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Greenschist facies metabasites from the Hellefiskefjord – G. B. Schley Fjord area, eastern Peary Land, North Greenland

by

R. E. Bevins and G. Rowbotham

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Abstract

Examination of mineral phases in metabasalts and metadolerites from lava flows and intrusions exposed in the Hellefiskefjord – G. B. Schley Fjord area of North Greenland shows that the metamorphic grade in this region is generally within the greenschist facies, with the development of assemblages containing actinolite-epidote-albite-chlorite-sphene±biotite±stilpnomelane. However, certain flows contain pumpellyite, which is indicative of a slightly lower grade of metamorphism. The reason for this variation is thought to be local permeability-controlled alteration within the flows.

The lateral equivalents of these metabasites in the area south of Independence Fjord show lower grades of metamorphism, within either the prehnite-pumpellyite or the zeolite facies. This is probably related to thinner Lower Palaeozoic sequences and/or the absence of Carboniferous to Tertiary Wandel Sea Basin sediments in the area to the south.

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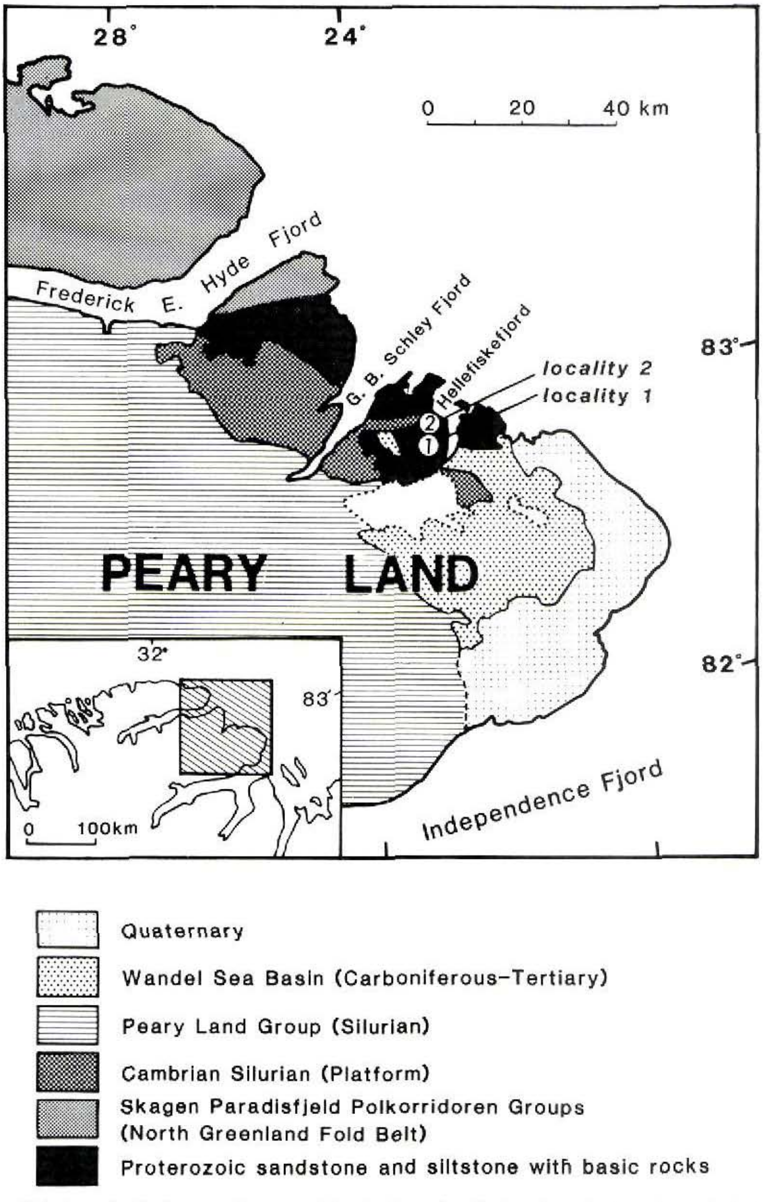

Fig. 1. Simplified geological map of eastern North Greenland, showing the location of Hellefiskefjord and G. B. Schley Fjord, along with the two main sampling sites.

INTRODUCTION

This paper describes the mineralogy, mineral assemblages and metamorphic grade of Proterozoic metabasalts and metadolerites exposed in the Hellefiskefjord – G. B. Schley Fjord area, in eastern Peary Land and compares these rocks with their correlatives to the south, in the Independence Fjord area. The samples were collected partly by the senior author and partly by H. F. Jepsen and R. J. Suthren during the 1979 GGU Peary Land geological expedition.

Regional geological setting

The Hellefiskefjord – G. B. Schley Fjord area lies in eastern Peary Land (fig. 1) to the north-east of a large tract of Silurian flysch deposits. The geological structure is complex, with major faults producing an irregular arrangement of lithological units.

