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THE GEOLOGY OF THE STRUMBLE HEAD - FISHGUARD REGION, DYFED, WALES

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Thesis submitted in accordance with the requirements of the University of Keele for the degree of Doctor of Philosophy.

1979

UNIVERSITY
OF KEELE

ABSTRACT

An investigation was undertaken on the volcanic and volcaniclastic rocks forming the Fishguard Volcanic Group of Lower Ordovician age, which crop out in the Strumble Head - Fishguard area of Southwest Dyfed (North Pembrokeshire).

The nature of the lavas and volcaniclastic rocks suggests that this episode of vulcanicity was entirely subaqueous in aspect.

It is shown that a variety of magma types were available for penecontemporaneous extrusion and intrusion at a high level. The form assumed by the extrusions depends primarily upon magma composition, which also largely determines magma viscosity. In addition these factors, plus the eruption depth, have also governed the development of volcaniclastic and pyroclastic debris. Basic magma was erupted quietly, and resulted in a thick lava pile with only a limited production of volcaniclastic and pyroclastic material. Similarily acidic magma also appears to have been erupted quietly in this area, although as a result of its viscosity it produced thick flows and domes, and abundant related autobreccias and collapse breccias.

From an examination of whole-rock major and trace element analyses of a representative suite of rocks it is demonstrated that the intrusions and extrusions, which have tholeiitic characteristics, are comagmatic and that the majority of the igneous rocks examined are related to each other by a process of high-level crystal fractionation.

The rocks of the area suffered low-grade regional metamorphism during the Caledonian Orogeny, indicated by the presence of

pumpellyite and prehnite within the meta-basites.

In spite of this alteration, clinopyroxene remains as a metastable, relict phase within the meta-basites. From a microprobe study of the composition of these clinopyroxenes, it is clearly demonstrated that the rocks have tholeiitic affinities in addition to the fact that the composition of clinopyroxene within igneous systems is dependant upon cooling history.

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ACKNOWLEDGEMENTS

This work was undertaken during tenurship of a University of Keele Demonstratorship and generous grants from the University of Keele for field expenses are gratefully acknowledged.

Dr. R. A. Roach suggested the topic for study and it was supervised by Drs. R. A. Roach and P. A. Floyd.

The facilities of the Department of Geology, University of Keele were kindly made available by Professor F. W. Cope and more lately by Professor G. Kelling, to whom I am indebted.

Stimulating discussions were held during the course of this work with many friends and colleagues, in particular Bob Roach, George Rowbotham, Graham Lees, Roger Suthren, Pete Kokelaar, Pete Floyd, Dave Alderton and Peter Dunkeley, to all of whom I wish to express sincere thanks.

Dr. G. Rowbotham kindly analysed clinopyroxenes on a Geoscan Mk. II Microprobe and the University of Manchester are thanked for allowing the use of these facilities. Mr. G. J. Lees provided technical skills on the use of x-ray equipment and computing techniques, as well as advice and encouragement at all stages on almost any geological problems encountered, and I am deeply indebted to him for this.

Drs. R. A. Roach, G. Rowbotham and P. A. Floyd read and improved various parts of the manuscript, whilst Miss Irene Taylor corrected many errors present in an early draft.

The technical staff, under the supervision of Mr. M. W. Stead provided expertise in many fields and thanks are expressed to all, in particular David Kelsall, David Emley, Peter Greatbatch and Margaret Aikin.

Thanks are expressed to Jane Install for expertly typing the script, as well as making sense of some of the remaining errors.

My parents, family and Irene have all shown tremendous understanding and support during the course of this and earlier work, without which none of this would have been at all possible, and I express extreme gratitude.

Finally I would like to thank all my colleagues and their families who have shown sincere friendship during my stay at Keele, in particular Phil and Helen Lane.

CHAPTER 1. INTRODUCTION

1.1. AIMS OF THIS THESIS

The initial aim of this work was to study aspects of Ordovician vulcanicity in S.W. Wales and particularly to concentrate on one suite of volcanics from which a detailed picture of the local volcanic history could be deciphered. After a reconnaissance of the various volcanic horizons in S.W. Wales, the Fishguard Volcanic Group of North Pembrokeshire was chosen for a more detailed study, in view of the good coastal exposures and the variety of rock types (see Fig. 1 and Table 1). Primarily, three key features were investigated, namely:

(i) the nature of the volcanism, as deduced from the volcanic and volcaniclastic rocks identified within the chosen area;

(ii) the petrology of the rocks, along with evidence for relationships between the various rock types; and

(iii) the geochemical characteristics of the magma or magmas responsible for this volcanic episode.

It was hoped that this investigation would help to solve the relationship between the various volcanic and high-level intrusive rocks present in the surrounding regions.

As work progressed, other beneficial lines of inquiry emerged. It was found, for example, that the clinopyroxenes within the basalts and dolerites of the Strumble Head Volcanic Formation (see Table 1) were unaltered. Their composition was investigated by use of the electron microprobe in the hope that they would assist in unravelling the

FIG. 1. Simplified geological map of S.W. Wales. The outlined area represents area of detailed investigation in this thesis.

S.W. WALES
GENERAL GEOLOGY

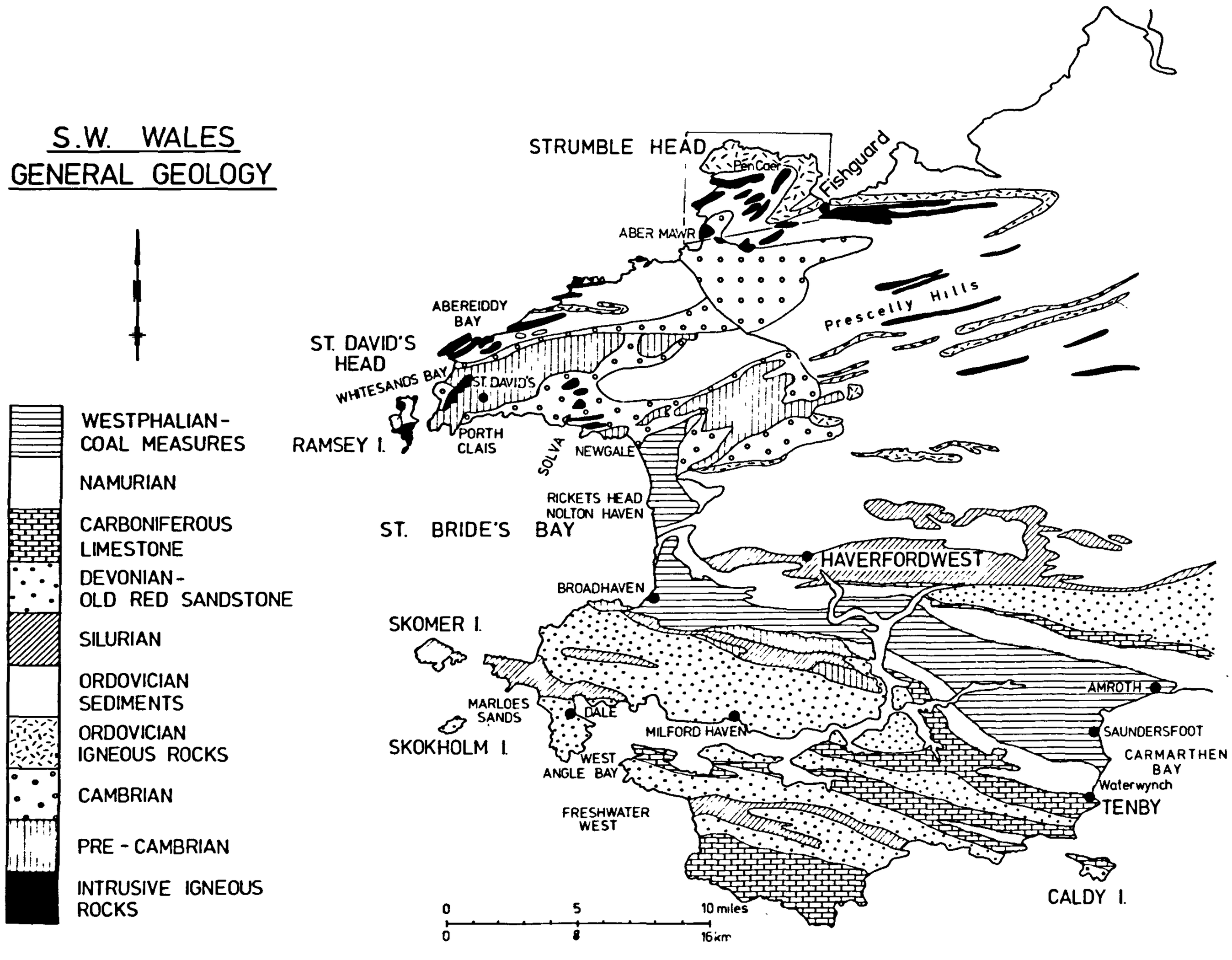


TABLE 1. STRATIGRAPHY OF THE FISHGUARD AREA

	THIS STUDY		COX (1930)		THOMAS AND THOMAS (1956)	
LLANDEILO	Calcareous Flags		Calcareous Flags		Calcareous Flags	
LLANVIRN	D. Bifidus Shales		D. Bifidus Shales		D. Bifidus Shales	
	Fishguard Volcanic Group	Goodwick Volcanic Formation	Fishguard Volcanic Group	The upper rhyolites	Fishguard Volcanic Series	Upper Rhyolite Division
		Strumble Head Volcanic Formation		The pillow lavas		Pillow Lava Division
		Porth Maen Melyn Volcanic Formation		The lower rhyolites		Lower Rhyolite Division
	D. Bifidus Shales		D. Bifidus Shales		D. Bifidus Shales	
ARENIG	Tetragrapus Shales		Tatragraptus Shales		Tetragraptus Shales	

characteristics of their parental magma. However, a far more illuminating picture emerged, illustrating the relationship between phase chemistry and physical conditions prevalent during crystallization.

Similarly, the identification of pumpellyite - and prehnite - bearing basalts led to a thorough investigation of the phase assemblages in the basic igneous rocks of the North Pembrokeshire region, in particular those of the Fishguard Volcanic Group. As a result, it is possible to suggest for this area the grade of metamorphism attained during the Caledonian Orogeny.

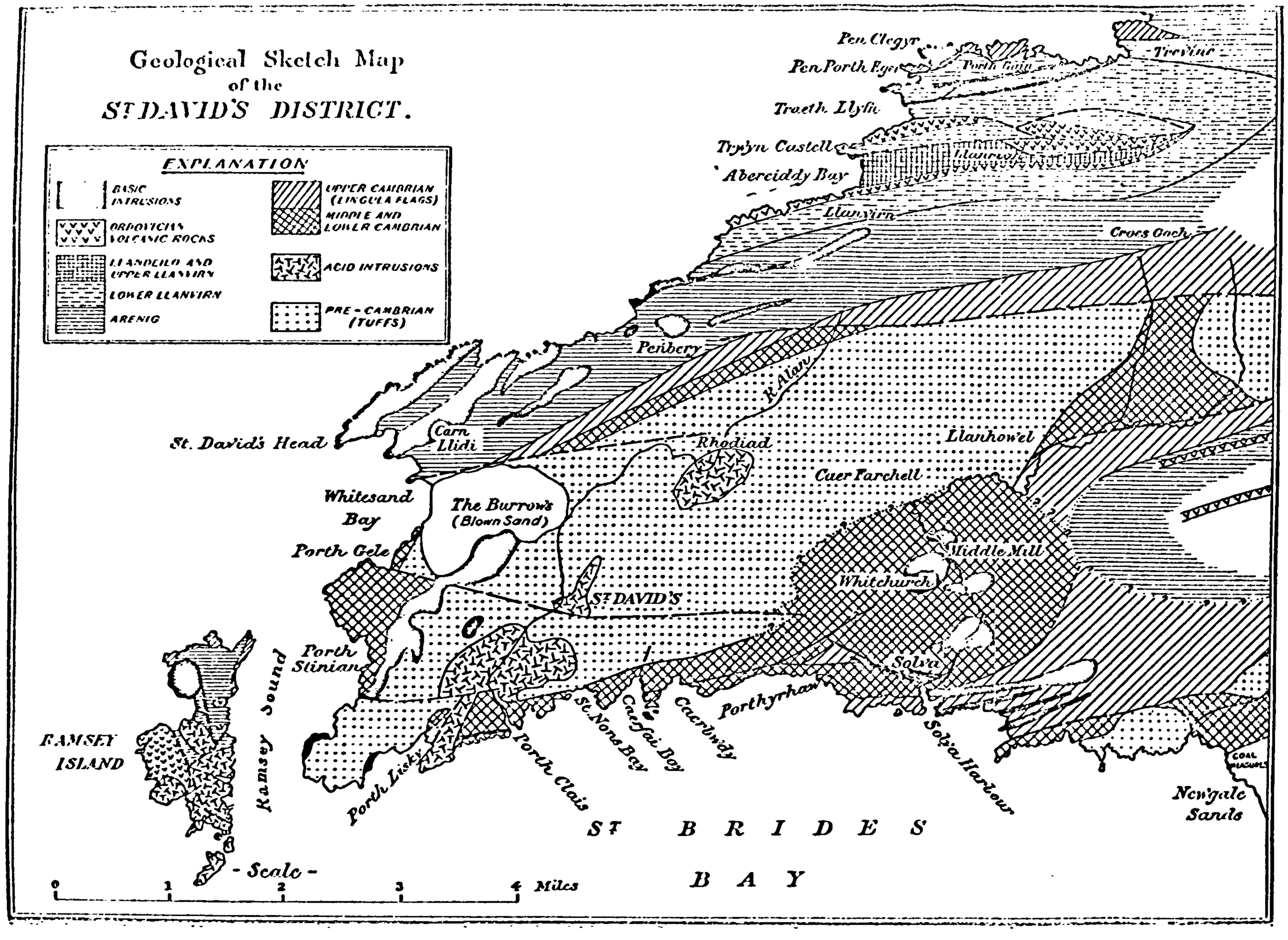
1.2. GENERAL GEOLOGY OF THE LOWER PALAEOZOIC ROCKS OF SOUTHWEST WALES

The Lower Palaeozoic sequence in S.W. Wales is a succession of marine sediments which, within the Lower Ordovician and Lower Silurian contain contemporaneous volcanic and volcaniclastic rocks, intruded by co-magmatic high-level sheets. This sequence was folded about E-W to ENE-WSW trending axes during the Caledonian Orogeny (George, 1970) (Fig. 1). The Lower Palaeozoic sequence overlies a late Precambrian basement comprising volcanic rocks (the Pebidian Complex), intruded by rocks of a plutonic aspect (the Dimetian Complex) which in North Pembrokeshire (the region north of St. Brides Bay and north of Haverfordwest - see Fig. 1) is exposed in: (i) the St. David's area in the core of the St. David's anticline (Hicks, 1884; Green, 1908; Williams, 1934); and (ii) the Trefgane, Roch and Haycastle area, in the core of the Haycastle anticline (Thomas and Cox, 1924). With the exception of these areas, the North Pembrokeshire region is composed almost exclusively of Cambrian and Ordovician strata and associated igneous rocks (Fig. 1).

Rocks of Cambrian age are well exposed on the southern flank of the

St. David's anticline along the north coast of St. Bride's Bay, from Porth Clais to Newgale (Fig. 2) (Cox et al., 1930a and b; Stead and Williams, 1971), with the maximum development (approximately 1500m) in the St. David's area. The Lower Cambrian Caerfai Series begins with a coarse basal conglomerate which is succeeded by green and purple sandstones. These pass upwards into sandy mudstones of the Solva Series (Middle Cambrian) which in turn are superseded by the Menevian Series (Middle Cambrian) of flags and shales. The Upper Cambrian is represented by the Lower Lingula Flags. Further exposures of Cambrian strata occur along the north flank of the St. David's anticline and also along the flanks of the Haycastle anticline. Good coastal exposures are also found along the North Pembrokeshire coast (Cox, 1915 and 1930), particularly in the Aber Mawr area (Fig. 1) where they are invaded by a number of thick basic sheets of Ordovician age - the gabbros and dolerites of Roach (1969)- as for example the Llech Dafad Intrusion (GR 882356). A distinctive feature of the Cambrian succession in North Pembrokeshire is the apparent lack of volcanic rocks, although some pre-Ordovician igneous activity is reflected in the presence of 'hornblende diorite-porphyrites' in the Cambrian succession along the southern flanks of the St. David's anticline (Fig. 2) (Cox et al., 1930a). Ordovician rocks are best exposed along the north coast of Pembrokeshire, where, in the Abereiddy Bay area, the type locality of the Llanvirn occurs. While observed contacts between Cambrian and Ordovician strata are frequently faulted there are two possible localities in North Pembrokeshire, one at the northern end of Ramsey Island (Pringle, 1930; Cox et al., 1930b) and the other at Trwynhwrddyn (GR 732273), in Whitesand Bay (Cox et al., 1930b; Jones, 1940; Evans, 1948; Owen et al., 1971; Bevins and Roach, personal observations) (Fig. 2), where possible undisturbed contacts may be observed. In both

FIG. 2. Geological map of the St. David's district, from Cox *et al*. (1930).

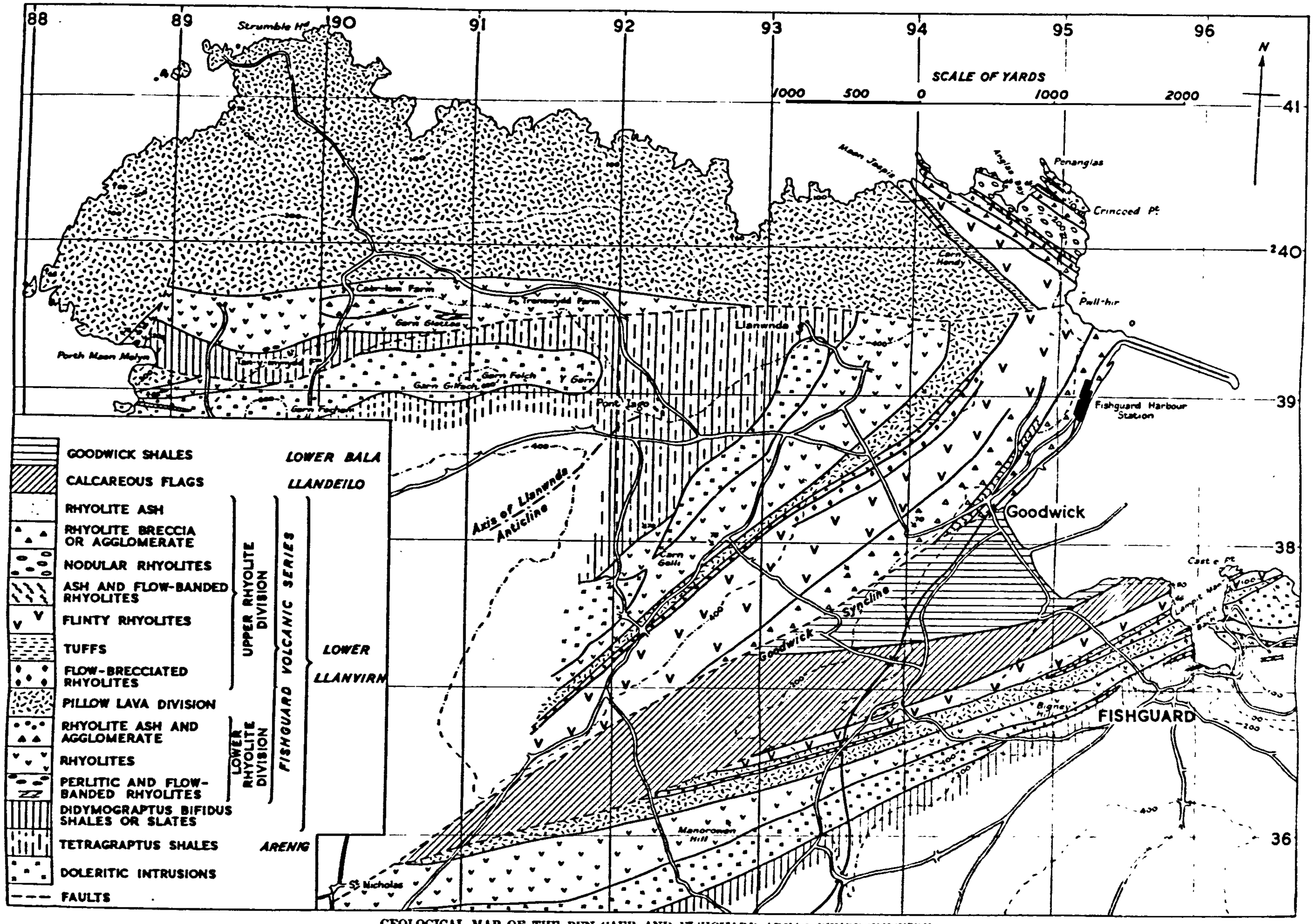

Geological Sketch Map
of the
ST DAVID'S DISTRICT.
EXPLANATION
BASIC INTRUSIONS
ORDOVICIAN VOLCANIC ROCKS
LLANDEILO AND UPPER LLANVIRN
LOWER LLANVIRN
ARENIG
UPPER CAMBRIAN (LINGULA FLAGS)
MIDDLE AND LOWER CAMBRIAN
ACID INTRUSIONS
PRE-CAMBRIAN (TUFFS)
Pen Clegyr
Pen Porth Eger
Porth Gain
Trevine
Traeth Llyfn
Trwyn Castell
Abereiddy Bay
Llanrian
Llanvirn
Croes Goch
Penbery
R. Alan
St. David's Head
Carn Llidi
Rhodiad
Llanhowel
Caer Farchell
Whitesand Bay
The Burrows (Blown Sand)
Porth Gele
Middle Mill
Whitchurch
ST DAVID'S
Porth Stinian
Solva
Porthyrhaw
Ramsey Sound
RAMSEY ISLAND
Porth Lisky
Porth Clais
St. Nons Bay
Caerfai Bay
Caerbwdy
Solva Harbour
COAL MEASURES
Newgale Sands
ST BRIDES BAY
- Scale -
0 1 2 3 4 Miles

localities the boundary may be a slight disconformity between Lower Lingula Flags and Lower Arenig. At Trwynhwrddyn the basal Arenig is possibly represented by a thin sequence of volcaniclastic sandstones and siltstones which may be the lateral equivalent of the Trefgarne Volcanic Group, also thought to be of Lower Arenig age (Thomas and Cox, 1924).

The Lower Arenig strata are predominantly sandstones and sandy shales forming the Ogof Hen Formation (Bates, 1969; Bassett, 1972). These pass upwards into dark grey and black cleaved mudstones, the Upper Arenig Tetragraptus Shales (Cox, 1915). These pass conformably into similar dark cleaved mudstones of Lower Llanvirn age (D. bifidus Shales). This boundary, which is biostratigraphic and marked by the incoming of Didymograptus bifidus was mapped out at Llanvirn-y-fran farm, the type locality. The beginning of the D. bifidus zone (Lower Llanvirn) is also marked by volcanic and volcaniclastic rocks, such as those forming the Abercastle Ashes (Cox, 1915) and the Sealyham Volcanic Group of the south Prescelly Hills region (Cox, 1915; Cox and Thomas, 1924; Evans, 1945; Bevins and Roach, in press).

The thickest development of volcanic rocks in North Pembrokeshire is the Fishguard Volcanic Group, which also occurs within the D. bifidus zone (Cox, 1930; Thomas, 1951; Thomas and Thomas, 1956). Volcanics of this group are best developed in Pen Caer, to the northwest of Fishguard (Figs. 1 and 3). Laterally they can be traced eastwards to Newport (Fig. 4) (Reed, 1895; Davies, 1936) and thence into the Prescelly Hills (Evans, 1945). Deposition of dark muds continued during Upper Llanvirn times to give the D. murchisoni Shales. In the Abereiddy Bay area the boundary with the Lower Llanvirn D. bifidus Shales is marked by

FIG. 3. Geological map of the Strumble Head-Fishguard region, from Thomas and Thomas (1956).



GEOLOGICAL MAP OF THE PEN CAER AND FISHGUARD AREAS, PEMBROKESHIRE.

FIG. 4. Geological map of the country between Fishguard and Newport (from Reed, 1895).

▭ Llandovery. ▭ Bala and Up. Llandeilo. ▭ Bala and Up. Llandeilo, volcanic rocks. ▭ Mid. Llandeilo. ▭ Lr. Llandeilo. ▭ Lr. Llandeilo, volcanic rocks. ▭ Llanvirn and Arenig. ▭ Intrusive diabase, etc. ▬ Faults.

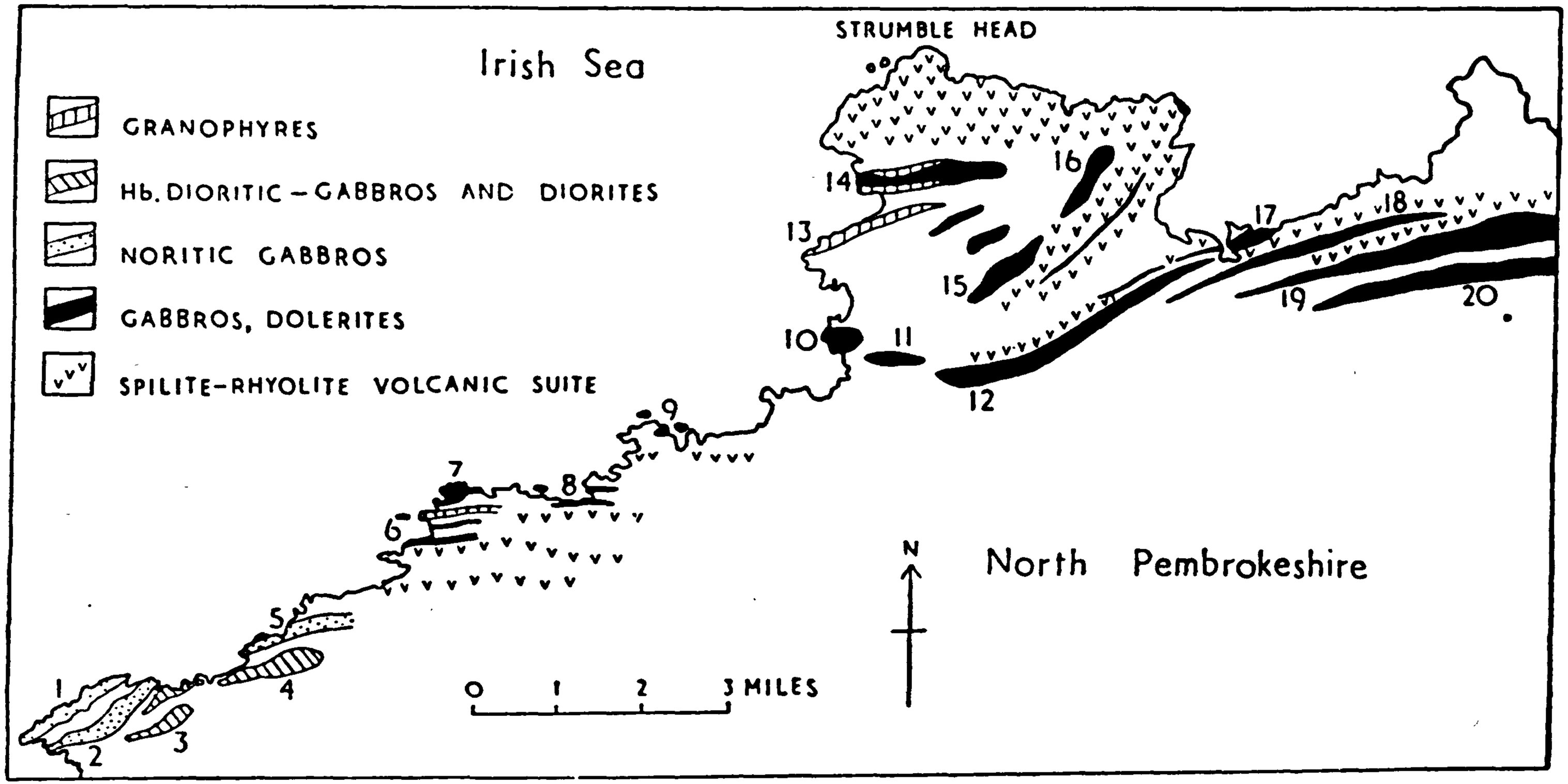
a distinctive volcanogenic deposit - the Murchisoni Ash (Cox, 1915).

A thick development of Lower Ordovician volcanic and volcanistic rocks is present on Ramsey Island (Fig. 2) (Pringle, 1930), although the precise age of these deposits is, as yet, uncertain (Bevins and Roach, in press).

Sediments of Llandeilo age are recognized within the overturned synclinal structure at Abereiddy Bay (Fig. 2), as well as in the tract of country between Fishguard and Newport (Fig. 4) (Reed, 1895; Davies, 1936; Thomas and Thomas, 1956). They are represented once more by dark shales, although at the top of the succession in Abereiddy Bay, a thin limestone, the Castell Limestone, is present (Waltham, 1971). The Caradocian strata have a similar distribution to the Llandeilo rocks, occurring in the fold at Abereiddy Bay and also to the north and east of Dinas (Myers, 1950; Bassett, 1972; James, 1975). However, in the latter region turbiditic sandstones become dominant in the upper part of the succession. Ashgillian sediments are not recognized in North Pembrokeshire and are only encountered further to the northeast, in the Llangranog district (Anketell, 1963).

Basic and intermediate intrusions are common in North Pembrokeshire (Fig. 5) and have been described by Elsden (1905, 1908); Cox (1915); Cox et al. (1930a); Evans, (1945); Roach (1969) and Bevins and Roach (in press). They invade Cambrian, Arenig, and Llanvirn strata (up to the D. bifidus shales) although none are known to exist in Llandeilo or Caradocian sediments. This, together with other evidence (see Chapter 2), suggests the contemporaneous nature of Ordovician intrusive and extrusive activity. The intrusive sheets are clearly folded with the sediments and thus are at least pre-deformation in age. This is substantiated by spots

FIG. 5. Sketch map of the North Pembrokeshire district, showing the approximate distribution of igneous rocks (from Roach, 1969).



Outline map showing the approximate distribution of igneous rocks along the North Pembrokeshire coast between St. David's Head and Dinas Head. The numbers refer to the following localities: 1, St. David's Head; 2, Carn Llidi; 3, Carnedd Lleithr; 4, Penbiri; 5, Pen Clegyr; 6, Traeth Llyfn; 7, Pen Clegyr; 8, Aber Felin; 9, Abercastle; 10, Llech Dafad; 11, Tre-llys; 12, St. Nicholas and Manorowen; 13, Pen Bwch-du; 14, Garn Fawr; 15, Ffynnon-Druidron; 16, Llanwnda; 17, Old Fishguard; 18, Carn Gelli; 19, Mynydd Dinas; 20, Mynydd Melyn.

within contact metamorphosed sediments which are flattened within the cleavage planes (Roach, 1969; and author's own observations). Petrological and geochemical evidence from the 'one-pyroxene' gabbros and dolerites (the 'gabbros and dolerites' of Roach, 1969), persuasively demonstrate a co-magmatic relationship with the lavas of the Fishguard Volcanic Group. Further evidence from the Pen Caer region shows that the sheets were commonly intruded into wet sediments associated with the volcanics of the Fishguard Volcanic Group.

1.3. AREA CHOSEN FOR STUDY

After a reconnaissance survey of the various Lower Palaeozoic volcanic horizons of North Pembrokeshire it was decided to focus attention on the Fishguard Volcanic Group in the Pen Caer region (see Fig. 1). Although surveyed by the Geological Survey during preparation of the 1" Geological Sheet no. 40 (which was published in 1845 and revised in 1857) no description of this area appeared as no memoir was ever published. Thus, the first detailed account of the area was that of Cowper Reed, in 1895 (see Fig. 4). This work recognized the existence of three or four groups of acid volcanic lavas, but unfortunately failed to recognize that the thick pile of basic rocks of the Pen Caer region was largely extrusive in character, instead suggesting the presence of a large 'laccolite'. Reed also allocated the volcanics to the Upper Llandeilo and Bala Series. Elsden (1905) briefly described the petrology of a number of the basic intrusive sheets between St. David's Head and Strumble Head. He drew a distinction between the fine grained basaltic rocks of the north coast of Strumble Head and the intrusive sheets and commenting on the basaltic rocks of the north coast he stated (Elsden, op. cit. p. 582) 'it is amygdaloidal or vesicular and often it closely simulates a true surface-flow'. The recognition of extrusive rocks in this area had to wait until Professor

A. H. Cox investigated the rocks of the North Pembrokeshire coast. In 1913, Cox and Jones reported the presence of pillow lavas in the Lower Palaeozoic sequences of North and South Wales. Further work by Cox resulted in considerable modifications in the stratigraphy of this coastline, including the recognition of the fact that the Fishguard volcanics were Llanvirnian in age. Cox (1930) forwarded a tripartite division for the volcanic group, namely the lower rhyolites, the pillow lavas and the upper rhyolites.

Little work appears to have been undertaken subsequently until Thomas (1951) and Thomas and Thomas (1956) made a thorough investigation of the volcanics of the Pen Caer peninsula. They retained a tripartite division, but named the divisions the Lower Rhyolite Division, the Pillow Lava Division and the Upper Rhyolite Division. A map was produced by these two workers (Fig. 3) which showed a greater variation of rock types within the rhyolitic divisions than had been previously recognized.

1.4. METHOD OF APPROACH

1.4.1. MAPPING

Due to the lack of inland exposure, mapping of this area is difficult and any map produced remains highly subjective. However, excellent coastal sections provide good exposures in the volcanic rocks from Porth Maen Melyn to Lower Fishguard (see Fig. 3), which enabled a detailed investigation of this section to be made. Local detailed maps were provided for such areas as Porth Maen Melyn and the Penanglas area (Fig. 3) whilst a more generalized map of the coastline was made in order to obtain thickness estimates of the formations. Six inch sheets SM 84 SE, SM 83 NE, SM 94 SW, SM 93 NW, and SM 93 NE (incorporating part

of SM 94 SE) cover the area in question. All grid references are given to six or eight figures, and are prefixed by SM, unless otherwise stated.

1.4.2. PETROLOGICAL INVESTIGATIONS

A petrological investigation of the components of the Fishguard Volcanic Group was made by examination of over 300 thin sections, prepared by the technical staff in the Department of Geology, University of Keele. This permitted major rock types to be examined thoroughly and allowed geochemical characteristics identified within these rocks to be related to the presence or absence of particular mineral phases.

1.4.3. GEOCHEMICAL INVESTIGATIONS

Geochemical investigations were conducted on both macro and micro scales. On the macro scale, a representative suite of igneous rocks and a small number of volcaniclastic rocks from the Fishguard Volcanic Group were collected and analysed for major and trace elements. These analyses were performed almost wholly by X-ray fluorescence techniques, although limited wet chemical methods were also employed. On a micro-scale, the chemistry of both primary and secondary mineral phases present within the basic rocks was examined by the utilization of electron microprobe facilities at the University of Manchester. Full details of this work appear in Appendix 1.

1.5. STRATIGRAPHY

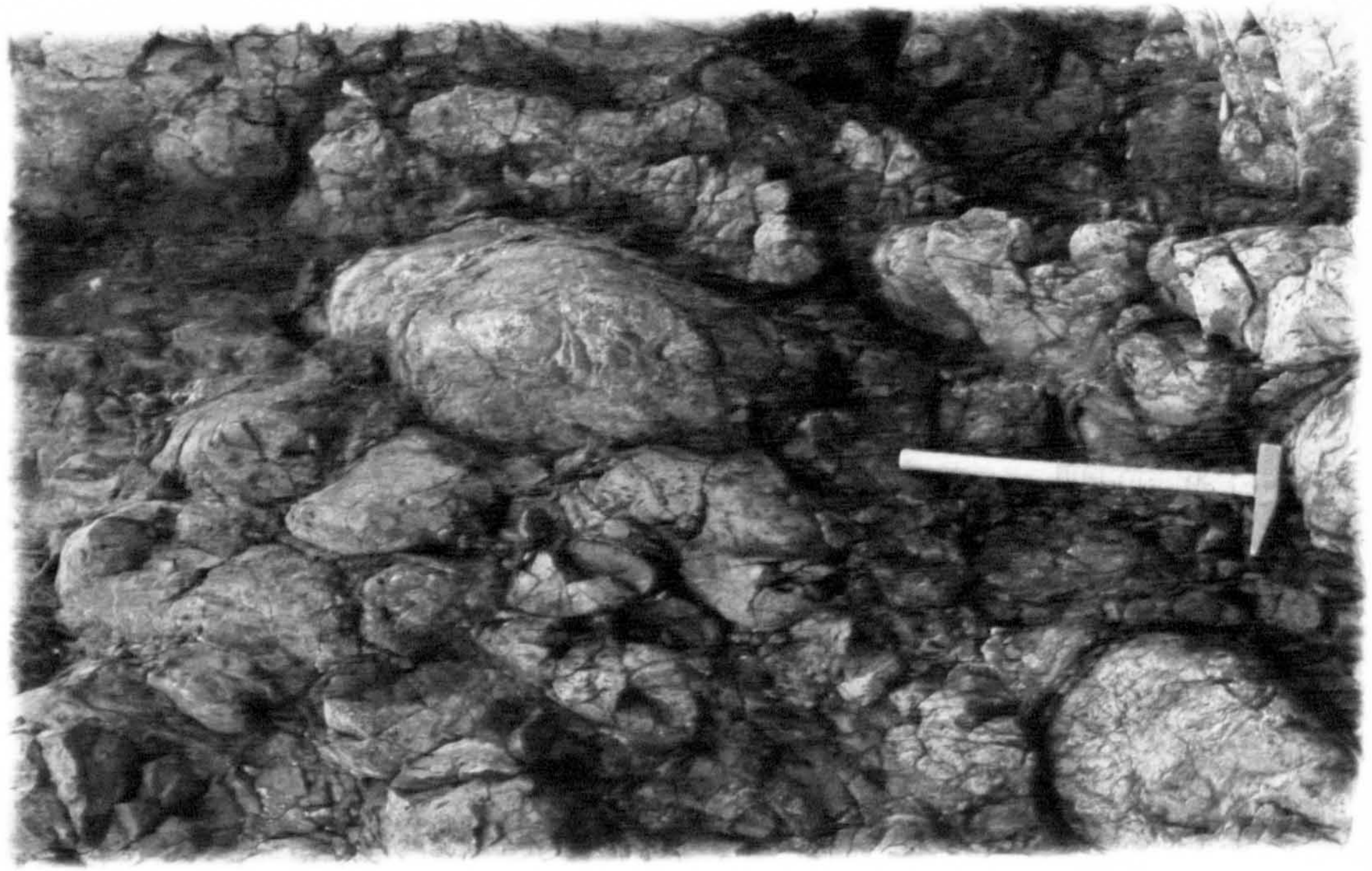
The stratigraphy used in this thesis differs from that of Cox (1930) and Thomas and Thomas (1956). It is based on field observations made during this study. Table 1 outlines the revised stratigraphy and compares it with previous works.

1.6. STRUCTURE

The Lower Palaeozoic rocks of Wales suffered deformation and metamorphism during the Caledonian Orogeny. In the Fishguard area, the rocks were folded into open anticlines and synclines, with axial planes striking approximately eastnortheast - westsouthwest, as in the Goodwick Syncline and the Llanwnda Anticline (Thomas and Thomas, 1956) (Fig. 3). Within the incompetent strata of the area, a strong, steeply dipping penetrative cleavage was developed. This strikes at approximately 060° and is thus nearly parallel to the limbs of the major folds. In the highly competent rocks, for example the volcanic horizons, a penetrative foliation is not usually developed, although locally the stress has been taken up along discrete zones of high strain. Such zones may be identified within the rhyolites at Penfathach (GR 941405) and also within the basic lava pile of the Strumble Head Volcanic Formation, for example at Carregwastad Point (GR 927405) and Porth Sychan (GR 907408). At the latter locality flattened pillows are seen, adjacent to undeformed pillows and the zone of flattening can be clearly identified (Figs. 6 and 7). The deformation in these rocks is clearly inhomogenous in character. Between these extremes of rock competencies, are rocks showing a poorly defined penetrative cleavage or a fracture-type cleavage. Where present, clasts are generally flattened.

The deformation history of the Lower Palaeozoic rocks of this area is no doubt quite complex. Evidence at Porth Maen Melyn (GR 888392) shows the existence of a sub-horizontal crenulation cleavage which deforms the strong slatey cleavage. Elsewhere, late cross-folds and kink bands have been observed.

FIGS. 6 and 7. Pillows showing evidence of flattening during Caledonian deformation. Porth Sychan (GR 907408). Diameter of lens cap in Fig. 6 is 57mm. Length of hammer handle in Fig. 7 is 54cm.



The rocks of this area suffered low-grade, prehnite-pumpellyite facies metamorphism during the Caledonian Orogeny (see Chapter 7) and this is considered to have occurred almost synchronous with the deformation outlined above (Bevins, 1978).

CHAPTER 2. DESCRIPTION OF THE IGNEOUS ROCKS OF THE FISHGUARD VOLCANIC GROUP

2.1. INTRODUCTION

As mentioned in Chapter 1, the three formations of the Fishguard Volcanic Group show a variety of igneous and volcaniclastic rocks. This chapter will deal with the igneous rocks whilst the volcaniclastics will be described in Chapter 3.

Magmas of basic, intermediate and acid compositions are all present and occur as extrusive lavas and high-level, comagmatic, intrusive sheets. Nearly all of the intrusive bodies form concordant sheets, with dyke-like forms being rare. As the composition of a magma largely controls its viscosity and hence its surface or sub-surface expression, the igneous rocks will be described under three subdivisions, namely: (i) basic; (ii) intermediate; and (iii) acid. Rocks were attributed to the various subdivisions following field, petrological and geochemical investigations.

2.2. BASIC IGNEOUS ROCKS

Basic igneous rocks occur within the Fishguard Volcanic Group both as lava flows and intrusive sheets. The flows form the Strumble Head Volcanic Formation whilst the sheets invade this pile and the underlying sediments. In Chapter 5, on a geochemical basis, these sheets are shown to be a co-magmatic intrusive suite and hence they will be described in this chapter, along with the rocks of the Fishguard Volcanic Group.

2.2.1. BASIC LAVA FLOWS

2.2.1.1. CHARACTER AND EXTENT

Basaltic flows are almost entirely limited in occurrence to the

Strumble Head Volcanic Formation. The boundaries of this Formation, shown in Figure 8, are broadly similar to those of the Pillow Lava Division of Thomas and Thomas (1956) (Fig. 3). In detail, however, certain differences are apparent:

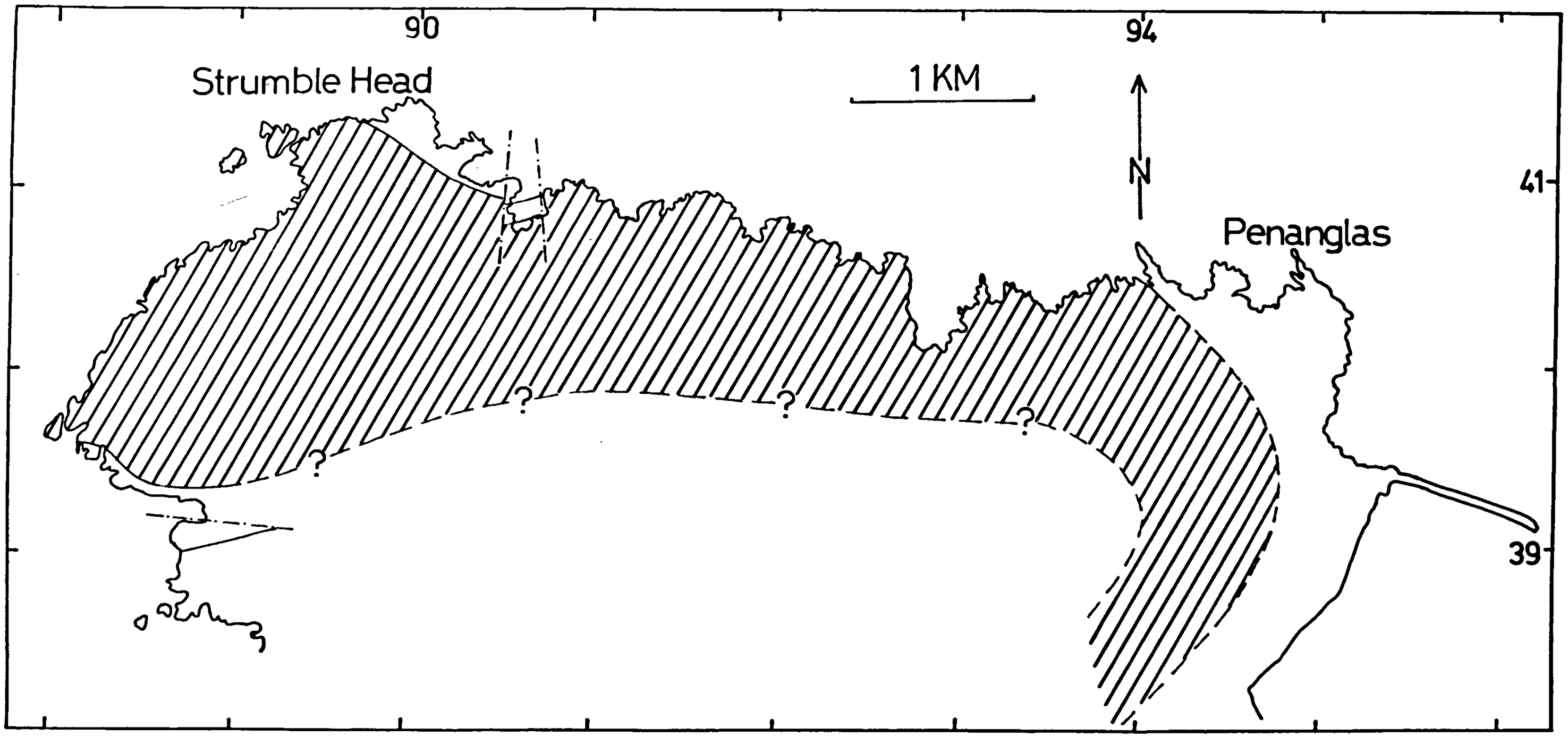
1. The lower contact of the Strumble Head Volcanic Formation at Porth Maen Melyn, where this Formation overlies the Porth Maen Melyn Volcanic Formation (which is approximately equivalent to the Lower Rhyolite Division of Thomas and Thomas (op. cit.), can be traced westwards from Porth Maen Melyn, towards Pen Brush (Figs. 8 and64);

2. There is no field evidence for an E-W trending fault constituting the southern boundary of the Strumble Head Volcanic Formation north of Llanwnda and reaching the east side of the Pen Caer peninsula at Pwll-hir (see Fig. 3); and

3. The acid and basic volcanic and volcaniclastic rocks east of Strumble Head and including the intraformational Strumble Head Series of Thomas and Thomas (Fig. 3) are here tentatively assigned to the Goodwick Volcanic Formation.

It can be seen that the maximum development occurs in the west of this area, with a thinning to the east and south. However, a considerable offshore extension of Lower Palaeozoic rocks has been identified (Dobson et al., 1973), much of which to the north and west of the Fishguard area is possibly composed of rocks belonging to the Fishguard Volcanic Group. From exposures in the Pen Caer region, only an approximation of true thickness can be obtained and not until more is known about the nature of the submarine extensions will a better estimate be possible.

FIG. 8. Sketch map of the Pen Caer district, showing the approximate extent of the Strumble Head Volcanic Formation (shaded area).

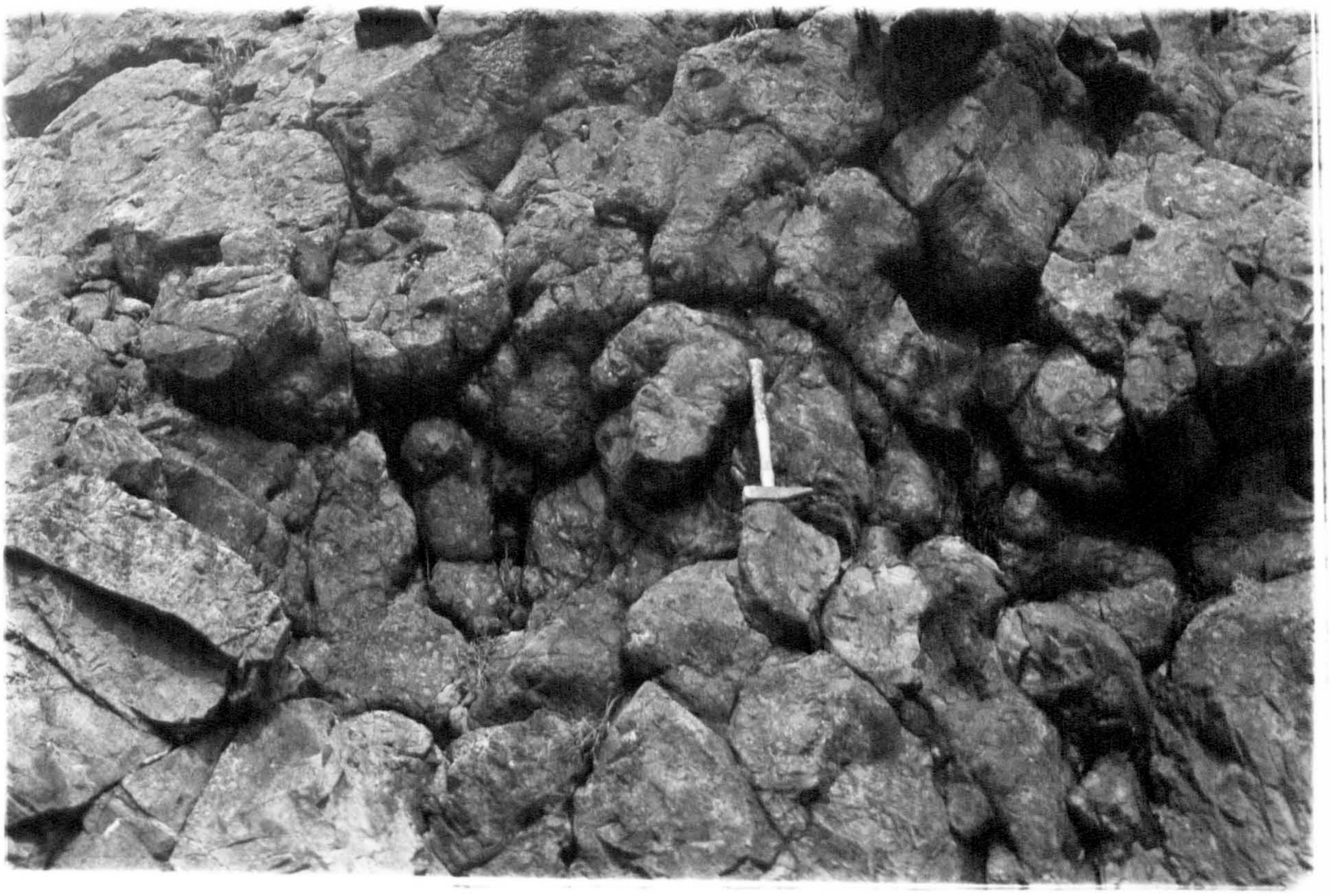

90
94
Strumble Head
1 KM
N
41
Penanglas
39

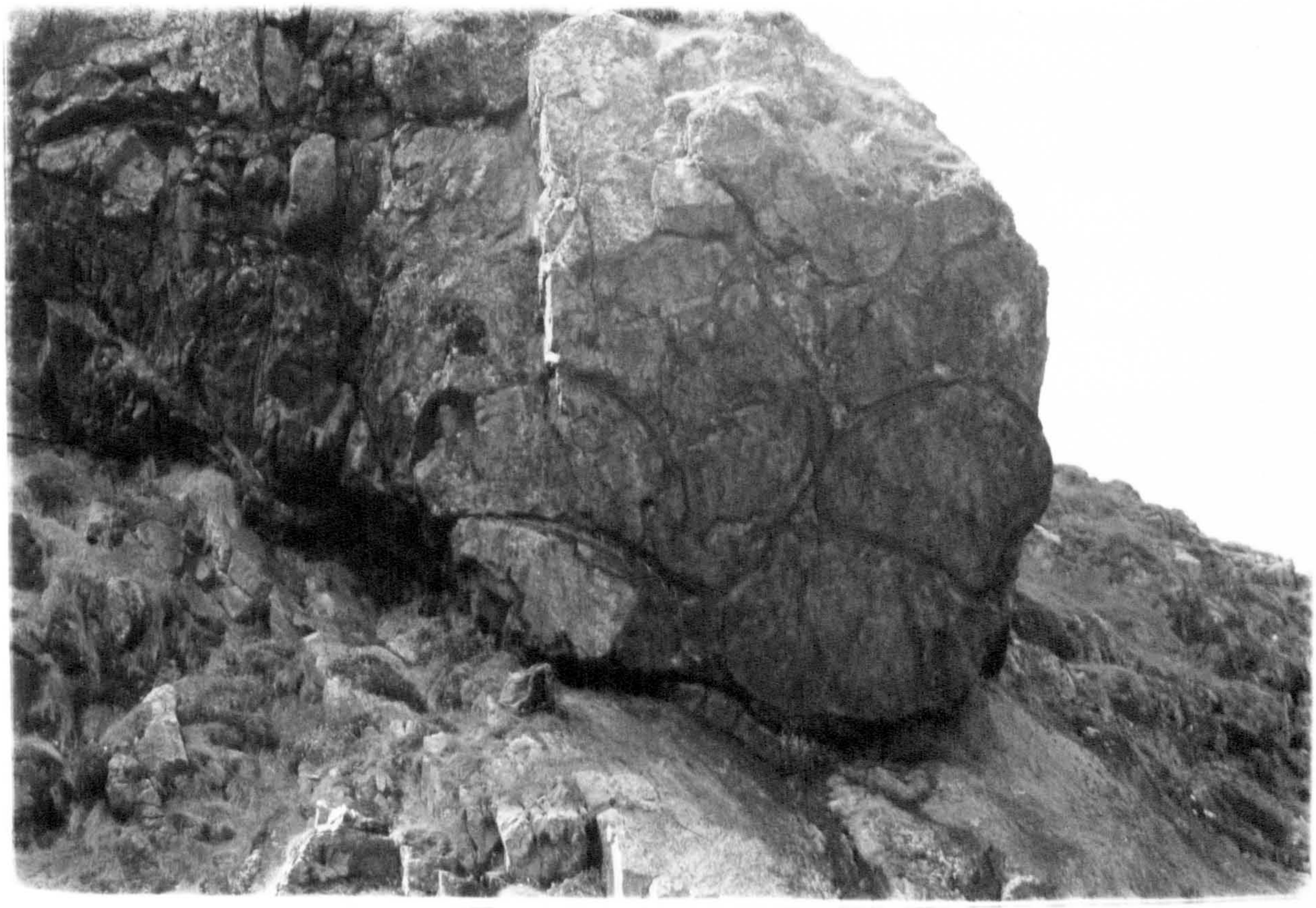
The lava pile is largely composed of pillowed lavas (Fig.9) with massive lava flows of minor importance. The beds generally dip in a northerly direction, although the amount of dip is very variable. However, the pile is considerably thickened by the massive basic sheets which were intruded contemporaneous with the extrusive activity. Clearly, it is difficult in some cases to decide which of the massive sheets represent truly extrusive lava flows and which are high-level intrusives. When only the pillowed flows are considered, an approximate minimum thickness for the lava pile of the Strumble Head Volcanic Formation of 800 metres is obtained. If the massive sheets are included, then the pile is approximately 1600 metres thick. In the Lower Fishguard Harbour area, the pile thins to about 5 metres on the west side of the Harbour whilst pillowed lava is not seen at all on the eastern side (Thomas and Thomas, 1956). However, this absence may be due to faulting, as basic pillowed lava is seen once more a short distance to the east, at Carn Gelli (GR 982375). Still further east, between Dinas and Newport, and also in the Prescelly Hills, extrusive basaltic magma is not seen at all within the Fishguard Volcanic Group and basic magma is confined to high-level, concordant sheets (Evans, 1945; Bevins and Roach, in press).

Individual pillowed units (the upper and lower boundaries of a pillowed unit are defined by the presence of sedimentary horizons within the lava pile) are generally discernable and range in thickness from a few metres to units 200 metres or more thick. However, it is not certain whether these represent the accumulations from single or multiple eruption episodes. The massive flows are generally structureless, whilst the pillowed flows exhibit a wide variety of structures and will thus be described in more detail.

FIG. 9. Well developed pillows within the Strumble Head Volcanic Formation, north of Porth Maen Melyn (GR 888393).

FIG. 10. Large pillows exposed in cliffs north of Carnfathach (GR 938405). Scale shown by rucksack, at base of cliff.





Pillow size varies greatly, ranging from very small 'globules', less than 5cm in diameter, to large bodies over 3m in diameter. It has been suggested by various workers (for example Schmincke and Staudigel, 1976) that pillow size may be correlated with chemical composition; the more silica-rich the lava, the larger the pillow. In the Fishguard Volcanic Group, some of the largest pillows are found at Trwyn Llwyd (GR 905410) and also belowCarnfathach (at GR 938405), as illustrated in Figures 22 and 9 respectively. A chemical analysis shows that the pillows from the Trwyn Llwyd area are of andesitic composition (see sample SBR11, Appendix 1). However, the basalts themselves, which form the majority of the pile, show widely varying sizes and it is considered here that many other factors, such as rate of lava effusion and eruption temperature, also control pillow size, and that the composition of the lava is probably of minor importance. The pillows are circular to ovate in cross-section and elongate to cylindrical normal to this section. The pillows exhibit a great variety of forms, but commonly show a 'Y' shaped base and a convex upper surface. The 'Y' shaped base is generally assumed to represent a primary structure formed when the overlying pillow was still plastic enough to mold itself into the gap between the underlying pillows (see Figs.11a-b and 9). These are the 'pedunculate' type pillows of Vuagnat (1976). Many pillows of the Strumble Head Volcanic Formation are of this type, although all the other forms described by Vuagnat (op. cit.), for example "bun", "balloon", or "bean" shaped, may also be recognized. Generally, little or no sediment or hyaloclastite is found between the pillows (Fig. 12). This suggests a rate of effusion rapid enough to cover pillows by further lava almost immediate upon their formation, with no time either for desquamation of the pillow to produce an inter-pillow hyaloclastite

FIG. 11a and b. Two views of pillows from the area to the east of Maen Jaspis (GR 93834045), illustrating fit between adjacent pillows.

FIG. 12. Pillowed lava from the Porth Maen Melyn area (GR 888393), showing the lack of inter-pillow material.

FIG. 13. A thin sedimentary parting within the Strumble Head Volcanic Formation, on the east side of Porth Sychan (GR 90804095).

or for the accumulation of sediment. Thin sedimentary intercalations are found in places and no doubt represent temporary cessations in extrusive activity. It is difficult usually to trace these thin sedimentary partings laterally and they probably represent accumulations in local basins on the uneven volcanic surface. Figure 13 shows one such thin sedimentary parting on the east side of Porthsychan (GR 908409). As can be seen, the sediment has accumulated over an uneven surface of pillows and draped the pillows, mimicking the original surface.

The pillows show evidence of the former presence of a glassy margin which has altered to produce a chloritic crust. Very occasionally this has spalled off and provided material to produce inter-pillow hyaloclastites composed of altered glass set within cryptocrystalline silica and small amounts of sediment.

Vesiculation is ubiquitous throughout the lava pile. Moore (1965) suggested that the vesicularility and bulk density of submarine basalts show a systematic change with the depth of emplacement of the lava. Samples from deep waters have higher specific gravity and contain fewer and smaller vesicles. This principal has been applied by various workers in attempting to infer approximate depths of emplacement (as opposed to depths of eruption) of ancient volcanic assemblages. One of these studies (Jones, 1969) attempted to suggest depths of emplacement for the pillow lavas of the Strumble Head Volcanic Formation. Jones (op. cit.) concluded that depths in the range 0-2000m (i.e. neritic-bathyal rather than abyssal) were originally present, with a shallowing of water depth during the development of the pile. However, attempts to reproduce these results in the present study were unsuccessful. Jones (op. cit. Fig. 4) showed that vesicle diameters range from 0.5 to 2mm and increase in size with

stratigraphic height. However, samples collected during this study appear to contradict these observations. A large basaltic pillow collected from close to the base of the pile (GR 885394), to the north of Porth Maen Melyn, shows vesicles of average diameter 2-3cm, whilst a sample collected from Carn Melyn, approximately half-way up the pile (GR 892408) has vesicles of a similar size. Vesicles with similar diameter size are also found within pillows from the uppermost flows of the pile, and no simple gradation appears to be present. The picture is further complicated by the presence of macro- and microvesicles which may, in fact, reflect a more complicated picture of vesicle development than envisaged by Jones (1969), producing variables which render the method in question inapplicable (see below). Other problems with this method are also commonly encountered, which are difficult to overcome. Firstly, ancient volcanic rocks are commonly deformed and circular or near circular vesicles are strained. Clearly, therefore, measurement of these deformed vesicles must be avoided. In the Strumble Head Volcanic Formation, this problem is easily overcome as the lavas generally form competent masses, with generally only a low degree of strain. Secondly, the assumption of a primary magmatic volatile content leads to further constraints because in ancient and generally even in modern volcanic rocks, this cannot be estimated. Water and other volatile constituents are highly variable in content and accordingly the degree of vesiculation may vary. A similar argument has been put forward by Schminke and Staudigel (1976). They described flows which may have erupted on land and subsequently flowed into water. Clearly, it is possible for degassing to occur on land and produce a submarine flow completely lacking in vesicles. Typical illustrations of vesiculated lavaflows and pillowed flows show the development of a vesiculated upper surface or crust.

However, in the case of the pillow lavas of the Fishguard Volcanic Group, the picture is more complex, suggesting a complicated history and requiring further explanation.

A complete gradation in vesicle size is commonly seen within individual pillows of the Fishguard Volcanic Group and certain pillows exhibit a zoned vesicle distribution. Other pillows, in contrast show only either a vesiculated outer margin or a vesiculated core. Figure 14 shows a pillow which possesses abundant vesicles and in which a certain distribution of vesicles is present. Relatively small vesicles, infilled with chlorite and calcite, occur throughout, whilst the larger, more irregular vesicles, which generally contain only calcite, appear to be absent from the outermost 6cm or so of the pillow. Pipe vesicles, infilled with chlorite, are found within the outermost 1cm. A two-stage development of the vesicles is thought possible. The smaller vesicles, which are pervasively developed throughout the pillow, along with the pipe vesicles, possibly represent the initial vesiculation of the magma, which is related to the emplacement of the liquid on to the sea-floor. As crystallization proceeded, the system closed and the volatile constituents became increasingly concentrated in the melt, until the point was reached where vapour pressure exceeded the sum of load pressure and surface tension, at which point vesiculation occurred resulting in the larger, more irregular vesicles. This process is known as retrograde boiling and can readily explain the presence of vesiculated cores of pillows. A zoned vesicle distribution may possibly be produced by successive episodes of retrograde boiling.

Certain vesicles within lavas of the Fishguard Volcanic Group bear a resemblance to segregation vesicles which have been previously

FIG. 14. Cut section of a pillow from the Strumble Head Volcanic Formation, illustrating a variation within the pillow of vesicle size, infilling, and distribution. The section is from pillow rim (uppermost) to pillow core (lowermost).

