GLAUCOPHANIC METAMORPHISM IN ANGLESEY

A thesis
presented for the degree of
Doctor of Philosophy

-by-

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SOME ARE CUT OFF

To my father and mother

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ABSTRACT

Igneous and sedimentary rocks of Precambrian age in Southern Anglesey are in a low grade of metamorphism over most of the area. The history of the basic igneous rocks has been traced from the practically unmetamorphosed state, through the greenschist stage, to low grade epidote-amphibole-schist stage. The associated semipelites have been converted to muscovite-epidote-garnet schist.

The occurrence of glaucophane and lawsonite within a restricted part of the area is of particular interest.

Not all the epidote-amphibole schists have necessarily passed through all the stages of increasing metamorphism. The very fine grained nature of these rocks suggests that some of them may have arisen direct from lavas, without having had to pass through the chlorite-schist stage But along the transitional zone between glaucophane schists and greenschists there is evidence of amphibole growing at the expense of chlorite.

The chemistry of the glaucophane-epidote schists is essentially the same as the chemistry of other basic rocks that do not contain glaucophane. The formation of glaucophane appears to depend on physical rather than chemical factors. It is suggested that glaucophane was formed in a restricted zone where the mean pressure was elevated, compared to the pressures in the rest of the area, as a result of tectonic overpressures.

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".....every one of its districts, and every one of its horizons, will present for a long time a rich field for further research."

- Edward Greenly, referring
  to Anglesey.

CHAPTER 1

INTRODUCTION

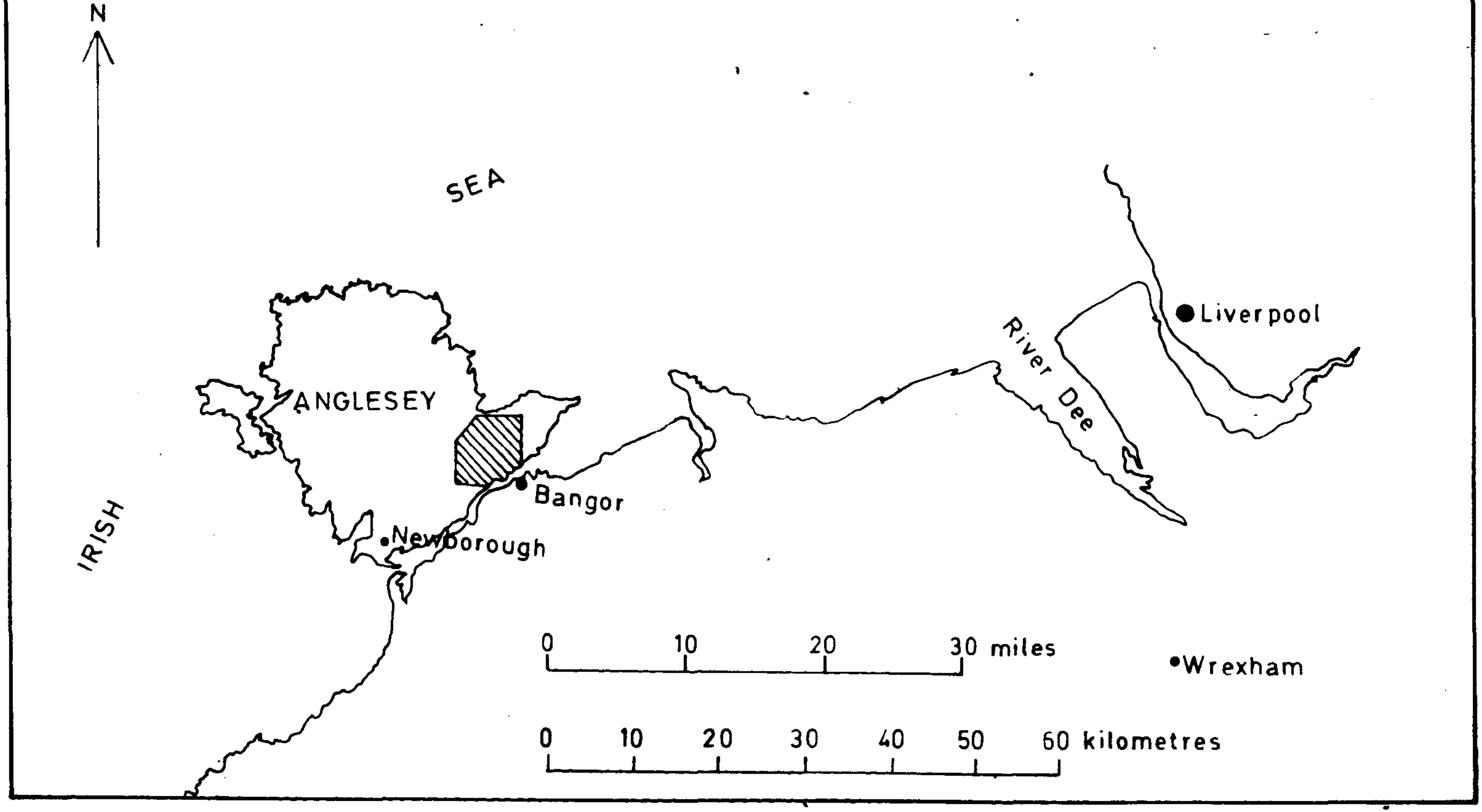
The region which forms the subject of this thesis lies in the southern part of Anglesey (Fig. 1.1). The island, which is a county in North Wales, Britain, was known as Môn to the Celts in the Middle Ages and later renamed Mona by the Romans. An area of twenty square miles was mapped on the basis of Ordnance Survey Sheet SH 57 (revised edition, 1963) on the scale of six inches to the mile. Further details were added on the 25":1 mile scale in a part of the area around Mynydd Llwydiarth (547790). This detail was later transferred on to the 6":1 mile map. The National Grid System on the Ordnance Survey sheets has been used, in addition to place-names where convenient, for the purpose of referring to locations on the geological map (Plate 1).

The aim of the investigation has been the study of the Precambrian rocks, particularly their metamorphic and structural features, with particular reference to the occurrence and origin of glaucophane in the central part of the area.

1. GENERAL GEOLOGICAL SETTING:

The island of Anglesey is composed for a large part of Precambrian rocks. Younger deposits occupy one large area and several smaller outliers and narrow tracts (Fig. 1. 2). The Precambrian Monian System exposed today consists mainly of metamorphosed psammites, pelites and volcanic material, the latter both pyroclastic and effusive, in mixtures of varying proportions,

FIG. 1.1



Anglesey and environment. The area which was studied for this work is shown hatched.

often together with thick limestones, jaspers and locally developed plutonic intrusives that scan a compositional range from granites to dunite-serpentinites. These rocks are distributed on either side of the north-easterly trending centrally situated Coedana granite (Fig. 1. 2).

The above assemblage represents a period within late Precambrian times. It has many features in common with other geosynclinal sequences. These features include the excellent graded greywackes of the South Stack Series on Holy Island, and basic pillow lavas of Newborough, Anglesey (424657) and Porth Dinllaen, south-west Caernarvonshire (276415). The series of events beginning with the accumulation of sediments and submarine lava flows, followed by intense deformation, metamorphism and granitization of the rocks and the injection of granitic magma, according to Shackleton (1953), constitutes a typical orogenic cycle.

2. BRIEF DETAILS OF THE MONIAN SYSTEM IN THE CONTEXT OF THE HISTORY OF PREVIOUS INVESTIGATIONS:

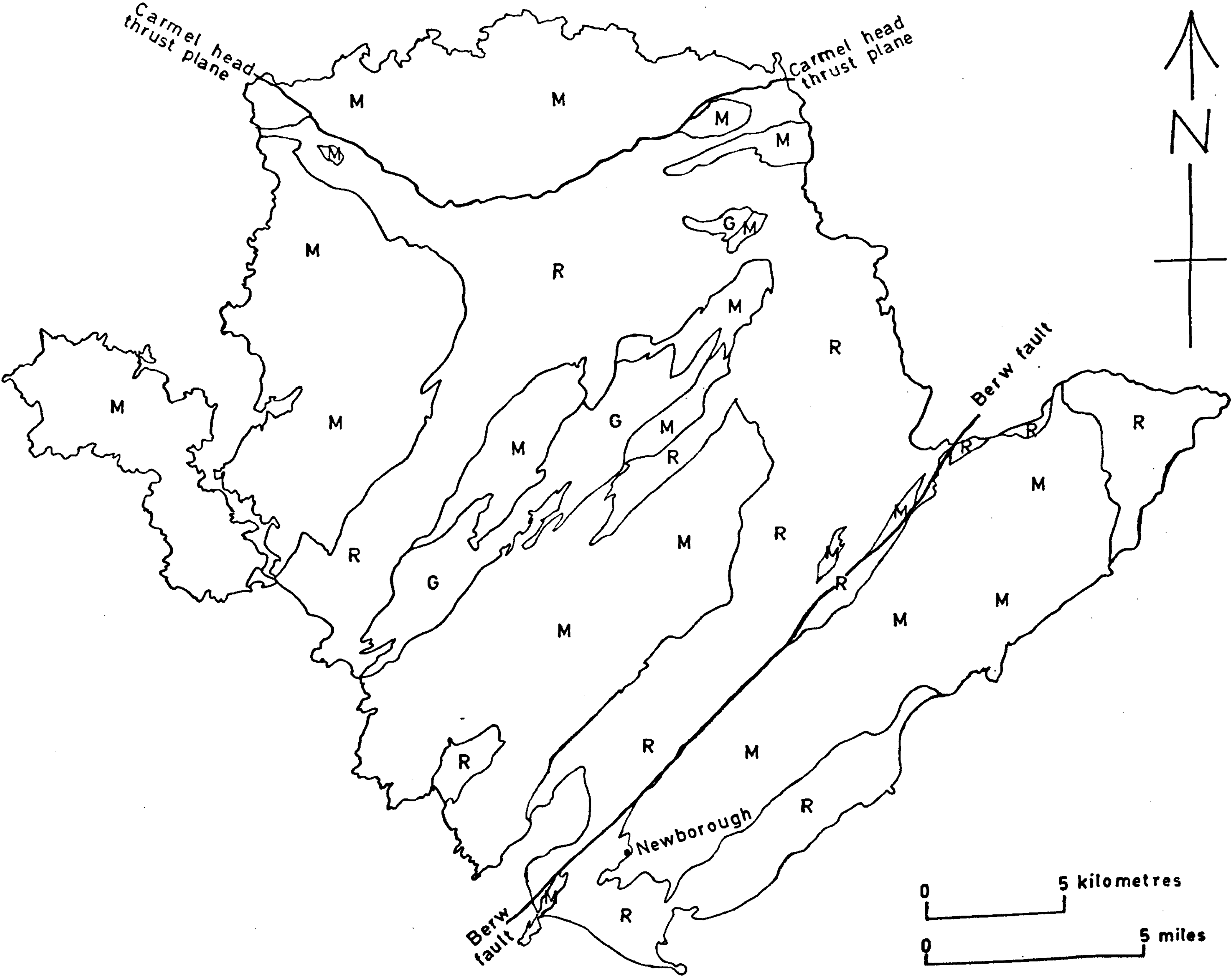
The first recorded interest in the geology of Anglesey probably came from Speed (1610). He referred to "those kind of stones which are called Molares, as of all other fittest to make Mill-stones or Grind-stones" and noted the presence of "an earth of aluminous quality."

During the interval between 1610, the year of publication of Speed's map, and 1822, about a dozen papers were written about

Fig. 1.2. Simplified map showing distribution of rocks in Anglesey.

R.....Cambrian and younger deposits.
G.....Coedana Granite
M.....rocks of Precambrian age, excluding the Coedana Granite.

FIG. 1.2


Carmel head thrust plane
Carmel head thrust plane
M
M
M
M
M
G
M
M
R
M
R
M
Berw fault
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Newborough
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0
5 kilometres
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5 miles
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the island. They dealt chiefly with the economic deposits and the excursion potentialities of Anglesey.

Henslow (1822) became the first to speculate on the age of rocks in Anglesey when he called them, with the exception of those in the central region and the granites, the "oldest stratified rocks."

In 1881, the Geological Survey published a memoir on the Geology of North Wales by Ramsay, in which he considered the metamorphosed rocks of Anglesey to be of Cambrian age, although he recognised the broad distinctions between the metamorphic nature of those rocks and the Cambrian of the mainland.

Hicks (1878), who was of the opinion that the rocks north of a line from Carmel Head on the western coast, through Llanfflewin to Porth y Corwgl on the eastern coast, were Precambrian in age, probably started that period of detailed research which culminated in Sir Archibald Geikie's presidential address to the Geological Society in 1891, which in turn reflected a general acceptance of the idea of Precambrian rocks being present in Anglesey. Sir Archibald was particularly struck by the remarkable resemblance of the gneisses in Central Anglesey to those of the north-west of Sutherland and Ross, the latter being acknowledged Precambrian in age. Earlier, in 1888, Blake had announced the discovery of glaucophane from Anglesey. It was again Blake who coined the term "Monian System" and allocated it to a period within the Precambrian times.

Detailed surveys on the scale of six inches to the mile followed, the chief participants being Greenly, Callaway and Matley. It was up to Matley (1899) to provide evidence of a more concrete nature than that of "similarity to Precambrian rocks found in other parts of the British Isles" in an attempt to demonstrate the age of the Anglesey rocks. He was able to show, on the basis of palaentological and stratigraphical evidence, that the "Green Series" had been subject to metamorphism, deformation and erosion before the deposition of the Ordovician (Glenkiln) rocks.

Greenly (1919, p.243) produced systematic evidence of the relation between the rocks of the Monian System and the younger rocks. The evidence includes superposition of various members of the System at several localities by the Didymograptus extensus zone (base of the Ordovician) and the fact that the conglomerate bed at the base of the extensus zones is built of pebbles derived from the Monian System. These pebbles show evidence of folding and metamorphism of the members of the System prior to the deposition of the Ordovician.

He further pointed out the difference in the character of the Monian System and that of the Cambrian rocks exposed on the Mainland across the Menai Strait. The first comprises a remarkable variety of rock types, the other comparatively uniform mechanical sediments; the thick purple slates of the mainland are absent on the island, whereas the persistent assemblage of thick limestones, quartzites, scarlet jaspers and spilitic lavas is confined to the latter. This difference, Greenly suggested, was far in excess of what may reasonably be expected to exist between contemporaneous deposits, in view of their proximity.

The rocks on the island are much more intensely deformed and metamorphosed than the younger rocks of the mainland. The Bangor Volcanic Series at Baron Hill and the Careg-Onen beds, which are outliers of possible Cambrian age, rest unconformably on the Monian System and are unaffected by the deformation and metamorphism to which the Monian rocks have been subjected.

Further evidence is available in the form of pebbles which occur in the conglomerates and pebbly grits near the base of the Cambrian on the mainland. These have, according to Greenly (1919, p.246), been derived from the Penmynydd zone of rocks, the Coedana Granite, the South Stack Series, the New Harbour beds and the Gwna Group, all of them members of the Monian System. Evidence of a similar nature is also provided by the Trefdraeth Conglomerate (407705).

The stratigraphy of the Monian System, as tabulated by Greenly (1919), is given below:

8. The plutonic intrusions.....Granite, diorite, gabbro, serpentinite, etc.

THE (7. Holyhead Quartzite..........Quartzite.
(
(6. South Stack Series..........Grits and mica schists.

BEDDED SUCCESSION	5.	New Harbour Group	Grit, mica schist, jasper, spilitic lava
	4.	Skerries Group	Conglomerate, grit and tuff
	3.	Gwna Group	Grit, phyllite, quartzite, limestone, jasper, graphitic phyllite, spilitic lava, albite diabase
	2.	Fydlyn Group	Felsitic lavas and tuffs.
	1.	The Gneisses	Basic and acid gneisses.

In addition to the above groups, Greenly postulated the Penmynydd Zone of Metamorphism, correlatable with grpups 2 and 3. This zone has no strict stratigraphic significance. It is merely the zone within which the metamorphosed equivalents of the Gwna Group and the Fydlyn Group occur.

Greenly believed The Gneisses to be an older generation of rocks than The Bedded Succession, the two separated by a complete cycle of deformation, metamorphism and erosion.

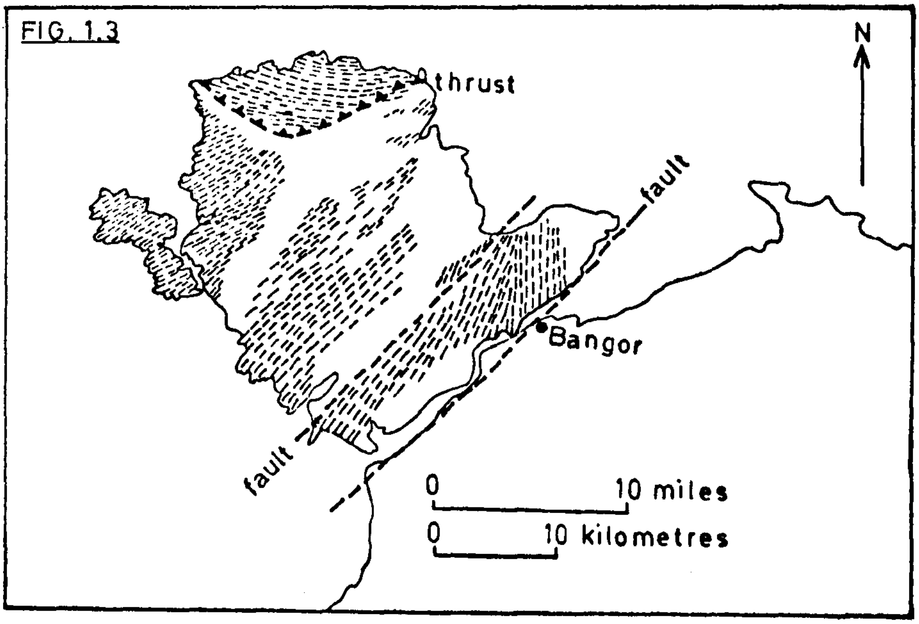
The above tabulation is the reverse of the observed superposition. Greenly favoured this interpretation on the basis of what he considered to be the probable overall structural picture of the Monian System, a picture of recumbent folding. Greenly's interpretation was largely based upon the identification of fragments of older rocks in younger. More recently, Shackleton (1954) has questioned the reliability of such a method and has shown, from observations of sedimentary structures, that Greenly's sequence is incorrect.

Moreover, Greenly visualised the movement of the upper layers, or vergence, in his postulated recumbent folds to be in a north-westerly direction. It is to be noted, in this connection, that the general sense of movement which resulted in the observed structures over the island was in a south-easterly direction. This observation, in conjunction with other detailed evidence from Northern Anglesey of a more sophisticated nature than that produced by Greenly to support his idea of a structural inversion over the island as a whole, leads to the conclusion that Greenly's hypothesis is untenable (Shackleton, 1954). The overall fold-structures suggest overturning to south-east with steep, rather than sub-horizontal, axial planes.

That being so, the sequence within the Monian System becomes the opposite of that proposed by Greenly. Further, the relation of The Gneisses to The Bedded Succession becomes problematic.

The structural grain over the island as a whole is north-easterly (Fig. 1. 3). The strike of the rocks, the foliation and fold axes, etc., apart from local deviations, have a north-easterly trend. The oldest members of the System, in the north-west, display a distinct style of deformation which may be interpreted as a result of plastic yield (Shackleton, 1953). But higher up in the sequence, particularly in the Gwna Group, the structures are less smooth and the formation of a mélange is widespread. The resulting structures are dominated by a blocky distribution of the various units of the Gwna Group. This jumble of rocks has been compared with other mélanges of the world,

FIG. 1.3



Generalised structural grain of the Precambrian rocks in Anglesey (After Shackleton, 1953).

particularly the Ankara Mélange which has been supposed to have been formed as a result of rocks being bulldozed by the Anatolien Nappe during the Upper Cretaceous times (Bailey & McCallien, 1953). But one peculiar feature of the Gwna Mélange, irreconcilable with a picture of "differential rolling" under the high pressure of a moving mass, is the sharp angularity of the blocks on all scales. The Gwna Mélange may be a submarine slide breccia in a tectonized condition and therefore possessing an added degree of disruption or it may be a completely tectonic breccia as Greenly believed.

The overall metamorphic picture of the Monian rocks is not yet sharply defined. One important aspect of the metamorphism of the Monian System is the production of glaucophane in association with epidote, lawsonite and calcite in the upper part of the System. As noted earlier, a large part of the Monian System exposed in Anglesey has attained only a low grade of metamorphism, the greenschist grade being the most widely developed. The two outstanding exceptions are the locally developed sillimanite-bearing metasediments and the gneissose rocks. The latter have been classed separately from the rest of the System by Greenly who came to the conclusion that they must have been the "ancient floor" on which The Bedded Succession was laid down. Since Greenly's postulated sequence was wrong, it seems more likely that in Anglesey one is dealing with a drastic telescoping of the conventional Barrovian metamorphic zones in places.

Shackleton (1953) has suggested a definite correlation between the metamorphosed sediments, which recrystallized at the highest temperatures and which now contain sillimanite, and the associated migmatites ("The Gneisses" of Greenly). These migmatites, he goes on to say, were formed mainly from the Monian sediments by granitization or permeation during the later stages of the orogenic movements. This aspect of metamorphism has to undergo detailed study before one can be certain of the position of the glaucophane schists within the general metamorphic configuration.

3. THE MONIAN SYSTEM AROUND LLANSADWRN: GENERAL SUMMARY.

That part of the Monian System which is dealt with in this thesis lies within the Gwna Group, and much of it can be included within the Penmynydd Zone of Metamorphism. These rocks are almost the youngest members of the System.

The overall stratigraphy in this area comprises a heterogenous assemblage of poorly sorted sedimentary and pyroclastic deposits. The present assemblage is mainly a mixture of semipelitic and basic schists. Limestones, sometimes in fairly thick bands and lenses, and jaspers are especially prominent towards the top of the succession. Thin quartzite bands are developed sporadically. Mineralogically, the dominant rock types may be named chlorite-albite-quartz-(epidote) schist, muscovite-quartz-albite-epidote schist and amphibole-epidote schist. The total thickness of these deposits is probably in the order of 20,000 feet.

There is a considerable amount of interfingering which, along with secondary discontinuous character imparted due to deformation, prevents precise correlation of horizons across outcrops. The characteristics of the broader zones, i.e., the basic to pelitic ratio, however, are preserved on a large scale. Eight such zones have been recognized and are given below:

8.	Upper Greenschist Group ("Gwna Greenschist")	Little metamorphosed tuffs, tuffaceous sediments, basaltic and spilitic lavas (including pillow lavas), limestone, jasper and chert.
7.	Lower Greenschist Group ("Gwna Greenschist")	Mainly tuffaceous, sometimes calcareous, sediments with thin quartzites and subordinate basic material, probably extrusive.
6.	Transition Group	Approximately equal proportions of sedimentary/tuffaceous material and basic extrusives.
5.	Upper Basic Schist Group	Dominantly basic rocks, probably extrusive, together with some tuffaceous horizons and subordinate sediment including chert.
4.	Upper Semipelitic Group ("Penmynydd Mica Schist")	Siliceous sediments, including quartzites, with thin tuffaceous horizons towards the top.
3.	Lower Basic Schist Group	Mainly basic tuffaceous material with probable subordinate basic extrusives.
2.	Lower Semipelitic Group ("Penmynydd Mica Schist")	Siliceous sediments with isolated lenticular bodies and intercalated horizons of basic (tuffaceous?) material.
1.	Amphibolite Group	Basic rocks of igneous(?) origin.

The lowest Group as given in the foregoing succession occurs in the western part of the area, and the highest in the east. No way-up structures were seen in the field to justify the above sequence being called stratigraphic. Tectonic disruption is widespread amongst these rocks and repetition of horizons are difficult to detect, particularly within the thick Lower Greenschist Group. Although no rigorous proof is available, there are indications (p. 25) that the above eight units are all unique and in stratigraphic order, and that the top of the succession is to the east.

The naming of these groups has been complicated by the fact that the metamorphic boundaries in the area are almost parallel to the stratigraphic boundaries, and because each group is characterized not by a pure end-member in terms of rock-types, but by a peculiar assemblage of discontinuous, intercalated basic and semipelitic bands. The boundaries between the groups are normally of a transitional nature, although faults or slides sometimes bring groups of sharply contrasting character directly against each other.

The sedimentary deposits are medium to coarse grained, irregularly bedded in discontinuous units ranging in thickness from less than an inch to a few feet. They lack any features such as graded bedding, current bedding or rhythmic banding. Fossils have not been found in them. Clastic grains of quartz, albite and occasional composite rock fragments are cemented together by a fine micaceous, chloritic or carbonate matrix.

Most of the volcanic rocks probably originated as lava flows and tuffs, and in some cases the original pillow-structures are still preserved. The pillow structure is best seen near to the Menai Strait, between Gazelle Hotel and Grey House (582743), but nowhere in the area under consideration does the perfection of preservation rival that at Newborough. Some of the basic metamorphosed rocks might conceivably have been intrusive. All the basic rocks tend to have an abnormally high water content. The plagioclase is sodic; the original pyroxene is rarely preserved and its identification is uncertain. Even the least altered lavas have in most cases been extensively chloritized. Amphiboles and epidote developed at a later stage in their metamorphism.

About thirty analyses to determine bulk rock chemistry were obtained from samples belonging to various rock types and at different stages of metamorphism. The results suggest that most of the rocks in the area can be included in one of the following three categories: (a) basic volcanics; (b) semipelites and (c) an admixture of basic volcanic and semipelitic material.

Slides, sub-parallel or parallel to the original stratification, are widespread and are especially noticeable, in individual outcrops, in the area east of the Transition Group. To the west, folds are more conspicuous and at least two episodes of fold-movements can be deciphered over most of this part of the area. The general trend of all structures, the 'grain' of the rocks, is north to north-easterly, although locally this trend may swing through more than a right-angle. Such swings, which are due to the second episode of folding, are most strongly developed on a large scale in those rocks which also bear glaucophane.

Faults and slides are not always readily recognizable on account of the tendency to monotonous recurrence of rock-types in the stratigraphy and the general lack of marker-beds.

It is postulated that the area under discussion forms part of a major overturned antiform generated during the first episode of folding (Fig. 3. 8). The plunge of the axis is shallow and towards north-north-east and the vergence is south-easterly. Other interpretations of the structure in this area are possible, and more evidence, including some from outside the area, is needed to discriminate between the possibilities.

The practically unmetamorphosed sedimentary-volcanic assemblage in the east is followed successively to the west by rocks which exhibit minerals belonging to the greenschist facies and to the low-grade amphibolite facies. The most common minerals developed are chlorite, muscovite, a blue-green amphibole and epidote. This metamorphism was accompanied by the earliest folding and major sliding.

A second episode of metamorphism is detectable in the central tract where the crystallization of glaucophane, lawsonite and epidote has been overprinted on the products of the earlier metamorphism. Aragonite and pumpellyite have been searched for, but not found. This second episode of metamorphism was accompanied by modification and tightening of the earlier structures and the production of those folds here designated as second.

The higest grade of rocks in this sequence occur at the western margin of the area, where they are faulted against the Ordovician along the Berw Fault Zone which trends roughly parallel to the regional strike of the Precambrian rocks.

Considerations of the rock chemistry, mineral assemblages and their relations indicate that the second episode of metamorphism, which resulted in the production of glaucophane and associated minerals, took place under conditions of high confining pressure relative to temperature.

It is tentatively suggested that the second episode of metamorphism took place at relatively shallow depths where the load pressure by itself was not sufficient to account for the high mean pressures achieved; and that tectonic movements played an important part in the production of such high excess pressures.

CHAPTER II

PETROLOGY

1. INTRODUCTION:

Almost all the rocks in this area are admixtures, in varying proportions, of basic or spilitic extrusives, pyroclastic rocks and sedimentary deposits, as well as metamorphic derivatives thereof. For the purpose of description, they have been divided into three classes. These are: (a) rocks of igneous origin, basic to spilitic in composition; (b) tuffaceous sediments, tuffs and their metamorphosed equivalents; and (c) essentially sedimentary rocks and their derivatives.

Each of the above classes has been described, with reference to metamorphic changes induced in rocks belonging to the class, as the rocks are followed from east to west, which is the direction of increasing metamorphic grade and increasing structural depth. Within each class, there exist several rock-types; each rock-type within the same class is distinguished by a typical mineral assemblage and by the particular level of metamorphism reached by the rock-type.

The basic assemblages, originally lavas and pyroclastic rocks, reach the amphibole-epidote stage of metamorphism as they are followed westwards, while the chief metamorphic minerals which develop in the semipelitic assemblages of sedimentary origin are chlorite, muscovite, epidote and a little garnet. A second generation of metamorphic minerals, the most important among them being glaucophane, has been superimposed on the first. Glaucophane has been developed in rocks of wide range of composition within a restricted part of the area.

Bulk rock analyses have been obtained for about thirty specimens. The results support the conclusions, based on textural and mineralogical evidence, regarding the origin of the rocks.

Other rock types, not included in the above classification, and not of widespread occurrence, have been treated in less detail.

2. FIELD RELATIONS:

Contacts between various rock types are seldom satisfactorily observed. Shearing and faulting are widespread, and boundaries between rocks of differing composition tend to become shear zones. In general, igneous and sedimentary components, lenticular in form, are closely intercalated. The boundaries, on a small scale, are fairly sharp, and there is little evidence of reaction between sediments and extrusives.

Faulting is widespread, and is a hindrance in the attempt to follow continuously the metamorphic changes induced in any rock. Exposures tend to be small isolated ones. While it would have been ideal to be able to demonstrate the postulated metamorphic changes in a continuous exposure, this ideal has not been achieved. But the author belives that tectonic effects such as block-movements on a large scale or of large magnitude can be reasonably ignored within the present area. This belief is due to the comparative regularity of several structural features over the area as a whole. The only exception is the "Tarn Wedge", referred

Plate 2. Inset from Plate 1; enlarged X2.