The geology of the area was briefly described by Christie & Ineson (1979) who described the occurrence of 'competent white quartzites and dark volcanic rocks' and reported that they were similar to and possibly correlatives of the sandstones and basalts of the platform region to the south of Peary Land (Collinson, 1979, 1980; Jepsen & Kalsbeek, 1979; Jepsen *et al.*, 1980). The general lithological characteristics of the sandstones and the occurrence of a 40 m red siltstone unit with halite pseudomorphs strongly suggest that the Hellefiskefjord sandstones are correlatives of the Independence Fjord Group (Collinson, 1980) to the south, whilst the overlying metabasalts are correlated with the 1230 m.y. old Zig-Zag Dal Basalt Formation (Jepsen *et al.*, 1980).

METABASITES OF THE HELLEFISKEFJORD – G. B. SCHLEY FJORD AREA

Petrography

Samples utilised in this study comprise 33 rocks (16 intrusives and 17 extrusives) from the Hellefiskefjord – G. B. Schley Fjord area which were collected during the 1979 field season. The samples were all examined petrographically and electron microprobe analyses determined for constituent minerals in seven of them (4 intrusives and 3 extrusives). Sample numbers refer to the GGU collections, and further specimen details (concerning sample sites etc.) can be obtained from the senior author. Fifteen of the 17 extrusive samples described were collected from one traverse through the lava pile near Hellefiskefjord (at locality 1, fig. 1), whilst seven of the 16 intrusives were taken from a nearby 130 metre thick sill (at locality 2, fig. 1), which invades the Proterozoic sandstone sequence.

In almost all samples there are no deformational fabrics and original textures are preserved to a greater or lesser extent. Original textures are only completely destroyed where metadolerites have been sheared in the vicinity of major faults, in which case non-diagnostic albite-chlorite-quartz mineral assemblages have been produced. In metadolerites varying degrees of recrystallization can sometimes be related to position within an intrusion. For example, samples 233925 and 233926, collected from the upper part of the intrusion at locality 2 (fig. 3) near its margin, show evidence of more extensive recrystallization than those from the central parts of the body. Unfortunately, scree cover precluded collection of samples from near the base of the intrusion.

In samples collected from the lava pile at locality 1 (fig. 2) igneous and metamorphic textures vary from flow to flow. The most common original igneous texture is intergranular, with lath-shaped plagioclase feldspars associated with clinopyroxene. Where extensive recrystallization has occurred actinolite is abundant and a metamorphic texture is well developed.

In some lava flows and at the top of the intrusion at locality 2 vesicles infilled with secondary minerals occur. Thin veins also occur in both the intrusive and extrusive rocks.

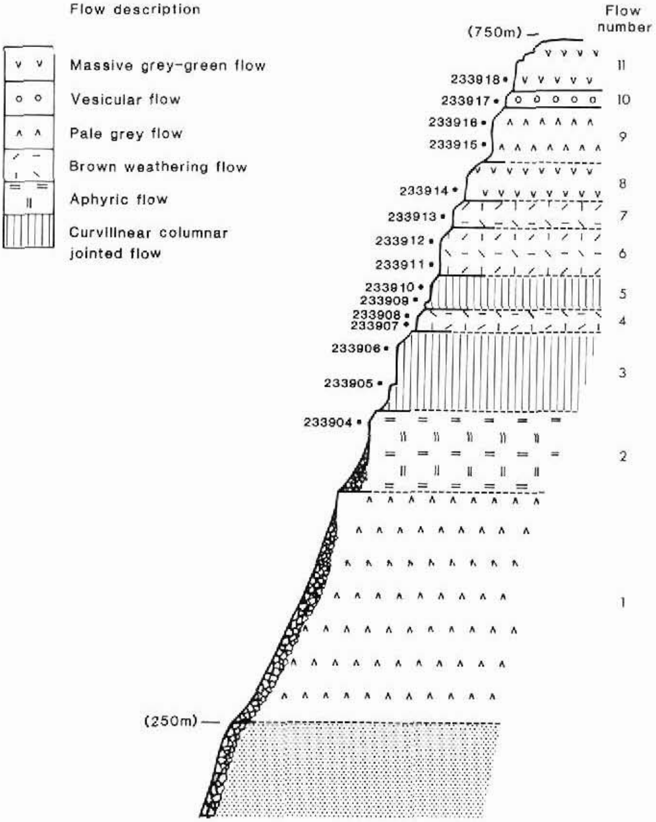

Fig. 2. Schematic section through the lava pile at locality 1, showing the locations of specimens utilised in this study and referred to in the text. Section details from H. F. Jepsen (personal communication).