5cm

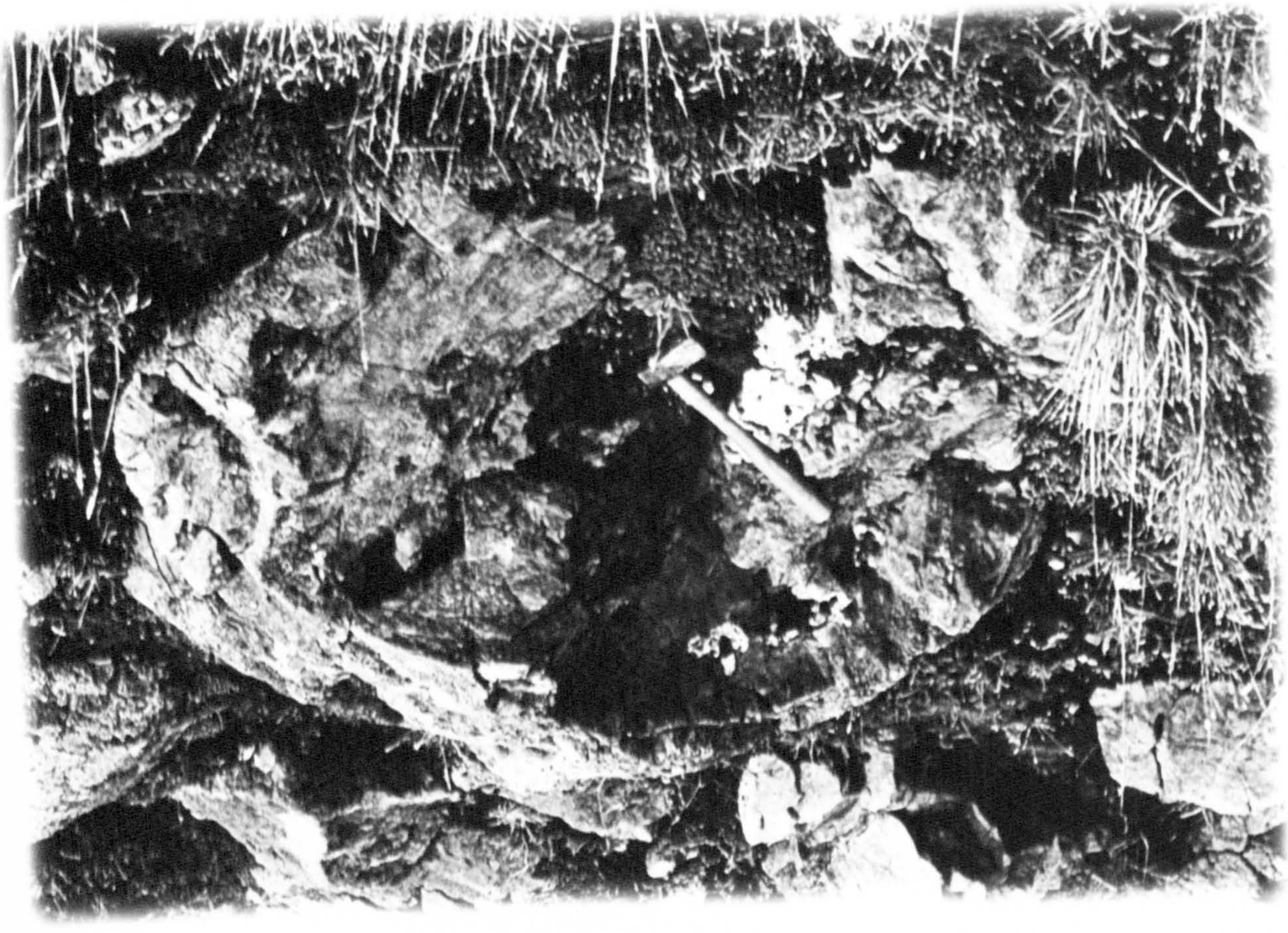
described by many workers. Smith (1967) ascribed the infilling of early formed vesicles by residual liquid as a result of lava moving into progressively deeper water. However, this is not considered necessary as 'segregation' vesicles in the lavas of the Fishguard Volcanic Group do not appear to have resulted from such a history. They appear different in many ways to previous descriptions of segregation vesicles, in particular due to the presence of purple-coloured (Ti-rich), dendritic clinopyroxene lining or filling these vesicles. Baragar et al. (1977) recently described so-called segregation vesicles in basalts from Site 335 on the Mid-Atlantic Ridge, which similarily contain Ti-rich clinopyroxenes. Surrounding the vesicles in the lavas of the Fishguard Volcanic Group, up to a distance of 1mm, the rock is usually dominated by dendritic, Ti-rich clinopyroxenes, of similar composition to those within the vesicles. This suggests that as vesiculation occurred, liquid entered the vesicles and a Ti-rich clinopyroxene crystallized. In the liquid surrounding the vesicle, chilling due to the removal of heat during vesiculation may have caused crystallization. Thus it appears that in no way may the liquid be described as residual. This is discussed below in more detail (S.2.2.1.2.).

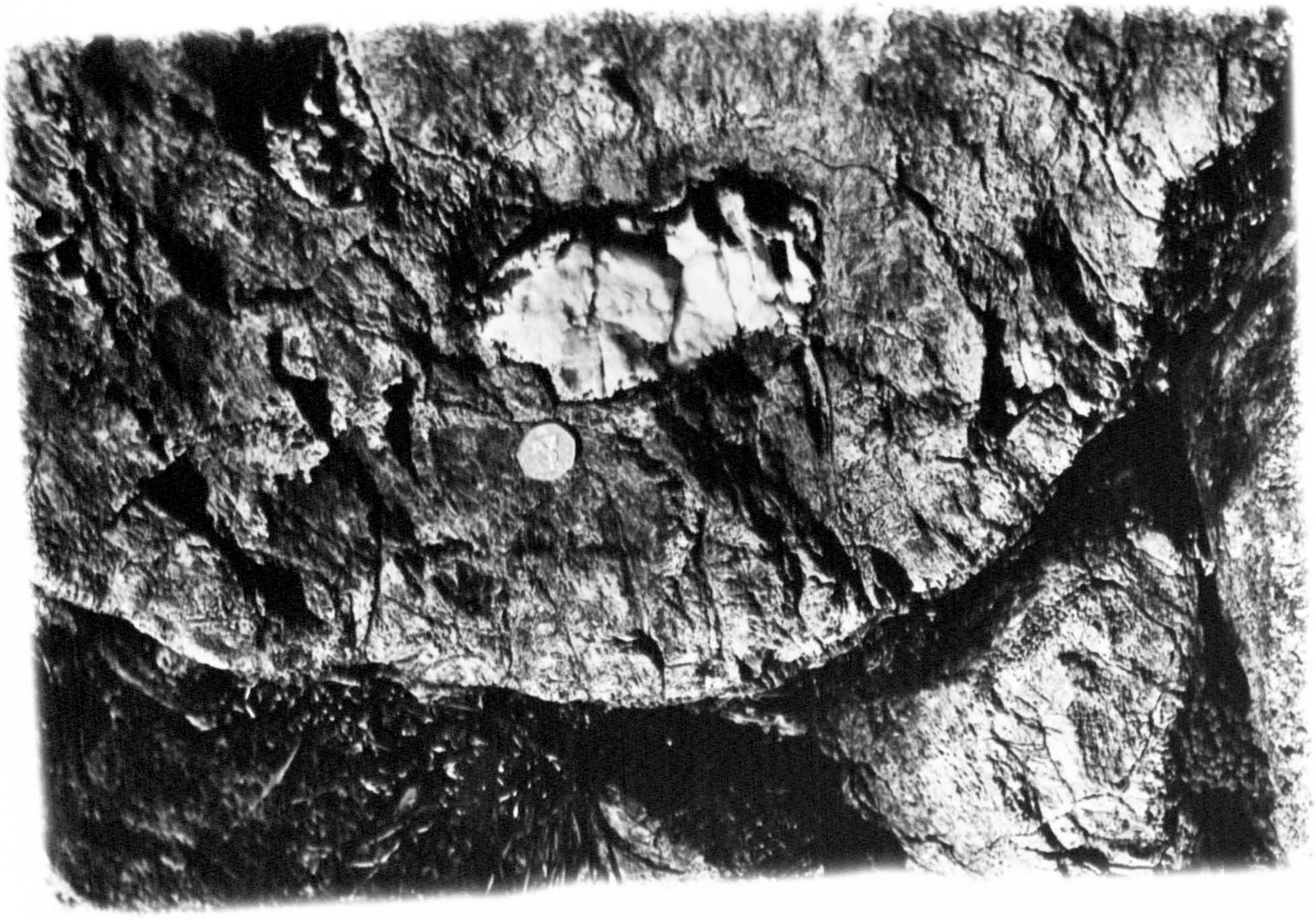
Radial cracks are a common feature of the Fishguard pillows (Fig.15), as indeed they are of pillows from many other regions. They are generally attributed to a volume reduction upon crystallization.

Within the lower part of the pillow-lava pile, epidote veins and lenses are occasionally found, for example north of Porth Maen Melyn (GR 886394), illustrated in Figures 16 and 17. The lenses represent infilled cavities within the pillow and commonly also contain quartz. These cavities have been used by various workers (for example Waters,

FIG. 15. Close-up of pillows from the Strumble Head Volcanic Formation. The pillow on the right shows a radial joint system, whilst a part of the centre pillow has been removed to reveal a sinuous flow tube. Diameter of lens cap 57mm.

FIGS. 16 and 17. Quartz- and epidote-infilled cavities within basic pillows at Porth Maen Melyn.





1960; Furnes, 1974) to show way-up in deformed pillow-lava sequences, as well as flow direction. The latter is determined by the relationship between the supposedly flat floor of the filled cavity and the base of the pillow (see Furnes, op. cit. p. 37). In the cavities examined here, no conclusive evidence was found for flow direction.

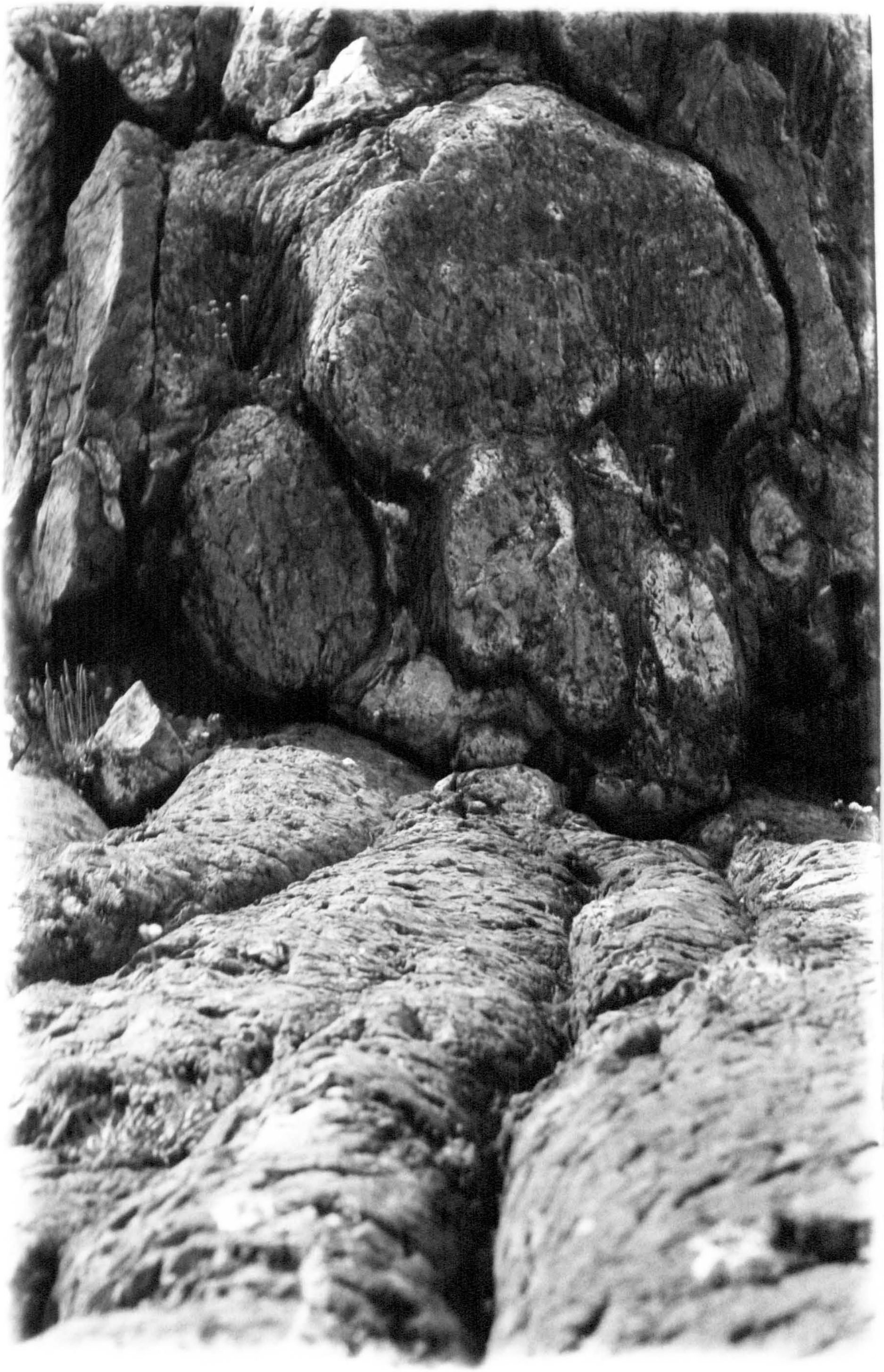
Despite the fact that pillow lava sequences have been recognized and described many times, the actual three-dimensional shape and origin of pillows is still largely a matter of controversy and only in recent years have pillowed flows actually been observed in the process of formation. The greatest controversy concerns whether pillows represent discrete, isolated sacs or merely protruberances on cylindrical, interconnected flow tubes. Work advocating the cylindrical, interconnected tube theory includes that of Jones (1968), Moore et al. (1971) and Vuagnat (1976), whilst Snyder and Fraser (1963), Johnson (1969) and Macdonald (1972) all favour discrete pillow 'sacs'. Attempts to collect discrete pillows from the Strumble Head Volcanic Formation were unsuccessful due to the fact that all pillows sampled had connections of one type or another to other pillows. Rounded masses of lava which had evidence of being discrete entities (i.e. completely surrounded by vestiges of a former glassy crust) were not found. However, only in a few places were cylinder-like forms observed. Examples of these forms are illustrated in Figures 18 to 22. Figure 15 shows a pillow which has been partly removed by hand and reveals a sinuous flow tube disappearing into the flow. As mentioned above, significant light has been shed on this problem in recent years by submarine investigations. These include scuba diving expeditions, as well as examinations by manned submersibles. Moore et al. (1971) investigated the submarine extension of the 1381 A.D. lava flow of Mount Etna, Sicily. They showed that elongate pillows

FIGS. 18 to 22. Pillowed lava from the Strumble Head Volcanic Formation, showing the development of a tube-like form.

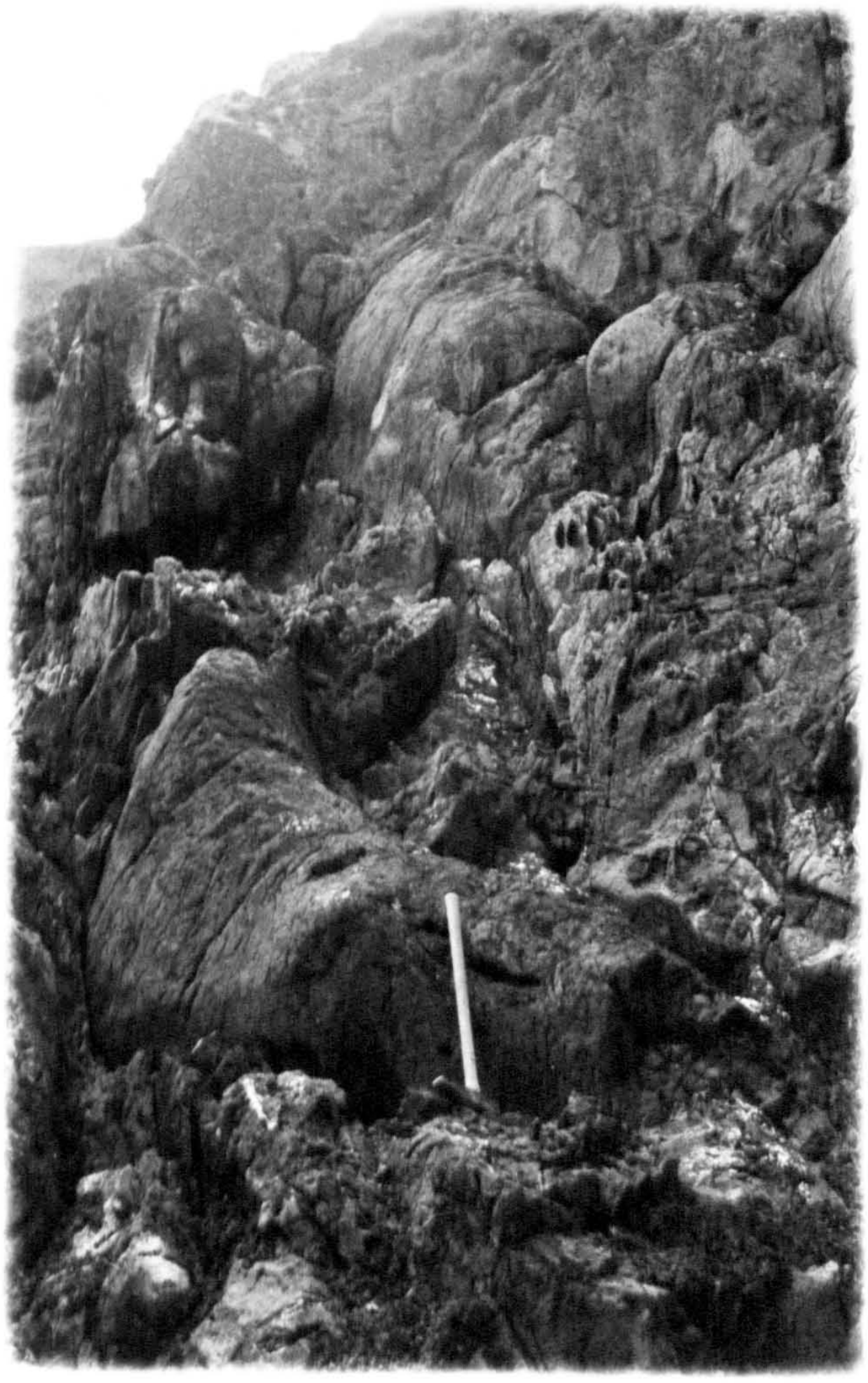
FIG. 18. Carn Melyn (GR 887406).

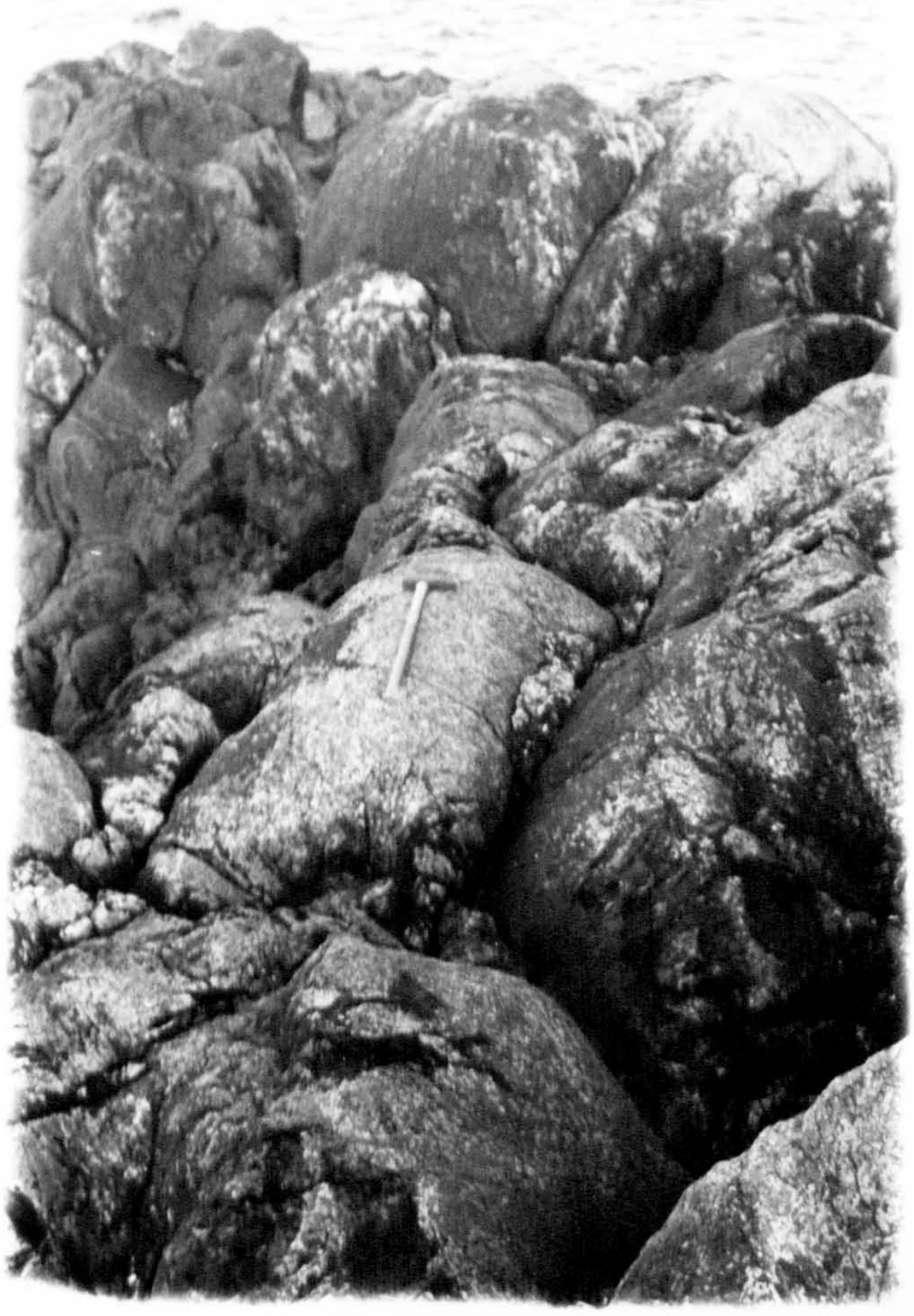
FIG. 19. Pwll Arian (GR 884403).

FIG. 20. Carn Melyn (GR 887406).



FIGS. 21 and 22. Trwyn Llwyd (GR 905400).

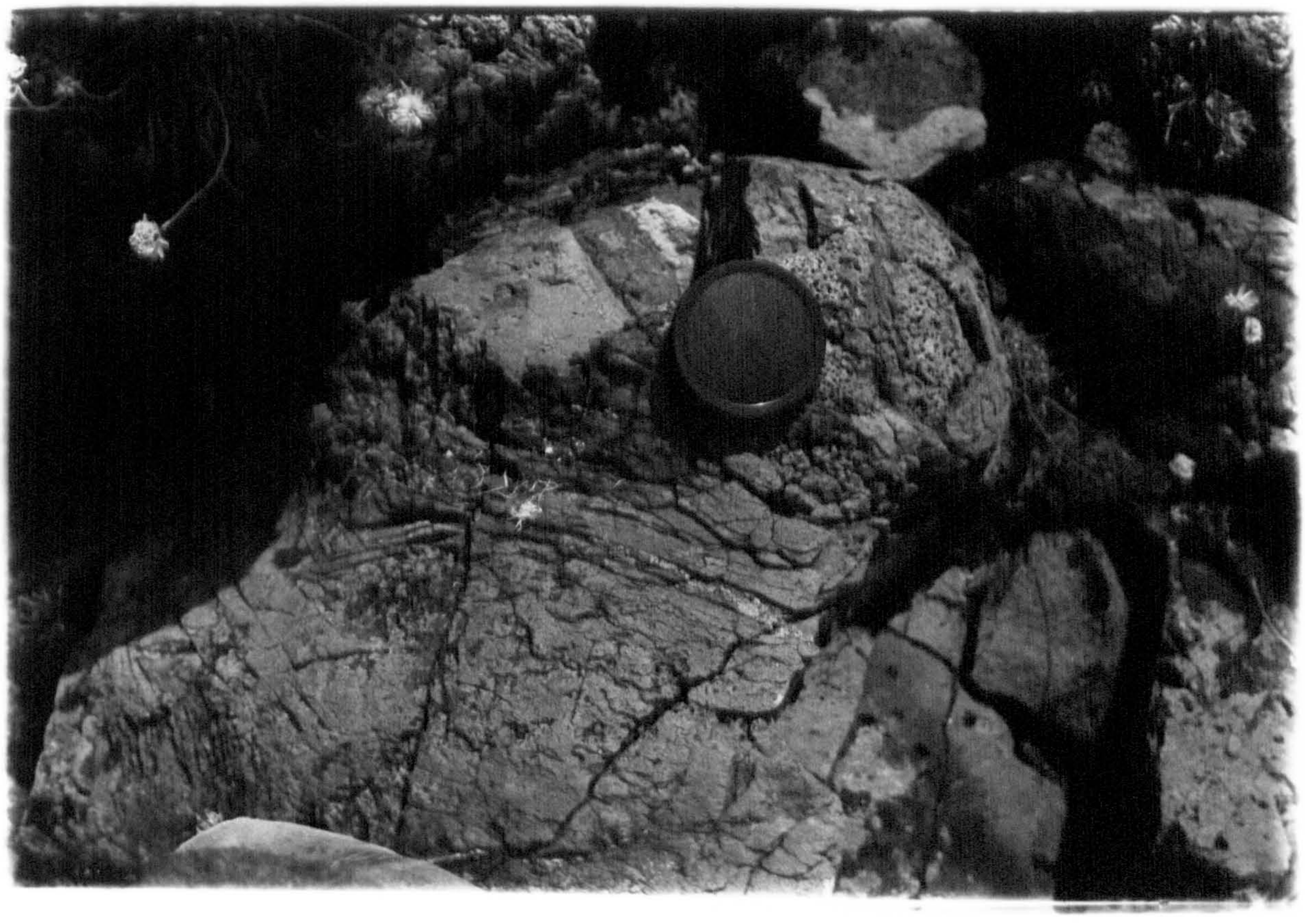




developed on steep submarine slopes, where extension caused thinning of the chilled glassy crust. Arculus (1973) studied the 1329 A.D. lava flow also from Mount Etna and reached similar conclusions, namely that a 'foreset' arrangement of cylinder-like flows was produced where the flow draped over a steep slope. All the pillowed flows studied by Moore et al. (1973) off the island of Hawaii were composed of interconnected, digitated, cylindrical lobes. From the various accounts, it is noticeable that a process of accumulation of discrete, isolate sacs at the base of a steep slope is not described. Such as a process, until recently, was believed by many workers, to be responsible for the development of pillow lava piles. Moore (1975) described in more detail the growth and development of pillowed lavas, as witnessed off the southeast coast of Hawaii. He noted that extension of the flow occurs when liquid lava issues from a crack in the consolidated lava crust. These cracks possess a variety of shapes and allow new lava to spread in any direction. This would account for the accumulation of a confused mass of interconnected flow lobes. Moore (op. cit.) also described surface ridges developed on pillowed lava. He identified two major types in flows from Kilauea, Hawaii, namely longitudinal corrugations and transverse cracks. The latter features he termed 'fault slivers'. It is thought that the surface features illustrated in Figures 23 and 24 from the Strumble Head Volcanic Formation represent the structures described by Moore.

The majority of evidence, therefore, would appear to suggest that pillowed lava piles generally represent the accumulation of a series of interconnected sinuous flow lobes or tubes. Such a conclusion is reached here for the origin of the basaltic pillow lavas of the Strumble Head Volcanic Formation and was similarily reached by Bevins and Roach (in press) for the pillow structures in the rhyodacite flow of the Porth Maen

FIGS. 23 and 24. Small-scale structures in pillowed lava from Pwll Arian (GR 884403).



Melyn Volcanic Formation (see below) and also by Vuagnat (1976) for pillowed lava sequences of the Western Alps.

Associated with the pillowed lavas of the Strumble Head Volcanic Formation are a number of massive, concordant sheets, some of which possess well developed columnar jointing. Three possible origins exist for these sheets and it is considered that each of these may have been in operation. Firstly, they may represent high-level intrusive sheets which intruded the developing lava pile contemporaneous with continued extrusive volcanic activity. A second possibility is that they represent intrusions of magma which reached the top of the volcanic pile, but invaded wet sediment. Whilst a third possibility is that they represent submarine lava flows. In many cases conclusive evidence of the genesis of these sheets was lacking. A similar problem regarding manner of emplacement of massive 'greenstones' was identified by Furnes (1974) within Lower Palaeozoic metavolcanics in the Solund area, Norway.
In the Fishguard volcanics, evidence for all of the above processes may be found. Certain sheets clearly show the disturbance of sediment both above and below the sheet, suggesting that it intruded into wet sediments. This is seen by the fact that well developed flame structures are found, along with detached lobes of basic lava within the sediment (Fig. 25). In contrast, local lenses of massive lava, such as are found on the southeast side of Aber Gwladus (GR 924406), no doubt represent surface flows. Lastly, thicker, coarse-grained sheets, possessing thin, fine-grained marginal zones, probably represent massive, intrusive sheets which invaded the pillow lava pile. In other cases, there appears to be a gradation from pillow lava through fine-grained massive lava to coarse-grained, well-jointed dolerite. This may represent a thick flow which locally developed a pillowed form. Clearly, the possibilities are numerous,

FIG. 25. Irregular, lobate contact between dark shales and intrusive, basic magma (light grey). Penanglas (GR 94864045).

but what is evident, and is illustrated in Figure 26, is that the massive sheets are found predominantly in the upper part of the volcanic pile, whilst pillowed lavas form the lower part. It appears, therefore, that initially the volcanic activity was predominantly extrusive in character whilst subsequent to the development of a thick pile, there was a greater tendancy for intrusive activity to prevail.

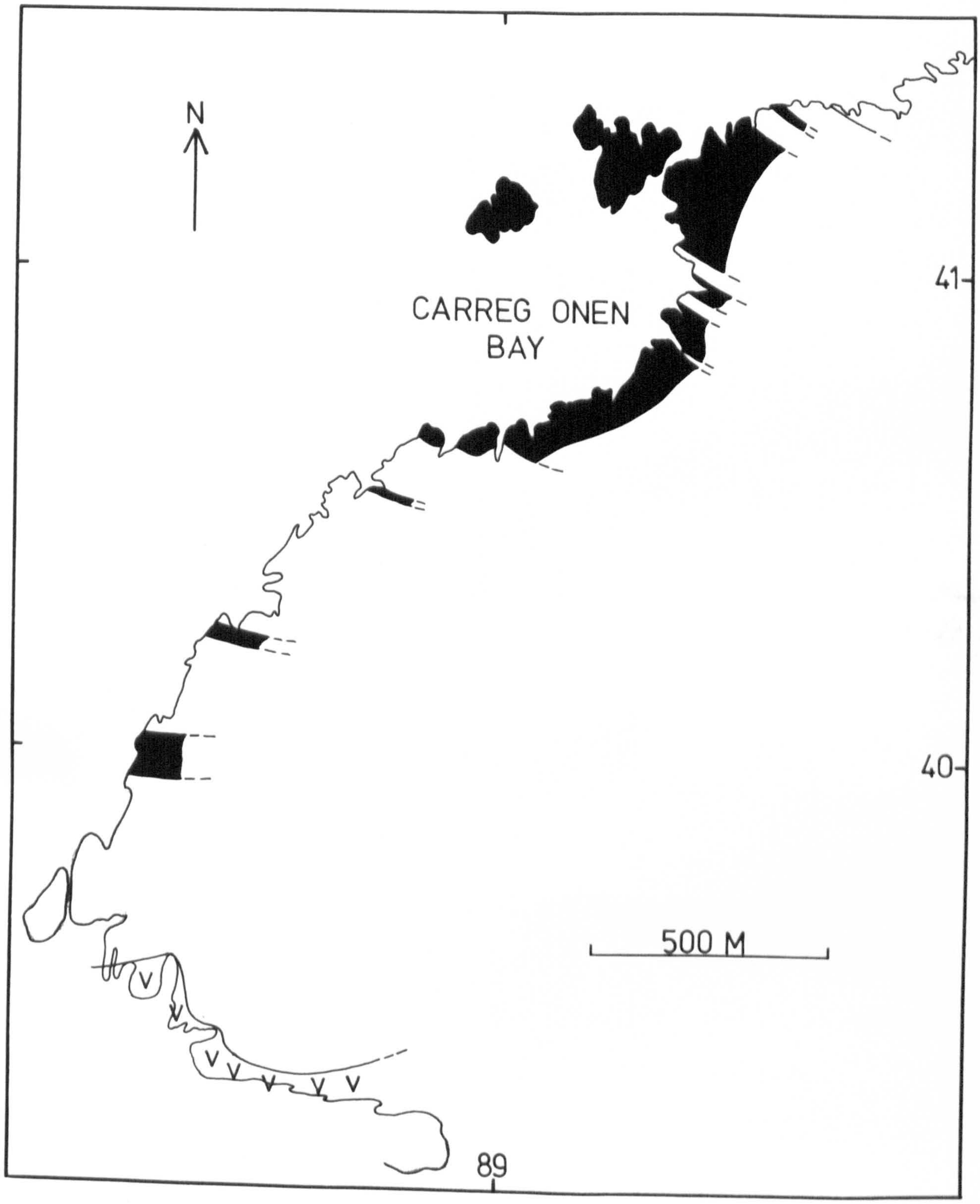
Within the uppermost few metres of the Strumble Head Volcanic Formation, in the area around Carnfathach (GR 403938), the basic lavas are noticeably lighter in colour than elsewhere and contain large, ovate siliceous nodules. Two chemical analyses of lavas from this horizon (SB13 and SB52, Appendix 1) show high silica contents and it is thought likely that these lavas have been affected, after eruption, by the ensuing episode of rhyolitic vulcanicity. A dolerite intrusion, which occurs at the junction between the acid and basic rocks, contains nodules and veins of jasper and thus similarily appears to have been affected by the rhyolitic vulcanicity.

2.2.1.2. PETROGRAPHY

The lava flows of basic composition display a wide variety of textures which can generally be correlated with the cooling history which the particular lava suffered. The lavas were erupted entirely within a subaqueous environment and consequently show evidence of a quenched history. Such quench textures have recently been well documented from young lava flows of the present ocean floors (e.g. Muir and Tilley, 1964; Bryan, 1972).

As the Fishguard basic lavas were erupted subaqueously, pillowed lava flows are common. Within individual pillows, a zoned textural arrangement is discernible, as well as a marked variation in the modal

FIG. 26. Sketch map of the west coast of Pen Caer, showing the relative proportions of massive, intrusive sheets (shaded black) to extrusive, pillowed lava (unshaded) within the Strumble Head Volcanic Formation. 'V' ornamentation represents rocks of the Porth Maen Melyn Volcanic Formation.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41
40
89

proportions of the phases present (see Figs. 27 and 28). The presence of these zones has important effects upon the geochemistry of the pillows (see Chapter 5).

The rims of the pillows commonly show a thin layer (approximately 2mm thick) of chlorite. This is thought to represent the outer glassy crust of the pillow which has subsequently recrystallized. Small, variolite-like structures composed of sphene are scattered throughout the chlorite, and probably crystallized as a result of the lack of available sites for Ca and Ti within the chlorite structure (note the analyses of chlorite in Appendix 2 are virtually free of any Ca or Ti). In some instances this former glassy rind is not present and may have spalled off at an early stage in the pillows history. In these cases, chlorite is generally present between the pillows, forming a meta-hyaloclastite.

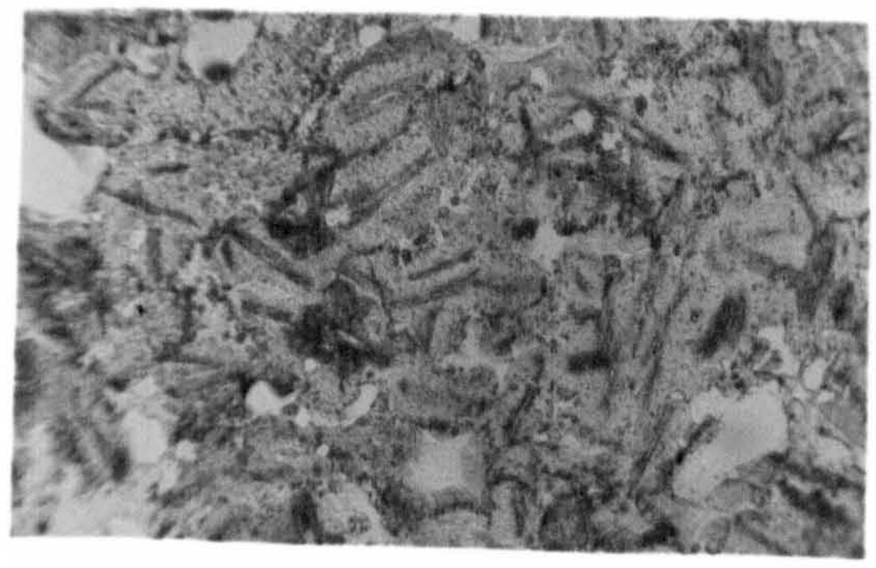
Inwards, towards the centre of the pillow, the glassy crust is replaced by a zone in which plagioclase is the chief mineral component occurring in spherulitic, bow-tie or sheaf-like aggregates (Figs. 28b, 29 and 30). In these forms, the crystals have extremely high length to breadth ratios. Phenocrysts of plagioclase and/or clinopyroxene may be present. When they do occur, plagioclase phenocrysts tend to show stout tabular crystals which pass laterally into the spherulitic forms. Commonly these phenocrysts can be seen to have acted as nucleii for subsequent groundmass crystals. Clinopyroxene phenocrysts or microphenocrysts are generally subhedral to euhedral and are colourless augites.

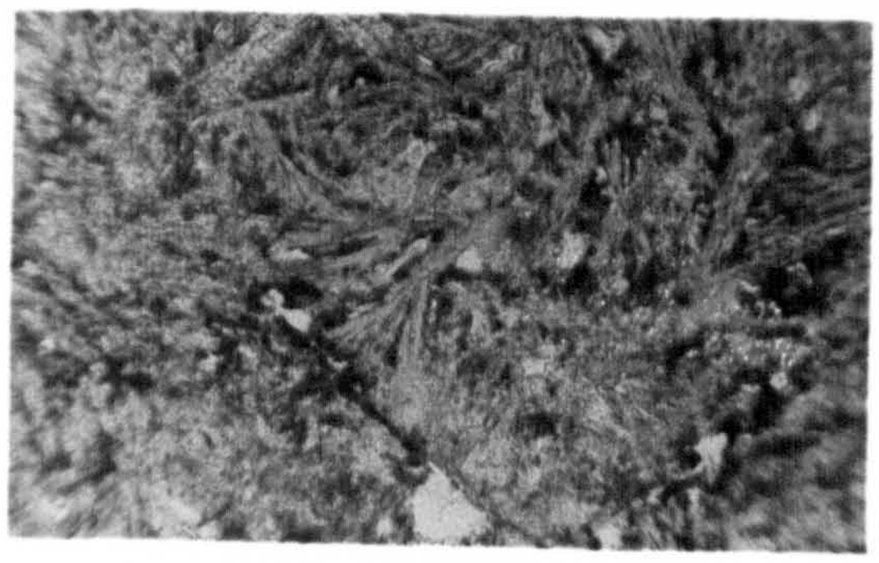
The centres of pillows are marked by an increase in the proportion of clinopyroxene. It appears typically as dendritic, purple-coloured,

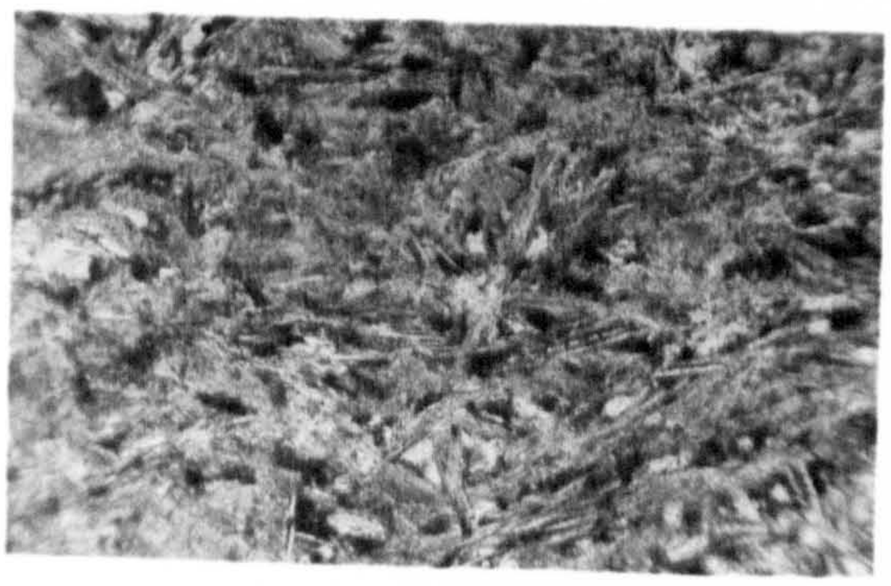
FIG. 27. Cut surface of a pillow lava from the Strumble Head Volcanic Formation, showing various zones, emphasized by a colour variation across the pillow (see Fig. 28).

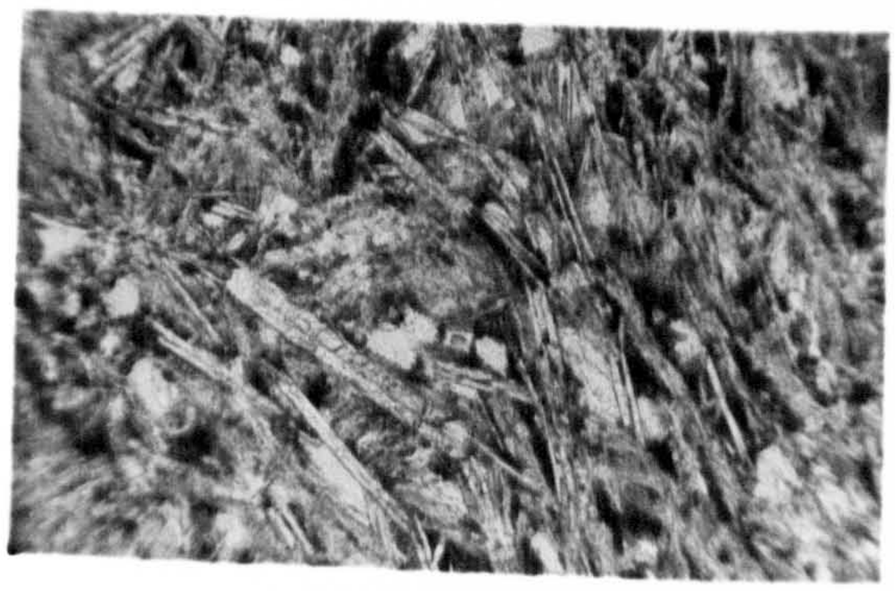
5cm

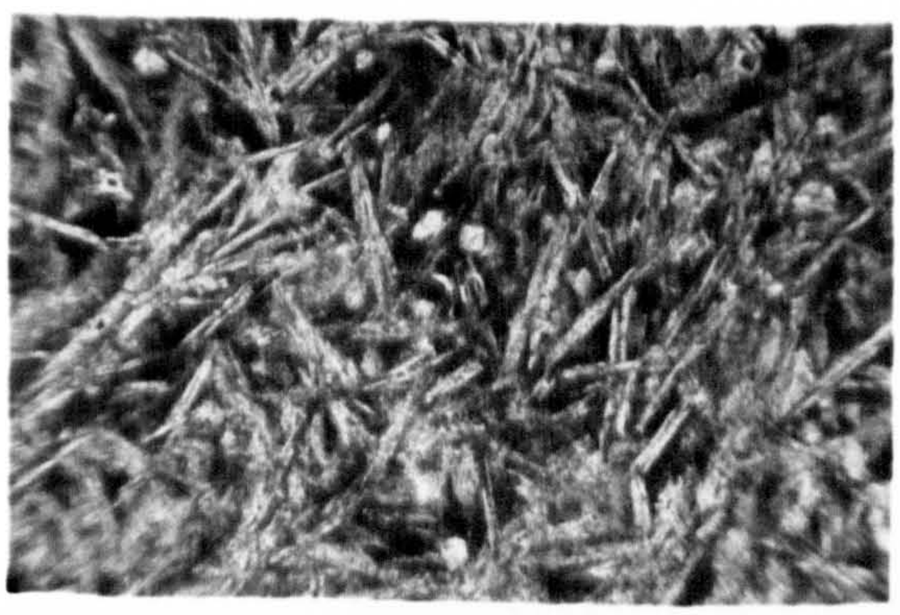
FIGS. 28a to f. Six photomicrographs representing complete rim to core coverage of the pillow illustrated in Fig. 27. Note the textural variation from rim (uppermost) through to core (lowermost). PPL. x60.









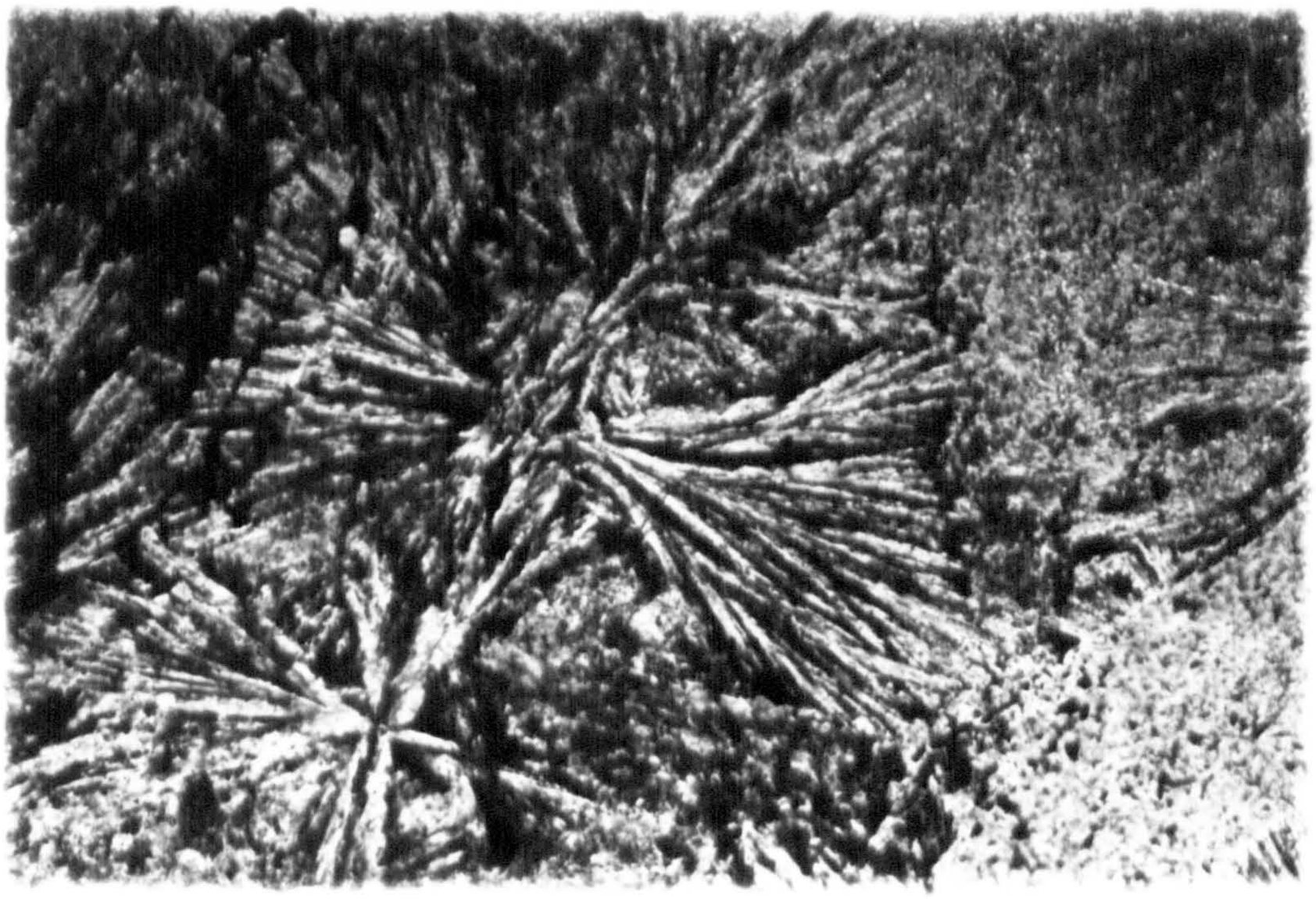


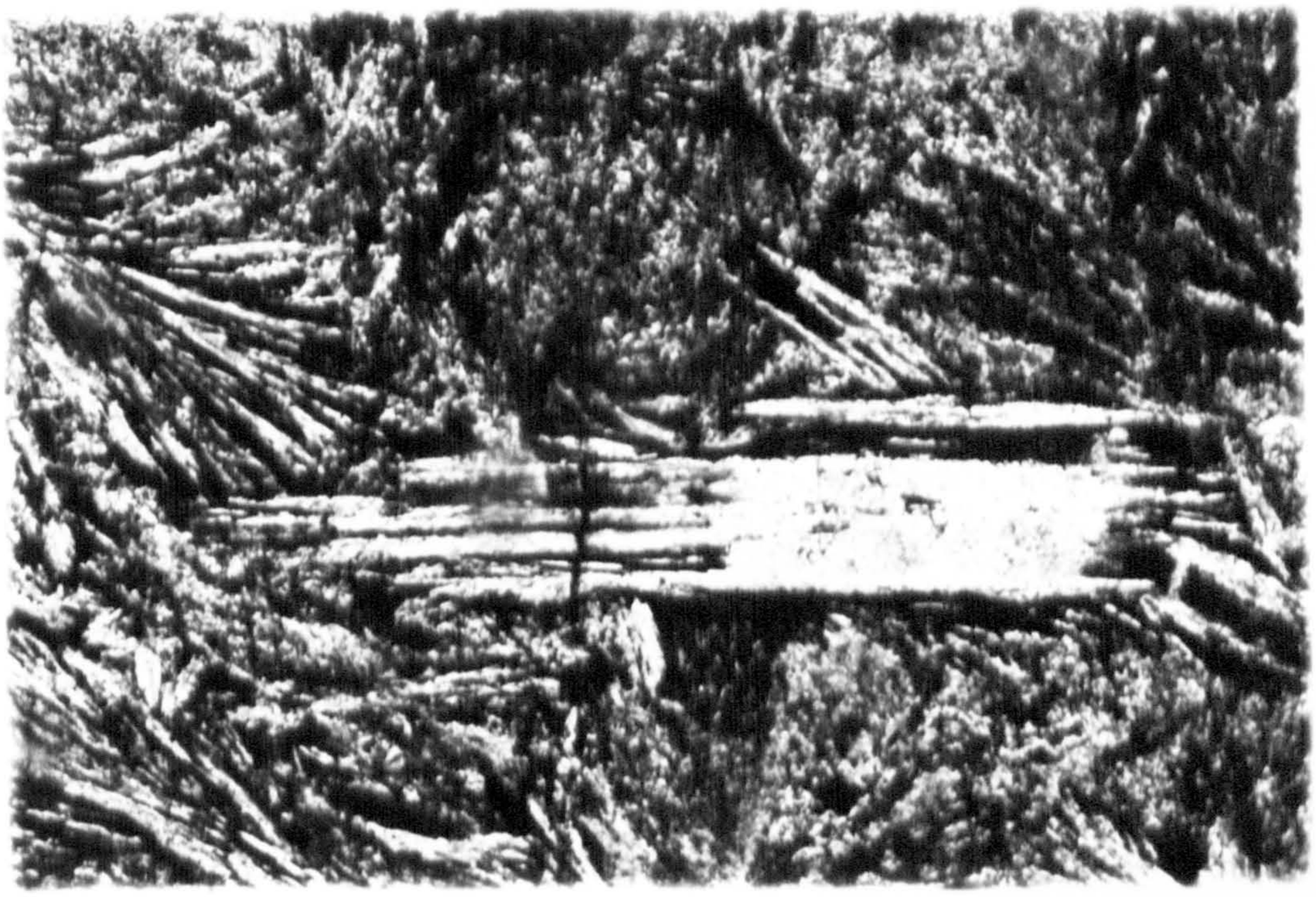
FIGS. 29a to c. Photomicrographs of plagioclase forms within pillows of the Strumble Head Volcanic Formation. Note spherulitic texture, as well as tabular crystals passing laterally (and with optical continuity) into spherulitic areas. All XP.

Scales: a) x220.

b) x170.

c) x170.

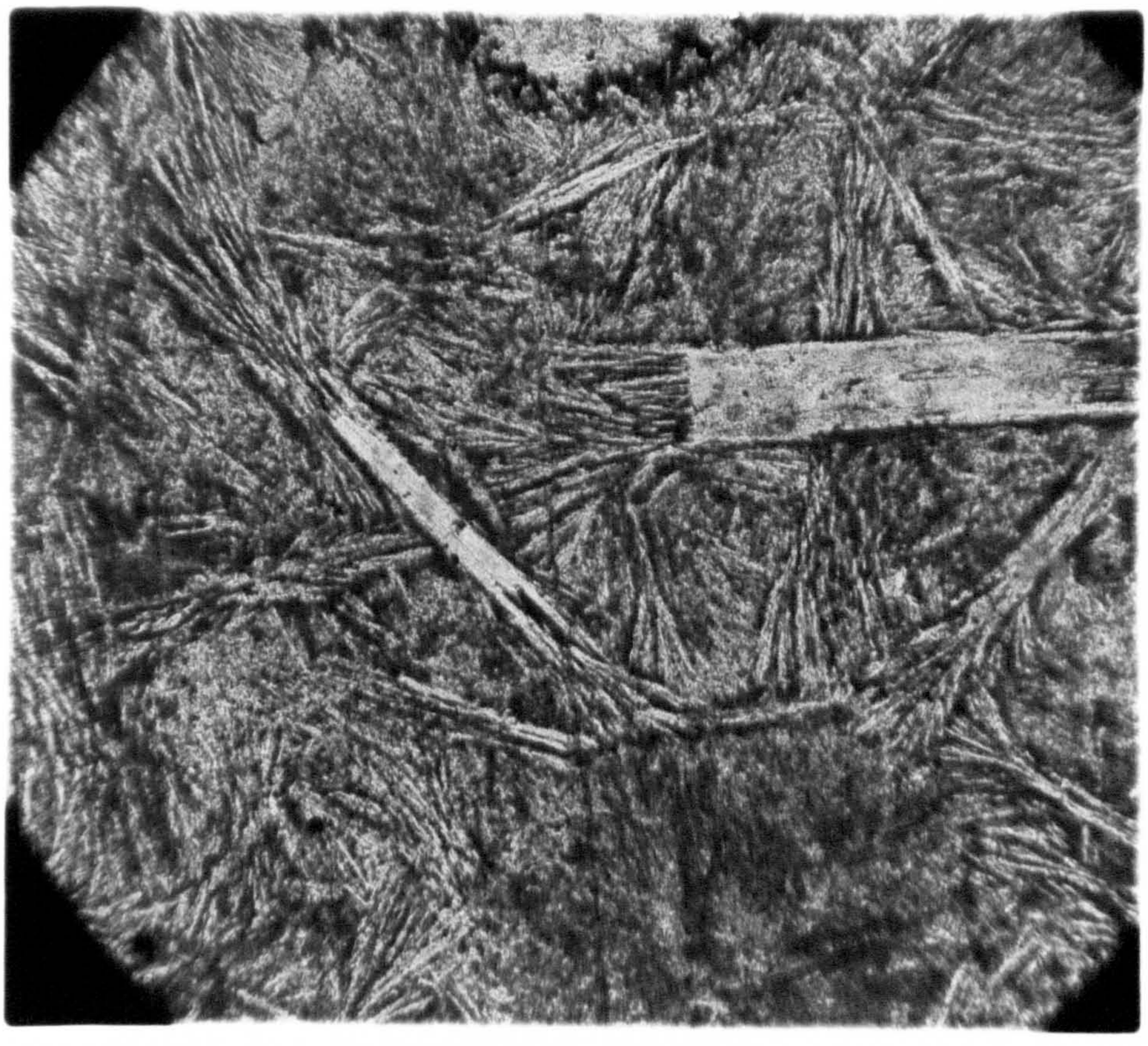


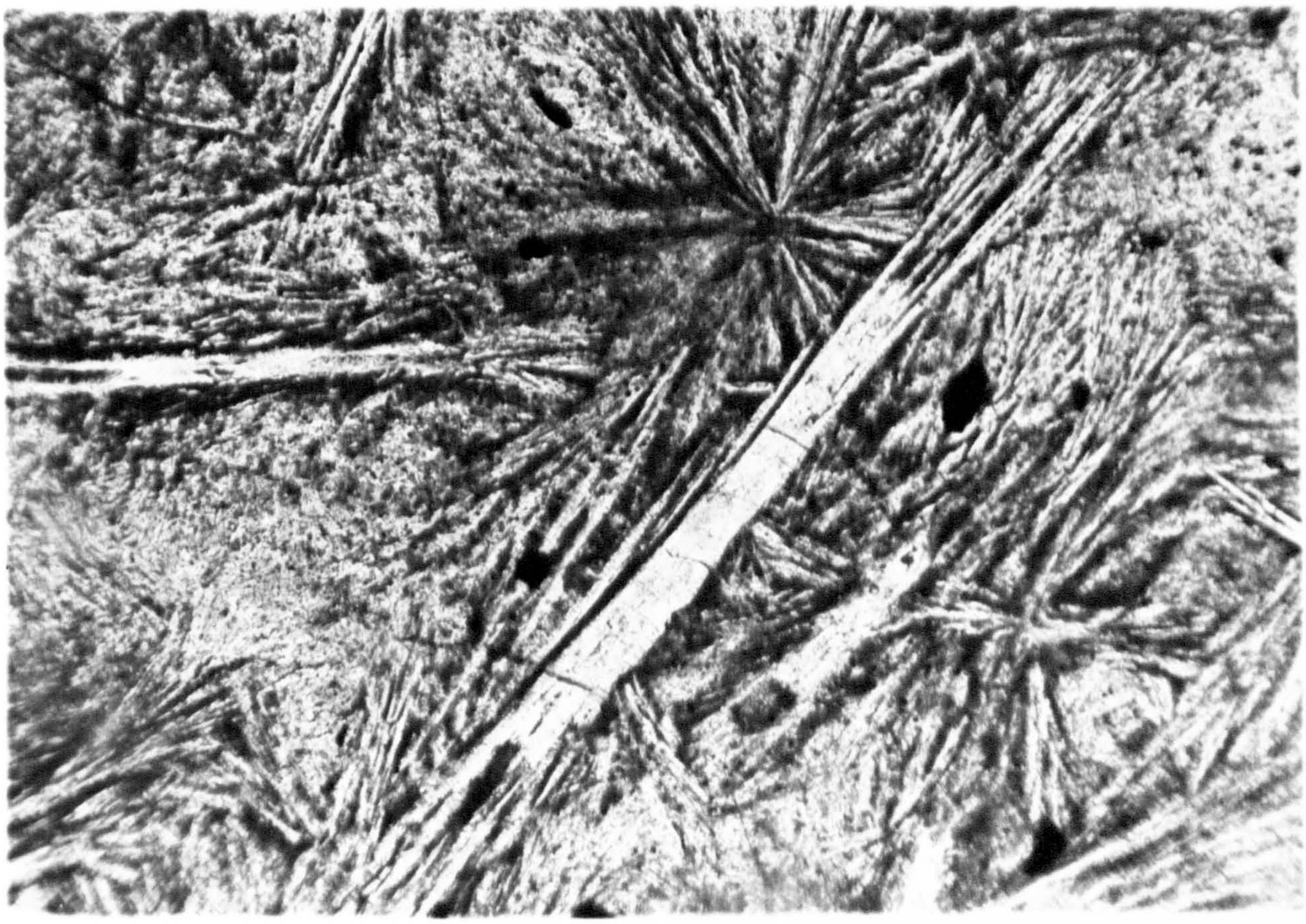


FIGS. 30a to b. Spherulitic plagioclase within pillowed lava of the Strumble Head Volcanic Formation. PPL.

a) x100.

b) x175.





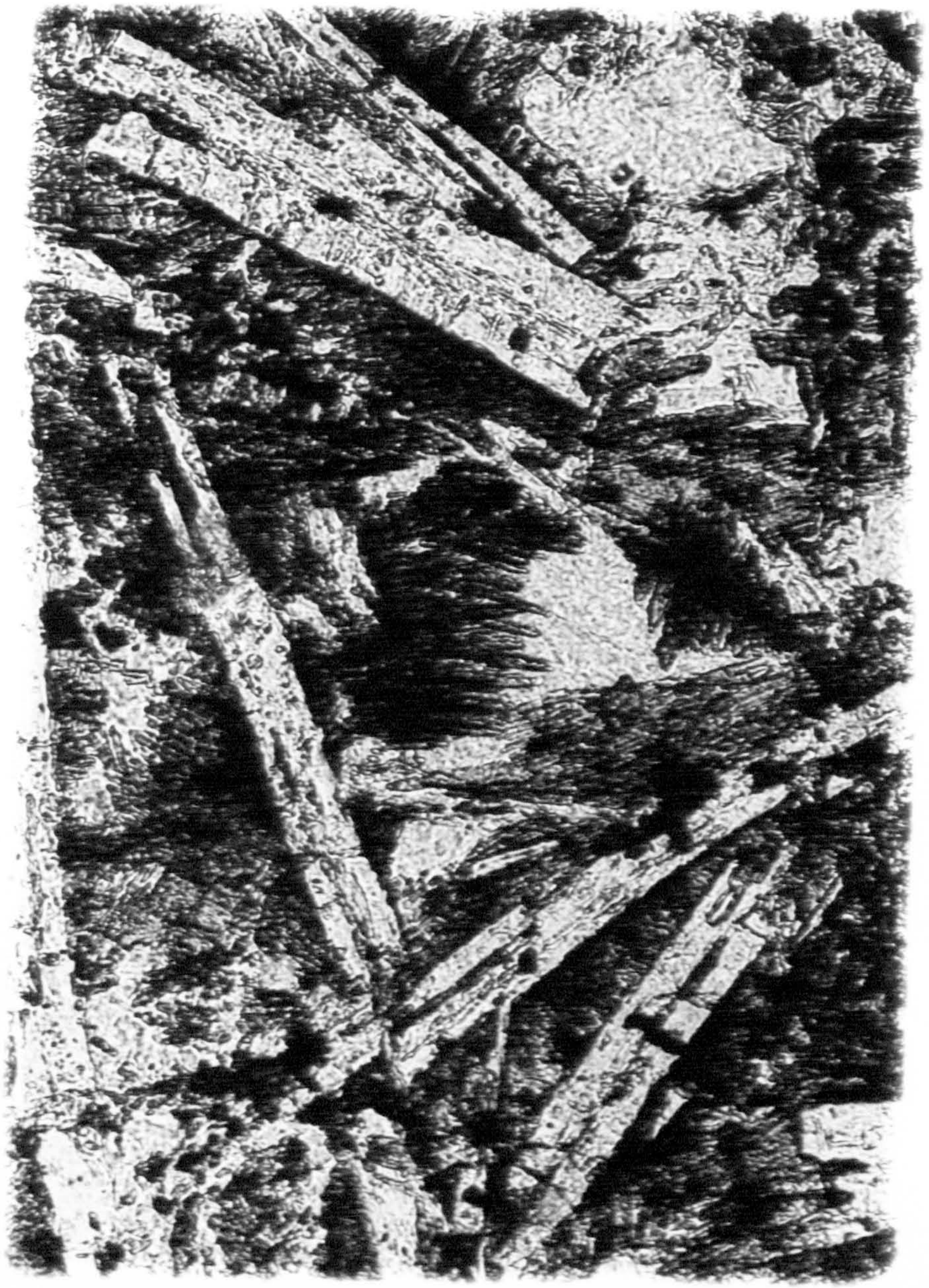
titaniferous augite, which commonly nucleated on plagioclase feldspar crystals (Figs. 28f and 31). The latter tend to show a more ordered crystal form within the cores of pillows, with lower length to breadth ratios. However, belt-buckle and swallow-tail crystals testify to the skeletal nature of these crystals (Figs. 28e - f and 32).
Occasionally, the rock is dominated by a felted mass of tabular plagioclase crystals, with a fluidal texture. The flow lines can be observed bending around vesicles and also phenocrysts. Certain flows, for example, sample SB31, show the presence of spherulitic intergrowths of colourless clinopyroxene and plagioclase feldspar (Fig. 33).
In these flows it is considered that simultaneous crystallization of these two phases occurred. Samples SB30 and SB34 show the presence of abundant clinopyroxene far in excess of the modal proportion typical for the lavas of this area. It commonly forms large, skeletal crystals and displays evidence of crystallizing before the feldspars.