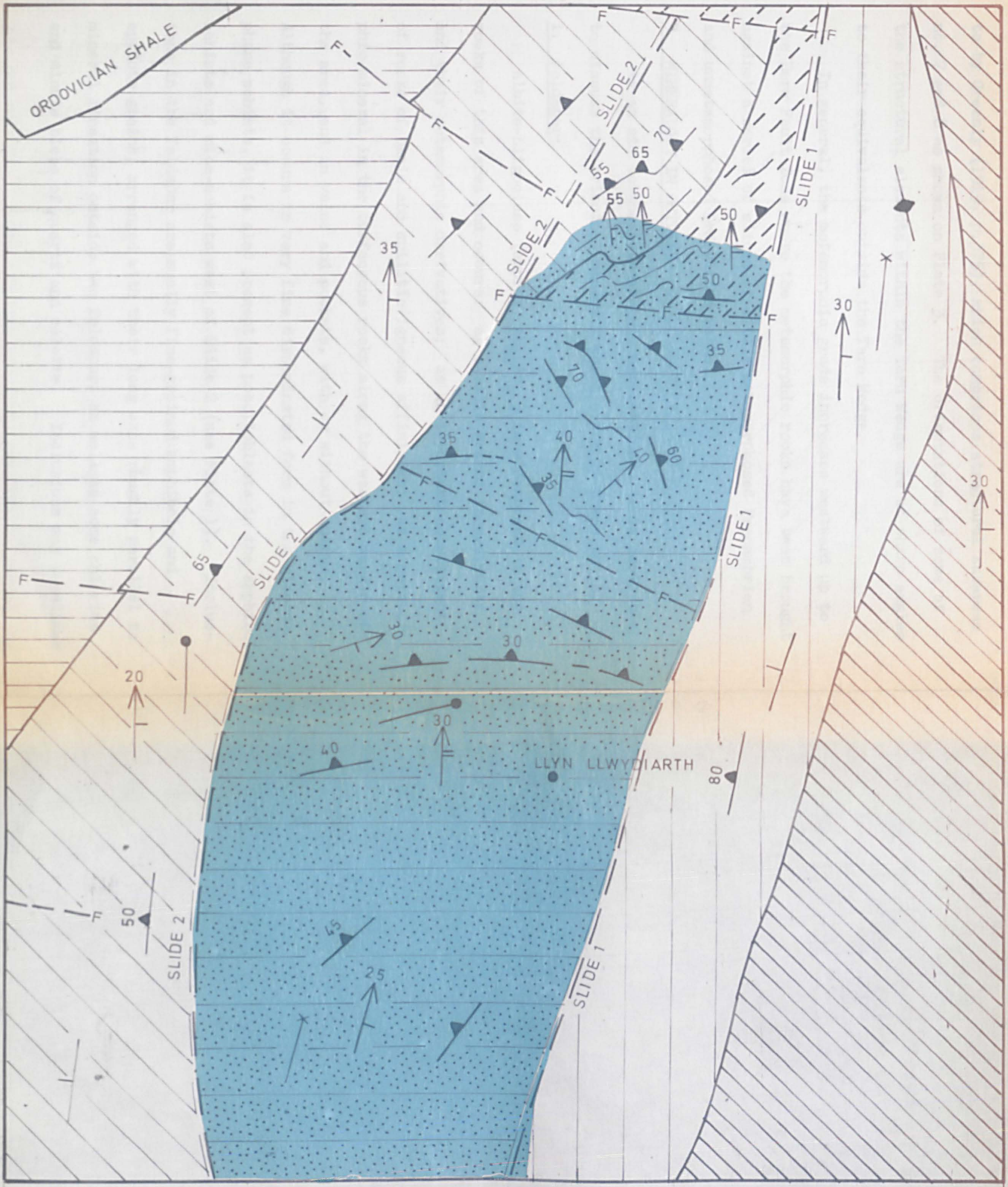


PLATE 2.

Inset from Plate 1: Enlarged X2.

For explanation of symbols, see Plate 1.

to by Greenly (1919, p.375), which comprises structural subareas no. 7 and 8 as shown on Plate 3. The orientations of some of the structural elements within the Tarn Wedge are at sharp angles to their equivalents outside the Tarn Wedge.

In general, the metamorphic grade increases westward up to the Berw Fault Zone where the metamorphic rocks have been brought against a series of slices of little metamorphosed Precambrian and unmetamorphosed Ordovician rocks.

3. MINERALOGY IN OUTLINE:

As an aid to the petrographic descriptions, it is desirable to discuss the principal minerals which occur in these rocks.

i. Feldspar:

Albite-oligoclase (approx. $Ab_{80}An_{20}$) is widespread in the rocks of this area and occurs: as clastic grains in sediments and their metamorphic derivatives; as an important constituent of rocks of basic and spilitic igneous affinities; as a metamorphic mineral in the tuffaceous rocks along the western margin of the area, and in veins and pockets, with or without quartz. Although it occurs in very fine disseminated form in the glaucophane schists, it is also present as poeciloblasts in the amphibole-schists and mica-schists west of Slide 2 (see Plate 1). Inclusions in the feldspar are usually fine-grained amphibole and epidote grains, arranged with their long axes roughly parallel to mineral lineation outside the feldspar, as well as some chlorite and minute blebs of quartz and calcite. Inclusions may sometimes be parallel to a well-developed cleavage, usually (010), in the feldspar grains.

ii. Epidote:

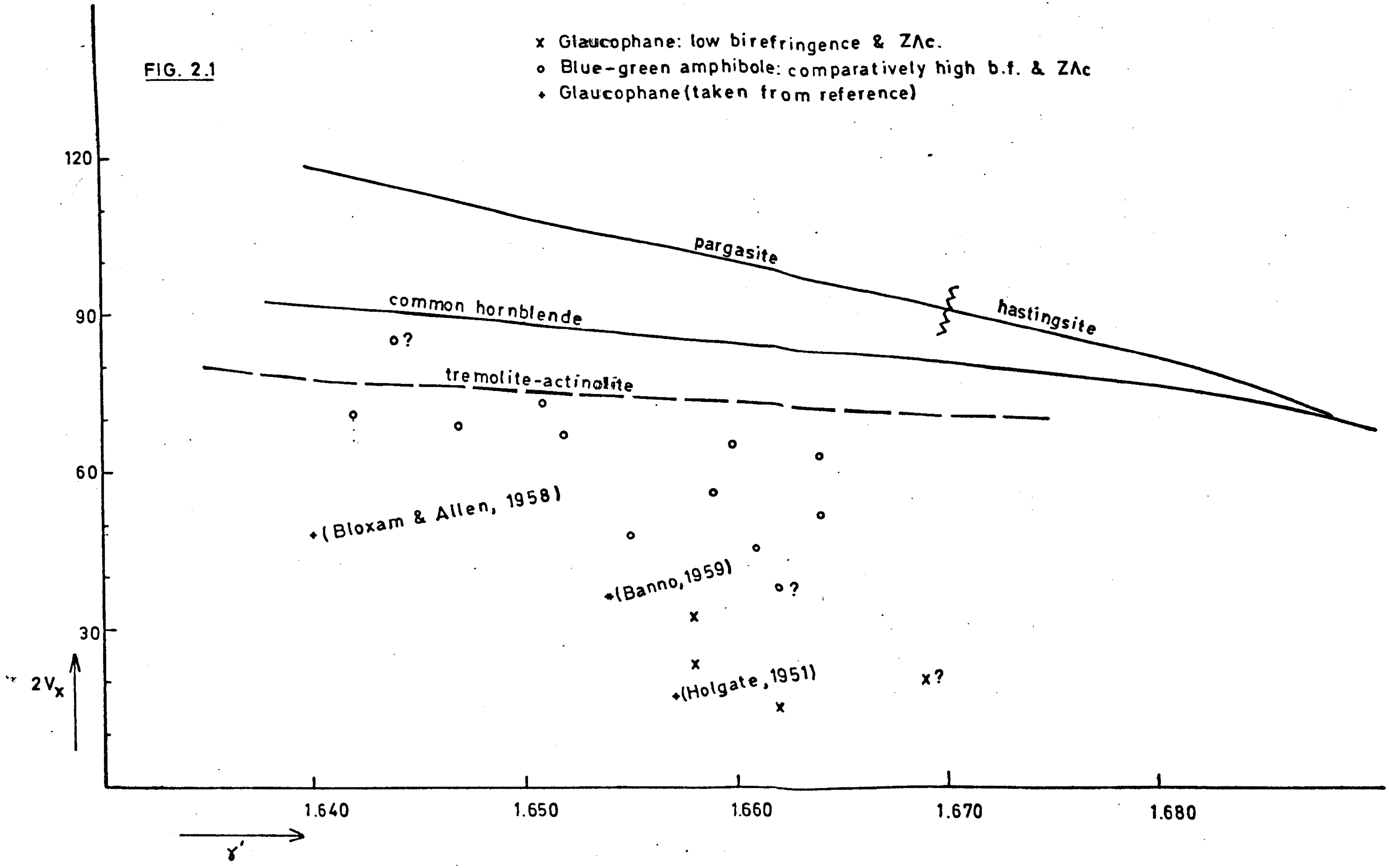
After quartz, epidote is the most widespread mineral in this area. It is present in almost all the rocks, and is an essential constituent of the glaucophane-schists. The grains seldom exceed 0.5 mm. in size, and generally show evidence of strain and fracturing.

Epidotes range from very fine-grained equidimensional xenomorphic grains to coarse, hypidiomorphic grains. The larger grains are partly replaced by chlorite, especially at the extremities of the long axes of the grains. The epidote exhibits a wide range of optical properties. Most of the grains in the basic schists have $2V_x = 75^\circ$-85°, whereas in the semipelites the mineral tends to be of finer grain size and exhibits higher values for $2V_x$. Furthermore, in the low grade chlorite-epidote schists near Llaniestyn Church, pleochroic epidote occurring in veins has $2V_x=60^\circ$-65°, and rather cloudy, amorphous, partially altered epidote clusters in the glaucophane schists show $2V_x$ about 65°. The latter are evidently comparatively rich in Fe and belong to an earlier generation than do associated smaller and clearer crystals which have crystallized simultaneously with glaucophane.

The birefringence of the epidote in glaucophane-schists is about .030, and $Z \wedge a = 27^\circ$-28°. As a rule, the dispersion is not strong. Zoned crystals are rare, and the difference in

Fig. 2.1. $2V_x$ vs. γ' plots for the blue-green amphiboles (o) and glaucophane (x). Also shown are the trends of correlations between the two optical properties for the hornblendes (adapted from Deer, Howie & Zussman, 1962). + marks the plots for glaucophane from earlier studies by Holgate (1951), Bloxam & Allen (1958) and Banno (1959).

FIG. 2.1


x Glaucophane: low birefringence & ZΛc.
o Blue-green amphibole: comparatively high b.f. & ZΛc
+ Glaucophane (taken from reference)
pargasite
hastingsite
common hornblende
tremolite-actinolite
o?
+(Bloxam & Allen, 1958)
+(Banno, 1959)
o?
+(Holgate, 1951)
x?
120
90
60
30
2Vx
1.640
1.650
1.660
1.670
1.680
γ′

the value of Z $\wedge$ a between the outer and inner zones does not exceed 1° or 2°. Cross-sections of the larger, better developed crystals exhibit good (001) and (100) cleavages.

iii. Amphiboles:

a. Introduction: Almost all the amphiboles belong to two main groups: (a) blue-green variety and (b) blue variety (glaucophane).

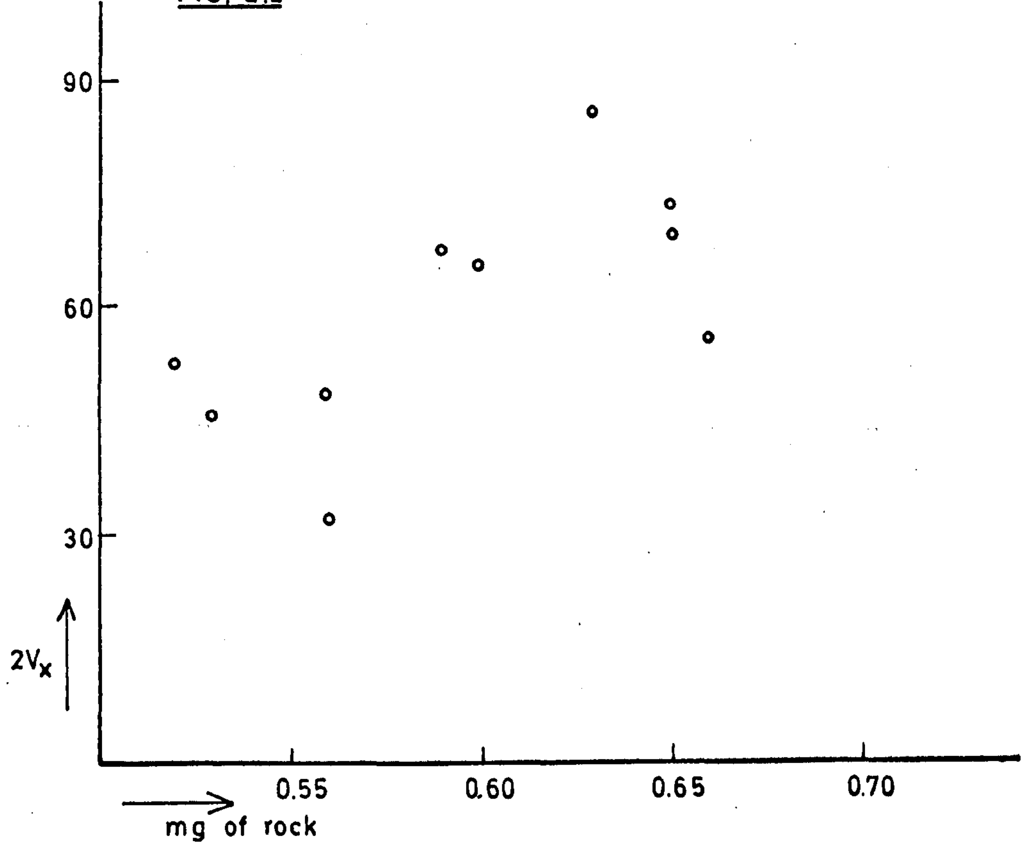
Although the refractive indices of the two varieties overlap, the blue-green variety has higher $2V_x$, Z $\wedge$ c and birefringence. The two may occur together in the same specimen.

The optical properties of the amphiboles belonging to each of the above varieties tend to be spread over a moderate range (see Tables 1 and 2). But the amphiboles of any one variety in any given specimen tend to possess optical characteristics within a much narrower range than the maximum possible. Adjacent bands of rock sometimes contain amphiboles which, though belonging to the same variety, possess rather different optics; this is especially true in the case of the blue-green amphibole. The nature of the controlling chemical factors is obscure as yet.

Amphibole in general post-dates the more pleochroic and comparatively iron-rich epidote (Plate 17a). But the clearer and comparatively iron-poor epidote seems to be contemporaneous with amphibole in the fine-grained rocks.

b. The blue-green variety: This variety, in one extreme of

FIG. 2.2



Plots of $2V_x$ of blue-green amphiboles against Niggli mg values of the host rocks (the latter have been taken from Table 7).

its properties, is very light coloured and has the pleochroic scheme: Z, very pale green (hardly any blue); Y, very pale yellow; X, colourless. Other optical properties are $\gamma' = 1.648$, $2V_x = 80^\circ$, b.f. = .022, $Z \wedge c = 25^\circ$.

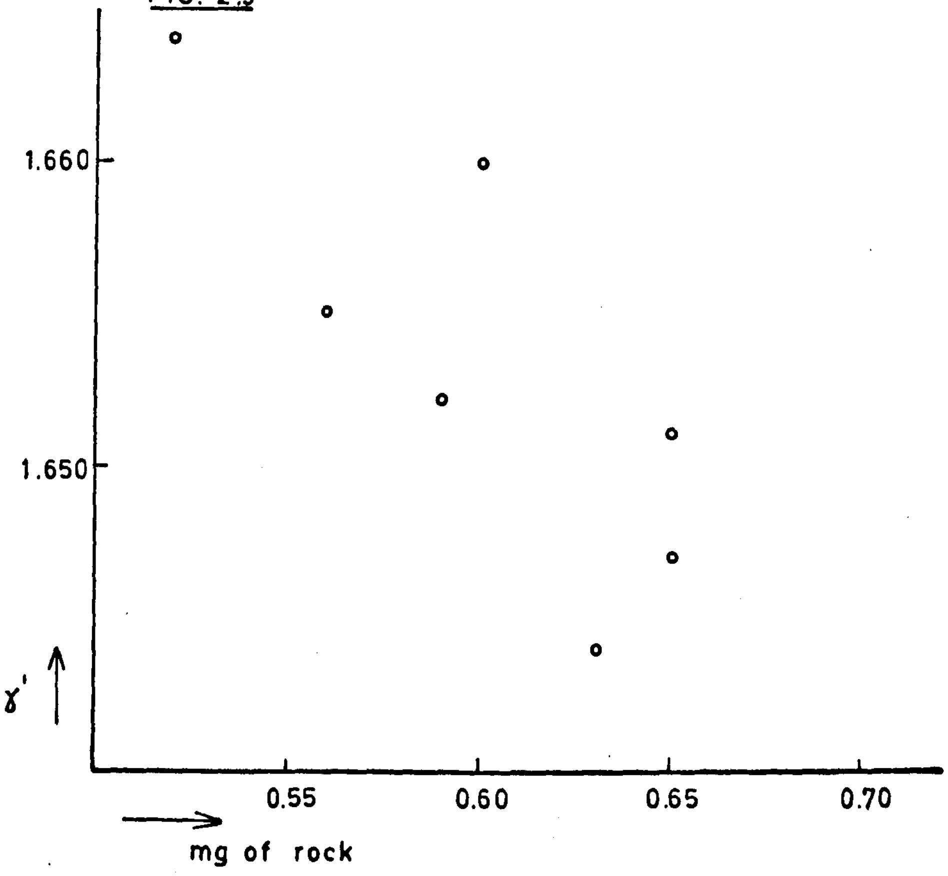
There are gradations towards the stronger coloured extreme where the pleochroic scheme can be given as: Z, deep blue-green; Y, pale yellow; X, colourless. The values for the other optical characteristics now become $\gamma' = 1.664$, $2V_x = 45^\circ$-50°, b.f. = .011, $Z \wedge c = 21^\circ$.

The increase in refractive index and the decrease in the values for $2V_x$ and birefringence appear to be related to the increase in colour-intensity, while $Z \wedge c$ bears no fixed relation to the other properties. Elongation is always negative.

Figs. 2.1-2.3 have been plotted to examine any correlation between the optic axial angle and $\gamma' (\simeq \gamma)$ of the various blue-green amphiboles (γ' being the maximum refractive index measured on cleavage fragments) as well as the mg content of the host rocks. The optical properties are listed on Table 1 and [illegible] the Niggli mg values are taken from Table 7.

For the purpose of petrographic description, all the amphiboles belonging to this variety will be referred to simply as the blue-green amphibole, without any efforts at finer distinctions. This variety of amphibole sometimes contains inclusions of sphene and rutile; some of the larger crystals are cross-fractured and the fractures have been healed by chlorite. The amphibole occurs as thin needles, only exceptionally longer than 1 mm., hypidiomorphic

FIG. 2.3



Plots of γ' of the blue-green amphiboles against Niggli mg values of the host rocks.

with faces (110) best developed. (010) is sometimes well developed. The crystals show strain and wavy extinction. In the more intensely sheared rocks, the needles have been stretched and separated into segments.

c. The blue variety (glaucophane): This variety has very characteristic pleochroism: Z, blue; Y, pale violet; X, colourless.

The grains are small and usually xenomorphic and precise measurements of refractive indices and other optic properties are almost impossible. A range of optic properties has however been established as follows: $\gamma' = 1.655$ to 1.669; $2V_x = 15^\circ$ to 45°; $Z \wedge c = 5^\circ$ to 10°; b.f. = .01 or less; elongation negative.

The optics place the blue variety of amphibole within the glaucophane field in the classification of alkali amphiboles (Miyashiro, 1957). There is some confusion as to whether it should be called "glaucophane proper" or crossite. The only available chemical analysis of the mineral (Holgate, 1951) suggests that it is crossite. Miyashiro (1957, p.67) believes that an "optically defined name is convenient for us in petrographical works." Such a definition means naming the mineral crossite only if it has the optical axial plane normal to (010) with b=Z and $c \wedge Y$=small. The blue amphibole dealt with in this thesis has its optic axial plane parallel to (010), b=Y, $c \wedge Z$ = small and $2V_x$ = small, and thus does not have the same optical properties as crossite. Whether the mineral is called "glaucophane proper" or crossite, it still falls within the glaucophane field in Miyashiro's classification. So, for the purpose of petrographic description, the mineral will be referred to as glaucophane, regardless of the variations in optical properties within the limits described earlier.

iv. Lawsonite:

Lawsonite is found only in very few localities, all within a limited strip immediately east of Slide 1 (Plate 1). It is almost always in a partially altered state and occurs as grains up to 1.5 mm. in length, and with anhedral, tabular form. Optical examination yielded the following data: parallel extinction; γ = 1.680; b.f. = .022; $2V_z$ rather variable about 90°, mostly between 80° and 86°; and all grains are length fast.

v. Other minerals:

Include quartz, carbonates, chlorites, garnet, potassium feldspars, muscovite, pyrite, rutile, sphene, tourmaline, haematite and magnetite. However, they were not investigated in detail.

Quartz and the micas are of widespread occurrence. Quartz frequently occurs in veins transverse and parallel to foliation. The white mica is probably all muscovite. The chlorites display very variable optical properties and must be of a variety of origins, ranging from early alteration type chlorite in volcanic rocks to late retrogressive type chlorite in the rocks near the western margin of the area.

Calcite is the prominent carbonate. Aragonite was not detected despite x-ray study of many carbonate powders, especially of rocks containing lawsonite.

Potassium-feldspars, both orthoclase and microcline, are infrequent, but do occur in small quantities in the mica-schists west of Slide 2 where they usually occur as large grains, sometimes coarse augen-shaped, with a considerable amount of included quartz.

Garnets are always minute in size and are generally colourless, sometimes light pink. The refractive index is 1.795 ± .004 in the case of pinkish garnets in a specimen of quartz-albite-chlorite-glaucophane schist which occurs $\frac{1}{4}$ mile north of Llyn Llwydiarth (549790). Measurements of refractive indices of garnets from other rocks range from 1.790 to 1.803. Most of the measurements were hindered by the presence of thin films of chlorite around the garnet grains.

4. DESCRIPTION OF ROCK TYPES (incorporating origin & metamorphism):

i. General:

Practically all the rocks exposed in the area can be divided into three classes, based primarily on their origin. These are given, together with their distribution, in Table 3. The most widespread class, Class 3, includes all rocks which are dominantly sedimentary in origin. These range from haematitic limestones to poorly sorted, rather albite-rich sediments. There is usually some igneous component present which is distributed erratically and is either derived from nearby igneous rocks or represents contemporaneous igneous activity. The next common class of rocks,

Table 3. Classification of Precambrian rocks around Llansadwrn.

TABLE 3.

Classification of Precambrian rocks around Llansadwrn

	CLASS		ROCK-TYPE	OCCURRENCE
DECREASING BASIC IGNEOUS COMPONENT	1. Basic igneous rocks (probably extrusive) and their derivatives	INCREASING METAMORPHIC GRADE	-Basaltitic and spilitic lavas -Greenstone -Chlorite-epidote schist (sub-types formed by presence of blue-green amphibole and/or glaucophane; and by presence of lawsonite-calcite veins) -Blue-green amphibole-epidote-glaucophane schist (sub-type formed by presence of chlorite) -Blue-green amphibole-epidote schist	60% in Upper Basic Schist Group 20% in Upper Greenschist Group 10% in Transition Group 10% elsewhere
	2. Tuffs, tuffaceous sediments and their derivatives	INCREASING METAMORPHIC GRADE	-Tuffaceous sediments -Epidote-bearing chlorite-quartz-albite schist -Chlorite-epidote-quartz-albite schist with blue-green amphibole (also glaucophane and/or lawsonite in some cases) -Blue-green amphibole-epidote-quartz-albite schist with some chlorite (subtype formed by presence of glaucophane) -Blue-green amphibole-epidote-quartz-albite schist	60% in Lower Basic Schist Group The rest sporadically distributed in the Upper and Lower Greenschist Groups, Upper and Lower Semipelitic Groups, and Upper Basic Schist Group
	3. Of chiefly sedimentary origin	a	-Quartz-chlorite-albite schist -Quartz-chlorite-albite-epidote schist -Limestone, chert, haematitic limestone, jasper, grit, haematitic quartzite, muscovite-albite-quartz-chlorite schist } in subordinate quantities	90% in Upper and Lower Greenschist Groups 10% in Transition Group
		b	-Muscovite-epidote-quartz-albite schist with garnet (subtype formed by presence of glaucophane and/or chlorite) -Chert, quartzite (in subordinate quantities)	80% in Upper and Lower Semipelitic Groups 15% in Upper Basic Schist Group 5% in Lower Basic Schist Group and Transition Group
	Rocks of uncertain origin		-Quartz-albite-muscovite-epidote schist (mylonite?)	70% in Upper Basic Schist Group 15% in Transition Group 15% elsewhere
			-Amphibolites	Amphibolite Group only

Class 2, comprises tuffs and tuffaceous sediments, and their metamorphosed equivalents. Class 1 includes rocks of igneous origin, mostly basic extrusives, which occur as thick bands with little or no sedimentary admixture, and their metamorphosed equivalents.

The above division into classes holds good in general. In detail, though, lenticular fragments of siliceous sedimentary material, basic tuffaceous sediments and extrusive igneous rocks are intercalated on a wide range of scales. While there are numerous instances of unadulterated igneous representatives measurable in tens of feet, this is hardly true of the sedimentary assemblages. The intimacy of this widespread layering has probably been accentuated by deformation involving intense shearing concentrated at, and subparallel to, the rock boundaries. Nevertheless, one can distinguish parts of the total thickness which are characterized in their make-up by a certain proportion of various rock-types. Units thus defined are given in Table 4, and their occurrences are shown in Plate 1. The thickness given for each unit is only a guide since each unit is subject to a good deal of variation in thickness either due to initial conditions during deposition, or due to the effect of deformation. Shearing has locally thinned the units, whereas the cumulative effect of small-scale tight folds may have increased the apparent thickness of many of the units.

The following indications suggest that each of the eight units given in Table 4 may be unique within this area:

Table 4. Names adopted for major units in the succession, together with other details.

TABLE 4.

	UNIT NAME ADOPTED	THICKNESS (maximum)	LITHOLOGY AND ORIGIN	GENERALISED METAMORPHIC CONDITION and MINERAL ASSEMBLAGES	TECTONIC CONDITION
8	Upper Greenschist Group (Gwna Greenschist)	2000′	Little metamorphosed tuffs, tuffaceous sediments, basaltic and spilitic lavas (including pillow lavas), limestone, jasper and chert	Chlorite-quartz-albite schist with some muscovite; little metamorphic epidote	Strongly disrupted tectonic mélange; shearing in excess of folding
7	Lower Greenschist Group (Gwna Greenschist)	8000′	Mainly tuffaceous, sometimes calcareous, sediments with thin quartzites and subordinate basic material, probably extrusive	Chlorite-epidote-quartz schists with some muscovite	Similar to above; but folding becoming more important. B_1 folding in excess of B_2
6	Transition Group	1800′	Approximately equal proportions of sedimetary/tuffaceous material and basic extrusives	Chlorite-epidote schists with lawsonite (earlier) and glaucophane (later); glaucophane restricted to part of the Group, increasing rapidly westwards Lawsonite occurs in a narrow zone along the eastern limit of glaucophane development	Folding and shearing equally developed. B_2 folds becoming more important, but B_1 still the dominant generation of folds.
5	Upper Basic Schist Group	3200′	Dominantly basic rocks, probably extrusive, together with some tuffaceous horizons and subordinate adinolised sediments including cherts and semi-pelite	Blue-green amphibole (earlier)-glaucophane (later)-epidote schists. No lawsonite	B_2 folds are the dominant tectonic features; B_1 folds widespread but subordinate to B_2
4	Upper Semi-pelitic Group (Penmynydd Micaschist)	1200′	Siliceous sediments, including quartzites with thin tuffaceous horizons towards east	Garnet bearing muscovite-quartz-albite schists	B_1 folds dominant; B_2 folds subordinate. shearing may be abundant, especially where associated with B_1
3	Lower Basic Schist Group	700′	Mainly basic tuffaceous sedimentary material with probable subordinate basic extrusives	Blue-green amphibole-epidote schists; no glaucophane except in a small zone in northern part of area (subarea 9 in Plate 3)	B_1 folds well developed; shearing widespread but not as obvious as B_1. B_2 rarely observed, but well developed in a small zone in northern part of area (subarea 9 in Plate 3)
2	Lower Semi-pelitic Group (Penmynydd Micaschist)	2500′	Siliceous sediments with isolated lenticular bodies and intercalated horizons of basic (tuffaceous?) material	Garnet bearing muscovite-quartz-albite schists	B_1 well developed; shearing subordinate B_2 virtually absent
1	Amphibolite Group	?	Basic rocks of igneous(?) origin	Amphibolite	B_1 present but not very obvious; shearing widespread, perhaps as a result of Berw faulting

(i) Metamorphic grade increases fairly continuously from the Beaumaris Coast in the east to the Berw Fault Zone in the west. This suggests that there has been no major folding or faulting which might have resulted in the repetition of units in this area after the initial metamorphism.

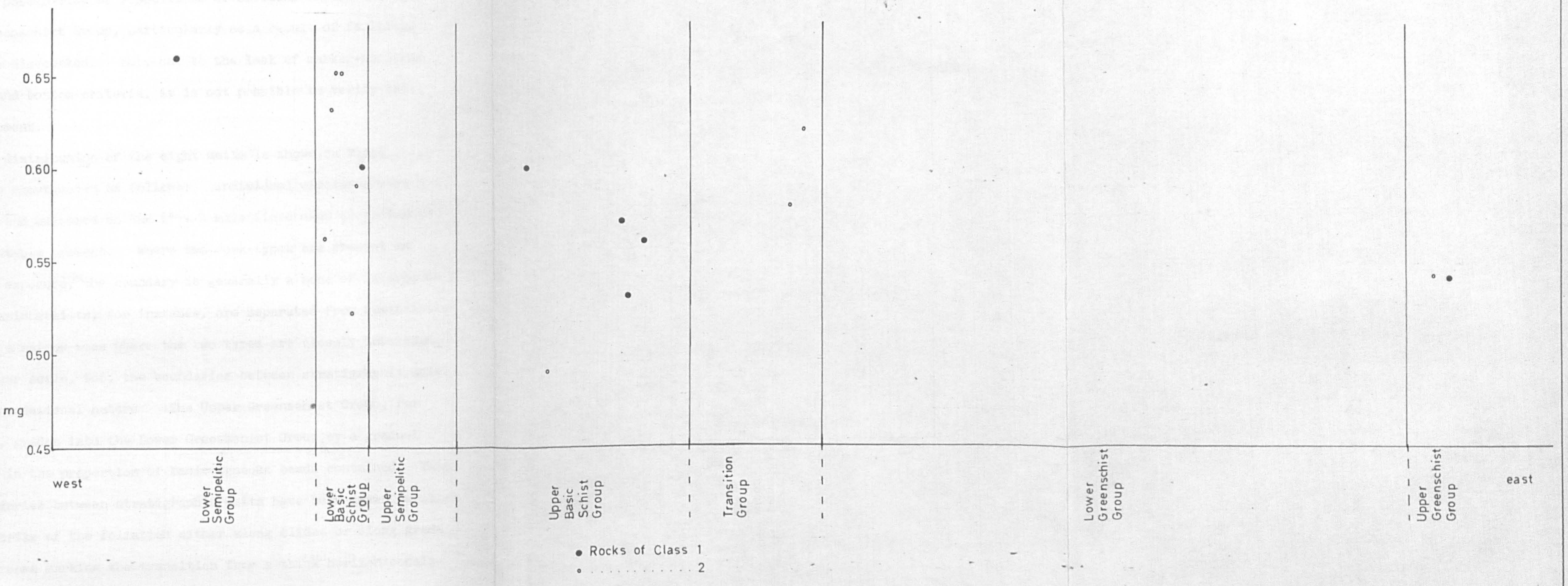
(ii) It does not seem likely that the Upper Basic Schist Group may be the same as the Lower Basic Schist Group, the repetition being caused by faulting or tight folding. The Upper Basic Schist Group is made up of metamorphosed basic igneous rocks with little sedimentary admixture whereas the Lower Basic Schist Group consists mainly of metamorphosed basic pyroclastic deposits with appreciable amounts of sedimentary admixture.

Similarly, it is difficult to equate the Greenschist Groups with the Semipelitic Groups because the former contain a higher percentage of basic volcanic material and are consequently richer in FeO, Fe_2O_3, CaO, MgO and poorer in SiO_2 **compared** to the rocks of the Semipelitic Groups.

(iii) The Niggli mg values for all the chemically analyzed basic rocks have been plotted against the distance across the strike (Fig. 2.4); the distance for each specimen was plotted with reference to the boundaries of the particular unit from which the specimen was obtained. There is a tendency for the mg value to decrease eastwards. This might suggest, to judge from the trend of differentiation of basic magmas (Walker & Poldervaart,

Fig. 2.4. Plots of Niggli mg values of rocks against distance across strike; the distance for each specimen has been plotted with reference to the boundaries of the major unit from which the specimen was obtained.

