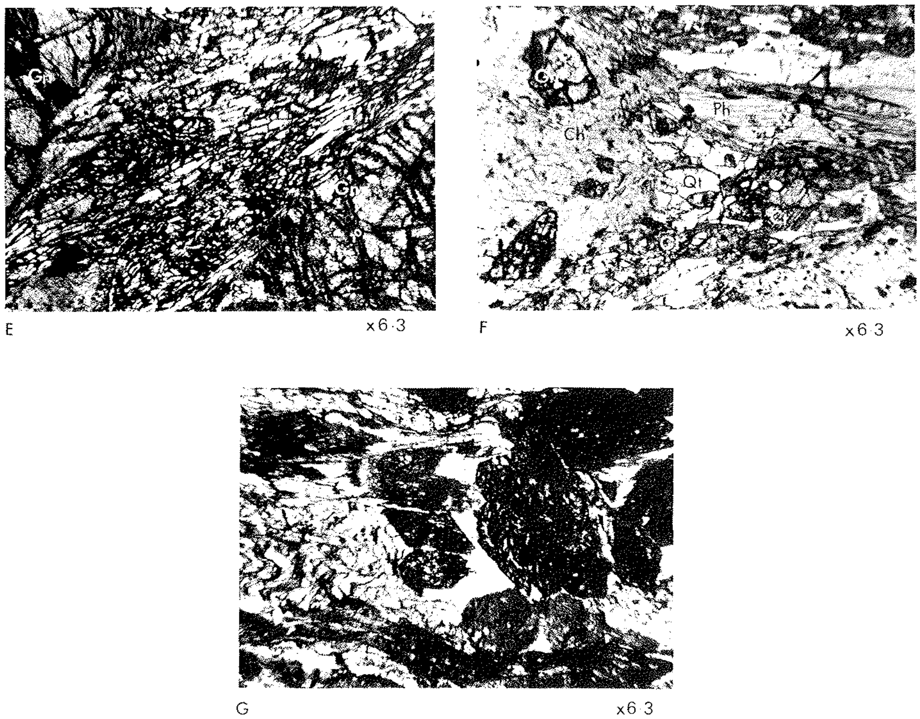

Fig. 7: Retrogression of Vestgötabreen formation eclogitic-glaucophane schists. E. Large sub-idioblastic garnets deflect glaucophane-phengite matrix which defines S_1 foliation. Garnets are slightly chloritized. F. S_1 foliation strongly developed, garnets almost completely chloritized. Phengite, glaucophane, quartz and calcite in matrix appear stable. G. S_1 foliation refolded by S_2 crenulations. Glaucophanes and garnets are completely replaced.

Abb. 7: Retrograde Metamorphose an Eklogit-Glaukophan-Schiefern der Vestgötabreen-Formation. E. Große subidioblastische Granate verbiegen eine Glaukophan-Phengit-Matrix, die eine s_1-Schieferung abbildet. Die Granate sind stark chloritisiert. F. S_1-Schieferung deutlich entwickelt. Granate meist vollständig chloritisiert. Phengit, Glaukophan, Quarz und Kalzit erscheinen stabil in der Matrix. G. S_1-Schieferung wieder gefaltet durch s_2-Runzelung. Glaukophane und Granate sind völlig verdrängt.

metamorphism and deformation, the cumulative thickness of the Holtedahl geosyncline and the low geothermal gradient allow an alternative interpretation.

If the PT field estimated for metamorphism of the Forland and Western Complexes is plotted on a grid the geothermal gradient (15° C/km) coincides, when extrapolated, at depth with the eclogite field (Fig. 8). This is convenient and at the thickness estimated pressures would have been sufficient to give the high almandine-pyrope garnet and omphacite assemblages in the Vestgötabreen formation somewhere near the base of the geosyncline. Reduction in confining pressures and the hydration necessary for the growth of glaucophane + epidote + muscovite was almost certainly facilitated by the onset of D_1 deformation and the development of the S_1 foliation.

The greenstones associated with the eclogitic glaucophane schists are also recognisably retrogressive in containing pyroxenite and serpentinite pods. Presumably the pyroxenite pods are relics of more extensive pyroxene granulites formed at the same time as the eclogites (?). Subsequent introduction of volatiles has given rise to typical greenschist facies assemblages with Act + Ch + Ep ± Ab ± Ct ± Qt or serpentine depending upon the $X_{CO_2} : X_{H_2O}$ and initial bulk rock chemistry.