Vesiculation is a common feature of the basic lavas of the Strumble Head Volcanic Formation and many of the vesicles are partially or completely infilled, as briefly outlined earlier (S.2.2.1.1.). Thus they appear similar in certain ways to the 'segregation vesicles' described by Smith (1967). However, certain evidence offers contrast with the vesicles described by Smith (op. cit.). The vesicles within the basic lavas at Fishguard are infilled and commonly surrounded by purple-coloured titaniferous clinopyroxene, along with chlorite (which is considered to be after glass) (Fig. 34). Plagioclase feldspar is noticeably absent from the vesicles and from areas surrounding the vesicles which are dominated by clinopyroxene. Analysis of the clinopyroxene crystals from within the vesicles and surrounding the vesicles shows little difference in composition. It is thus thought likely that at the time of vesiculation, the melt was almost entirely crystal-free and that as a result of

FIGS. 31a to b. Dendritic clinopyroxene (dark), associated with tabular, skeletal plagioclase feldspar. Strumble Head Volcanic Formation. PPL.

a) x280.

b) x280.



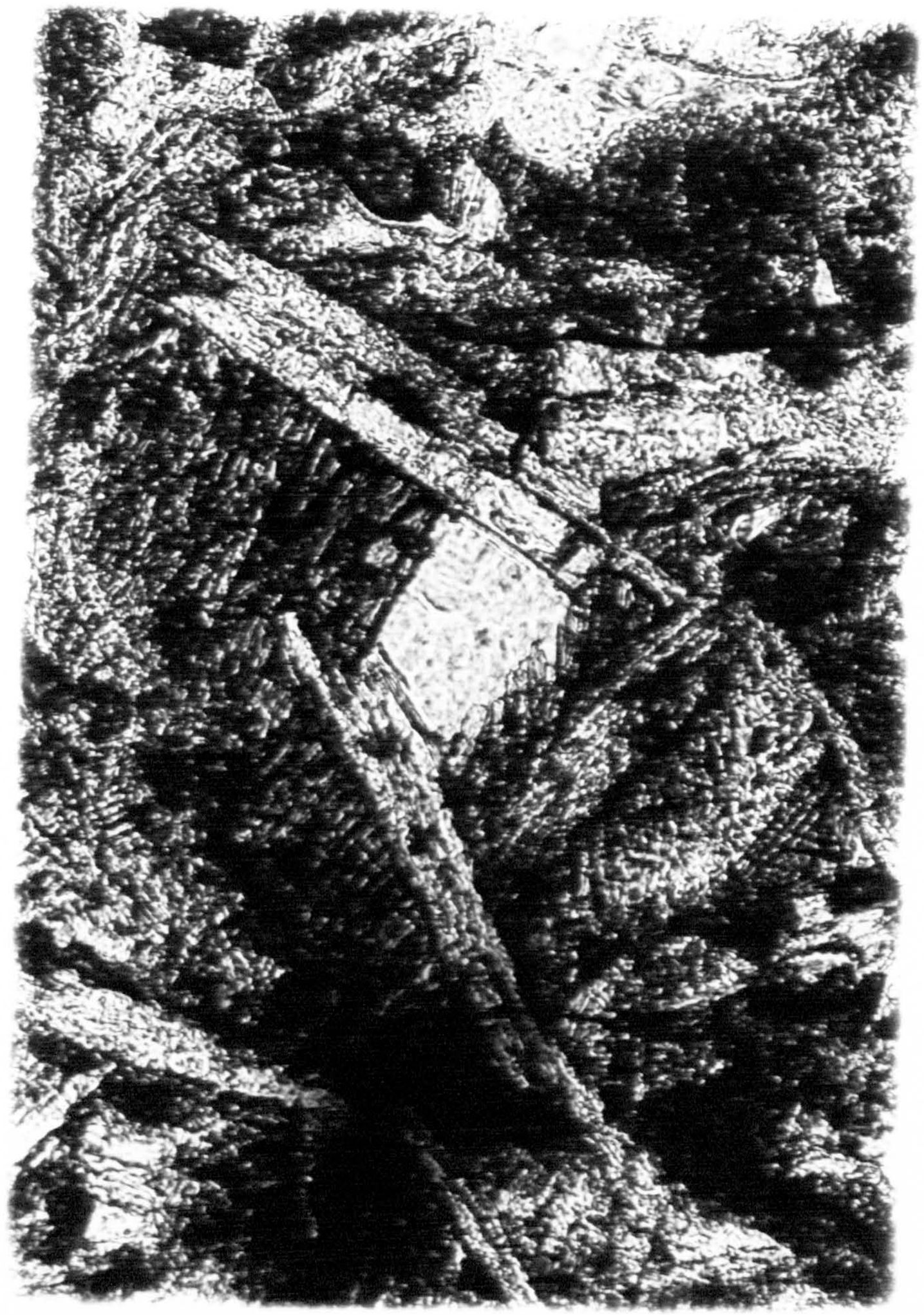
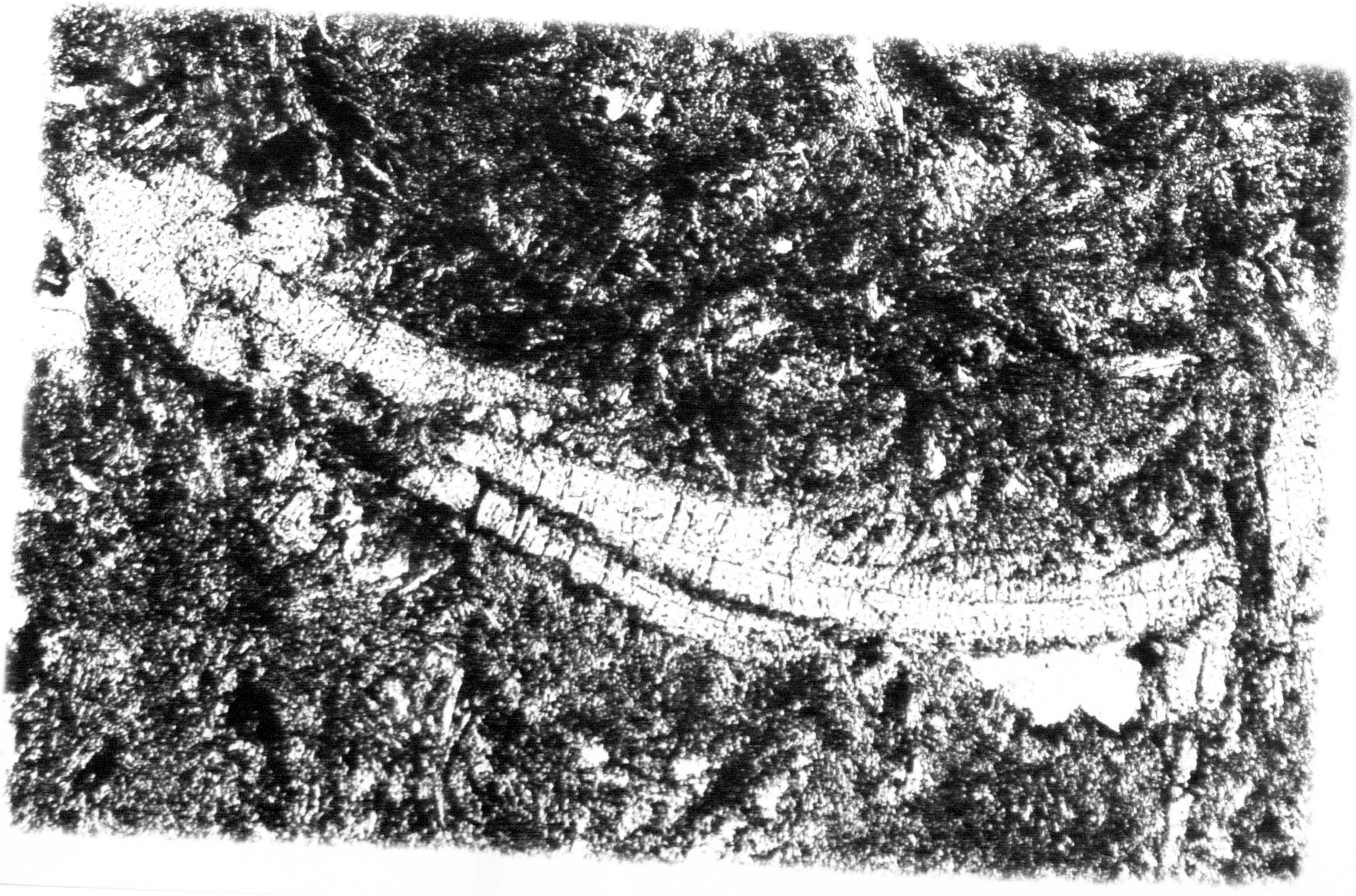


FIG. 32. Skeletal plagioclase feldspar within basic lava of the Strumble Head Volcanic Formation. PPL. x200.

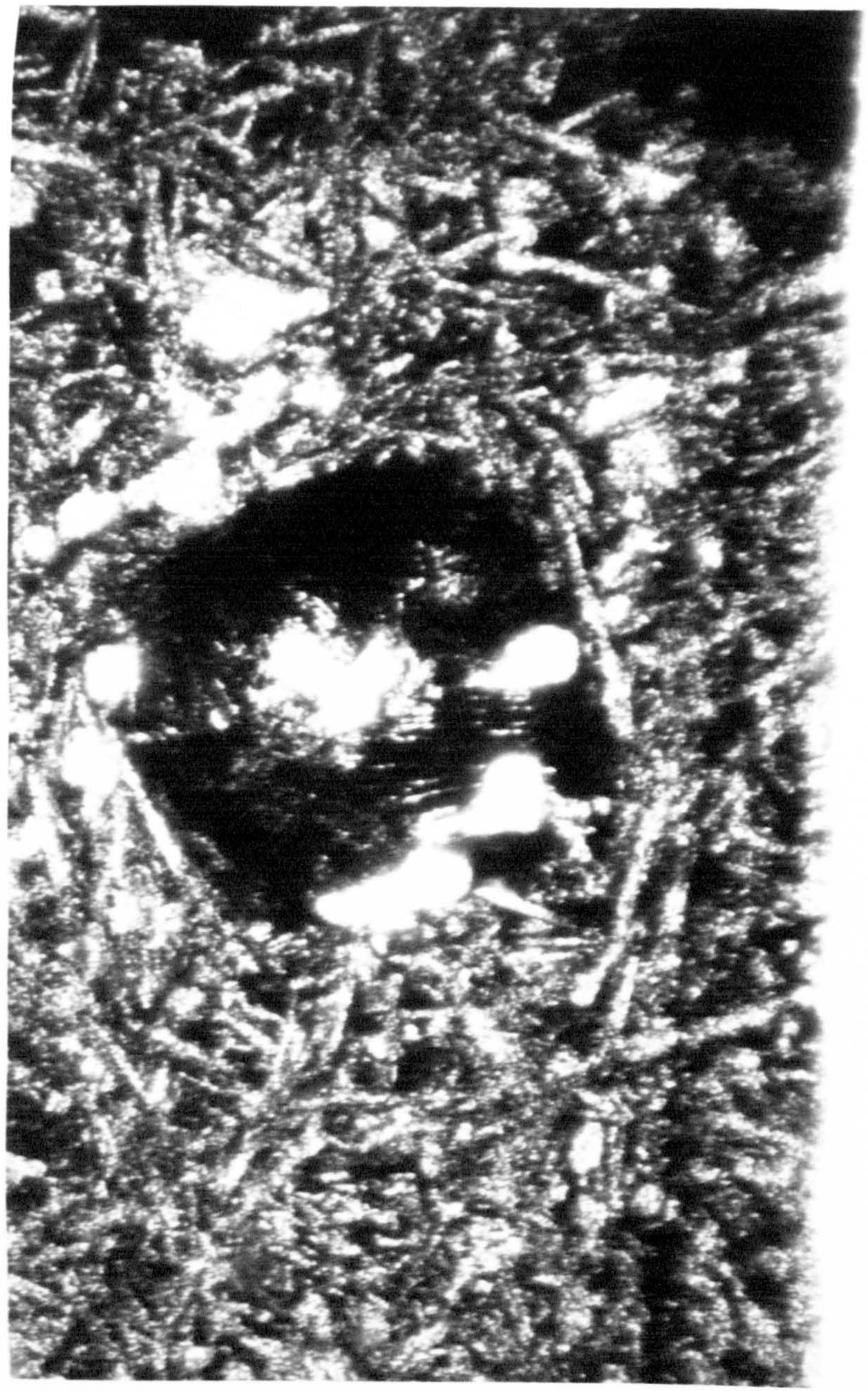
FIG. 33. Curved, clinopyroxene microphenocryst in basic pillowed lava, Strumble Head Volcanic Formation. PPL. x280.

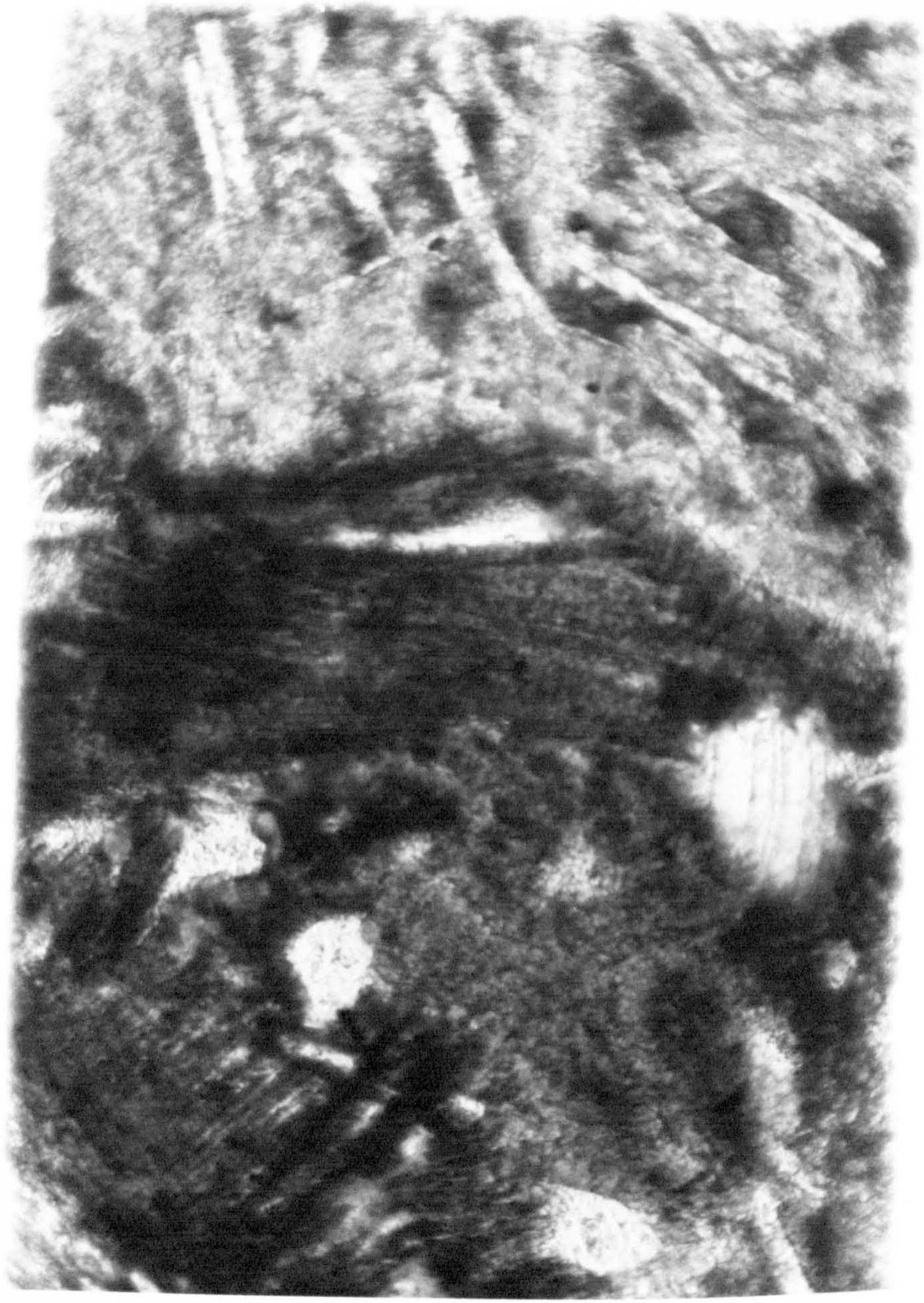


FIGS. 34a and b. Clinopyroxene infilling vesicles within basic lavas of the Strumble Head Volcanic Formation. PPL.

a) x140.

b) x70.





vesiculation, the liquid crystallized predominantly Ti-rich clinopyroxene, the remainder crystallizing as glass (now chlorite). Some of the liquid appears to have flowed into the cavities produced. Thus, infilling of the vesicles was at an early stage and not at a late stage as suggested by Smith (op. cit.).

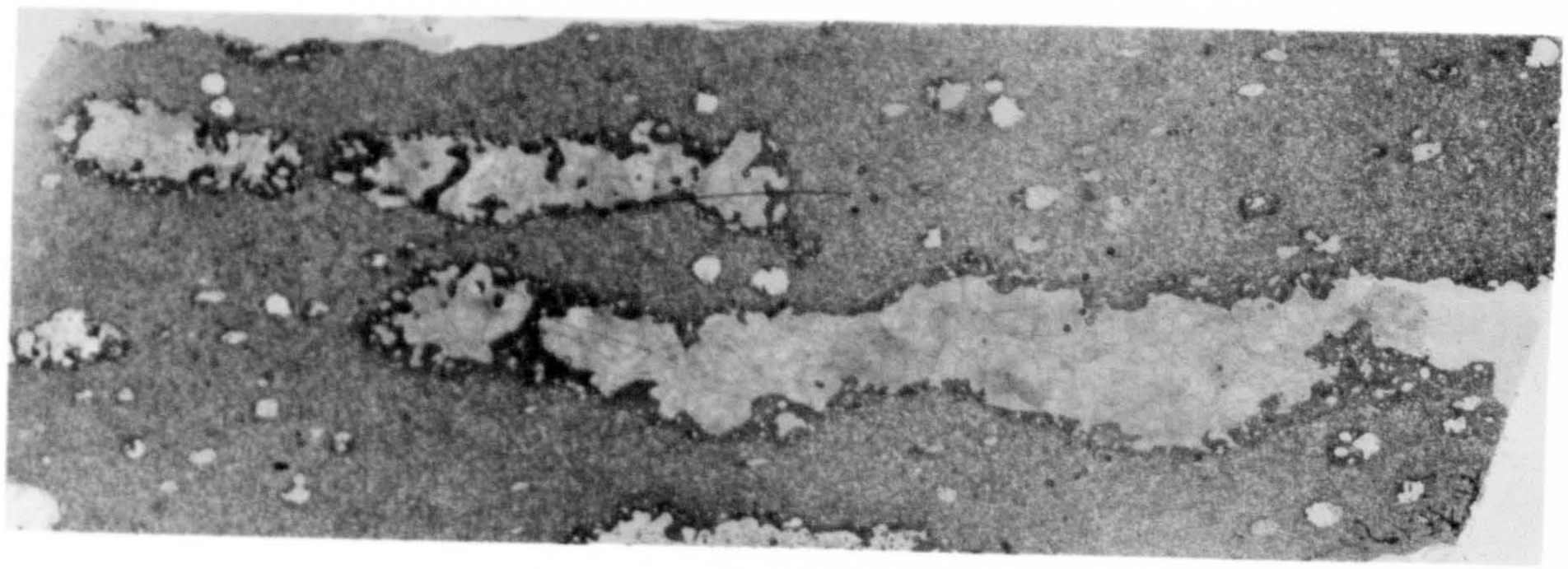
In other samples investigated a similar history may be discerned surrounding pipe-vesicles. For example, in sample YPP10, from Y Penrhyn, dendritic Ti-rich clinopyroxene infills or lines the pipe-vesicles (Figs.35a and 6). Surrounding these vesicles, the rock is dominated by dendritic, Ti-rich clinopyroxene or large, skeletal, Ti-rich clinopyroxene crystals, which show high length to breadth ratios (Figs.36a and 6). End sections of crystals demonstrate their hollow nature, as well as the fact that they are commonly composed of bundles of branching crystals, which, in three dimensions, have a tree-like aspect (Figs. 37 and 38). The matrix, in between the branches, is presently chlorite and is considered to have been glass originally. These crystals no doubt grew within a liquid which was free of other crystals which would have interfered with their development. Other areas show rosette-type radiating clusters of Ti-rich clinopyroxene crystals, or fan-shaped aggregates, once again intimately associated with chlorite.

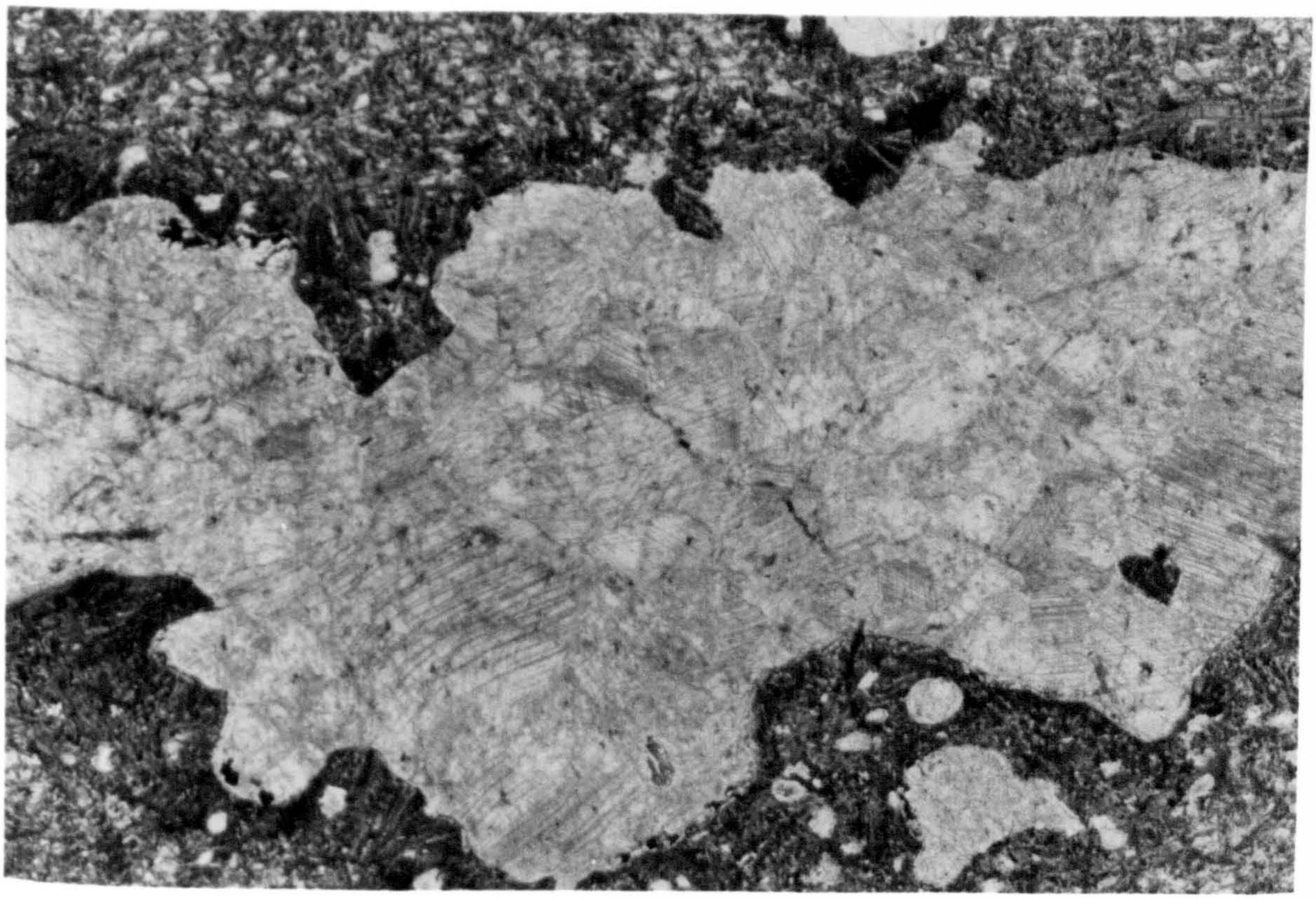
The development of these peculiar textures appears intimately associated with the process of vesiculation and it is possible to speculate a tentative history. All the cases described above show a predominance of clinopyroxene which displays dendritic or skeletal forms. Such forms are typical of liquids which have suffered relatively rapid cooling. As vesiculation is an endothermic process, heat will be removed from the zone immediately surrounding the vesicles. Such a zone may also be

FIGS. 35a and b. Pipe vesicles in basic lava from the Strumble Head Volcanic Formation. Note the development of abundant clinopyroxene in the area immediately surrounding the pipe vesicle. PPL.

a) x2.5.

b) x12.





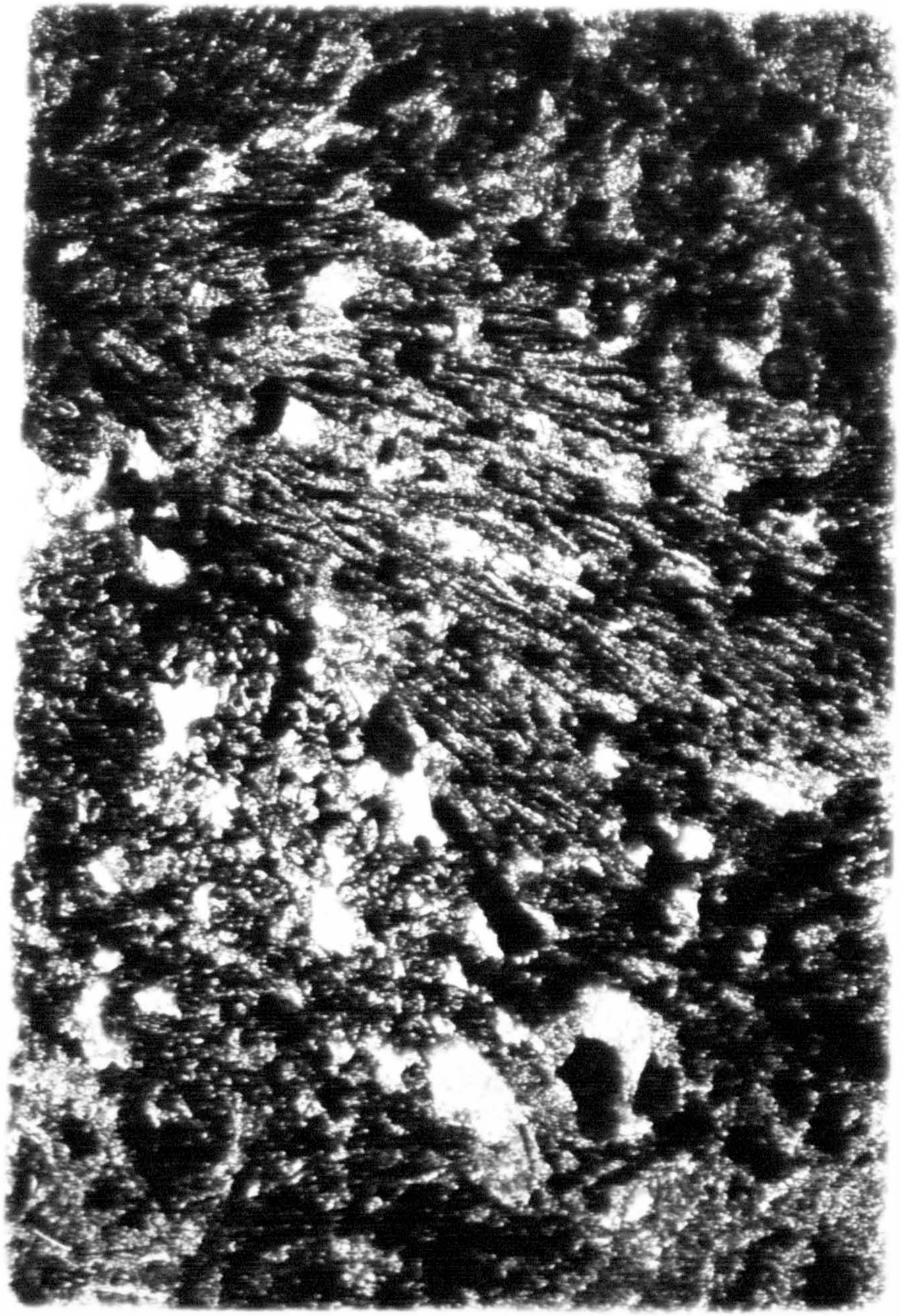
FIGS. 36a and b. Clinopyroxene-rich domain surrounding pipe vesicles within basic lava of the Strumble Head Volcanic Formation. PPL.

a) x200.

b) x250.

FIG. 37. Branching, tree-like clinopyroxene within dolerite from Carn Fathach (GR 938405). XP. x16.

FIG. 38. Elongate, branched clinopyroxene from intrusive sheet within Strumble Head Volcanic Formation, south of Strumble Head (from GR 88894070). PPL. x200.



expected to be rich in gases, including water vapour. Thus rapid cooling would result in crystallization and this may be dominated by clinopyroxene due to the high water vapour pressure developed locally. High PH_2O is known to suppress the crystallization of plagioclase. The Ti-rich nature of the clinopyroxenes is similarily related to cooling rate, as described later (Chapter 4). A certain amount of this cooled liquid may have entered the vesicle immediately after vesiculation, partially infilling the vesicle.

2.2.2. BASIC INTRUSIVE ROCKS

2.2.2.1. FORM AND EXTENT

Basic rocks are found intruding the lavas, the volcaniclastics and the thin sedimentary intercalations of the Fishguard Volcanic Group. They also invade other sediments which underlie this pile, whilst at Pen Anglas (GR 950405) an intrusive sheet cuts sediments which overlie the volcanic rocks of the Goodwick Volcanic Formation. It is thought that this intrusive sheet represents one of the last events of this volcanic episode. Intrusions which invade the older sediments presently produce prominent east-west ridges, such as Y Garn-Garn Fechan, on Pen Caer (see Fig. 5).

The intrusions are almost exclusively of concordant attitude, being locally discordant where a change of stratigraphic horizon is encountered. A dyke-like form, however, is assumed by one intrusive sheet on the north coast of Porth Maen Melyn (GR 884393) (see Fig. 64). Elsden (1905, p. 582) recorded the presence of fine-grained dykes on Garn Folch (GR 910392) but these were not observed during this study. Columnar jointing is generally well developed and is finely displayed on Ynys Onen (GR 890412) and at Penanglas (Fig. 8). The basic rocks forming the intrusions are usually dark green in colour and weather to produce a rusty-brown crust.

On fresh surfaces both plagioclase and dark-green clinopyroxene can be readily identified and an oxide phase may also be discerned when present in sufficient abundance. The plagioclase is generally discoloured to a light green colour, reflecting its state of alteration. Alteration veins are very rarely seen, although in places the rock is fine-grained and considerable recrystallization has occurred. An ophitic texture may be identified in many of the larger intrusions, with large clinopyroxene plates up to 4cm across. Xenoliths are noticeably rare, although where intrusions have invaded wet sediments large clasts are sometimes incorporated. Vesiculated margins to the sheets are commonly developed and take the form of pipe vesicles. These reach 10cm in length and are oriented perpendicular to the flow direction (Fig.39). A second type of vesicle, which is seen at Penrhyn (GR 913408), is parallel to the margin of the sheet (Fig. 40). These vesicles are found some 50cm from the margin of the body, whilst the outermost zone, which represents the chilled contact, has normal pipe vesicles. It is thought that this second variety of vesicle, here called longitudinal vesicles, record the movement of lava within the intrusion after the outer zone had solidified.

Intrusive sheets within the volcanic pile of the Fishguard Volcanic Group commonly intrude into thin sedimentary horizons. The disruption of these sediments suggests that they were unconsolidated at the time of emplacement and the intrusion probably took place very close to the surface of the pile. In other cases, however, the sheets appear to have invaded along the sediment partings, due to their weaker nature in comparison with the surrounding competent volcanic rocks. All the field evidence suggests, however, that the intrusive sheets are of a contemporaneous nature with the volcanic rocks of the area, a feature which is important in obtaining an understanding of the igneous history of the North Pembrokeshire area.

FIG. 39. Pipe vesicles developed at the margin of an intrusive sheet. North coast of Pen Caer.

FIG. 40. Elongate 'longitudinal' vesicles developed parallel to the margin of an intrusive sheet. North of Penrhyn (GR 91254085).

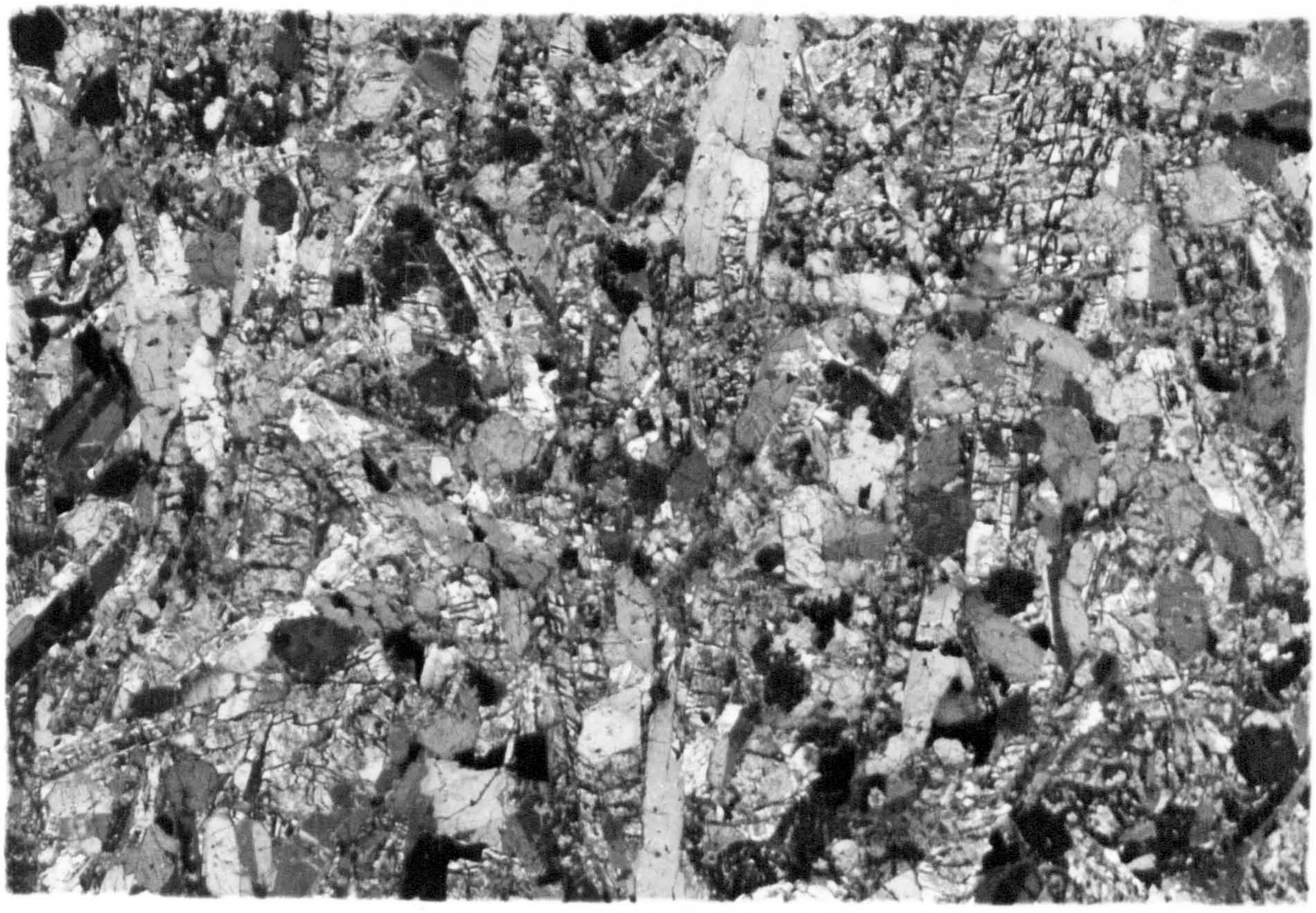
Combined with geochemical and petrographical evidence, this suggests that the 'Llanwnda-type' gabbros and dolerites of Elsden (1905) and Roach (1969), which outcrop in the area between Traeth Llyfn in the west and the Prescelly Hills in the east, are directly related to the lavas and intrusive sheets of the Fishguard Volcanic Group (Bevins and Roach, in press) and, as a result, their period of intrusion is uniquely timed. They appear to invade rocks ranging in age from the Cambrian (e.g. the Llech Dafad intrusion, see Fig. 5) to the D. bifidus zone of the Llanvirn Series. In comparison, the noritic gabbro and dioritic intrusions of Carn Llidi - St. David's Head and Pen Biri and Carnedd Lleithr (Roach, 1969) (Fig. 5), which appear petrographically and geochemically distinct from the 'Llanwnda-type' intrusions, do not appear to invade sediments younger than of Arenig age and consequently may be temporally, as well as magmatically, distinct.

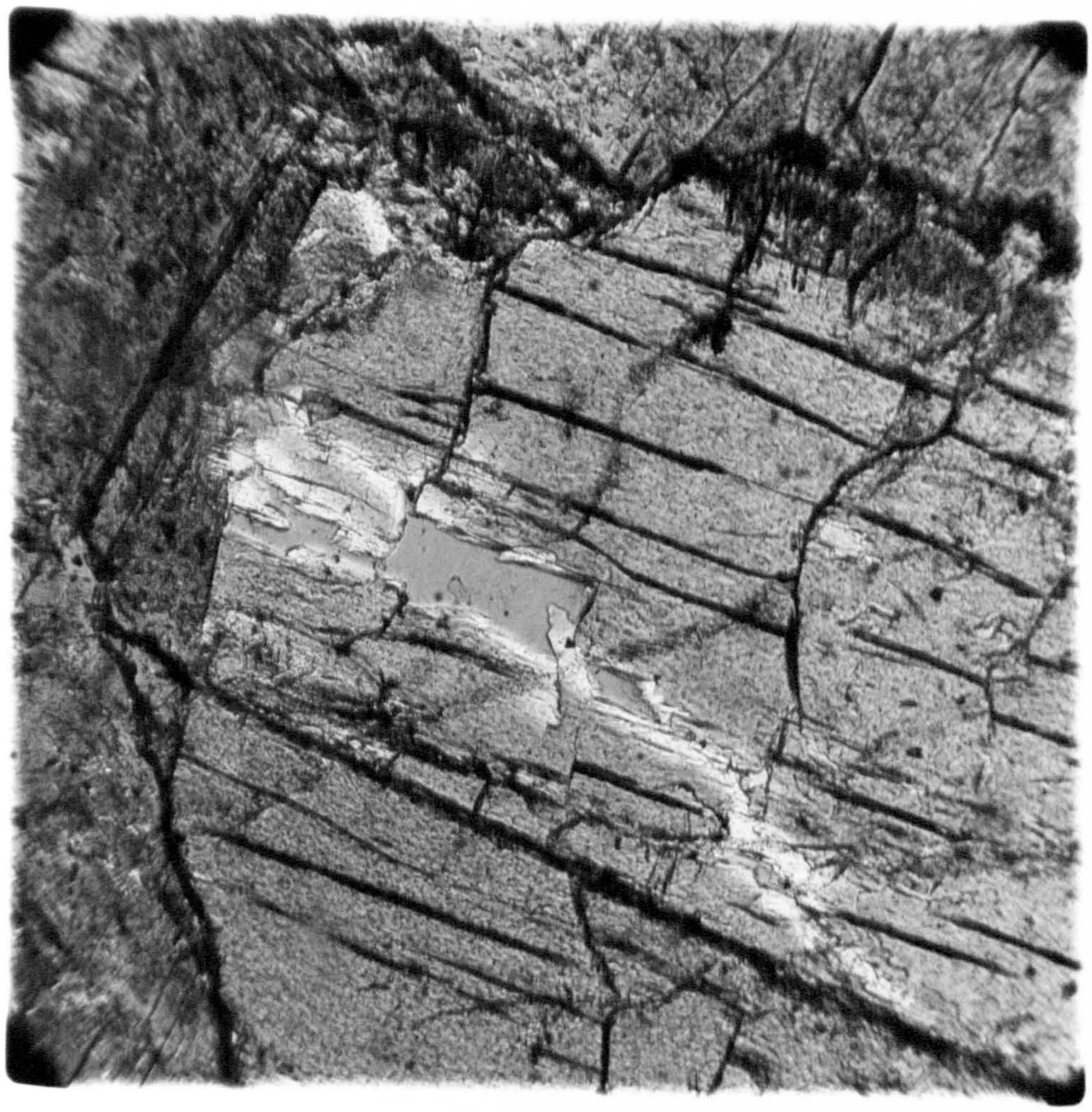
The intrusive sheets are comparatively thick bodies, of the order of up to 200 metres or so. Contacts are rarely observed but the sediments of the surrounding country rock are commonly spotted, as seen for example in the quarry on the northwest side of Carngelli (GR 922381). Further evidence for the pre-deformation intrusion of the sheets is provided by the presence of spots deformed within the cleavage planes.

Rapid textural variations in the gabbroic and doleritic rocks can be identified. The Llanwnda gabbroic intrusion (Fig. 5) clearly demonstrates these variations and it appears possible that this body may in fact be composed of a number of separate intrusive sheets. Within the body, a preferred crystal orientation is present, producing a layering effect which is parallel to the upper and lower surfaces (Fig. 41). Within the layers, clinopyroxenes and plagioclase feldspars have a sub-

FIG. 41. Preferred crystal orientation of plagioclase and clinopyroxene within the Llanwnda Gabbro. XP. x12.

FIG. 42. Clinopyroxene within dolerite from the Fishguard area. XP. x120.





parallel alignment which produces an igneous foliation. However sections normal to the top and base of the body show only a random orientation of crystals and thus this texture may have resulted from local crystal accumulation.

Pegmatitic facies are rarely developed. On Garngilfach (GR 910391), however, plagioclase feldspar and clinopyroxene crystals reach 2 cm in length in local patches.

2.2.2.2. PETROGRAPHY

The basic intrusive rocks of the Fishguard area possess a large number of mineral phases and display a wide variety of textures. The mineral assemblages are made up of both primary and secondary phases and accordingly the primary igneous textures are modified to varying degrees. Although it is commonly difficult to decide whether certain massive sheets of basic magma within the Strumble Head Volcanic Formation are extrusive or intrusive, this section will describe the textures and petrography of the phaneritic rocks, whilst the aphanitic rocks and (meta-) hyaline rocks are described elsewhere (section 2.2.1.2.).

Clinopyroxene is the only abundant primary mineral present within these rocks (Fig. 42) and occurs as a metastable relict phase, not having recrystallized during the Caledonian low-grade metamorphic episode. Minor amounts of apatite occur in a number of the more differentiated intrusives (e.g. sample SB55) and this is also considered to be a relict primary phase (Fig. 43). From a consideration of petrographical and geochemical evidence, it would appear that plagioclase feldspar (probably labradorite) was also a primary crystallizing phase, along with accessory

FIG. 43. Euhedral apatite crystals associated with chlorite in dolerite from Treseissyllt (GR 8923513). PPL. x220.

FIG. 44. Ophitic texture in dolerite from Garn Fawr (GR 900439). XP. x50.

amounts of an iron-titanium ore phase. Olivine may possibly have been present in very minor amounts in some of the least differentiated magmas. However, due to subsequent alteration, these phases have been altered. Quartz, present in a number of samples may be of either primary or secondary origin. However, it is considered more likely to be secondary.

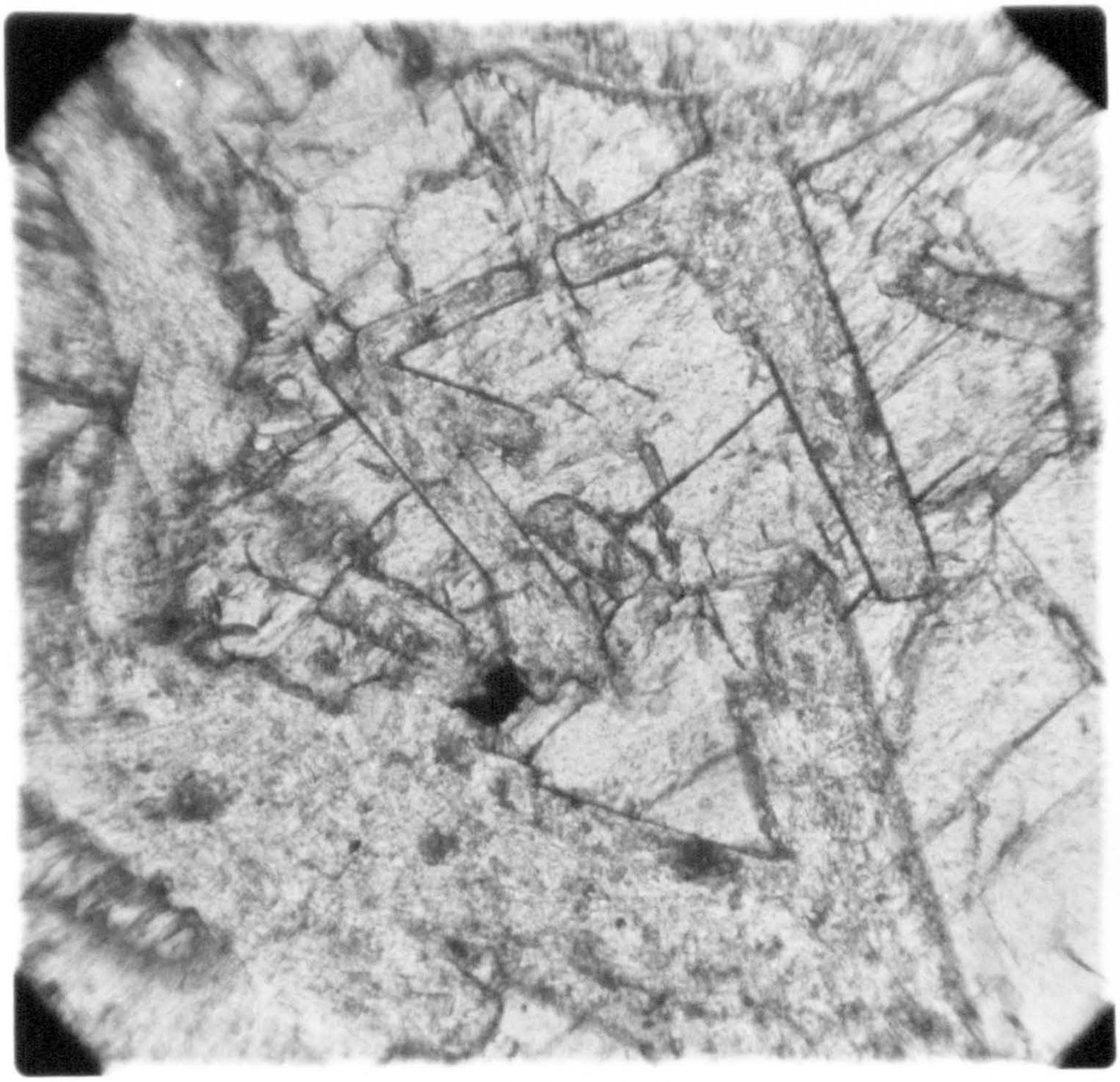
A variety of secondary minerals were produced at various intervals in the history of the Fishguard Volcanic Group (e.g. during sea-water alteration, low-grade metamorphism etc.). These include chlorite, calcite, epidote, sphene, prehnite, pumpellyite, actinolite, stilpnomelane, hornblende, and brown amphibole.

The coarse-grained intrusive rocks are generally holocrystalline, although chlorite-epidote aggregates in certain gabbroic intrusions (Fig. 49) are here interpreted as altered glass and hence these rocks were originally hypocrystalline. Clinopyroxene and plagioclase predominate in the gabbros, producing an hypidiomorphic-granular texture (for example in samples SB57 and SB55) (see App. 3) although where a tabular habit is present, the texture may be described as panidiomorphic granular (e.g. in LG65). Textures in the Y Garn and Llech Dafad intrusions are sub-ophitic to ophitic with large, chemically homogeneous clinopyroxene crystals incorporating altered plagioclase feldspars (Figs. 44 to 46). These large clinopyroxenes reach up to 4cm in diameter. Marginal replacement of clinopyroxene by hornblende has occurred within the Llech Dafad intrusion (Fig. 47).

In the medium- to fine-grained intrusive rocks the texture is usually intergranular, that is laths of plagioclase with interstitial

FIG. 45. Ophitic texture in dolerite from Llech Dafad (GR 882356). Minor chlorite is present, replacing the clinopyroxene in marginal area. PPL. x50.

FIG. 46. Ophitic texture in dolerite from Y Garn (GR 916390). XP. x5.5.



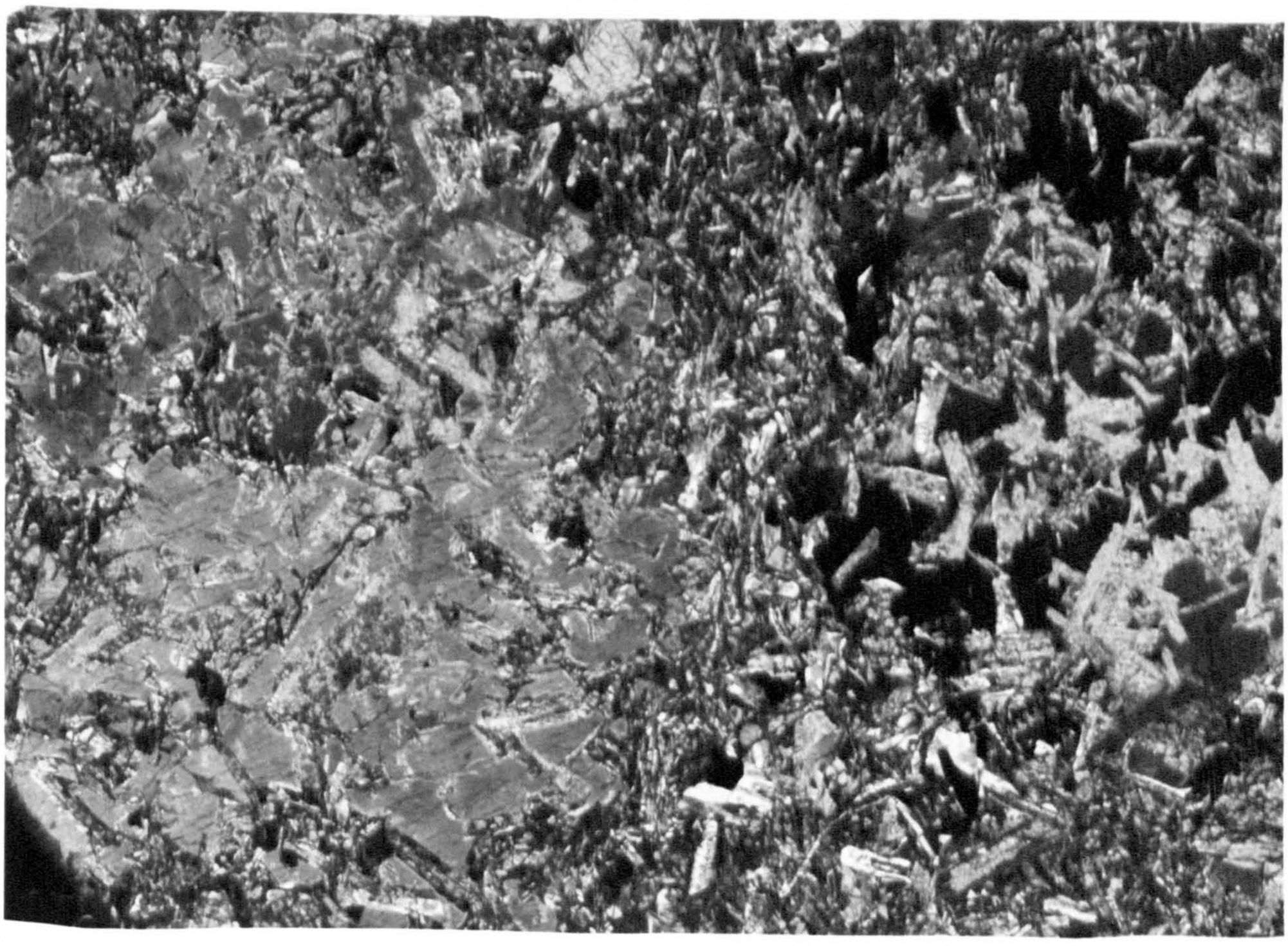
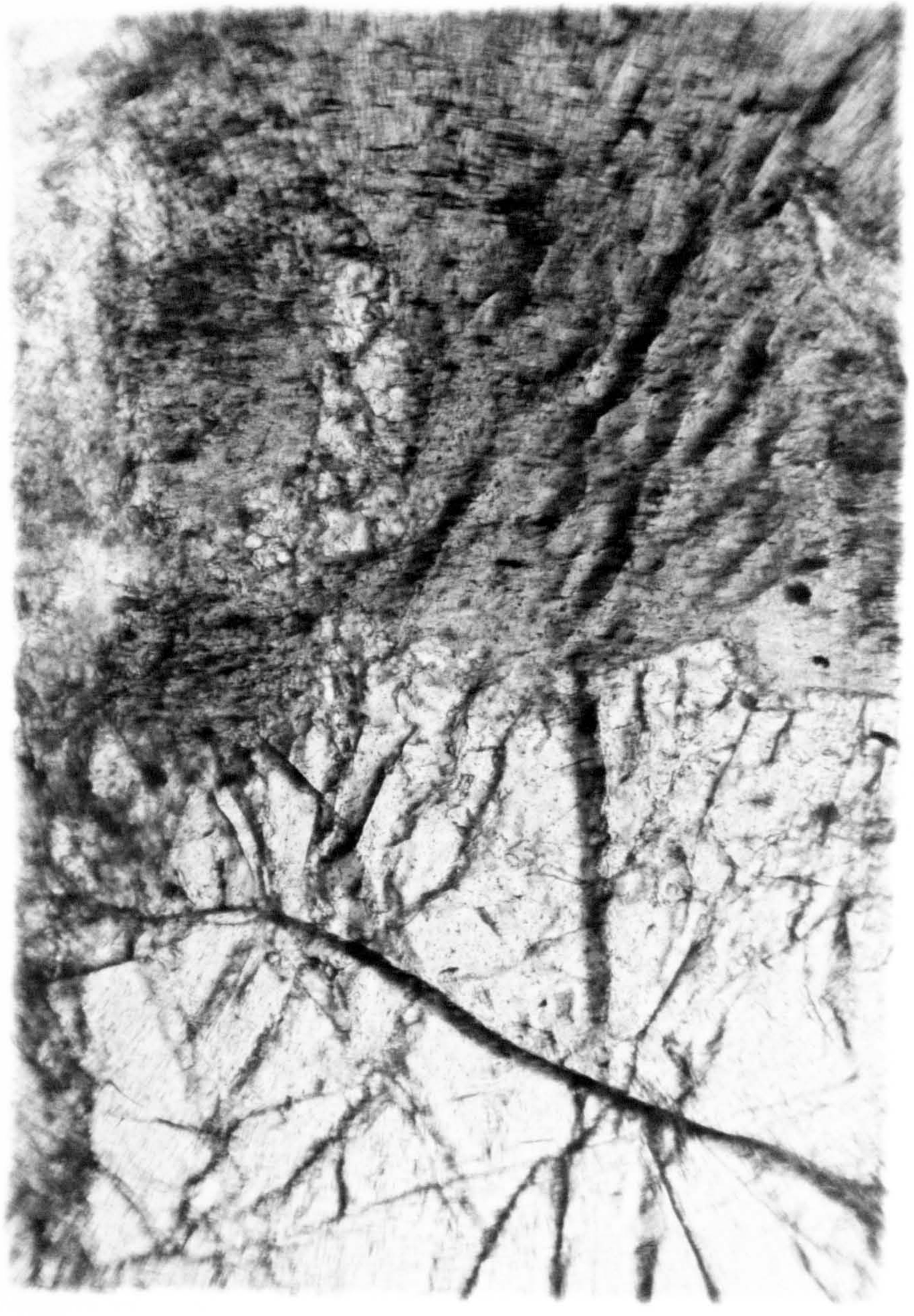
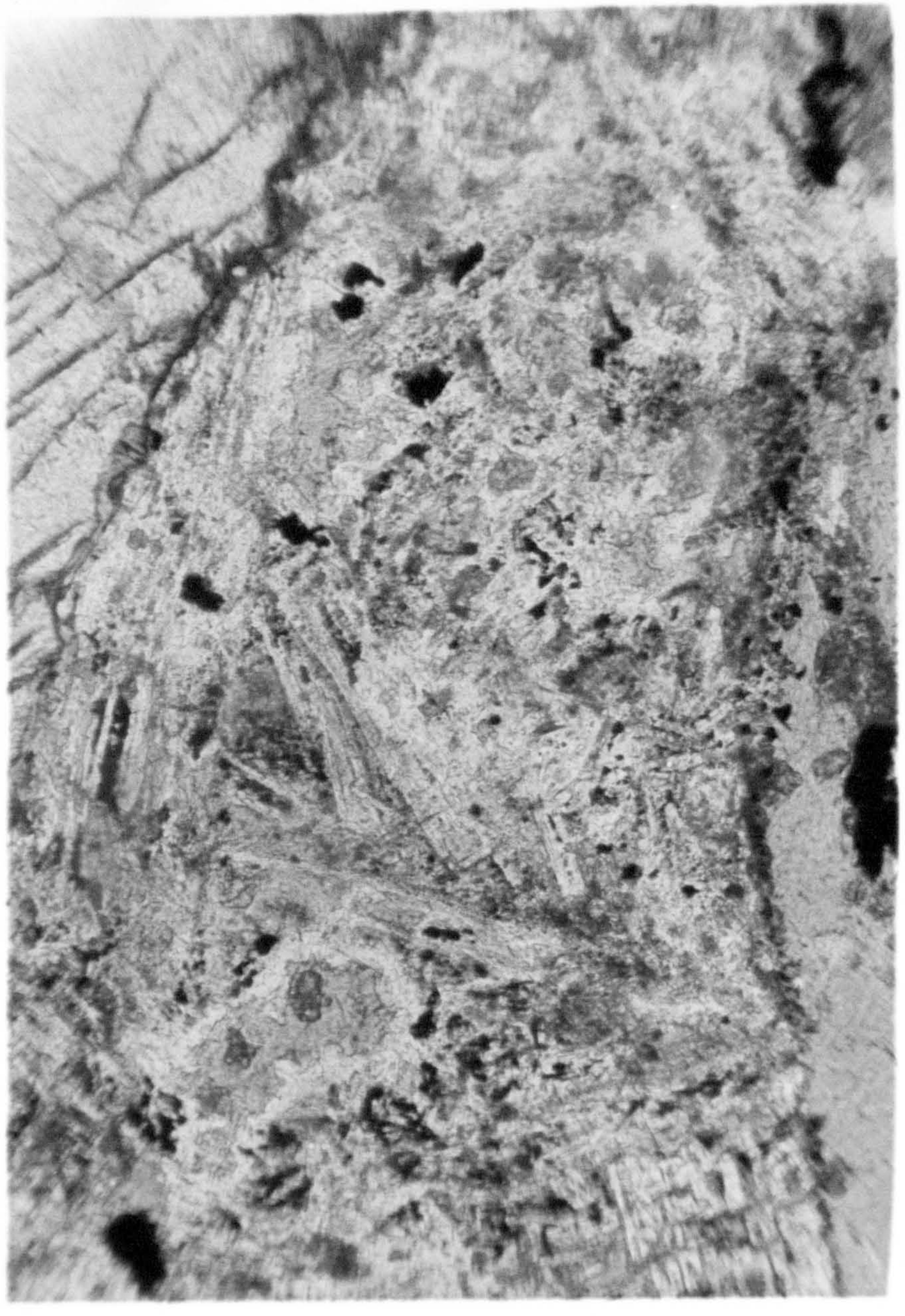


FIG. 47. Clinopyroxene (left) showing marginal replacement by blue-green hornblende (right) Llech Dafad Intrusion (GR 882356). PPL. x200.

FIG. 48. Fine-grained area between stout clinopyroxene and plagioclase feldspar crystals from the Llanwnda Intrusion. (GR 933392). PPL. x220.





clinopyroxene. In some cases, however, the texture becomes intersertal where chlorite and other secondary phases after glass are present between the feldspar crystals.