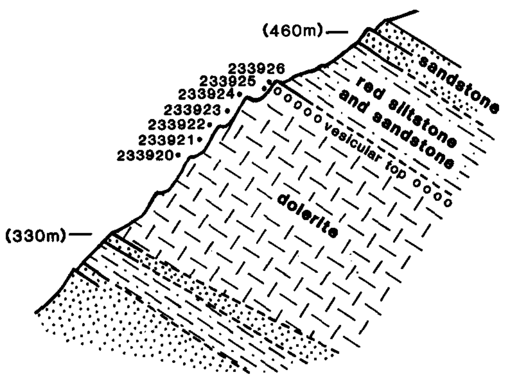

Fig. 3. Schematic section through the intrusion at locality 2, showing sampling sites of specimens utilised in this study and referred to in the text. Section details from H. F. Jepsen (personal communication).

Clinopyroxene is the only important relict igneous phase in the Hellefiskefjord metabasites although it is commonly partially or completely altered to chlorite or actinolite and a blastophitic texture is present. Further details of the clinopyroxenes within the Hellefiskefjord metabasites will be given elsewhere. Chloritic pseudomorphs in a number of samples (e.g. 233920 and 233924) suggest the possible former presence of minor orthopyroxene. No fresh orthopyroxene crystals were located, a feature in common with other relatively low-grade metamorphic terrains, as it is typical for orthopyroxene to be replaced before clinopyroxene.

Original calcium-rich feldspar is usually pseudomorphed by albite or, very rarely, K-feldspar and no relict igneous feldspar has been detected. Where little affected by alteration, albite forms tabular crystals either in blastophitic intergrowth with clinopyroxene or with intergranular clinopyroxene. Where alteration is intense, original feldspar crystals are totally overprinted by intergrowths of actinolite, epidote, chlorite or white mica. Albite crystals are usually cloudy and twinning is absent. Commonly they contain small inclusions of chlorite, epidote, white mica or (as in 233910) pumpellyite. Original magmatic crystals of Fe-Ti oxides are almost entirely altered, with the production of abundant small granular aggregates of sphene, either rimming or pseudomorphing the original igneous crystals. Primary igneous apatite also occurs in minor amounts in some samples, which probably represent more fractionated liquids, in which P_2O_5 concentrations were slightly elevated.

Of the secondary phases which are developed in the Hellefiskefjord metabasites chlorite is the most abundant. It commonly occurs in the groundmass of metabasalts (possibly after volcanic glass), in larger irregular patches in the intrusions, or in vesicles. In all these cases chlorite is associated with idioblastic iron-rich epidote. More rarely it forms inclusions in plagioclase or occurs as a replacement mineral after clinopyroxene or more rarely orthopyroxene. In rocks which have suffered extensive recrystallization chlorite is partially replaced by actinolite or biotite. Pumpellyite has been identified in only four metabasalt samples from the Hellefiskefjord region and has not been observed in any of the metadolerites. It is present as small inclusions in feldspar crystals in samples 233905, 233906, 233910 and 233911, which are from two lava flows (flows 3 and 5) both possessing a distinctive curvilinear ('banana') columnar jointing pattern (Jepsen *et al.*, 1980). The pumpellyite is strongly pleochroic (α = pale greenish-yellow; β= green; γ = colourless) and shows anomalous blue interference colours. Sphene is ubiquitous in both the metabasalts and metadolerites, where it occurs as small granular aggregates, particularly in close association with chlorite, and also replacing original igneous oxide minerals. Brown ferristilpnomelane was observed in a small number of metadolerites and analyses have been obtained from specimen 233922. It forms small, strongly pleochroic (α = straw yellow; $\beta = \gamma$ = red-brown) radiating needles overprinting chlorite and replacing feldspar. Actinolite is widely developed, occurring in both intrusive and extrusive metabasites and most typically occurs as randomly distributed needle-like crystals overprinting or replacing earlier phases, such as chlorite. It also forms both epitaxial overgrowths on clinopyroxene and discrete, well-formed crystals in rocks where the primary igneous textures have been almost entirely obliterated by recrystallization. Epidote is widely developed in the Hellefiskefjord metabasites and occurs in a number of forms, which include small, well-formed crystals in feldspar, thin irregular veins, vesicle infillings, idioblastic crystals in association with chlorite and granular aggregates in association with chlorite overprinting original igneous textures. Strongly pleochroic green to colourless biotite has been identified in metadolerites collected from the intrusion at locality 2 (fig. 1), in samples 233920, 233925, and 233926. It is interesting to note that these samples are the lowermost and uppermost samples collected, and of all the metabasites examined in this study show evidence of the most advanced stages of recrystallization (reflected in the virtual absence of relict clinopyroxenes and near total replacement of igneous textures). Biotite appears to be a late phase and overprints both