FIG. 2.4


mg
0.65
0.60
0.55
0.50
0.45
west
east
Lower Semipelitic Group
Lower Basic Schist Group
Upper Semipelitic Group
Upper Basic Schist Group
Transition Group
Lower Greenschist Group
Upper Greenschist Group
● Rocks of Class 1
○ 2

1949; see also Fig. 2.5), that the igneous deposits formed earliest in the sequence lie in the west and that the top of the sequence is towards east.

The possibility of repetitions of horizons within the thick Lower Greenschist Group, particularly as a result of faulting, cannot be discounted. But, due to the lack of marker-horizons and top and bottom criteria, it is not possible to verify this at the moment.

The distribution of the eight units is shown on Plate 1 which was constructed as follows: individual exposures were outlined and coloured on the 6" : 1 mile field maps according to the rock-types present. Where two rock-types are present in the same exposure, the boundary is generally a zone of interbanding. Basic schists, for instance, are separated from semipelitic rocks by a narrow zone where the two types are closely interbanded. On a larger scale, too, the boundaries between stratigraphic units are of a gradational nature. The Upper Greenschist Group, for instance, grades into the Lower Greenschist Group by a gradual decrease in the proportion of Basic igneous bands contained. Thus the boundaries between stratigraphic units have been drawn parallel to the strike of the foliation either along slides or along gradational zones marking the transition from a thick horizon consisting of one dominant rock type to another horizon made up of a different rock type. On this basis the eight units listed on Table 4 and shown on Plate 1 were recognized. It is along the boundaries of the main stratigraphic units that it is usual to find intercalations of two rock types in the same exposure. Sliding along the boundary of two units may be indicated in areas where such gradational relations are absent. For instance, the boundary between the Upper Basic Schist Group and Upper Semipelitic Group is a gradational one south of Penhesgyn (535742) but becomes a sharp boundary northwards. Further north, the Upper and Lower Basic Schist Groups occur side by side and the Upper Semipelitic Group is absent. Strong physiographic features mark the locations of Slides 1 and 2 north of Hendrefor (549770) where the effects of sliding may have been most marked, as suggested by the thinning out of the Upper Semipelitic Group. The Lower Greenschist Group is much thicker than any of the other units, but there are no reasonable grounds for further subdivision. The Transition Group occupies a special position because it is transitional in more than one sense. It consists of mixed sedimentary and igneous rocks occupying a much wider part of the succession than is usual for any other gradational zone. Further, it also marks the transition from the greenschists to the glaucophane schists. The area within which glaucophane-bearing rocks occur was delineated by the examination of thin sections. The orientation of foliation, fold axes, axial planes of minor folds and lineations was plotted on the 6": 1 mile field maps within the subareas analysed on Plate 3. No detailed observations were made outside these subareas. The generalized attitudes of the structural elements shown on Plate 1 were drawn by inspection of the field maps and stereograms obtained from closely related groups of exposures.

No attempt has been made to arbitrarily define the proportions of different components that a rock must possess in order for it to be included in one particular class. The gradations from one class to another are continuous. Any quantitative definitions, although tenable in unaltered rocks, would be difficult to maintain in the metamorphosed rocks.

Separate petrographic description of each of the three classes follows. They allude to specimens which may be considered homogeneous on the scale of a foot or thereabouts. Each class is described so as to provide a picture of the metamorphic changes which have taken place in that particular class. The metamorphic grade increases from the eastern boundary of the area westwards upto the Berw Fault Zone (see Plate 1). The boundaries between metamorphic zones are essentially parallel to stratigraphic boundaries. A summary of the metamorphic states to be found in the various stratigraphic units is given in Table 4.

ii. Basic igneous rocks and their derivatives (Class 1):

A. Occurrence: These rocks make up a little under 20% of all the rocks exposed in the area. Most of the basic extrusive material is to be found in the Upper Basic Schist Group, with the minority constituting part of the Transition Group and the Upper Greenschist Group. The Amphibolite Group contains what appear to be metamorphosed intrusives, and as their connection with the metamorphosed igneous rocks elsewhere in the area is obscure, they have been treated separately under "rocks of uncertain origin" (p. 49). A small proportion of the basic rocks is distributed widely over the rest of the area, mostly occurring in little lenticular pockets intercalated with sedimentary or tuffaceous material.

B. Details:

(a) east of Slide 1......The basic igneous rocks are found in their least altered form within the Upper Greenschist Group. Within this group, along the Beaumaris coast, and at many places inland, particularly around Llaniestyn Church (586796), are seen bands of more or less altered, massive, fine-grained rocks which belong to the class under discussion. It is not possible to ascertain their original nature in all cases, due to the alteration and deformation to which they have been subjected. But, in a few instances (p.12), pillow structures may be observed, thus suggesting an extrusive igneous origin (Plate 5).

In the exposures along the coast, near Grey House (583743), pillow-shaped masses of fine-grained rock, ranging in size from 6" to two or three feet along their long axes, are enclosed in a near-schistose chloritic matrix. The rock has evidently undergone some compression. The chlorite matrix is probably the alteration product of softer parts of the original lava mass. Laths of feldspar, chlorite and some pale brown pyroxene, probably augite, are the main constituents of the lavas. Olivine has not been identified. The feldspar, which is albite, sometimes occurs as fine-grained laths in sub-ophitic relation to the altered augite, and at other times as phenocrysts. Variolitic textures and vesicles are seen in the less altered lavas (Plate 7a).

Plate 4. Gently dipping basic igneous band (dark) within sedimentary rocks in the Lower Greenschist Group. Note 6" ruler above the basic band. Near Gazelle Hotel(580741).

They are best preserved in rocks of the Upper Greenschist Group along the Beaumaris coast (585745). These textures are also seen infrequently in the lower Greenschist Group upto a mile west of the boundary between the Lower and Upper Greenschist Groups.

The augite and feldspar are seen clearly only in rare cases. Mostly, the augite is altered to an impure chloritic mass. The feldspar is usually broken-up and partially replaced by chlorite, epidote, carbonates and sericitic dust.

This process of breakdown of the lava results in partial or complete loss of the original structures, and in the production of greenstone. The ferromagnesian minerals are gradually converted to a dull, vaguely schistose, chloritic matrix, with tiny grains of epidote and other unidentifiable minerals, including carbonate dust, interspersed within it. The broken-up feldspars continue to shatter, and the cracks are filled with calcite, sericite, and epidote. The latter minerals increase in amount at the expense of feldspar which is gradually and almost completely consumed.

There is not much evidence available at present regarding the early history of these probable submarine lava deposits. The feldspar, for instance, may well owe its albitic composition to secondary changes, although this has not been proved yet; whether interaction with sea-water brought about important changes in the initial magma remains to be established.

There is presumably some fair proportion of intrusive igneous

Plate 5. Partially preserved pillow-structures in the road-cutting above Menai Strait (582742).

rocks associated with the lavas, but apart from a few minor dikes and cross-cutting veins, no larger dikes,or plugs of any size, have been identified. As mentioned above, rocks that are decidedly extrusive undergo gradual early metamorphic and structural changes, leading to the formation of a greenstone. The lavas are sheared parallel to the initial layering, and weakly schistose matter eats into the compact pillows gradually, concentrically as well as at the extremes. This deformation is accompanied by an increasing amount of dull chlorite-schist together with other minute unidentifiable minerals. The original layering of the lavas is retained in the form of banding in the greenstone. Similar greenstones present over wide tracts east of Slide 1 are probably the result of such deformation and alteration of lavas. There is no contrary evidence to indicate that any significant proportion of the greenstones may have been derived from intrusive rocks. In some localities, particularly within the Lower Greenschist Group, greenstones are found in close association with limestones and cherts.

The rock at this stage is termed greenstone, rather than greenschist, because it has no thoroughly penetrative schistosity as such, although the closely spaced shear planes do give it a laminated look. It is cryptocrystalline, except for the occasional relict structures and pseudomorphs, the latter sometimes demonstrably of original twinned albite or ferromagnesian phenocrysts (Plate 8a).

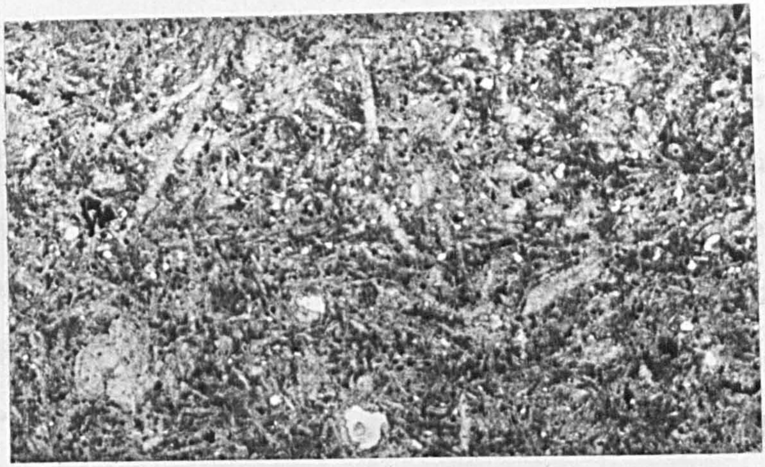


Plate 6a. Altered basic igneous rock, probably spilitic lava, from the road-cutting near Gazelle Hotel (580741), Beaumaris coast. p.p.l. X35.

Plate 6b. Spilitic lava from Newborough. Lent by D.S. Wood. p.p.l. X35.

This fine-grained product of the sheared lavas undergoes an early stage of recrystallization. This is usually marked by the appearance of fresh chlorite and epidote, with the albite remaining as minute grains. The most obvious constituent is chlorite, most of it occurring as a dense felt interspersed with granules of pleochroic epidote. Minute grains and aggregates of sodic feldspar can still be seen , though appreciable quantities of fine-grained quartz are present, the two being not readily distinguished from each other. Thin bands of pleochroic epidote can be seen to fill cracks up to 0.25 cm. in width. Now the rock can be termed chlorite-epidote schist, since the recrystallized chlorite flakes define a schistosity.

This chlorite-epidote schist stage in the metamorphism of the basic rocks continues for about 1½ miles west of the boundary between the Upper and Lower Greenschist Groups. By now, the chlorite and epidote are better developed, though the rock is still very fine-grained. The schistosity is more definite, and there are occasional veins of quartz and/or albite, upto ½" thick, parallel to the schistosity. Some clear, untwinned albite is seen in the chlorite-epidote groundmass, and is presumably recrystallized albite. Some sphene is encountered, as well as opaque iron ore.

Minute grains of very pale green amphibole can also be identified 1½ miles west of the Upper/Lower Greenschist boundary. These minute needles of amphibole belong to the blue-green variety.

Plate 7a. Vesicular lava from Beaumaris coast (582743). Note shearing and alteration (mainly chloritisation) at left hand bottom. o.l. X5.

Plate 7b. Haematitic tuff from Beaumaris coast (581741). Some of the fragmentation is a result of shattering after compaction. o.l. X5.

(b) in the neighbourhood of Slide 1...... It is in rocks of the last description, i.e., fine-grained chlorite-epidote schist (with possibly a little blue-green amphibole), that glaucophane is first encountered. It is first noticed as small blue wisps growing in a green chloritic matrix in the rocks 1/6th mile east of Slide 1. This appearance of incipient glaucophane is accompanied by the presence of veins of calcite, lawsonite and quartz. But the lawsonite is seldom found in a fresh state. It appears to be incorporated rapidly into the main body of the rock during powerful deformational movements, and at the same time to be extensively replaced by glaucophane, epidote, carbonate, and quartz. Chlorite-epidote schists containing lawsonite and glaucophane are restricted to a very narrow zone immediately east of Slide 1.

The amphibole content of the basic rocks in the vicinity of Slide 1 is of importance. Immediately east of the slide, the rocks do not contain appreciable amounts of blue-green amphibole. The mineral, when present, is always in slender needles. Glaucophane, on the other hand, is present in appreciable quantities immediately east of the slide. Its development is rapid, and within a distance of 1/6th mile, glaucophane grows in status from incipient wisps to be an important constituent of the chlorite-epidote schist. The increase in the amount and size of glaucophane is reasonably continuous across the slide. On the other hand, the amount and size of the blue-green amphibole in the rocks increases sharply westwards across the slide. The slide divides chlorite-epidote schists with subordinate blue-green amphibole on the eastern side from the blue-green amphibole-epidote-chlorite schists on the west. Thüs, while the increase in the content of glaucophane of the rock is fairly continuous across the slide, there is a sudden increase in the content of blue-green amphibole on the western side of the slide. Also, west of the slide, glaucophane occurs as rims around grains of blue-green amphibole (plates 19b, 20a & b), a relation not observed on the eastern side of the slide. These relations are taken to indicate that the formation of glaucophane post-dates that of blue-green amphibole; and that movements along the slide intervened during the period between the formation of the two minerals.

(c) <u>between Slides 1 and 2</u>......The foliation is quite well developed in the blue-green amphibole-epidote-glaucophane-(chlorite) schists on the western side of Slide 1, and is usually accentuated by parallel quartz veins. The constituent minerals are the two kinds of amphiboles in varying proportions, epidote, chlorite, quartz, albite and some muscovite, zoisite, haematite, ilmenite and sphene. The very fine-grained nature of these rocks suggests that they may have arisen direct from lavas or their sheared products, without having had to pass through the chlorite-schist stage.

The amphiboles seldom have well developed faces, and usually occur as needles and felts. Rhombic sections are comparatively common, and it is in them that the rimming of blue-green amphibole by glaucophane is evident. When in contact with chlorite, the

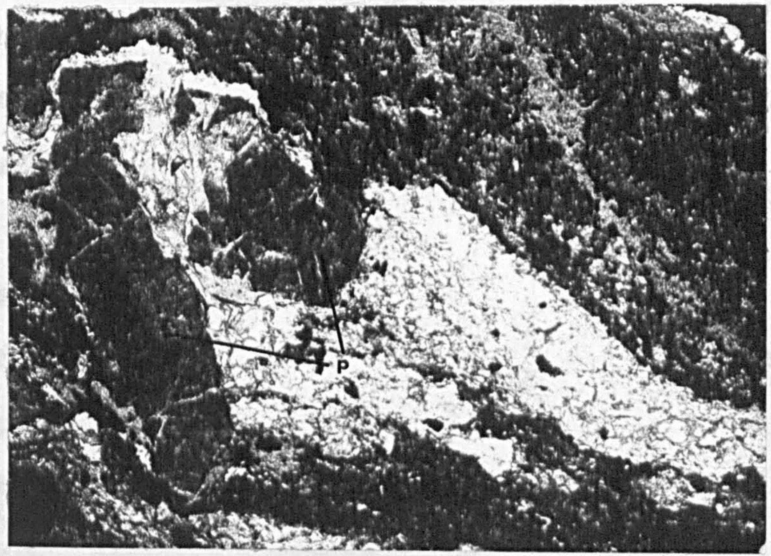


Plate 8a. Pyroxene (probably augite) pseudomorphs (p) in altered basic rock from near St. Iestyn's Church (585796). p.p.l. X25.

Plate 8b. Inclusion of haematitic spilite in quartzose sediment from Hendrefor (548770). p.p.l. X35.

faces of the amphiboles are often sharp.

Garnet is rarely found and is always extremely minute.

Albite is never present as large grains except in the occasional quartz-albite veins. It is usually found in interstitial spaces in close association with quartz.

Both the amphiboles often form semi-continuous strings elongated parallel to the c-axis, and the direction of the strings cuts across irregularities in the chlorite-epidote matrix. (Pla [illegible]

The epidotes usually occur in two distinct forms. The larger, more pleochroic grains, which also tend to be rather dusty, often occur in aggregates. These aggregates are tightly knit together to form an overall spheroidal shape. Amphibole needles cut through such clusters of epidote. This variety of epidote, to judge from its optics ($2V_x = 65^\circ$; see p. 18), contains more iron than the second variety, the latter being small clear grains, intimately intertwined with glaucophane, suggesting contemporaneous crystallization of glaucophane and the second variety of epidote. The amphibole schists are often rich in epidosite-bands. The first variety of epidote makes up the bulk of these bands, together with some quartz and occasional feldspar. The epidosite bands have acted as competent material during the B_1 folding (see p 56) and often have been broken up to form boudins.

(d) west of Slide 2...... In the area between Slides 1 and 2, the rocks of Class 1 continue to be blue-green-amphibole-epidote-glaucophane schists. West of Slide 2, this class is hardly represented. There is certainly not sufficient of it to enable metamorphic changes in this class to be followed further westwards with reasonable certainty. What is definite is that there is no glaucophane to be found in this class west of Slide 2.

iii. Tuffs, tuffaceous sediments and their derivatives (Class 2):

This class covers a rather wide range of rocks, which are dominantly basic in composition. There may be upto about 15-25% light coloured material of probable sedimentary origin. The igneous and sedimentary materials are intimately mixed in the form of narrow strings, lenticles and bands and such an admixture has been further irregularized by deformation involving shear.

A. Occurrence: The class is very widespread, and is liable to occur anywhere as the result of more or less simultaneous volcanic and sedimentary action. The thick units of the Upper and Lower Greenschist Groups, Upper and Lower Semipelitic Groups, which are themselves dominantly of sedimentary origin, contain lenticular bodies rich in basic components derived from originally igneous material. Within the Upper Basic Schist Group, too, though to a lesser extent, such pockets of material of mixed origin occur. The single major occurrence of the rocks of Class 2, however, is the Lower Basic Schist Group. This unit is composed of igneous and sedimentary material in a proportion of roughly 5:1.

Plate 9a. Rare relict of variolitic texture in basic material included within quartzose sediment from Hendrefor (548770). p.p.l. X35.

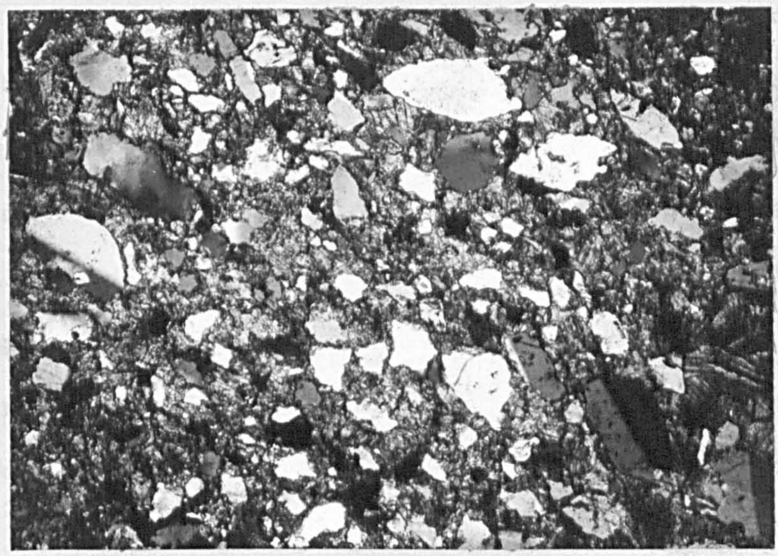


Plate 9b. Sedimentary quartz-feldspar assemblage in carbonate matrix from near Glan-yr-afon (548767). Such layers alternate with chloritic layers derived from basic volcanic material(not shown in photo). x.n. X35.

B. Details:

(a) east of Slide 1...... Along the Beaumaris coast, tuffaceous sediments may be seen in a partly altered state. The rock can be termed epidote-bearing chlorite-quartz-albite schist.

Epidote can make up upto 10% of the rock. The schistosity is ill-developed, and is confined to the more altered mafic portions. This altered part of the rock, under the microscope, is seen to resemble closely the cataclastic product of the deformed lavas (see p.31). The matrix is fine-grained, highly sheared and dominantly chloritic, with infrequent grains of nearly altered original ferromagnesian minerals. Associated with chloritic bands are thin lenticular bands of clastic grains of quartz and albite. The main effect of the initial deformation upon these clastic bands is a peripheral granulation of the quartz and feldspar grains (Plate 11b). The impression is that the bands rich in chlorite were able to take up much of the deformation by internal sliding, and the bands with rounded quartz-albite grains were comparatively shielded.

There is a variable amount of carbonate present, sometimes in the form of lenticular masses. Often the carbonate is interstitial. The presence of carbonate matrix has the effect of protecting clastic quartz and feldspar from granulation. Haematite and opaque iron ore are frequent.

Although deformation has ruined much of the original features of the pyroclastic rocks, fragmented agglomeratic varieties have

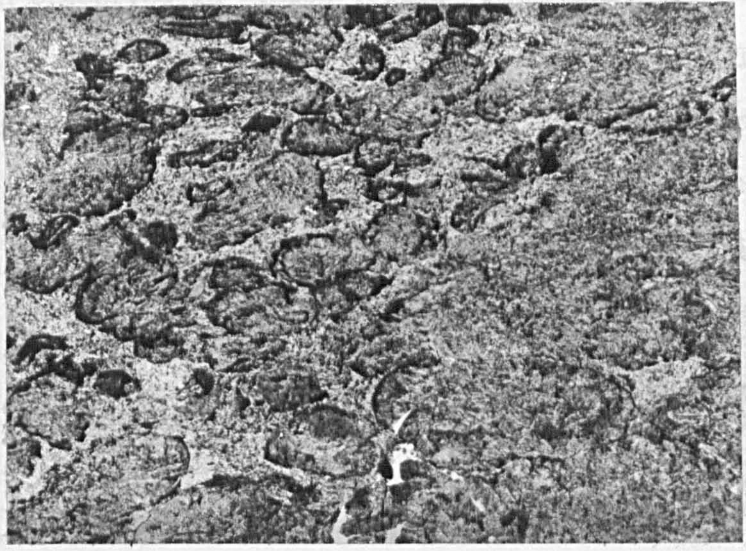


Plate 10a. Spherulitic texture in various stages of destruction. The original texture is fairly well preserved on the left hand side; to the right, the rock becomes altered to a greenstone. From Beaumaris coast north-east of Grey House (587745). p.p.l. X35.

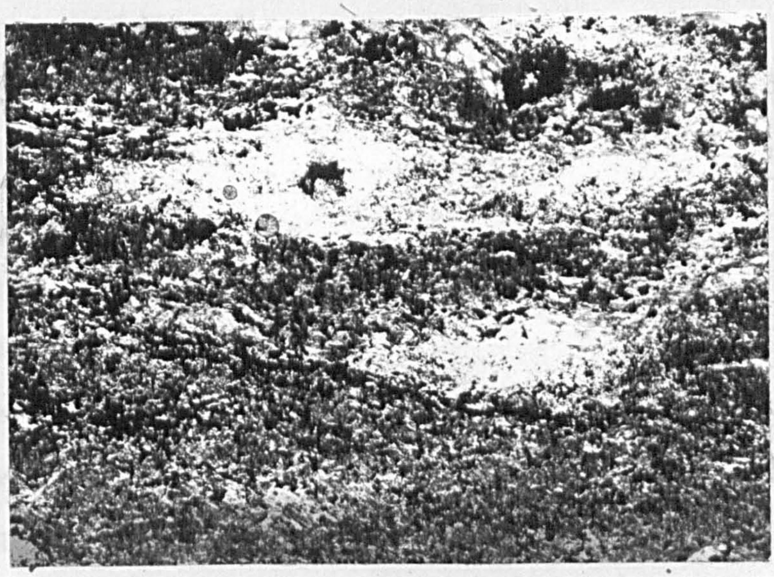


Plate 10b. Partially altered vesicular lava. The vesicles are filled with chlorite. The chief identifiable minerals in the groundmass are chlorite, cloudy albite and opaque ore. From Beaumaris coast near Garth view (577738). p.p.l. X35.

have been preserved in places (Plate 7b). They are best seen near Gazelle Hotel on the Beaumaris Coast (581741). In such cases, one can pick out the original depositional lamination. The constituents of the agglomerates include angular, broken parts of undoubted lavas, which are similar to the material found in the more compact massive lavas nearby. In addition, there is clastic quartz, albite and carbonate material. Partly consumed relicts of spilitic material are encountered upto 1½ miles west of the Lower/Upper Greenschist Group boundary.

The initial stages of metamorphic and structural effects on the basic bands of the tuffs are quite similar to those described in connection with the truly igneous varieties in the preceding class (p. 32). The bands rich in quartz and albite persist with only marginal alteration, while the igneous components are converted to a fine-grained chlorite-epidote schist with subordinate amounts of minute albite, sphene and a variable amount of carbonate. The epidote occurs as small dirty grains set in a dense felt of chlorite.

The first pale green wisps of blue-green amphibole in these rocks are encountered about 1½ miles west of the Lower/Upper Greenschist Group boundary; the amount and size of the amphibole as well as epidote increases westward towards Slide 1, where the rock may be termed chlorite-epidote-quartz-albite schist with some blue-green amphibole. The amphibole replaces chlorite and if well developed, can be seen to have sharp faces against the chloritic groundmass (Plate 12).

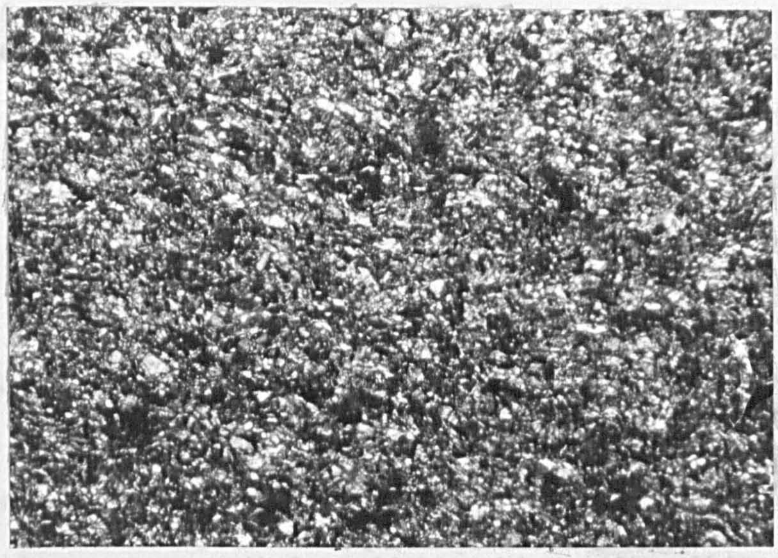


Plate 11a. Chlorite-quartz-epidote-albite schist derived by recrystallization of basic igneous rock. From Carwad (585791). x.n. X35.

Plate 11b. Preferential granulation of feldspar grain (f). Along the right-hand side boundary, the grain has been broken down by the grinding action of neighbouring grains; the granulation is less severe on the left-hand side due to the shielding effect of carbonate matrix (c). From Hendrefor (548770). x.n. X80.

Immediately east of Slide 1, glaucophane and lawsonite are both found in the rocks of this class. The mutual relations between glaucophane, lawsonite, chlorite and the blue-green amphibole are similar to those described in the previous class (p. 33).

(b) between Slides 1 and 2..... Across Slide 1, upto Slide 2, this class is infrequent. The blue-green amphibole is very noticeably developed in amount and size, and the rock can be called blue-green amphibole-epidote schist, with albite, quartz, chlorite, muscovite, zoisite, sphene and calcite. Epidote, too, is better developed than it is east of Slide 1.

These rocks tend to be coarser-grained than the metamorphosed lavas, and the amphiboles have better developed prism faces.

Between Slides 1 and 2, the rocks of Class 2 contain appreciable glaucophane. Glaucophane usually rims the blue-green amphibole or is developed as a lateral variation of the blue-green amphibole needles. In appropriate sections the blue-green colour of the latter can be seen to pass along the length of the grain into a striking blue colour.

(c) west of Slide 2...... Here, the rocks of this class revert to blue-green amphibole schists with no glaucophane. The major minerals are better developed than anywhere eastward. The amount of chlorite is much less than in the east. The schistosity is very well developed here, and the amphiboles occur with well developed prism faces. The epidote is bigger, too; zoisite can sometimes be identified. Albite occasionally occurs as grains

Plate 12. Blue-green amphibole (a) growing in a dense felt of chlorite (c). From Gareg-Llandeg (534778). p.p.l. X210.

which appear to be not original clastic material, but a clear untwinned metamorphic mineral. The secondary albite has been found, in rare instances, to enclose minute groups of pale blue-green amphiboles and epidote. These amphiboles needles are often preferentially oriented, usually parallel to the external lineation, but they have also been observed, in rare cases, to lie at an angle to the latter, or to form an S-shaped orientation.

There are often appreciable quantities of disseminated albite, and there is evidence of an appreciable amount of cataclastic breakdown of the sedimentary quartz and feldspar grains. Quartz and sphene are occasionally plentiful; other minerals to be found are muscovite, magnetite, ilmenite, zircon, apatite and rutile. Muscovite is infrequently an essential constituent of the quartz-albite bands.

Near the western margin of the area, particularly at Orsedd-garnech-goch (513724), and at Capel Gilead (521735), these rocks attain a spotted appearance due to well developed grains of secondary sodic feldspars, which may be identified in hand-specimens, being set in a comparatively coarse-grained amphibole-epidote base. The effects of late cataclastic movements are pronounced here. The metamorphic minerals have been mechanically disturbed, and individual amphibole crystals have been distorted by movements along the rhombic cleavage faces (Plate 21A). There is retrograde chlorite in some of these rocks.

iv. Rocks of chiefly sedimentary origin and their derivatives (Class 3, a & b)

A. Occurrence: The rocks in this class may be divided into

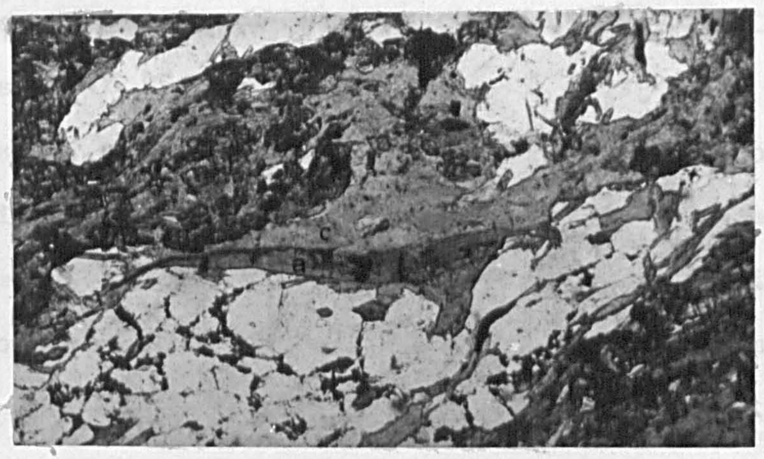


Plate 13a. Blue-green amphibole (a) growing in a dense felt of chlorite (c). From Gareg-Llandeg (534778). p.p.l. X40.