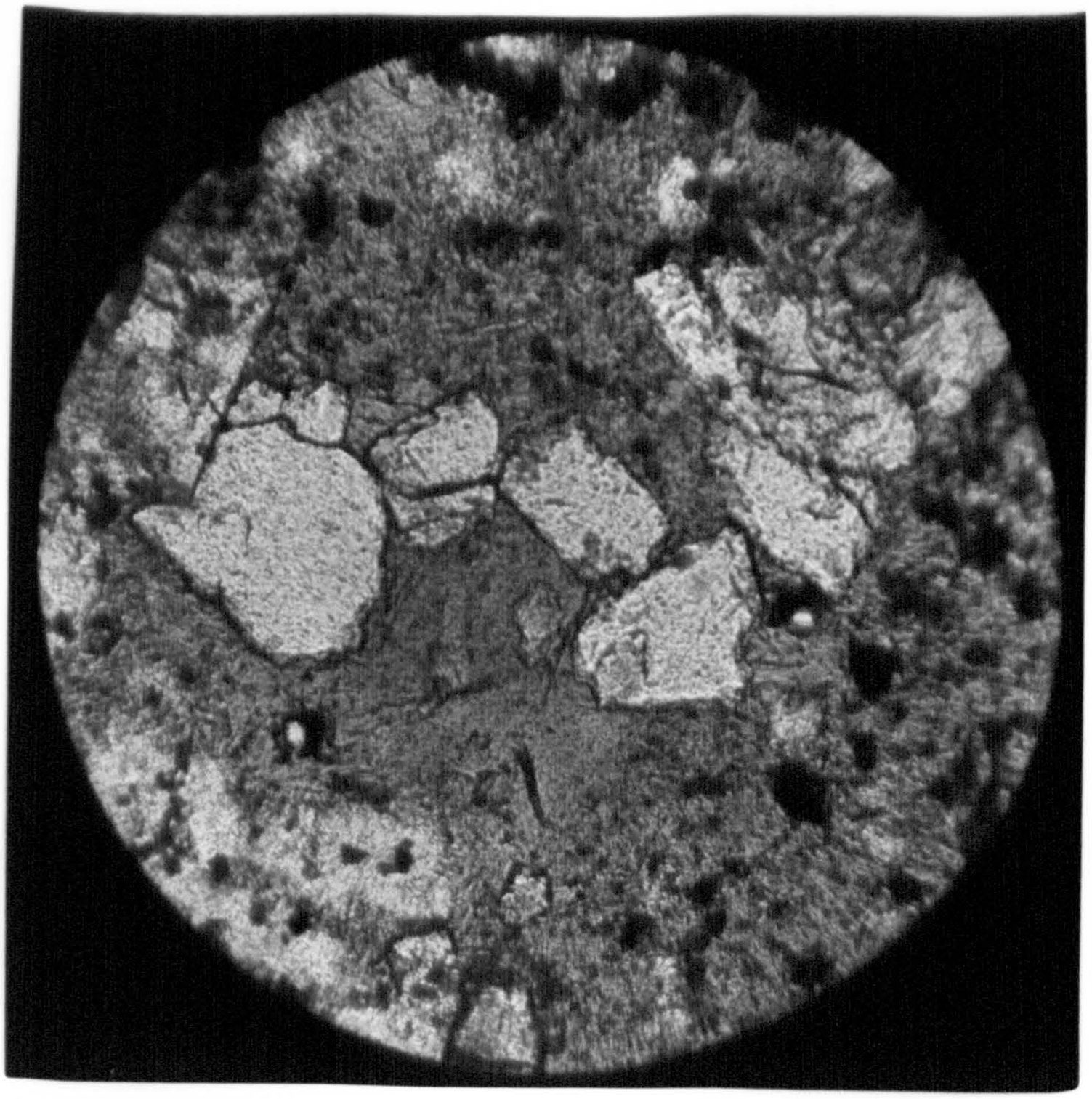
Certain intrusive rocks exhibit a bimodal distribution of crystal size, for example sample LG6 from the Llanwnda Intrusion (Fig. 48). Large tabular or equant plagioclase and clinopyroxene crystals are separated by a fine-grained groundmass, in which dendritic, spherulitic, and skeletal plagioclase crystals predominate. These groundmass crystals clearly record crystallization conditions different from those responsible for the larger crystals. This may be caused by a rapid temperature drop after the larger crystals had formed, or alternatively it is possible that other factors, such as nucleation rate, modified the size and character of the crystals which formed. Other samples show interstitial chlorite or chlorite and epidote aggregates (Figs. 49a - b) separated by tabular plagioclase and clinopyroxene. Occasional apatite crystals occur within the chlorite. Various lines of evidence suggest that these interstitial patches represent altered glass. These interstitial areas would probably have contained the residual iron-enriched portion of the liquid. During rapid crystallization this would have produced an iron-rich glass and subsequent alteration of this would result in the formation of an iron-rich phase, such as chlorite. In addition, these residual fractions of the liquid might be expected to contain relatively high concentrations of incompatible elements such as phosphorous. This would result in the crystallization of apatite. Similar textures within gabbroic rocks have recently been described by Stoeser (1975), from Leg 30 of the Deep Sea Drilling Project.

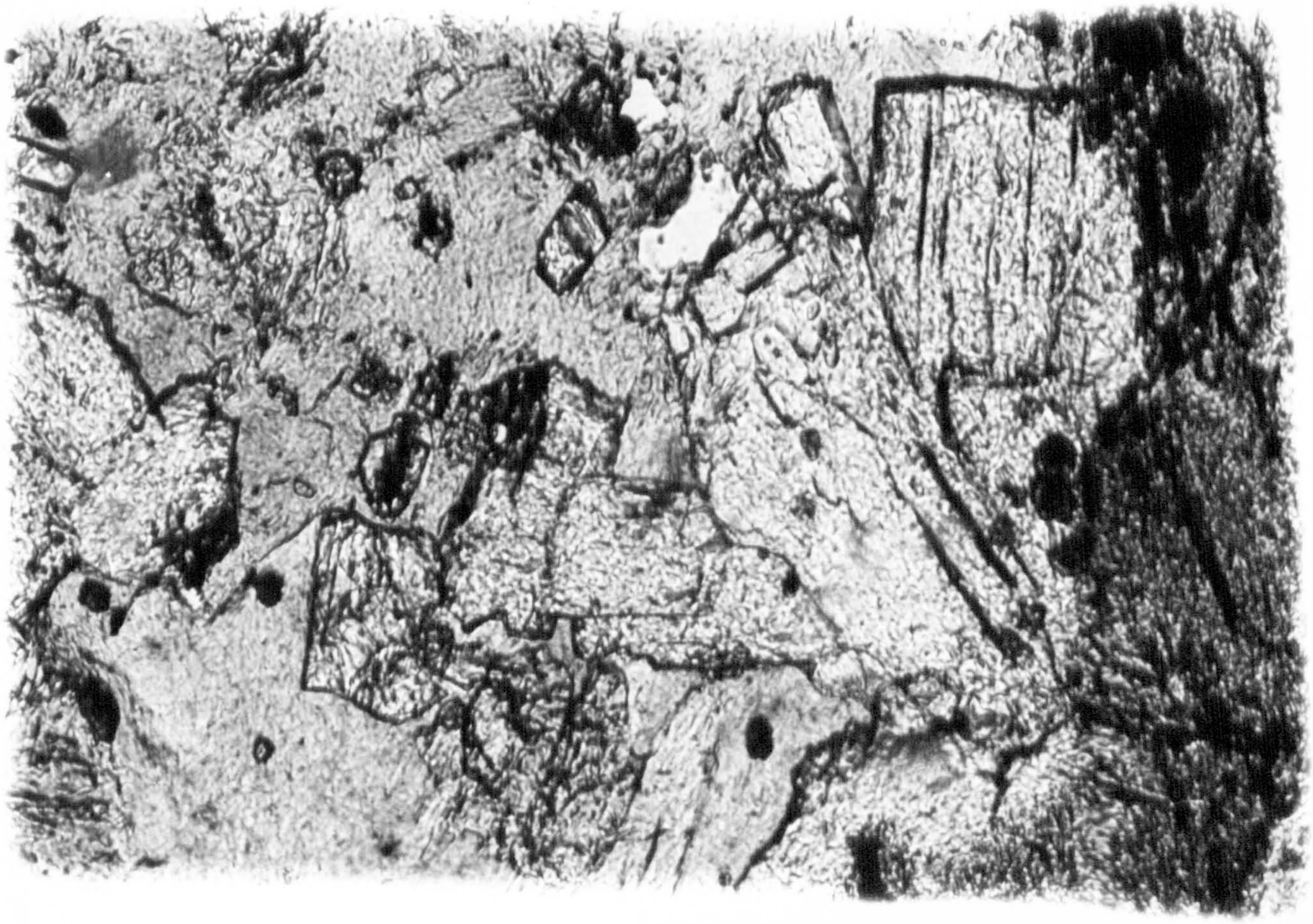
A number of intrusive sheets, particularly those invading the volcanic pile, possess clinopyroxenes which display a skeletal habit.

FIGS. 49a and b. Subhedral to euhedral epidote associated with chlorite in dolerite from the Fishguard area. Small, rounded aggregates of sphene are abundant. PPL.

a) x200.

b) x200.





Generally, these crystals have high length to breadth ratios and sometimes show a branching form. Interstices and hollows within the crystals and crystal aggregates are commonly infilled with chlorite (Figs.50a and b). Sample SB25 shows a very high proportion of clinopyroxene to plagioclase, although this does not appear to significantly modify the whole rock chemistry.

Within single intrusions, a wide variety of textures are commonly displayed. This is particularly pronounced in the Llanwnda Intrusion, which also shows a variation in the modal proportions of the major mineral phases. Varying degrees of differentiation are possibly responsible for the variation in the modal proportions of the phases. Evidence for crystal accumulation is suggested by the presence of an igneous foliation (described above), along with the occurrence of granular aggregates of sub-rounded clinopyroxene crystals. These aggregates may also, however, be formed by synneusis.

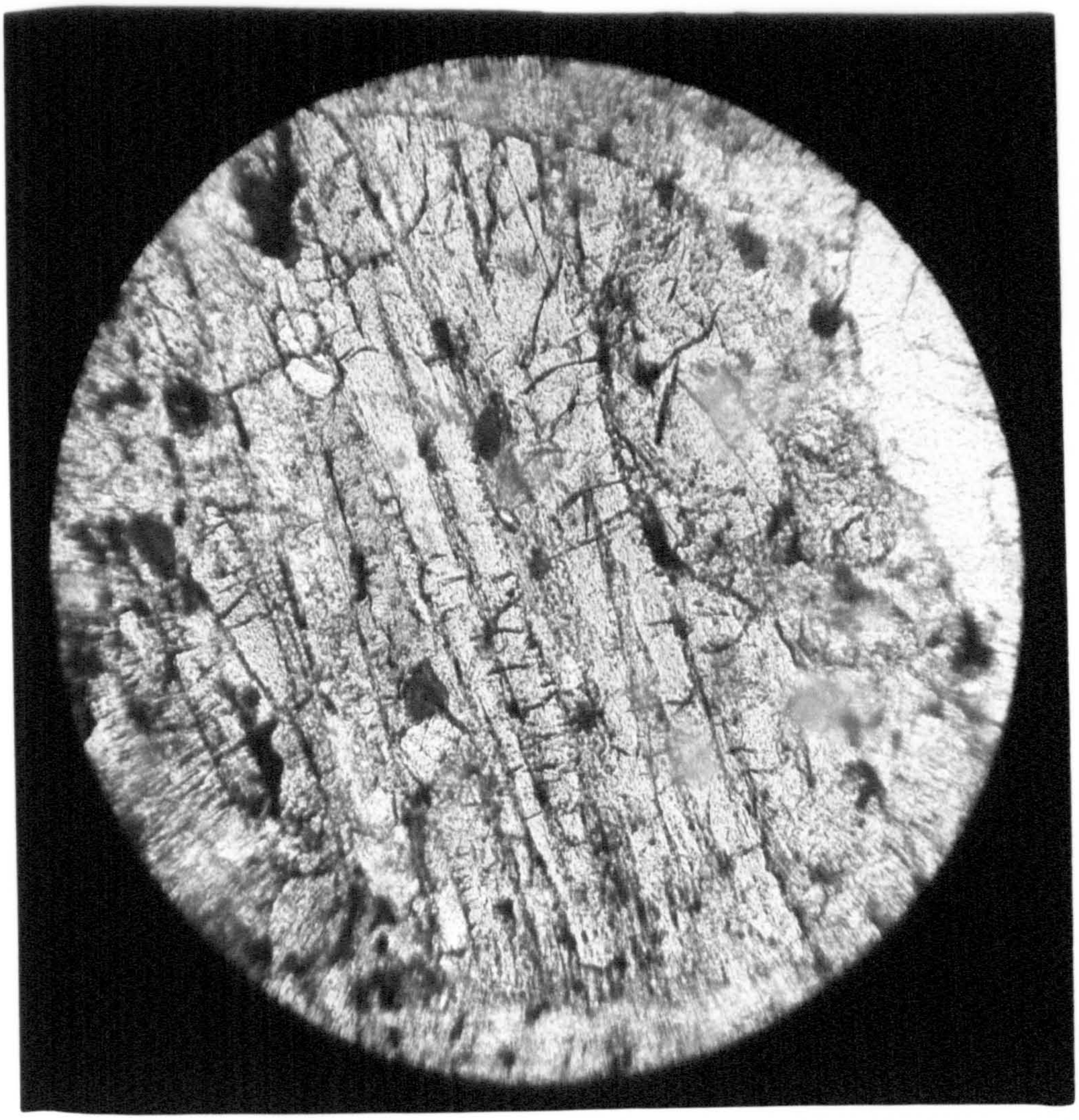
Ultramafic rocks are not seen in the Fishguard area and only one sample, collected from below Foel Trigarn, at GR SN 15783340, in the Prescelly Hills area, may in fact be classed as such.

Clinopyroxene and plagioclase feldspar are the chief liquidus phases in these rocks, with accessory amounts of an iron-titanium ore and apatite. In more fractionated liquids the latter minerals increase in importance. The iron-titanium phase appears to have originally been ilmenite and thin exsolution lamellae of magnetite may be discerned, for example in specimen 502. Subsequently, however, the ilmenite has suffered alteration to sphene and/or leucoxene whilst the magnetite lamellae have remained unaltered, as illustrated in Figures51a and b . Apatite forms needles up to 1mm in length and is commonly associated with chlorite (Fig. 43).

FIGS. 50a and b. Branching and skeletal, coloured clinopyroxene within intrusive sheets from the lava pile of the Strumble Head Volcanic Formation. Areas between clinopyroxenes are generally chlorite-filled. PPL.

a) x120.

b) x120.

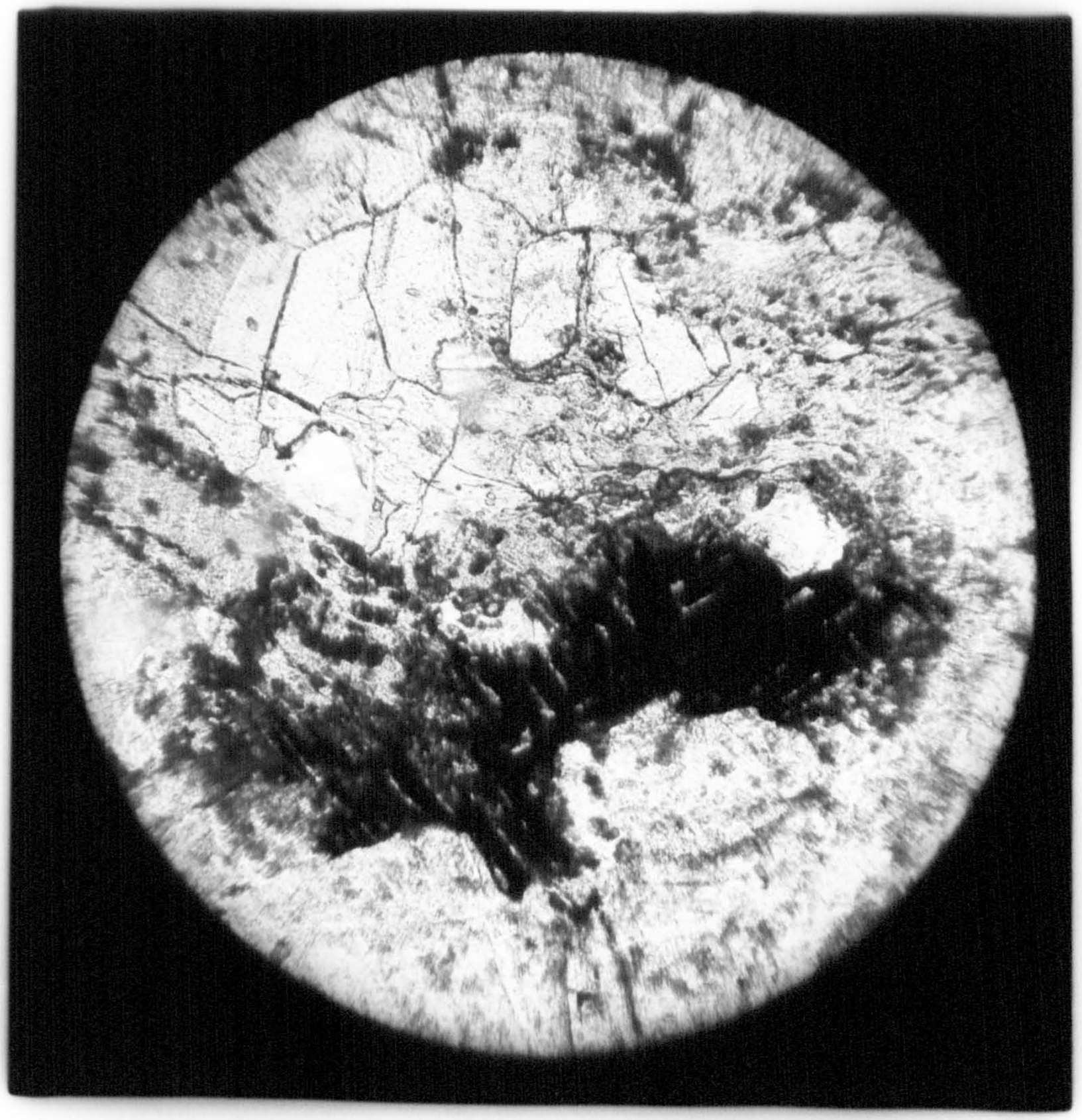


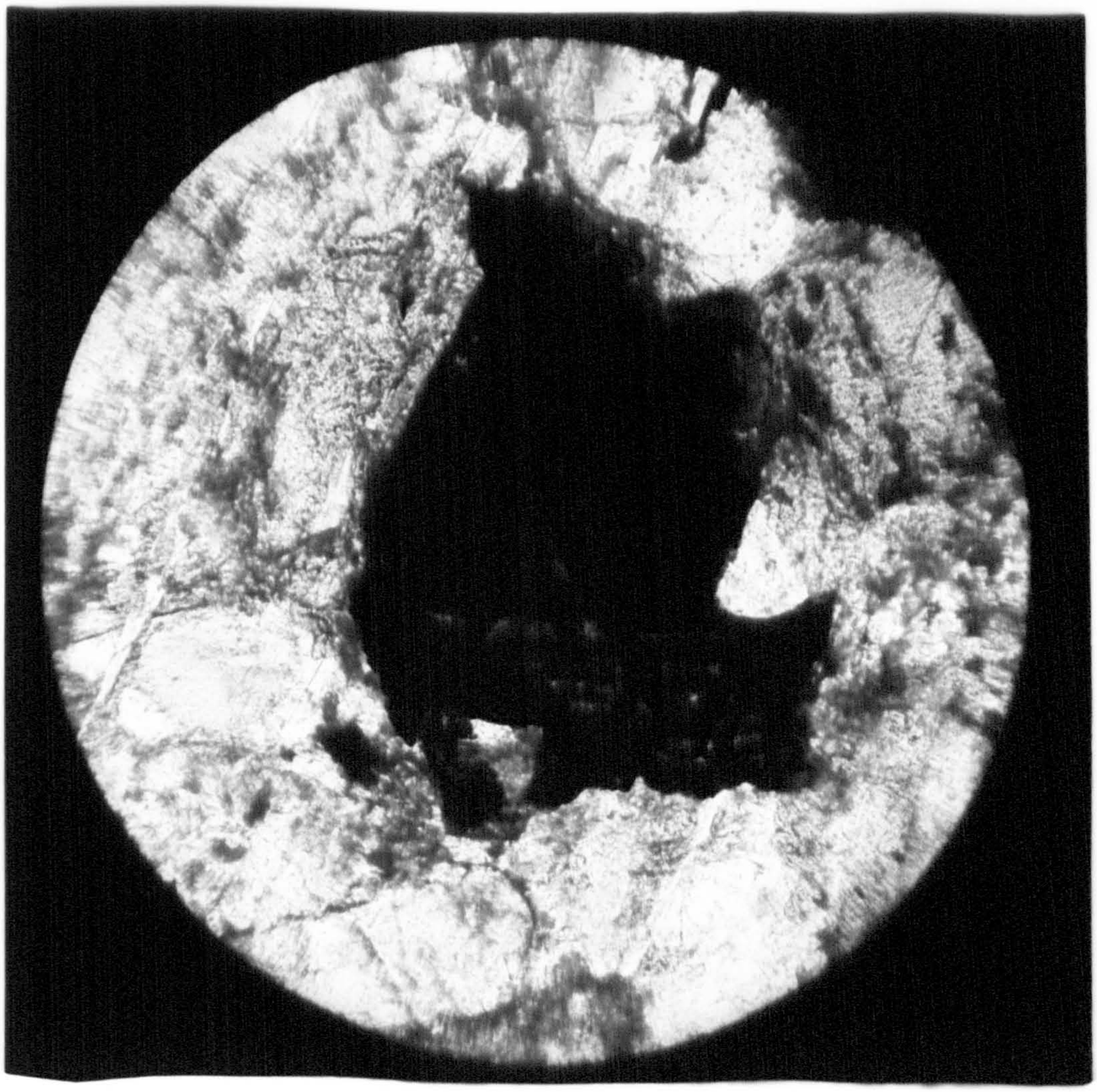
FIGS. 51a and b. Altered ore in dolerites from the Fishguard area.

Note the iron-rich lamellae surrounded by haloes of sphene. PPL.

a) x100.

b) x100.





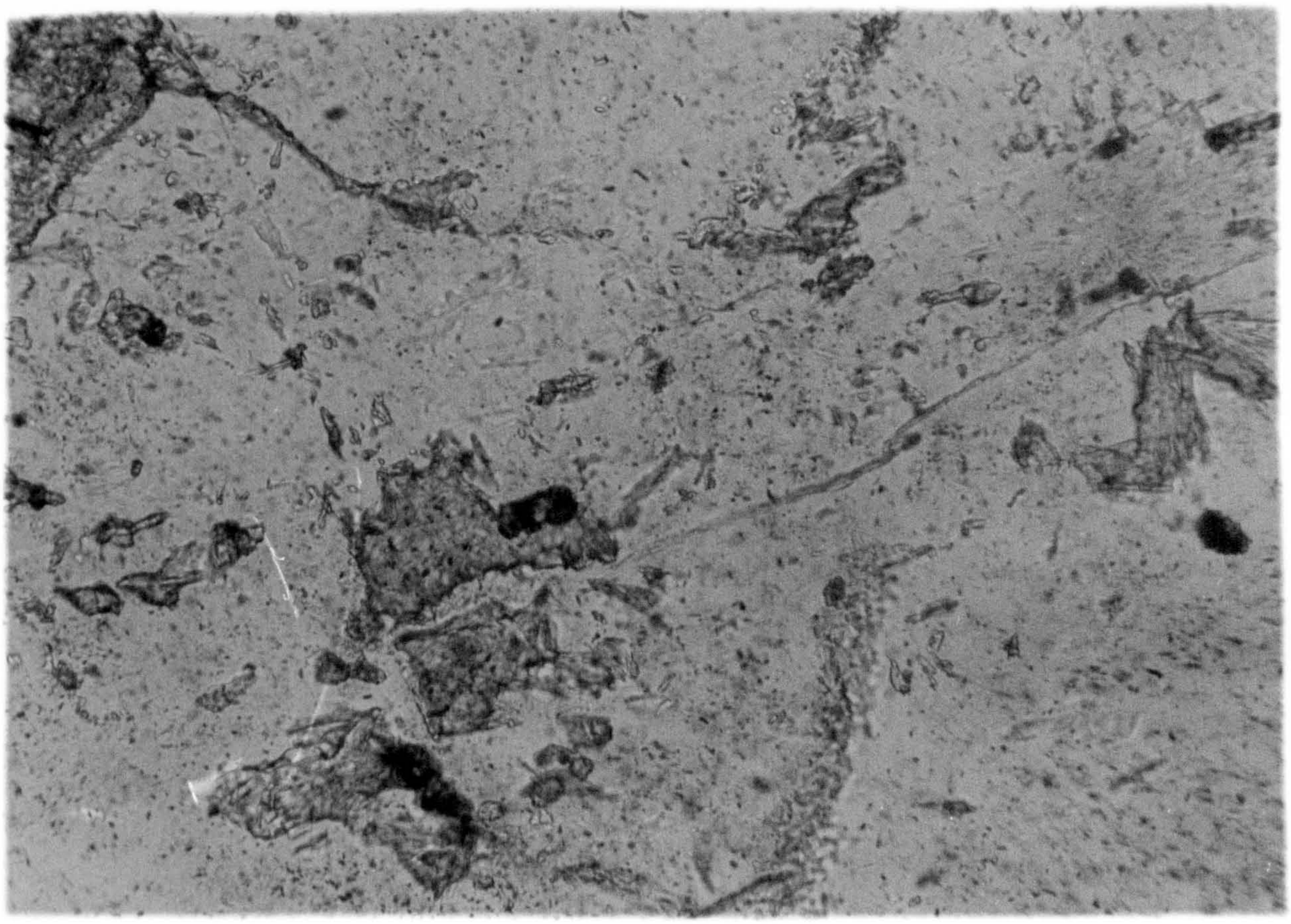
Chlorite is the most ubiquitous of the secondary phases developed. It may be partly metamorphic in origin, although it may also have formed during initial sea-water alteration of volcanic glass. It is generally green to colourless, moderately pleochroic and shows anomalous blue, or rarely brown, interference colours. Microprobe analyses show these to be chiefly brunsvigites or pycnochlorites (see Chapter 4). Commonly chlorite is associated with epidote, an assemblage which appears to be in equilibrium, as suggested by the faceted form of the epidote crystals. Plagioclase feldspar shows various alteration states. Usually the primary calcic plagioclase has been variably albitised, along with the development of other secondary phases. Sericitic mica forms small, felted masses of crystals, commonly completely pseudomorphing the original crystal. Crystal aggregates of pumpellyite are also present in many feldspars (Figs.52a and b), as described and illustrated by Bevins (1978). Prehnite may also occur in this form but more typically occurs in alteration veins, associated with pumpellyite (Figs. 53 and 54) or in interstitial areas, associated with chlorite. A characteristic feature of prehnite is the wavy or undulose extinction of bow-tie shaped or radiating crystal aggregates (Fig. 55). Small sphene spherules or granular aggregates are scattered throughout most of the intrusive rocks. Analysis of one such spherule (see Chapter 4) suggests that they may in fact be grothites (i.e. Al, Fe-rich sphenes). Generally clinopyroxene is unaltered, but in a number of intrusions secondary replacement is found. In the Llech Dafad intrusion this takes the form of marginal replacement of large ophitic clinopyroxene crystals by hornblende (see Fig. 47). Samples from the Llanwnda gabbro show the ubiquitous development of small, highly pleochroic, brown amphibole crystals developed within the clinopyroxene crystals. Occasionally

FIGS. 52a and b. Pumpellyite within plagioclase feldspar crystals.

a) from Strumble Head Volcanic Formation, b) from Garn Fawr intrusion. PPL.

a) x250.

b) x250.



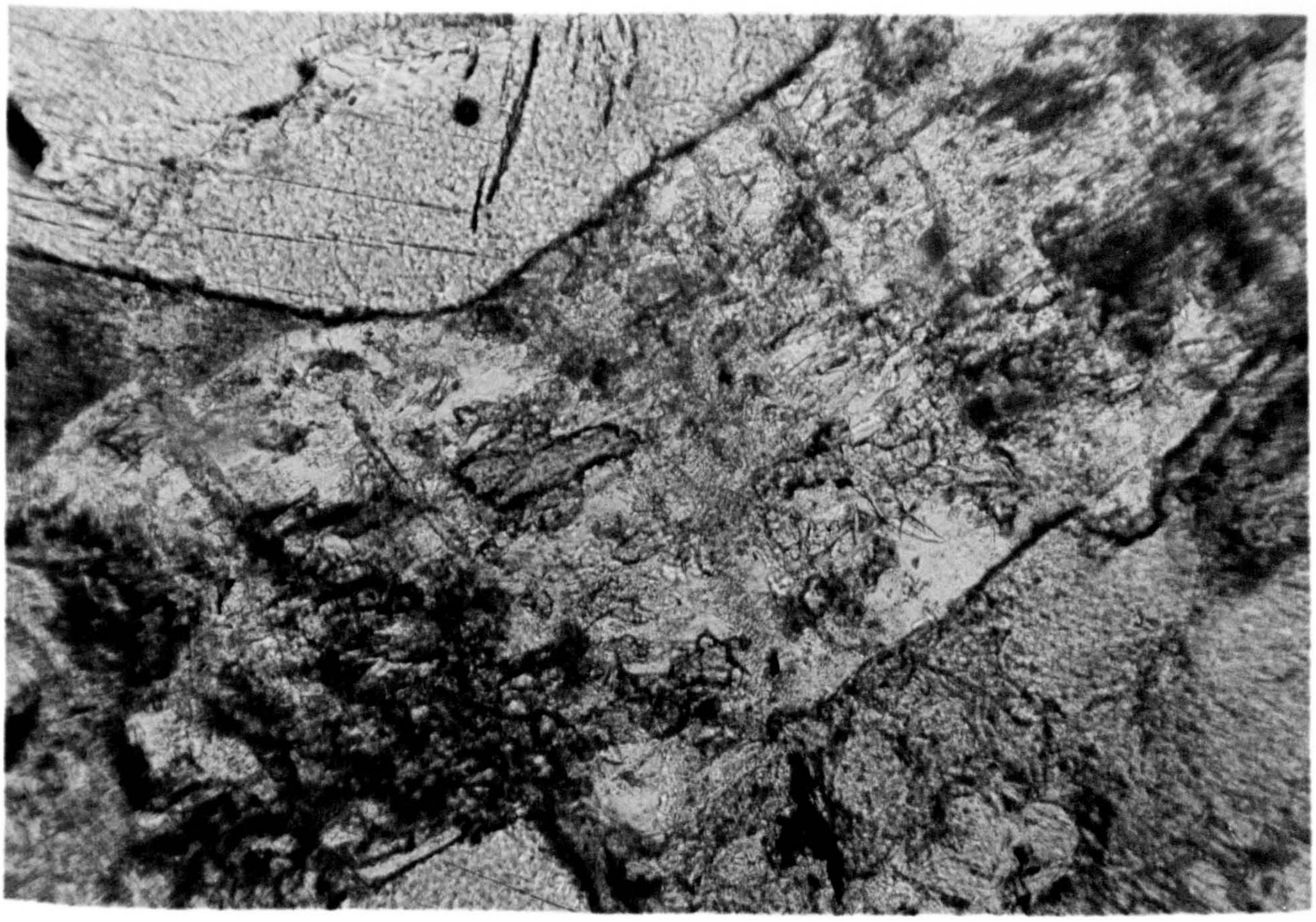
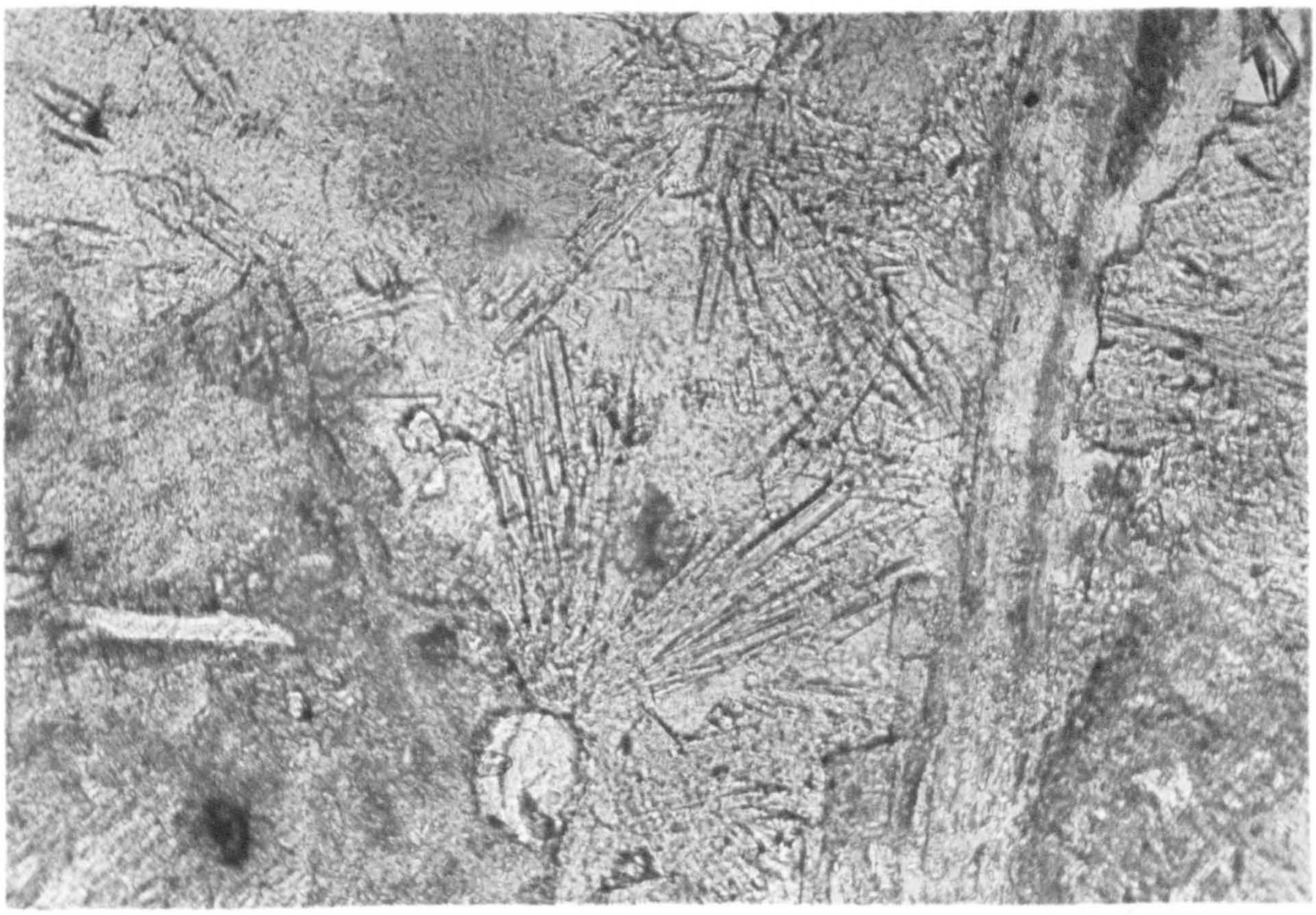


FIG. 53. Radiating pumpellyite crystals within prehnite in alteration vein. Y Garn. PPL. x100.

FIG. 54. Pumpellyite associated with chlorite and prehnite in dolerite from the Fishguard area. PPL. x100.

FIG. 55. Prehnite aggregate in dolerite, showing radiating, undulose extinction. Garn Fawr. XP. x75.



chlorite or pumpellyite is seen replacing clinopyroxene (Figs. 56 and 57). Stilpnomelane is found locally within the intrusive rocks. It occurs in scattered foliae, composed of strongly coloured, highly pleochroic crystals. The pleochroic scheme is dark brown to colourless, suggesting a ferristilpnomelane variety. Calcite, although not as abundant as in the extrusive rocks, is also present in many of the intrusive rocks. Scapolite, identified by Elsden (1905) was not recognized during the course of this study.

The mineralogy and phase chemistry of the basic igneous rocks are described in more detail in Chapter 4.

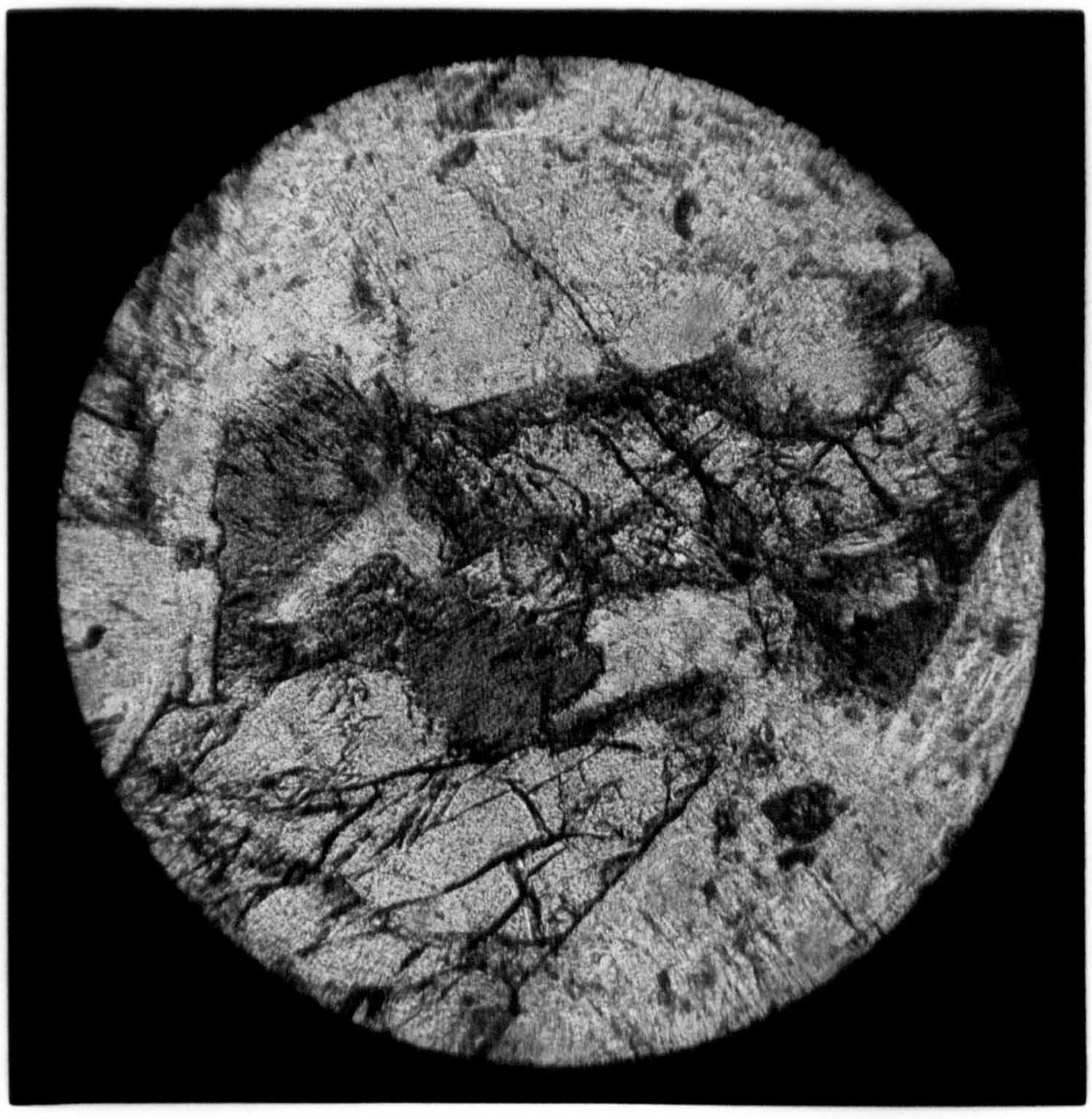
2.3. INTERMEDIATE IGNEOUS ROCKS

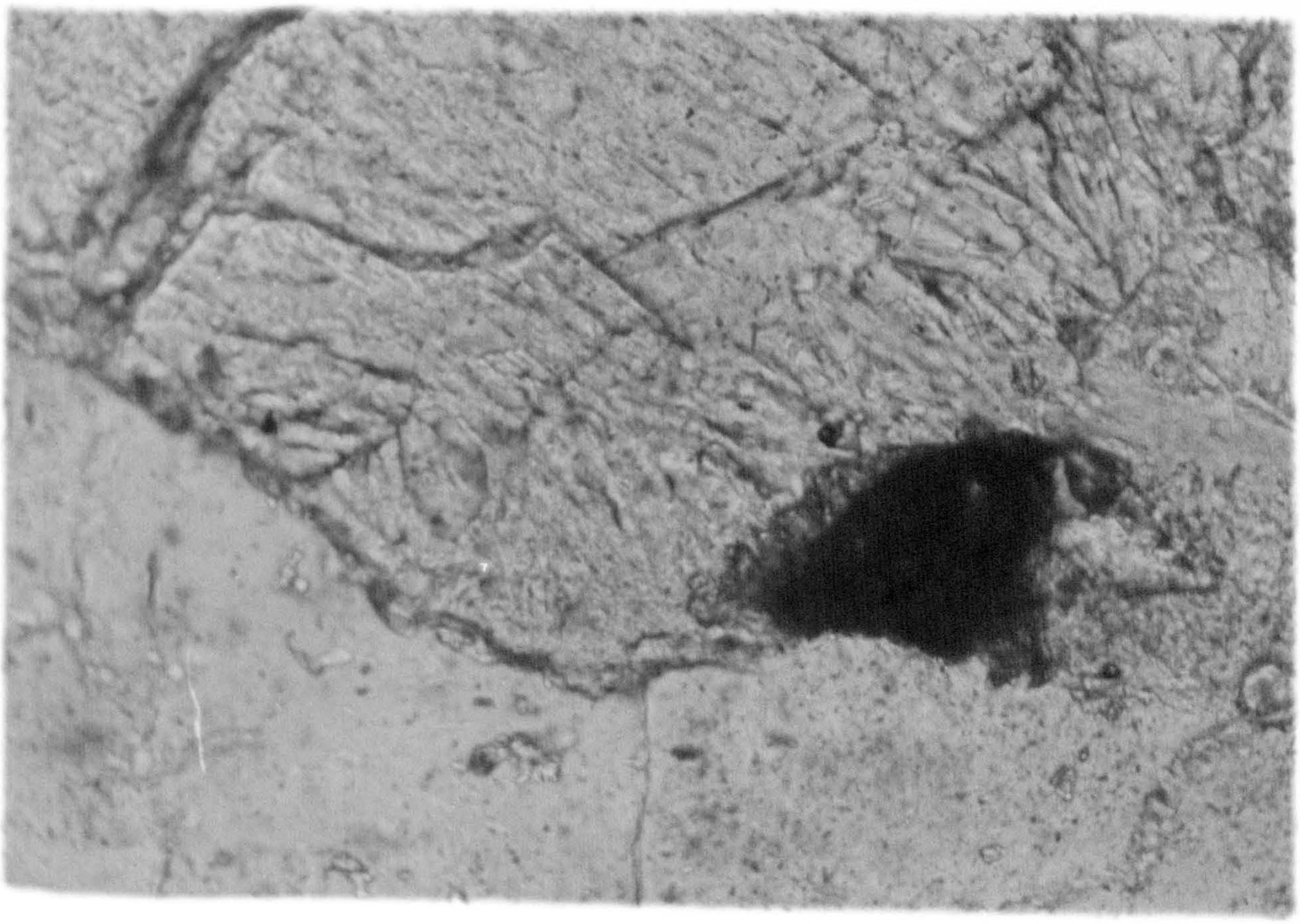
In this study rocks of intermediate composition are classed as those possessing between 52% and 66% SiO_2. Although a mineralogical classification would be more desirable than a chemical classification, this is impractical in view of the altered state of the primary phases, particularily plagioclase feldspar.

Within the intermediate rocks of the Fishguard Volcanic Group, two main groups may be discerned. Firstly, a few thin lava flows and intrusive sheets of the Strumble Head Volcanic Formation possess comparatively high silica contents. These are samples belonging to magma group two (see Chapter 5) and are basaltic andesites and andesites. In the field, they are indistinguishable from the more basic lavas (magma group one) and, as such, have been included in the previous section. The second group of samples fall close to the intermediate-acid boundary, with SiO_2 contents in the region of 65%-67% SiO_2 (magma group three). These rocks occur both as extrusives and intrusives and may accordingly be termed dacites or rhyodacites and quartz-diorites, tonalites or

FIG. 56. Marginal replacement of clinopyroxene by hornblende. Llech Dafad Intrusion. PPL. x125.

FIG. 57. Replacement of clinopyroxene by pumpellyite in a dolerite from the Fishguard area. PPL. x400.





granodiorites respectively. The extrusive lavas form a part of the Porth Maen Melyn Volcanic Formation, whilst the intrusions form the masses of Garn Fawr and Penbwchdy (Fig. 83). A small number of thin, quartz-diorite or tonalite sheets, such as that which invades the dark shales in the eastern cliffs of Porth Maen Melyn (Fig. 63), may also belong to this suite, although no chemical analyses of these sheets have been attempted in view of their state of alteration.

2.3.1. LAVA FLOWS OF INTERMEDIATE COMPOSITION

2.3.1.1. DESCRIPTION OF THE PORTH MAEN MELYN LAVA FLOW

Lava of dacite/rhyodacite composition forms the upper part of the Porth Maen Melyn Volcanic Formation and is exposed as a single unit some 40m thick which represents one episode of extrusive volcanic activity. The flow does, however, display morphological variations and these are described separately below. Although one of these forms may be more strictly described in the volcaniclastic section, it is described here for continuity.

(i) Massive Lava.

For the most part, the flow is massive and structureless. This form may be observed at the eastern and western extremities of the exposed section (see Fig. 59). The lava varies in colour from grey to dark green and is cryptocrystalline in aspect. A perlitic texture is readily observed in hand specimen, with individual perlites reaching 5cm in diameter (Fig. 58). This indicates that subsequent hydration and recrystallization has affected the lava, which was originally glassy in parts. A complete section through this flow may be observed at

FIG. 58. Perlitic texture in massive, rhyodacite lava from the Porth Maen Melyn Volcanic Formation.

FIG. 59. Contact between volcaniclastic siltstones (right) and overlying massive, rhyodacite lava (left) at Porth Maen Melyn. Note that the junction is slightly irregular in nature.

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GR 888394. The base of the flow is undulatory and it appears that the flow covered the underlying crystal-lithic volcaniclastic sandstones and siltstones before they were lithified (Fig. 59). As a result, the flow loaded into the underlying sediments and poorly formed flame structures were developed. In the centre of the unit, flow banding may be discerned, as illustrated in Figure 60. Little or no vesiculation appears to have occurred. Small quartz spherulites, up to 5cm in diameter, are present throughout the lava and are considered to be of secondary origin. Within the uppermost 5m, the lava is brecciated. Angular lava fragments are set within a fine grained matrix and this probably represents an autobreccia (Fig. 61). The contact of the flow with the overlying basic pillow lavas of the Strumble Head Volcanic Formation is marked by a thin horizon of hyaloclastite. Grey rhyodacite lava blocks are incorporated in a chlorite matrix (Figs.62a and b) suggesting that the earliest basic magma mixed with blocks of the underlying flow (possibly loose blocks on the flows upper surface).

In the extreme west of the exposed section (GR 882396) further outcrops of massive lava are present. The upper contact with the basic pillow lavas reveals the presence of a number of dip faults in this area. A basic sheet cuts through the lava and in view of the irregular, lobate contacts between the two rock types (Figs.63a and b) it is thought that intrusion followed very shortly after extrusion of the lava flow. This reveals a pattern repeated throughout the development of the Fishguard Volcanic Group; that of the simultaneous availability of magmas of contrasting composition.

FIG. 60. Flow banding within rhyodacite lava of the Porth Maen Melyn Volcanic Formation.

FIG. 61. Rhyodacite lava fragments within rhyodacite lava at the top of the flow of the Porth Maen Melyn Volcanic Formation.

FIGS. 62a and b. Thin zone of hyaloclastite containing angular, rhyodacite blocks at the junction between the Porth Maen Melyn and Strumble Head Volcanic Formations.

FIGS. 63a and b. Irregular contacts between dolerite (dark grey) and rhyodacite (light grey), southeast of Pen Brush (GR 88253949).

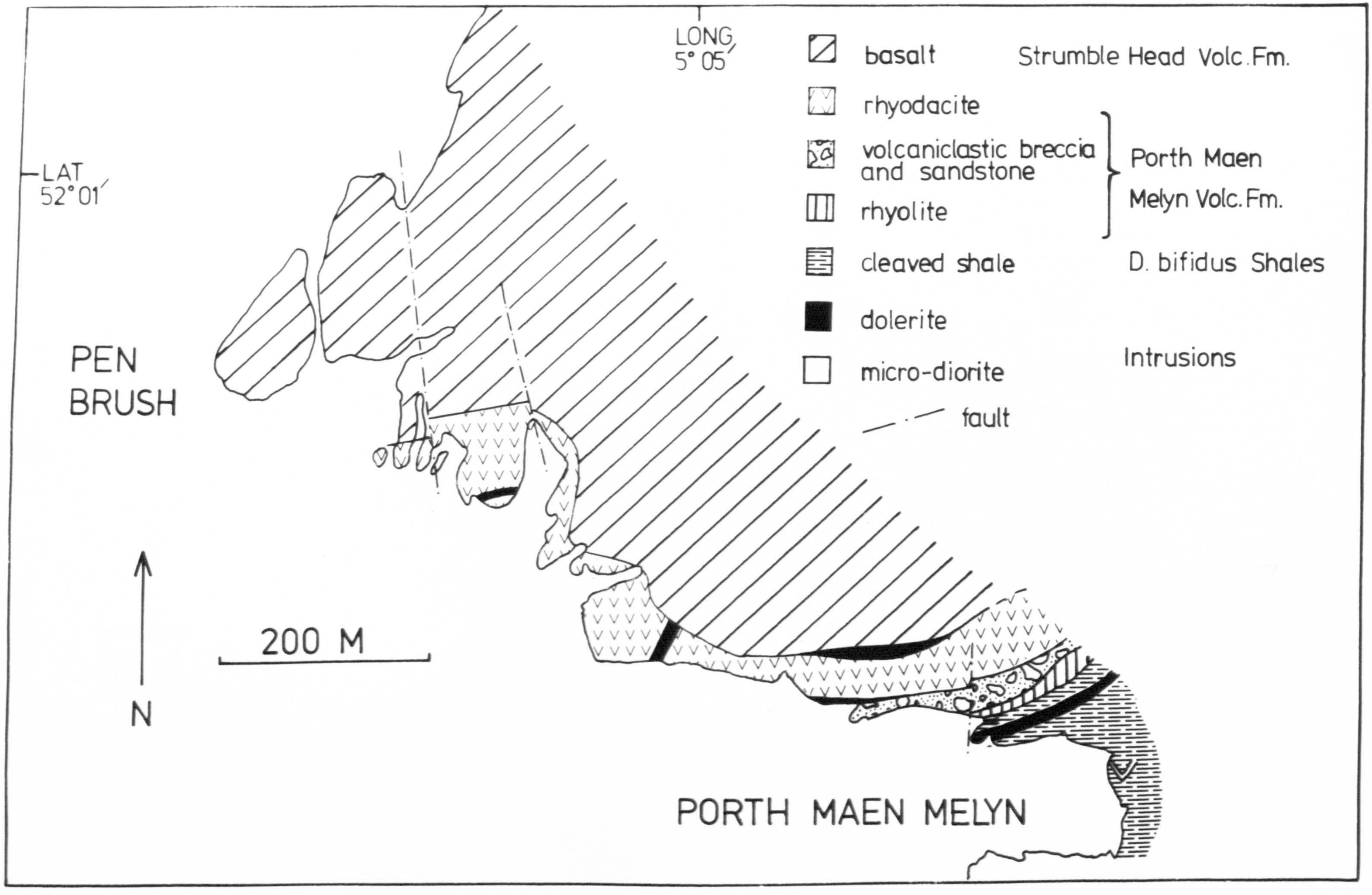
(ii) Lava tubes and pillows.

Some 400m from the northeast corner of Porth Maen Melyn (Fig. 64) the rhyodacite lava flow contains flow tubes and cylinder-like pillows (GR 88453933). Unfortunately, due to the inaccessible nature of the cliff, the transition from massive lava to pillowed lava with tubes cannot be directly observed. The cylinders appear to plunge approximately southwards at a moderate angle and range in diameter from 0.5 to 3 metres. They vary considerably in form, particularly along their axes, with numerous constrictions and protruberances. Figures 65a and b illustrate typical tubeforms. The longest cylinder-like tube observed has a length of approximately 10m. Where no matrix occurs between the tubes, drape structures may be preserved. The lava forming the tubes is a massive, irregularly-jointed dacite or rhyodacite which is grey to purple in colour, identical to the massive lava described above. A peculiar vein-network is commonly developed in the margins of many tubes (Fig. 66). Although their origin is not certain, it is thought that they were produced during the initial fracturing of the lavas upon cooling.

In the area where flow tubes are developed, the top of the flow is represented by a white, micro-crystalline lava which possesses a particularly well-developed perlitic texture.

At the top of this section, the junction with the overlying basic pillows is marked by a thin (60cm) pelitic horizon, which has been invaded by a thick columnar-jointed intrusive sheet. Traced laterally, the contact is seen to be somewhat undulating, striking approximately east-west and dipping gently northwards. It can be clearly picked out due to

FIG. 64. Geological sketch map of the area north of Porth Maen Melyn.


LONG
5° 05′
LAT
52° 01′
PEN
BRUSH
basalt
Strumble Head Volc. Fm.
rhyodacite
volcaniclastic breccia and sandstone
rhyolite
Porth Maen
Melyn Volc. Fm.
cleaved shale
D. bifidus Shales
dolerite
micro-diorite
Intrusions
fault
200 M
N
PORTH MAEN MELYN

FIGS. 65a and b. Lava tubes within rhyodacite lava, north side of Porth Maen Melyn (GR 88503933).

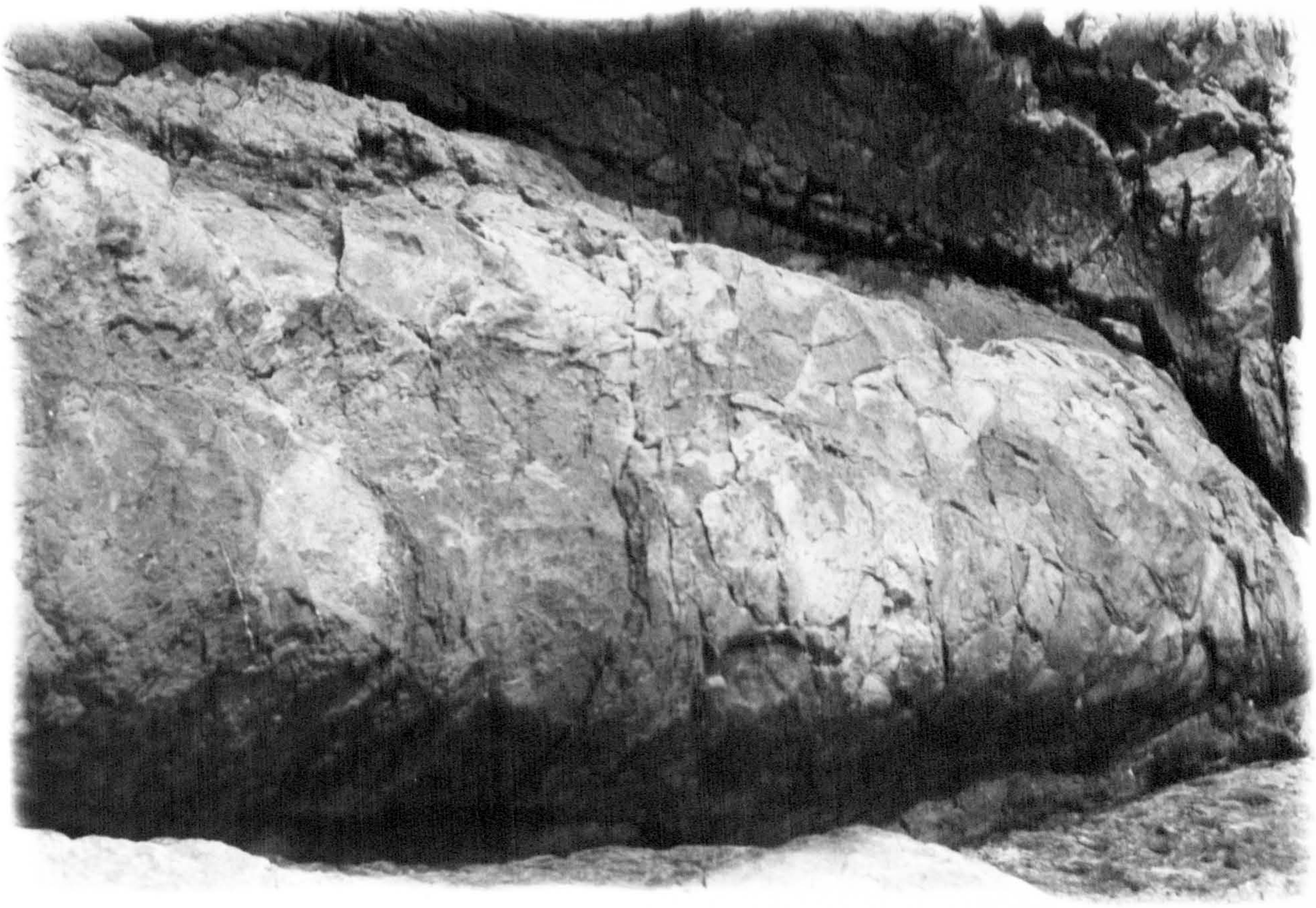


FIG. 66. Vein-network in marginal part of flow tube. North side of Porth Maen Melyn (GR 88503933).

the colour contrast between the weathered surfaces of the basic and intermediate lavas, particularly when observed from the south side of Porth Maen Melyn (Fig. 67).

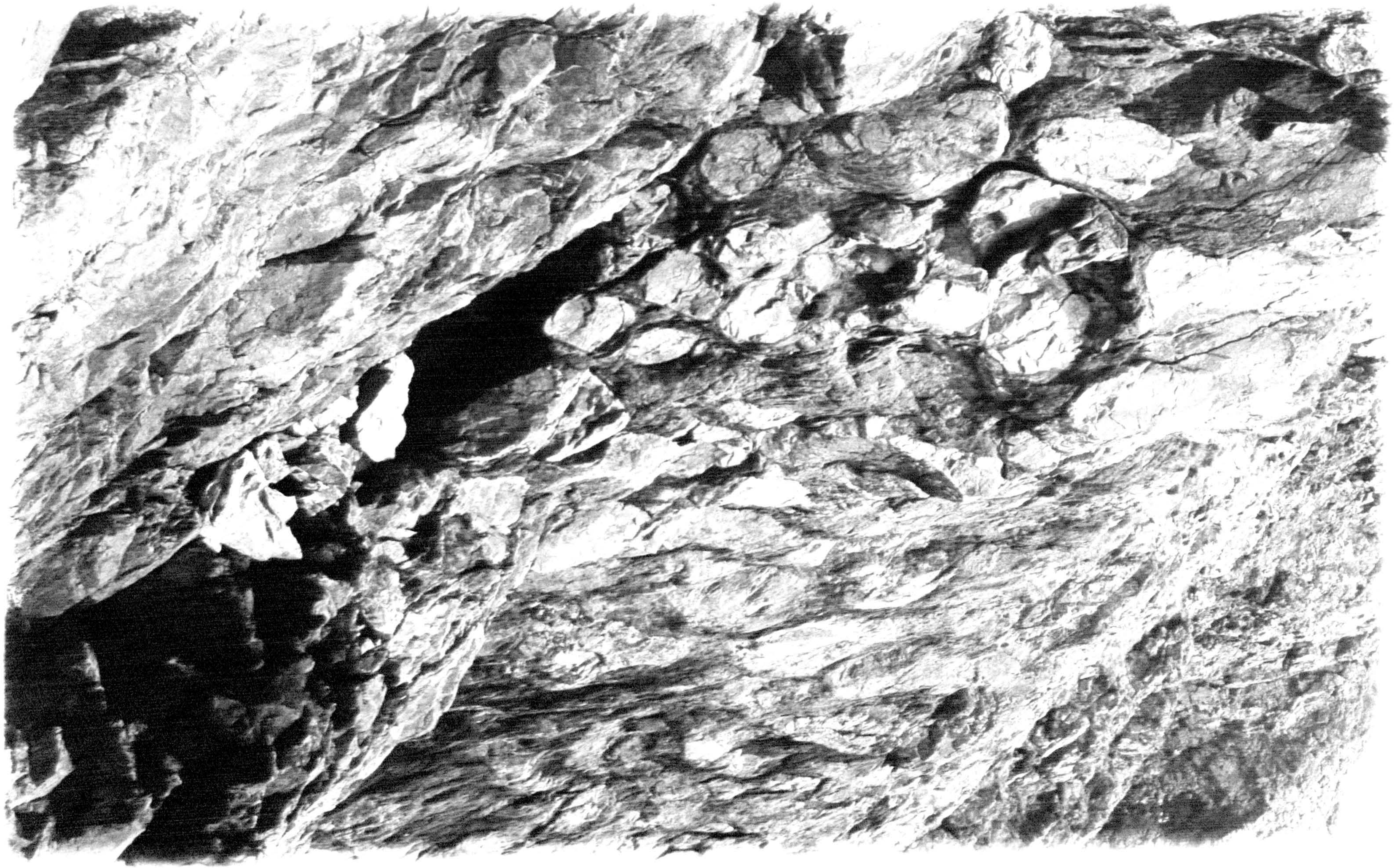
(iii) Isolated-pillow breccia.

A traverse eastwards from the exposures of lava tubes and pillows, described above, reveals a gradation into isolated, discrete and unbroken pillows, set within a clastic matrix. Rocks possessing these characteristics were termed isolated-pillow breccias by Carlisle (1963). Although they would be more correctly described in Section 3.3., they will be dealt with here for continuity.

The pillows form spheroidal to discoidal shaped bodies, up to 2m in diameter (Figs. 68 and 69). Some, however, assume an ovate shape due to slight flattening during Caledonian deformation (Fig. 70). Generally they are larger than the basic pillows of the Strumble Head Volcanic Formation, one of a number of contrasts that the rhyodacite pillows show when compared with the overlying basic pillows. The lava, as elsewhere within the flow, is grey-green to purple and microcrystalline. An irregular, concentric joint system is present in a number of pillows (Fig.69b), contrasting with the typical radial joint patterns of the basic pillows (Fig. 15). At the margins of some pillows white, subrounded alteration patches are present. On close examination, they are found to possess dark green, chlorite cores which are microcrystalline and contain traces of a perlitic cracking (Fig. 71). Material occurring between the pillows, and forming the matrix of this breccia, is present in variable quantities, amounting to about 50% of the total rock volume in certain areas. This variation can be seen in Figure 72. The inter-pillow material contains two main components which are readily distinguishable

FIG. 67. View across Porth Maen Melyn, looking northwards. Junction between the Porth Maen Melyn Volcanic Formation and the Strumble Head Volcanic Formation may be seen in the cliffs opposite.

FIG. 68. Isolated rhyodacite pillows within isolated-pillow breccia of the Porth Maen Melyn Volcanic Formation (GR 88533934).