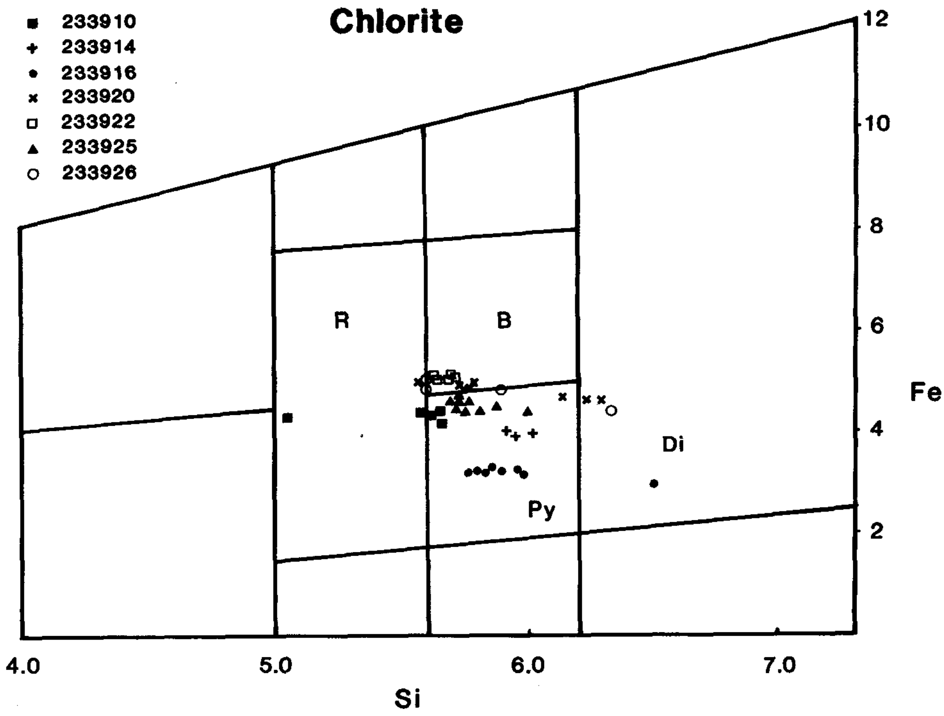

Fig. 4. Si versus Fe diagram of Hey (1954) showing the composition of Hellefiskefjord chlorites. R = ripidolite, B = brunsvigite, Py = pycnochlorite and Di = diabantite.

chlorite and actinolite, as well as forming small crystals in plagioclase and alteration rims around clinopyroxene. A reaction involving chlorite and actinolite was possibly responsible for biotite growth, perhaps by the reaction muscovite+actinolite+chlorite→biotite+epidote (although it is possible that K was derived from the original igneous feldspars). However, the general absence of stilpnomelane in these rocks may be due to the reaction muscovite (or plagioclase feldspar) + stilpnomelane+actinolite→biotite+chlorite+epidote (see Turner, 1981, p. 356). White mica occurs as small thin colourless flakes, most commonly occurring within plagioclase grains. It is most abundant in rocks which have suffered lesser degrees of alteration, and is generally absent from those rocks with higher grade assemblages, including actinolite and biotite. Calcite is relatively rare in the metabasites of the Hellefiskefjord area and suggests that μCO_2 was low during metamorphism (Zen, 1974; Coombs *et al.*, 1976).

Chemistry of the metamorphic phases

Mineral analyses were determined on a Cameca (Camebax) electron microprobe at the University of Manchester.

Chlorite

Microprobe determinations show that, following the classification of Hey (1954), the chlorites are generally pycnochlorites, with occasional brunsvigites, ripidolites and diabantites (fig. 4). These are similar to chlorites developed in the metabasites of relatively low-grade metamorphic terrains as, for example, described by Oliver & Leggett (1980) and