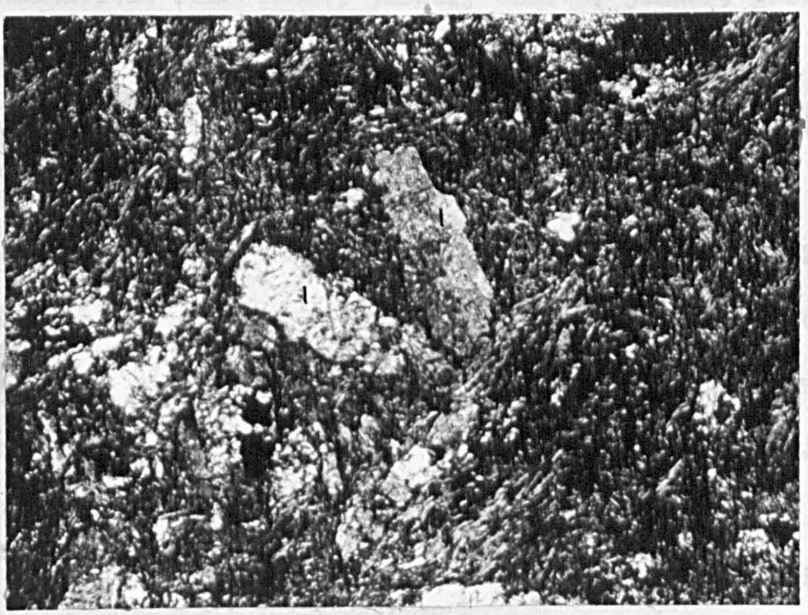


Plate 13b. Partially altered crystals of lawsonite (l) in greenschist. North of Hendrefor (548773). x.n. X35.

two subclasses. This subdivision is based primarily on the observation that the sedimentary rocks in the Upper and Lower Greenschist Groups have a consistently higher content of basic components than the sedimentary rocks of the Upper and Lower Semipelitic Groups. The probable reason for this is that the meta-sedimentary rocks of the Greenschist Groups were initially richer, compared with the sedimentary deposits of the Semipelitic Groups, in material derived from basic igneous and pyroclastic rocks. The first subclass occurs east of Slide 1. Some of it is in the Upper Greenschist Group, and it makes up most of the Lower Greenschist Group. These rocks include very low-grade greenschists of variable composition. There are, in addition, haematitic limestones, jaspery cherts, jasper, grit, etc., which are best seen along the Beaumaris coast.

In the second subclass are sedimentary rocks west of Slide 1; quartz, muscovite, albite, epidote and garnet are the chief constituents of these rocks. They too have a wide compositional range, although it is possible that metamorphism has helped to regularize the compositional distribution. They make up the bulk of the Upper and Lower Semipelitic Groups, and also occur sporadically within the Upper Basic Schist Group.

There are examples of rocks that belong, strictly speaking, to neither of the two subclasses, but on the whole are closer to the second. These occur in the Transition Group east of Slide 1. They contain some fresh chlorite in addition to the essential minerals which are muscovite, albite, epidote and

Plate 14a. Typical chlorite-epidote schist from north of Carreg-Iago (549732). The thin section shows rare wisps of glaucophane which cannot be distinguished in the photograph. p.p.l. X35.

Plate 14b. Chlorite-epidote schist from north of Friar Farm (548763). Glaucophane is better developed than in 14a (above). The light coloured vein at the bottom consists mainly of quartz with a little epidote and needles of glaucophane. The minerals present elsewhere are epidote (high relief), chlorite and glaucophane (both have low relief and are light-coloured; the two cannot be distinguished from each other in the photograph), opaque ore and sphene(?). There is a considerable amount of glaucophane in this rock. p.p.l. X35.

quartz, and they are lacking in garnets.

Both subclasses have, the first to a greater extent, been mixed with basic material derived from igneous masses.

It is likely that the rocks of the second subclass actually grade eastward into those of the first subclass by a gradual increase in the amount of reworked volcanic material. Certainly, there are examples of intermediate types in the vicinity of Slide 1, particularly on the eastern side. But a continuous change cannot be observed, and the rocks of this class on the two sides of Slide 1 present a mineralogical and chemical contrast.

B. Details:

(a) east of Slide 1......The following description is confined to rocks that may be loosely termed greenschists. It excludes other types which occur only sporadically, viz., cherts, grits, limestones, jasper, etc., which are of too limited an occurrence to be treated in detail in terms of ascending metamorphism.

The striking feature of these rocks is their irregularity, both from a physical and a chemical point of view. The most common assemblage can be loosely termed a quartz-albite-chlorite schist. Besides albite and quartz, which occur in variable ratios, it also contains appreciable amounts chlorite and white mica. Muscovite never predominates, nor does it occur as large or well-developed flakes. The chlorite is usually in the fine-grained mass; it is sometimes the main constituent of thin discontinuous bands, which also contain sphene, iron ore, sericite, and some fine-grained powdery epidote. Apatite is frequently an important

Plate 15a. Metamorphosed tuffaceous sediment: layers of clastic quartz and feldspar alternate with chloritic layers rich in opaque ore with a few minute grains of epidote. North of Tynymynydd (558793). x.n. X35.

Plate 15b. A grain of lawsonite which has been stretched and broken; quartz and glaucophane(?) have recrystallized in the fractures. North of Hendrefor. p.p.l. X80.

constituent of these bands. These chloritic bands, whose thickness is of the order of 1 cm. or less, sometimes exhibit igneous textures, particularly sub-ophitic and variolitic types (Plate 9a). These are thin bands of igneous origin that have been enclosed within the sedimentary material. Minor amounts of fragmentary igneous material, chiefly spilitic, are present in the rock (Plate 8b).

In most parts of the rock chlorite is scarce, and the chief minerals are quartz and albite, often clastic in appearance. It is not easy to distinguish between the two even under the microscope. In some instances where the albite is easily distinguished by its twinning, it forms more than 60% of the clastic grains. On the whole, quartz probably just dominates. Some of the quartz is venous; the mineral may have mobilized during deformation, recrystallized and concentrated in veins. The albite grains often consist of two or three twinned individuals and have an estimated composition which is slightly variable about $Ab_{90}An_{10}$. Albite, too, occurs in veins, with or without quartz, but not quite so often as the latter.

Carbonate may constitute upto 10% of the rock. Rarely it has the appearance of rounded clastic grains; more often it forms the interstitial material separating rounded grains of quartz and feldspars. In places the carbonate is secondary and replaces the feldspar.

Under the microscope the clastic grains can be seen to be poorly sorted and rather angular in the relatively fresh rock.

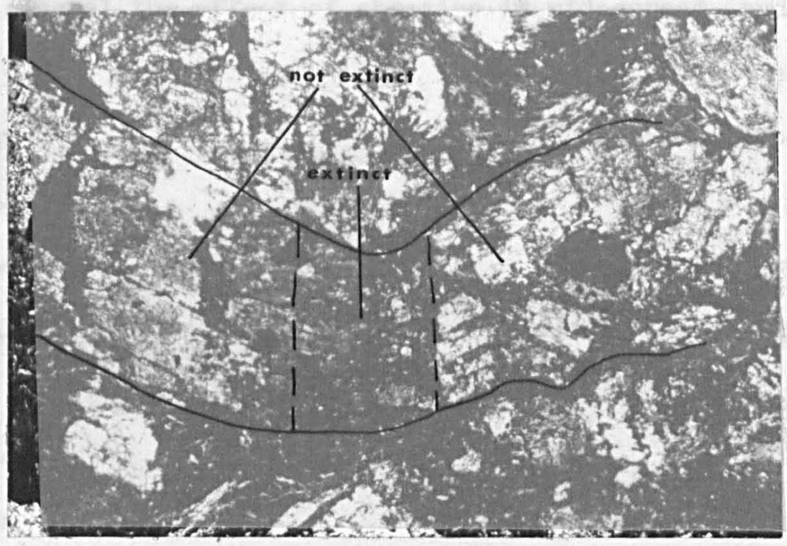


Plate 16a. A single grain of lawsonite has been deformed by folding (B_2?). Note undulatory extinction; only the central part of the crystal is extinct. From north of Hendrefor (548773). x.n. X80.

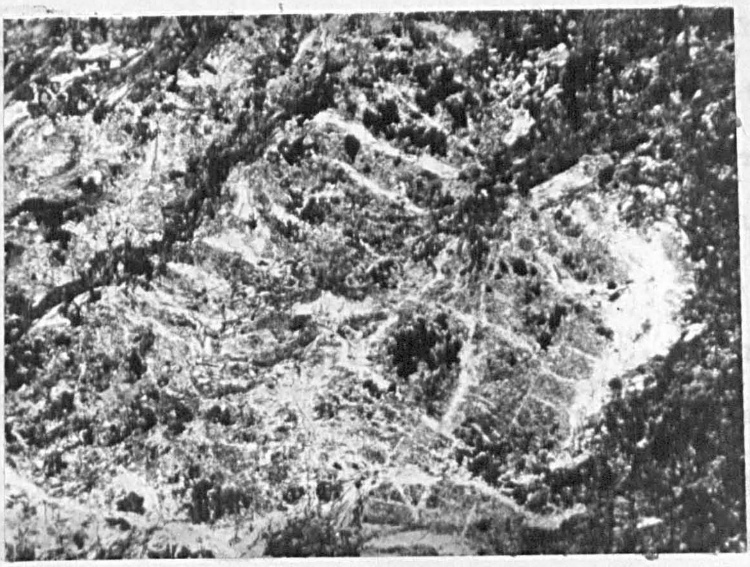


Plate 16b. Tabular pseudomorphs of lawsonite, now consisting mainly of carbonate, quartz, opaque ore, glaucophane and epidote(?). North of Friar Farm(548763). p.p.l. X35.

But in general the effect of abrasion is widespread, and the quartz and feldspar grains tend to be of a rounded shape due to marginal granulation. Such cataclastic effect is more pronounced westward. Any schistose chloritic material present tends to soften this effect by acting as a buffer against the external forces. Where the rock is practically all quartz and albite, with little chlorite or interstitial carbonate, the effect of deformation is most pronounced. Rocks of such compositions can present a mylonitized appearance. Undulatory extinction is widespread in grains thus affected. Quartz has often undergone recrystallization in the more severely deformed cases.

The above picture is a generalized one, and applies to the majority of the sedimentary rocks in this subarea. There is no regular bedding in these rocks, and related sedimentary structures are not seen. Nevertheless, there are narrow zones parallel to strike which, though not strictly continuous or persistent, possess distinct mineralogical features. One such horizon is a haematitic quartzose horizon about 10 metres thick, that can be traced for nearly two miles northwards from near Pedair Groeslon (552739). In thin sections, specimens from this horizon have a gritty appearance, and look as if they might have been subjected to some recrystallization. Another zone, of white quartzite in this case, can be followed for half-a-mile, and occurs northeast of Llyn Llwydiarth near Tynymynydd (557792).

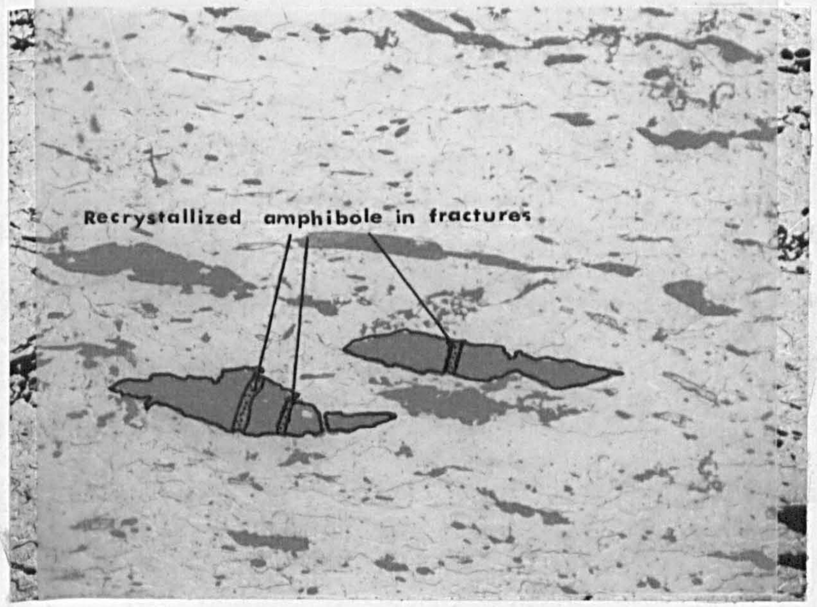


Plate 17. Fine grained quartz-albite-amphibole schist (see under 'Mylonites' on p. 48). Some of the amphibole grains are in a state of boudinage type of breakdown and the fractures have been filled by fresh amphibole. From Mynydd Llwydiarth. p.p.l. X40.

These zones run parallel to the regional foliation.

With increasing amounts of volcanic admixture, the overall aspect of these rocks grades, more or less continuously, into that of a tuff. On the other hand, towards Slide 1, semipelitic rocks with abundant albite and quartz grains, well developed muscovite and some fresh pleochroic chlorite, occur. There is some epidote in these rocks as well as a little garnet. The best example of such muscovite-albite schist east of Slide 1 is the exposure half-a-mile north of Four Crosses (547737). These contain virtually no identifiable volcanic material. These rocks may be considered partly to bridge the gap between the two subclasses 3a and 3b, and thus to provide indication of the gradation of subclass 3b (in the west) into subclass 3a (in the east).

(b) west of Slide 1......The sedimentary rocks in this subarea have been metamorphosed to muscovite-epidote-schist. The schistosity is well-developed, although its continuity is influenced by eye-shaped patches of sodic feldspar which are sometimes very common. The chief minerals are muscovite, quartz, albite, epidote and garnet. The albite-quartz assemblage, which is sometimes in the form of clastic grains, is in such cases similar to that in the sedimentary rocks of subclass 3a. There is comparatively little ferromagnesian component in these rocks and muscovite is abundant. Patches of chlorite are very common, but generally are of a retrograde nature. Garnet is present as small grains in most specimens examined under the microscope.

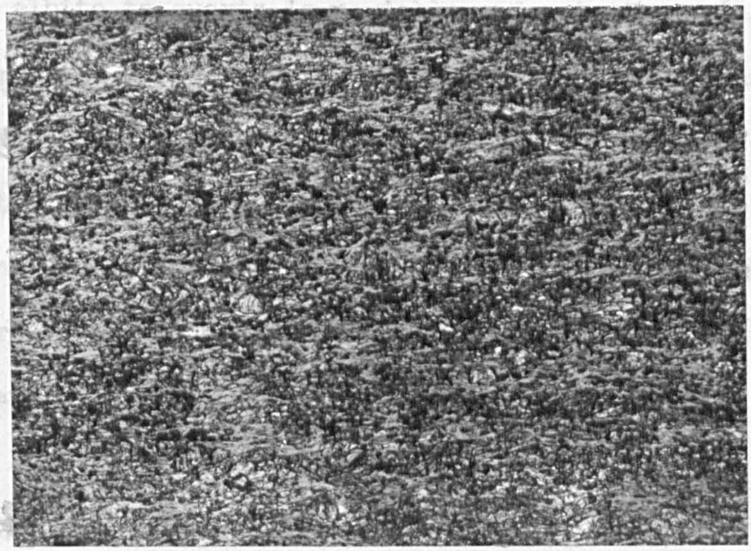


Plate 18a. Typical glaucophane-epidote schist: glaucophane (low relief; occupies most of the area), epidote (high relief) and sphene (minute dark grains) are the main constituents here. North of Felinengan (537737). p.p.l. X35.

Plate 18b. Boudinaged grains of glaucophane (g) in muscovite-epidote-glaucophane-quartz schist. North of Llyn Llwydiarth (549788). p.p.l. X80.

The ratio of albite to quartz is variable and not always easily determinable; the total is usually 60% of the rock, and quartz of probably the predominant mineral of the two. Muscovite can form upto between 20% and 40% of the rock. Epidote always occurs, but never in large grains. Biotite is absent. Amphiboles are rarely found, and their occurrences are confined to within the Tarn Wedge.

The less common minerals found in the mica schists include zoisite, sphene, zircon, apatite, rutile, haematite, iron ore, phlogopite (?) and microcline.

There is generally an alternation of quartzo-feldspathic and phyllitic bands of upto 0.5 mm thickness. However, one can find discontinuous bands two or three centimetres thick which are rich in quartz and albite. The quartz is usually recrystallized, particularly in the zones where mica is scarce. Albite frequently occurs as poeciloblasts containing minute inclusions of epidote and muscovite. It is usually untwinned. Garnets, in the rare cases where they are clear enough, show trains of inclusions which suggest that the garnets grew after the crystallization of muscovite and quartz. Some of the larger grains of garnet have been flattened and stretched.

The most common variety of mica-schist has conspicuous bands rich in quartz. These bands contain no identifiable clastic material; they may have been formed as a result of metamorphic segregation. The possibility that some of them may represent original layering cannot be ruled out. There are also fine-grained mica-schists which contain no quartz-rich bands. The latter can be called pelites, but they constitute no more than about 10% of all the mica-schists. Often these pelites are replaced laterally by semipelites.

Within the Tarn Wedge, the area made up of the two structural subareas no. 7 and 8 as shown on Plate 3, there are a number of occurrences of mica-schists interbanded with amphibole-schists. Most of them are covered by the above description; the main differences are the rarity of garnet in the mica-schists within the Tarn Wedge, and the somewhat higher percentage of fresh chlorite. In one such occurrence, $\frac{1}{4}$ mile north of Llyn Llwydiarth (549790), glaucophane has developed. The grains, which are very small, possess well-defined prism faces and replace chlorite. There is no blue-green amphibole in this rock. An attempt was made to measure any preferred orientation of the glaucophane, but the grains were too small. There is a strong 'stretching' effect in these rocks between Slides 1 and 2. Individual crystals of glaucophane have been boudinaged and now exist in several segments.

There are very thin bands of chert interspersed with the semipelites in the Tarn Wedge. Minute rhombs of glaucophane and grains of epidote are present in these cherts.

While the above assemblages have been treated as derived by metamorphism of sedimentary deposits, other possible origins for these mica-schists must not be overlooked. A subordinate amount

Plate 19a. Typical blue-green amphibole-epidote-quartz schist with subordinate chlorite; derived from tuffaceous sediment. Mynydd Llwydiarth (547792). x.n. X35.

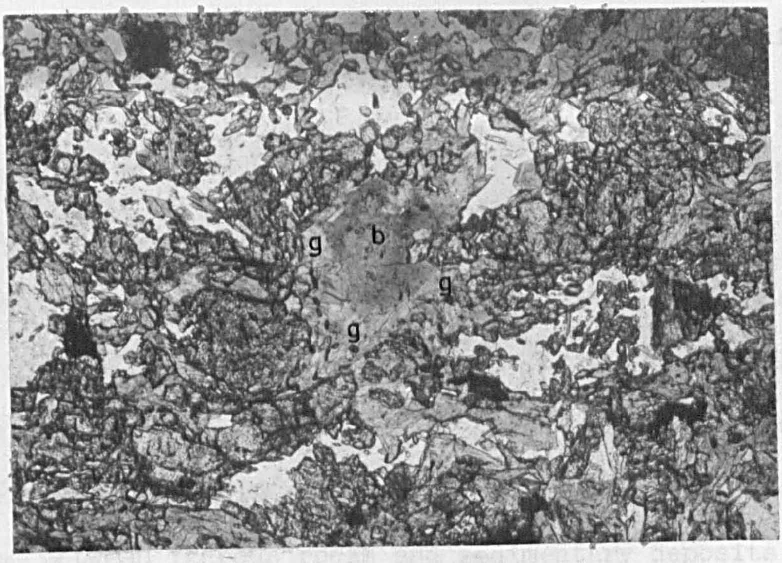


Plate 19b. Glaucophane (light coloured, labelled g) rimming blue-green amphibole (dark coloured, labelled b) in amphibole-epidote schist. North of Llyn Llwydiarth (548788). p.p.l. X80.

may have been derived from igneous rocks, although no evidence for it is available as yet.

v. Rocks of uncertain origin:

a. Mylonite (?): One of the more problematic rocks seen in the area is a fine-grained quartz-albite-muscovite-epidote-(amphibole) schist. It is rich in albite and quartz, usually with an appreciable amount of epidote and sometimes one or both types of amphiboles. Most of the albite and quartz grains have been severely granulated and recrystallized. The thin sections often present a mylonitic appearance. Elongated quartz and feldspar grains are arranged parallel to the long axes of amphibole grains. The amphiboles are sometimes stretched and broken, with occasional recrystallization of fresh amphibole or chlorite in the fractures. These rocks invariably occur either as bands within basic igneous derivatives, or at the junction of the latter with metasedimentary rocks. Between the Slides 1 and 2, glaucophane is well developed in these rocks.

Greenly (1919, p.121) suggested that these rocks may be adinoles. However, it is notable that they are present only between the western margin of the Lower Basic Schist Group in the west and about $\frac{1}{4}$ mile east of Slide 1 in the east. There is little evidence of any reaction between igneous rocks and sedimentary deposits anywhere else in the area. There are no comparable rocks in the practically unmetamorphosed assemblages of the Upper Greenschist Group, where

Plate 20a. A composite grain of glaucophane (dark coloured, labelled g) and blue-green amphibole (light coloured, labelled b) in amphibole-epidote-quartz-albite schist. East of Felinengan(537735). p.p.l. X210.

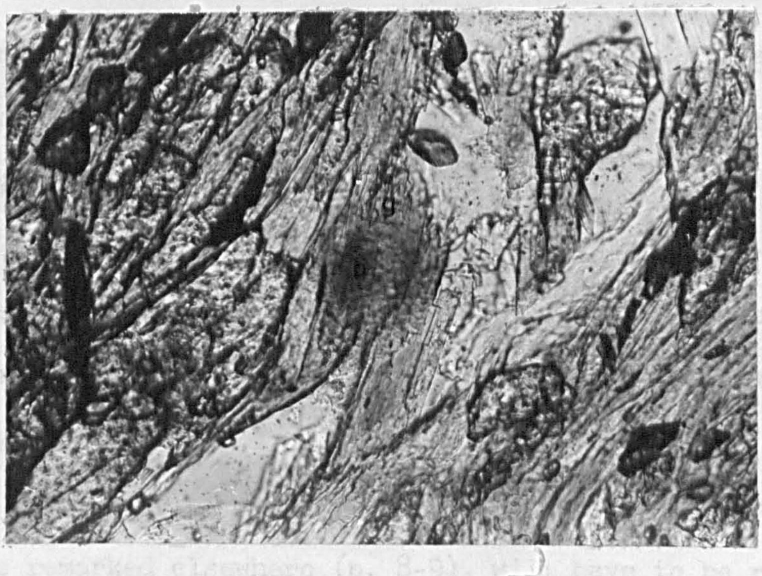


Plate 20b. Glaucophane (light coloured, labelled g) rimming blue-green amphibole (dark coloured, labelled b) in amphibole-epidote schist. South of Castellior (543739). p.p.l. X210.

abundant basic igneous rocks and sedimentary deposits occur together. It seems possible that these rocks may be the cataclastic products of semipelitic sedimentary deposits as a result of shearing concentrated near the boundaries of basic rocks and semipelites.

b. Amphibolites (rocks of the Amphibolite Group): These rocks are coarser than all the other basic rocks in the area. The amphiboles are of two varieties: deep brown, and colourless. Epidote is the next most common mineral, followed by quartz and albite. The epidote is not pleochroic and appears to be relatively poor in iron. Both the amphiboles can occur in the same specimen, and generally this is the case.

The rocks have undergone strong cataclastic deformation, to judge from the numerous shear planes that pervade them, and from the shattering effect observed in individual grains of all minerals. This is probably the effect of Berw Fault movements.

The relations of this group to the other amphibole-bearing rocks are obscure. These amphibolites occur in only one isolated unit and there appear to be no clear relationships with other amphibole-rocks. No gradational types between them have been found. These, in fact, are part of the "ancient floor", one of Greenly's concepts and one which, as remarked elsewhere (p. 8-9), will have to be re-examined and probably modified.

Plate 21a. Comparatively coarse-grained amphibole-epidote-quartz schist from south of Capel Gilead (520733). Individual grains show cataclastic effects (see, for instance, the grain of amphibole above b). p.p.l. X35.

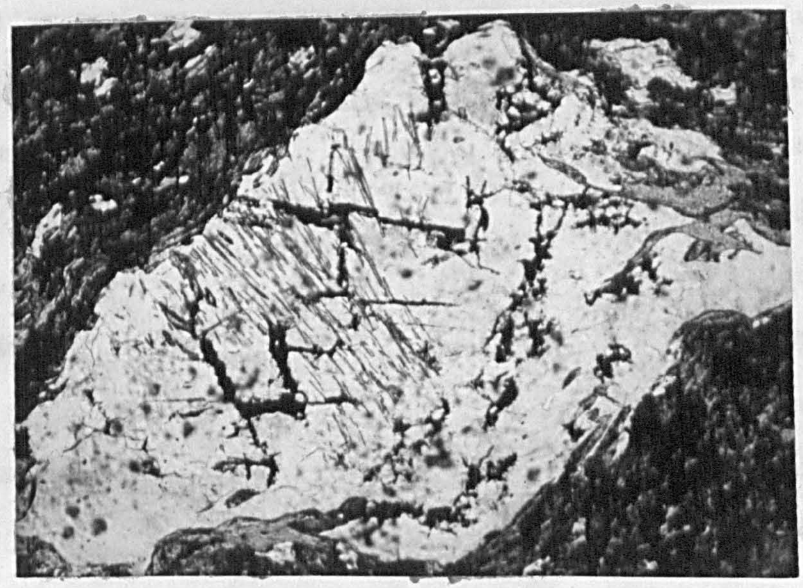


Plate 21b. Amphibole needles within feldspar are preferentially oriented at an angle to the external schistosity. From Gigfran (549793). p.p.l. X50.

5. CHEMISTRY OF THE ROCKS:

i. Introduction:

About thirty bulk rock analyses were obtained by x-ray fluorescence. Most of the rocks analysed are from the three main classes. Details of individual specimens are given in Table 5. A specimen of spilite from Newborough (Specimen no. 30) was chosen for analysis because it was considered to be similar to the spilitic rocks from which the majority of the glaucophane-bearing basic schists under discussion have been derived. Specimens of spilite, free from the effects of weathering, and suitable for analyses, could not be obtained from the Beaumaris coast. The basic amphibole-bearing rocks had been initially selected in order to determine if there is a correlation between the bulk rock chemistry and the chemistry of the amphibole contained. It was assumed that variations in the chemistry of the amphiboles are related to the variations in the optic properties. Thus the rocks selected for analyses contained, between them, amphiboles that covered the range of optic properties as described on p. 20-21. This line of study had to be abandoned when it was found practically impossible to separate samples of amphibole sufficiently pure for chemical analyses. However, the rocks were analysed and they are probably a fair representation of metamorphosed basic rocks from the area. The other rocks were selected for chemical analyses such that all the mineral-assemblages were represented.

The results of the analyses are presented in Table 6. The

Table 5. Details of chemically analysed specimens.

TABLE 5.

Chemically analysed specimens

	Specimen No.	DESCRIPTION	OCCURRENCE
CLASS 1	10 D	Fine grained blue-green amphibole-epidote-glaucophane schist: rich in epidosite bands and lenses	Upper Basic Schist Group
	55	Fine grained blue-green amphibole-epidote schist: quartz is an important accessory	Lower Basic Schist Group
	83	Fine grained blue-green amphibole-epidote-glaucophane schist: epidote-albite?-quartz-calcite veins	Upper Basic Schist Group
	345	Blue-green amphibole-epidote-glaucophane schist with epidosite seams	do
	369	Greenstone: slightly schistose chlorite-quartz-epidote rock with some albite	Upper Greenschist Group
	404	Blue-green amphibole-epidote-glaucophane schist: quartz and muscovite present: epidosite seams	Upper Basic Schist Group
	417	Fine-grained chlorite-epidote schist with blue-green amphibole: rich in epidosite veins	Lower Semipelitic Group
CLASS 2	130	Fine grained strongly sheared chlorite-epidote-quartz schist with calcite-lawsonite veins	Transition Group
	206	Blue-green amphibole-epidote-quartz-albite schist	Lower Basic Schist Group
	211	As above, slightly higher content of blue-green amphibole and epidote which are also better developed	do
	290	Chlorite-lawsonite-glaucophane-(blue-green)amphibole schist with some quartz	Transition Group
	348	Comparatively medium grained blue-green amphibole-epidote-quartz-albite schist: some retrogressive chlorite	Lower Basic Schist Group
	400	As above: amphibole and epidote not quite as well developed, though	do
	403	Blue-green amphibole-epidote-quartz schist: chlorite forms about 10% of rock epidosite seams rather frequent	do
	410	Chlorite-quartz-albite schist with blue-green amphibole	do
	431	Epidote-bearing chlorite-quartz-albite rock with weak schistosity: contains half-digested pyroclastic fragments and pyroxene pseudomorphs: carbonate veins	Upper Greenschist Group
	433	Blue-green amphibole-glaucophane-epidote-quartz-albite schist: muscovite an important accessory	Upper Basic Schist Group
CLASS 3A	291	Quartz-chlorite-muscovite-albite-schist: some admixture of adinole type rock	Transition Group
	292	Chlorite-quartz schist with appreciable muscovite, albite and epidote: carbonate veins	do
	304 A	Chlorite-quartz schist with some haematitic spilite admixture	Berw Fault zone
	304 B	Chlorite-quartz schist as above, but with no spilitic admixture	do
CLASS 3B	107	Muscovite-quartz-albite schist with epidote and garnet	Lower Semipelitic Group
	296	Muscovite-quartz-chlorite schist with some albite: green pleochroic mica present(chlorite?)	Transition Group
	418	Muscovite-quartz-albite-epidote schist with garnet	Lower Semipelitic Group
OTHERS	101	Quartz-albite-muscovite schist: partly mylonitised: a little chlorite	Upper Basic Schist Group
	106	As above: abundant muscovite	do
	214	Quartz-albite-mica schist: some green micaceous streaks present(chlorite?)	do
	30	Spilitic lava: slightly altered	Newborough

Fe^{+++}/Fe^{++} ratio may be unreliable due to the high-powered mechanical grinding (Tema grinder) used for preparing the specimens. MnO content is negligible and hence has been ignored.

The analyses were converted to Niggli values for graphical presentation. The Niggli values for the specimens are on Table 7. Plots involving mg, c, al, alk and ti would seem to be significant (Figs. 2.5 - 2.9).

ii. Results and interpretation:

In a paper on the origin of amphibolites from Northwest Adirondacks, Leake (1963) has suggested that different trends of chemical variation may be used to distinguish ortho- and para-amphibolites. The principles discussed by Leake in that paper have been employed in the interpretation of the present results.

a. c/mg ratios (Fig. 2.5): The rocks of Class 1 tend to provide the closest concentration of points. This concentration lies upon the trend displayed by Karroo dolerites (Walker and Poldervaart, 1949). The Karroo dolerites have been used as a background against which to view the present analyses, since their chemistry has been studied in detail.

Rocks from Class 3b are also well concentrated and fall within or near the expected pelite and semi-pelite range. Plots from Class 3a fall away from those of 3b, towards the plots of Class 1.

Rocks of Class 2 lie mostly in the same area as those of Class 1, but are more spread out and with a distinct tendency towards the semipelite zone. The overall picture illustrates what has already been stated regarding these rocks in general:

Table 6. Results of chemical analyses.

TABLE 6.