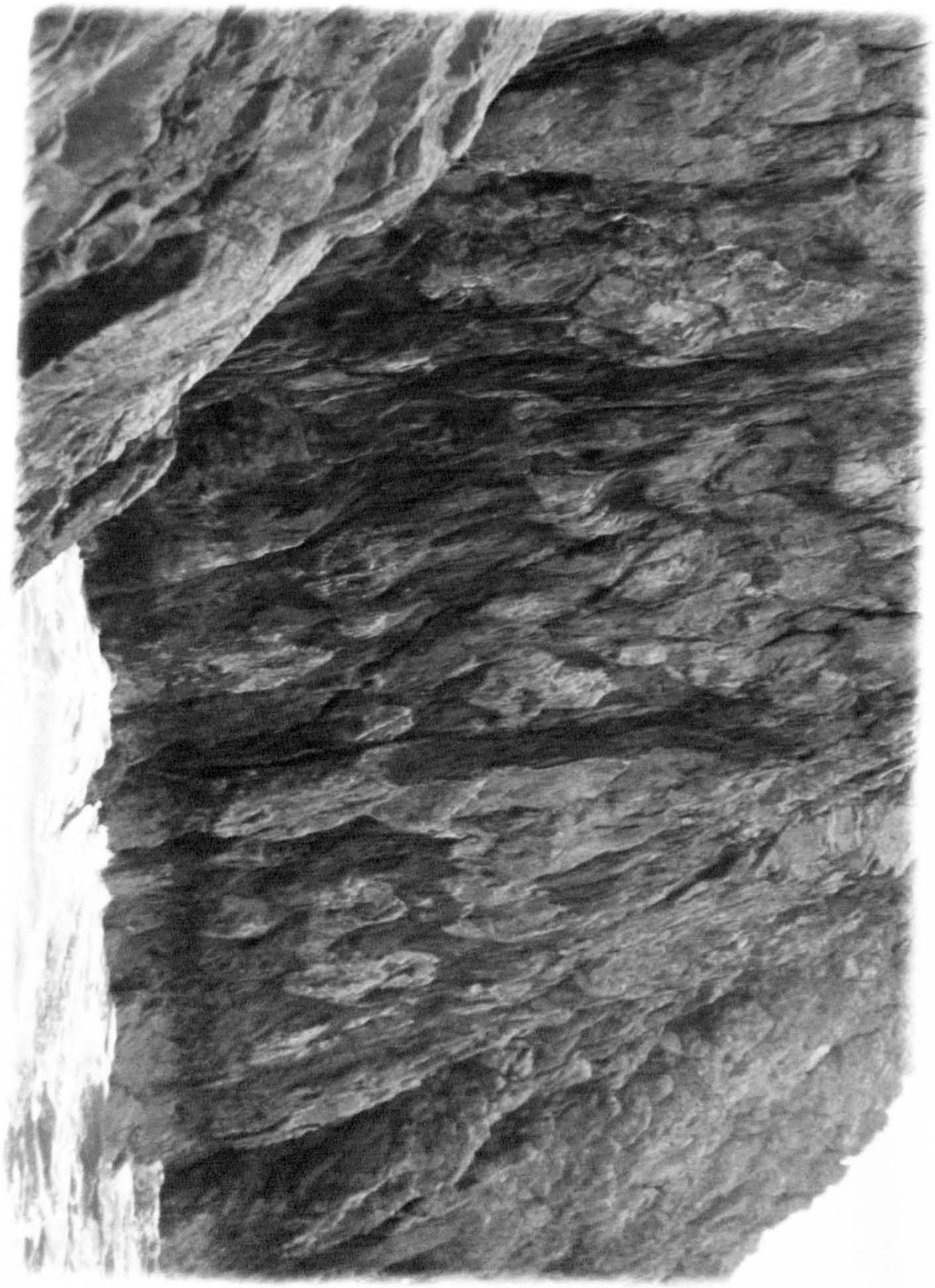


FIGS. 69a and b. Discrete pillows in isolated-pillow breccia of the Porth Maen Melyn Volcanic Formation. Note concentric joint pattern in Fig. 69b (GR 88533934).

FIG. 70. Rhyodacite pillow in isolated-pillow breccia at GR 88533934. Foliation in the matrix of the breccia is deformed around the pillows which are slightly flattened due to the effects of Caledonian deformation.

FIG. 71. Margin of rhyodacite pillow, showing the development of white, sub-rounded patches. The matrix, composed essentially of phengitic mica and quartz, possesses a steeply-dipping planar foliation. GR 88533934.

FIG. 72. View eastwards from above locality, showing the abundant matrix of the isolated-pillow breccia in this area.



in Figure 73; namely dark brown, angular, micaceous fragments set within fine-grained quartz-rich areas, which take the form of a series of veins. Occasional white spheroids are seen weathered out on exposed surfaces. These are similar to the white, sub-rounded patches present within the pillow margins and suggests that the matrix was derived from fragmented pillow material. This contention is supported by the transitional junction between the lava and matrix which may be observed in pressure shadow regions at the top and bottom of the pillows (Fig. 74). The effects of deformation were stronger in the rock matrix than in the pillows themselves, and as a result an irregular schistose foliation, formed by the parallel alignment of micaflakes, occurs within the matrix. The general strike orientation of this foliation is east-northeast, dipping steeply south-southeast, although it is deflected in the neighbourhood of the more competent pillows (Fig. 70). Slickensided surfaces are common within the matrix.

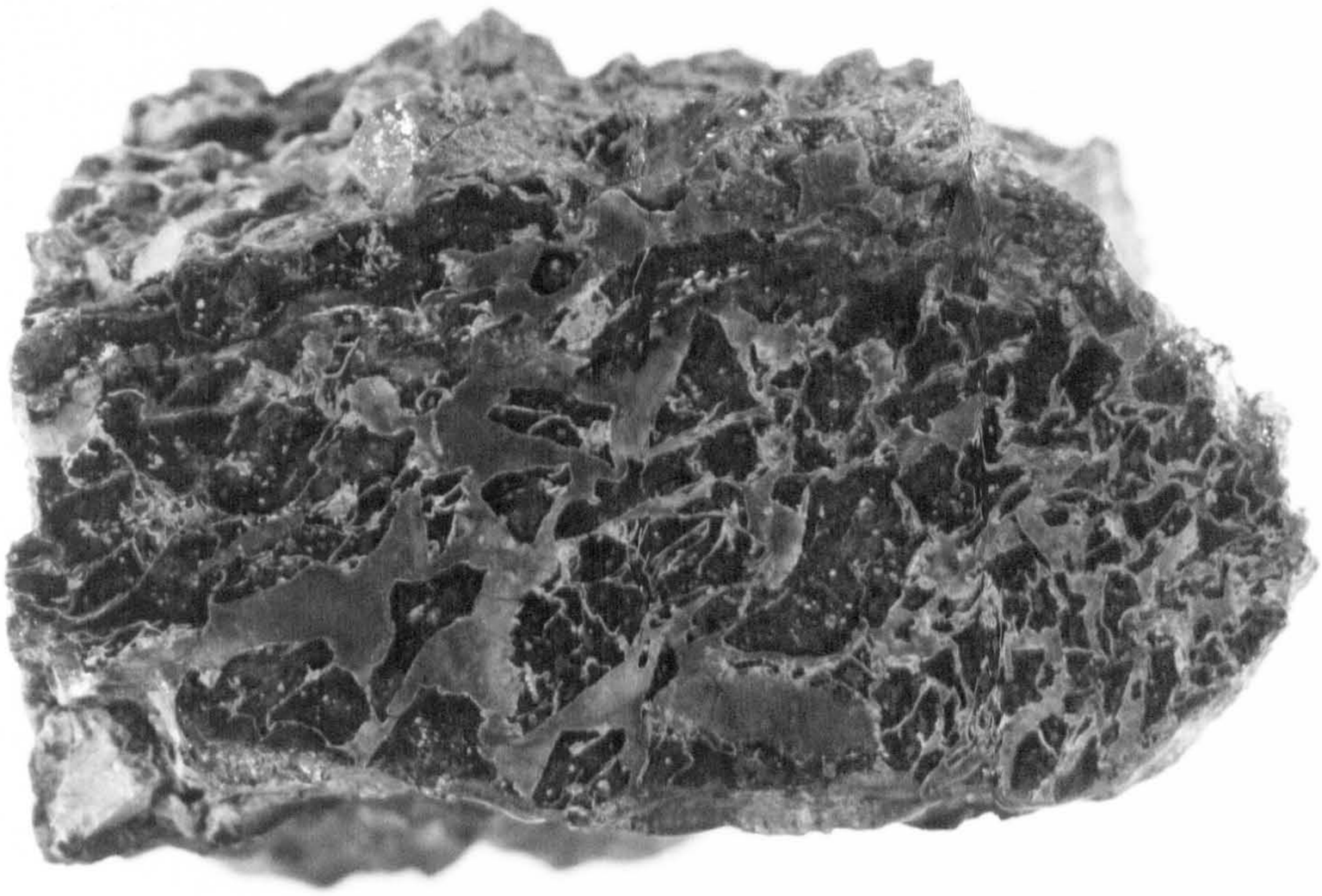
2.3.1.2. PETROGRAPHICAL DESCRIPTION OF THE PORTH MAEN MELYN FLOW

(i) Rhyodacite lava (massive and pillowed).

From petrographical evidence, it can be demonstrated that the Porth Maen Melyn rhyodacite flow was initially partly glassy and partly crystalline in character. The glassy areas have subsequently suffered hydration and recrystallization and a perlitic texture is well developed. Plagioclase phenocrysts were contained within the liquid lava and show evidence of magmatic corrosion. Glomeroporphyritic clusters, as illustrated in Figure 75, are occasionally developed. The plagioclase is generally altered, with crystals of sericitic mica incorporated within them. Extinction angle determinations suggest that the feldspar is highly sodic, probably albite, but it is not determinable whether this

FIG. 73. Isolated-pillow breccia matrix, showing two components; the dark mica fragments and the lighter quartzo-feldspathic areas.

FIG. 74. Margin of rhyodacite pillow, showing the gradual transition from lava to isolated-pillow breccia in a pressure-shadow region.



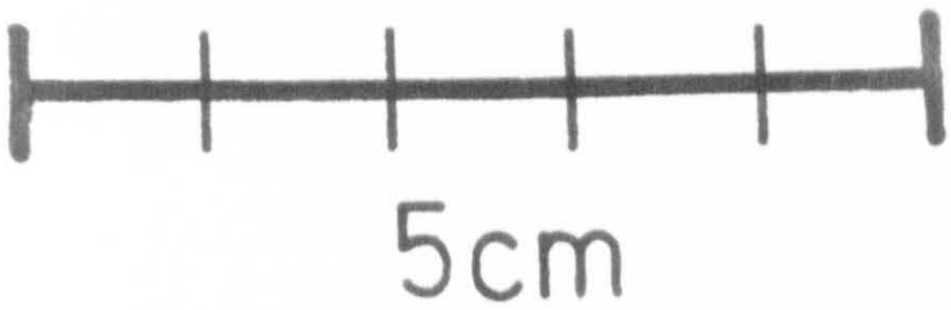
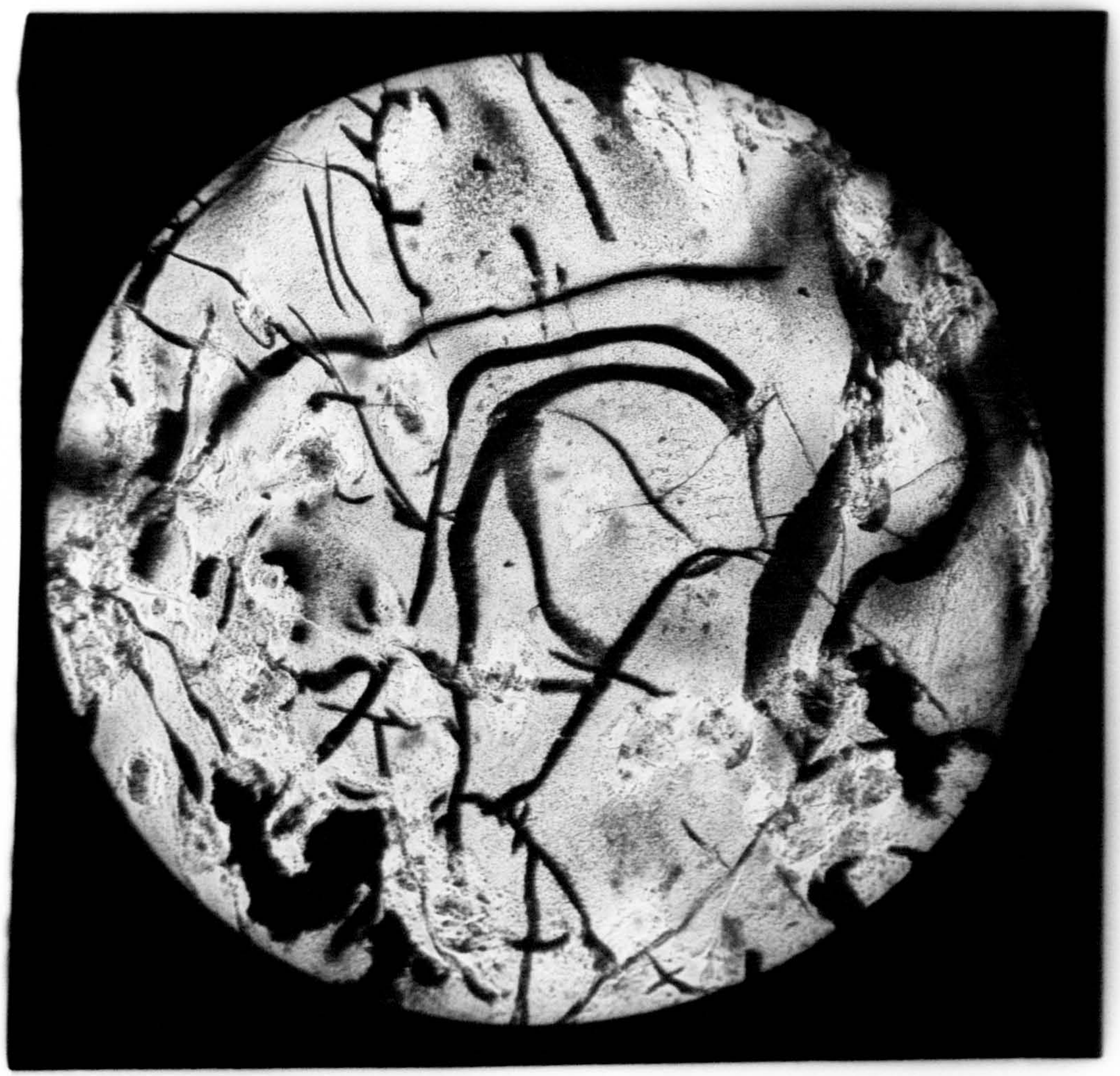
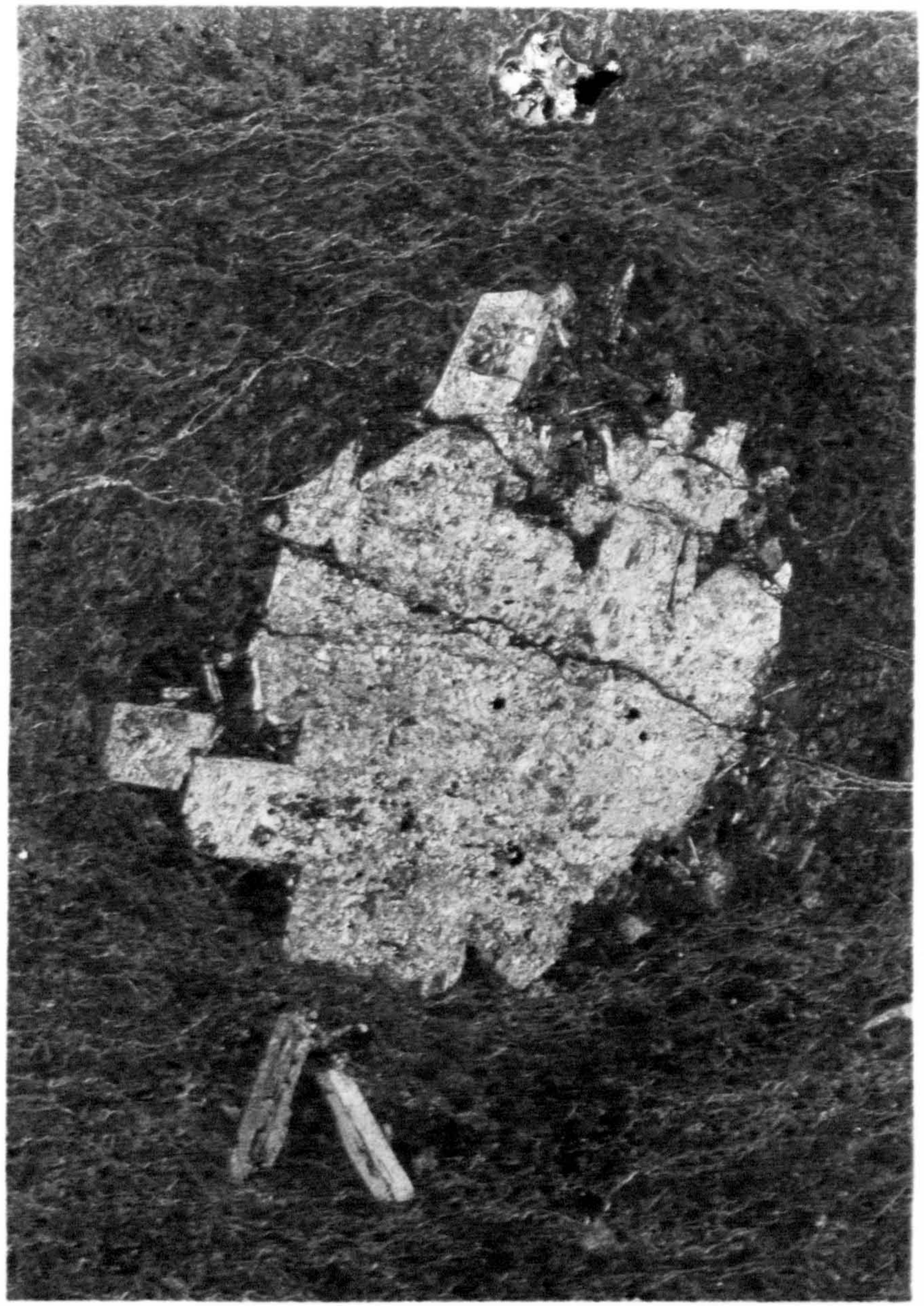

5cm

FIG. 75. Glomeroporphyritic cluster of plagioclase feldspar (now altered) in rhyodacite lava from the Porth Maen Melyn Volcanic Formation. PPL. x25.

FIG. 76. Perlitic texture in metasomatized rhyodacite from the Porth Maen Melyn Volcanic Formation. Outlines of fractures emphasized by sphene. PPL. x100.





composition is primary or secondary, although it is almost certainly the latter. These 'phenocrysts' are considered to be truly intratelluric, in contrast to the large crystals present within some of the basic pillows which appear to have resulted from changing physical conditions, during monotonic cooling and as such are not the direct result of two distinct stages of crystallization. This view is enforced both by the evidence of magmatic corrosion and the lack of spherulitic overgrowths, as commonly displayed by crystals which developed during one continuous growth period.

A glassy groundmass was present in areas where flow tubes and isolated-pillow breccias developed. Subsequent recrystallization led to the development of a microscopic intergrowth of crystals, showing a variety of forms. X-ray diffraction examination of this groundmass revealed both quartz and albite, with minor potassic feldspar. As such, the flow is probably dacitic to rhyodacitic in character, although the term rhyodacite was adopted by Bevins and Roach (in press), after a consideration of both mineralogy and whole-rock geochemistry. Unfortunately, the altered state of the rocks in question negates the use of a truly reliable mineralogical classification. Small, granular sphene aggregates occur disseminated throughout the rock, as do small, skeletal crystals of ore. Thin, irregular quartz, calcite, and epidote veins traverse the lava.

In thin section, the white, microcrystalline lava which occurs at the top of the lava pile, is seen to possess occasional, rounded pseudomorphs after feldspar, within a fine grained groundmass. These are similar to the phenocrysts in the main part of the rhyodacite lava. A perlitic texture is well developed and is emphasized by small sphene

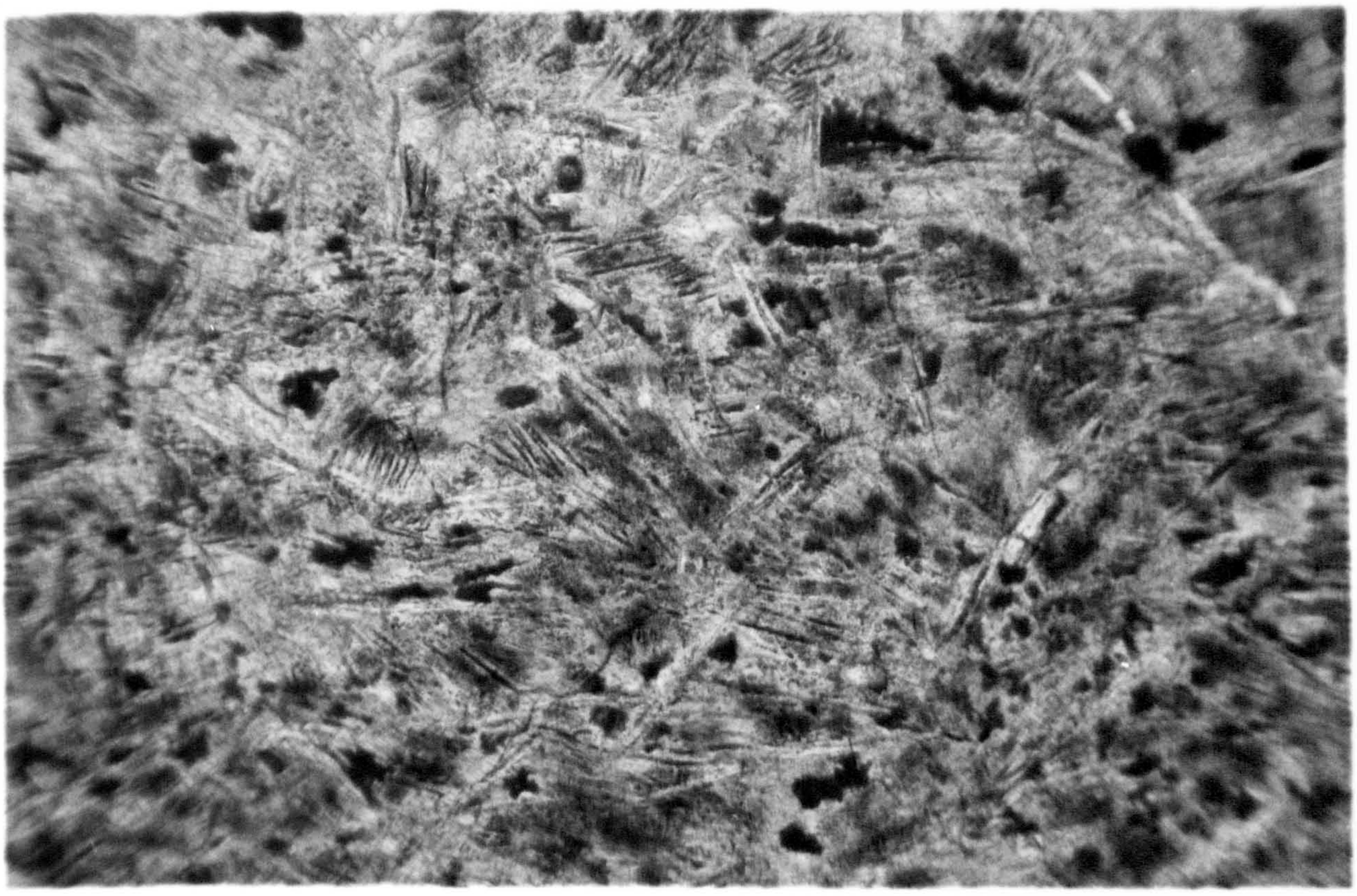
granules which nucleated along the cracks (Fig. 76). An x-ray diffraction trace of the groundmass of this rock reveals the presence of significant amounts of K-feldspar and quartz, with only minor albite.

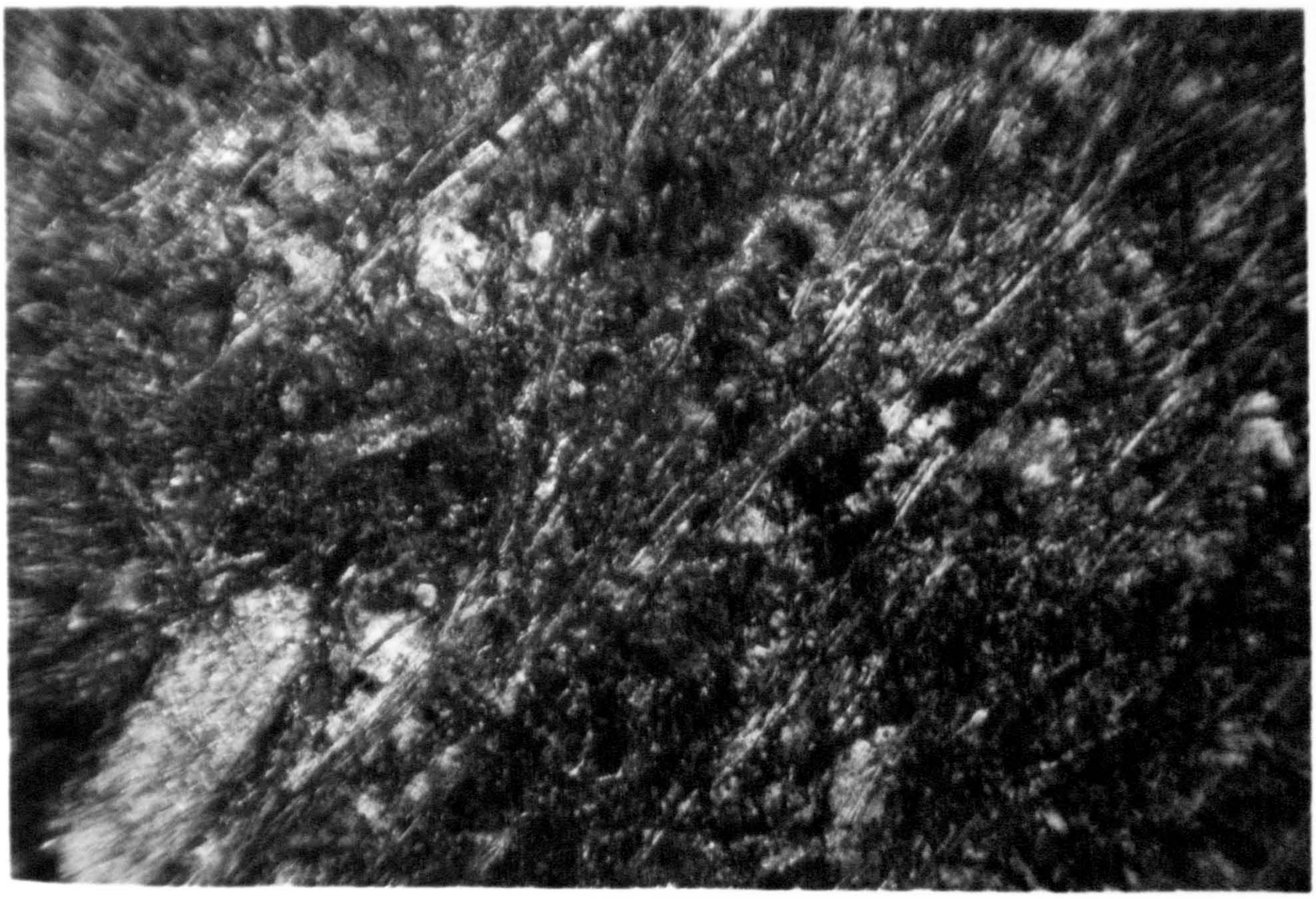
It is thought that this part of the flow has suffered extensive potassic metasomatism (see analysis REB414, Appendix 1). Further evidence of local metasomatic potassic enrichment is provided by the potash-rich spherules which occur within the marginal areas of the isolated pillows (see analysis 175S, Appendix 1), as well as the highly-potassic nature of the matrix of the isolated-pillow breccias (see analysis of phengitic mica, Appendix 2). It is possible to suggest an age for this alteration and this results in an approximate age limit for the formation of the isolated-pillow breccia. It appears that the alteration occurred prior to deposition of the overlying basic lavas, as no evidence of potassic alteration is seen within the latter rocks. At this stage, sea-water was able to penetrate through the rocks particularly utilising channelways such as inter-tube areas. As a result, the inter-tube areas, along with the marginal parts of the tubes or flow lobes themselves suffered extensive metasomatism. Clearly, the isolated-pillow breccia, according to this model, was generated at an early stage.

Those parts of the flow which had a primary crystalline character show a variety of crystal morphologies. Large, skeletal feldspars reach up to 3mm in length and are commonly overgrown by spherulitic feldspars which are in optical continuity. These appear to represent the products of rapid crystallization and similar textures have been reproduced by Lofgren (1974) during rapid cooling experiments. The remainder of the crystalline groundmass is composed of plagioclase showing a dendritic

FIG. 77. Dendritic growth in groundmass of rhyodacite lava from Porth Maen Melyn. x150.

FIG. 78. Flow aligned feldspars in rhyodacite lava from Porth Maen Melyn. x80.





growth pattern (Fig. 77). Occasionally, small crystallites may be identified. Evidence for a primary mafic phase is rare, although sample 330 contains chlorite pseudomorphs up to 1mm in length, probably after clinopyroxene. Skeletal ore is sometimes present in an unaltered state, although the abundance of secondary (probably metamorphic) sphene suggests that much of the ore has been replaced. The character of the spheroidal structures in the pillow margins is described below.

Certain other interesting textural features are revealed by thin section examination of these rocks. Firstly, specimen 408, which was originally hemicrystalline in character, possesses a well-developed perlitic texture. In places, this can be seen cutting through primary plagioclase crystals, showing that a perlitic texture may form in rocks which were partially crystalline in aspect. Similar to other examples, sphene granules within the cracks highlight this perlitic texture. A flow foliation is defined by the parallel alignment of feldspar crystals in a number of specimens from this flow (Fig. 78).

(ii) Isolated-pillow breccia.

Pillows within the isolated-pillow breccia are composed of rhyodacite lava and show identical petrographical characteristics to the rhyodacite lava of the main part of the flow. The matrix is composed of two distinct components: (i) brown micaceous fragments, set within; (ii) a network of siliceous veins (Fig. 73).

The mica is moderately birefringent and possesses a brown colour, locally intense and weakly pleochroic. This presumably reflects the moderate iron content of the mica (see analysis of mica in Appendix 2).

The potassium content is also moderately high in this mica and as such it falls between the end members of the muscovite-celadonite series. An x-ray diffraction analysis suggests that it is a 2M type polymorph and is phengite. This agrees with the chemical data. Titanium and calcium are high for typical mica structures, but this is thought to be due to the presence of abundant small sphene granules, scattered throughout the mica (see Fig. 79). Unfortunately, it was not possible to separate these from the mica. The origin of this mica is thought to be related to the alteration of rhyodacitic lava fragments, a contention supported by the presence, within the mica, of rounded, altered plagioclase phenocrysts, similar to those occurring within the lava. The marginal zones of the mica fragments show colloform leucoxene and sphene (Fig. 80). These patterns are similar to iron-oxide zones developed around basaltic hyaloclastite fragments, as described by Bonatti (1970), Jackobsson (1972), and Furnes (1975). Consequently, they may have formed in a similar manner to that described by the above authors, that is by the interaction between glass and sea-water.

The white, globular to sub-rounded structures present within the marginal parts of pillows and within the matrix of the isolated-pillow breccias are composed in part of small, circular, quartz spherules (Fig.81). The potash-rich character of these structures (analysis 175s, Appendix 1), however, suggests that a potassic feldspar is also present. These spherulitic aggregates commonly surround a dark green, cryptocrystalline chloritic core. A perlitic fracture system, emphasised by sphene granules, is present within the spherules, although it is largely obliterated by the chlorite possibly suggesting a late-stage origin for the chlorite (Fig. 82). The history and chemical development of these spherules is clearly complex.

FIG. 79. Spherical sphene granules within phengitic mica. From the isolated-pillow breccia within the Porth Maen Melyn Volcanic Formation. PPL. x20.

FIG. 80. Zoned margins to phengitic mica fragments. Isolated-pillow breccia, Porth Maen Melyn. PPL. x10.

FIG. 81. Photomicrograph of a globular to sub-rounded body within the isolated-pillow breccia at Porth Maen Melyn. The dark core is chloritic, and is surrounded by small quartzo-feldspathic spherules. PPL. x12.

FIG. 82. Close-up of a part of Fig. 81, showing the perlitic texture overprinted by chlorite. PPL. x25.

The mica fragments are enclosed within a siliceous matrix, which assumes a vein-like aspect. The veins are between 0.1 and 2.0cm thick but vary rapidly in both thickness and orientation. In places, this matrix is dark, with a dusty appearance caused by the presence of abundant, microgranular sphene and leucoxene aggregates. Rare plagioclase microphenocrysts are present and are similar to those of the massive rhyodacite lava. Pyrite aggregates occur sporadically throughout. Some of the silica of these vein-like areas may have been released from the glass fragments during their alteration to phengite.

(iii) Interpretation of the Porth Maen Melyn lava flow.

The Porth Maen Melyn rhyodacite lava flow is considered to be unique in the Lower Palaeozoic volcanic sequences of Wales and indeed is a rare geological phenomenon when considered in a wider context. Although basic pillow lavas are relatively common and have been identified and described many times, pillow forms in rocks of acid to intermediate composition, as identified here, are rare features. Salterley (1941a and b) described rhyolitic pillow lavas in the Precambrian of Ontario, whilst more recently, Lipple (1972) has documented silica-rich pillow lavas from Western Australia. However, such accounts are not common. The Porth Maen Melyn section exhibits a variety of forms within one single flow, the origin for which will be described below.

As described previously, the Porth Maen Melyn flow represents a 40m thick, partly glassy, rhyodacite lava flow which extruded on to the seafloor and flowed over unconsolidated crystal-lithic volcaniclastic sandstones and siltstones. Local variations within this flow were produced and these resulted in the generation of elongate lava tubes and

pillows along with the development of isolated-pillow breccias. The cylinder-like tubes possess a moderate southward plunge and it is considered that this resulted from extension of the flow, caused by the lava flowing over a submarine slope. Moore et al. (1971) and Arculus (1973) described the submarine continuations of the 1381 A.D. and 1329 A.D. Mount Etna lava flows, where elongate tube-like forms and 'pillows' were produced as the basaltic lava flow draped over steep submarine slopes. This resulted in a thinning of the glassy crust, with extension allowing budding and the formation of new flow tubes. A similar mechanism is envisaged for the production of the rhyodacite tubes and pillows at Porth Maen Melyn. Generally, however, pillows are not developed in acidic lava flows, due to the high viscosity of such magmas. It is clear that factors capable of lowering the viscosity must have been in operation. Bevins and Roach (in press) concluded that a combination of the fast effusion rate of a hot magma which was poor or lacking in phenocrysts may have produced a magma of sufficient fluidity to develop tube and pillow-like forms at a point where the lava flowed down a submarine slope. The lack of evidence for extensive vesiculation may also be important in that volatile-rich magmas are generally more fluid than gas-poor magmas. Pichler (1965) stressed that acidic magmas generally produce explosive eruptions. However, where these are not recognized, the magma may be capable of producing a lava flow of comparative fluidity. Lipple (op. cit.) gave no suggestions to account for the mode of formation of the Soansville silica-rich pillows, but clearly chemical and textural similarities between lavas and the Porth Maen Melyn flow exist.

Laterally, this zone of flow-tubes and pillows can be traced into an area where isolated-pillow breccias are developed. These are composed

of rounded, discrete, unbroken pillows, set within a matrix of angular, micaceous fragments which are surrounded by a siliceous cement. The mica fragments are considered to be pseudomorphs after rhyodacitic glass. These fragments were probably produced as a result of the desquamation of the hot magma, in contact with the relatively cold sea-water. As such, these inter-pillow areas of the isolated pillow breccias constitute a variety of hyaloclastite. Acid hyaloclastites are not common, although Pichler (1965) described such rocks from the Western Ponza Islands in the Tyrrhenian Sea. He stated that acid hyaloclastites may form either due to the auto-brecciation of the outer part of developing flows or domes or as a result of the rapid chilling and shattering of hot lava in contact with sea-water. Both processes probably operate simultaneously and "are an example of convergency" (Pichler, op. cit., p. 306). He also stated that acid hyaloclastites, besides their chemical differences, differ from basic hyaloclastites in that, due to their high viscosity, they do not occur associated with pillows. The example described here contradicts this statement. He suggested that highly explosive eruptions destroy the chances of formation of acid hyaloclastites, whilst quiet eruptions allow significant quantities of hyaloclastites to develop. The lack of evidence for an explosive episode during the eruption of the Porth Maen Melyn rhyodacitic lava flow appears to confirm the contention of Pichler. However, the isolated-pillow breccia developed only locally and conditions for extensive desquamation were not widespread. A site suitable for such a process to occur effectively is at the flow front. If abundant magma was continually available, then significant areas of hot magma could be exposed to the chilling effects of the cold sea. Thus, flow tubes would suffer marginal shattering, a process which would be arrested either by the shattered lava

fragments forming an insulating carapace to the still-liquid interior, or by the cooling and consolidation of the whole flow. The concentric joint pattern, seen in a number of pillows, may also have developed at this time.

As stated above, it appears that extensive metasomatic activity has affected these rocks, producing the K-rich spherules, as well as the phengitic mica within the matrix. Although no direct analogies to these rocks have been documented, many workers have noticed considerable increases in K_2O in oceanic basalts and hyaloclastites during sea-water alteration processes. Bonatti (1970) reported that during hydration of basaltic glass dredged from the Southeast Pacific depletion of Ca, Mg, Na and Mn occurred, whilst, in contrast, both Fe and K were considerably enriched. Moore (1966) also recorded considerable enrichment in potassium within palagonitized basaltic glass from Muana Kea, Hawaii and he attributed this to alkali transfer. Other cases of potassium enrichment in basaltic lavas by sea-water have been reported by Frey et al. (1974), Hart (1969) and Hart (1973). Although in the Porth Maen Melyn case the primary material is of a different composition, it is considered possible that the alteration effects may have been of a similar nature.

Thus, it is apparent that the rhyodacite lava flow of Porth Maen Melyn shows a variety of morphological and chemical features. For the most part, the flow appears to have been massive, with an irregular base and a rubbly, autobrecciated top. Locally, however, possibly due to the presence of a submarine escarpment, the lava flow produced elongate flow tubes and pillow-like forms, as it extended downslope. Exposure of hot magma on the slope and at the flow front allowed desquamation to occur and resulted in the generation of isolated-pillow breccias.

2.3.2. INTRUSIONS OF INTERMEDIATE COMPOSITION

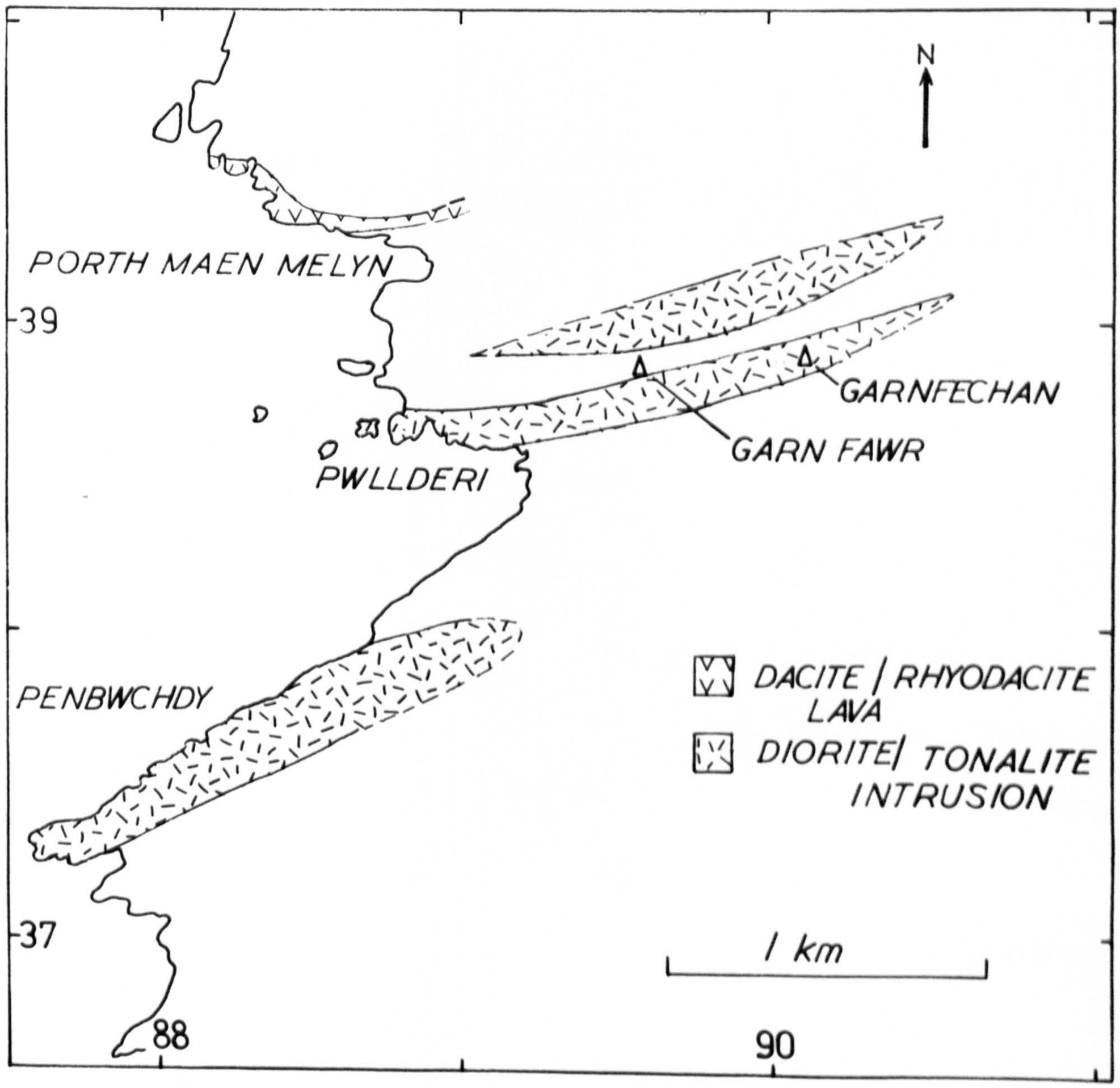
In the area to the south of Porth Maen Melyn, a number of large intrusive sheets invade the Arenig and Llanvirn sediments (Fig. 83). The rocks constituting these sheets are light grey in colour, due to a predominance of plagioclase feldspar (up to 70% modal proportion). The largest of these sheets is Penbwchdy, where the intrusion forms the steep sea cliffs from Carn Ogof (GR 888379) to Penbwchdy (GR 876374). A second sheet occurs further north, in the Garn Fawr - Garn Fechan area (Fig. 1). Although this is seen at the surface as two distinct outcrops, separated by dolerite, the exact relationships are unclear and it is thought that the two outcrops of intermediate rock are linked at depth. Good columnar jointing is particularly well developed in these latter outcrops.

A minor intrusive sheet, also light grey in colour, and composed predominantly of plagioclase feldspar, is present in the cove at Porth Maen Melyn. This sheet invades dark, unfossiliferous shales, which are probably Llanvirn in age (Fig. 64).

2.3.2.1. INTRUSIVE SHEET AT PORTH MAEN MELYN

This minor intrusion shows evidence of having been emplaced into wet sediments and it probably represents one of the earliest volcanic events in the history of the Fishguard Volcanic Group. The upper and lower contacts of the sheet are irregular and large flames of sediment inject into the body. Detached, baked xenoliths of sediment are present within the sheet. A thin, chilled zone surrounds the intrusion for a distance of approximately 5cm.

FIG. 83. Sketch map illustrating the distribution of magma of an intermediate composition in the western area of Pen Caer.


N
PORTH MAEN MELYN
39
GARNFECHAN
GARN FAWR
PWLLDERI
PENBWCHDY
DACITE / RHYODACITE LAVA
DIORITE/ TONALITE INTRUSION
37
1 km
88
90

In thin section, it can be seen that the sheet is composed almost entirely of plagioclase feldspar which has been variably altered. As a result there is abundant calcite present (Fig.84). Andesine is locally preserved and crystals commonly show evidence of compositional zoning. Skeletal ore is scattered throughout the rock and in many cases shows evidence of alteration to sphene. An iron-rich mica is also sparsely present.

Due to the pervasive carbonation, a chemical analysis of this rock was not attempted. It is thought, however, that since it was intruded whilst the sediments were wet, it may represent an intrusive phase approximately equivalent to the overlying rhyodacite lava flow of the Porth Maen Melyn Volcanic Formation. Petrographically, the two magmas are similar with the exception of grain size.

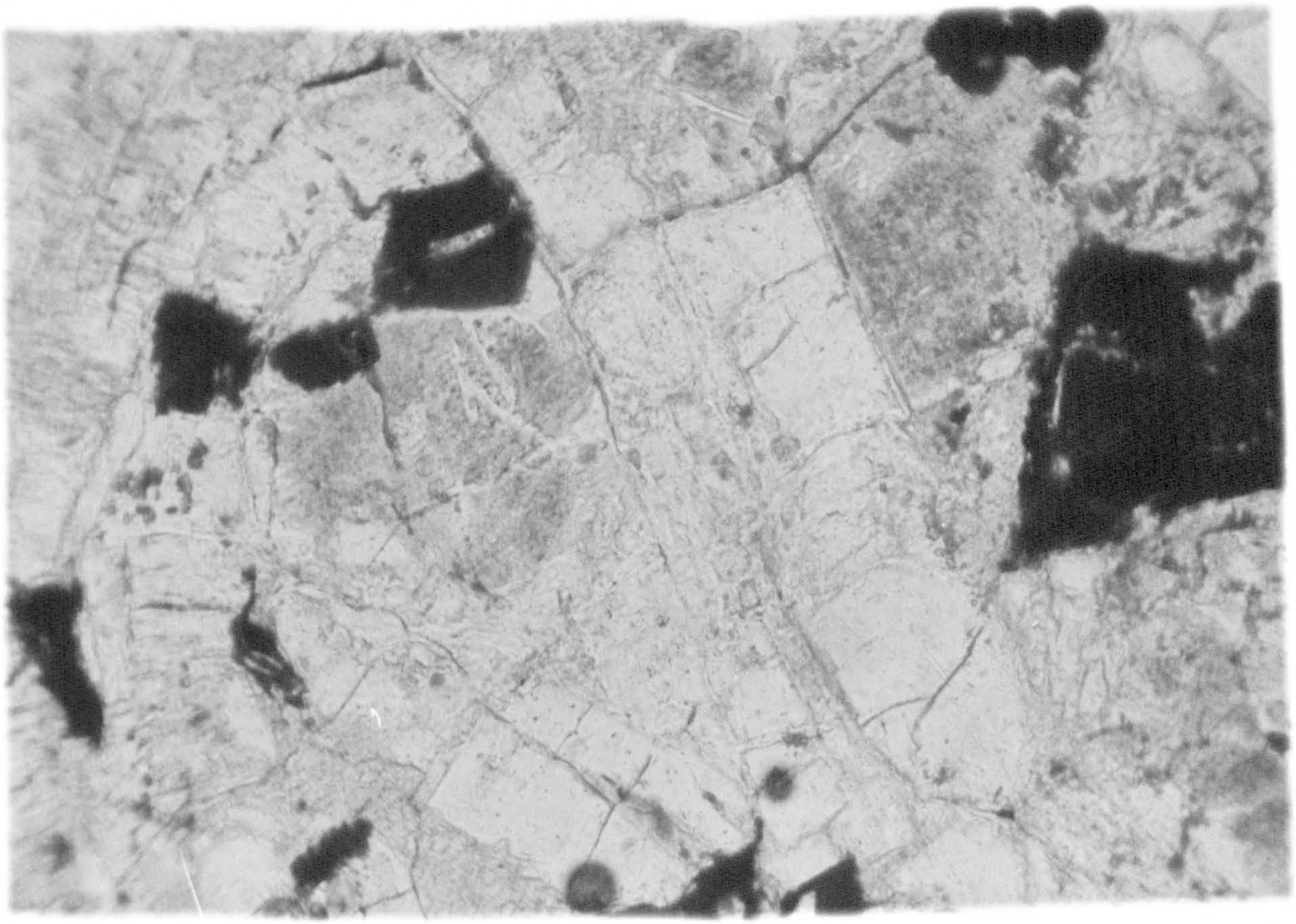
2.3.2.2. THE GARN FAWR - GARN FECHAN INTRUSIVE SHEET

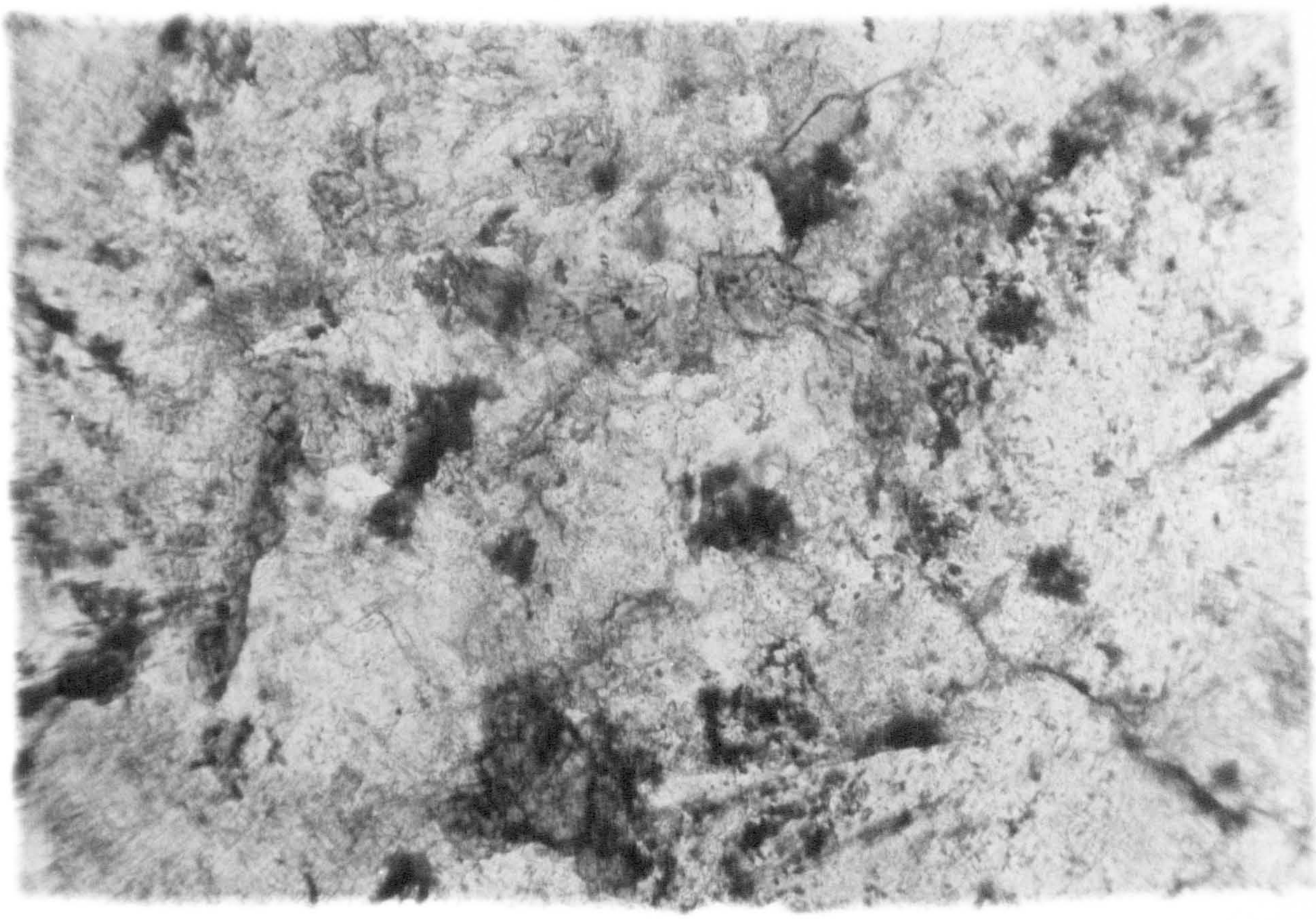
This east-west trending sheet forms the crags of Garn Fawr and Garn Fechan. On Garn Fechan, dolerite occurs on the north side of the crags, but its relationship with the rocks described here cannot be discerned due to the lack of exposure.

These rocks were first described by Cowper-Reed (1895) who identified the presence of 'tachylitic' rocks. He described two varieties of tachylite, one possessing long, chain-like crystallites set within a finely crystalline groundmass and the second containing only a fine-grained groundmass, devoid of the crystallites. Both of these varieties were recognized during the present study.

FIG. 84. Plagioclase feldspar, ore and calcite within a thin intrusive sheet at Porth Maen Melyn (GR 88893922). PPL. x125.

FIG. 85. Biotite crystals in fine-grained, feldspar rich groundmass. Microdiorite from Garn Fawr. x200.





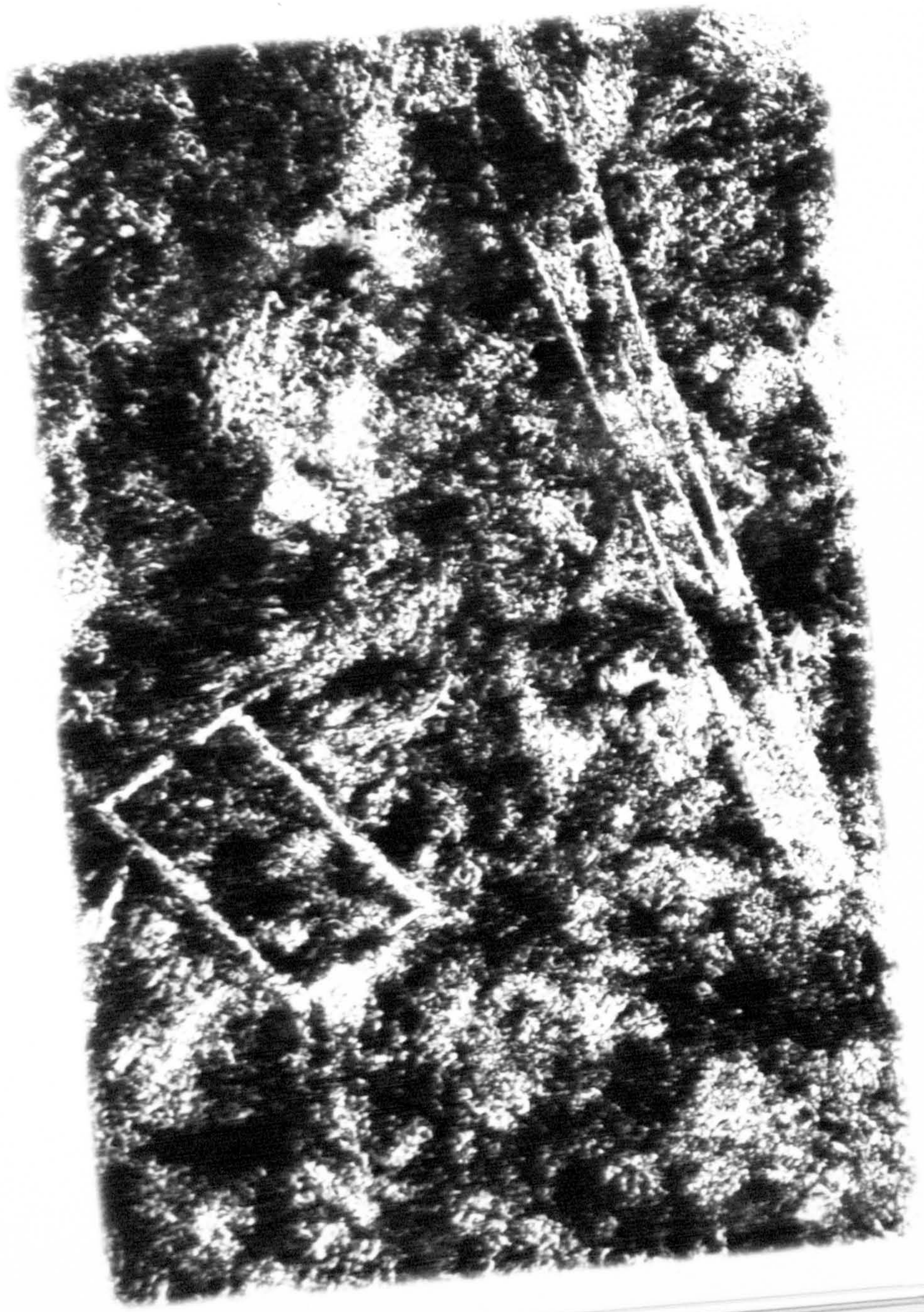
The groundmass is composed predominantly of plagioclase feldspar and some quartz with rare biotite, elongate, chain-like clinopyroxene and secondary chlorite and sphene (Figs. 85 and 88). Occasional tabular plagioclase microphenocrysts, up to 3mm in length, occur, as for example in sample RD260, and extinction angle measurements show these to be of an albitic composition. The groundmass feldspars show a considerable variation in size and form. Elongate and tabular crystals, up to 2mm in length, are present as euhedral crystals with a length to breadth ratio of up to 20 : 1. Dendritic forms (Fig. 87) are also common. More rarely, they are equant. Most of the crystals are hollow and show typical 'belt-buckle' structures (Fig. 86). Commonly, the tabular crystals of the groundmass and the microphenocrysts pass laterally into other crystal forms. In sample RD260, for example, the tabular crystals of the groundmass are overgrown by a dendritic form with which they are in optical continuity. In sample RD256, however, the tabular crystals are encompassed by spherulitic plagioclase, once again in optical continuity. Accessory amounts of apatite and zircon are also present.

Due to the secondary alteration and variability in modal proportions of the phases present, it is difficult to give these rocks a petrographic name. It is felt, however, that all of the intrusions described in this section fall within the fields of tonalites or diorites (or micro-tonalites and micro-diorites), which are locally granophyric.

The crystal textures described are similar to those produced during experiments on lunar and terrestrial rocks by such workers as Lofgren, Donalds Usselman. It is possible to reproduce these textures during cooling experiments either by monotonic cooling or isothermal cooling. In the

FIG. 86. Skeletal, hollow plagioclase microphenocrysts within microtonalite. Garn Fawr. PPL. x200.

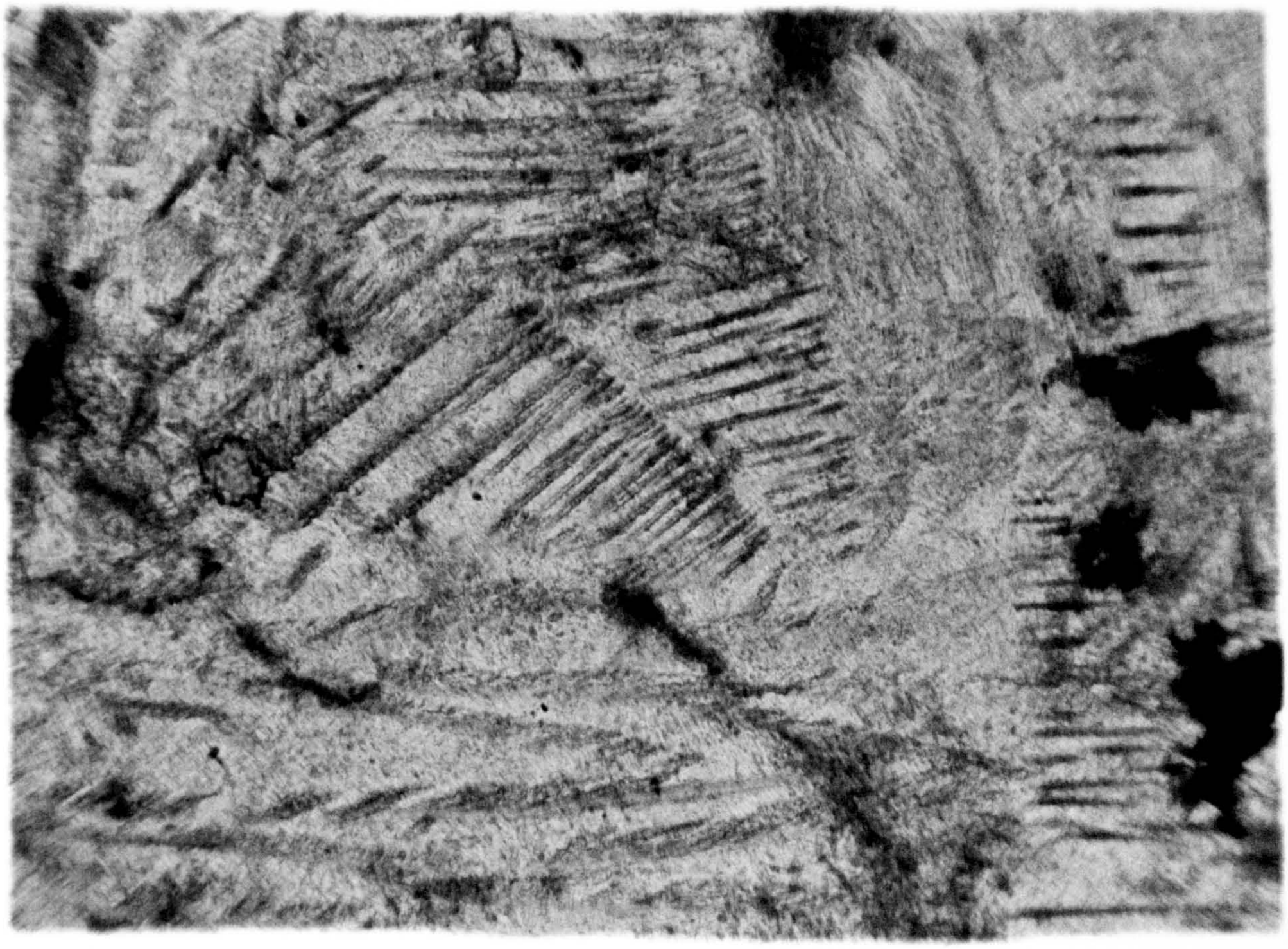
FIG. 87. Dendritic plagioclase feldspar. Locality as above. XP. x200.



FIGS. 88a and b. Elongate and dendritic clinopyroxene (now altered to chlorite). From micro-tonalite, Garn Fawr-Garn Fechan Intrusion. PPL.

a) x100.

b) x85.



former experiments, charges are cooled at a controlled rate to approximately solidus temperatures and then quenched, whilst in the latter experiments the charge is rapidly cooled (at up to rates of 2500°/hr.) to a crystallization isotherm, which is then maintained for a given time before final quenching. Thus, the textures present within the Garnfechan - Garn Fawr intrusion may have been produced either by a rapid cooling or by suffering a large amount of undercooling. The uniformity of the textures across such a thick sheet suggest that the magma could possibly have been intruded at a relatively low temperature, after which rapid nucleation occurred, producing the textures described above. Donaldson et al. (1975) reproduced chain-like olivines and pyroxenes at cooling rates of 100°c/hr. to 380°c/hr. and also at supercooled temperatures in the range 80°c to 150°c. Although these were obtained by melting lunar olivine basalt, the method of producing the textures within the Garn Fawr intrusion is no doubt related to one, or possibly both, of the above processes. Lofgren (1974, Plates 3c and 3d) illustrates textures identical with those described above. These were produced by suddenly induced large drops in temperature during cooling. It is therefore possible that rapid nucleation occurred due to a drop in temperature below the liquidus temperature, followed by a steady decline in temperature. The plagioclase microphenocrysts probably represent intratelluric crystals and therefore crystallized under different conditions from the main body of the rock.

The elongate, needle-like clinopyroxene crystals were first described by Cowper-Reed (1895), who compared them with crystallites from Arran pitchstones and from the Weiselberg pitchstone, figured by Rosenbusch (1885, 1887). In some cases, the crystals have been replaced

by chlorite but the overall structure is still present. The length to breadth ratio of these crystals is of the order of 50 : 1 and they are clearly dendritic, with secondary or tertiary branches (Fig. 88). Elongate, chain-like clinopyroxenes and dendritic pyroxenes have also been reproduced experimentally and result from the rapid cooling or supercooling of magmatic liquids.