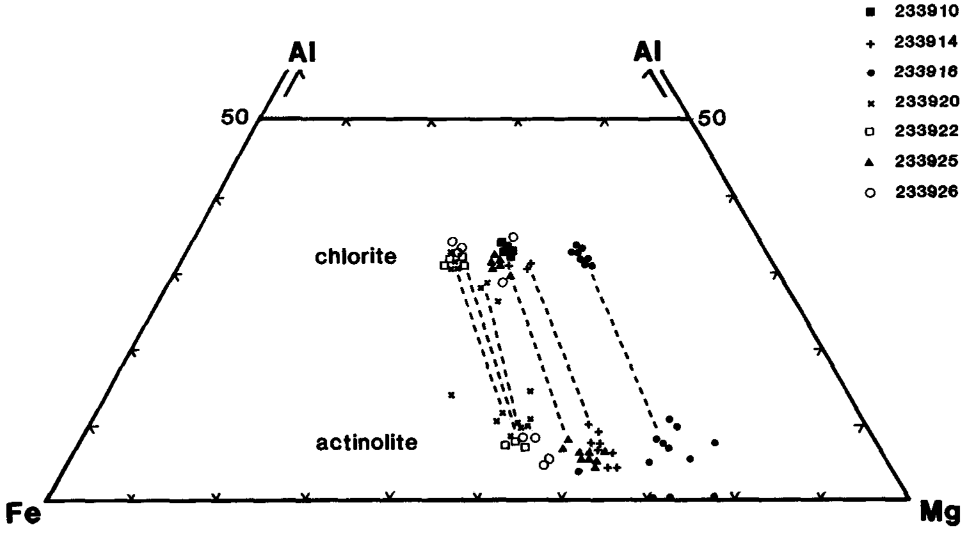

Fig. 5. Al:Fe:Mg diagram, showing the distribution of chlorites and actinolites from Hellefiskefjord metabasites. Dashed tie lines join chlorite and actinolite crystals from the same rock (but not necessarily in contact).

Bevins & Rowbotham (1983) from the paratectonic Caledonides of the British Isles. There is a sympathetic variation in Mg/Fe ratios between chlorites and actinolites developed within the same rock (fig. 5), indicating an approach towards equilibrium. The analysed chlorites contain only low concentrations of minor oxides such as TiO_2, K_2O and CaO, suggesting that they are relatively pure chlorites, with no interlayering.

Pumpellyite

The pumpellyites analysed from sample 233910 are close in composition to pumpellyites from low-grade metamorphic terrains such as Wakatipu (Zones I and II), and Vancouver Island (fig. 6). As with pumpellyites from other terrains the main chemical variation observed is the substitution $Al \rightleftharpoons Fe^{3+}$, although the range is not sufficient to reveal any $Mg \rightleftharpoons Fe^{2+}$ substitution. The maximum Fe_2O_3 recorded in pumpellyite in this rock is 13.4 per cent.

Possible reasons for the presence of pumpellyite in the lava flows with curvilinear cooling joints are discussed below.

Albite and K-feldspar

Almost pure albite compositions are present, but there is a range from An_{01} to An_{09}. In sample 233925 a potassic feldspar (possibly adularia) was identified.

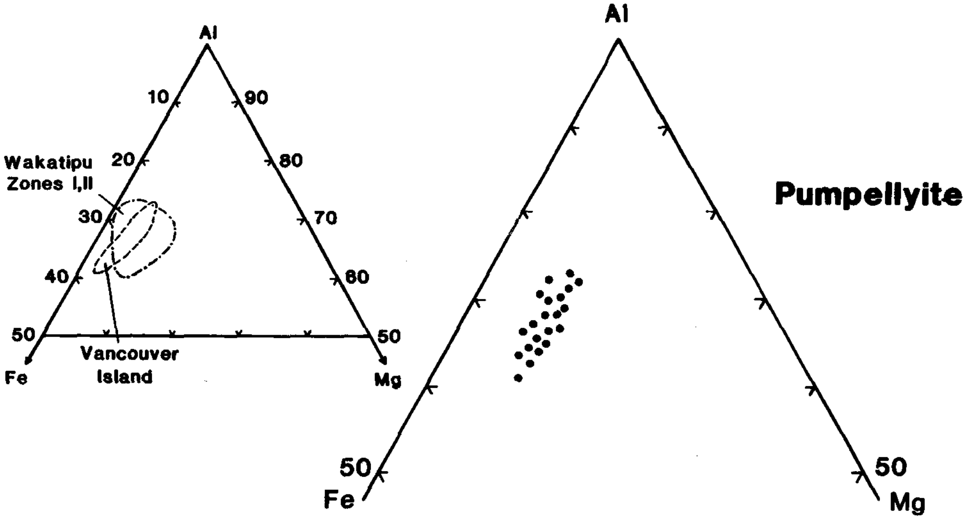

Fig. 6. Al:Fe:Mg diagram for pumpellyites, showing the distribution of Hellefiskefjord analyses from sample 233910 (black dots), with the fields of pumpellyites from Wakatipu zones I and II (Kawachi, 1975), and Vancouver Island (Surdam, 1969), for comparison.

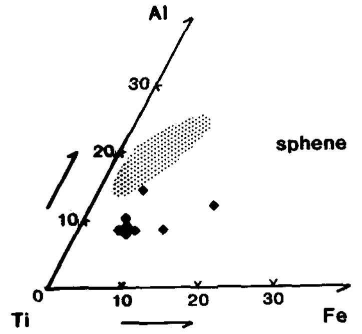

Fig. 7. Al:Ti:Fe diagram for sphenes, showing the distribution of Hellefiskefjord samples (diamond symbols) and the field of sphenes from Wales (shaded, from Bevins & Rowbotham, 1983) for comparison.