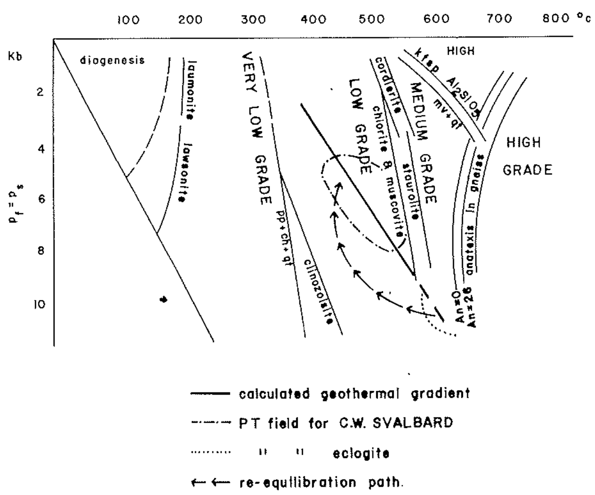

Fig. 8: The four divisions of metamorphic grade (after WINKLER, 1976) showing P/T fields of metamorphism for Central Western Svalbard and the suggested re-equilibration path for the eclogitic glaucophane schists.

Abb. 8: Die vier Metamorphosegrade (nach WINKLER 1976) mit dem Druck-Temperatur-Feld der Metamorphose in Zentral-Westspitzbergen und der vermutliche Verlauf des retrograden Gleichgewichtes für die eklogitischen Glaukophanschiefer. Durchgezogene Linie = berechneter geothermischer Gradient; Strich-Punkt-Linie = Druck-Temperatur-Feld für Zentral-Westspitzbergen (Svalbard); punktiert = Druck-Temperatur-Feld der Eklogite; Pfeile = Verlauf des retrometamorphen Gleichgewichtes.

A similar association of eclogitic glaucophane schists and greenstones (praisinites) is reported by BEARTH (1966) from the Western Alps. In Central Western Svalbard as in the Western Alps the eclogitic glaucophane schists are interpreted as being transitional between eclogites and greenstones. Simplistically, the re-equilibration with metamorphism-deformation for the eclogites through eclogitic glaucophane schists to greenstones is illustrated in Fig. 8.

5. CONCLUSIONS

It has been estimated that the Forland and Western Complexes constitute 12+km of the initial 30+km of sediments and volcanics deposited in the Holtedahl geosyncline. Metamorphism was initiated prior to and continued with the main penetrative deformation and successively older rocks record higher grades of metamorphism. Within this geosynclinal sequence metamorphic zones are broad (biotite to garnet zones over 12 km) and a geothermal gradient of $\sim$ 15° C/km is calculated. Pressures are estimated in the range of 5—8 kb. Under these high pressures, low geothermal gradient type conditions eclogites could form near the base of the geosyncline. Subsequent influx of volatiles during deformation retrograded the eclogites to eclogitic glaucophane schists and greenstones.

It is suggested therefore that it is unnecessary to invoke compressive plate boundary-subduction zone tectonics to explain the origin of the Vestgötabreen formation schists. They are simply the result of metamorphism under high pressure, low geothermal gradient conditions in a miogeosynclinal environment.

ACKNOWLEDGEMENTS

This paper is based on field and laboratory work carried out in the course of the author's Ph. D. project which was financed by N. E. R. C. Mr. W. B. Harland, Director of the Cambridge Spitsbergen Expedition is thanked for his advice and support throughout the course of this work. Dr. D. G. Helm and Dr. B. Roberts are thanked for their comments and criticisms. The author also thanks Mr. A. Quaterman for his technical

assistance in producing the plates and thin sections and Miss M. O'Donoghue for the final drafting of the figures.

References

Bearth, P. (1965): Zur Entstehung alpinotyper Eclogite. — Schweiz. Mineral. Petrog. Mitt. 45: 179—188.

Coleman, R. G., Lee, D. E., Beatty, L. B. & W. W. Brannock (1965): Eclogites and Eclogites: Their Differences and Similarities. — Geol. Soc. Am. Bull. 76: 483—508.

Harland, W. B. (1969): Contribution of Spitsbergen to the Understanding of the Tectonic Evolution of North Atlantic Region. — In: M. Kay, ed., North Atlantic Geology and Continental Drift, Am. Ass. Petrol. Geol. Mem. 12: 817—851.

Harland, W. B. & R. A. Gayer (1972): The Arctic Caledonides and Earlier Oceans. — Geol. Mag. 10 (4): 289—384.

Harland, W. B., Horsfield, W. T., Manby, G. M. & A. P. Morris (in press): Outline of the Pre-Carboniferous Stratigraphy of Western Central Spitsbergen. — Norsk. Polarinst. Skr.

Horsfield, W. T. (1970): The Geology of Oscar II Land, Spitsbergen. — Unpub. Ph. D. thesis Univ. Cambridge.

Horsfield, W. T. (1972): Glaucophane Schists of Caledonian Age from Spitsbergen. — Geol. Mag. 109 (1): 29—36.

Mather, J. D. (1970): The Biotite Isograd and The Lower Greenschist Facies. In: The Dalradian Rocks of Scotland, J. Petrology II: 253—275.

Smulikowski, K. (1968): Differentiation of Eclogites and its Possible Causes. — Lithos 1 (2): 89—101.