Biotite, identified in sample RD254, is seen to be in reaction relationship with chlorite. Although it is not clear exactly which way the reaction is proceeding, it is thought likely that the biotite is a relict igneous phase showing partial replacement by chlorite.

2.3.2.3. PENBWCHDY INTRUSIVE SHEET

The headland of Penbwchdy is composed of a large intrusive sheet which invades arenaceous sediments of Arenig age. The rock is holocrystalline, with a coarse, equigranular texture, locally granophyric. Although not described in any of the early literature (e.g. Cowper-Reed, 1895; Elsden, 1905 etc.), Roach (1969) differentiated this body from the surrounding basic intrusions. This sheet, along with the Garn Fawr - Garn Fechan Intrusion, was termed 'granophyric' by Roach (op. cit.).

The rock is slightly porphyritic, with plagioclase phenocrysts up to 2mm in length set within in a groundmass composed of plagioclase feldspar, quartz and quartz/feldspar intergrowths. The plagioclase of the phenocrysts is albitic, although this may not reflect the primary composition. Chlorite is abundant throughout, as is another secondary phase which has moderate birefringence and weak green to colourless pleochroism (possibly stilpnomelane). These phases occasionally are seen to be pseudomorphing a primary mafic phase (probably clinopyroxene).

Minor sphene and epidote are also present, along with haematite which replaces a primary ore phase, probably magnetite. Apatite and zircon occur in accessory amounts.

2.3.2.4. INTRUSIVE SHEET OF CARN LLWYD (GR 920408)

A thin, light-coloured, discordant, intrusive sheet cuts the basic lavas on the headland of Carn Llwyd, close to the summit of the small knoll on the headland. The rock is composed of equant, strongly zoned, plagioclase crystals, set within a dusty groundmass of spherulitic and dendritic plagioclase and minor quartz. Sphene is scattered throughout the rock but pseudomorphs after an original mafic phase are noticeably absent. Petrographically, the rock appears to be similar to the intermediate rocks described above and hence is included here. However, if it is of similar composition it testifies to the presence of magmas of intermediate composition during or after the eruption of thick basic lava pile of the Strumble Head Volcanic Formation.

2.3.3. RELATIONSHIPS BETWEEN THE LAVAS AND INTRUSIVE SHEETS OF INTERMEDIATE COMPOSITION

The lavas and intrusions described above all have petrographic similarities, although grain sizes and other textural features are slightly variable. Their major feature is the high modal proportion of plagioclase feldspar and a corresponding lack of mafic constituents.

In an attempt to determine whether the various sheets and flows were a part of the same magmatic suite, a number of chemical analyses were determined and combined with unpublished analyses provided by

Dr. R. A. Roach. As previously stated, no attempt was made to analyse the composition of the thin, intrusive sheet at Porth Maen Melyn in view of its highly carbonated nature. However, analyses of the Porth Maen Melyn lava flow, the Garn Fawr - Garn Fechan sheet and the Penbwchdy sheet were determined and these are to be found in Appendix 1. Examination of these analyses reveals certain similarities. The slight variations within the major element results may be analytical, due to the fact that the analyses were made in two laboratories. However, the trace element results reported were all determined by the author by x-ray fluorescence techniques at the University of Keele. A close similarity in the concentrations of some of the so-called 'immobile elements' within the lavas and intrusive rocks may be seen (for example, the Y and Zr contents). It is thus suggested that the various intrusive sheets belong to the same magmatic suite as the extrusive flow of Porth Maen Melyn. This, once again, emphasises the contemporaneous nature of the intrusive and extrusive activity in this area during Early Ordovician times.

2.4. ACID IGNEOUS ROCKS

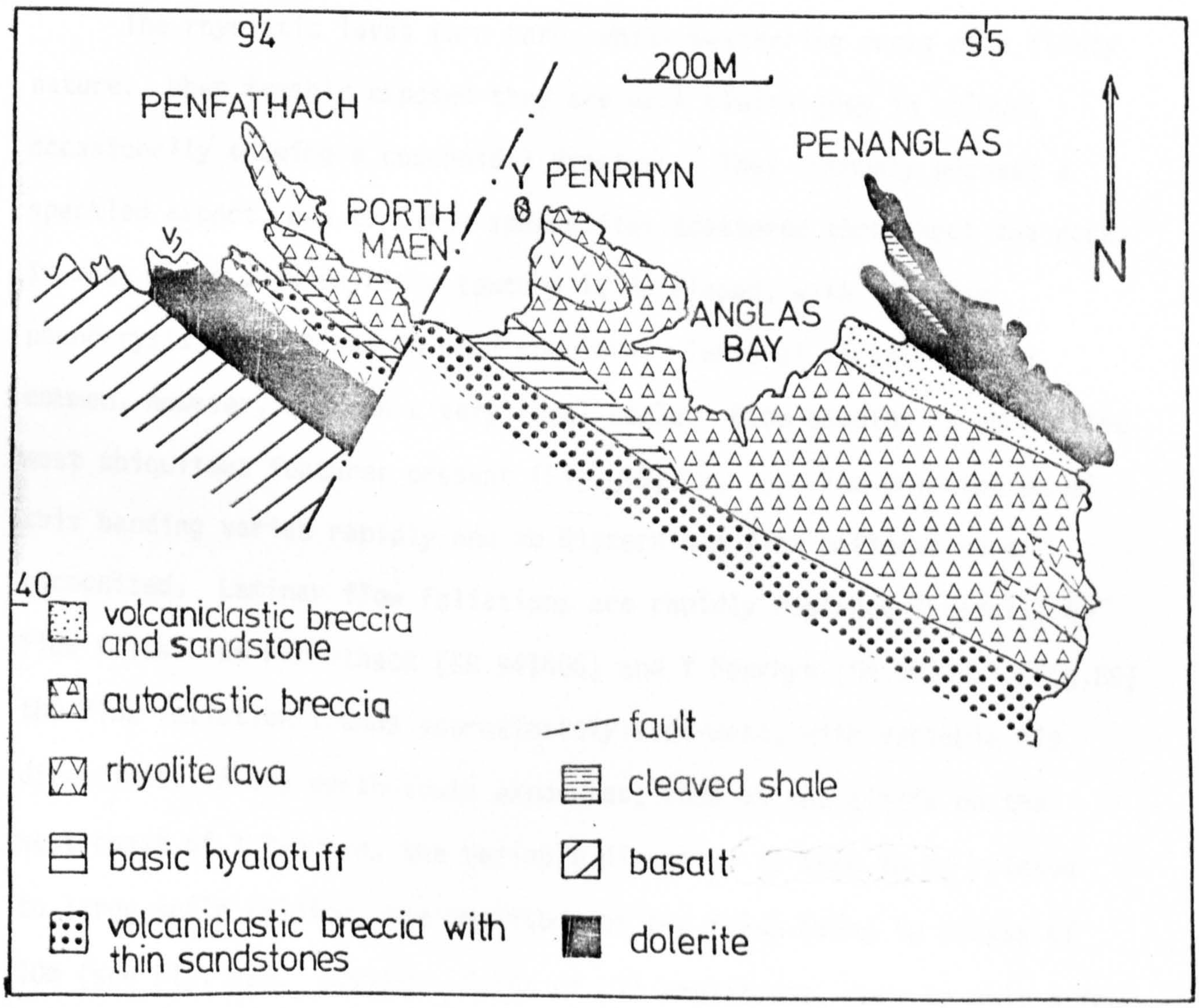
Acid igneous rocks form a significant volume of the Fishguard Volcanic Group in the Strumble Head - Fishguard area. When traced eastwards, into the Newport - Prescelly Hills area, it appears that their importance may be even greater (Reed, 1895; Davies, 1936; Thomas and Thomas, 1956). This may principally be due to an increase in the amount of acidic volcaniclastic material in that region (Evans, 1945; Bevins and Roach, in press). However, this region was not surveyed in detail during the present study.

The acidic rocks of the Strumble Head - Newport area were initially described by Reed (1895), who identified both lava flows and associated volcaniclastic rocks. Cox (1930) briefly described the acidic volcanic rocks of the Strumble Head region whilst they were described some years later, in greater detail, by Thomas and Thomas (1956). In contrast with the basic and intermediate magmas, high-level intrusive sheets of acidic composition were not recognized in this area and the magma appears to have been, for the most part, extruded on to the sea-floor to produce thick lava flows and domes. This situation offers contrast to that of North Wales, where thick, acidic, intrusive sheets have been described by a number of workers, for example, Davies (1958), Bromley (1965) and Rast (1969).

Chemically, the acidic lava flows can be clearly distinguished from the intermediate lava flow at Porth Maen Melyn (see Appendix 1), whilst they can also be readily distinguished in the field by a number of morphological differences, which are described in detail below.

Rhyolitic lavas are found associated with autoclastic rocks of a number of localities on the Pen Caer peninsula. The most extensive outcrops occur within the Goodwick Volcanic Formation, in the vicinity of Goodwick Harbour Village (GR 948390), particularly along the road section from Goodwick, and the Warren area (GR 950401), at the eastern end of the Peninsula. Other, less extensive flows are found within the Porth Maen Melyn Volcanic Formation, in the neighbourhood of Caer-Lem Farm (GR 903395), Carngelli (GR 923379) and also at the base of the succession at Porth Maen Melyn (Fig.64). Unfortunately the lack of inland exposure in the Fishguard region commonly negates the interpretation and possible correlation of many of these lava sequences.

FIG. 89. Geological sketch map of the area north of Goodwick.


9'4
9'5
200 M
PENFATHACH
PENANGLAS
Y PENRHYN
PORTH MAEN
ANGLAS BAY
N
40
volcaniclastic breccia and sandstone
autoclastic breccia
rhyolite lava
basic hyalotuff
volcaniclastic breccia with thin sandstones
fault
cleaved shale
basalt
dolerite

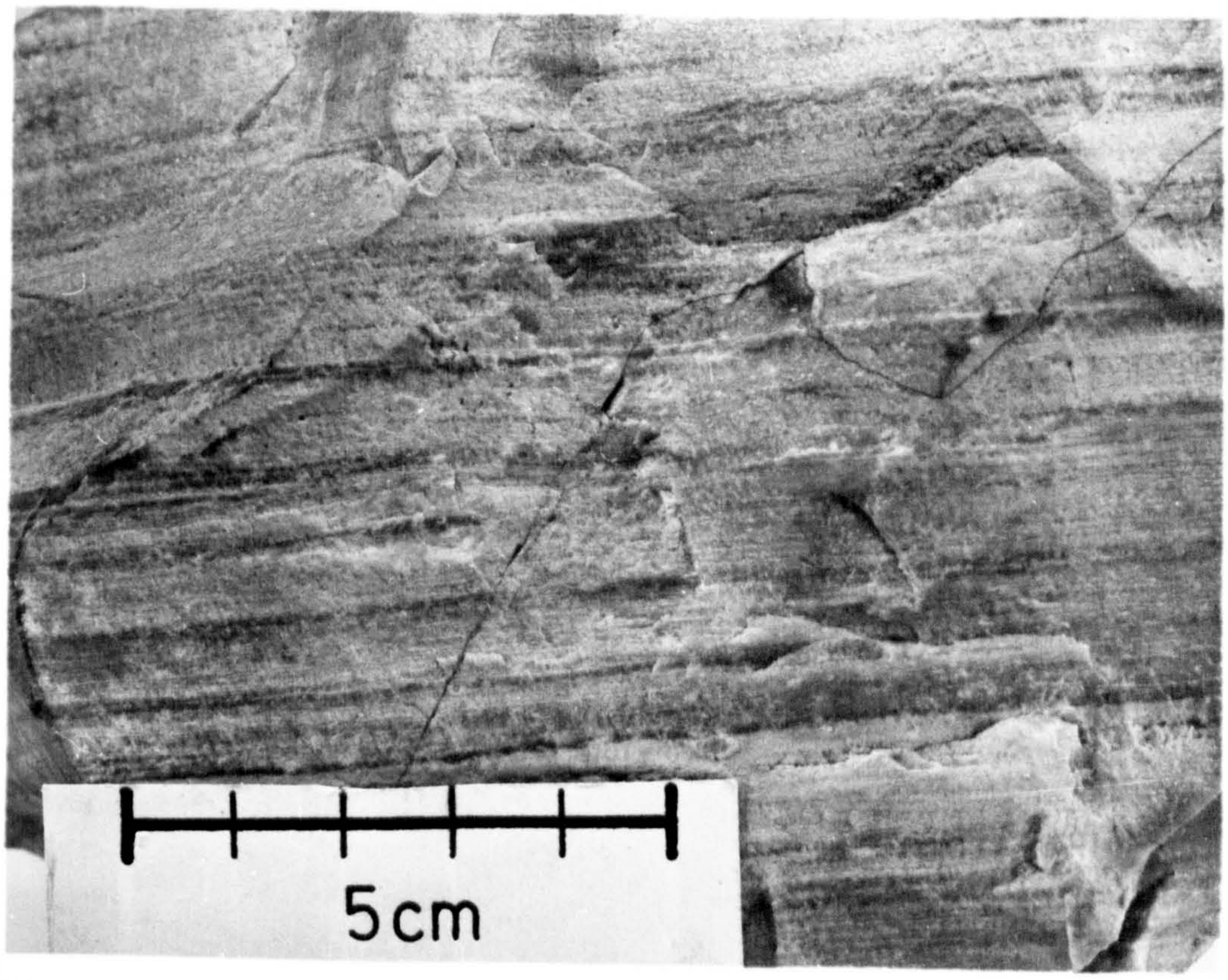
Consequently exposures in coastal regions are most useful and the exposures on the Warren, Y Penrhyn and Penfathach (Fig. 89) are the most illustrative in interpreting the nature of this episode of acidic volcanicity.

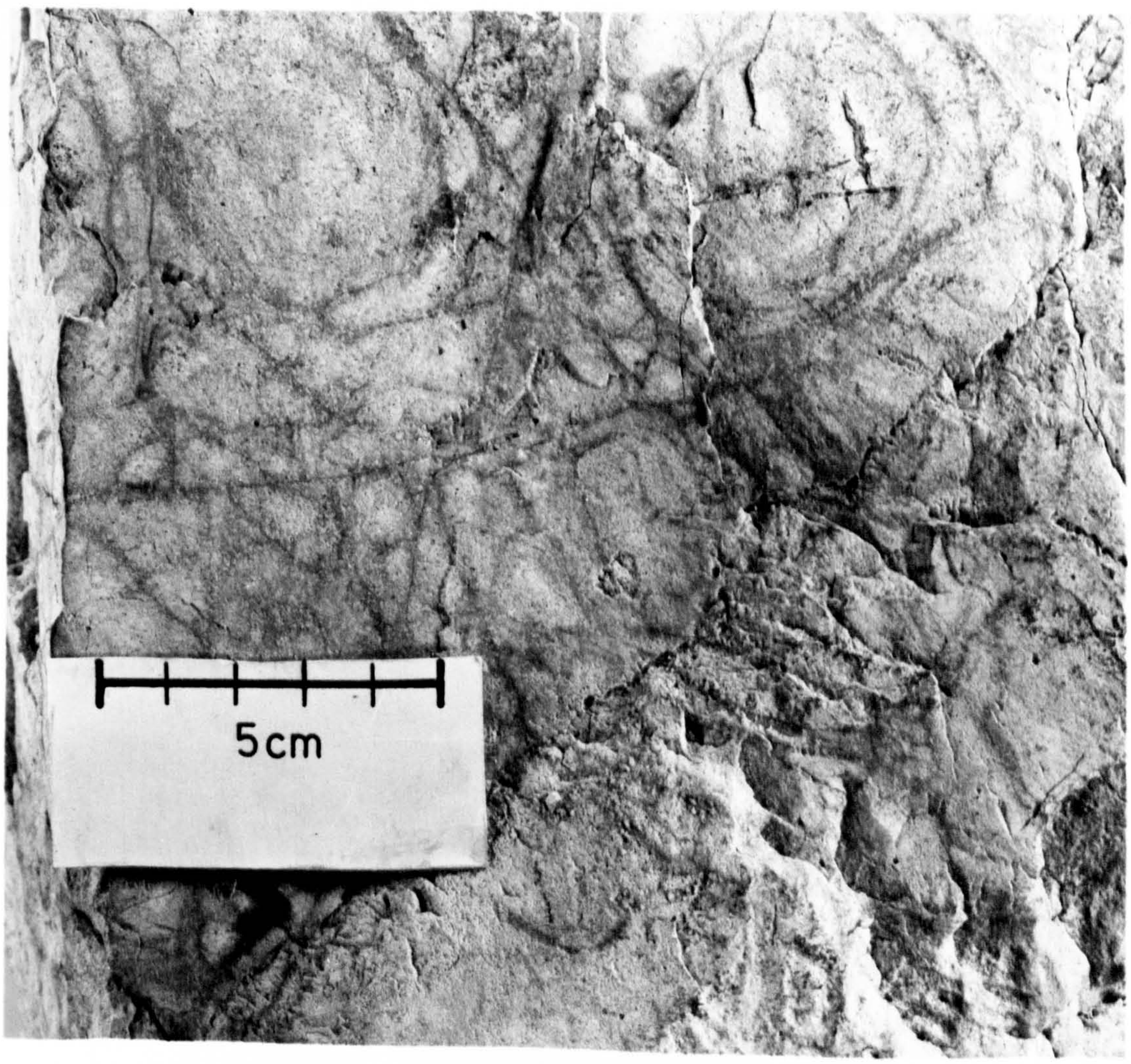
2.4.1. FIELD CHARACTERISTICS OF THE RHYOLITIC LAVAS

The rhyolitic lavas form hard, white-weathering rocks of a flinty nature. When freshly exposed they are dark bluish-grey in colour, occasionally showing a conchoidal fracture. They commonly possess a speckled aspect, due to large spherulites scattered throughout the rock. In most flows a porphyritic texture is developed, with feldspar phenocrysts discernible in hand specimen. Textural variations are common, however, even on a very local scale. Flow banding is one of the most ubiquitous features present (Fig. 90). The orientation of this banding varies rapidly and no discernible flow patterns were recognized. Laminar flow foliations are rapidly replaced laterally by flow folds. On Penfathach (GR 941406) and Y Penrhyn (GR 944405) (Fig.89) the flow foliation trends approximately east-west, with variable dip directions. Along north-south exposures, such as the cliffs on the west coast of Y Penrhyn, the variable direction is seen to be related to large scale folding, the amplitude of the folds being in excess of 10m (see Fig. 92). However, folds of all amplitudes, down to only a few centimetres, are superimposed upon these larger folds (Figs. 93 and 94). Large blocks, up to 6cm in diameter and totally devoid of any igneous foliation, are occasionally observed in the flow banded lava and are considered to represent blocks of lava which had solidified at an earlier stage, suffered brecciation and subsequently been incorporated into the flow.

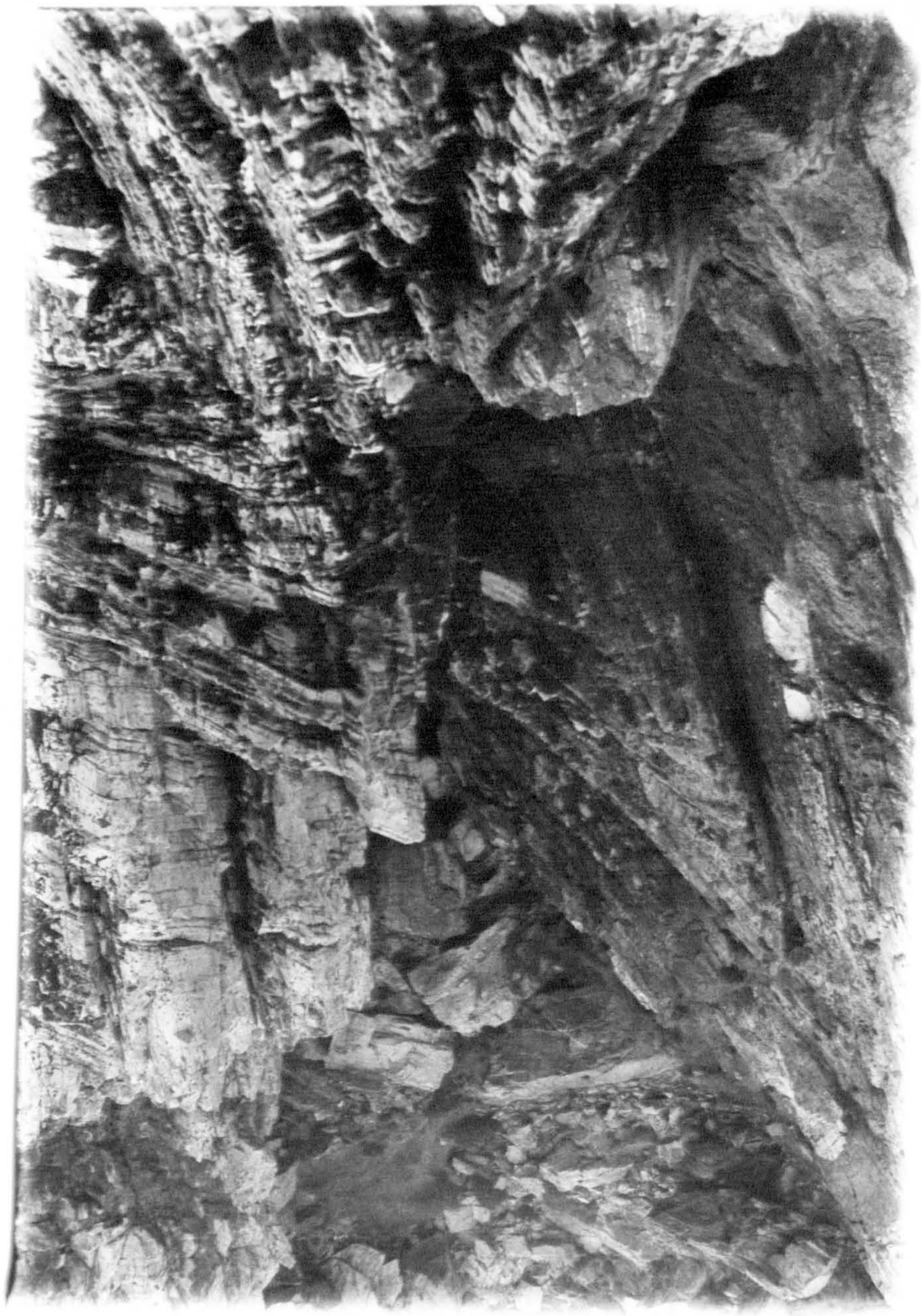
FIG. 90. Flow banding in rhyolite from Penfathach.

FIG. 91. Perlitic texture in rhyolite from Penfathach.

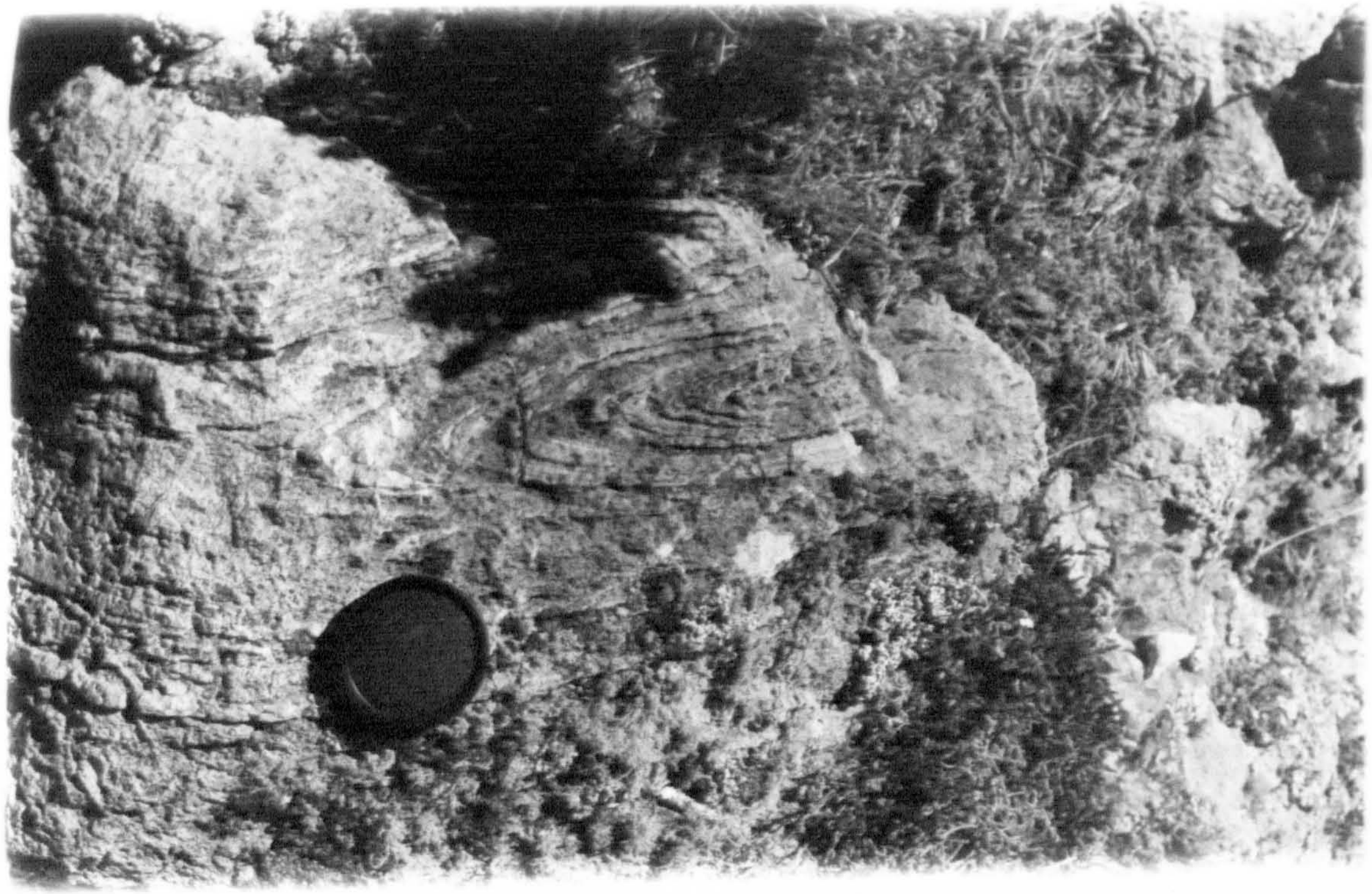

5cm


5cm

FIGS. 92a and b. Large scale flow folding in rhyolitic lava on the west coast of Y Penrhyn.



FIGS. 93a and b. Small scale flow folding in rhyolite from Y Penrhyn.



FIGS. 94a and b. Small scale flow folding in rhyolitic lava from Maen Jaspis area (GR 93864048).

The flow foliation is produced by alternating light and dark facies of the silicic rock. Such banding occurs in the rhyolitic lava flows of Lipari (Roach, pers. comm.), where it appears to be controlled by varying degrees of vesiculation. However, in view of the absence of recognizable vesicles within the rhyolites of the Fishguard area, it is considered that this is unlikely to be responsible for the banding in this case. Thomas and Thomas (1956) attributed the banding in the Fishguard rhyolites to variations in the original water content of the respective bands, which subsequently resulted in a variation of textures during recrystallization. Hughes and Malpas (1971) suggested that flow banding on such a scale may be produced by differential recrystallization. In certain samples of the rhyolites from the Fishguard Volcanic Group, the banding is accentuated by the modal proportion of clay within the layers.

A perlitic texture is seen at certain horizons within the flows and is particularly well developed on Penfathach (Fig. 91). The perlites reach 10cm in diameter and produce a nodular surface upon weathering (the nodular rhyolites of Thomas and Thomas, op. cit.). It is evident that many flows were initially glassy and would originally have been obsidian flows. In other parts, the flows were hemicrystalline, as shown by the presence of plagioclase feldspar phenocrysts. All the glass has subsequently suffered recrystallization to quartz/feldspar intergrowths.

Certain areas of rhyolitic rocks within the Fishguard area are devoid of flow banding or a perlitic texture and consequently are flinty, structureless rocks, whose origin is difficult to ascertain directly.

However, these areas may be traced laterally into rocks which show the textures and structures described above and thus it is possible to suggest that these rocks also represent lava flows. In other cases, where no such lateral extrapolation is possible, the origin of the rocks remains uncertain.

Generally, these rhyolitic rocks were resistant to deformation and show little evidence of Caledonian deformation. However, deformation was inhomogeneous in North Pembrokeshire and within the belts of competent rocks, the deformation was frequently concentrated along discrete zones. Such a zone of high strain may be identified on Penfathach. Here the rock appears to possess a very strong planar fabric and is green in colour. The presence of this foliation has seriously weakened the rocks resistance to erosion and consequently, due to the influence of marine erosion, is weathered out, to produce distinct gulleys.

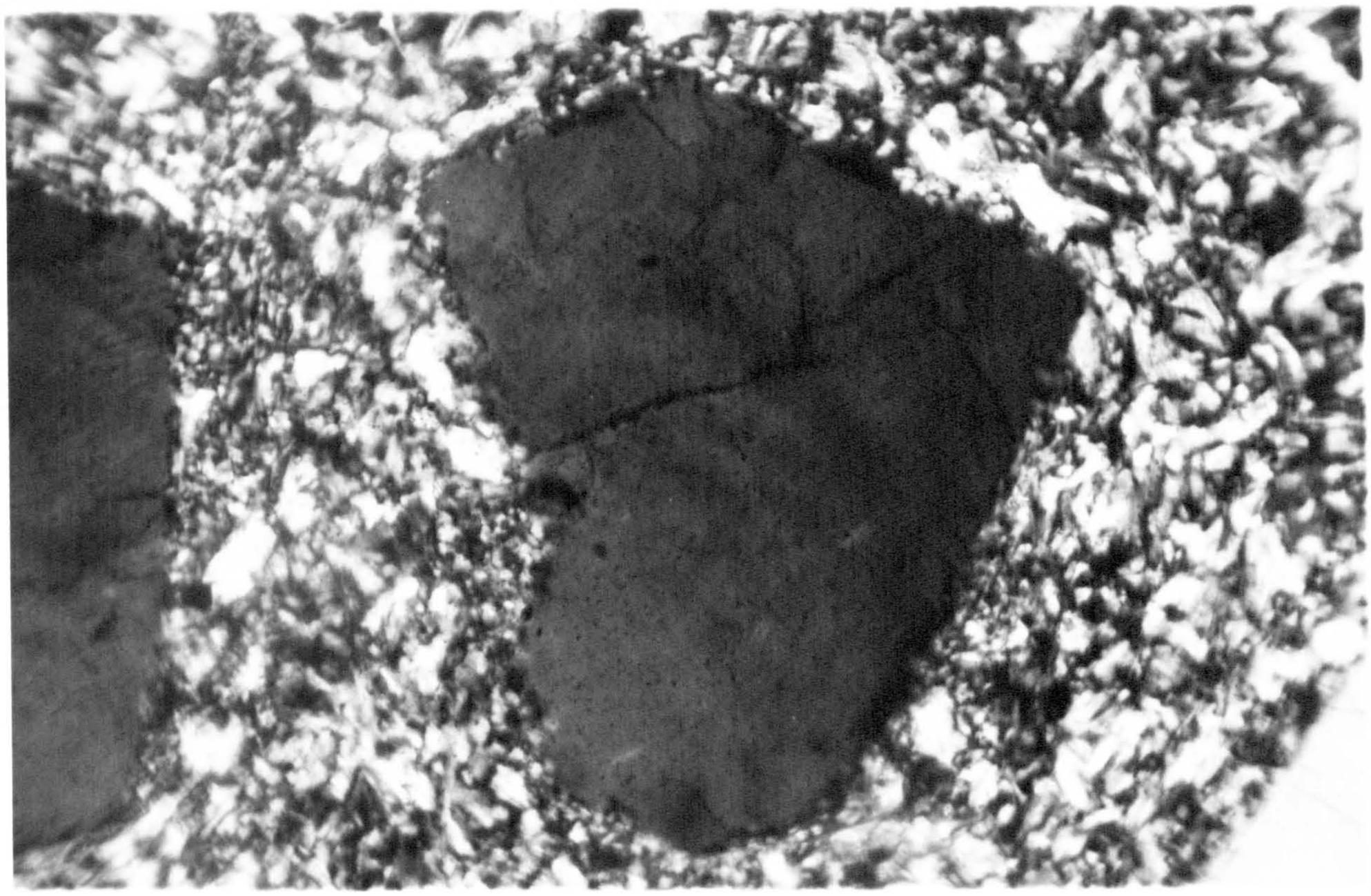
An integral part of the acidic volcanic pile are breccias composed of angular rhyolitic fragments, set within a fine-grained crystalline groundmass. All cases are identified from areas where occasional blocks of rhyolite occur within lava, to areaswhere breccias are predominant, but contain thin partings of lava (for example in the neighbourhood of Crincoed Point, GR 952403). However, flow banded lava is generally completely surrounded by breccia. The interpretation of these breccias and their relationship to the lavas will be described more fully in section 3.4.

2.4.2. PETROGRAPHY OF THE ACID LAVAS

The lavas are generally porphyritic in character, plagioclase feldspar being the prominent phenocryst phase. Commonly, the feldspar is albite or oligoclase, although occasionally it is orthoclase. However, as outlined, below, it is thought likely that there has been considerable movement of Na and K during a period of hydration and associated alkali metasomatism. This accounts for the high contents of K_2O (9.00 in SA8) and Na_2O (9.39 in SA9) which are locally observed and also possibly resulted in the pseudomorphing of the primary phenocrystic phase. Hughes and Malpas (1971) described similar effects in acidic lavas of late Pre-Cambrian age from Newfoundland. In rocks with more typical contents of the alkalis from the Fishguard area, the phenocryst phase is albite or oligoclase and for this reason it is thought likely that this approximates to the original composition of the phenocrysts. In certain samples, such as SP47, a flow-banded lava from Y Penrhyn, quartz phenocrysts also occur. It commonly shows a faceted form, although embayments are also typically present. Figure 95 illustrates the above textures in a lava block from a breccia exposed to the southeast of Caer-lem Farm (GR 903395). When present, the feldspar phenocrysts are commonly in glomeroporphyritic clusters and in these cases the crystals may reach 1mm in length (Fig. 96). In other cases the feldspars are aligned parallel to the flow banding, producing a fluidal texture. A peculiar texture is produced by the intergrowth of quartz and feldspar (either plagioclase or alkali-feldspar), as illustrated in Figure 97. This texture was termed 'micropoikilitic' by Reed (1895). In these aggregates, quartz forms the host and encloses or partly encloses the feldspars. The significance of this texture is

FIG. 95. Quartz crystal in breccia from Caer-Lem Farm. Note a faceted form to the left and irregular, slightly embayed form to the right. XPL. x100.

FIG. 96. Glomeroporphyritic plagioclase feldspar in a rhyolitic lava from the Fishguard area. XP. x125.



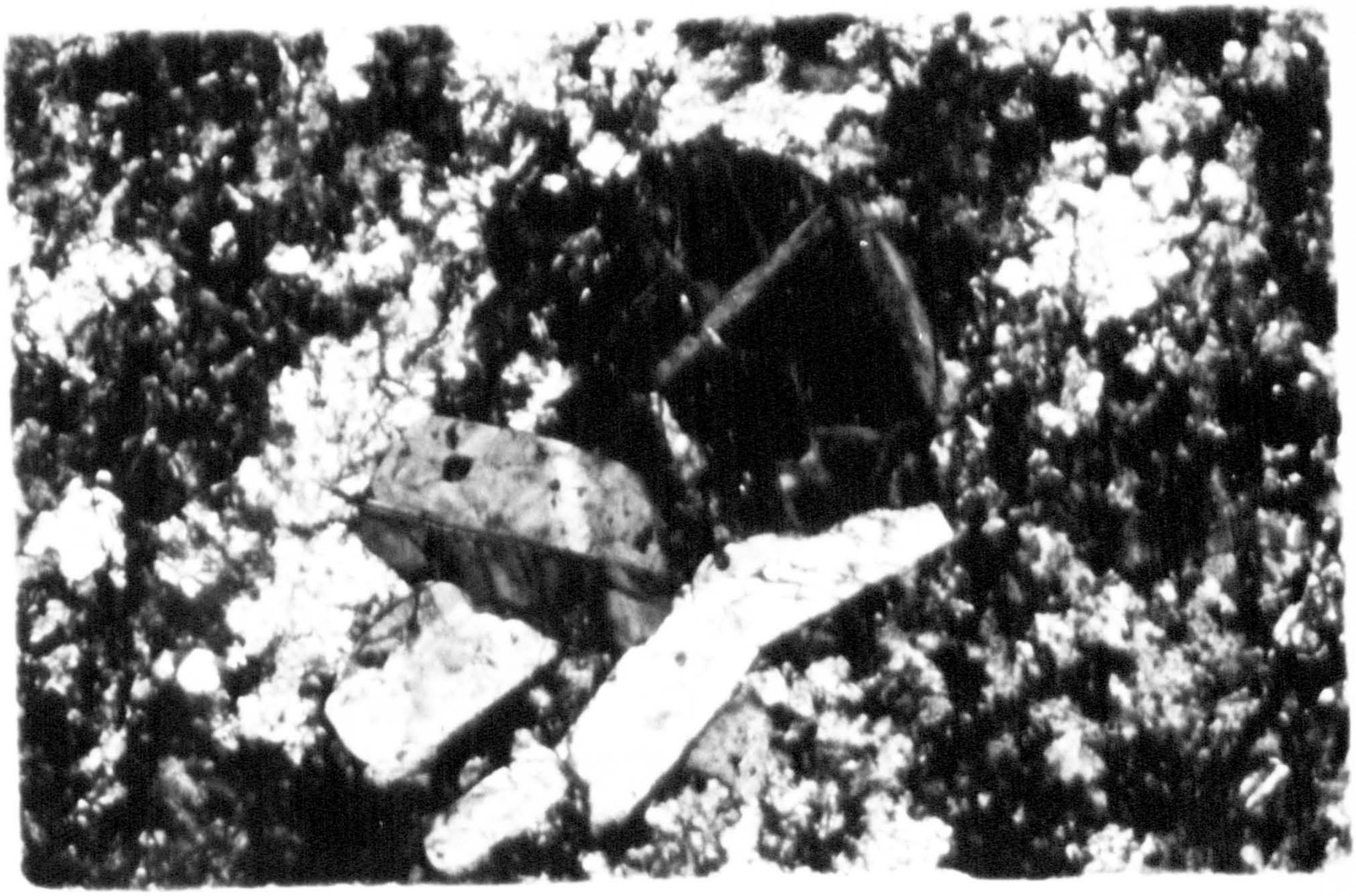
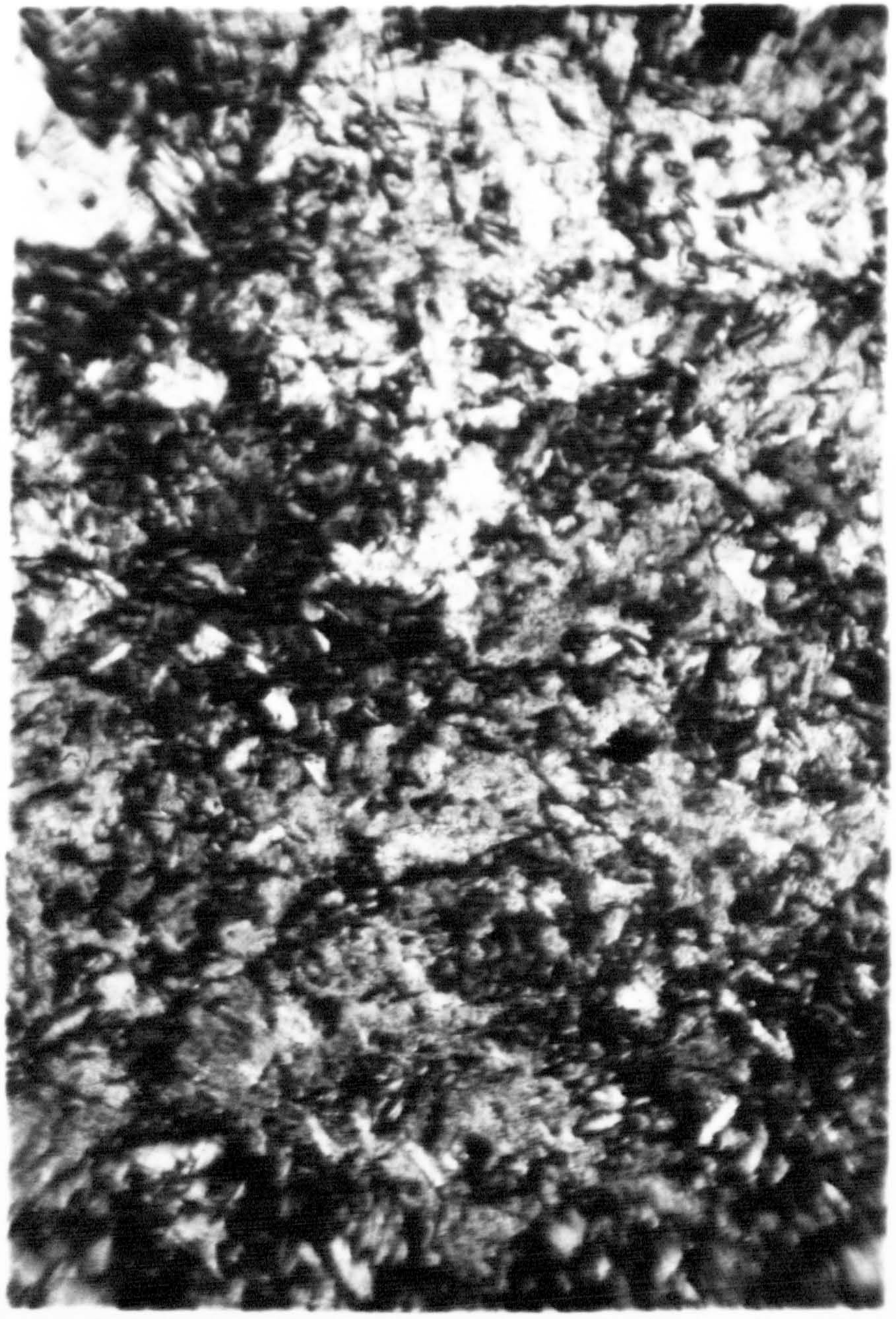
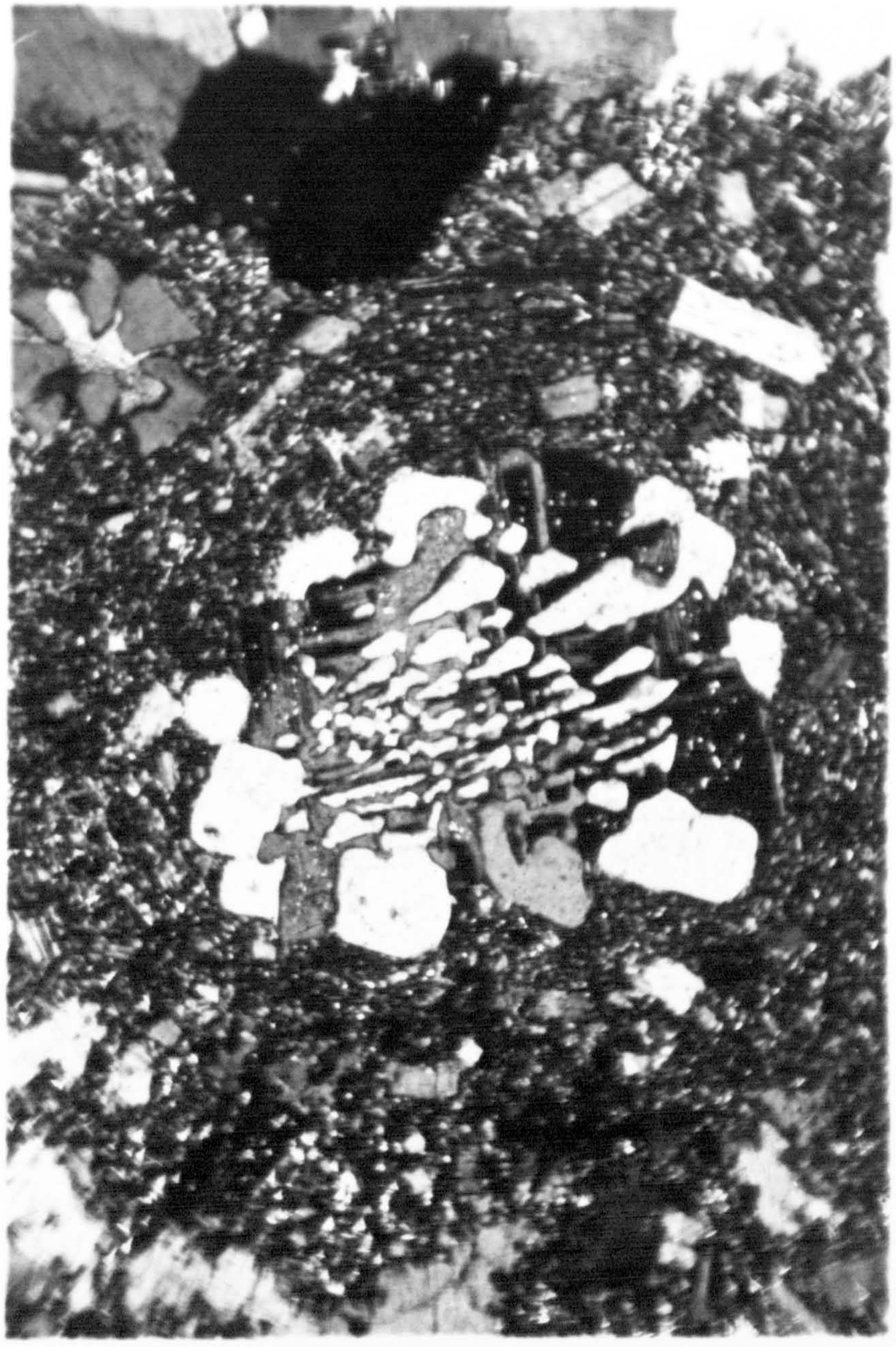


FIG. 97. Micropoikilitic intergrowth of quartz and feldspar. Rhyolite lava from Y Penrhyn. XP. x150.

FIG. 98. Snowflake texture in rhyolitic lava from Caer Lem Farm area. XP. x175.





described in section 3.3. Rarely, pseudomorphs after a ferromagnesian mineral may be identified, as for example in sample 271, a rhyolite from Carn Fran (GR 978377), to the east of Fishguard, where chlorite occurs, probably replacing biotite. Biotite, of probable primary origin, is present within sample SP47. Apatite occurs in a number of samples, such as sample 350, a flow banded rhyolite from Carn Ffoi (GR 048379), near Newport. Both apatite and zircon were reported by Thomas and Thomas (1956) to be present in accessory amounts, although the latter has not been identified with certainty during the present study. A tetragonal mineral with high relief was identified in a number of samples, but the birefringence was anomalously low for zircon. An identification of this phase, however, was not possible due to the very low concentration.

The phenocryst phases described above typically occur in a fine-grained groundmass of quartz and feldspar. An x-ray diffraction investigation of this groundmass suggests that the feldspar is predominantly an alkali feldspar. Some of the lavas show a complex intergrowth of quartz and alkali feldspar, resulting in optically continuous patches up to 0.2mm in diameter (Fig. 98). These textures are similar to those reported by Anderson (1969) and Torske (1975). In experiments performed by Lofgren (1970) acidic glasses were devitrified by hydrothermal alkali-rich fluids. This suggests that certain of the Fishguard rhyolites were probably glassy in character, a contention further supported by the presence of the well-developed perlitic textures described above. It is, however, to be expected that these flows were originally glassy in view of the fact that they were erupted in a submarine environment, where rapid cooling is likely to have occurred.

From theoretical considerations and field evidence, it is possible to suggest a timing for the hydration, devitrification and alteration of the lavas. Rhyolitic lava clasts in breccias from outcrops near Caer-lem Farm (e.g. sample 98) show a variety of devritrification textures, including a snowflake texture in certain clasts (Fig. 98). The fact that these different textures are found in neighbouring clasts within the same breccia suggests that they formed very early in the history of the lava. Different parts of flows may have suffered a different alteration history prior to brecciation. Subsequently the lava flow was brecciated and clasts from different parts of the flow or flows were admixed. Lofgren (1970) showed that devitrification is promoted by hydration, particularly if the solution is rich in Na or K. The reason considered to be responsible for this is that OH^- breaks the bridging bands in the Si-O-Si network and as a result the glass is expanded, producing a perlitic texture. Individual SiO_4 tetrahedra are produced as a result of the breaking of the bridging bonds, thus enabling network modifers (particularly Na and K) to pass through the more open system. Reorientation of the SiO_4 tetrahedra and incorporation of Na and K result in the crystallization of quartz and feldspar. At this stage, phenocryst phases may also be altered (Hughes and Malpas, 1971). The resultant composition of the feldspar appears to be dominated by the composition of the fluid passing through the rock (Lofgren, op. cit. p. 558). If the fluid is Na rich, the feldspar produced is a soda feldspar, whilst if the fluid is K rich, then a potash-rich feldspar crystallizes. It is probable, therefore, that the present alkali composition in the Fishguard rhyolites in no way resembles the original concentrations; a fact reported by Noble (1967) for most devitrified acid glasses.

It would appear, therefore, that hydration and devitrification occurred at an early stage in the history of the rhyolites of the Fishguard Volcanic Group. In some cases the circulating fluid was extremely rich in Na and/or K, producing an increase in either or both of those elements in the rhyolite and promoting recrystallization. This results in Na_2O and K_2O whole rock concentrations and phase assemblages (probably including phenocrysts also) different from those which occurred initially. These observations appear to agree with those of Torske (1975) in his suggestion that the snowflake textures in the Ordovician rhyolitic lavas of Stord, Western Norway, probably formed very shortly after extrusion of the lava.

Epidote and sericite were also produced during alteration of the lavas. Epidote, along with quartz, is seen in veins in sample SA11, whilst in other lavas, it forms stout, anhedral crystals. A peculiar form commonly assumed by epidote in these lavas is in spongy aggregates composed of small, rounded crystals, producing a 'pseudo-poikilitic' texture. Sericite is common in most rocks, typically present as an alteration product of phenocrystic plagioclase. In sample SP47, however, it occurs as small crystals, scattered throughout the groundmass of certain layers and accentuates the flow banding.

CHAPTER 3. DESCRIPTION OF THE VOLCANICLASTIC ROCKS OF THE FISHGUARD VOLCANIC GROUP

3.1. INTRODUCTION

This chapter describes the volcaniclastic rocks occurring within the Fishguard Volcanic Group. Volcanicastic is used in the sense of Fisher (1961) and as such includes all the rocks of pyroclastic and autoclastic origin, along with those deposits derived from subaqueous ashflows, composed of reworked volcanically-derived material.

Volcaniclastic rocks form an important, though volumetrically minor, component of the Fishguard Volcanic Group in the study area, although it appears that they probably become more significant in the ground to the east, between Fishguard and Newport (Reed, 1895; Davies, 1936; Bevins and Roach, in press). However, the volcaniclastic rocks are important in respect that they enable a more complete picture regarding the nature of the volcanism to be envisaged. These rocks will be described here on a compositional basis, that is on the nature of the magma from which they were directly, or indirectly, derived. This results in a reversal of relative volumes between basic and acidic rocks when compared with the lavas. Basic magma forms much of the Fishguard Volcanic Group, but, as already shown in the previous chapter, it was quietly erupted in relatively fluid flows or intruded as high-level sheets. As a result, only minor amounts of basic, volcaniclastic debris were produced. In contrast, the more viscous, acidic magmas produced a limited amount of rhyolitic lava with the production of comparatively large amounts of associated volcaniclastic material.

3.2. VOLCANICLASTIC ROCKS OF BASIC COMPOSITION

Volcaniclastic rocks of basic composition are comparatively rare when compared with the large amounts of basic lava erupted. Where present, they occur chiefly as hyaloclastites or isolated- and broken-pillow breccias. A number of occurrences of these rocks will be described below. Thomas and Thomas (1956) noted the presence of spilitic breccias and agglomerates, but a different terminology to that of Thomas and Thomas will be used here.

3.2.1. HYALOCLASTITES

Hyaloclastites, that is rocks formed of broken, glassy* fragments, are found at a number of localities within both the Strumble Head Volcanic Formation and the Goodwick Volcanic Formation. They reach their maximum development in the latter formation, which is predominantly composed of acidic lavas and associated volcaniclastic rocks. Two principal types of hyaloclastite are identified, namely rocks composed of vesiculated, glassy fragments and those composed of non-vesiculated, glassy fragments. The two varieties recognized from the Fishguard Volcanic Group correspond with the hyalotuffs and hyaloclastites of Honnorez and Kirst (1975). These authors attempted to distinguish between the two rock types which, although both composed predominantly of glass fragments, possess different geneses. The term 'hyaloclastite' was first adopted by Rittmann (1958), to replace 'palagonitic tuff' in describing the accumulations resulting from the disintegration of glassy rinds of pillows. However, it was later realised that more than one kind of 'hyaloclastite' exists. Honnorez (1961) drew attention to accumulations of hyaloclastites in which no

* Although glass is not seen in the rocks of the Fishguard Volcanic Group, chlorite or quartz is interpreted as pseudormorphing glass in many rocks and these will be termed 'glassy'.

pillowed masses of lava were to be found. These are thought to be generated as a result of the granulation of glass, produced when the liquid lava is rapidly quenched when it comes into contact with cold sea-water. Such 'hyaloclastites' have been described by Nayudu (1962) and Carlisle (1963). A further type of hyaloclastite identified is produced as a result of the explosive interaction between basaltic magma and water, such as described by Tazieff (1968 and 1972), from the Afar region. Tazieff (1972) reviewed the mechanisms for hyaloclastite generation and concluded that the majority of hyaloclastites are produced as a result of the explosion of trapped, super-heated steam. This fractures the rock and so provides more hot surfaces for the process to continue, which does so until the rock has been thoroughly granulated. Volcaniclastic rocks of this nature have also been described from the shallow submarine eruptions of Capelhinos (1957-8) and Surtsey (1963-4). Honnorez and Kirst (1975) stress, however, that the term 'hyaloclastite' should be reserved for the vitric accumulations produced from pillow lavas, or as a result of the direct granulation of lava in contact with sea-water. Other vitroclastic rocks of the type described above, they suggest, should be termed 'hyalotuffs'. Although this classification is somewhat difficult to apply in the field, it has merits when basic, vitroclastic rocks are examined petrographically and consequently it will be used in this study. As can be seen below, both true hyaloclastites as well as hyalotuffs occur within the Fishguard Volcanic Group.

3.2.1.1. HYALOCLASTITES

Hyaloclastites, produced as a result of desquamation of the glassy selvedges of pillows (Rittmann, 1958 and 1960), are poorly developed

within the Fishguard Volcanic Group. However, hyaloclastites not associated with pillows, and therefore presumably produced due to the thermal shattering of the magma as it came into contact with the cold sea-water, are found at a number of localities. To the south of Porth Maen Melyn, a small faulted outcrop of the Strumble Head Volcanic Group contains basaltic pillowed lavas, as well as minor hyaloclastites. The glassy fragments are up to 1cm in diameter and have suffered alteration. Secondary mineral assemblages replacing the glass are variable, but include chlorite, chlorite-quartz, chlorite-quartz-epidote, chlorite-quartz-epidote-prehnite and chlorite-prehnite. Sphene is ubiquitous in these assemblages. These minerals are set in a fine-grained, recrystallized groundmass of chlorite, sphene, quartz and epidote. Thin, colloform zones surround the fragments and appear to be composed of nearly isotopic chlorite and sphene. Zoned rims around palagonitized glass fragments have been described from the ocean floor and Bonatti (1970) showed such zones to be composed of iron hydroxides. Consequently, iron concentrations in these zones are higher than in the original, unaltered glass. In the Porth Maen Melyn case the fragments appear to be largely non-vesicular and they may be described as angular and equant in shape. This is clearly illustrated in Figure 99, which shows a loose block of hyaloclastite from the cliff top to the north of Porth Maen Melyn. Another example of a basic hyaloclastite was identified to the east of Aber Gwaldus (GR 92454058) (see Fig.100) and occurs between the pillows of the flow. This interpillow breccia is a hyaloclastite in the true sense of Rittmann (1958), in that it represents an accumulation of glassy fragments which spalled off from the developing pillows. Once again, angular, glassy fragments are enclosed within a

FIG. 99. Loose block of basic hyaloclastite. Note the angular outline of the glass (now chlorite) fragments. North of Porth Maen Melyn.

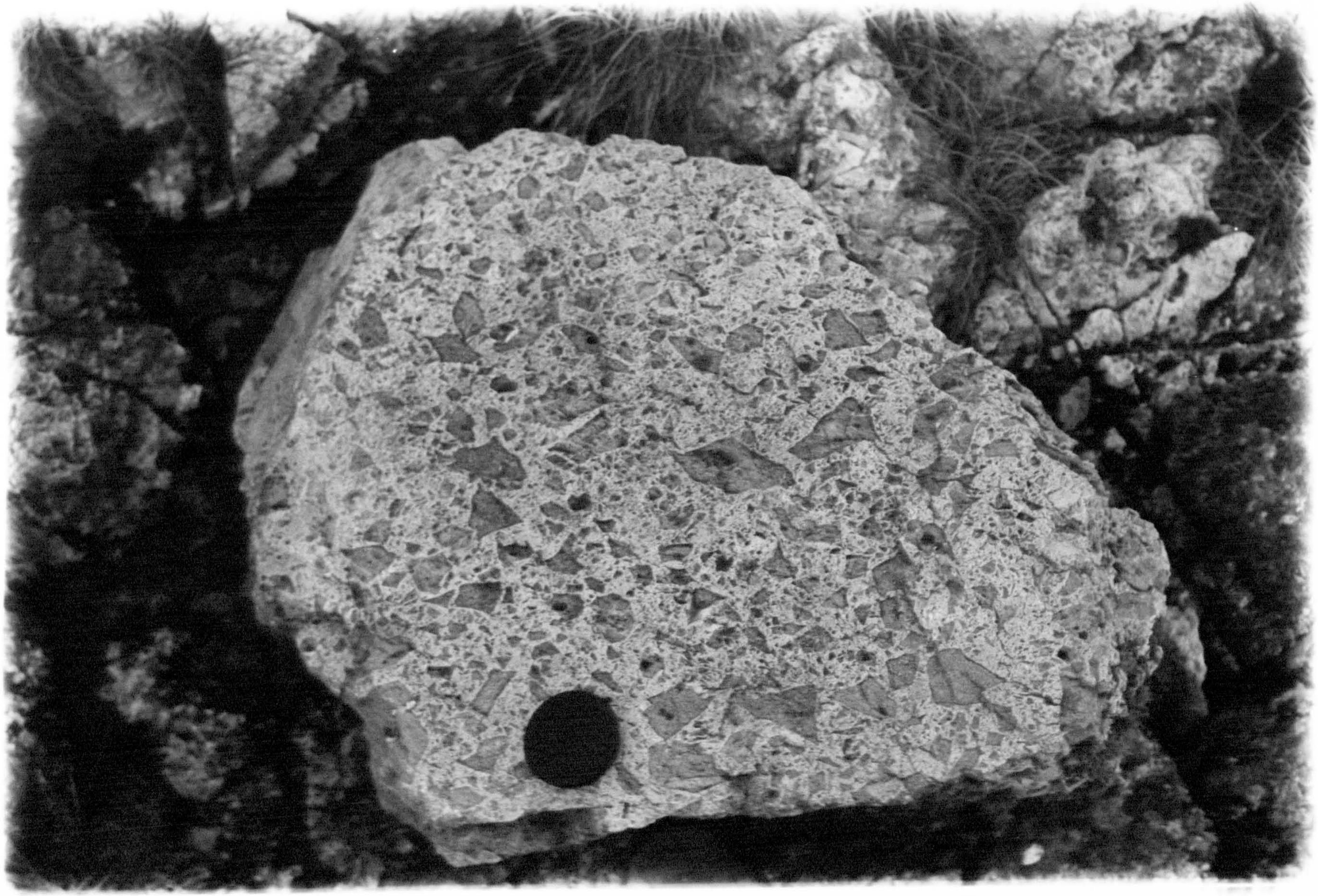
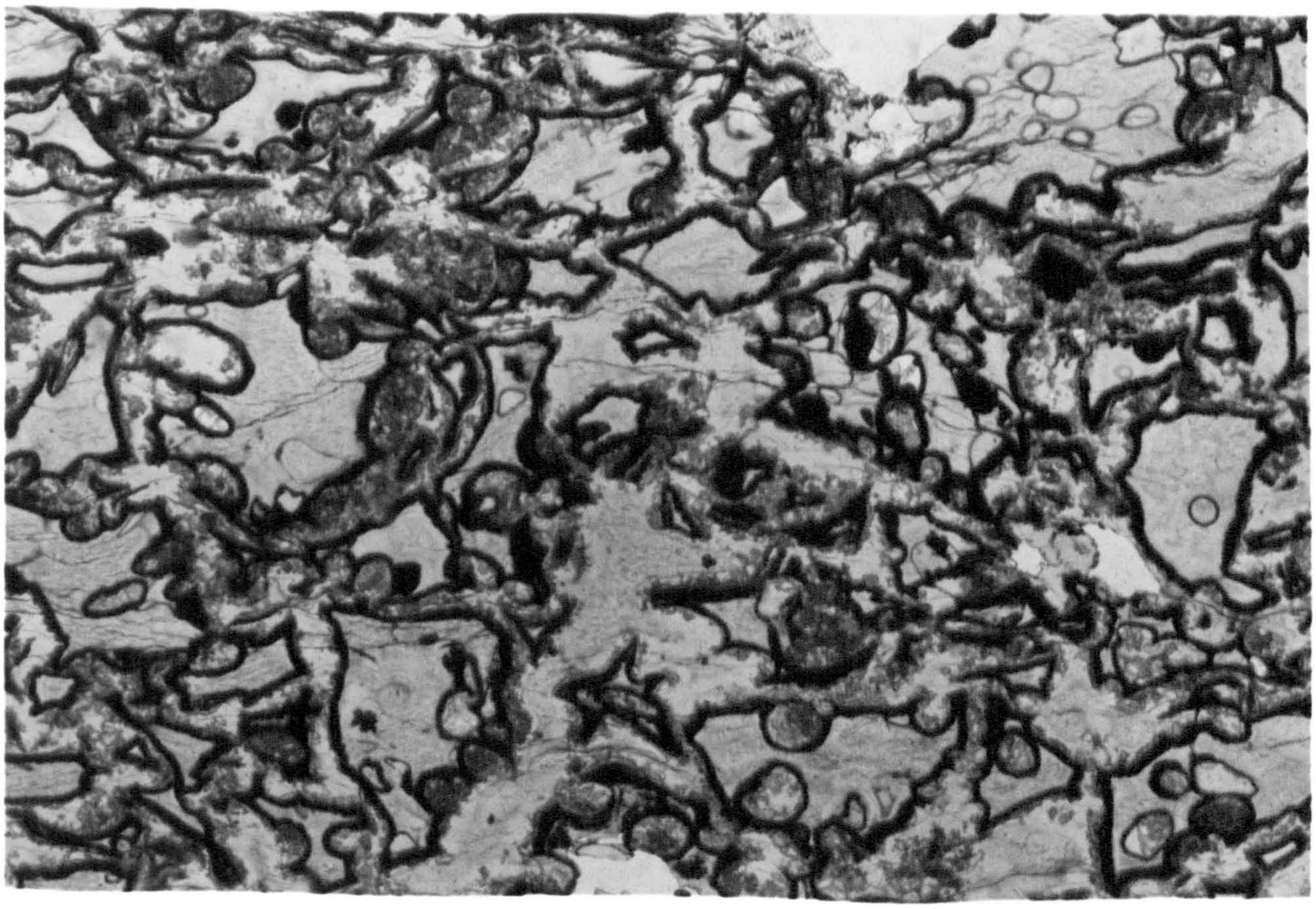


FIG. 100. Glassy fragments with a perlitic texture in hyaloclastite from Gwaldus (GR 92454058). PPL. x18.