No.	10 D^{+}	55	83^{+}	345^{+}	369	404^{+}	417	130$^{\wedge}$	206	211	290$^{+\wedge}$	348	400	403	410	431	433^{+}	291	292	304 A	304 B	101	106	214	107	296	418	30	
SiO_2	44.0	48.0	48.5	48.5	48.5	48.0	49.0	47.0	49.0	48.5	46.0	47.0	47.0	49.5	48.0	42.5	48.0	72.0	54.0	50.0	45.0	72.0	67.0	72.5	66.0	66.0	67.0	48.0	SiO_2
TiO_2	1.96	1.56	1.48	1.84	2.10	2.00	1.36	1.52	2.08	2.18	1.72	1.60	1.42	2.08	1.60	2.76	3.10	0.36	2.05	2.65	2.90	0.36	0.59	0.32	0.66	0.92	0.75	2.00	TiO_2
Al_2O_3	10.20	11.50	13.10	11.20	10.90	11.00	11.20	11.10	11.70	11.70	13.30	11.60	12.30	11.70	11.10	14.10	12.40	13.20	15.80	13.20	12.70	13.30	16.00	13.50	16.10	15.40	14.60	10.90	Al_2O_3
Fe_2O_3	13.2	5.52	3.96	4.81	6.62	4.52	2.40	3.10	4.23	7.94	6.02	3.69	1.61	4.89	3.71	7.55	4.76	1.08	4.31	5.07	3.00	0.88	2.10	0.01	0.75	1.85	0.46	2.60	Fe_2O_3
FeO		5.56	6.56	6.47	6.10	7.98	7.06	7.38	6.81	3.61	5.91	6.58	7.88	6.62	6.82	7.60	6.74	2.32	4.63	7.32	10.81	2.09	2.07	2.38	3.52	4.81	4.17	8.42	FeO
MgO	8.50	8.80	8.35	8.00	7.90	7.60	7.70	9.10	7.60	8.60	8.60	9.10	9.80	6.60	10.3	9.25	5.80	2.60	3.90	8.00	10.50	2.40	2.30	1.90	2.20	3.30	2.50	7.4	MgO
CaO	13.65	12.70	11.10	12.10	10.0	11.40	13.00	9.32	11.0	10.20	6.70	12.40	12.75	11.35	10.65	6.35	10.15	0.60	5.93	3.52	4.40	0.80	0.35	0.55	0.50	0.38	1.20	11.55	CaO
Na_2O	1.11	1.27	2.35	2.26	1.49	2.56	2.33	5.88	2.80	2.76	6.24	2.72	2.51	2.65	1.68	1.06	2.48	3.71	5.85	2.30	0.46	3.43	2.75	4.30	2.69	2.64	3.36	3.47	Na_2O_3
K_2O	0.30	0.01	0.38	0.25	0.20	0.35	0.25	0.50	0.25	0.32	0.20	0.68	0,15	0.40	0.10	1.15	1.70	2.65	0.35	1.10	1.28	1.42	3.50	1.75	4.45	2.50	2.90	0.15	K_2O
H_2O^+	8.66	4.46	4.00	3.79	5.28	3.95	5.42	6.88	3.84	4.26	6.61	4.76	4.48	4.00	5.00	8.79	4.28	2.01	2.75	7.13	7.00	2.05	3.00	1.90	3.78	3.26	3.79	4.36	H_2O^+
Total	101.58	99.38	99.78	99.22	99.09	99.36	99.72	101.78	99.31	100.07	101.30	100.13	99.90	99.79	98.96	101.11	99.41	100.53	99.57	100.29	98.05	98.73	99.66	99.11	100.65	101.06	100.73	98.85	Total

+ contains glacophane ^ contains lawsonite that, although there are well-defined basic igneous rocks (Class 1) and there are rocks that are quite close to semi-pelites in composition (Class 3b), there also exist gradations between the two, caused by their mixtures in varying proportions (Classes 2 & 3a). The manner in which the three Classes 1 to 3b are arranged in Fig. 2.5 appears to adequately justify the scheme of classification adopted and which is largely independent of stratigraphic units.

b. 100 mg+c+ (al-alk) = 100: Much the same interpretation as above (in the section dealing with c/mg ratios) can be applied to these plots (Fig. 2.9), although the plots of the igneous rocks and derivatives in this case fall rather off the trend exhibited by the Karroo dolerites.

c. mg/ti ratios: The mg against ti plots of the rocks of Class 1 provide a good negative correlation which would extrapolate to ti=0 at (approximately) mg=0.8 (Fig. 2.6). This compares well with the mg/ti plots for the Karroo dolerites. The plots of Class 2 provide a similar, but much dispersed, correlation between ti and mg. The rocks of Class 3a and 3b show a different state of affairs from those of Classes 1 and 2. Although apparently, the rocks of sub-class 3a have on the whole a higher ti content than those of 3b, this will have to be confirmed or denied by further analyses.

d. alk/mg ratios: The alk/mg plots for all the rocks of Class 1 fall within the range displayed by the Karroo dolerites (Fig. 2.7). Plots of Class 2 fall mostly in the same range, but there is a very slight tendency to have a higher alk/mg ratio.

Table 7. Niggli values computed from Table 6.

TABLE 7.

Niggli values

No.	10 D^{+}	55	83^{+}	345^{+}	369	404^{+}	417	130$^{\wedge}$	206	211	290$^{+\wedge}$	348	400	403	410	431	433^{+}	291	292	304 A	304 B	101	106	214	107	296	418	30	
si	98.8	110.2	112.7	113.1	119.5	112.1	121.3	105.1	117.3	114.0	105.7	104.7	102.4	120.9	110.2	99.5	121.4	354.1	151.0	137.5	111.2	380.8	313.5	388.7	296.7	275.4	297.2	113.5	si
al	13.46	15.5	17.9	15.4	15.8	15.1	16.3	14.6	16.5	16.2	18.0	15.2	15.8	16.8	15.0	19.4	18.4	38.2	27.0	21.4	18.5	41.4	44.0	42.6	42.6	37.8	38.1	15.2	al
fm	50.8	50.4	48.7	49.0	53.9	50.1	43.2	49.5	48.5	51.4	51.3	48.4	49.0	46.6	54.9	60.5	45.2	32.7	37.5	60.2	66.8	31.7	31.3	26.0	30.5	43.2	33.6	47.4	fm
c	32.9	31.3	27.6	30.2	26.4	28.5	34.5	22.3	28.2	25.7	16.5	29.6	29.8	29.7	26.2	15.9	27.5	3.2	18.4	10.4	11.7	4.5	1.75	3.2	2.4	1.7	5.7	29.3	c
alk	2.84	2.8	5.9	5.5	3.9	6.3	6.0	12.8	6.9	6.8	14.2	6.8	5.5	6.9	3.9	4.1	8.8	26.0	17.1	8.1	3.1	22.3	22.9	28.3	24.5	17.3	22.6	8.2	alk
ti	3.28	2.7	2.6	3.2	3.9	3.5	2.5	2.6	3.7	3.8	3.0	2.7	2.3	3.8	2.8	4.8	5.9	1.3	4.8	5.5	5.4	1.4	2.1	1.3	2.2	2.9	2.5	3.5	ti
k	0.15	0.01	0.10	0.07	0.08	0.08	0.07	0.05	0.06	0.07	0.02	0.14	0.04	0.09	0.04	0.41	0.31	0.32	0.38	0.24	0.65	0.21	0.46	0.21	0.52	0.38	0.36	0.03	k
mg	0.56	0.60	0.60	0.57	0.54	0.53	0.66	0.62	0.56	0.59	0.58	0.63	0.65	0.52	0.65	0.54	0.49	0.59	0.45	0.55	0.58	0.60	0.52	0.59	0.49	0.48	0.50	0.55	mg

+ contains glaucophane ^ contains lawsonite

This tendency is more obvious in rocks of Class 3a; Class 3b has consistently the highest alk/mg ratio.

e. k/mg ratios: The k vs. mg plots provide a rather dispersed picture for all the classes; the only definite point it makes is that the k/mg ratio of the basic rocks is consistently lower than that of the Karroo dolerites (Fig. 2.8). All the other rocks yield scattered points.

iii. Discussion:

In short, the analyses of the rocks of Class 1, in each case but one, provide good concentrations or weak trends. In the case of concentrations, these lie within the field of expected trends of ortho-amphibolites. Similarly, the weak trends also closely follow the expected trends. The plots of Class 2, although close to those of Class 1, reflect an admixture of semipelitic compositions to a small extent. The exception to the generally favourable results is the k/mg plot. However, it does not contribute any contrary evidence.

Rocks of sub-classes 3a and 3b need more analyses if variations within the class are to be interpreted. In general, 3b compares favourably with semipelitic compositions, while the plots of 3a are compatible with what might be expected from a mixture of semipelitic rocks and basic igneous material.

Compositions of some other rock types have also been plotted. A comparison of the plots of the unmetamorphosed spilite with those of glaucophane-bearing basic schists suggests that metasomatism was not an important factor in the derivation of the

Figs. 2.5-2.9. Plots of Niggli values for the chemically analysed specimens.

2.5. Plots of c against mg.
2.6. Plots of ti against mg.
2.7. Plots of alk against mg.
2.8. Plots of k against mg.
2.9. Plots of 100mg+c+(al-alk) = 100.

FIG. 2.5

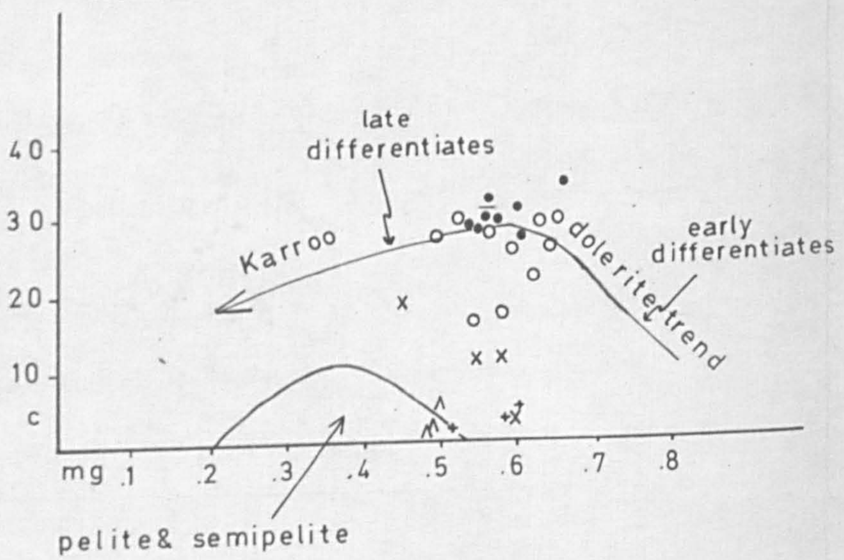


FIG. 2.6

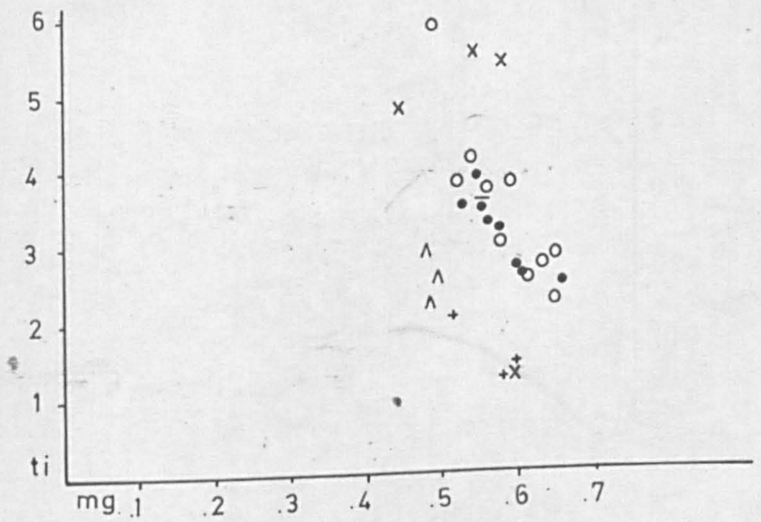


FIG. 2.7

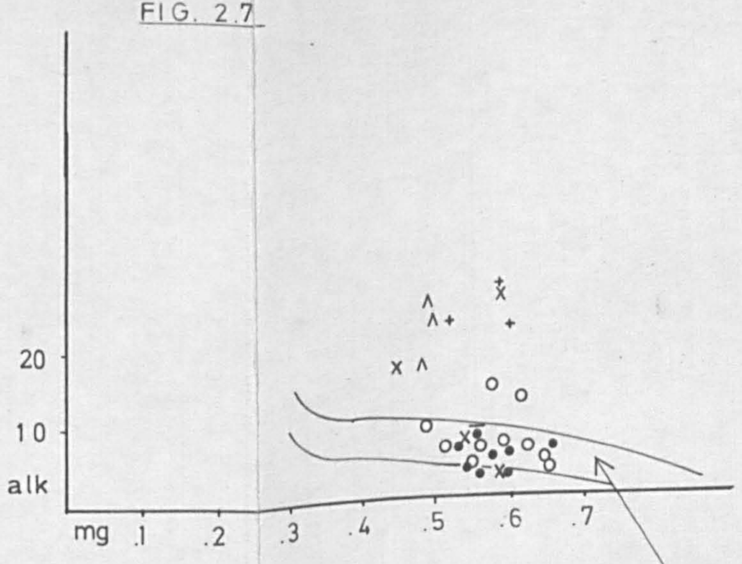
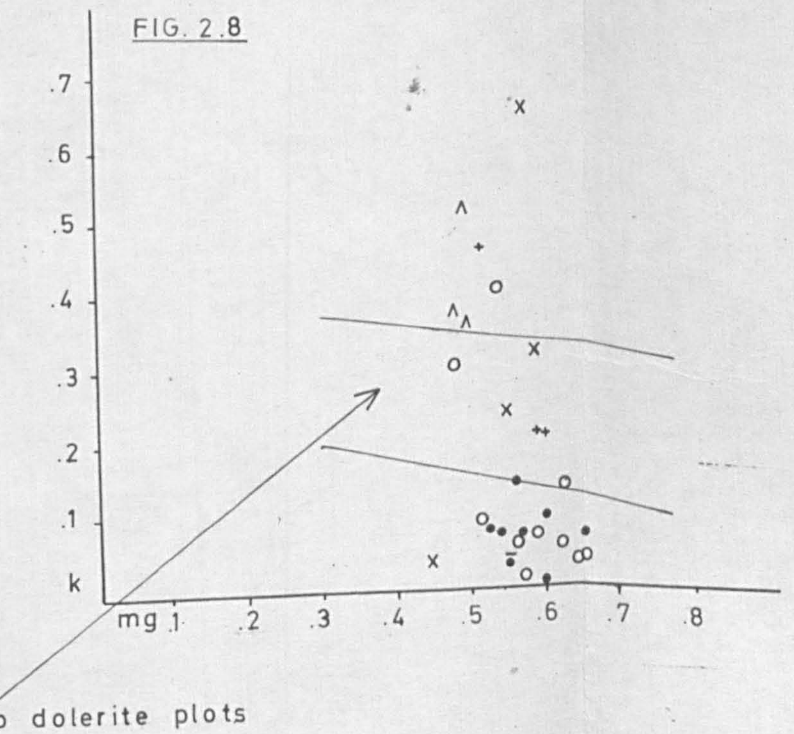
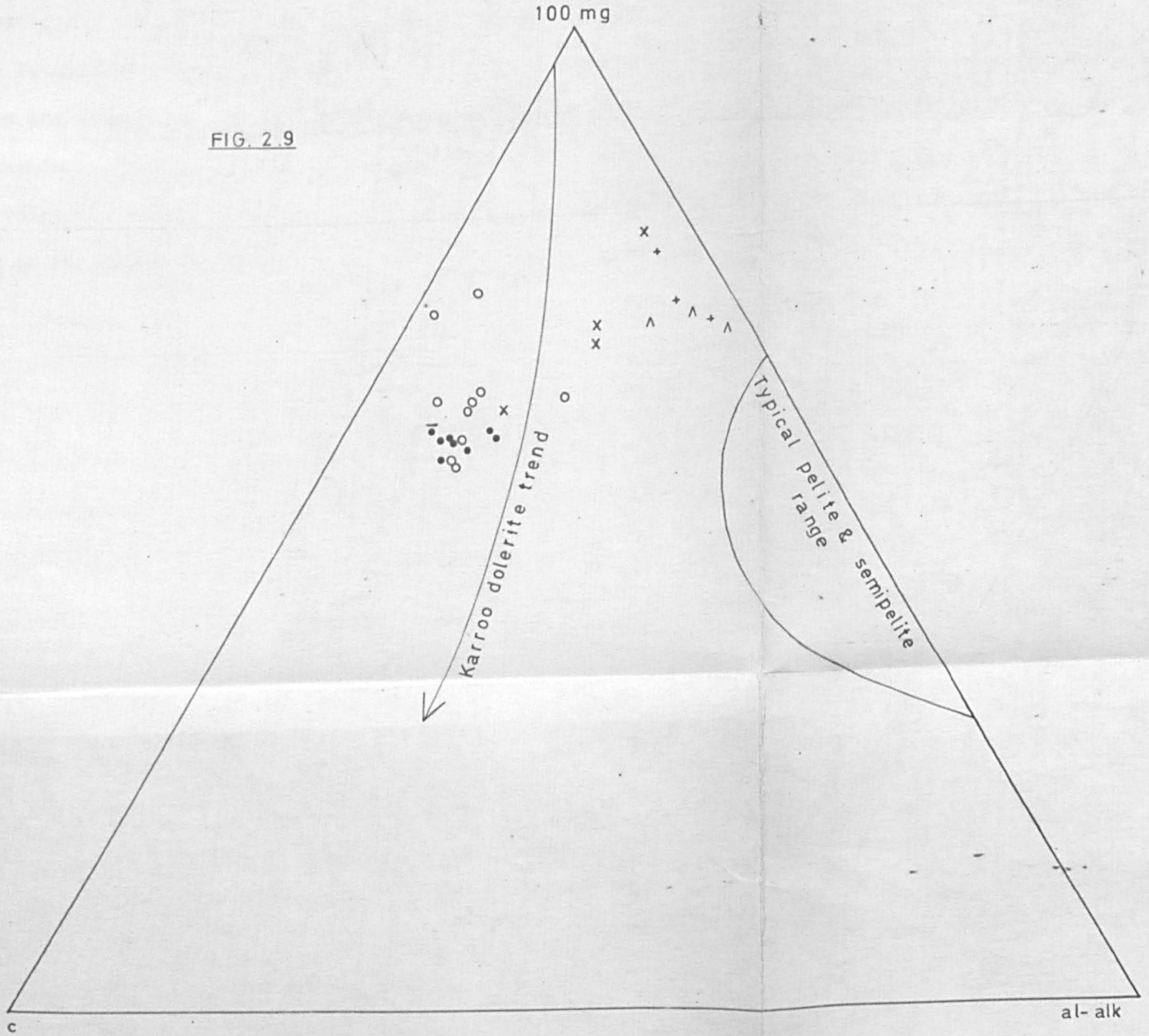


FIG. 2.8



Range of Karroo dolerite plots

FIG. 2.9



ANALYSIS OF BULK ROCK CHEMISTRY

- • plots of rocks from class 1
- o 2
- x 3a
- ^ 3b
- \+ . . . . . Quartz-albite-muscovite schist of mylonitic aspect (see text, p.48)
- •̄ . . . . . Spilitic lava from Newborough

latter; nor was the Na-content of the parent rock unusually high. Tables 6 and 7 also show which of the chemically analyzed specimens contain glaucophane and/or lawsonite. It seems significant that rocks which do bear glaucophane are not consistently different in bulk chemistry, as far as Al_2O_3, MgO, CaO, Na_2O and total Fe contents are concerned, from rocks that do not contain glaucophane. The comparatively uniform chemistry of the basic rocks as a whole argues against selective introduction of fluids as a control for glaucophane development in this area and suggests that a search for a structural or deformational control would be more profitable.

Plots of mylonitic rocks of uncertain origin (described on p.48) are rather similar to those of Class 3b. This is agreement with the possibility suggested earlier (p.49) that the mylonitic rocks may be cataclastic products of semipelitic rocks. However, more analyses are required, particularly of those mylonitic rocks which bear amphibole, before any definite conclusions can be reached regarding the possibility of reaction having occurred along the boundary of the basic igneous rocks and the semipelitic rocks.

CHAPTER III

STRUCTURAL GEOLOGY

1. INTRODUCTION:

The structural picture of this part of Anglesey has been built up from detailed investigation of the structural elements observed within nine subareas. Plate 3 shows the limits of each subarea and should be viewed in conjunction with Plate 1. Each subarea was delineated with a view to obtaining a consistent picture of the geometry of structural elements within areally restricted zones. Details are given below (p. 58) on how these sub-divisions were made.

The structural elements most widely observed within the subareas are the foliation plane S_1, which is essentially a metamorphic feature, one or more sets of fold axes, various associated linear features and the corresponding axial planes.

The structural data obtained have been analysed, in the first instance, separately for each subarea. In addition to field-observations regarding the mutual relationships between the various structural elements, the data obtained have been plotted to produce lower hemisphere stereonet projections for each subarea. These stereograms are presented on Plate 3.

The most obvious structural feature in all the subareas is the foliation plane S_1. The poles to foliation plane readings in each subarea, when plotted on the stereographic net, lie in a restricted zone defined by a complete or a partial girdle.

Although the precise orientation of the girdle, and its sharpness, varies from one subarea to another, all the girdle axes have a northerly plunge. Most linear elements in any subarea are closely associated with the pole of the foliation plane girdle for that subarea.

2. GENERALIZED RESULTS:

It is possible to distinguish at least two sets of folds that fold the foliation/ S_1 in most subareas. The most widespread folds trend northerly and plunge at low angles to the north. These are tight or isoclinal folds and have an amplitude several times the wavelength in the western part of the area; eastward, the folding is less tight and less frequent, and appears to die away towards the coast, where shearing becomes more prominent. Axial plane cleavage is rarely developed. These folds may be observed on the scale of a few feet fairly easily, but their existence on a larger scale has not been demonstrated. The difficulty lies in the lack of suitable marker horizons, the discontinuous nature of the exposures, and the generally tight, shallow-plunging geometry of these folds. These folds are hereafter referred to as the first folds, folds of the first generation, or B_1 folds.

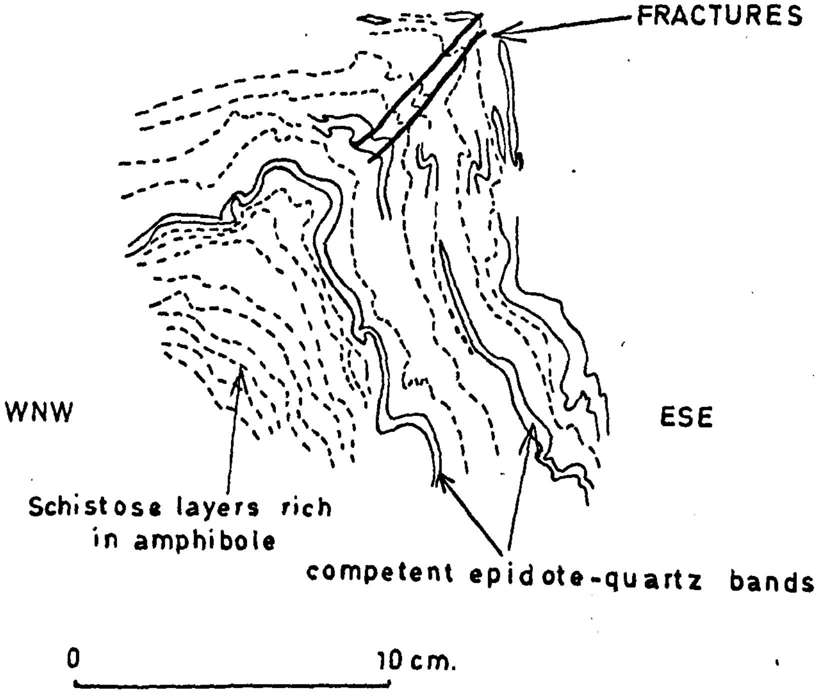
Associated with first folds are lineations b_1, which may be formed by preferred orientation of minerals, or by a "rodding" effect caused by spindle-shaped tectonic residues of more competent rock within schistose material. These lineations are parallel to the axes of the B_1 folds. Rarely, a slight angle can be discerned between the rodding and mineral lineations. Whenever this is the case, the mineral lineation is superimposed on the rodding.

The second generation of folds, B_2, tend to possess a comparatively open geometry (Fig 3. 1). The angle between the two limbs is usually between 40° and 90°, and the amplitude and wavelength have comparable magnitudes. These folds are responsible for the changes in the trend of the foliation plane S_1 as observed in subareas 1, 3, 7, 8 and 9. The trend of the B_2 axes in general is also northwards and the plunge usually shallow to the north. Their axial planes dip at moderate or high angles to the north-west. Occasionally a micro-fold crumpling produces a lineation parallel to the B_2 fold axes, especially in subarea 8.

A third set of folds is seen around Felinengan (537736) in subarea 3. These folds, termed B_3, overturn to the north-east, and refold the two earlier generations of folds. Their existence is doubted elsewhere; even at Felinengan, they are found only on a small scale, the largest examples not exceeding two feet in amplitude or wavelength. Amplitude of individual B_3 folds is approximately half the wavelength. They are accompanied by a strong crumpling lineation parallel to the fold axes.

Gentle undulations of the S_1 foliation about an east-west shallow plunging axis give rise to what have been termed the B_4 folds. These folds are accompanied by a weakly developed crumpling lineation parallel to the B_4 axes. These structures have been noticed infrequently in subareas 1 and 3. They are more

FIG.3.1



SKETCH OF B_2 FOLD
MYNYDD LLWYDIARTH
(547787)

common east of a line drawn through Llandegfan (561743) and Llansadwrn (554758), a zone that lies outside the subareas analyzed on Plate 3.

The folds of second generation, B_2, are areally associated with faults in subareas 1, 3, 7, 8 and 9, where these folds are most strongly developed. It can be seen in many instances that the intensity of these folds increases towards fault zones. Such a relationship is particularly noticeable just north of Felinengan (537736) in subarea 3, and north of Llyn Llwydiarth (549788) in subarea 7.

The structurally analyzed area was divided into subareas in the following manner. The initial sub-division was made along Slides 1 and 2 (Plate 1). This effectively created three zones, each characterized by a unique overall attitude of the foliation S_1. In the western zone, to the west of Slide 2, the foliation dips at moderate angles to the west; in the central zone, between Slides 1 and 2, it has a variable attitude due to the superimposition of B_2 folds on B_1 folds; and in the eastern zone, to the east of Slide 1, the foliation has vertical or steep dips. Amongst these three zones, the variability in the orientation of foliation S_1 is the least in the western zone, and the greatest in the central zone. This characteristic, i.e., the variability in the orientation of foliation S_1, thus served as the most important basis for the sub-division of the area. Further sub-divisions were made on the basis of contrasts in the development and orientations of the B_1, B_2 and B_3 structures. Consideration of B_1

structures resulted in a separation of the central zone into three subzones, because the B_1 structures in a part of the central zone (ultimately consisting of subareas 7 and 8) are oriented in a north-easterly direction, while they are northerly in the rest of this zone.

Within the central zone, i.e., the area between Slides 1 and 2, the attitude of the foliation is very variable. Subareas 1 and 3 are separated from 7, 8 and 9 by about two miles of unexposed ground. Subarea 3 has been treated separately from 1 only because of the occurrence within the former of B_3 folds which are practically absent in subarea 1. Subareas 7 and 8 were separated from each other on the basis of the fault that divides them, although subsequently it is found that there is a great deal of similarity between the stereograms obtained from them. They may therefore be treated together. Subarea 2 is made up of two parts, separated from each other by unexposed ground. The geometry of the structural elements is essentially the same in both parts, and consequently they have been given the same reference number. The same applies to subarea 4.

3. THE STRUCTURAL ELEMENTS:

i. Planar structures:

a. The original compositional banding is best seen in the south-east of the area near to the Menai Strait (580740), where it is due to an alternation of discontinuous basic and siliceous lenticles. The basic bands are of practically unmetamorphosed volcanic rock and the siliceous bands are of sedimentary origin. The spacing of this banding is very variable; individual bands may be a few feet thick or only a few tenths of an inch thick. The compositional banding seen in other parts of the area is probably partly derived from original stratification, as suggested by the presence of clastic grains of quartz in some of the siliceous bands.

b. Along the eastern edge of the area, between Gazelle Hotel (580740) and Rhos Llaniestyn(582795), closely spaced shear planes are parallel to the overall orientation of the original compositional banding, but can be seen to cut across the irregularities of the latter on the small scale. There is hardly any recrystallization along these shear planes. Further to the west, recrystallization has resulted in a fine, evenly spaced compositional layering which is also parallel to the overall attitude of the coarser and variably spaced banding, the latter probably representing original stratification. This new banding is principally due to alternation of layers rich in quartz,chlorite or epidote. The orientation of the layering is generally parallel to the rock-type boundaries on a large scale. The basal planes of platy minerals and the longest axes of prismatic minerals lie within this planar structure which is named S_1 foliation. The word foliation as used hereafter implies S_1 foliation unless otherwise qualified.

c. The S_1 foliation plane has been folded by two or three generations of folding over much of the area. Normally, the axial planes of these folds have only abstract significance. Rarely, secondary foliation planes are developed parallel to one or other of these axial planes. Such instances are made possible by rearrangement of the basal planes of micaceous minerals along the axial plane of folds; by the development of strain-slip cleavage; and by the growth of new minerals such as mica, epidote, amphibole or sphene preferentially developed along the strain-slip cleavage. These secondary foliation planes are confined to the incompetent layers in layered sequences.

d. Another prominent set of S-planes to be seen in much of the area consists of joint planes nearly normal to the northerly trending fold axes. They are best developed in subareas 1, 3, 7, 8 and 9.

ii. Linear structures:

All the penetrative linear structures are reconcilable with one or other of the fold generations. A linear structure may be expected to lie parallel to the axis of the associated fold, and to be best developed in areas of strong folding.

a. Micro-folds have a corrugating or crumpling effect on the foliation. They are locally well-developed in several parts of the area. Usually this effect is not pronounced, but most of the occurrences are about axes that are demonstrably parallel to neighbouring mesoscopic folds. When the fold hinges are closely spaced, say, in the order of a few millimetres, the effect is a strong micro-fold crumpling lineation.

b. Lineation due to intersection of two planes is hardly ever developed, and consequently this type of lineation has been observed but rarely.

c. Rodding, boudins: these linear structures have been produced by disruption of the more competent bands within a layered sequence. Fragments thus formed from competent material have their long axes parallel to the fold axis and are most common in zones of strong folding. Such rods and boudins may be built from various rock types in their respective settings, i.e., quartz-rich material within semipelites, or epidotic bands within glaucophane schist. The precise form of these linear inclusions is presumably controlled by the relative competency, and by the intensity of deformation.

d. Quartzo-feldspathic lenticles with their longest directions parallel to the B_1 fold axes sometimes occur, especially in subareas 3 and 7. They are most common in zones where the B_1 folds are best developed.

The rodding, boudin and mineral lineations are more particularly related to the earliest folds, whereas the minor fold corrugations, and to some extent the rodding, are more closely related to the later fold movements.

b_1, b_2, etc., are symbols used for lineations associated with B_1, B_2 folds, etc., respectively.

4. HISTORY OF FOLDING:

All the folds seen in this area fold the S_1 foliation. It is possible that the S_1 foliation was developed during an episode of folding earlier than those now seen in the area, but if that is the case, no evidence has been found for it.

i. Folds of first generations:

The earliest folds seen in these rocks are very tight structures with northerly axes and shallow plunges. This structure is obvious only on a relatively small scale. The possibility of similar folds being present on a larger scale, with amplitudes in the order of several tens of metres, cannot be readily discounted. Indeed, close examination of the variation in dip and strike of the foliation on Mynydd Llwydiarth (547790) might suggest the presence of such structures, but lack of suitable stratigraphic marker horizons would make their recognition difficult. No such structures have been mapped on the 6": 1 mile map. The author believes it is very unlikely that large tight folds affect these rocks so as to cause repetition, within the area covered by Plate 1, of any of the eight units listed on Table 4. To the east of subarea 4, these folds become less frequent and are practically absent near to the eastern boundary of the area.

Lineations parallel to the axes of these folds are widespread. These include the preferred orientation of amphiboles and epidote grains in the Upper and Lower Basic Schist Groups.

ii. Folds of second generation:

The rocks in subareas 1, 3, 7, 8 and 9 bear clear evidence of superimposed folding. Individual folds of the earliest generation, B_1, which are practically isoclinal in form over much of these subareas, have their axial planes folded by the later set of folds, B_2.