Sphene

Minor amounts of Fe and Al are present in the Hellefiskefjord sphenes, considered by Coombs *et al.* (1976) to enter the crystal structure as a result of the substitution (Al, Fe^{3+}) (OH, F) $\rightleftharpoons$ (Ti) (O). Boles & Coombs (1977) suggested that such a substitution is typical of sphenes in low-grade metamorphic rocks, and it has been recorded in other low-grade terrains, as for example Wales (Bevins & Rowbotham, 1983) and the Southern Uplands of Scotland (Oliver & Leggett, 1980). The Hellefiskefjord sphenes possess more Fe and less Al than the recently described sphenes from Wales (fig. 7).

Stilpnomelane

Stilpnomelane has been analysed in only one metabasite sample from the Hellefiskefjord area. It has been suggested that stilpnomelane may occur as an additional phase in rocks with low Mg/Fe (Zen, 1974). Such a control has recently been emphasized by Bevins & Rowbotham (1983) from Wales, and it is supported here by the fact that the analysed stilpnomelane-bearing Hellefiskefjord sample (233922) possesses a relatively low Mg/Fe

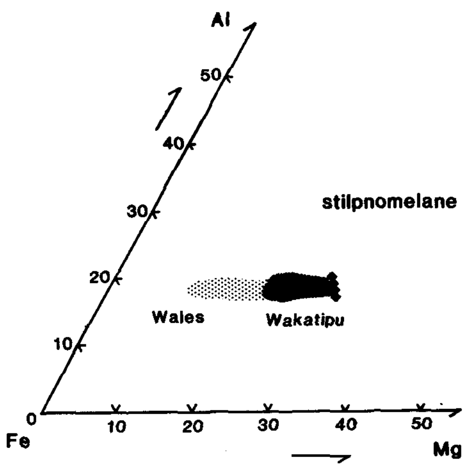

Fig. 8. Al:Fe:Mg diagram for stilpnomelane analyses. Hellefiskefjord samples (diamond symbols) compared with analyses from Wales (Bevins & Rowbotham, 1983) and Wakatipu (Kawachi, 1975).

ratio (0.41), in comparison with other metabasites from this area (H. F. Jepsen, unpublished data). However, the stilpnomelane has a higher Mg/Fe ratio compared with analyses from either Wales or Wakatipu (fig. 8).

Actinolite

In Hellefiskefjord metabasites there is a close correlation between Mg/Fe ratios in actinolites and chlorites from the same sample (fig. 5), which elsewhere has been taken to indicate an approach towards chemical equilibrium (Coombs *et al.*, 1976). Al_2O_3 concentrations are in the range 0.20 to 0.75 per cent which are noticeably lower than in actinolites from Loèche (Coombs *et al.*, 1976), Wakatipu (Kawachi, 1975) and Wales (Bevins & Rowbotham, 1983).

Epidote

The epidotes analysed in Hellefiskefjord metabasites have high Fe contents, reaching a maximum of approximately Ps_{34} in sample 233914 (see fig. 9). In those rocks with actinolite, epidotes have a compositional range Ps_{26} to Ps_{34}, whilst the only pumpellyite-bearing sample analysed (233910) has much lower Fe concentrations (in the range Ps_{12} to Ps_{24}). Normally higher Fe contents occur in epidotes of lower grade rocks (e.g. pumpellyite-bearing assemblages) and lower contents of Fe occur in higher grade assemblages. Such changes, reported first by Miyashiro & Seki (1958), are taken to reflect decreasing fo_2 with advancing grade of metamorphism. Further, Bird & Helgeson (1981) recently reported that the composition and stability of epidotes are highly sensitive to changes of oxygen fugacity and bulk composition. As no obvious differences in bulk composition exist in the samples under examination here (e.g. total Fe_2O_3 = 10.94 per cent in 233910; total Fe_2O_3 = 11.63 per cent in 233914), it appears likely that oxygen fugacity may well have been substantially lower in the pumpellyite-bearing flows (see below).

Most of the epidotes analysed show relatively uniform compositions both within individual grains and between grains within individual rocks. However, epidotes in sample 233910 show marked zoning from iron-rich cores (about Ps_{21}) to iron-poor rims (about Ps_{12}). Such zoned epidotes have been reported from other low-grade metamorphic terrains. In the paratectonic Caledonides of Wales, for example, Bevins & Rowbotham (1983) noted that zoned epidotes occur in rocks where pumpellyite is breaking down and where actinolite is developing, a feature reported earlier by Brown (1967) from Eastern Otago.