FIG. 101. Vesiculated basic glass in hyalotuff from Trwyn Llwyd (GR 909410). PPL. x12.5.



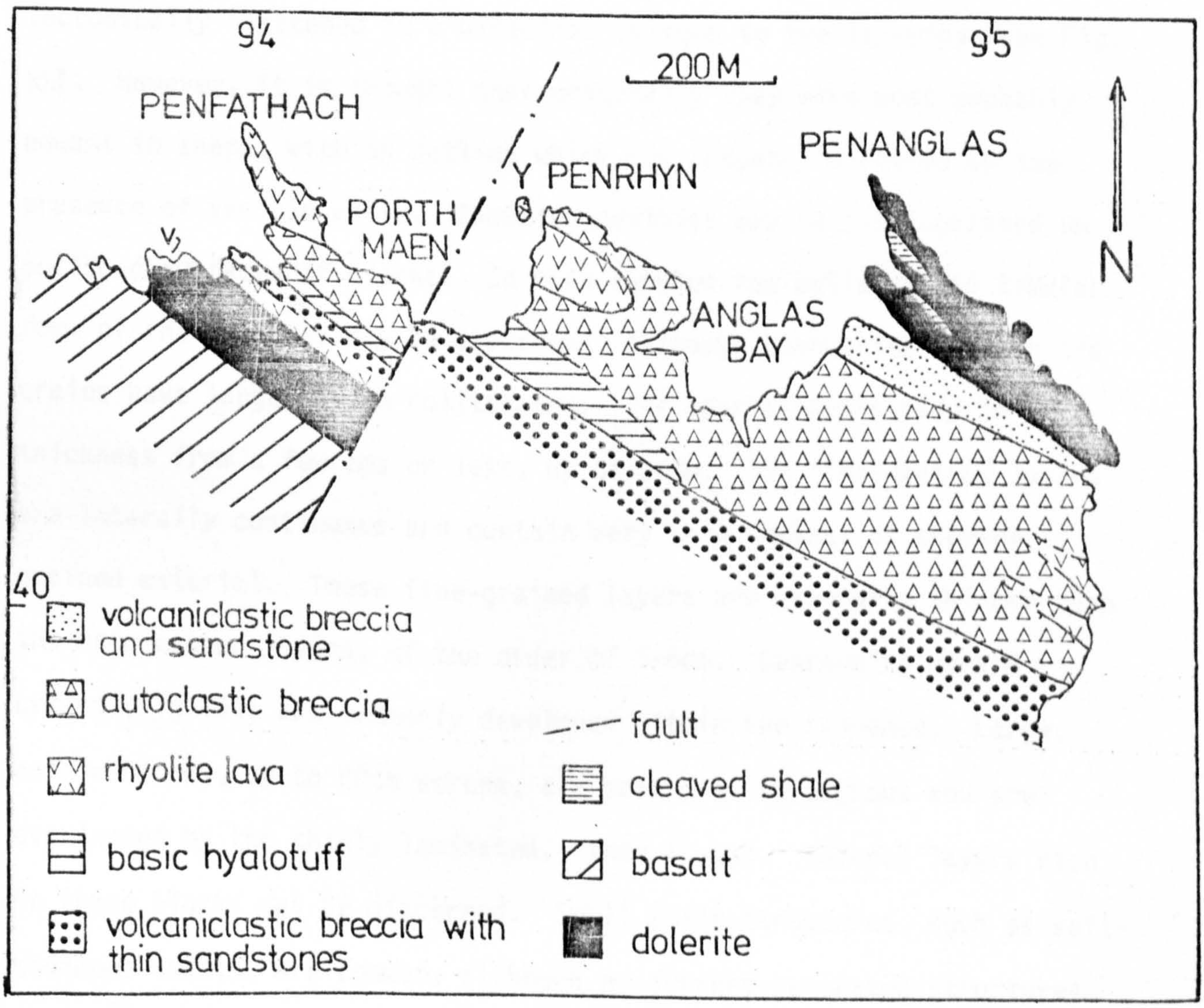
fine-grained, recrystallized groundmass. A strong perlitic texture testifies to the former glassy nature of these fragments (Fig. 100) with the perlites emphasized by the presence of abundant, small sphene granules. In the cliff section at Lower Fishguard Harbour, a thinned sequence of the Strumble Head Volcanic Formation contains a horizon of basic volcaniclastic rocks, of which some are hyaloclastites and others hyalotuffs. In all of the examples described above, the fragments are essentially non-vesicular and the outlines of the glassy fragments are angular. These shapes result from the granulation of the rapidly chilled magma when it came into contact with cold sea-water.

3.2.1.2. HYALOTUFFS (IN THE SENSE OF HONNOREZ AND KIRST, 1975)

Hyalotuffs are scarcely developed within the Strumble Head Volcanic Formation. Highly vesiculated glass shards and fragments are found at Trwyn Llwyd (GR 909410) (see Fig.101) where they are associated with whole and broken pillows and intercalated muddy sediments. In the Lower Fishguard Harbour area, both hyalotuffs and hyaloclastites occur, although intense secondary carbonation largely obliterates the primary textures of the hyalotuffs (the calcareous agglomerate or breccia of Thomas and Thomas, 1956, Fig. 6).

The thickest and most spectacular development of hyalotuffs occurs within the predominantly acidic Goodwick Volcanic Formation. A thick deposit (>60m) of hyalotuffs is exposed in the bay at Porth Maen (GR 942405) (Fig.102) and again a little further to the west, at Ogof Mati (GR 941405), although in the latter area the outcrop is inaccessible. In the bay at Porth Maen, the hyalotuffs generally dip

FIG. 102. Geological sketch map of the area north of Goodwick.

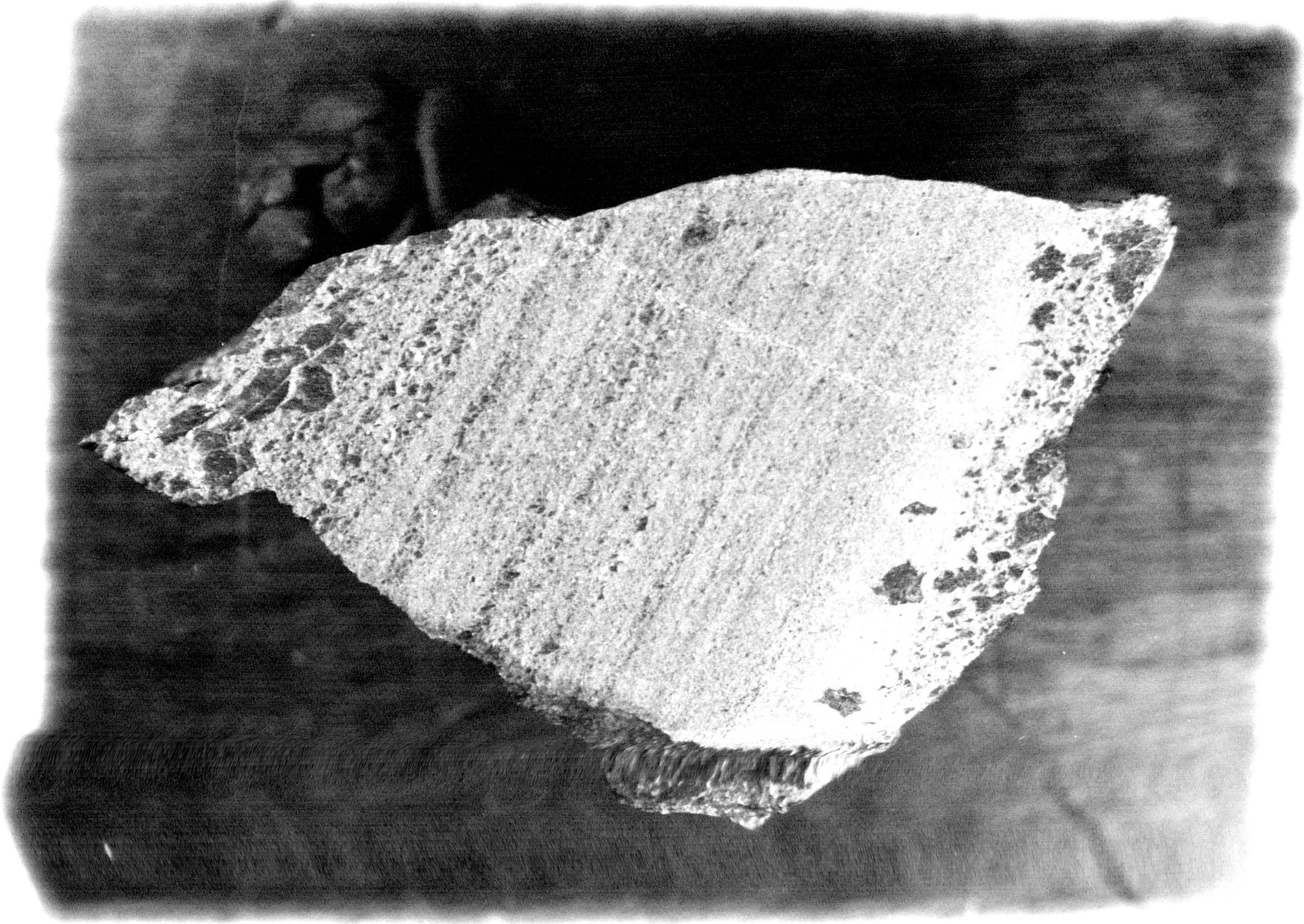

9'4
9'5
200 M
PENFATHACH
PENANGLAS
Y PENRHYN
PORTH MAEN
ANGLAS BAY
N
40
volcaniclastic breccia and sandstone
autoclastic breccia
rhyolite lava
basic hyalotuff
volcaniclastic breccia with thin sandstones
fault
cleaved shale
basalt
dolerite

northeastwards, with dips becoming north-northeast further to the east. The sequence is made up of a large number of thin layers which show a variation in grain size. Figure 103 shows a number of these thin layers in a specimen collected from Porth Maen. The coarse layers are composed of dark green chloritic fragments, the size of which are usually in the range 0.5 to 1.5cm. The fragments have been tectonically flattened in a direction oblique to the layering (see Fig. 103). However, it is thought that originally they were most probably equant in shape, with an outline which was cuspate, dictated by the presence of vesicle walls. These concavities may be distinguished on polished surfaces of blocks. In thin section the cellular and tabular form of the vesicles may be discerned, although boundaries between the grains have largely been obliterated. The coarse layers vary in thickness from a few cms or less, up to 3-4m. The fine-grained layers are laterally continuous and contain very thin laminae of coarser grained material. These fine-grained layers are generally thinner than the main coarse layers, of the order of 5-6cm. Coarsening upward cycles (Fig.104) are commonly developed within the sequence. Large, acidic blocks, up to 20cm across, are scattered throughout and are overlapped by the thinly laminated, finer layers. Several layers rich in these blocks may be discerned. Small scale structures, such as soft-sediment faults, are common, although no current-generated structures appear to be present. Well-formed cubes of pyrite, up to 2cm across, occur regularily throughout.

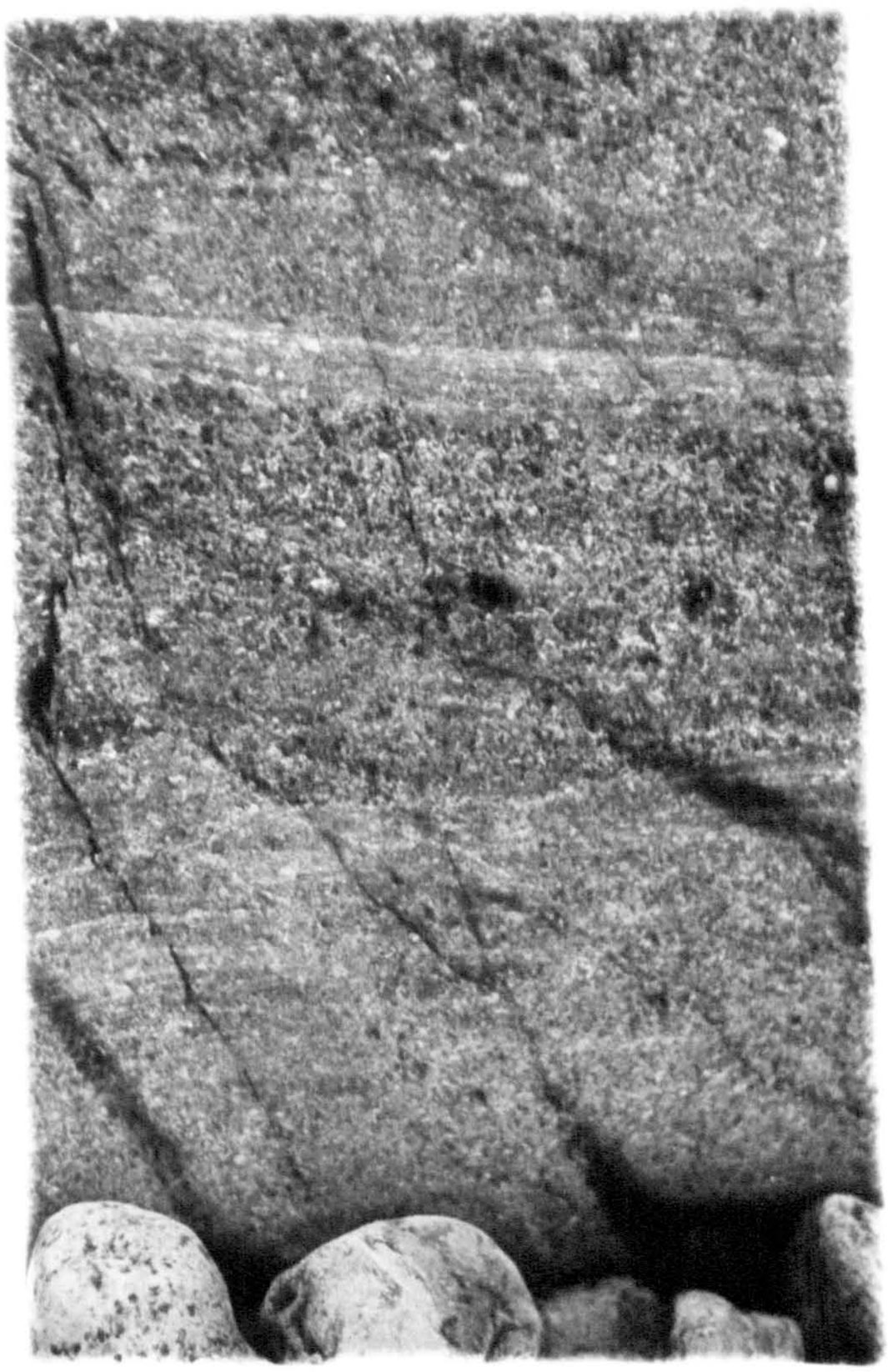
In thin section, altered plagioclase microphenocrysts, now replaced by sericite, occur within the former glassy fragments. The groundmass appears to be composed predominantly of smaller, chloritic fragments,

FIG. 103. Cut block of bedded hyalotuffs, Porth Maen.

(GR 942405). Length of specimen approximately 10cm.



FIGS. 104a and b. Bedded hyalotuffs from Porth Maen, showing coarsening upward cycles, as well as evidence for soft sediment deformation.



again showing tubed or cellular vesicles, surrounded and sometimes replaced by spherulitic quartz. The entire sequence appears therefore to be comprised of glassy, angular, vesiculated lava fragments of varying sizes.

This accumulation of hyalotuffs is considered to result from the explosive shattering of basaltic glass which formed as a result of the rapid chilling of magma coming into contact with cold sea-water, and is similar to the 'hyaloclastite' deposits described by Cristofilini et al. (1973) from the Iblean Highlands, Sicily. The magma was no doubt vesiculating immediately prior to the formation of a glass. It is clearly possible that shattering resulted from both tempering of the glass as well as from the explosive effect of super-heated steam trapped within the vesicles. Both processes are thought to have operated during the Capelinhos eruption (see Honnorez and Kirst, 1975, p. 458). In the Porth Maen case, it appears that as the material settled through a column of water, the smaller fragments became water-logged more quickly than the larger fragments and so sank earlier, thus producing the coarsening-upward sequences seen. The thin, finely laminated layers may represent the finest dust which later settled out of suspension. Clearly, water depths at this time were shallower than approximately 500 metres (the depth of the critical confining pressure for oceanic tholeiites, below which no extensive vesiculation will occur, [Moore, 1970]). It is not known, however, whether the vent was at, or close to sea-level, such as in the case of the Capelinhos and Surtsey eruptions, or whether it was submerged at all times, possibly at considerable depths. The lack of evidence for current action or reworking suggests that considerable water depths may in fact have been

present at all times. As such, these deposits could represent debris accumulating in and around the vicinity of a submarine vent, perhaps resulting in the development of a tuff-ring. In view of the thickness exposed, the accumulation was probably both continuous and rapid, without the intervention of volcanicity of another character, or cessation, during which time sediments may have accumulated.

The only other example of true hyalotuffs recognized within the area, as mentioned above, occurs in the cliff section at Lower Fishguard Harbour. Here, the glassy material is associated with abundant debris of block size, as is common in 'hyaloclastite' accumulations on submarine cones. However, intense carbonation has overprinted most of the primary features. In sample 255, however, it may be seen that the fragments are extensively vesiculated. Thin sections reveal that the vesicles are drawn out and infilled with chlorite and calcite. This elongation is probably the result of deformation during the Caledonian Orogeny. Unfortunately, the deformation present negates the use of the quantitative classification proposed by Honnorez and Kirst (1975).

3.2.2. PILLOW BRECCIAS

The term pillow breccia was first used by Henderson (1953) in describing an occurrence of broken, basic pillow lavas in the Precambrian, at Yellowknife, in Canada. The term was later extended by Carlisle (1963), who defined isolated-pillow breccia and broken-pillow breccia, in describing rocks from Quadra Island, British Columbia. More recently, Furnes (1972) has described isolated- and broken-pillow breccias of Ordovician age from Solund, in West Norway.

Although the terms isolated-pillow breccia and broken-pillow breccia describe essentially different volcaniclastic rocks, it is not easy to categorize certain units from the Fishguard Volcanic Group, as they contain both discrete whole pillows, as well as broken-pillows. Consequently, the term pillow breccia will be applied to these units. A 15 metre thick unit at Carn Melyn (GR 887406) affords the best example of such a pillow breccia (Fig. 105). The unit, which dips northeastwards at approximately 40°, has an overall bedded aspect but lacks internal stratification. It overlies pillowed lava (Fig.106), but in turn is overlain by a massive lava flow. Such a sequence is identical to that described by Carlisle (op. cit. p. 51) from Quadra Island. Within the pillow breccia both isolated pillows as well as broken pillows occur in a fine-grained, siliceous matrix. The size of the fragments is highly variable, reaching a maximum diameter of 50cm. Figure 107 illustrates the typical size and form of whole pillows, set within the siliceous tuffaceous matrix. These pillows possess a dark, fine-grained rim and a lighter, crystalline core and are commonly vesiculated. The broken pillow fragments assume a variety of shapes, but generally they are almost triangular, with the arcuate-shaped edge showing well-developed vesicles. Thus they appear to represent fragmented pillows, which have broken along radial cracks. Such radial cracks are present in many of the pillows of the Strumble Head Volcanic Formation (see S.2.2.1.1.).

An overall coarsening upwards in fragment size, coupled with a decrease in the proportion of matrix, is seen within the Carn Melyn pillow breccia. Figure 108 illustrates the nature of the pillow breccia close to the base and shows both angular and rounded fragments. Figure 109 shows the nature of the upper part of the unit and the increased proportion of fragments can be discerned. The fragments within

FIG. 105. Pillow breccia unit, Carn Melyn (GR 887406).

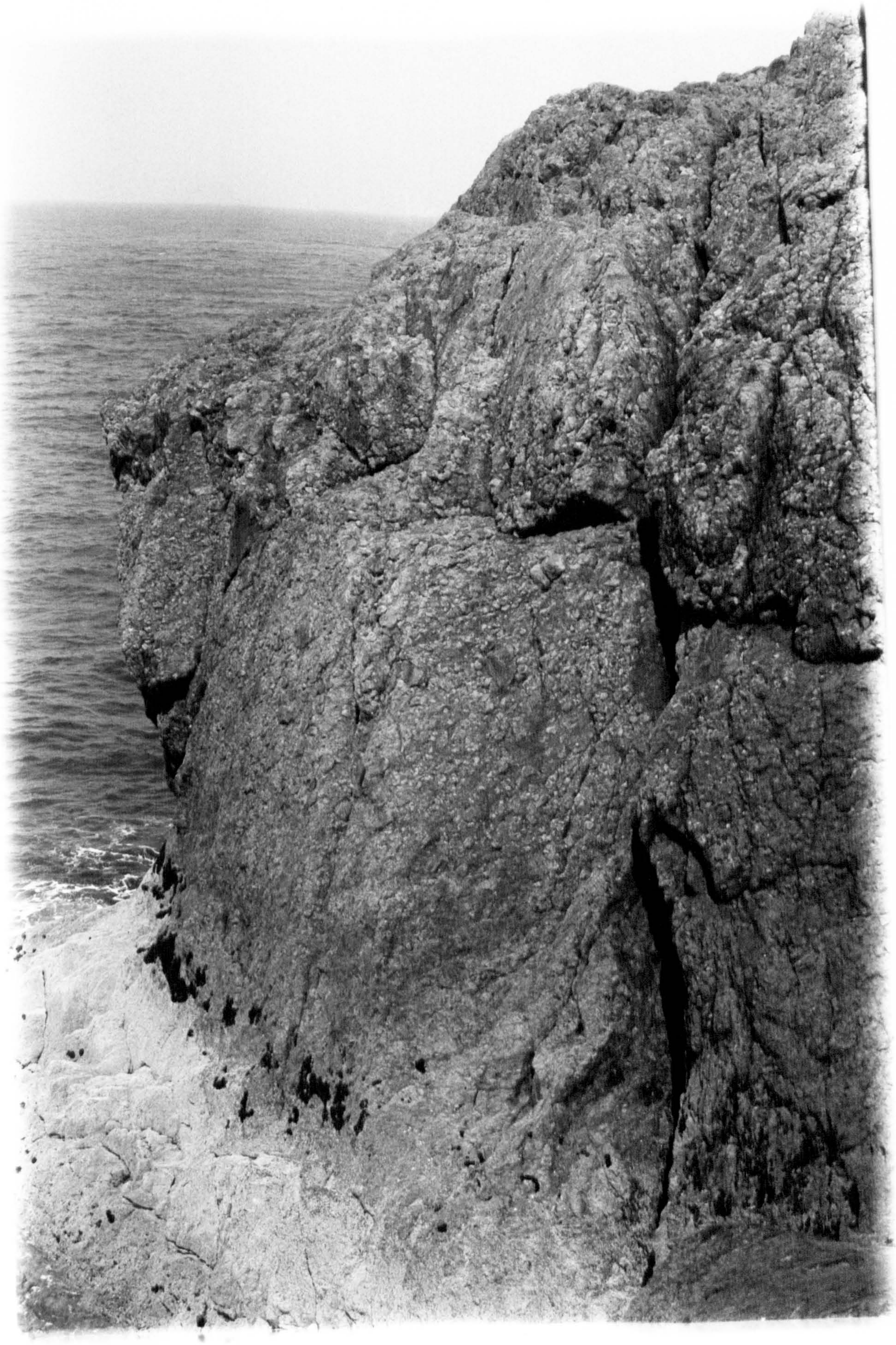


FIG. 106. Exposure of junction between pillow breccia (above) and pillow lava (below). Carn Melyn (GR 887406).

FIG. 107. Whole pillows within pillow breccia. Carn Melyn (GR 887406).

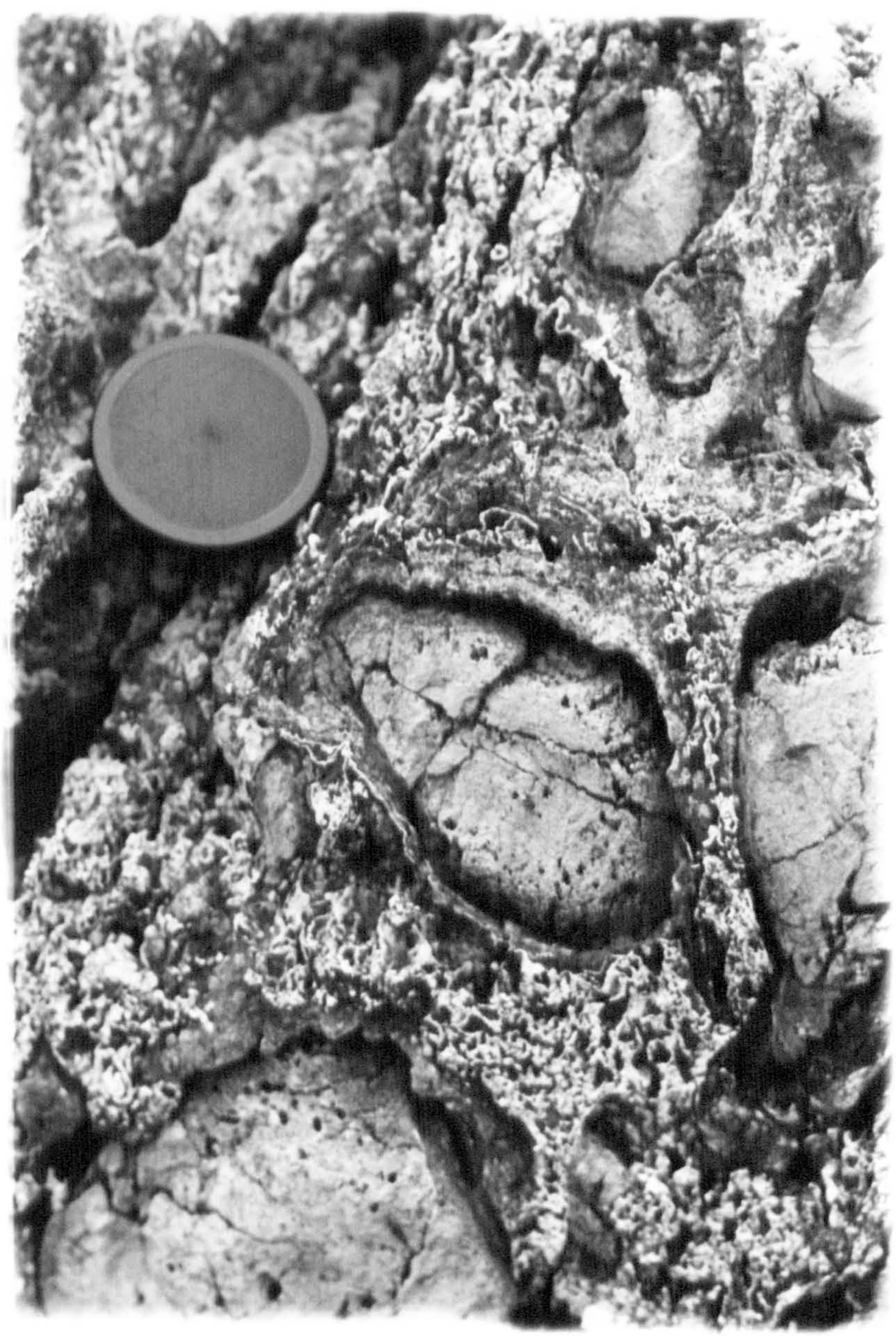
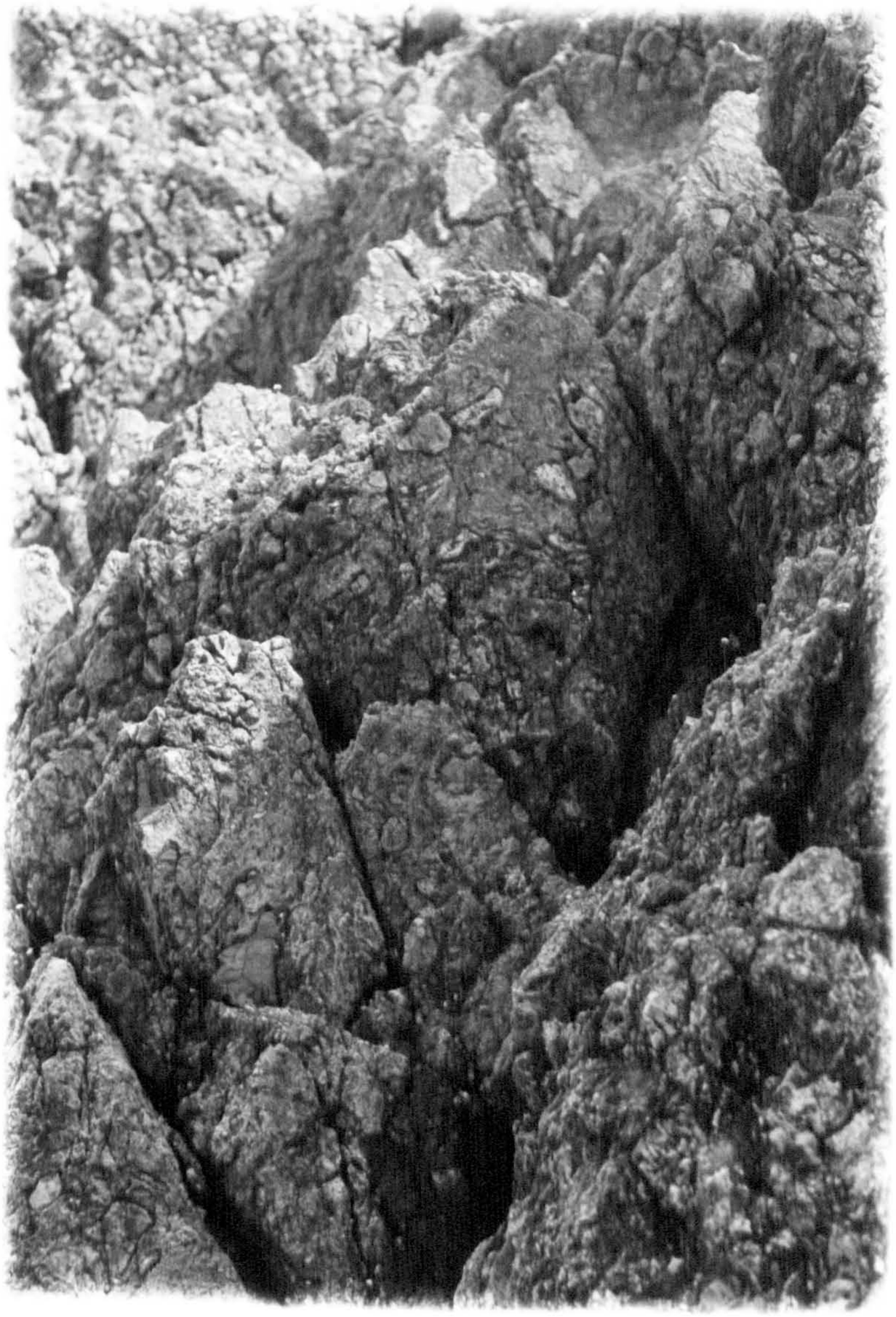


FIG. 108. Nature of pillow breccia unit of Carn Melyn near to the base. Note the presence of both angular and rounded fragments (GR 887406).

FIG. 109. Nature of Carn Melyn pillow breccia unit at the top, illustrating the increased proportion of fragments (GR 887406).



this upper part of the unit also appear to be predominantly angular in shape, with only a limited number of rounded pillows present. Carlisle (op. cit.) reported a transition from predominantly isolated-pillow breccia passing upwards into broken-pillow breccia.

A petrographical examination of the matrix reveals glass fragments averaging 5mm in diameter, which have been replaced by chlorite and epidote. These are set within a fine-grained groundmass. Both the fragments and the groundmass show evidence of partial replacement by silica with small spherulites of quartz pseudomorphing the original textures. Minor pumpellyite is also present.

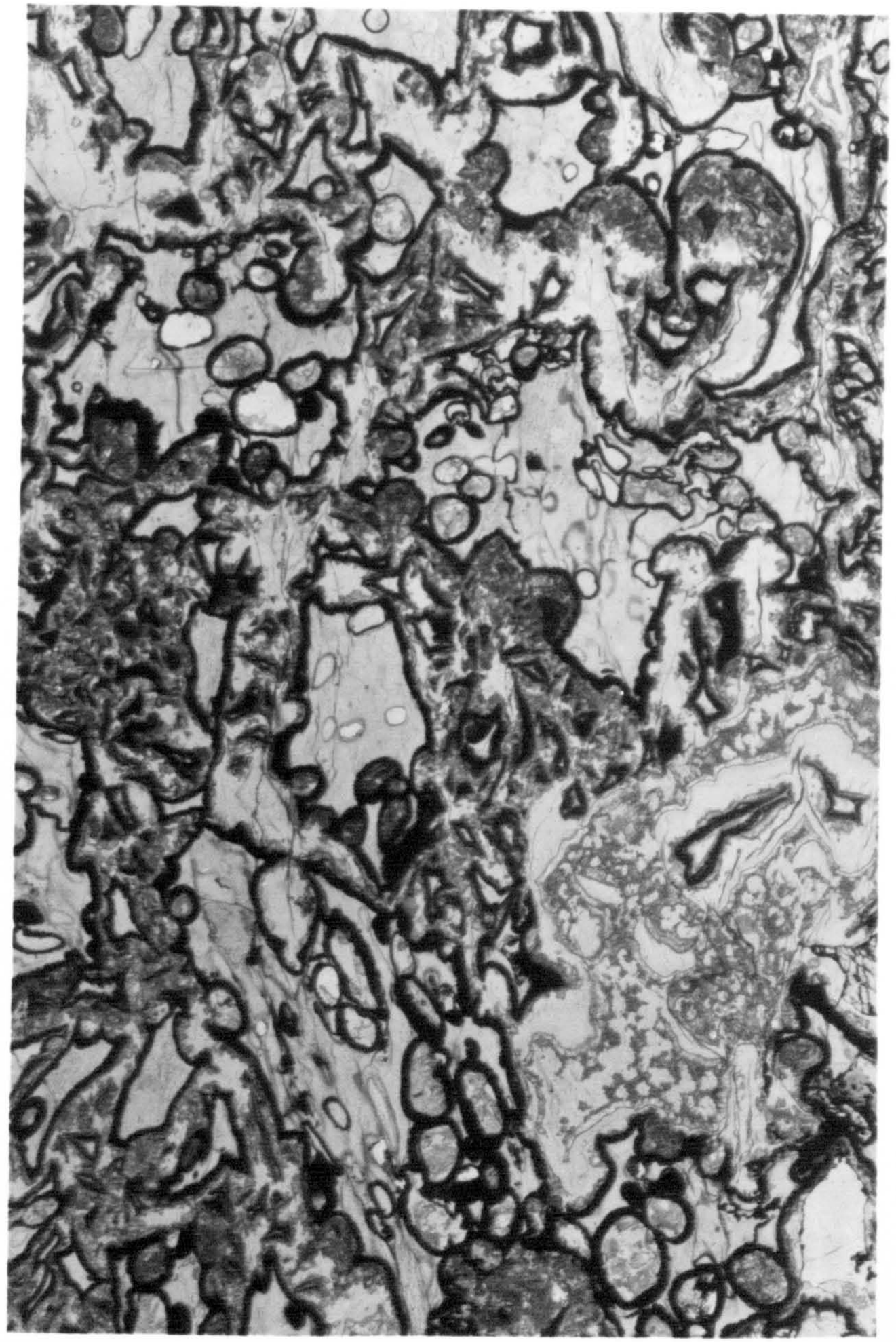
Many of the features described above appear similar to those described by Carlisle (op. cit.) from Quadra Island and by Furnes (op. cit.) from the Solund area. Carlisle, in attempting to account for the genesis of broken-pillow breccias, suggested that they may represent debris deposited from submarine slumps, which were derived from thick accumulations of incoherent steam-laden pillows. This mechanism is also envisaged for the Carn Melyn pillow breccia and, as such, the unit is not of a pyroclastic origin. A reworking of pre-existing pillows and talus from pillowed lava probably occurred during the downslope movement of the mass flow, resulting in the generation of the broken pillows. Small glass shards and spalled material from broken pillows formed the matrix. Unfortunately, due to the lack of inland exposure, along with the presence of dip-slip faults, this unit cannot be traced laterally and thus estimations regarding the extent and the distance of the mass flow from its source cannot be made.

A second pillow breccia containing both broken and unbroken pillows, up to 1m in diameter, and enclosed within a vitroclastic matrix crops out on the north coast of Pen Caer, at Trwyn Llwyd (GR 920408).

FIGS. 110 and 111. Vitroclastic matrix of pillow breccia from Trwyn Llwyd. PPL.

110. x12.5.

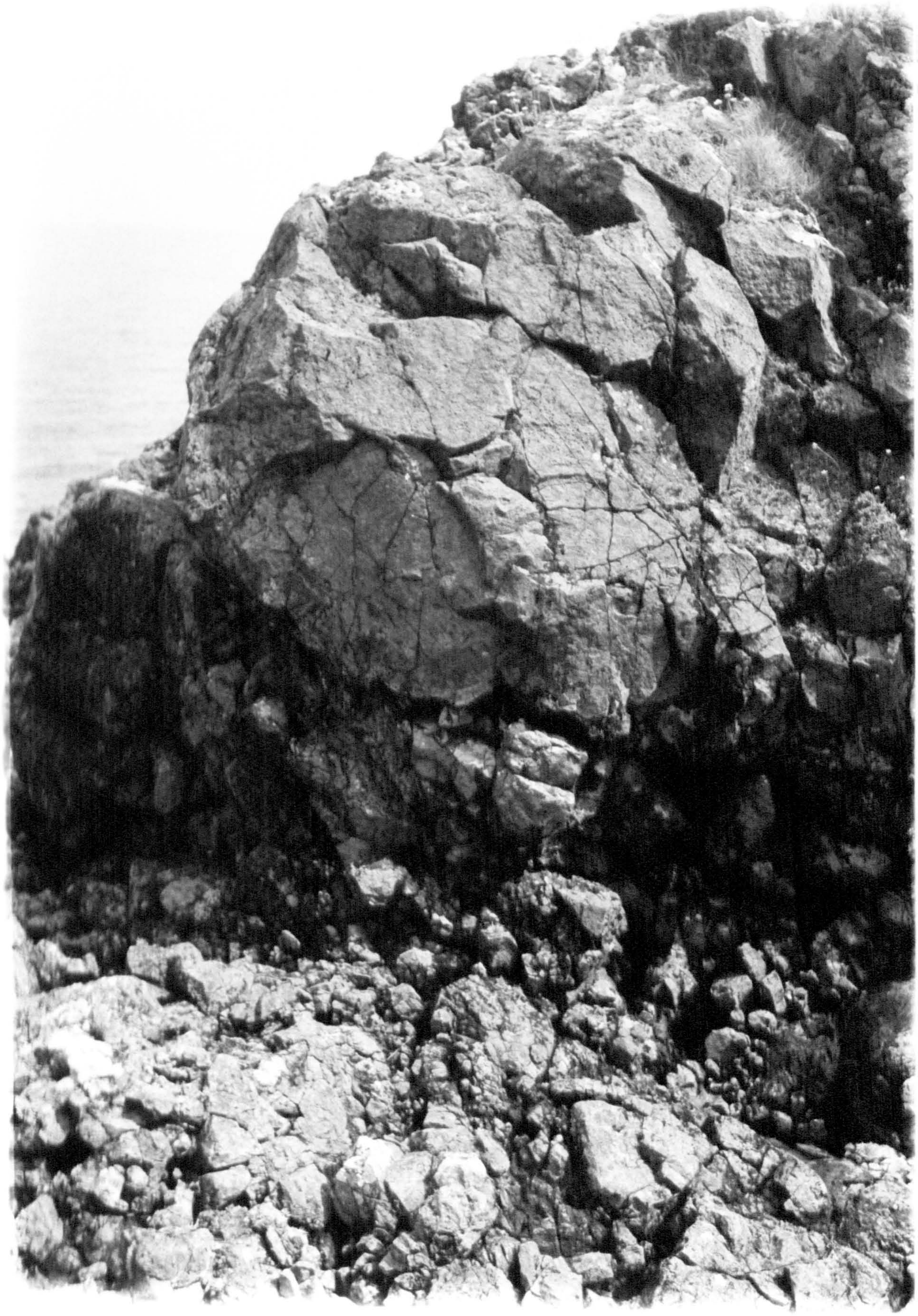
111. x12.5.



This unit is considerably thinner than the Carn Melyn breccia and also contains blocks of sediment. Upwards it grades into fine-grained sediments. The matrix of this breccia is also noticeably different from both the Carn Melyn breccia and the breccias from Quadra Island. As illustrated in Figures 110 and 111, the glassy fragments of the matrix are extensively vesiculated and this has resulted in their disintegration, producing shard-like fragments, with cupate outlines. In contrast, therefore, the matrix of this particular breccia appears to be pyroclastic in origin; a fact which is important when considering the genesis of the breccia. The explosive vesiculation of the liquid lava, as it came into contact with the cold sea-water, may have produced a vapour-rich flow, incorporating both the chilled vesiculated glass fragments, 'pillows' of chilled lava, as well as the sediment of the substrate. The flow would no doubt be very short-lived.

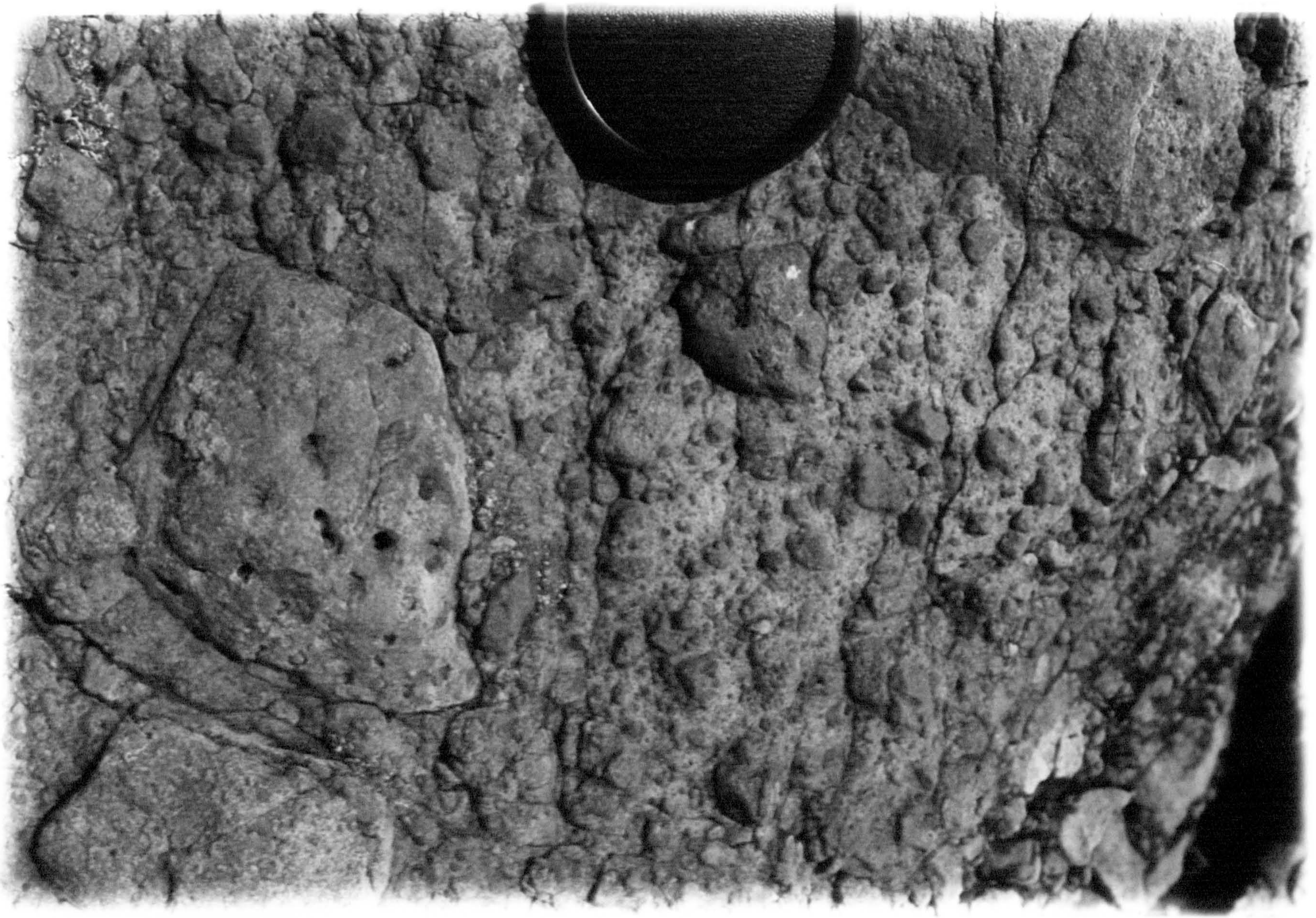
A true broken-pillow breccia occurs at Carregwastad Point (GR 927406) (Fig.112). In the eastern part of this headland, the breccia is in fault contact with the overlying pillow lavas but when traced westwards, the contact is normal and irregular, but generally dips northwards at approximately 20° (Fig.112). In this area, the unit is comparatively thin, being of the order of 3 metres, whereas in the east the unit is thicker, possibly due to repetition by the fault. Everywhere at the base the contact is gradational into pillow lavas. The fragments of this breccia are variable in size, as shown in Figures 113 and 114. The majority are angular fragments of vesiculated, basaltic lava, with only a limited number showing a pillowed form (Fig. 115). This breccia appears to result from the in-situ brecciation of the surrounding lava and thus may represent the autobrecciated upper surface of a lava flow or possible talus debris from a flow. The sharp,

FIG. 112. Junction between broken-pillow breccia (below) and pillow lavas (upper). Carregwastad Point (GR 927406).



FIGS. 113 and 114. Broken-pillow breccia of Carregwastad Point (GR 927406).

FIG. 115. Broken-pillow breccia. Carregwastad Point (GR 927406).



irregular upper contact represents the junction with the overlying flow.

Other thin occurrences of pillow breccia were recognized on the east coast of Pen Globo (GR 917408) and on the west coast of Aber Gwladus (GR 924406). In the latter area, large, vesiculated, basic fragments, up to 10cm in diameter are present (Figs. 116 and 117). These are generally sub-rounded, resembling small pillow-like bodies and are enclosed within a matrix composed of stretched and flattened vesiculated glass fragments, the latter reaching 1cm in length. Between these glass fragments is abundant shard like debris, no doubt derived from the disintegration of other glass fragments. Occasional altered plagioclase phenocrysts can also be discerned. The unit appears to have a bedded form and probably represents material which has been locally reworked.

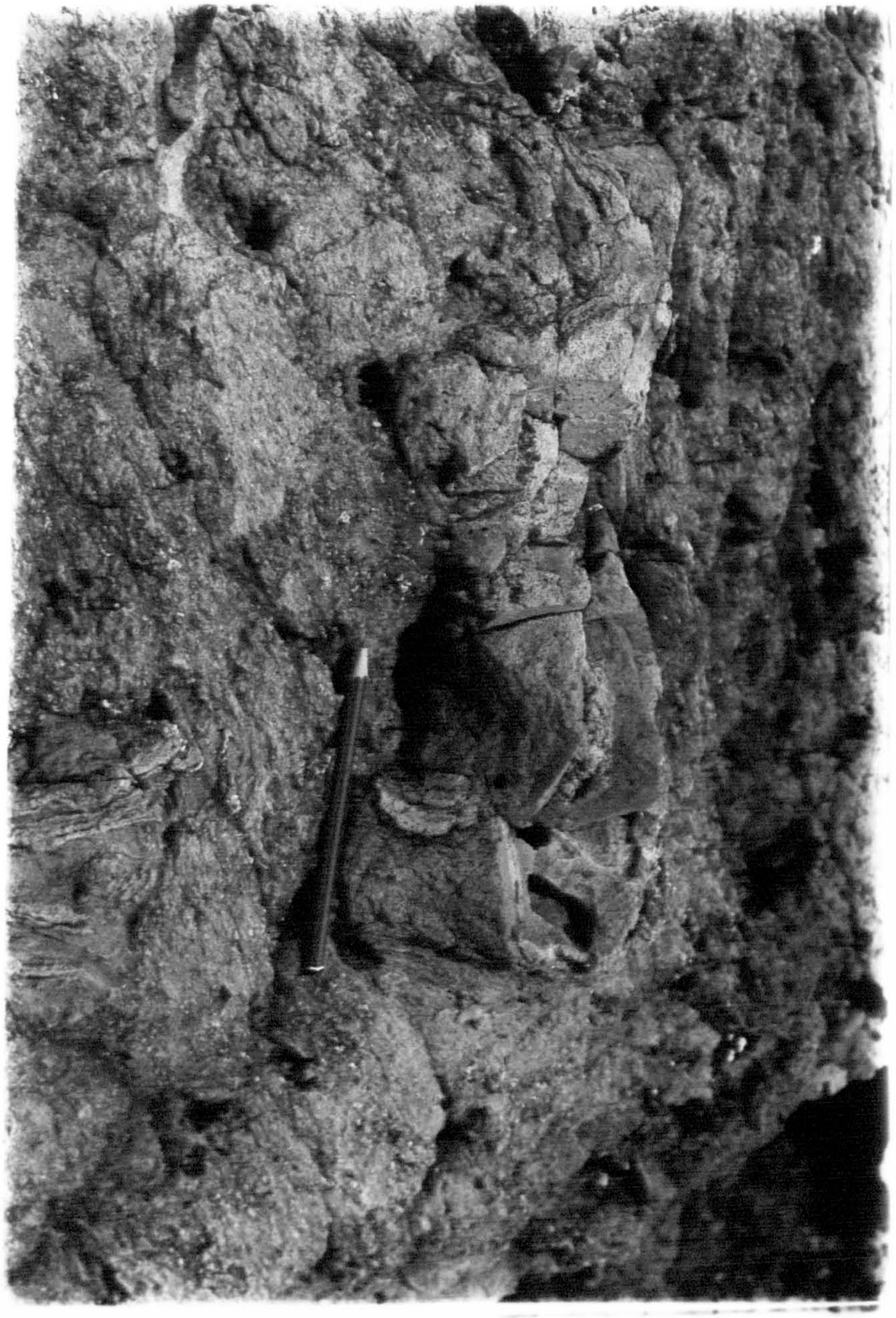
3.3. VOLCANICLASTIC ROCKS OF INTERMEDIATE COMPOSITION

Rocks of intermediate composition are not abundant within the Fishguard Volcanic Group and, where seen, generally form high-level intrusive sheets. Lavas of an intermediate character are only locally developed. Certain horizons within the Strumble Head Volcanic Formation are composed of pillow lavas of andesitic composition, but no attendant volcaniclastic rocks are present. Within the Porth Maen Melyn Volcanic Formation, however, a thick rhyodacite/dacite lava flow shows the development of elongate lava flow tubes and locally pillowed forms are developed, with isolated-pillow breccias. These are described more fully in Chapter 2 and also by Bevins and Roach (in press).

3.4. VOLCANICLASTIC ROCKS OF ACIDIC COMPOSITION

Volcaniclastic rocks derived from magmas of acidic composition are identified at a number of horizons within the Fishguard Volcanic Group

FIGS. 116 and 117. Pillow breccia from Aber Gwladus (GR 924406). Basic lava fragments are enclosed within a vitroclastic matrix.



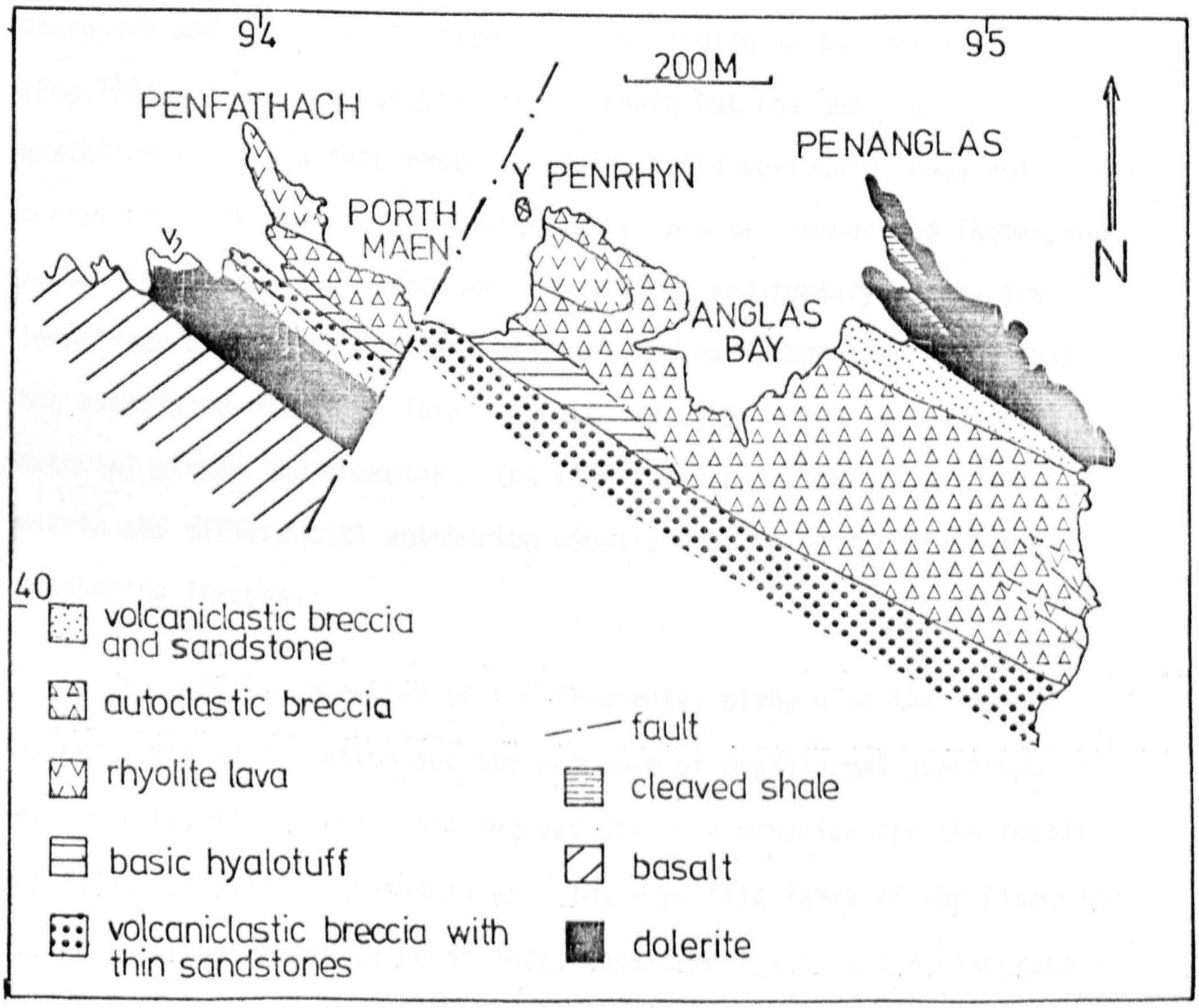
and they reach their maximum development in the Goodwick Volcanic Formation, in the vicinity of Anglas Bay, to the north of Goodwick (Fig.118). Other exposures of acidic volcaniclastic rocks occur at Porth Maen Melyn, at Caer-Lem Farm, and also in the cliff section exposed in Lower Fishguard Harbour (although the latter will not be described in any detail; see, however, Thomas and Thomas, 1956, Figs. 6 and 7). Very few of the volcaniclastic rocks described here are pyroclastic in origin, although pyroclastic rocks appear to be more important in the ground to the east of Fishguard, towards Newport (Davies, 1936; Bevins and Roach, in press).

The rhyolites (described in Section 2.4.) show little evidence of vesiculation and accordingly it is assumed that, for the most part, the acidic volcanism of this area was essentially non-explosive in nature. The volcaniclastic rocks developed were, therefore, generated as a result of autobrecciation and the subsequent reworking of this autobrecciated debris. These two categories will be dealt with separately below, although it is realized that an exact distinction is commonly difficult and transitions from one to the other occur.

3.4.1. RHYOLITIC AUTOBRECCIAS

As outlined in Section 2.4., rhyolitic lavas are found at a number of localities in the Fishguard region. In the area investigated, these lavas are best developed in the vicinity of Anglas Bay (Fig. 118), near Caer-Lem Farm, in the vicinity of Carngelli and at Goodwick Harbour Village (Fig. 3). At each of these localities coarse, poorly sorted, monolithic lava breccias are found. Reed (1895) suggested that these represent agglomerates derived from explosions within the vents which were the source of the rhyolites; an origin re-enforced by Thomas and Thomas (1956).

FIG. 118. Simplified geological map of northeast Pen Caer.

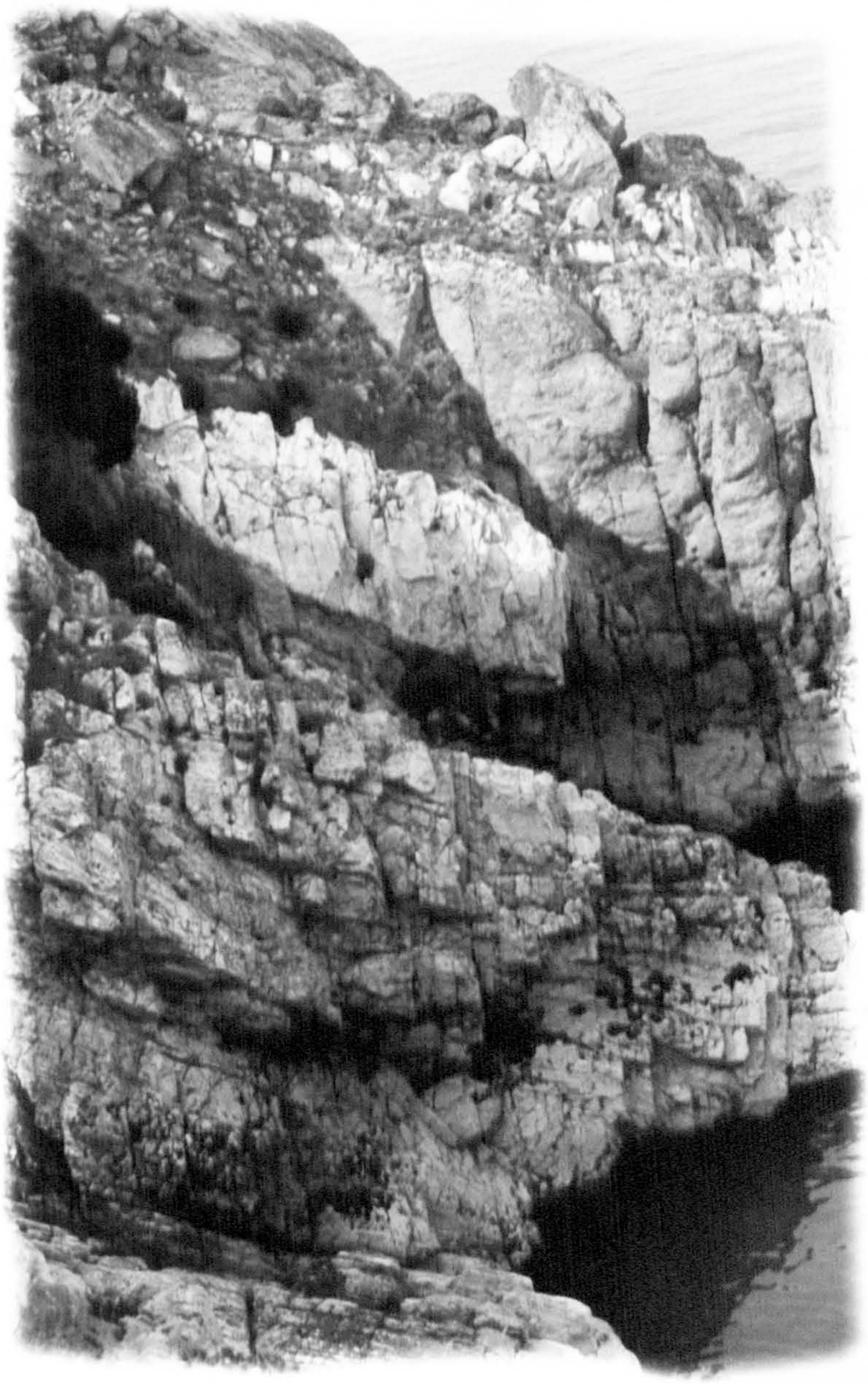

9'4
9'5
200 M
PENFATHACH
PENANGLAS
Y PENRHYN
PORTH MAEN
ANGLAS BAY
N
40
volcaniclastic breccia and sandstone
autoclastic breccia
rhyolite lava
basic hyalotuff
volcaniclastic breccia with thin sandstones
fault
cleaved shale
basalt
dolerite

The breccias are composed almost entirely of rhyolitic lava fragments which reach a maximum diameter of about 50cm. The fragments are angular in outline and, in places, a fit between adjacent fragments can be discerned. At Y Penrhyn (Fig.118) and the Warren (GR 951402) the junction between rhyolitic lava and rhyolitic breccia can be clearly observed. This junction is seen to be transitional in character and in adjacent fragments flow banding is sub-parallel (Fig.119). Thus, the junction is not sharp but one observes a gradation from lava into breccia. This, quite obviously, does not correspond with the picture envisaged by Reed or Thomas and Thomas, and another model must be suggested. Occasional sedimentary clasts are identified within the breccias at Caer-Lem, as indeed they are within the associated rhyolitic lavas. These represent the only accidental material within the breccias. The clasts are set within a siliceous matrix and differential weathering usually results in the fragments weathering inwards.

The uniform character of the fragments, along with the lack of evidence for vesiculation and the presence of gradational junctions with the rhyolitic lavas, all suggest that the breccias are the result of autobrecciation of these lavas. The rhyolitic lavas of the Fishguard Volcanic Group appear to be of local development and in the Fishguard - Strumble Head area, there are four important occurrences (outlined above). At each of these localities, the flows, when traced laterally, pass into breccias. These local lava flows are here considered to have been thick flows or, more probably, dome-like structures. If this is the case then the breccias are thought to represent a type of crumble-breccia (in the sense of MacDonald, 1972), produced during growth of such domes. Similar breccias were described, for example, from the domes of Santorini

FIG. 119. Rhyolitic autobreccia from Y Penrhyn (GR 945406), with fragments of flow banded rhyolite showing a parallel alignement of flow banding.

FIG. 120. Thin rhyolitic lava flow within thick sequence of rhyolitic breccias south of Crincoed Point (GR 952401).



by Fouque (1879). Evidence is presented below showing that the domes appear to have been surface features, developed on the submarine floor, and thus offer contrast to the intrusive rhyolite domes of North Wales, as described, for example, by Roberts (1967). Where submarine lava domes have emerged above sea-level their surfaces have commonly been covered by a mass of rubble, as for example McCulloch Peak, in the Bogoslof Islands (Jaggar, 1908) and the submarine dome of the Sangi Islands, described by Winchmann (1921). It is considered likely, however, that once such a dome is established, later magma rising up may intrude the dome and its carapace of crumble breccia and thus, although the dome is a surface feature, part of its development may be by endogenous growth. This would explain the presence of thin, flow banded sheets within certain areas of the breccias in the Fishguard area, for example, the thin lavas exposed on the coast to the south of Crincoed Point (GR 952401), illustrated in Figure 120.