It is notable that the axes of the second generation of folds are essentially parallel to those of the first generation (Fig. 3. 4). It is possible to distinguish between the two generations when they occur together. Otherwise, over most of the area, one has to fall back on the general differences in styles and orientation of axial planes in order to achieve the distinction. It becomes feasible to allocate individual folds in most cases to one or the other generation confidently on the basis of one or more of these features. The axial planes of the B_2 generation of folds tend to be variable, even in individual exposures, although they lean pretty consistently to the east or south-east (Fig. 3. 2).

Crumpling lineation is sometimes associated with the second generation of folds. This crumpling lineation is parallel to the axes of the B_2 folds themselves.

The B_2 folds are developed on a scale sufficiently large to be mapped on the 6": 1 mile scale within subareas 1, 3, 7, 8 and 9. The two extreme positions of the foliation plane folded by B_2 may be generalized. They are:

(a) moderate to steep dips towards west-north-west

and (b) moderate to low dips towards north-north-east to east-north-east.

Stereograms have been constructed by plotting the poles to the foliation observed in the subareas mentioned above, viz., 1, 3, 7, 8 and 9 (See Plate 3). The results consistently display a girdle whose axis plunges at low or moderate amounts to the north, and is in general agreement with the plunge of the second fold axes. The rather diffused distribution patterns of the poles to the foliation planes are due partly to the somewhat gradual change in the orientation of the S_1 planes around the B_2 hinges, and partly due to the variable attitudes of the axial plane controlling the orientation of the fold limbs. It should be noted that the presence of the earliest folds would tend to accentuate the picture of a girdle, since the two fold generations are essentially co-axial. It is not practicable to separate this additive effect on the stereogram.

The B_2 folds were probably produced by a compressive stress acting in a plane approximately normal to the fold axes, and resulting in slip along S_1. The general absence of axial plane cleavage suggests that the B_2 folds are flexural folds rather than slip folds. Minor B_2 folds are often apparently controlled by buckled relatively competent layers (Fig. 3. 1). The irregular orientation of the axial planes of B_2 folds also indicates that the folds were formed by compression rather than shear.

5. DETAILS FROM SUB-AREAS (Refer to Plate 3):

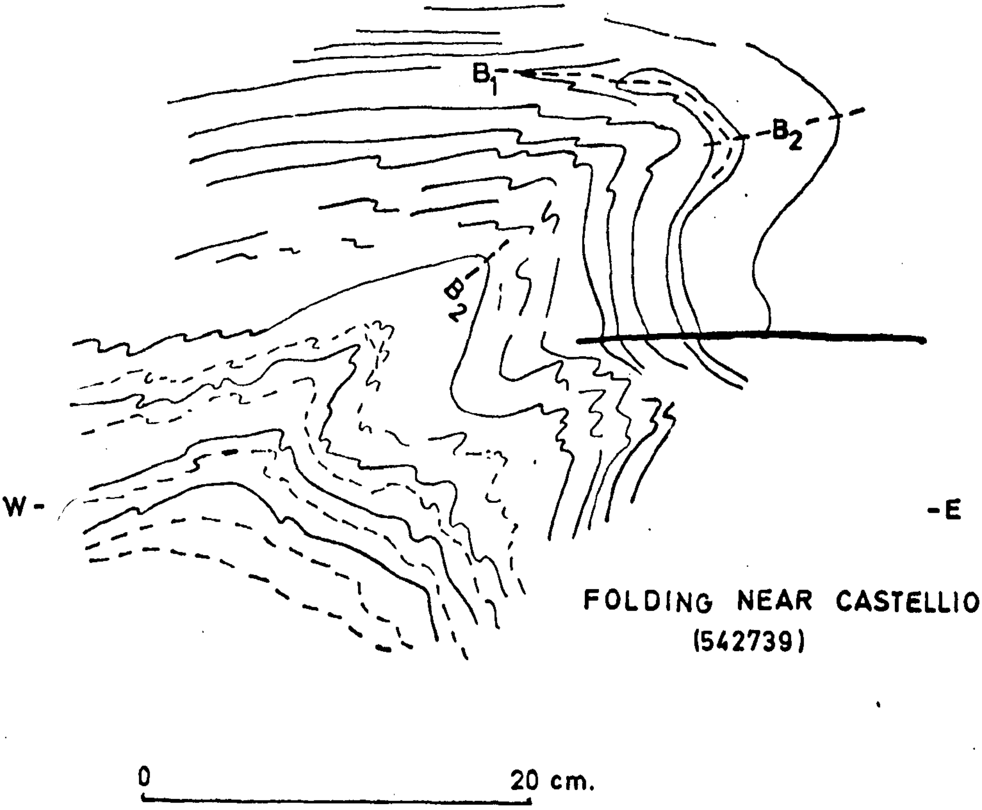
i. Subarea 3:

This subarea has been described first because it displays all the episodes of folding better than any other. A plot of the poles to the foliation planes and B_1 axial planes results in a partial girdle the axis of which plunges about 30° due north or slightly west of north. The prime cause of this pattern is the folding of the foliation plane around the B_2 axes. The observed B_2 axes have also been plotted on the stereogram.

The presence of the B_2 folds is reflected in the variations in the strike of the foliation on the 6": 1 mile map (Plate 1). The axial planes are not consistently oriented, but usually dip from 30° to 50° towards northwest or west. The plunge of the B_2 fold axes is scattered around 30° to the north. But it is notable that even in a single fold, or in a group of folds within a small space, the precise orientation of the axial plane is variable from rather steep to nearly flat dips towards west or northwest (Fig. 3. 2). The poles to these axial planes fall roughly on a great circle whose pole plunges due north at a low angle.

The causes of such variations in the orientation of the axial planes of the B_2 folds were probably manifold. In some cases, it can be seen that the change in dip of the axial plane is due to a fanning effect, even in minor folds. Occasionally, in minor refolds it can be observed that the axial plane of the B_2 fold undergoes a slight change in orientation as it crosses the axial plane of the B_1 fold. This would suggest that the earlier folds themselves were in some instances tightened up during the generation of the B_2 folds. Also, the axial planes

FIG. 3.2



FOLDING NEAR CASTELLIOR
(542739)

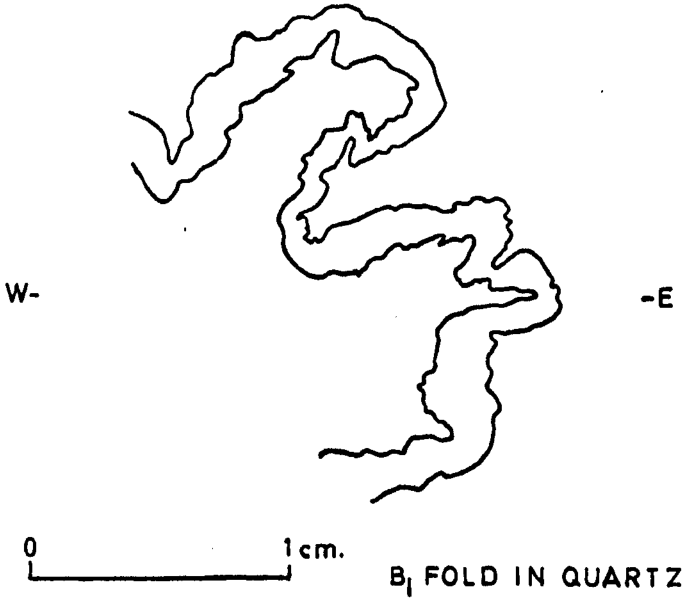
of folds developed in the earlier stages of the B_2 deformation were subject to the effect of rotation about B_2 axes in later stages of the same generation of folding.

There is, particularly in this subarea, a third generation of folding to be discerned. These are overturned consistently towards north-east, and their axial planes dip at moderate angles towards south-west. Within a small area north of Felinengan (537736), where they are well developed, the axial planes to these third generation folds tend to be reasonably consistent. Minor crumpling produces a lineation which is well developed parallel to the axes of these B_3 folds. The plunge of this linear structure is shallow to moderate in the north-western quadrant.

The stereogram plot of the poles to the foliation plane does not divulge the presence of more than one distinct set of axes of rotation. The most reliable method of demonstrating the existence of refolding lies in being able to show that the axial planes of the minor B_1 folds have been flexed by the B_2 folds (Figs. 3. 2 & 3. 4). A plot of the poles to the earlier axial planes provides information about the later fold axes, always assuming an initially constant orientation of the former. The axial planes of the B_1 folds, which were originally probably dipping at moderate angles to north-west, when refolded, tend to lie on a girdle whose pole is not materially different from the pole to the foliation plane girdle.

It was noted in the field that linear structures connected

FIG. 3.3



B_1 FOLD IN QUARTZOSE BAND
NEAR YR-ALLT (553732)

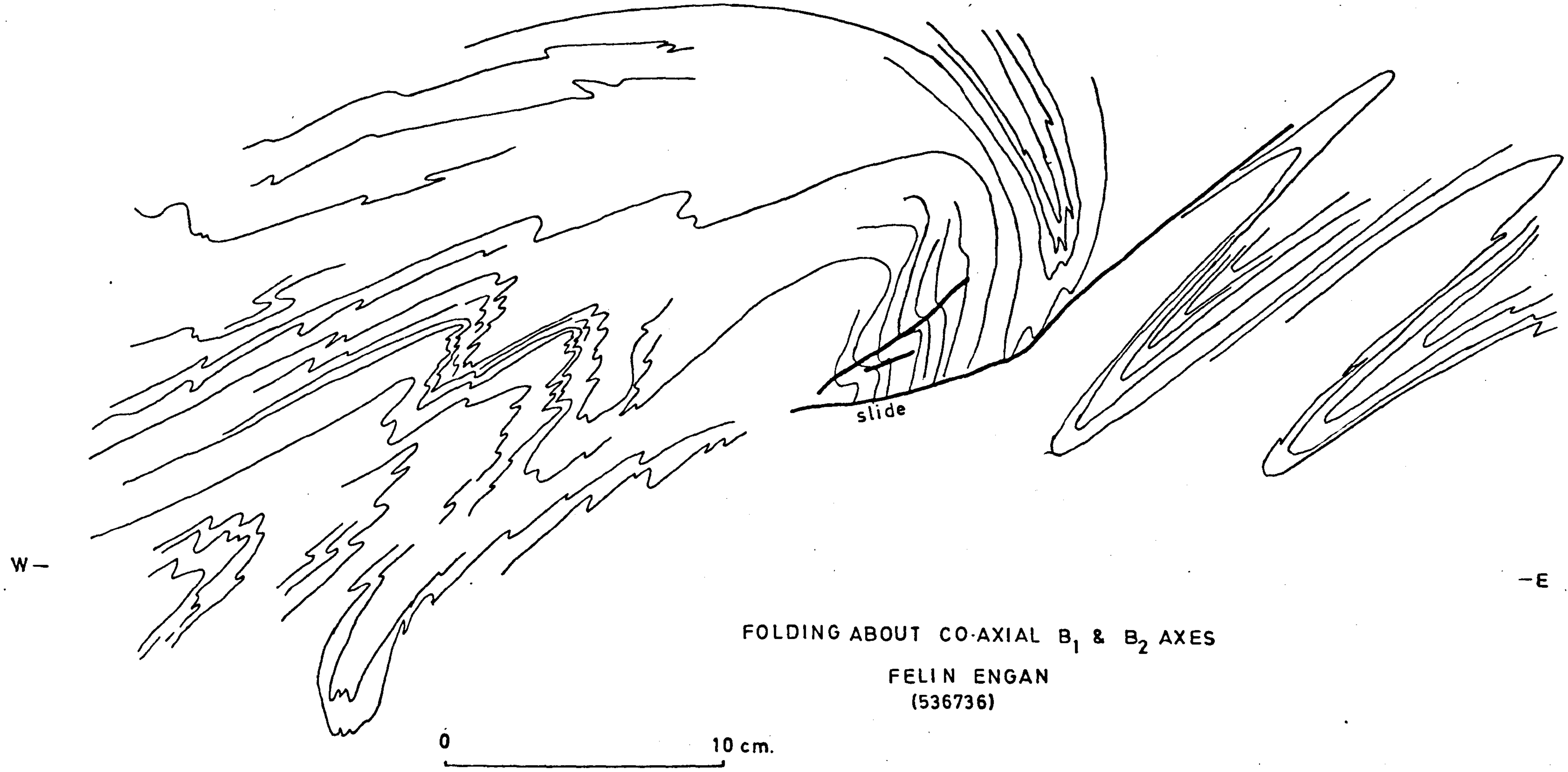
with the B_1 folds are better developed within the subareas where the B_2 folds are best developed as well. In the subarea under discussion at present, B_1 folds with amplitudes upto ten feet can be seen, and they are usually accompanied by b_1 linear structures such as quartz-rodding and quartzo-feldspathic lenticles. These linear structures are more strongly developed within this subarea, as well as in subareas 1, 7 and 8 than they are elsewhere. Further, in these subareas, particularly where the overall dip of foliation is at low angles to the north or north-east the B_1 folds tend to be tighter than elsewhere. The above features suggest, either, that B_1 structures were initially better developed in these subareas; alternatively, that the B_1 folds were tightened up during the B_2 fold movements. The latter alternative is preferred. Such renewed folding would have been facilitated by the nearness of the B_1 and B_2 axes of rotations.

The more direct effects of the refolding of B_1 structures by B_2 folds are not always obvious. The axial planes themselves, as mentioned above, are flexed about the B_2 axes. The earlier axial planes, which are associated with folds of large amplitudes and small wavelengths, are dispersed along a great circle whose pole is similarly oriented as that of the foliation plane girdle. Sometimes, quartzo-feldspathic veins parallel to the second axial planes cut across the first.

The first folds were accompanied, probably in the later stages, by fractures subparallel to the axial plane, with an occasional hint of displacement having taken place along such

Fig. 3.4. Folding about co-axial B_1 and B_2 axes at Felinengan (536736).

FIG. 3.4



FOLDING ABOUT CO-AXIAL B_1 & B_2 AXES

FELIN ENGAN

(536736)

fractures. Such fractures might have developed as a result of the inability of material to counteract the local pressures by sufficiently rapid flow or creep. These fractures have themselves been flexed during the B_2 movements.

ii. Subarea 1:

The details of structural features in this subarea are essentially the same as in subarea 3. There is no significant difference in the stereograms prepared from the two subareas. The B_3 folds, however, are less well developed here.

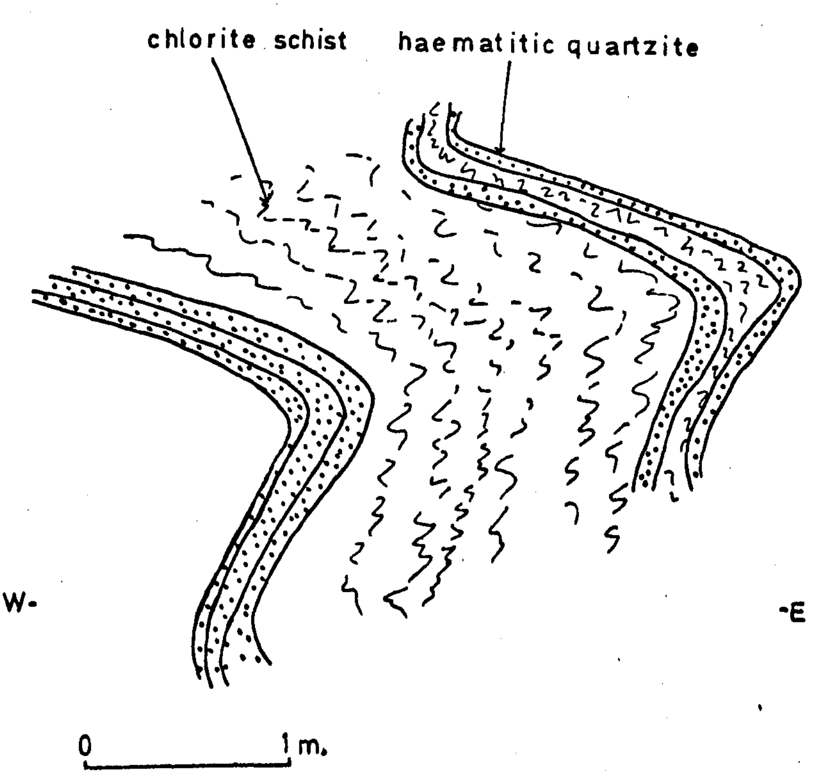
iii. Subarea 4:

The rocks included in this subarea are of a very heterogeneous nature, and represent a transitional period between dominantly sedimentary deposition and dominantly igneous activity. The original banding is highly irregular; individual rock units present lenticular sections. It should be noted that some difficulty was encountered in deciding the precise attitude of the S_1 plane at any particular point. The scale on which a measurement was taken was of vital importance (Fig. 3. 5). The stereogram is made from readings on a scale in the order of metres, in conformity with the general practice adopted in reading attitudes of structural elements in other subareas. On a larger scale, say, tens of metres or even larger, the average dip of the S_1 planes is very steep.

The clear relations between B_1 and B_2 structures are absent here. There is certainly little refolding to be observed. The general impression is one of intense compression, resulting in corrugation of early planar structures, and widespread break-up

FIG. 3.5

FOLDING NEAR TY-GWYN (555739)



of thin competent bands. The long axes of these disjointed rock units frequently form a strong lineation. Their orientation is conformable to the minor B_1 fold axes observed in the neighbourhood, as well as to the pole of the S_1 planes' girdle in the subarea.

iv. Subareas 5 & 6:

These subareas are characterised by the comparative uniformity of the strike of foliation S_1. The effects of the B_1 and B_2 folds can be seen in individual exposures. But the B_2 folds are nowhere as well developed as in subarea 3. A few B_2 folds may be observed along the eastern edge of these subareas. Tight B_1 structures can be seen in suitable sections, and there is a strong hint in places of their existence on the scale of tens of metres. These B_1 structures appear to be better developed within thick bands of schistose rock of uniform composition, when they cause violent contortion of the foliation. But the boundaries of thick bands of widely different composition seldom reflect the effect of B_1 folding. A possible reason is that sliding may have occurred along such boundaries and taken care of the stresses developed, in preference to the folds.

The relations between various structural features are basically the same as in subarea 3. The main points of difference are the lack of B_3 folds, and the steepening of the northerly plunge of folds in subarea 6. A plot of poles to foliation S_1 provides a single concentration, a reflection of the tight folding around B_1 axes.

v. Subarea 9:

This small subarea has been treated separately because the second generation of folds are well developed here (see Plate 2). On the whole, the plunge of B_1 and B_2 folds are steep in a northerly or north-westerly direction. It is not easy to distinguish one set of axes from the other, but the minor folds seem to be fairly evenly divided between the two sets. The rodding and mineral lineations, in individual cases, have a slight obliquity to the B_2 axes, and where they can be observed with clarity are parallel to axes of tight folds of the first generation.

vi. Subareas 7 & 8:

Each of these subareas is characterized by an attitude of the foliation that is very different from the regional attitude. These two subareas, collectively termed Tarn Wedge (Greenly, 1919; p. 375), are bounded on the east and west by faults that converge towards the north; hence the term "wedge", which is a convenient though, strictly speaking, inaccurate description. The southern boundary may be faulted, too, though this cannot be readily demonstrated.

The mutual relations between the various structural elements within the Tarn Wedge are somewhat different from the usual. B_3 folds are practically absent. The B_2 folds can be seen to be very well developed over most of Tarn Wedge. There is usually a strong corrugation lineation developed parallel to the B_2 fold axes. These folds may be seen in small scale exposures. They are represented on the 25": 1 mile scale by swings in strike from 80°N to 140-160°N. Some of these swings can also be discerned on Plate 2.

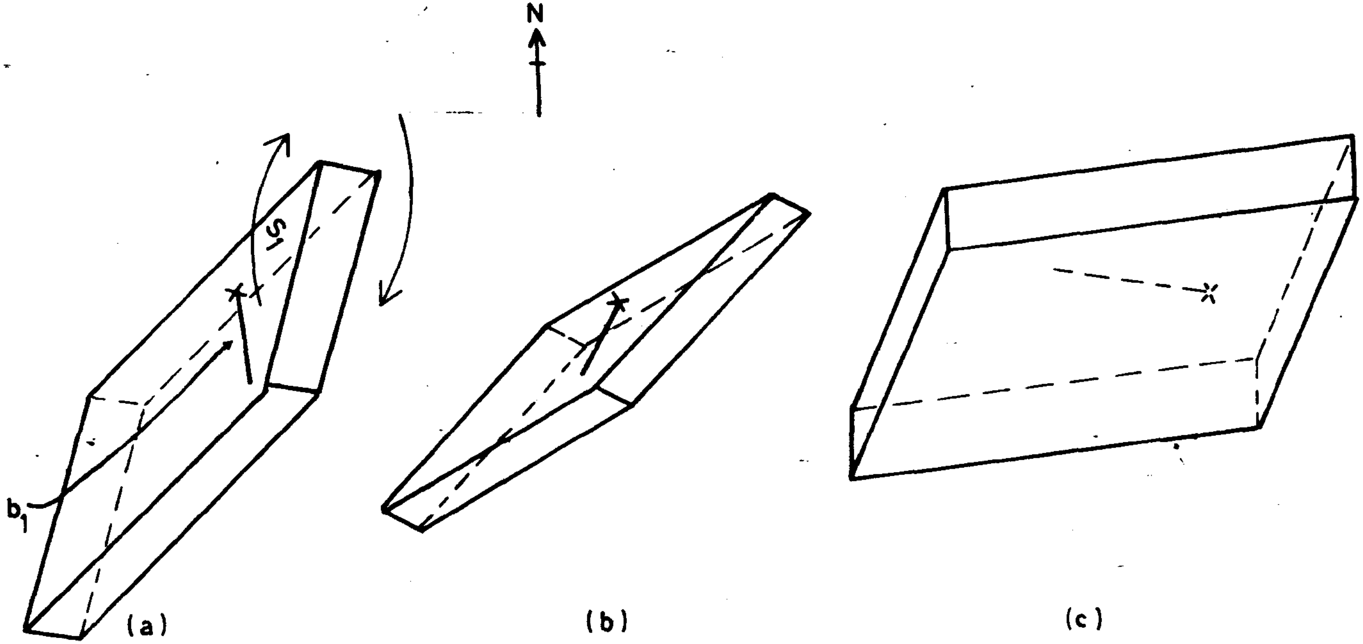
The axial planes of minor B_2 folds consistently lean in a south-easterly direction. They are oriented with moderate to steep dips due north-west over most of Tarn Wedge, but tend to be steeply dipping due north-north-west in the northern part of Tarn Wedge. The B_2 axes plunge at variably moderate amounts to the north.

Within Tarn Wedge, particularly immediately north of Llyn Llwydiarth (548788), there are instances of development of secondary foliation planes parallel to the B_2 axial planes. These secondary foliation planes are best developed in the incompetent bands within folded layers.

Apart from the overall discordant attitude of the foliation plane, it is the orientation of the b_1 structures which makes Tarn Wedge stand out from among the neighbouring subareas. The B_1 fold axes, and associated mineral lineation and rodding structures trend in a north-easterly or east-north-easterly direction over much of the two subareas (see stereograms in Plate 3; also see Plate 2). This is especially clear in subarea 7, where the structures associated with the B_1 folds are well developed. In places the rodding lineation is sufficiently well developed to obliterate the S_1 foliation. The stereograms plotted from the subareas within the 'Wedge' reflect this orientation of b_1 structures.

The unique distribution pattern of B_1 folds and associated linear elements that emerges from a composite plot in and around Tarn Wedge seems to be controlled entirely by faulting, rather than by the later B_2 folding. Fig. 3. 6 illustrates what is suggested as

FIG. 3.6



Proposed pattern of block-movement resulting in the reoriented S_1 foliation and b_1 lineation as seen within Tarn Wedge. (see p.72-73).

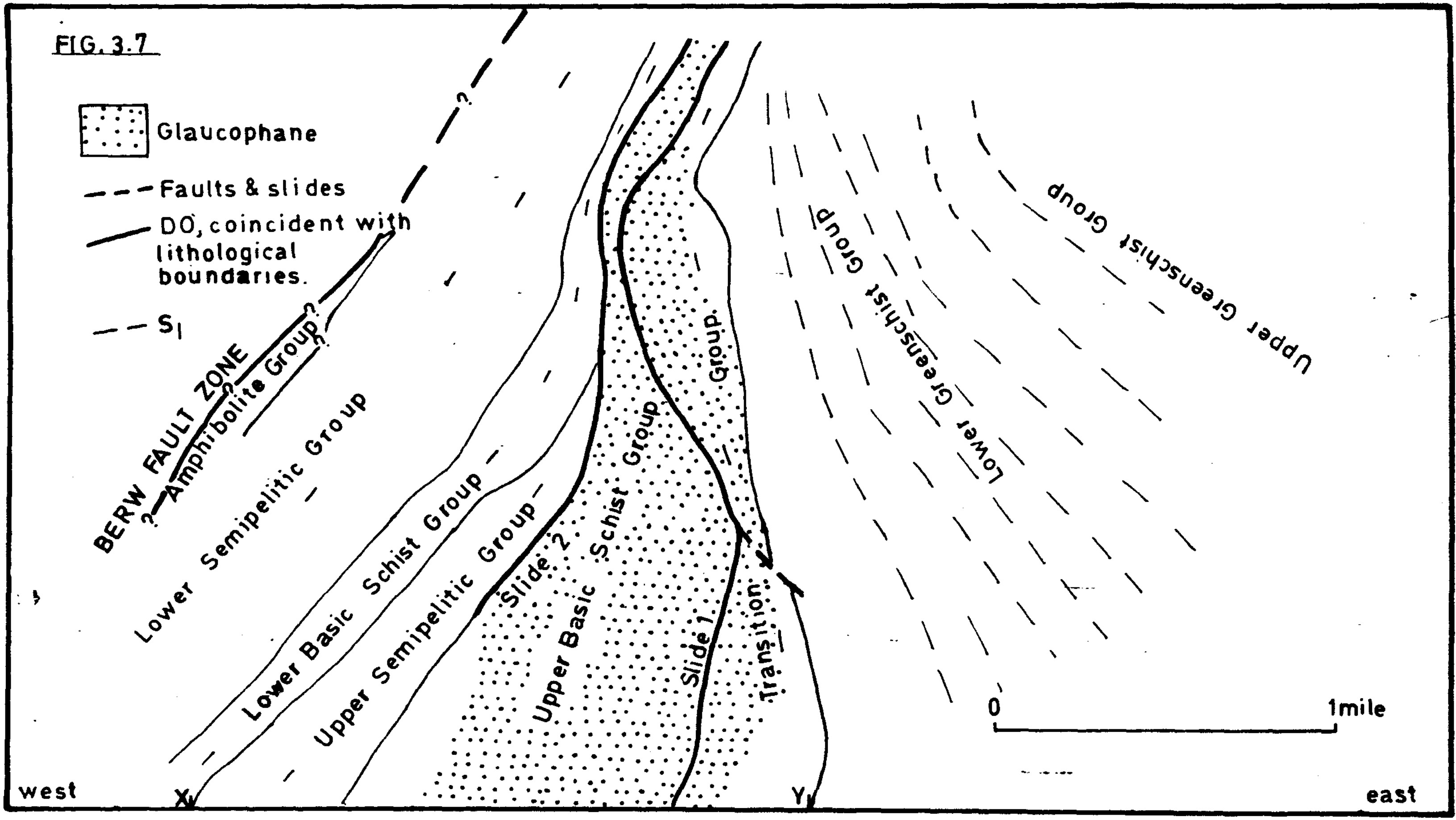
being the fault pattern that would explain the reorientation of the b_1 lineations. Fig. 3. 6(a) shows the initial orientation of S_1 in the block that was later to become the reoriented Tarn Wedge, with the b_1 lineation at the time trending roughly northerly. This block, bound by two converging fault planes, presumably was caught between the two flanking masses. Movement along the faults had a rotational effect, caused by the flanking material, on the block. Fig. 3. 6 (b) and (c) illustrate an intermediate and the final orientations, respectively, of S_1 within the block. The corresponding orientations of b_1 are also shown.

6. SYNOPSIS:

Table 4 summarises the various tectonic features that can be observed within each Group.

A profile (Fig. 3. 7) was constructed normal to an axis plunging 30° towards 12° N, which is taken as the general orientation of the B_1 and B_2 fold axes in the area. The base of this profile is along the line marked XY on Plate 1. Nine serial sections were drawn at approximately half-mile intervals along lines parallel to XY. If the distance on the map between any two of these lines of section be d, then the distance between their projections on to the plane of the profile is d sin 30°. Accordingly, the sections were laid on the same sheet of paper, each separated from its neighbours by the appropriate distance. For instance, the section along a line parallel to and $\frac{1}{2}$ mile north of XY was placed $\frac{1}{2}$. sin 30° miles (reduced to scale) above the section obtained along XY. Extra-

FIG. 3.7



Profile showing the changes in the dip of S_1 foliation and lithological boundaries in the area.

polations between these nine serial sections were then made to produce the profile shown in Fig. 3.7. The serial sections used for this construction should ideally have been drawn on planes dipping 60° due south; in the corrected profile drawn in this manner the lithological boundaries and foliation would show gentler dips than they do in Fig. 3. 7. Further, some distortion was unavoidably introduced during the extrapolations between the serial sections.

The salient feature in Fig. 3. 7 is the change in the overall dip of the foliation and lithological boundaries across the section. This change may be summarised as follows: (i) In the west, a zone of low to moderate dips towards the west, with a gradual swing to (ii) verticality in the centre of the section followed by (iii) eastward dips, gradually departing from steep to gentle attitudes, as the foliation is followed east. It is tentatively proposed that the features shown on Fig. 3. 7 are part of a much larger antiformal B_1 structure (Fig. 3.8). The formation of the proposed major B_1 structure was followed by major sliding movements. B_2 folds were then superimposed in a restricted zone within the area covered by Plate 1. Minor B_1 folds were tightened up during the formation of B_2 folds. Other interpretations of the structure in this area are possible. These may include the possibility that various units from different stratigraphic levels and in different tectonic states have been brought together by faulting or sliding, thus constituting a large-scale tectonic mélange. Another possibility

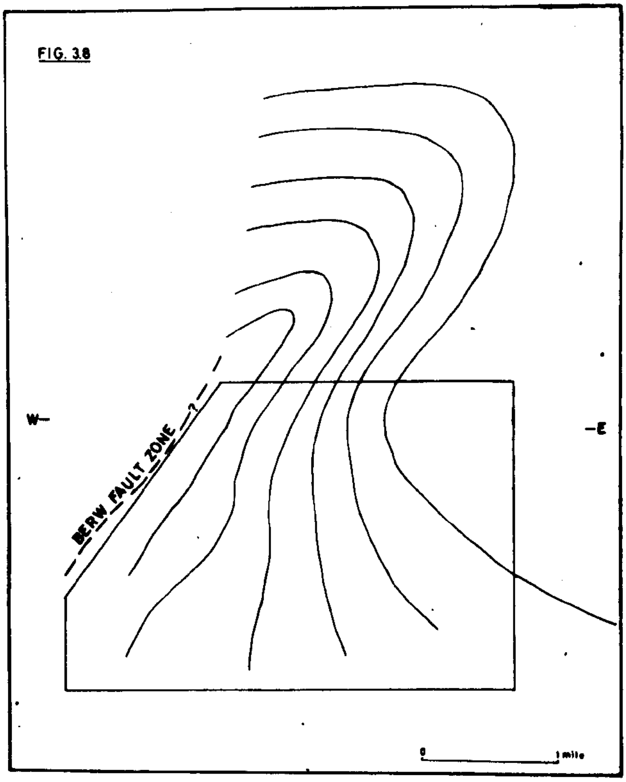


Fig. 3.8. A possible interpretation of the overall B_1 structure, a part (inset) of it being seen in the present area.