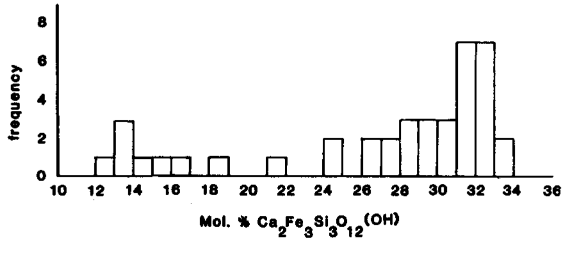

Fig. 9. Frequency diagram for mol% $Ca_2Fe_3Si_3O_{12}(OH)$ in Hellefiskefjord epidotes.

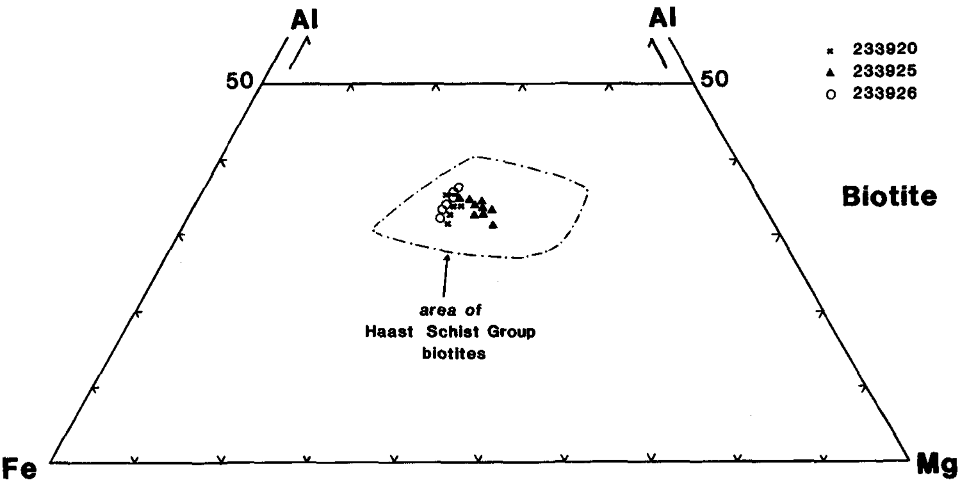

Fig. 10. Al:Fe:Mg diagram for biotites. Hellefiskefjord data compared with Haast Schist Group biotites (from Cooper, 1972).

Biotite

Biotite analyses plotted on an Al:Fe:Mg diagram (fig. 10) reveal little compositional variation and are of similar composition to biotites in metabasites from the Haast Schist Group of New Zealand, reported by Cooper (1972).

DISCUSSION OF METAMORPHIC CONDITIONS

It appears that the metabasites of the Hellefiskefjord area have suffered greenschist facies metamorphism, characterized by the diagnostic mineral assemblage actinolite-epidote-albite-chlorite-sphene±biotite±stilpnomelane. However, specimens collected from those Hellefiskefjord lava flows which show particularly well-formed curvilinear columnar joints (flows 3 and 5) possess assemblages containing pumpellyite-epidote-albite-chlorite-sphene±actinolite, characteristic of a lower grade of metamorphism (prehnite-pumpellyite facies if actinolite is not present, pumpellyite-actinolite facies if actinolite is present). This apparent anomaly warrants further discussion.

It has long been recognised that the physical character of a rock mass is capable of influencing metamorphic reactions by controlling the passage of fluids. Two examples serve to illustrate this process. Jolly & Smith (1972) recorded variable alteration patterns in individual basaltic lava flows of the Keweenawan Lavas of Northern Michigan, U.S.A. The amygdaloidal flow tops acted as channelways for migrating fluids and hence possessed abundant secondary phases diagnostic of prehnite-pumpellyite facies metamorphism whereas the more massive central and lower parts of the flows, remote from the migrating fluids, suffered little alteration. This local alteration pattern is superimposed on a more general pattern of increasing metamorphic grade with depth in the lava pile. A similar model has been proposed by Levi *et al.* (1982) to account for the distribution of secondary phases in

Cretaceous lava flows from Central Chile. Once again the lava pile as a whole shows an increase in grade from the top downwards, whilst individual flows show evidence of more advanced recrystallization from the base upwards.

Thus it might be argued that the pumpellyite-bearing Hellefiskefjord flows with well-developed curvilinear joints were not as permeable as the other (actinolite-bearing) flows of the lava pile. Reaction rates in these relatively impermeable flows would have been slower and fo_2 lower; accordingly epidotes would possess lower Fe/Al ratios. Low whole rock Fe_2O_3/FeO ratios in the flows with curvilinear joints (H. F. Jepsen, unpublished data) provides evidence for low fo_2.

Support for this model is provided by the variable intensity of recrystallization in the thick intrusion at locality 2 (fig. 3). Here samples collected from the margins of the intrusion show more advanced recrystallization compared with samples from the centre, possibly related to fluids preferentially passing along the margins of the intrusion, whilst the massive centre remains little altered. Thus local patterns of alteration were created, obscuring the overall picture of grade of metamorphic recrystallization.