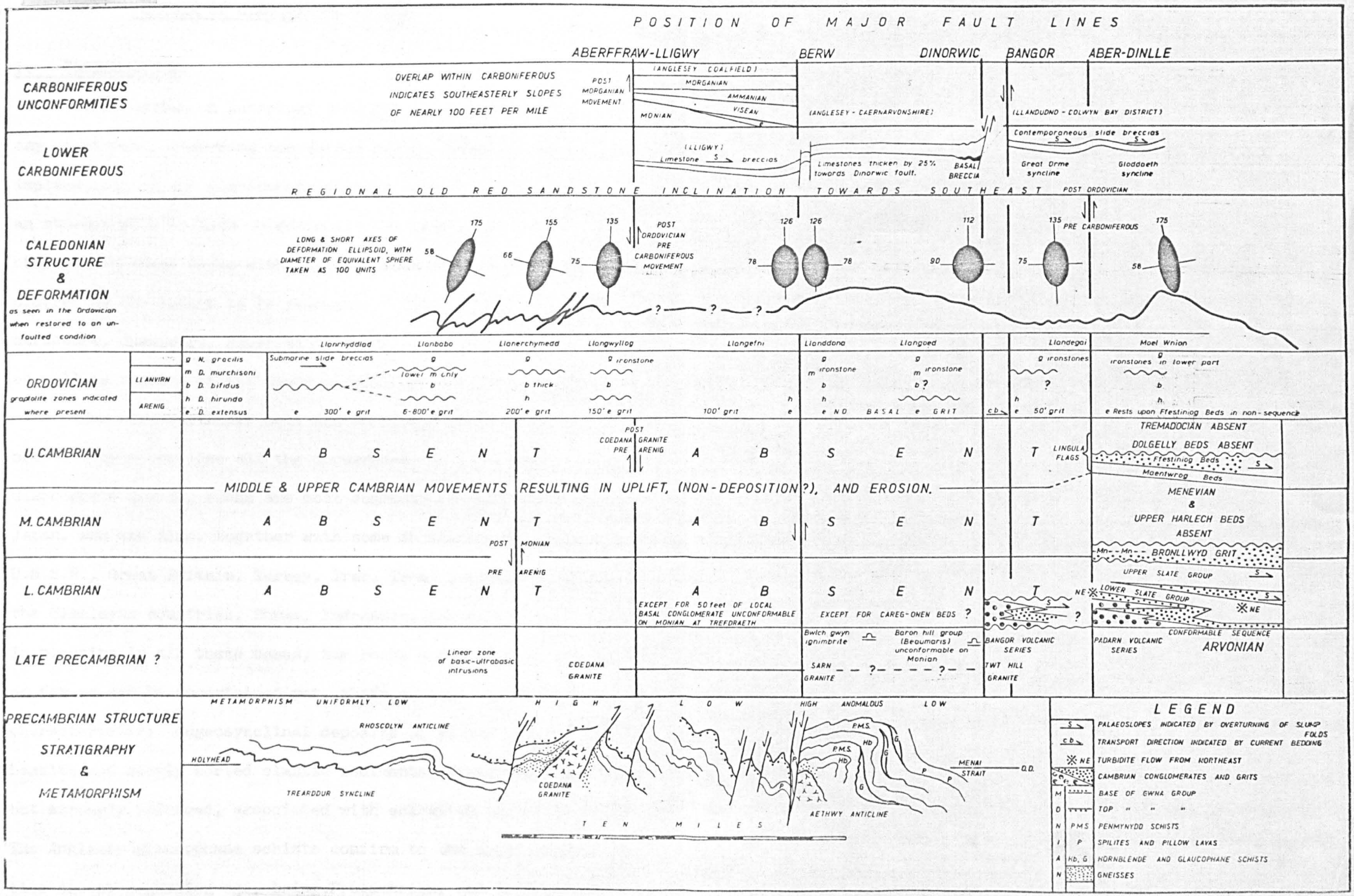
is that the succession as seen today contains repetitions of stratigraphic horizons on a large scale due to isoclinal folding which has gone undetected because of the lack of marker horizons and the absence of top and bottom criteria. There is no definite evidence as yet to support one or the other of these possibilities.

Although the B_1 and B_2 folds have been ascribed to different generations in time, they have certain characteristics in common. Their axes are similarly oriented, and the overall sense of rotation is south-easterly in both cases. It appears possible that the forces that operated during the B_1 folding continued, after a short interval, to generate the B_2 folds within a restricted area.

Fig. 3. 9 (D.S.Wood, personal communication; unpublished) includes a section across Anglesey from Holyhead to the Menai Strait showing the Precambrian structure, stratigraphy and metamorphism as proposed by Wood. Fig. 3. 9 has been shown here to give the reader some idea of how the area discussed in this thesis (lying between Berw Fault and Menai Strait) may possibly be related to the rest of Anglesey.

Fig. 3.9. Some geological features of Anglesey from Precambrian to Carboniferous times (unpublished work by D.S. Wood).

Fig. 3.9


POSITION OF MAJOR FAULT LINES
ABERFFRAW-LLIGWY
BERW
DINORWIC
BANGOR
ABER-DINLLE
CARBONIFEROUS UNCONFORMITIES
OVERLAP WITHIN CARBONIFEROUS INDICATES SOUTHEASTERLY SLOPES OF NEARLY 100 FEET PER MILE
POST MORGANIAN MOVEMENT
(ANGLESEY COALFIELD)
MORGANIAN
AMMANIAN
VISEAN
MONIAN
(ANGLESEY - CAERNARVONSHIRE)
(LLANDUDNO - COLWYN BAY DISTRICT)
LOWER CARBONIFEROUS
(LLIGWY)
Limestone S breccias
Limestones thicken by 25% towards Dinorwic fault.
BASAL BRECCIA
Contemporaneous slide breccias
Great Orme syncline
Gloddaeth syncline
REGIONAL OLD RED SANDSTONE INCLINATION TOWARDS SOUTHEAST
POST ORDOVICIAN
CALEDONIAN STRUCTURE & DEFORMATION as seen in the Ordovician when restored to an unfaulted condition
LONG & SHORT AXES OF DEFORMATION ELLIPSOID, WITH DIAMETER OF EQUIVALENT SPHERE TAKEN AS 100 UNITS
175
58
155
66
135
75
POST ORDOVICIAN PRE CARBONIFEROUS MOVEMENT
126
78
126
78
112
90
135
75
PRE CARBONIFEROUS
175
58
? ? ?
ORDOVICIAN graptolite zones indicated where present
LLANVIRN
ARENIG
g N. gracilis
m D. murchisoni
b D. bifidus
h D. hirundo
e D. extensus
Llanrhyddlad
Submarine slide breccias
e 300' e grit
Llanbabo
g
lower m only
b
h
6-800' e grit
Llanerchymedd
g
b thick
h
200' e grit
Llangwyllog
g ironstone
b
h
150' e grit
Llangefni
100' grit
h
e
Llanddona
g
m ironstone
b
h
e NO BASAL e GRIT
Llangoed
g
m ironstone
b?
cb
Llandegai
g ironstones
?
h
e 50' grit
Moel Wnion
g
ironstones in lower part
b
h
e Rests upon Ffestiniog Beds in non-sequence
U. CAMBRIAN
A B S E N T
POST COEDANA GRANITE PRE ARENIG
A B S E N T
LINGULA FLAGS
TREMADOCIAN ABSENT
DOLGELLY BEDS ABSENT
Ffestiniog Beds
S
Maentwrog Beds
MIDDLE & UPPER CAMBRIAN MOVEMENTS RESULTING IN UPLIFT, (NON-DEPOSITION?), AND EROSION.
M. CAMBRIAN
A B S E N T
A B S E N T
MENEVIAN & UPPER HARLECH BEDS ABSENT
POST MONIAN PRE ARENIG
Mn - Mn - BRONLLWYD GRIT
UPPER SLATE GROUP
L. CAMBRIAN
A B S E N T
A B S E N T
EXCEPT FOR 50 feet OF LOCAL BASAL CONGLOMERATE UNCONFORMABLE ON MONIAN AT TREFDRAETH
EXCEPT FOR CAREG-ONEN BEDS ?
NE
LOWER SLATE GROUP
S
NE
?
LATE PRECAMBRIAN ?
Linear zone of basic-ultrabasic intrusions
COEDANA GRANITE
Bwlch gwyn ignimbrite
Baron hill group (Beaumaris) unconformable on Monian
SARN GRANITE
? ?
BANGOR VOLCANIC SERIES
TWT HILL GRANITE
PADARN VOLCANIC SERIES
CONFORMABLE SEQUENCE
ARVONIAN
PRECAMBRIAN STRUCTURE STRATIGRAPHY & METAMORPHISM
METAMORPHISM UNIFORMLY LOW
HIGH
LOW
HIGH
ANOMALOUS
LOW
HOLYHEAD
RHOSCOLYN ANTICLINE
TREARDDUR SYNCLINE
COEDANA GRANITE
P
P.M.S.
P.M.S.
Hb
Hb
G
G
P
AETHWY ANTICLINE
MENAI STRAIT
O.D.
TEN MILES
LEGEND
S PALAEOSLOPES INDICATED BY OVERTURNING OF SLUMP FOLDS
cb TRANSPORT DIRECTION INDICATED BY CURRENT BEDDING
※ NE TURBIDITE FLOW FROM NORTHEAST
CAMBRIAN CONGLOMERATES AND GRITS
M BASE OF GWNA GROUP
O TOP " " "
N PMS PENMYNYDD SCHISTS
I P SPILITES AND PILLOW LAVAS
A Hb, G HORNBLENDE AND GLAUCOPHANE SCHISTS
N GNEISSES

CHAPTER IV

ORIGIN OF GLAUCOPHANE SCHIST

1. INTRODUCTION:

The chapter on petrology avoided, as far as practicable, any commitments regarding the facies classification and related implications of the glaucophane-schists from Anglesey. Here, an attempt will be made to reconcile the progressive metamorphism observed in these rocks with certain other aspects which are considered by the author to be relevant. These aspects include structure, chemistry, experimental work on mineral associations, as well as results of the study of similar rocks elsewhere.

The circum-pacific belt and the Eurasian tertiary chain practically monopolise all the occurrences of glaucophane schists. Glaucophane bearing rocks are most commonly found in California, Japan, and the Alps, together with some in Alaska, South America, U.S.S.R., Great Britain, Turkey, Iran, Iraq, probably in some of the Himalayan countries, Burma, Indonesia, Australia and Antarctica. In practically all these cases, the rocks are post-Palaeozoic, and as far as can be ascertained yet, their geologic setting is rather characteristic: eugeosynclinal deposits of pillow lavas, spilites, basalts and poorly sorted clastic sediments, feebly metamorphosed but strongly deformed, associated with eclogites and serpentinites. The Anglesey glaucophane schists confirm to the above characteristics except regarding age, being Precambrian, and in the lack of eclogite associations. The relations between the serpentinites and glaucophane-schists of Anglesey is not an intimate one of the type described from other glaucophanic terrains (Bloxam, 1966).

Glaucophane occurs in a wide range of rocks, and in general is associated with aragonite, lawsonite and pumpellyite. On the basis of mineral assemblages and the fact that glaucophane-bearing rocks may be derived from diverse bulk-compositions, the controlling factors of glaucophanic metamorphism have been suggested to be physical rather than chemical. On the other hand, the association of serpentinites and the fact that some of the glaucophane-bearing rocks are rich in Na_2O and MgO relative to Al_2O_3 as well as poor in CaO has led others to support a theory of chemical control for the formation of glaucophane.

The postulation of a physical control seems to be more justified in general, in spite of the abnormal low temperature-high pressure combination (compared with Barrovian metamorphic conditions) required for the stable association of glaucophane with Ca-al silicates, carbonate, lawsonite, jadeite, pumpellyite, aragonite and paragonite.

2. THEORIES:

Several theories have been advanced to account for the origin of glaucophane-bearing rocks:

(i) Extended fields of stability of the normally high pressure-low temperature minerals, due to chemical factors which were not taken into account in the laboratory synthesis of the minerals; such as the presence in the rocks of suitable "catalysts" or "foreign ions."

(ii) Rapid burial of sediments to required depths ($>$ 20 km. and upto 35 km.) so that the temperature rise lags behind; followed by rapid uplift so that the minerals belonging to the more normal pressure-temperature ranges do not have a chance to replace the high pressure-low temperature ones.

(iii) Sufficiently deep tectonic burial of the rocks due to superposition of nappes.

(iv) Metamorphism proceeding at comparatively shallow depths with respect to the high pressures required, the load pressures being augmented by tectonic overpressures.

(v) Metastable growth of the minerals.

(vi) Fluid overpressures.

(vii) Overpressures created by thermal expansion.

Various factors, which have to be considered when weighing up the points for or against any of the theories, are examined below in the light of the field and laboratory work done till now, particularly the present one.

3. THE ROLES OF VARIOUS FACTORS:

i. Chemistry:

The chemical analyses of the glaucophane schists (p. 51-54) show that the rocks are not abnormally rich in Na_2O or MgO relative to Al_2O_3, nor poor in CaO; the opposite would be nearer the facts. Further, a comparison of the glaucophane-bearing basic assemblages and the other basic rocks fails to reveal any consistent difference in their chemistry. The analyses are by no means exhaustive for this purpose, particularly where trace elements are concerned, but it would not be unreasonable to state tentatively that the glaucophane schists of Anglesey do not possess any outstanding chemical characteristics which might explain the development of glaucophanic assemblages in the rocks in preference to minerals of the greenschist or epidote-amphibolite facies.

If one attempts to explain the origin of glaucophane and associated high pressure-low temperature minerals on the basis of either (a) metastable formation of the minerals under favourable chemical conditions or (b) the actual extension of the stability fields of the minerals in the presence of foreign ions, then one must also try to account for the coincidence that all the index minerals normally belonging to the high pressure-low temperature field of stability also happen to need the same chemical environment to extend their stability field or for their metastable growth.

The chemical factors involved have been treated on the basis of available chemical analyses and experimental results by Ernst (1963a). Suggesting that glaucophane schists may originate in several ways, he goes on to state, "The association of glaucophane with carbonate, calcium-aluminium silicate or paragonite, or the presence of lawsonite, jadeitic pyroxene, or metamorphic aragonite, results from relatively high pressures or low temperatures, or both, characteristic of the blueschist facies......Glaucophane by itself is not necessarily an indication of special physical conditions as it may appear equally well in hypersodic and subcalcic rocks of greenschist and epidote-amphibolite facies metamorphism" (p. 25-26).

Thus, although Ernst recognises that abnormal chemistry can be responsible for the production of glaucophane, he is of the opinion that other associated minerals require high pressure-low temperature conditions for their formation.

Writing on the Franciscan glaucophane schists, Bailey and others (1964) discard the chemical theories. "The many chemical analyses now available, however, clearly indicate most of the Franciscan blueschists are chemically similar to sedimentary or volcanic rocks of the Franciscan, and no addition of soda is required for the formation of the blueschists. "(p. 106)....."The Franciscan metamorphic rocks.....are believed to be normal Franciscan sedimentary and volcanic rocks isochemically metamorphosed, chiefly as a result of load metamorphism under conditions of abnormally low temperatures relative to pressures."(p. 105).

ii. Pressure-temperature conditions:

Experimental studies of the stability fields of those minerals which distinguish typical glaucophane-bearing schists from greenschists suggest that the former require a higher pressure for stable existence at a given temperature. Fyfe & others (1958) suggest, from a consideration of many of the common minerals present in both the assemblages, that the temperature range for both is around 300°C, and that pressure is the critical factor. "Where temperatures are relatively low even at considerable depth (high pressure), the greenschist facies might grade, with decreasing temperature or increasing pressure, into the glaucophane-schist facies."(p. 218, Fyfe & others, 1958). Within the temperature range, glaucophane itself can form at pressures typical for the greenschists. But the minerals jadeite, aragonite and lawsonite require pressures in excess of 4 kb. or thereabouts (Fig. 4. 1). With this in mind, Fyfe & Turner (1966) write: "....we propose to rename what has been termed the glaucophane-schist as the glaucophane-lawsonite-schist facies......The diagnostic assemblages contain lawsonite and commonly aragonite and jadeite-quartz, as well as glaucophane."(p. 361). Thus they recognize the possibility of glaucophane occurring in rocks of the greenschist facies, formed at low to moderate temperatures and pressures.

A word about the stability field for glaucophane. Although glaucophane can be formed within the greenschist pressure-temperature range, this would require a high Na_2O content and low CaO/Al_2O_3 ratio for the rock. Glaucophane formed under such conditions would be the low pressure polymorph, with a larger unit cell volume (Ernst, 1963b) compared with that of the high pressure polymorph. The low-pressure polymorph of glaucophane, called glaucophane I, has not yet been identified in natural rocks. In the Franciscan rocks, Bloxam (1966) refers to strips of blueschist that follow serpentinite contacts and pass outward into pale glaucophane-poor metagreywackes (p. 785). Such an environment may be a suitable one for the search of glaucophane I. Ernst (1965), on the other hand, is emphatic that, in Panoche Pass, California, at least, "Serpentinite intrusions present in the area are not mantled by metasomatic glaucophane schist aureoles." (p. 879).

Although the Anglesey glaucophane has not yet been proved to

Fig. 4. 1. Results of experimental studies regarding stability fields of minerals associated with glaucophanic metamorphism.

Curve 1. Jadeite + quartz $\rightleftharpoons$ albite (Newton & Smith, 1967).

Curve 2. Aragonite $\rightleftharpoons$ calcite (Crawford & Fyfe, 1964 & 1965).

Curve 3. Lawsonite + quartz + H_2O $\rightleftharpoons$ laumontite (Crawford & Fyfe, 1965).

Curve 4. Lawsonite $\rightleftharpoons$ anorthite + H_2O (Crawford & Fyfe, 1965).

Curve 5. Lawsonite $\rightleftharpoons$ zoisite + kyanite + quartz + H_2O (Newton & Kennedy, 1963).

Curve 6. Epidote + quartz $\rightleftharpoons$ anorthite + (grossularite-andradite) + haematite (Holdaway, 1966).

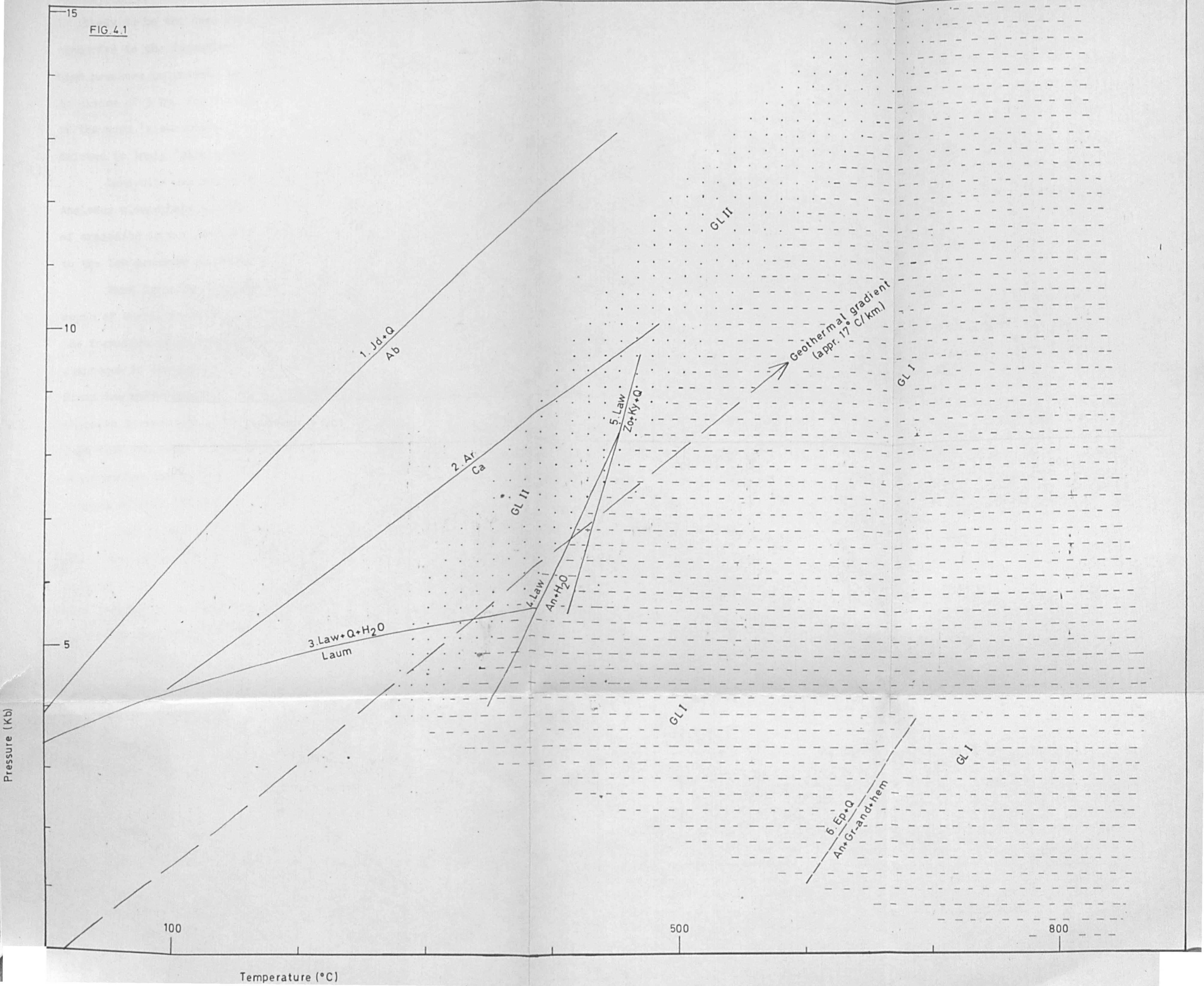
The ornamented field is adopted from Ernst (1963b). It shows the physical conditions in which Ernst was able to grow glaucophane crystals of various cell sizes from the bulk composition $Na_2O.\ 3MgO.\ Al_2O_3.\ 8SiO_2.\ + H_2O$.

The entire field has been divided approximately into two parts. The sub-field indicated by the dashed ornamentation is that in which glaucophane I, the low pressure-high temperature polymorph, might be expected to form (given suitable chemical environment).

The dotted sub-field covers part of the pressure-temperature conditions which might be expected to have existed during the crystallization of glaucophane II, the high pressure-low temperature polymorph.

In Ernst's experiments, glaucophane II was also stable at pressures above that shown in this diagram, up to 30 kb.

FIG. 4.1


15
10
5
Pressure (Kb)
100
500
800
Temperature (°C)
1. Jd+Q
Ab
2. Ar
Ca
3. Law+Q+H2O
Laum
4. Law
An+H2O
5. Law
Zo+Ky+Q
6. Ep+Q
An+Gr-and+hem
GL II
GL II
GL I
GL I
GL I
Geothermal gradient
(appr. 17 °C/km.)

be the high pressure polymorph with the smaller unit cell, this is likely to be the case since the chemistry of the rock is not conducive to the formation of the alternative polymorph. The high pressure polymorph, termed glaucophane II, requires pressures in excess of 3 kb. for its formation. The discussion and the use of the word 'glaucophane' in the rest of this thesis will be restricted to imply 'glaucophane II', unless otherwise stated.

Lawsonite has been noted within a restricted area in the Anglesey glaucophane schists, but it is not abundant. The absence of aragonite is not necessarily significant, since it easily reverts to the low-pressure polymorph calcite.

Even ignoring the marginal development of lawsonite, the depth of burial required to provide the necessary pressures for the formation of glaucophane in rocks of composition such as encountered in the Upper Basic Schist Group would be about 11 km. Since the most widespread Ca-al silicate associated with glaucophane in Anglesey is epidote, and lawsonite is rare, it may be said that the range of pressures developed during the glaucophanic metamorphism lay between 3 and 8 kb., and probably in the lower reaches of this range for most part.

Thus it would appear that this late phase of metamorphism, which was characterized by development of glaucophane and epidote as well as some lawsonite, occurred in an "abnormal" high pressure-low temperature field, while the earlier phase gives no indication of having been formed in such "abnormal" circumstances. The development of chlorite, epidote and blue-green amphibole suggests a near-normal pressure-temperature field for the early phase of metamorphism.

iii. Geothermal gradient, depth of burial and load pressures developed:

Experimental evidence has tended, in the past few years, to moderate the initially proposed extreme high pressure-low temperature requirements for the formation of glaucophane and associated metamorphic minerals. Newton & Smith (1967) have brought down by 2 kb. the previous estimate of the equilibrium curve at 200°C for the albite $\rightleftharpoons$ jadeite+quartz transition. Such revisions are bound to diminish the abnormality of conditions expected for the formation of these rocks. In fact, where extreme thicknesses of geosynclinal and volcanic accumulations are present, given geothermal gradients of approximately 17° C/km., there exist fair opportunities for the formation of the glaucophane and lawsonite minerals under load pressures of approximately 5.3 to 6.5 kb. (See Fig. 4.1). These load pressures would exist at depths from 19 to 24 km. (assuming density = 2.8). Under such conditions the genesis of glaucophane and lawsonite is no longer a problem! Lower values of geothermal gradient further increase the probability of metamorphic crystallization of the typical "high pressure-low temperature" indicator minerals. The gradient of approximately 17°C/km., as plotted in Fig.4.1, was obtained by Birch(1956)using a theor etical model for the crust having assumed values for the mean rate of heat generation in the crust, surface heat flow, mean thermal resistivity and for contributions of heat from below the crust. That the geothermal gradient in parts of the crust may be as low as 9°C/km. is suggested by measurements at Grass Valley, California (Clark, 1957), where the heat flow is only about 0.7 microcal/cm^2.sec. The suggested existence of such comparatively sluggish heat flow (the average rate in other areas being 1.48-1.65 microcal./cm.^{2} sec.) is corroborated by Lee and MacDonald (1963) and by Uyeda and Horai (1964).

There is a lack of conclusive evidence of glaucophanic metamorphism having taken place at depths great enough to provide sufficient load pressures to carry the rock into the required pressure-temperature region without any other aid. Much of the available literature mentions the difficulties encountered in the estimation of the depth of burial. An excerpt from Bailey (1964; 9.151), referring to the structural complexities in the Franciscan, relates some of the reasons for such difficulties: "Such normally simple things as determining the positions of anticlines and synclines are made difficult, if not impossible, by the local crumpling that leads to erratic strikes and dips, by the lack of continuity in distinguishable units from one limb to another, and by the prevalence of faults in the axial areas. Even more difficult are the problems presented by the shear zones, as the lack of recognizable units generally precludes correlation across such zones." Estimating the probable thickness of the Franciscan, Bailey (1964) writes: "Considering all the possibilities our best inference is that the accumulation itself is very thick, probably over 50,000 feet thick. Unfortunately this figure cannot be checked by measurements of total or partial stratigraphic sections because of structural complexities......A thickness of 50,000 feet is greater than has generally been attributed to the Franciscan, but this thickness does not appear to be excessive." (p. 111). Bailey's estimate falls rather short of the depth of burial required for the formation of the jadeite-aragonite assemblages in the glaucophane-schists of California.

A value of 8 km. has been suggested for the California glaucophane schists and associated rocks by Bloxam (1956).

Zwart (1967) is of the opinion that the glaucophane-schists of the Alps were formed when the rocks were buried sufficiently deep, not as a result of thick accumulation of deposits, but due to superposition of nappes. "Although it is not certain that the Upper Pennine nappes west of the Tessin culmination can be connected with these to the east, or that the East Alpine nappes have covered the Pennine nappes, such assumptions can explain a total thickness of several tens of kilometres sufficient to account for the high pressures" (Zwart, 1967, p. 297).

In Anglesey, too, the depth of burial of the rocks undergoing glaucophanic metamorphism is complicated by several factors. A tentative value for the thickness of sediments between the Transition

Group, where the glaucophane first makes its appearance, and the top of the Precambrian in the area as seen today, has been given elsewhere (Table 4) as 12,000 feet, or 3.6 kilometers. The load pressures at such depth would normally be only about 1 kilobar. However, the complicating factors tend to add to this basic estimation of load pressures; these are: (a) Erosion might have removed a significant part of the top of the Precambrian during the period between the glaucophanic metamorphism and subsequent renewed deposition. (b) Water pressures in ocean deeps can be expected, if present at the time of metamorphism, to contribute to the load pressures due to the overlying sediments. (c). The thickness of the cover above the glaucophane-bearing rocks was, at the time of the second episode of metamorphism during which glaucophane was formed, conceivably greater than the true thickness. This is based on the tentatively proposed style of the major B_1 fold (see Fig. 3. 8).

iv. Tectonic effects

a. Overpressures: Among other means by which an abnormally elevatedpressure condition in relation to the temperature may be created is the possible existence of non-hydrostatic stress which contributes significantly to the load pressures.

Coleman and Lee (1962) have put forward the possibility of lateral tectonic pressures contributing substantially to the mean pressure, thus helping the attainment of the required high pressures at relatively shallow depths. A number of unknown factors enter such calculations, among them the rock-strength and its variation with depth, temperature and strain rate.

Estimates of shear strength of these rocks under the given conditions of lithostatic pressure, temperature and geological time factor are hard to make without experimental support. The few experimental facts that are available regarding shear strengths of rocks are on the whole inapplicable to the problem under consideration. What does emerge from such experiments, as far as they concern the current problem, is the wide range of interrelations that may exist between the various factors involved. An example is provided by the comparison of the effect of strain rate on shear strength in two different instances. Riecker and Seifert (1964), experimenting on olivine at room temperature, conclude; "A 1000-fold variation in strain rate from 1 to 10^{-3}/sec. had no significant effect on shear strength." (p. 572). Heard (1963), on the other hand, in his experiments with Yule marble found that at 400°C the strain rate is a very important factor especially at rates less than 10^{-5}/sec. Such comparisons emphasize the need for closer control of experiments, over the range of values which may be expected to be encountered during metamorphism, as a prerequisite to estimating precisely the contribution of various factors to the shear strength of rocks.

Griggs and others (1960) have shown that the strength of basalt at strain rates of 2-4% per minute and a confining pressure of 5 kb. varies from about 12 kb. at 300°C to 10 kb. at 500°C. Obviously the picture would be very different at strain rates 10^{-10} -10^{-12} times those used in their experiments. But extrapolations of rock strengths to geologic strain rates, using currently available data, remains rather hazardous, particularly at low temperatures of 300°C.

From a choice of 1,500 bars to 7,000 bars Coleman and Lee (1962) have selected 3000 bars as a probable value for the shear strength of basalt during metamorphism. They come to the conclusion that tectonic overpressures of the order of several kilobars may be sustained by basaltic rocks during metamorphism. "Further careful experimental and field work are needed to define completely the tectonic conditions characterizing the glaucophane schist facies. The evidence, upto now, however, strongly suggests that low geothermal gradients combined with strong lateral tectonic pressures provide the conditions necessary to promote such an assemblage" (Coleman & Lee, 1962; p. 594).