Another possible control over secondary mineral assemblages is minor variations in bulk rock chemistry. From the data available however (H. F. Jepsen, personal communication), this does not appear to be the case.

The metamorphic grade in rocks of this area contrasts markedly with that of their correlatives further to the south, in the Independence Fjord area (Collinson, 1980; Jepsen *et al.*, 1980). Here no actinolite has been observed and the grade of metamorphism appears to be below that of the greenschist facies. The identification of abundant prehnite (Jepsen & Kalsbeek, 1979), abundant pumpellyite and possible laumontite (R. E. Bevins, unpublished data) strongly suggests that the grade of metamorphism in the Independence Fjord area is within either the prehnite-pumpellyite or the zeolite facies.

The reason for the contrast in metamorphic grade between the two areas is difficult to determine. Firstly, it may be related to the relative positions of these two areas with respect to the North Greenland Fold Belt (Dawes & Soper, 1973). Metamorphic grade in this belt gradually decreases southwards, from a maximum in the Kap Morris Jesup area, where amphibolite facies rocks are exposed (Dawes & Soper, 1979). This is not the likely cause, however, because the southernmost Lower Palaeozoic rocks of the fold belt are of only a 'low-grade' (N. J. Soper, personal communication). Secondly, the grade of metamorphism in the two areas may have been strongly influenced by their depths of burial. In the Hellefiskefjord region the Proterozoic rocks are overlain by a thick sequence of Lower Palaeozoic strata comprising some 2000 m of platform carbonates of Cambrian, Ordovician and lower to middle Silurian age, which are in turn overlain by a considerable thickness, possibly 'some thousands of metres' (Christie & Ineson, 1979), of Silurian flysch. These flysch deposits accumulated in a large east–west oriented trough, described by Hurst *et al.* (1983), which is thought to be related to depression of the platform area, on which the carbonates were accumulating, in advance of the Caledonian nappes. To the south, in the area to the south of Independence Fjord, rocks of equivalent age, if ever deposited, have been removed by erosion and so it is not possible to define the southern margin of this trough with any certainty. It is tempting, however, to suggest that the carbonate platform to the south of Independence Fjord did not collapse, but persisted throughout Silurian times with relatively thin accumulations of sediment. Accordingly, the Proterozoic lavas and intrusions of the Hellefiskefjord area may have been buried under a considerably greater thickness of strata (perhaps in the range 3000 to 6000 m), resulting in higher metamorphic grades. This would place a constraint on the southern margin of the trough identified by Hurst *et al.* (1983) to the area between Hellefiskefjord and the southern shore of Independence Fjord. Unfortunately, no rocks of Silurian age crop out south of Independence Fjord and thus this cannot be tested.

Whilst this model is that most attractive to the authors, there is however a further possibility. The Silurian and older rocks in the Hellefiskefjord region are unconformably overlain by Carboniferous and younger strata of the Wandel Sea Basin. The main outcrops of Wandel Sea sediments occur to the south-east of Hellefiskefjord but in all probability the basin covered the whole of eastern Peary Land prior to erosion. The Wandel Sea Basin persisted from Carboniferous through Tertiary times during which time over 3000 m of sediment accumulated (Håkansson, 1979). There is no evidence of such deposits overlying the Proterozoic and Lower Palaeozoic strata in the Independence Fjord area to the south and so it is possible that the higher metamorphic grades in the Hellefiskefjord metabasites result from burial beneath this considerable thickness of Wandel Sea sediments. Unfortunately, either because of erosion or non-deposition it is not possible to test this model either. Finally it is possible that it is the combined effects of the relatively thick Lower Palaeozoic trough sediments and the Wandel Sea Basin sequence which is responsible for the increased metamorphic grade in the Hellefiskefjord area.

CONCLUSIONS

The Proterozoic metabasic rocks of the Hellefiskefjord area have generally recrystallized within the greenschist facies, with the production of assemblages including actinolite-epidote-albite-chlorite-sphene±biotite±stilpnomelane. However, certain flows within the lava pile have assemblages diagnostic of somewhat lower grades, containing pumpellyite-epidote-albite-chlorite-sphene±actinolite. This internal variation in a normally depth-controlled metamorphic sequence is thought to be due to the presence of local permeability-controlled patterns in the flows.

The overall higher metamorphic grade of these Proterozoic rocks, compared with their equivalents to the south around Independence Fjord, is possibly a part of the general southwards decrease in grade seen in the North Greenland Fold Belt. However, original stratigraphic thickness of the Lower Palaeozoic cover sequences and/or the presence of Carboniferous – Tertiary Wandel Sea Basin sediments may have resulted in a greater depth of burial of the Proterozoic rocks in the Hellefiskefjord area compared with those in the Independence Fjord area.

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