In the Anglesey glaucophane schists, the low temperature and probable high value of strain rate are both favourable factors for the maintenance of a high shear strength during metamorphism. Glaucophane occurs within a zone approximately bound by the positions of Slides 1 and 2 and is a product of the second episode of metamorphism which may be related to the B_2 fold movements. The B_2 folds are most conspicuously developed within the zone where glaucophane schists occur. The deformation in this restricted zone may have been a contributing factor to the crystallization of glaucophane.

b. Deformation and recrystallization: The precise role that deformation plays in promoting metamorphism, apart from the possibility of producing tectonic overpressures, has not been evaluated yet. We can only guess that deformation is indeed an important factor. Speculating on the causes of episodic metamorphism, Sutton (1965) has commented: "Retrograde metamorphism in general is rare, and many rocks show a history of steady or increasing metamorphic grade. Does this mean that the temperatures remained high through the time when episodic metamorphism took place, or are we to imagine fluctuating temperatures where the periodic falls were so rapid that no retrogressive metamorphism occurred? My personal preference is for the first alternative, largely because successive episodes and even metamorphic events have in some areas produced rocks of different ages whose metamorphic grade varies across a terrain in rather similar fashion. This might suggest a pattern of heat flow established over a longer period of time than that required for the development of a single metamorphic episode. If this is a correct picture, then the conclusion that the incidence of tectonic movement promotes metamorphic reaction may become very important indeed. One could then visualise a mass of rock held at a steady or increasing temperature in which incipient metamorphic reactions were periodically triggered off, as it were, by deformation." (p. 41-42).

On a much smaller scale, metallurgists have long realised the importance of deformation in the production of crystals. W.C. Burgers (1963), in a review of metallurgical concepts as applied to crystallization, states: "The 'birth' of the new

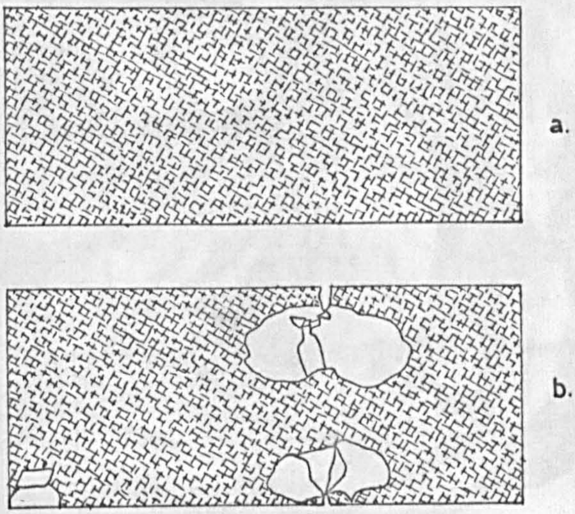
Fig. 4. 2. Illustrating one effect of inhomogeneous deformation in promoting recrystallization (adapted from van Arkel and Ploos van Amstel, 1930).

a. shows a fine-grained aluminium specimen, before deformation and recrystallization.

Incisions are made at the top and bottom of the plate. Extension of the plate results in a disproportionately large amount of deformation in the vicinity of the incisions.

On heating, the new crystallites grow almost exclusively in the immediate neighbourhood of the incisions. In the initial stages they are no larger than the size of a pinhead.

FIG.4.2



b. shows the new crystallites in a fairly advanced stage of growth. They may grow further outwards till the entire plate is consumed.

crystallites occurs at places in the matrix where the extension has caused strong local deformation.....the formation of new crystals can be locally stimulated by local deformations produced by pinpricks or notches" (p. 419). This is illustrated in Fig. 4.2. Burgers goes on to state: "We mention two other important observations that are essential for any understanding of nucleation in recrystallization.....the first is the fact that newly formed crystals are preferentially formed at places where the deformation has been highly inhomogeneous and the second is the fact that the orientation of the new crystallites is almost never completely at random, but is related in some way to the texture of the matrix." (p. 437). (see Fig. 4.3).

On p. 441, Burgers (1963) amplifies the last point further: ".....lattice regions with a special orientation with respect to the deformation directions might polygonize and thus form nuclei sooner than other regions. This would cause a recrystallization texture, whose crystallographic character would depend on the relation between the original matrix and the directions of deformation."

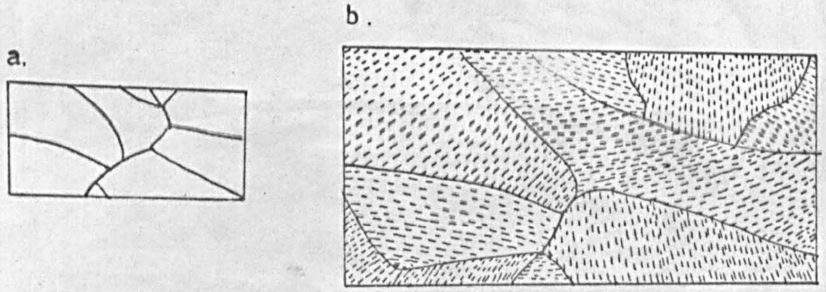
It would appear that while confining pressure does, among other factors, dictate stability or otherwise of a phase, inhomogeneous deformation must be relied on to actually nucleate successive stable phases.

Bailey (1964) also stresses the probable role of tectonic movements in promoting the crystallization of blueschists in the Franciscan rocks: "The role of directed stress, or of abnormally

Fig. 4.3. Illustrating the control by pre-existing fabric on the orientation of recrystallized grains (adapted from van Arkel, 1932).

a. shows an aluminium specimen, before deformation and recrystallization. The specimen comprises several crystals variously oriented; their boundaries are indicated in the diagram.

FIG 4.3



b. rolling followed by recrystallization has resulted in the production of numerous fine-grained crystallites. These new crystallites are preferentially oriented within small domains which are evidently relatable to a high degree with the areas occupied by the original single crystals. (The dash-pattern is schematic and does not necessarily correspond to any given crystallographic direction).

high pressure developed in a local area as a result of tectonic movements, is difficult to assess.....the limited occurrence of at least the glaucophane-bearing blueschists in belts that parallel the prevalent directions of shearing, suggests even a small increase in stress may have been operative in triggering the metamorphism of rocks already under high lithostatic pressure." (p.107).

c. Shearing stresses: The effects of high shearing stresses on the stability range of high pressure minerals has long been argued. However, it is generally accepted now that shearing stresses by themselves do not perceptibly alter stability relations. The presence of shearing stresses may have certain effects (Dachille & Roy, 1960):

A. They may promote reactions which are already dictated by the existing pressure-temperature conditions. This may be due to the breakage of bonds and/or storage of strain energy due to the high shearing stresses, resulting in a marked acceleration of the kinetics of transformation.

B. Shearing can generate a "spectrum" of hydrostatic pressures whose effective maximum may be 15-20 kb. Such quasi-hydrostatic pressures are not necessarily uniformly distributed.

v. Deep burial of rocks:

Perhaps the most commonly used theory to explain the formation of conditions favourable for the formation of high pressure-low temperature minerals is that of a rapidly accumulating thick eugeosynclinal deposit, so that the oldest parts of it were subjected to an unusually fast increase in load pressures, the temperatures therefore lagging in comparison. There is a fair amount of justification for such a model.

That being so, one may expect the pressure temperature gap to be narrowed with passage of time, and the more "normal" assemblages of the epidote-amphibolite facies to take over from glaucophanic assemblages. This may not happen if the uplift of the sediments was also equally rapid following submergence, as might have been the case in the Franciscan rocks: "As Franciscan blueschists do not normally show any sign of having been in the greenschist environment, we may infer that they not only reached considerable depths rapidly but also were subsequently uplifted to higher levels before a normal thermal gradient was established." (Bailey, 1964; p. 112).

Plas (1959) records that the glaucophane metamorphism in the Swiss Alps occurred prior to blue-green amphibole metamorphism. This would be in agreement with the hypothesis of rapid burial of thick eugeosynclinal sediments.

In Anglesey, however, glaucophane always rims the blue-green amphibole. What is therefore significant here is that the rocks must temporarily have been in the blue-green amphibole field, and then gone out of it into the glaucophane field. To explain this change in the pressure-temperature conditions with the aid of the rapid sedimentation theory would require tortuous modifications to be made to the theory. The author believes that, in Anglesey at least, this theory should be discarded.

Zwart (1967) has proposed that sufficiently deep burial of rocks for the formation of glaucophanic assemblages may be achieved by the superposition of nappes. According to Zwart, deep tectonic burial probably due to superposition of nappes was followed by isostatic uplift. This sequence of events gave rise to the Alpine plurifacial metamorphism which is dependent on a decrease in pressure. In Anglesey, however, the glaucophane bearing rocks are developed in zones of steep rather than sub-horizontal structures. Deep burial due to superposition of nappes appears unlikely to have been a cause of glaucophanic metamorphism in Anglesey.

vi. Metastable growth; fluid and thermal expansion overpressures:

It appears unlikely that glaucophane could have grown metastably in the Anglesey glaucophane schists, since one would not expect metastable crystals of glaucophane if nuclei and crystals of blue-green amphibole were already present. Fluid overpressures and thermal expansion overpressures will both have to be left as mere theories at the moment due to lack of relevant data. In general, it seems unlikely that thermal expansion could result in abnormally high pressures relative to temperature.

4. DISCUSSION:

An evaluation of the timing of the metamorphism in Anglesey is of some consequence in the ultimate solution to the problem of physical conditions accompanying the metamorphism. If the metamorphism took place in early Precambrian times, even as early as to have been semi-contemporaneous with the sedimentation and volcanic activity, this would introduce the possibility of a large thickness of overlying sediments, since eroded away, having been on top of the glaucophanic rocks. One reason has been given earlier (p.91-92) why the author believes that the metamorphism was post-depositional. Studies over the rest of Anglesey also suggest that it is unlikely that the metamorphism took place in the early history of the geosynclinal deposition and uplift. The rocks at the base of the Monian System (i.e., Holyhead Quartzite) are no more metamorphosed than those at the top of the System (Upper and Lower Greenschist Groups). The general impression is one of the metamorphism having occurred after the uplift of geosynclinal sediments, and after the older rocks to the north had been tilted and brought up against the younger ones to the south.

The metamorphism of the Anglesey Precambrian rocks can be regarded essentially as a single event, polyphasal in parts of the island. It has the appearance of having occurred during a short period of heating in the earth's crust (Shackleton, 1953; p. 264), coupled with probably rapid and short-lived deformation. The relation between the ascent of the Coedana Granite, the formation of the migmatites ("The Gneisses" of Greenly; see p.6) and the metamorphism of the Precambrian rocks of Anglesey is still a subject for detailed research. Published results (Shackleton, 1953 and 1956; Moorbath and Shackleton, 1966) indicate that these events may be closely interconnected in time. The best dates yet available for the intrusion of the Coedana Granite (Moorbath and Shackleton, 1966) place the act at the closing stages of the Precambrian times. Until more is known about the relations, both in space and time, between the Coedana Granite and the glaucophanic metamorphism in Anglesey, any estimates of the temperatures prevalent during the metamorphism would be highly speculative. A range of 300°-400°C may be taken as a working hypothesis, as this is in agreement with the generally accepted estimates based on field and laboratory studies (Turner and Verhoogen, 1960, p. 544; Winkler, 1965, p.150).

The required pressure for the stable existence of glaucophane II and lawsonite in the above temperature range would be around 5 kb. Glaucophane II alone could be formed at lower pressures, down to about 3.5 kb. The thickness of the Precambrian rocks above the glaucophane-lawsonite schists as seen today is 3.6 km. and would account for 1 kb. of the required pressure. The remaining pressure of 4 kb. may have been exerted by about 14 km. of cover since eroded away. Thus, deep burial combined with a low geothermal gradient (compared to gradients in the order of 100°C/km. reported from regions of Hercynian metamorphism; see Zwart, 1967, p. 293) could have carried the rocks of the Transition Group and the Upper Basic Schist Group into the glaucophane-lawsonite field shown in Fig. 4. 1.

Of the alternative ways of obtaining the required high pressures, the tectonic means seem to be more readily acceptable, in the case of the Anglesey glaucophane schists, than the other modes suggested by workers in other glaucophanic terrains. The question of rock strength under conditions of metamorphism remains unsolved for the moment. How crucial was its role in the glaucophanic metamorphism in Anglesey? Let us determine the required shear strength S for the rocks undergoing metamorphism, if the mean pressure M was 5 kb. and the load pressure L was 1 kb. The maximum difference in magnitude that can exist between the principal axes of stress being twice the shear strength S, the relation between M, S and L is given by :M= $(3L + 4S)/3$ kb. Solving this for M= 5 kb. and L= 1 kb., we have S= 3 kb.

Thus, two possibilities seem to arise in the case of the Anglesey glaucophane schists: first, that deep burial of the rocks combined with a low geothermal gradient may have resulted in the high pressure-low temperature metamorphism; alternatively, that high pressures relative to temperature were produced chiefly as a result of tectonic overpressures in rocks whose shear strength was about 3 kb. The author believes that the first alternative is rather unlikely, because of the following indications:

(i) High pressures due to deep burial of rocks may be expected to result in a more widespread occurrence of glaucophane than appears to be the case within the Monian System. The restricted occurrence of glaucophane-schists seems to point to a localized increase in pressure within a thick succession of rocks.

(ii) In other areas, where it is possible that the glaucophane-schists were formed as a result of deep burial, isostatic uplift seems to have resulted in a characteristic sequence of successive metamorphic facies: "Thus there is a general tendency in these metamorphic suites to show the succession glaucophane-schist to greenschist. Occasionally the succession is eclogite to glaucophane-schist to greenschist," (Zwart, 1967; referring to the Alpine metamorphism; p. 292). This does not seem to have been the same in Anglesey, where glaucophane has been formed after blue-green amphibole.

(iii) Another feature which may be expected as a result of deep burial and low geothermal gradients is summed up by Zwart (1967, p.293-294): "If it is assumed that high pressure metamorphism is directly related to deep burial, then the temperature gradient during the Alpine metamorphism must have been very small.....The slow drop in temperature towards the surface resulted in very thick metamorphic zones and over large tracts the grade of metamorphism is equal. This is particularly well illustrated in the Pennine nappes where with a relief of more than 3000 m the grade of metamorphism is the same at the summits of the mountains and in the bottoms of the valleys, clearly showing that each individual zone has a thickness of several thousands of metres. This is in strong contrast to the thin metamorphic zones in the Hercynian chain."

Zwart's description of thick metamorphic zones from the Alps is also in strong contrast to the generally thin metamorphic zones in Anglesey. "It seems as though the metamorphic zones are thin and one sees high and low grade rocks close together." (Shackleton, 1953, p.264). Such thin zones imply either a high geothermal gradient or a drastic telescoping effect, both characteristic of high temperature metamorphism.

One drawback to the theory of tectonic overpressures is that the shear strength of rocks under metamorphic conditions is not known. In the case of the Anglesey schists, the required shear strength of 3 kb. at a relatively low temperature may well prove to be within the realms of possibility. It may never be possible to demonstrate that these rocks were (or were not, as the case may be) buried under about 18 km. of cover during metamorphism. It is, however, much more likely that our increasing knowledge of the shear strength of rocks under the appropriate conditions for glaucophanic metamorphism will eventually enable us to decide the role played by tectonic overpressure. Until more evidence is available to the contrary, it seems that the chief cause of glaucophanic metamorphism in Anglesey was the creation of localized zones of high tectonic overpressures, rather than deep burial of the rocks. The rock chemistry had comparatively little say in deciding whether or not glaucophane was formed.

"In the fascinating subject of the tectonics and metamorphism of these rocks, investigators must be prepared to abandon many an attractive theory, confident, however, that the sounder one which takes its place will prove yet more attractive and more stimulating."

- Sir J. Teall.

on p. 351 in E. Greenly's "The Succession and Metamorphism in the Mona Complex." Quart. Journ. Geol. Soc., 1923, vol. 79.

REFERENCES

ARKEL, A.E. van & PLOOS van AMSTEL, J.J.A. (1930): Verhinderung des Kristallwachstums durch schwache Deformation. Z. Physik., vol. 62, p. 43-45.

ARKEL, A.E. van (1932): Polytechnisch Weekblad., vol. 26, p. 397.

BAILEY, E.B. & McCALLIEN, W.J. (1953): Serpentine lavas, the Ankara Mélange and the Anatolian Thrust. Trans. Roy. Soc. Edinburgh, vol. 62, p. 403-442.

BAILEY, E.H., IRWIN, W.P. & JONES, D.L. (1964): Franciscan and related rocks. Bull. 183, Calif. Div. Mines & Geol.

BANNO, S. (1959): Notes on rock-forming minerals (10). Glaucophanes and garnet from the Kôtu District, Sikoku. Jour. Geol. Soc. Japan, vol. 65, p. 658-663.

BIRCH, F. (1955): Physics of the Crust. Geol. Soc. Amer. Special paper 62, p. 101-118.

BLAKE, J.F. (1888): On the occurrence of a glaucophane-bearing rock in Anglesey. Geol. Mag., vol. 5, p. 125-127.

BLOXAM, T.W. (1956): Jadeite-bearing metagraywackes in California. Amer. Min.,vol41,p.488-496.

BLOXAM, T.W. & ALLEN, J.B. (1958): Glaucophane-schist, eclogite, and associated rocks from Knockormal in the Girvan Ballantrae Complex, S. Ayrshire. Trans. Roy. Soc. Edinburgh, vol. LXIV, p. 1-27.

BLOXAM, T.W. (1966): Jadeite-rocks and blueschists in California. Bull. Geol. Soc. Amer., vol. 77, p. 781-786.

BURGERS, W.G. (1963): Principles of recrystallization. The art and science of growing crystals. Edited by J.J. Gilman.

CLARK, S.P. Jr. (1957): Heat flow at Grass Valley, California. Trans. Amer. Geoph. Union, vol. 38, p. 239-244.

COLEMAN, R.G. & LEE, D.E. (1962): Metamorphic aragonite in the glaucophane schists of Cazadero, California. Amer. Journ. Sci., vol. 260, p. 577-595.

CRAWFORD, W.A. & FYFE, W.S. (1964): Calcite-aragonite equilibrium at 100°C. Science, vol. 144, p. 1569-1570.

CRAWFORD, W.A. & FYFE, W.S. (1965): Lawsonite equilibria. Amer. Journ. Sci,,vol. 263, p. 262-270.

DACHILLE, F. & ROY, R. (1960): High-pressure phase transformations in laboratory mechanical mixers and mortars. Nature, vol. 186, p. 34, 71.

DEER,W.A., HOWIE,R.A. AND ZUSSMAN,J. (1962): Rock-forming minerals, vol. 2. (Longmans).

ERNST, W.G. (1963 a): Petrogenesis of glaucophane schists. Journ. Pet., vol. 4, p. 1-30.

ERNST, W.G. (1963 b): Polymorphism in alkali amphiboles. Amer. Min., vol. 48, p. 241-260.

ERNST, W.G. (1965): Mineral paragenesis in Franciscan metamorphic rocks, Panoche Pass, California. Bull. Geol. Soc. Amer., vol. 76, p. 879-914.

FYFE, W.S., TURNER, F.J. & VERHOOGEN, J. (1958): Metamorphic reactions and metamorphic facies. Mem. Geol. Soc. Amer., vol. 73, p. 1-259.

FYFE, W.S. & TURNER, F.J. (1966): Reapprisal of the metamorphic facies concept. Contr. Mineral & Petrol., vol. 12, p. 354-364.

GEIKIE, A. (1891): History of volcanic action in the British Isles. Quart. Journ. Geol. Soc., President's address, vol. XLVII, p. 63-162.

GREENLY, E. (1919): Geology of Anglesey; Mem. Geol. Surv. Gt. Br.

GRIGGS, D.T., TURNER, F.J. & HEARD, H.C. (1960): Deformation of rocks at 500° to 800°C. Mem. Geol. Soc. Amer., vol 79, p. 39-104.

HEARD, H.C. (1963): Effect of large changes in strain rate in the experimental deformation of Yule Marble. Journ. Geol., vol. 71, p. 162-195.

HENSLOW, J.S. (1822): Geological description of Anglesey. Trans. Cam. Phil. Soc., vol. i, p. 359.

HICKS, H. (1878): On some Precambrian Areas in Wales. Geol. Mag., vol. 5, p. 460-461.

HOLDAWAY, M.J. (1966): Hydrothermal stability of clinozoisite plus quartz. Amer. Journ. Sci., vol. 264, p. 643-667.

HOLGATE, N. (1951): On crossite from Anglesey. Min. Mag., vol. 29, p. 792-798.

LEAKE, B.E. (1963): Origin of amphibolites from northwest Adirondacks, New York. Bull. Geol. Soc. Amer., vol. 74, p. 1193-1202.

LEE, W.H.K. & MacDONALD, G.J.F. (1963): The global variation of terrestial heat flow. Journ. Geoph. Res., vol. 68, p. 6481-6492.

MATLEY, C.A. (1899): On the geology of Northern Anglesey. Quart. Journ. Geol. Soc., vol. 55, p. 635.

MIYASHIRO, A. (1957): The chemistry, optics and genesis of the alkali-amphiboles. Journ. Fac. Sci. Tokyo, Sec. 2, Vol XI, Pt. 1, p. 57-83.

MOORBATH, S. & SHACKLETON, R.M. (1966): Isotopic ages from the Precambrian Mona Complex of Anglesey, North Wales. Earth and Plan. Sci. Letters, vol. 1, p.113-117.

NEWTON, R.C. & KENNEDY, G.C. (1963): Some equilibrium reactions in the join $CaAl_2Si_2O_8$-H_2O. Journ. Geoph. Res., vol. 68, p. 2967-2983.

NEWTON, R.C. & SMITH, J.V. (1967): Investigations concerning the breakdown of albite at depth in the earth. Journ. Geol., vol. 75, p. 268-286.

PLAS, L. van der (1959): Petrology of the Northern Adula region, Switzerland. Leidse Geol. Med., vol. 24, p. 415-602.

RAMSAY, A.C. (1881): The Geology of North Wales. Mem. Geol. Surv. Gt. Br., vol. III.

RIECKER, R.E. & SEIFERT, K.E. (1964): Olivine shear strength at high pressure and room temperature. Bull. Geol. Soc. Amer., vol. 75, p. 571-574.

SHACKLETON, R.M. (1953): The structural evolution of North Wales. (Pres. address). Liv. Man. Geol. Journ., vol. 1, p. 261-297.

SHACKLETON, R.M. (1954): The structure and succession of Anglesey and the Lleyn Peninsula. Adv. Sci., vol 11, p. 106-108.

SHACKLETON, R.M. (1956): Notes on the structure and relations of the Pre-cambrian and Ordovician rocks of south-western Lleyn, Caernarvonshire. Liv. Man. Geol. Journ., vol. 1, p. 400-409.

SPEED, J. (1610): Map of Anglesey. Speed's Atlas.

SUTTON, J. (1965): Some recent advances in our understanding of the controls of metamorphism. "Controls of Metamorphism." Edited by W.S. Pitcher and G.W. Flinn.

TURNER, F.J., & VERHOOGEN, J. (1960): Igneous and metamorphic petrology. (McGraw-Hill Book Company, Inc.).

UYEDA, S. & HORAI, K. (1964): Terrestial heat flow in Japan. Journ. Geoph. Res., vol. 69, p. 2121-2141.

WALKER, F. & POLDERVAART, A. (1949): Karroo dolerites of the Union of South Africa. Bull. Geol. Soc. Amer., vol. 60, p. 591-706.

WINKLER, H.G.F. (1965): Petrogenesis of metamorphic rocks. (Springer-Verlag).

ZWART, H.J. (1967): The duality of orogenic belts. Geol. Mijn., vol. 46, p. 283-309.

TABLE 1

Optical properties of some blue-green amphiboles

Specimen No.	Pleochroism		$2V_x$	mg of rock (from Table 7)	birefringence low: < .012 moderate .012-.018 high:018-.024	$Z \wedge c$ low: 4°-12° moderate: 12°-2 high: 20°-26°
10D	- v. pale green - colourless.	1.655	48°	0.56	moderate	moderate
56	-deep blue green -green -colourless	1.662	38° strong absorption affects readings	-	moderate	high
83	-light green -colourless	1.660	65°	0.60	moderate	high
123	-patchy blue green -dark green -colourless	1.661	45°	-	high	high
206	-blue green -green -colourless	-	32° rather variable; some grains have values up to 50°-55°.	0.56	high	high
211	-blue green -green -colourless	1.652	67°	0.59	high	moderate
226	-light blue green -pale yellowish green -colourless	1.659	56°	-	moderate	moderate
240	-blue green -dull green -colourless	1.664	63° strong absorption affects readings.	-	moderate	moderate
348	-blue green -light green -colourless	1.644	85°	0.63	high	high
400	-pale yellowish green -very pale yellow -colourless	1.651	73°	0.65	high	moderate
403	-strong blue green -yellowish green -colourless	1.664	52° rather variable; some grains have values down to 35-40°.	0.52	moderate	high
404	-blue green -green -very pale yellow	-	45°	0.53	moderate	high
410	-pale blue green -pale green -colourless	1.647	69°	0.65	high	high
417	-very pale blue-green -colourless	-	55°	0.66	-	-
429	-extremely pale yellow-green -colourless	1.642	72°	-	moderate	moderate

56.	Quartz-albite schist with some blue-green amphibole and epidote. From Lower Basic Schist Group, Mynydd Llwydiarth.
123.	Blue-green amphibole-epidote-glaucophane schist comparatively rich in sphene. From the Upper Basic Schist Group north of Llyn Llwydiarth.
226.	Blue-green amphibole-epidote-glaucophane-chlorite schist from the Upper Basic Schist Group north of Llyn Llwydiarth.
240.	Mylonitic rock at the junction of Lower Basic Schist Group and Lower Semipelitic Group, Mynydd Llwydiarth. The chief minerals are quartz, albite, blue-green amphibole and epidote.
429.	Quartz-muscovite-epidote-amphibole schist; from the Upper Semipelitic Group south of Penhesgyn.

For details of other specimens, see Table 5.

TABLE 2

Optical properties of some glaucophanes

Specimen No. or Reference.	Pleochroism.		$2V_x$	mg of rock (from Table 7)	birefringence low: < .012 moderate: .012-.018 high: .018-.024.	$Z \wedge c$ low: 4°-12° moderate: 12°-20° high: 20°-26°
42	-blue -violet -colourless.	1.662	15° Strong absorption affects readings		low	low
223	-deep blue -violet -colourless.	1.669	20° Strong absorption and dispersion affect the readings.		low	low
345	-blue -violet -colourless	1.658	32°	0.57	low	low
404	-blue -violet -colourless	1.658	23°	0.53	moderate	low
Holgate (1951)	-"sky blue" -"pale grey violet" -"pale neutral tint"	1.657	17°		low	low
Bloxam & Allen (1958)	-"pale lavender" -"pale blue" -"colourless"	1.639	48°		high	low
Banno (1959)		1.654	34-38°			

42. Fine-grained quartz-albite-chlorite schist with subordinate epidote and glaucophane; from the Upper Basic Schist Group north of Llyn Llwydiarth

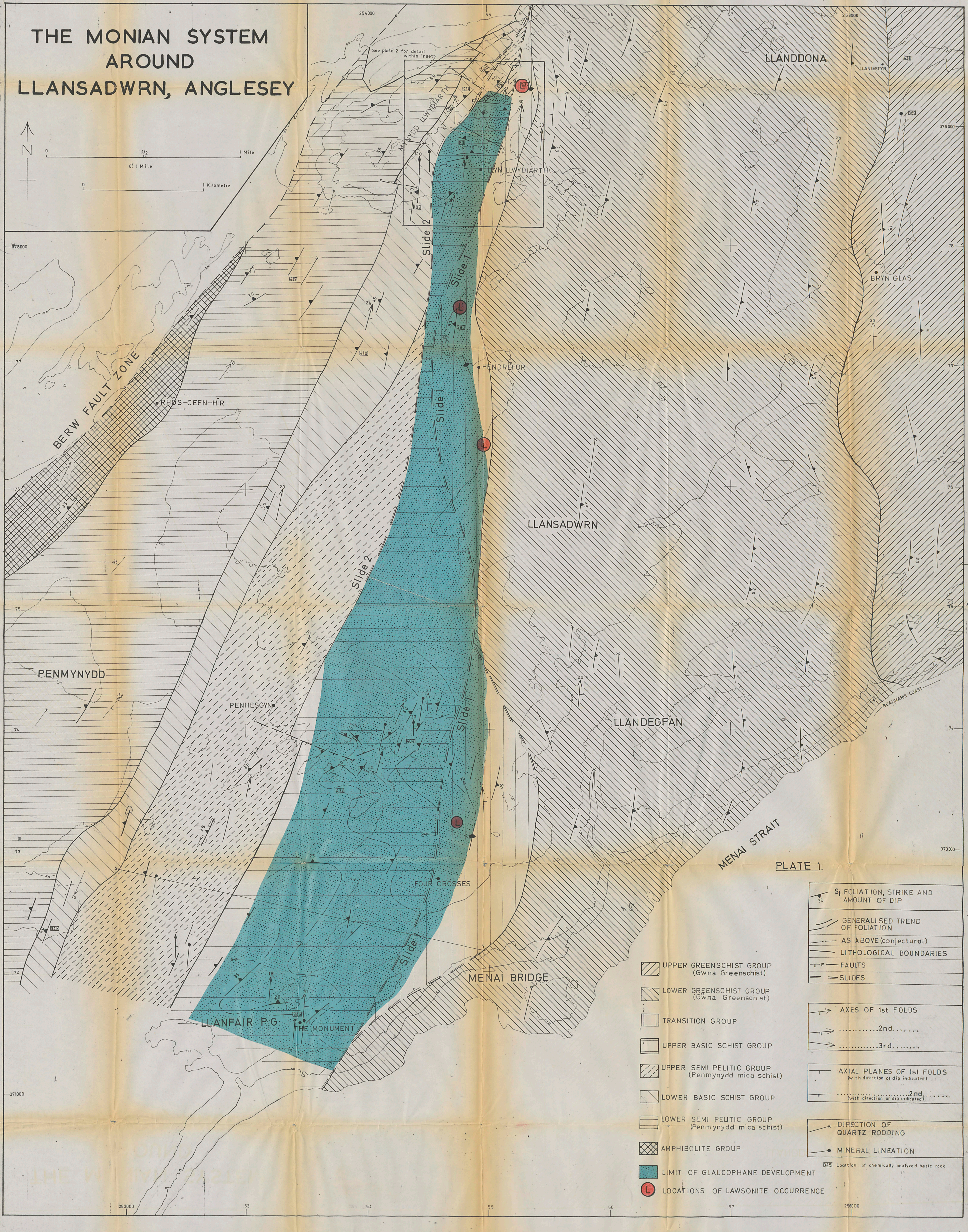
223. Muscovite - quartz-glaucophane-chlorite schist from the Upper Basic Schist Group north of Llyn Llwydiarth

Holgate (1951): Amphibole-epidote-quartz-albite schist from the Upper Basic Schist Group near the Monument.

Bloxam & Allen (1958): Glaucophane-epidote-chlorite schist from Knockormal, South Ayrshire.

Banno (1959): Glaucophane-epidote-chlorite-garnet-albite-quartz schist with sphene and muscovite from Japan.

For descriptions of other specimens see Table 5.



THE MONIAN SYSTEM AROUND LLANSADWRN, ANGLESEY

PLATE 1.

PLATE 3.

BOUNDARIES OF SUBAREAS
NATURAL BOUNDARIES, FROM PLATE 1, FOR REFERENCE
PATTERN OF MINOR FOLDS IN THE SUBAREA (viewed normal to axis)
B2
PLOTS OF POLES TO S1 FOLIATION PLANE
AXIAL PLANES OF B4 FOLDS
. . . . B3 . . .
. . . . B2 . . .
. . . . B1 . . .
V AXES OF B4 FOLDS & PARALLEL LINEATIONS
Λ . . . . B3 . . . .
+ . . . . B2 . . . .
x . . . . B1 . . . .
N
1
2
3
4
5
6
7
8
9
B1
B2
252000
53
54
55
56
57
258000
371000
72
73
373000
74
75
76
77
78
378000
379000