Horikoshi (1969) described a series of dacitic domes associated with Kuroko-type ore bodies from the Kosaka district of Japan. Intimately associated with the domes are breccias composed entirely of angular, dacitic fragments. These, Horikoshi suggested, were generated by violent phreatomagmatic explosions as the dacitic magma rose to the surface and came into contact with the relatively cold sea-water. He states (op. cit. p. 337) that three cases are possible:

(i) the lava produces a dome which formed on the seafloor after extrusion of the magma;

(ii) the magma intruded the still wet sediments close to the surface and partly extruded onto the seafloor; or

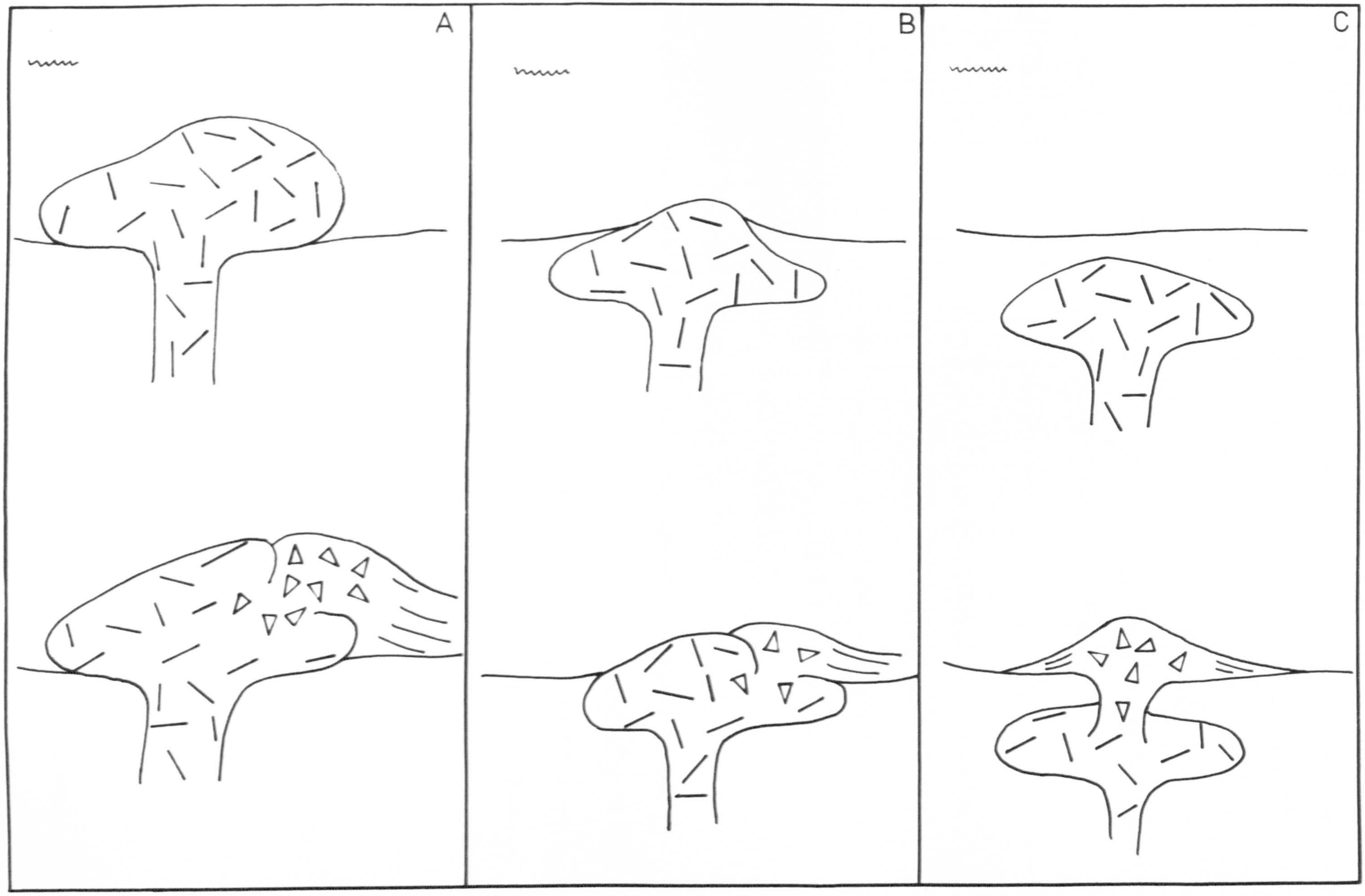
(iii) the magma intruded the wet sediments, but did not extrude onto the seafloor.

These are illustrated in Figure121, after Horikoshi (1969, Fig. 19) and he concludes that a number of the above forms were assumed during the production of the nine domes identified within the Kosaka Formation. However, it is difficult to discriminate between breccias produced by steam explosions in the manner envisaged by Horikoshi and those produced by autobrecciation due to internal expansion. Clearly, the possibility exists that both mechanisms could operate simultaneously, producing breccias of a complex origin. Further discussions on the models of Horikoshi are to be found below (S.3.4.2.).

In the description of the breccias, Horikoshi (op. cit. p. 336) describes a cyclic grading, produced as a result of fall through a column of water, following the explosive activity. Such a grading is not seen within the Fishguard breccias; instead they are poorly sorted. In the Kosaka breccias sharp contacts with surrounding lithologies are seen, in contrast with the gradational boundaries between rhyolitic lavas and breccias of the Fishguard examples. For these reasons, it is thought that the breccias of the Fishguard Volcanic Group were probably produced by autobrecciation, as a result of expansion within the developing domes, contrasting with the picture, described earlier, of Reed (1895) and Thomas and Thomas (1956).

Further evidence against the vent source for these breccias may be obtained by examining other vent breccias. Vents and pipes in which agglomeratic material is present offer many contrasts. A lamination is commonly developed within the matrix material of such pyroclastic rocks and welding may even be present (as in the Glas Eilean Vent, Ardnamurchan). In addition, the material in these vents and pipes is distinctly heterolithic, with rhyolitic debris, basement rocks (which in

FIG. 121. Three possible mechanisms of breccia production due to phreatomagmatic explosions. After Horikoshi (1969, Fig. 19).


A
B
C

the case of those vents on the Isle of Mull is Moinian psammite), in addition to much of the near-surface lithologies through which the pipe reached the surface (commonly Mesozoic sediments in the case of vents on the Isle of Mull). It would, in fact, be difficult to imagine in the Fishguard examples such explosive activity in a submarine environment without the incorporation of much of the adjacent sedimentary material, which undoubtedly was still largely unconsolidated at the time of volcanicity.

The breccias show a variable petrography, depending upon which lava dome they are associated. The breccias of Crincoed Point (GR 952401) are composed entirely of angular fragments of rhyolite, up to 10cm in diameter. These rhyolitic lava fragments are uniform in nature and possess crystals of quartz and feldspar along with micropoikilitic intergrowths of quartz and felspar, set within a microcrystalline groundmass. The junction between fragments is not always readily discernible microscopically, although occasionally it may be identified due to the presence of calcite within the groundmass (e.g. sample 247). In contrast, breccias from exposures near Caer-Lem Farm (Fig. 3), show a variety of constituents. They are predominantly rhyolitic lava fragments with a well developed snowflake texture, identical to the lavas exposed a short distance to the southeast. In addition, however, certain fragments are of a lava type not exposed at this locality. This lava is porphyritic, with large, turbid plagioclase feldspars and rounded, embayed quartz crystals. The plagioclase crystals contain abundant apatite needles, up to 0.5mm in length. Apatite is also readily developed within the groundmass. Small, euhedral crystals, showing high relief and moderate birefringence are also present, although the exact identification of these crystals is hampered by their scarcity.

3.4.2. OTHER VOLCANICLASTIC ROCKS OF THE FISHGUARD VOLCANIC GROUP

Acidic volcaniclastic rocks, other than the rhyolitic lava breccias described above, occur within both the Porth Maen Melyn and the Goodwick Volcanic Formations. They are not common, however, within the Strumble Head Volcanic Formation. The volcaniclastics of the Porth Maen Melyn Volcanic Formation will be described first.

The lowermost member of the Porth Maen Melyn Volcanic Formation is a 15 metre thick, cryptocrystalline, acidic unit of a rhyolitic nature (Fig.122). The rock shows a peculiar recrystallization texture which produces elliptical or spherical 'pseudonodules' (Fig.123). These 'pseudonodules' are characterized by the development of a snowflake texture. They are relatively coarse, crystalline areas and are separated by finely crystalline, quartzo-feldspathic areas, characteristically associated with feldspar and quartz phenocrysts and secondary epidote (Fig.125). The development of this texture has completely overprinted any primary textures which may have been present. However, it is considered likely that the rocks were glassy in nature and possibly devoid of any such primary textures. In places the secondary recrystallization texture gives the appearance of a sedimentary origin for these rocks, whilst in other areas the more concentric 'pseudonodules' are reminiscent of accretionary lapilli. However, when compared with other devitrified volcanic rocks of the Fishguard area, the secondary origin for the textures in the rocks of this member is evident. Snowflake textures similar to those described above are seen within rhyolitic lavas and rhyolitic breccia clasts from the area around Caer-Lem Farm. The presence of occasional, small microphenocrysts, along with the suggestion that the rocks were once glassy in nature, implies that this member probably represents a

FIG. 122. Simplified geological map of the Porth Maen Melyn area.

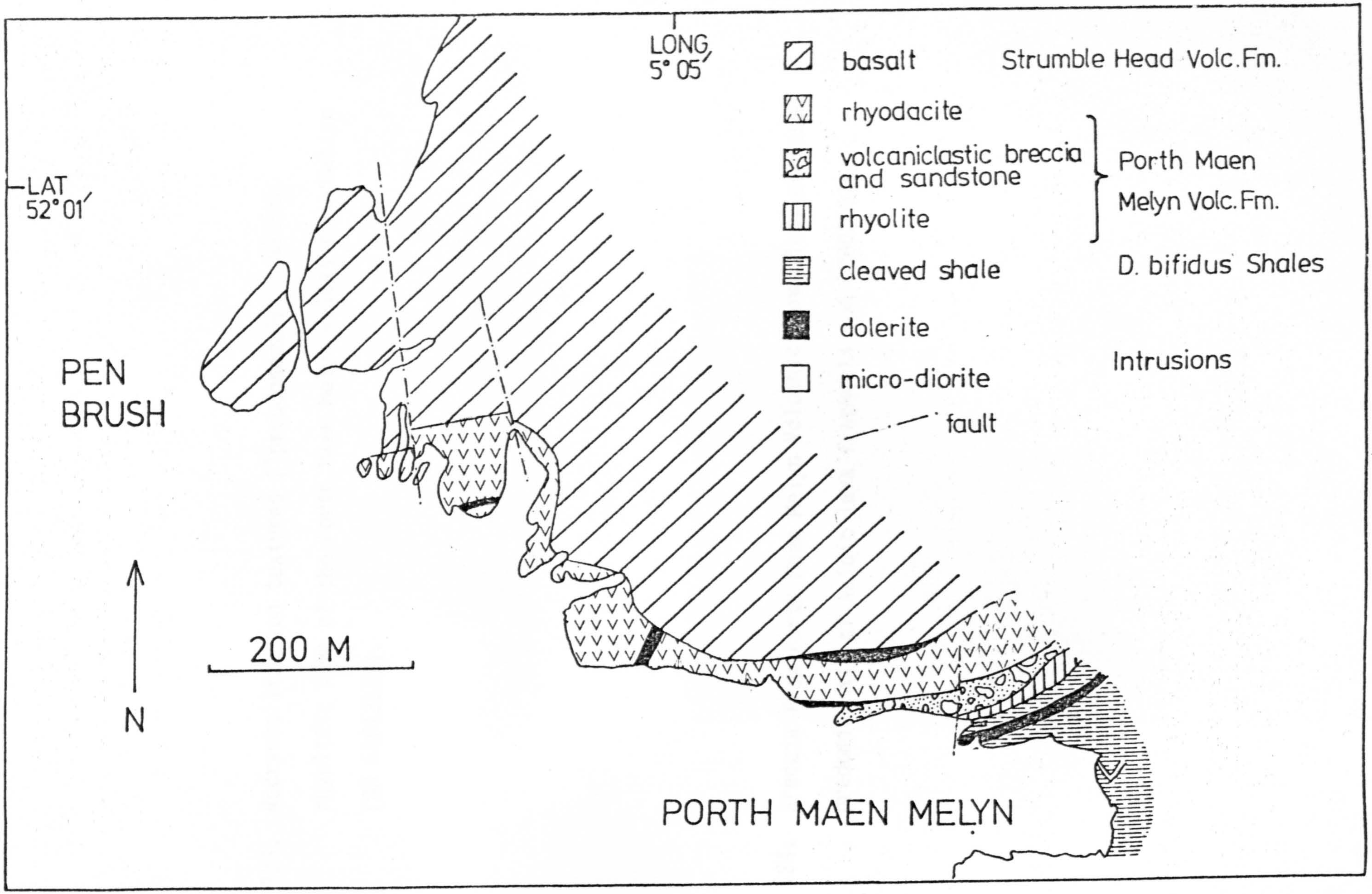
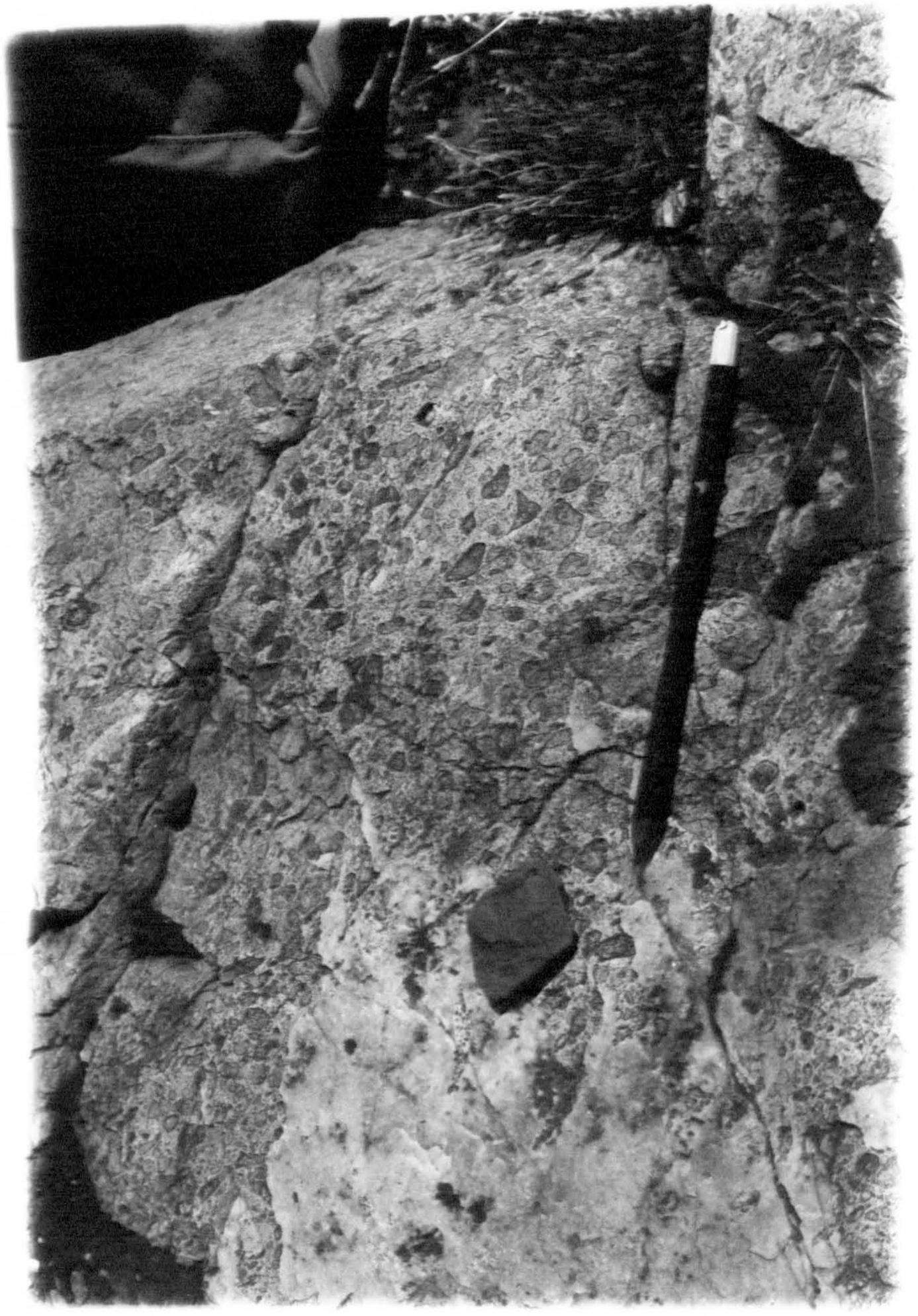
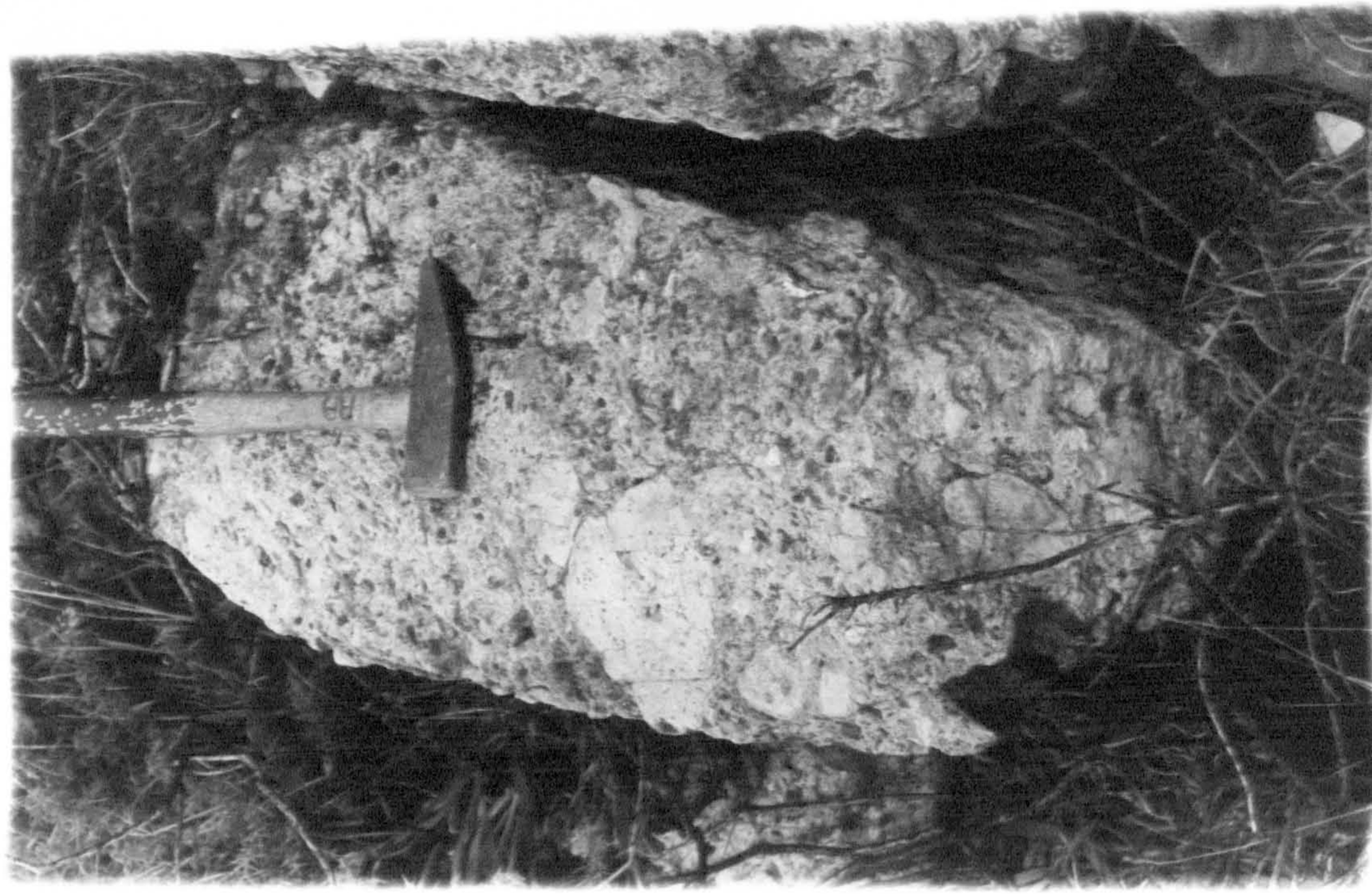

LONG
5° 05′
LAT
52° 01′
PEN
BRUSH
basalt
Strumble Head Volc.Fm.
rhyodacite
volcaniclastic breccia
and sandstone
rhyolite
Porth Maen
Melyn Volc.Fm.
cleaved shale
D. bifidus Shales
dolerite
micro-diorite
Intrusions
fault
200 M
N
PORTH MAEN MELYN

FIG. 123. Recrystallization textures ('pseudonodules') within rhyolitic lava of the Porth Maen Melyn Volcanic Formation (GR 88813932).

FIG. 124. Breccia from Porth Maen Melyn Volcanic Formation, composed predominantly of acidic lava fragments (GR 88803932).

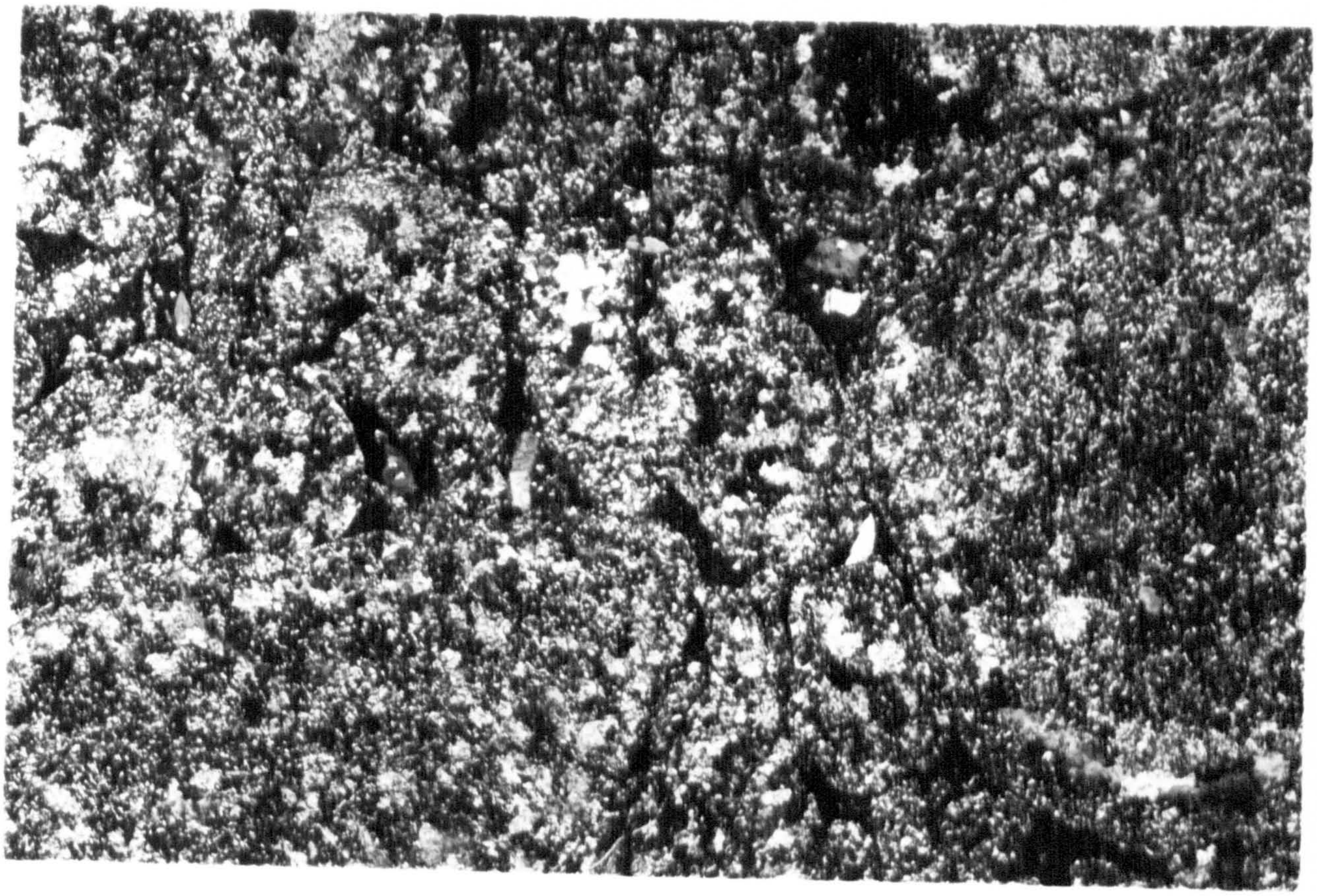


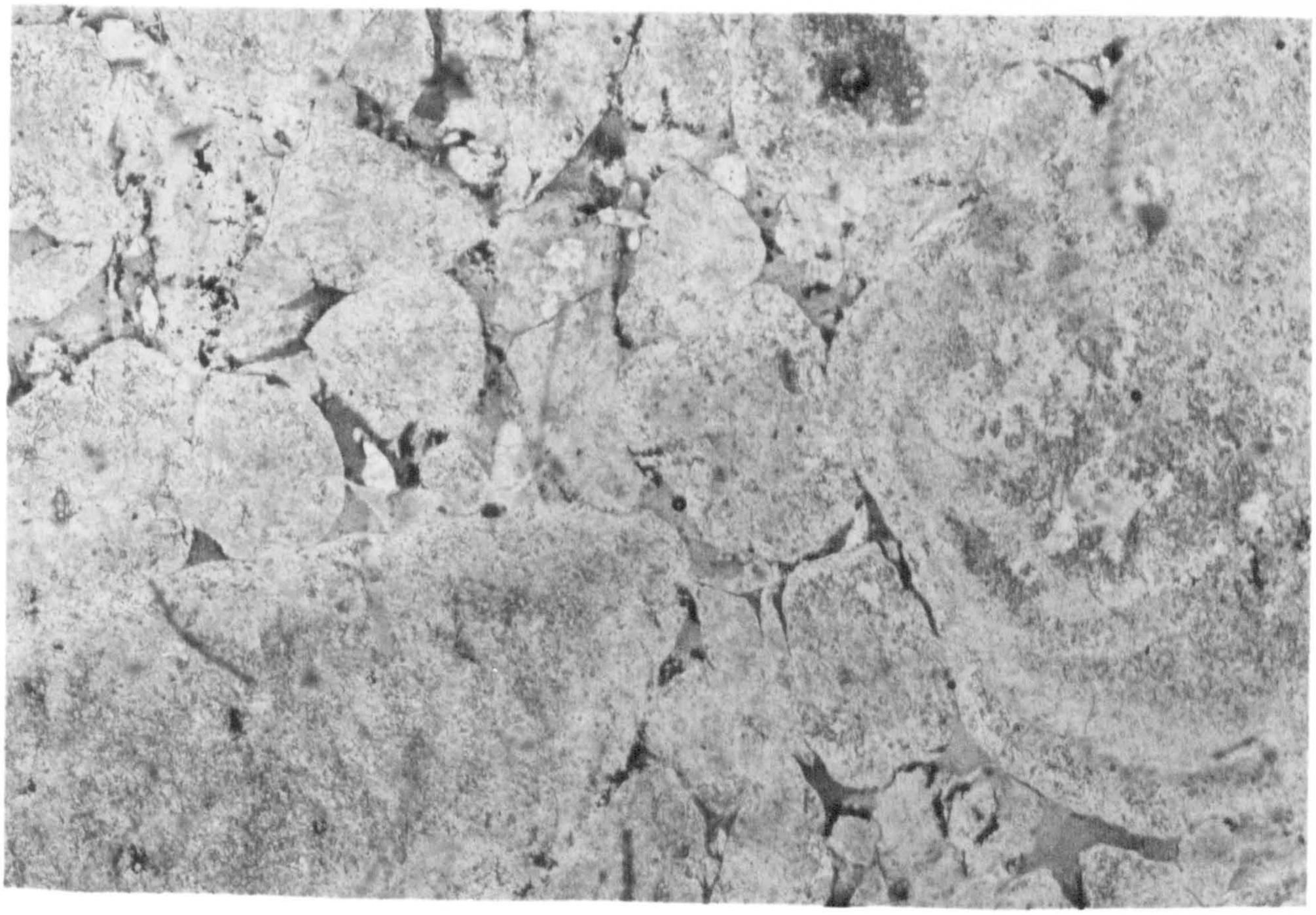


FIGS. 125a and b. 'Pseudonodules' in altered rhyolite from Porth Maen Melyn Volcanic Formation.

a) XP. x12.5.

b) PPL. x12.5.





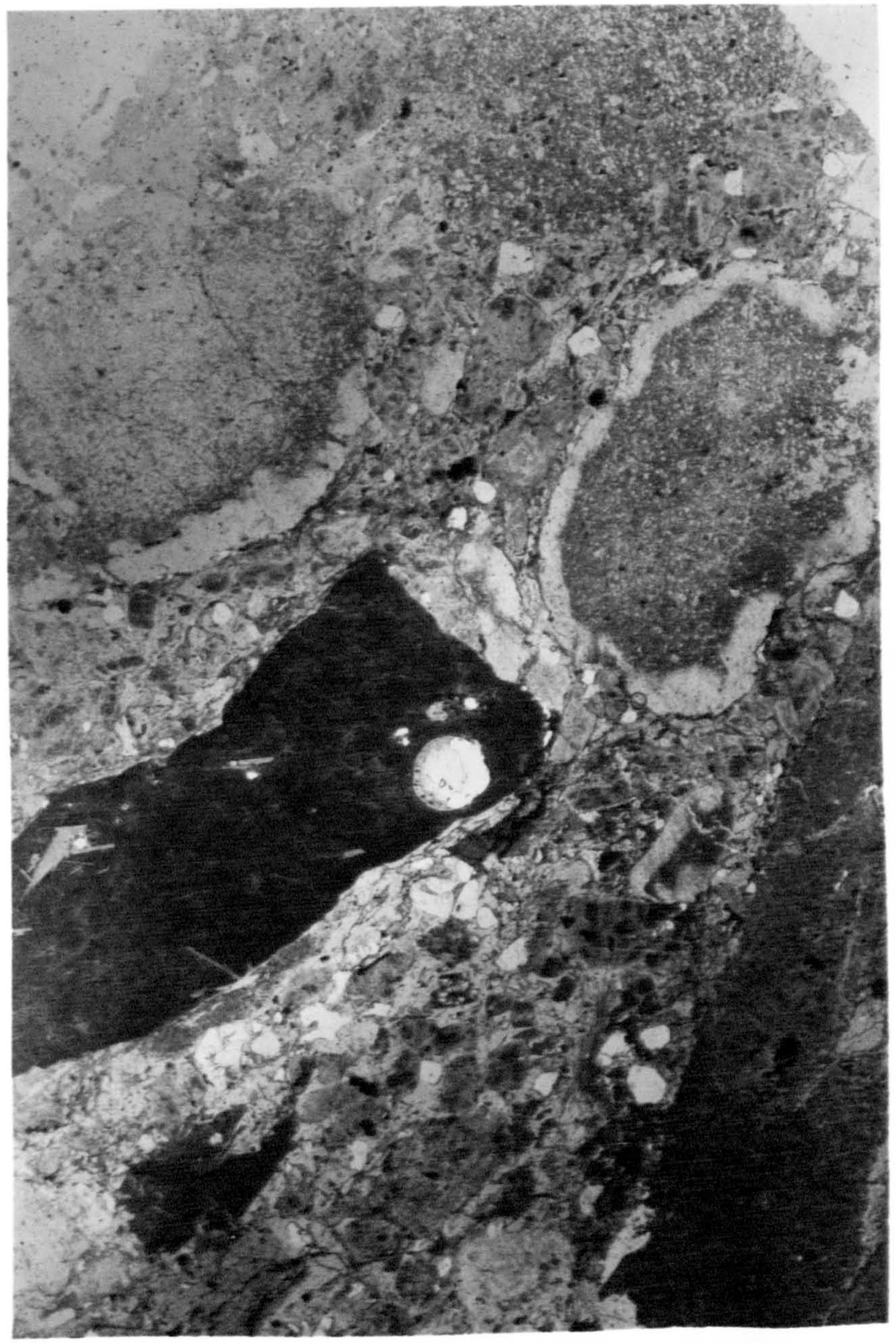
recrystallized glassy lava flow. Small sedimentary clasts are sometimes present, as they are within the lavas around Caer-Lem Farm. Further evidence for an igneous origin for this member may be drawn from the geochemistry of the rocks. A whole-rock analysis of a sample of this member was determined and is listed in Appendix 1 (sample SA5). As can be seen, it shows a similar geochemistry to the rhyolitic lavas of the Pen Caer region and it is therefore considered that the rocks comprising this member are recrystallized, glassy rhyolitic lavas. Parkinson (1897) and Evans (1945) both illustrate similar textures to those described here in rocks from the Prescelly Hills and also consider that the rocks represent glassy lavas which have subsequently recrystallized.

Overlying this lowermost member of the Porth Maen Melyn Volcanic Formation is a 25m thick, graded volcaniclastic breccia (Fig. 122). The actual contact between the rhyolitic member described above and this graded breccia is not clearly exposed, but it appears irregular. The lowermost 10 metres of this graded member is a very coarse breccia with fragments up to 50cm in diameter, although the majority are in the range 10-30cm. Acidic lava fragments predominate (Figs.124 and 126). These are generally composed of fine-grained rhyolitic lava, sometimes showing a perlitic texture. However, near to the base of this member a high proportion of basaltic and doleritic fragments are present (Figs.127a and 6), along with occasional deformed, fine-grained, sedimentary clasts. Little or no sorting is present at this level. Above the lowermost 10 metres an overall reduction in the number of clasts is seen and the member passes from a clast supported breccia to a matrix supported breccia. The fragments within the breccia are chiefly of rhyolitic lava, whilst the matrix contains small rhyolitic and crystal fragments. Upwards, the breccia passes into a coarse volcaniclastic sandstone some 2 metres in thickness. This principally contains the same material as

FIG. 126. Breccia from the Porth Maen Melyn Volcanic Formation, illustrating the angular nature of the fragments (GR 88803932).

FIGS. 127a and b. Sub-rounded to angular basic fragments within breccia of Porth Maen Melyn Volcanic Formation (GR 88803932).

FIG. 128. Components of breccia from Porth Maen Melyn, showing basic fragment (lower centre), rhyolite clasts (left, upper and lower) and abundant crystal debris, particularly quartz, in the matrix. PPL. x6.



the breccias, although crystal debris is more abundant. This coarse sandstone is replaced upwards by 9 metres of fine-grained volcaniclastic sandstone and siltstone. A sharp contact is observed between these beds and the overlying rhyodacite lava flow. As illustrated in Figure 59 this junction is slightly undulatory and it appears that the rhyodacite flow loaded down into the volcaniclastic sediments. Poorly developed flame structures may also be seen.

The breccias are composed of a number of components (Fig.128). Rhyolitic fragments predominate and show a variety of textures, including well-developed perlites and a snowflake texture. Most of the fragments are angular, although a few possess a sub-rounded outline. Basic fragments are rarer. The crystals present are chiefly of broken, angular feldspar and rounded, embayed quartz. The feldspars commonly contain well-formed crystals of apatite. Sometimes these are hollow and contain fluid inclusions, whilst those which are not hollow are generally chemically zoned. The fragments are similar in many aspects to those within the rhyolitic lava breccias exposed around Caer-Lem Farm, described above (S.3.4.1.).

A number of possible origins exist for this volcaniclastic member. Its graded appearance suggests that, unlike the breccias described above (S.3.4.1.), transportation and subsequent deposition of the components has occurred. Horikoshi (1969) described two rock-units from the Kosaka district of Japan which bear resemblances with the member described here. The first of these rock-units, the Uwamuki Tuff Breccia, was deposited from a very dense, gravity-driven, flow of volcanic debris. The second unit, the Motoyama Volcanic Breccia, was produced during a single steam explosion which resulted from the interaction of hot rising magma and relatively cold sea-water. Jaggar (1908) similarily described

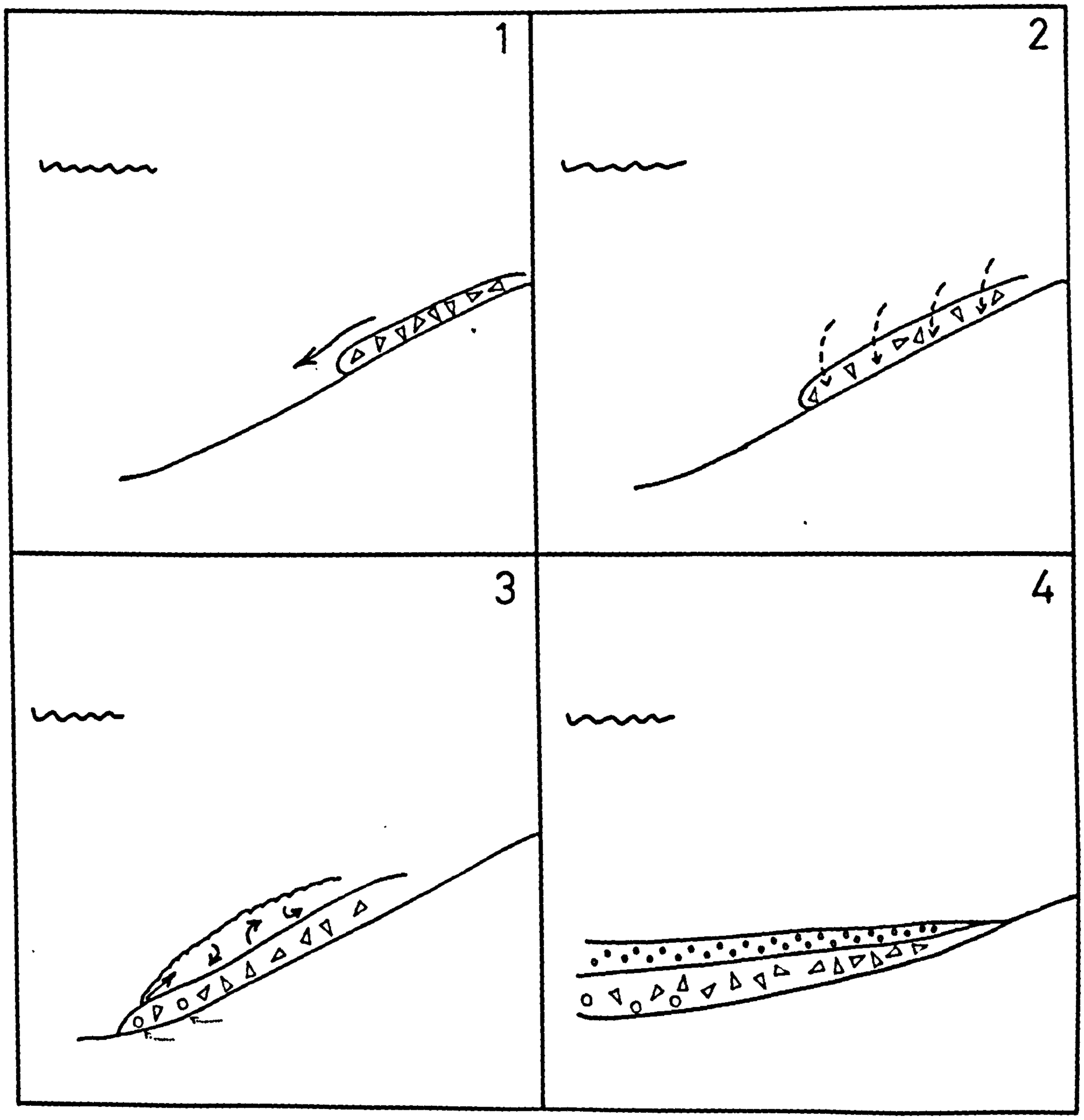
the production of breccias on the Bogoslof Island, Alaska, due to the penetration of sea-water into the fractured domes, resulting in vapourization and explosive disintegration.

The products of these two processes are broadly similar, that is poorly sorted, rhyolitic breccias (with fragments up to 50cm), with a crude bedding and showing a fining upwards in fragment size. In the Porth Maen Melyn breccia, the presence of basic blocks is problematical. If the breccia results from the thermal shattering of the rising rhyolitic magma, then the surrounding strata may also have been shattered and become incorporated with the rhyolitic fragments. Fall of this material through a column of water may result in the crude grading seen.

Alternatively, it is possible that the breccia represents the deposit from a coarse debris flow which was gravity generated. The submarine environment is ideal for the generation of such debris flows. If, as a result of instabilities in the local environment, submarine slides were generated, the incorporation of a small amount of sea-water into this slide would transform it into a highly mobile debris flow. This would move along by internal shear, with the larger blocks being transported by a mixture of interstitial fluid and fine sediment (see Hampton, 1972). Continued flow would result in a region of reverse shear at the front of the flow and material would be eroded from the front of the flow and thrown up into suspension above. This turbid cloud would settle out to produce a fine-grained deposit, overlying a crudely bedded, poorly sorted deposit. As a result of the reverse shear action, the lowermost 1 to 2m are commonly finer-grained than the main part of such units. This process is diagramatically illustrated in Figure 129.

FIG. 129. Possible mechanism for the generation of debris flows and the subsequent formation of deposits similar to that at Porth Maen Melyn.

1. Movement of debris due to instabilities.
2. Incorporation of water, transforming the slide to a debris flow.
3. Turbulent cloud of finer material produced above debris flow. Also incorporation of underlying sediment, particularly if it is unlithified.
4. Freezing of debris flow and settling out of finer cloud above.


1
2
3
4

Further evidence for the origin of this member from a subaqueous debris flow is provided by the lack of evidence for extensive vesiculation within the rhyolitic lavas, which might be expected if the breccias resulted from steam explosions. As mentioned earlier, transitional junctions between rhyolitic lavas and autobreccias are seen in places. These would almost certainly have been destroyed if explosive activity had occurred. In addition, Tazieff (1971), in discussion of Horikoshi's model of steam explosions, states that steam explosions do not occur in a massive body of lava emplaced below sea-level. Only where prior fragmentation of the rock by magmatic explosions (i.e. vesiculation) has occurred do steam explosions take place. Clearly, the lack of evidence for vesiculation within the rhyolitic lavas and rhyolitic breccias of the Fishguard area suggests that steam explosions were not responsible for the origin of these breccias. In addition, the absence of vitric material in this member similarily negates the possibility of extensive vesiculation.

Due to lack of inland exposures, volcaniclastic rocks of the Porth Maen Melyn Volcanic Formation cannot be traced over the Pen Caer region. However, in the Fishguard area, a number of outcrops provide sufficient evidence to illustrate the nature of volcaniclastic horizons in this area. On the east and west sides of Lower Fishguard Harbour the 'porphyritic rhyolitic ash' of Thomas and Thomas (1956, Figs. 6 and 7) crops out. It is composed essentially of crystal fragments along with a small amount of lithic and vitric debris, set within a siliceous matrix. The crystals appear to be predominantly tabular feldspars, up to 2mm in length and green in colour due to alteration, along with broken, quartz crystals. The lithic fragments are of both rhyolitic lava and fine-grained mudstone. On the western side of the harbour the

basal contact of this unit with the underlying sediments is clearly exposed. The junction is highly irregular, with flames of sediment injecting upwards into the volcaniclastics. This, together with presence of incorporated mudstone clasts, suggests that this unit may also represent the deposit of a subaqueous ash flow, similar to that described by Fiske (1963) and Fiske and Matsuda (1964).

In contrast with the Porth Maen Melyn Volcanic Formation, the Goodwick Volcanic Formation displays a wide variety of acidic volcaniclastic rocks. One of the most important horizons is exposed on the eastern side of Anglas Bay (Fig. 118), and may be traced across the headland of Penanglas southeastwards towards Crincoed Point. The apparent thinning in this direction is probably due to slight down-cutting by the adjacent basic intrusive sheet. This member, which is some 60m thick, graded and poorly bedded, is composed of grey volcaniclastic sandstones and breccias which contain abundant lithic fragments (Fig. 130). It displays a gradual fining upwards, with the upper 10m or so composed of fine volcaniclastic siltstones. The base of this member is coarse and rubbly and it overlies the autobreccias of the underlying rhyolitic dome. Although silicified, the lowermost 3 to 5m appear to be composed largely of fragments similar to those of the underlying rhyolitic autobreccias. The nature of the fragments within this member is very variable, with angular rhyolitic lava fragments, dark grey volcaniclastic fragments and occasional fragments of basic lava. The size of these fragments averages 5-6cm, although the larger volcaniclastic fragments reach 30cm in length. The latter are generally elongate and commonly possess a peculiar cuspate outline. They give the appearance of having been in

a semi-consolidated condition prior to erosion, transportation and subsequent deposition within the deposit described here. The matrix which supports these fragments is fine-grained, light grey and contains considerable crystal debris.

Thin section examination of the volcaniclastic fragments within this deposit reveals that they are composed essentially of similar components to those occurring within the matrix of the deposit itself. Both contain quartz and feldspar crystals, as well as micropoikilitic intergrowths of these two phases, set within a siliceous matrix. These are typical phenocryst components of the rhyolitic lavas, and it is suggested that this volcaniclastic deposit was derived from the autobrecciated rhyolitic lavas of a contemporaneous dome. The nature of their derivation, however, is somewhat problematical. The deposit must have been derived from a debris flow which had considerable erosive and transportation potential. In addition, a mechanism must be suggested which was responsible for the separation of the crystals from the rhyolitic lava. It is unlikely that separation occurred at an early stage, such as by ejection of crystals from a vent during explosive activity, as no evidence of such explosive activity is recorded. This offers marked contrast with the crystal rich ash-flow deposits described by Horikoshi (1969), Fiske (1963) and Fiske and Matsuda (1964). At present, however, it is not possible to suggest a mechanism capable of separating the crystals from the liquid lava.

This member is of considerable importance in the reconstruction of a theoretical model for the nature of rhyolitic volcanicity in the Fishguard area. As the rhyolitic domes and their autobrecciated

FIG. 130. Volcaniclastic rocks at Penanglas, showing the presence of included lithic clasts.

carapaces are actually covered by these volcaniclastic rocks, it suggests that the domes represented surface features, that is they were extrusive in nature. As a result, the autobrecciated carapace of loose material provided debris for reworking, resulting in the production of certain volcaniclastic deposits within the area.

Further to the west, volcaniclastic rocks are exposed in the area between Pwll yr Aren (GR 898413) and Pwlluog (GR 904412), and along the west side of Porthsychan (GR 905408). The relationship of the beds between these two areas is complicated by the presence of dip-slip faults. From petrographical considerations, it is thought that they probably represent deposits of a similar origin, both in source of material and mechanism of deposition. The most continuous and well-exposed section extends from Pwll yr Aren eastwards to Carreg Gibi. This section exposes some 15-20m of well bedded, volcaniclastic rocks with bedding striking approximately east-southeast, dipping northeast at about 40°-50° (Figs. 131 and 132). The basal beds are coarse but give rise upwards to volcanic sandstones and siltstones. The coarse beds contain blocks of both basic and acidic volcanic rocks, as well as clasts of sediments and volcaniclastics. The basic blocks are generally angular pillow fragments, although a number are distinctly rounded in outline (Fig. 133) resembling small pillows. Angular, white weathering rhyolitic blocks, up to 6cm in diameter, form the acidic component. Wispy, cuspate, dark grey, lithic clasts are also predominant (Fig. 134) and are similar in nature to the dark grey clasts present within the thick volcaniclastic member at Penanglas. Occasionally, fine-grained sediment occurs as

FIG. 131. Bedded, acid volcaniclastic rocks at Pwll yr Aren (GR 898413).

FIG. 132. Bedded, acidic volcaniclastic rocks at Carreg Gibi (GR 904412).

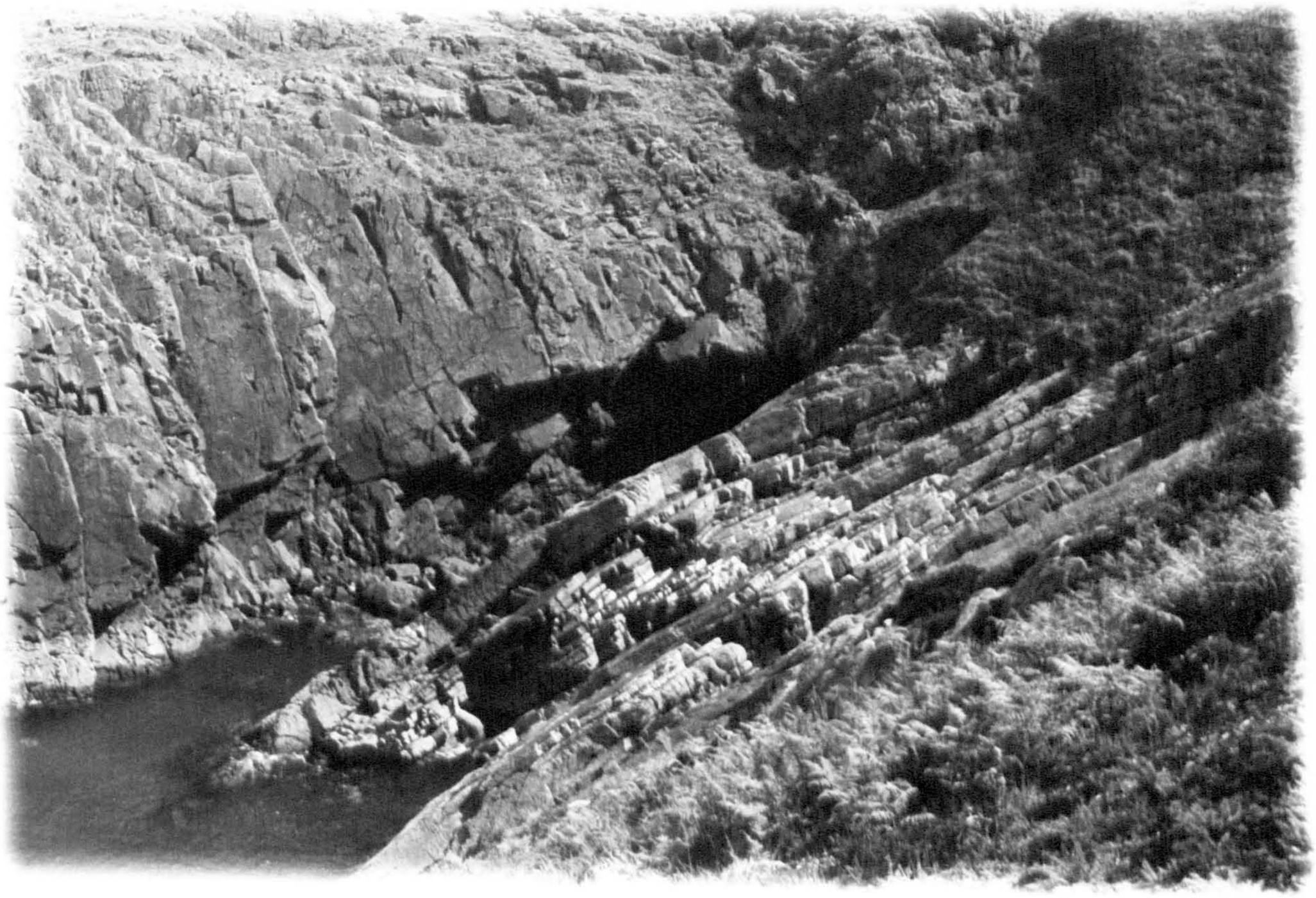
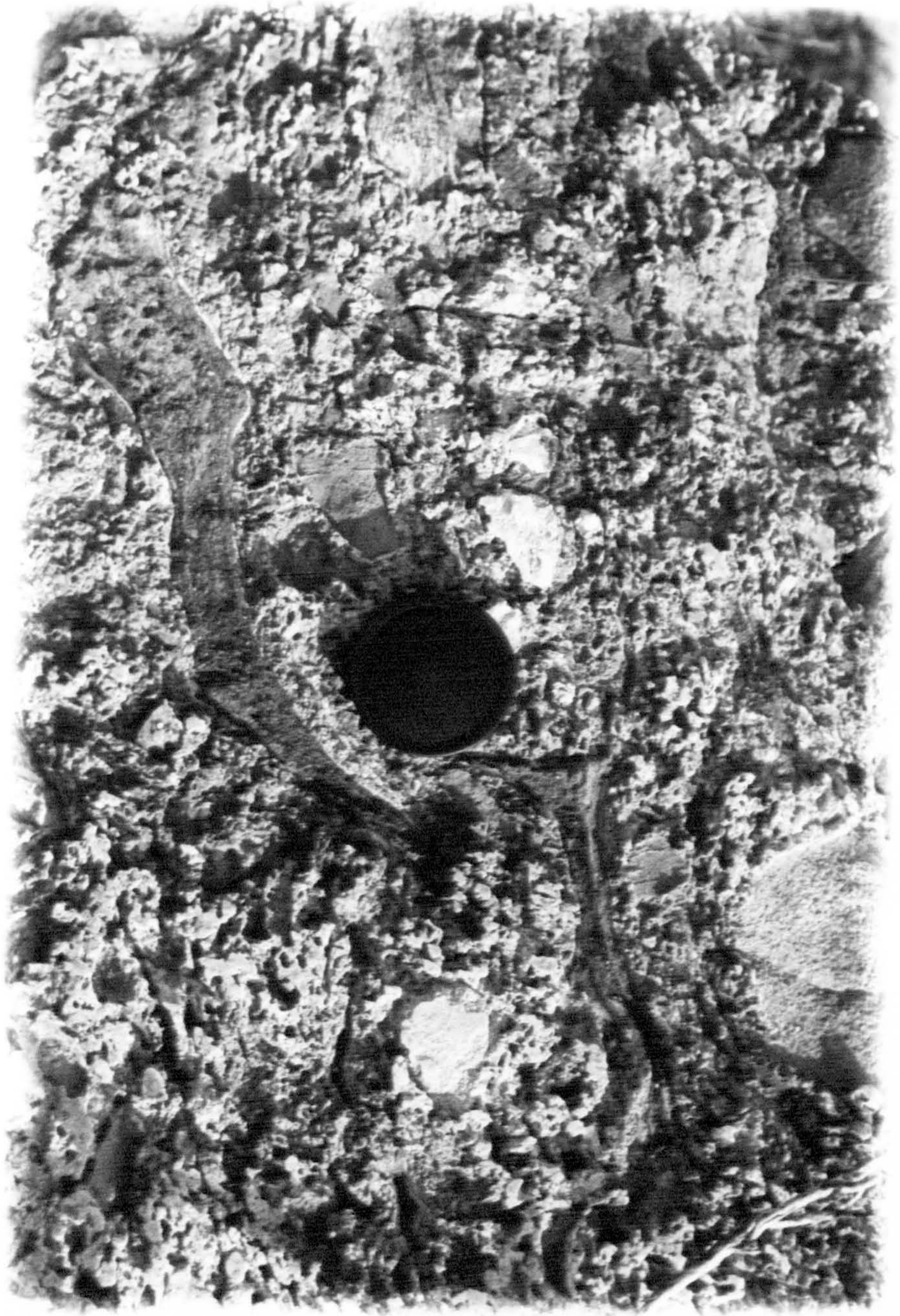


FIG. 133. Rounded basic igneous fragment with coarse volcaniclastic rock, above Pwll yr Aren.

FIG. 134. Cuspate, volcaniclastic fragments within volcaniclastic horizon, above Pwll yr Aren.



thin, flattened clasts which were clearly unlithified at the time of their incorporation. Other clasts retain a planar banding and are thought to have been compacted and probably lithified prior to incorporation. Locally, the underlying sediments have been disturbed and it appears that this member represents a further example of a debris flow deposit.

Thin section examination confirms that the volcaniclastic fragments contain the same components as present within the Penanglas member; that is quartz, plagioclase and minor orthoclase feldspar crystals, as well as micropoikilitic intergrowths of quartz and feldspar. However, in this rock they are set within a chloritized groundmass. Prehnite occurs throughout and commonly replaces the sedimentary and crystal fragments. Vesiculated basic glass fragments are pseudomorphed by chlorite.

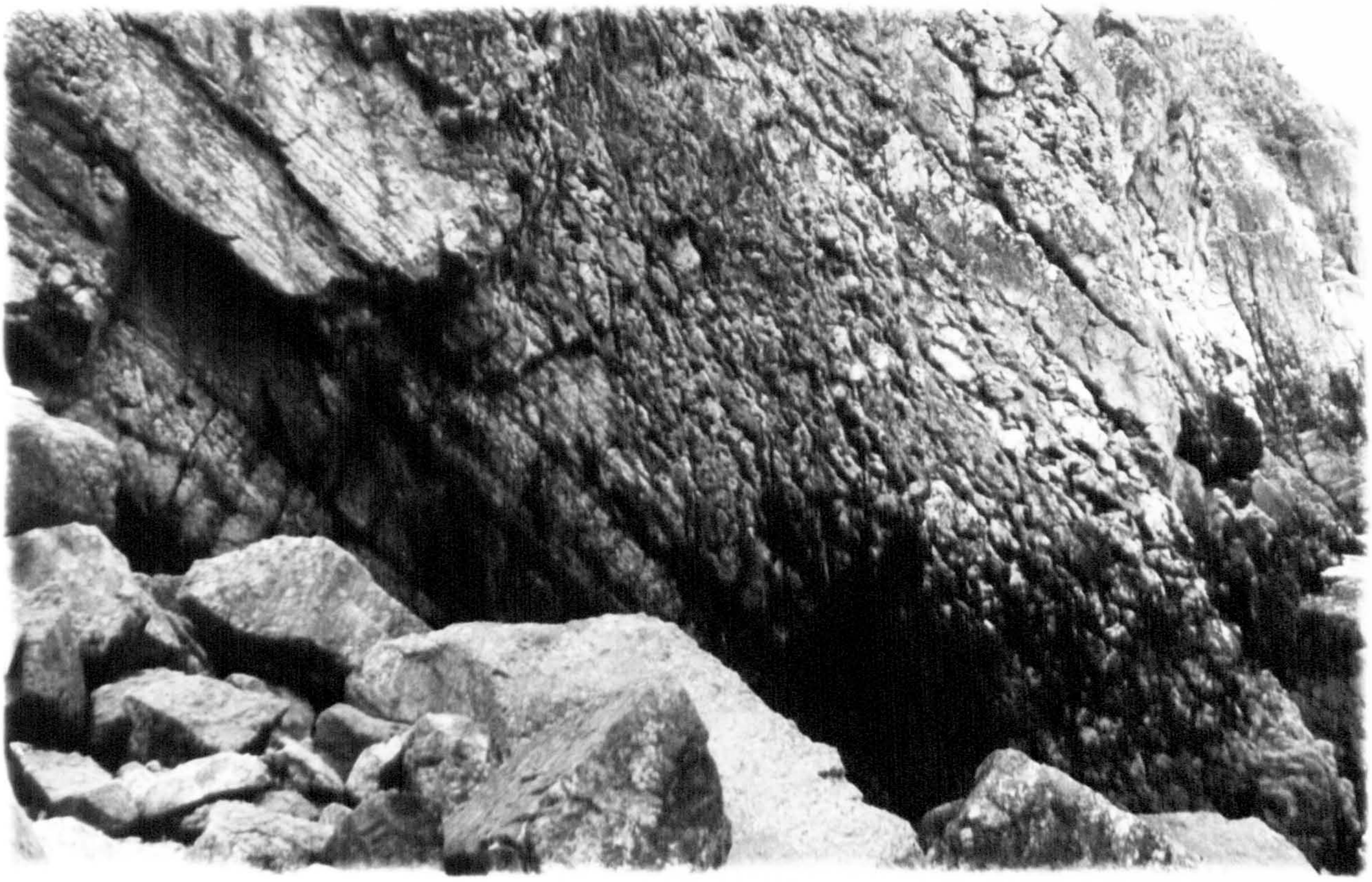
The overlying finer beds, the volcaniclastic sandstones and siltstones mentioned above, were termed 'adinoles and spilosites' by Thomas and Thomas (1956). These rocks show an alternation in grain size although fining upward sequences are occasionally observed. Ripple-drift cross-lamination and load structures are locally present. These represent some of the few sedimentary structures identified within the rocks of the Fishguard Volcanic Group of this area. Within the finer beds small, rounded spherulites, approximately 5mm in diameter are developed (Fig. 135) and are formed due to recrystallization of the fine-grained, siliceous groundmass. No evidence of the introduction of sodium into these rocks from the adjacent Pen Caer doleritic intrusion as suggested by Thomas and Thomas (1956) was found during the present study.

FIG. 135. Spherulitic recrystallization structures in fine-grained, acidic volcaniclastic rock, east of Pwll yr Aren.

Volcaniclastic rocks of a similar nature to those described above are exposed at Porth Sychan (GR 905408), the 'feldspar sands' of Thomas and Thomas (1956). Once again, a coarse base is present, containing both acid and basic lava fragments and volcaniclastic clasts. Above this, however, the beds are fine and appear to be well bedded, as well as showing locally intense folding about E-W axes. The finer beds are grey-brown in colour and contain abundant crystal material which is easily distinguishable in hand specimen. In thin section, this is seen to be composed predominantly of plagioclase feldspar and rounded, embayed quartz crystals, with minor amounts of zircon, set within a fine-grained, siliceous and partly sericitized groundmass.

It is deduced that these volcaniclastic rocks are composed of sand-sized and silt-sized material derived from the neighbouring rhyolitic lavas and were deposited from gravity- or possibly turbidity-driven currents. If this interpretation is correct, then other thin, siliceous horizons containing sparse crystal debris and identified from other horizons in adjacent areas of North Pembrokeshire may represent the fine-grained, distal equivalents of such flows. Units of this kind have been identified, for example, at Trwyn Castel, north of Abereiddy Bay, between Fishguard and St. David's Head.

Possible lateral equivalents of the beds described above are present in the bay at Porth Maen, occurring immediately below the bedded hyalotuffs which were described in section 3.2.1.2. Here bedded, volcaniclastic rocks (Fig. 136) form a unit some 60m thick. Poor exposure limits inland extrapolation, but rocks of a similar nature are also exposed in the Goodwick Harbour area and at Pwll-hir



(GR 952396). These rocks have a very distinctive character, with dark, elongate, wispy clasts set within a light green siliceous matrix (Fig. 137). Thin section examination shows three varieties of fragments, namely:

(i) elongate, glassy, vesiculated fragments of a basic composition containing occasional glomeroporphyritic clusters of plagioclase feldspar crystals;

(ii) fragments of volcaniclastic rocks similar in nature to those from Pen Anglas and Carreg Gibi; and

(iii) acidic lava fragments.

Many fragments appear elongated and are sub-parallel, producing a banding which parallels the bedding. No simple fining upwards is seen, although certain horizons are distinctly finer, with other horizons containing abundant fragmental material (see Figs. 138a and 138b).

One of the rare occurrences of pyroclastic rocks of acidic composition within the Fishguard Volcanic Group of this area crops out at the northern end of the section exposed along the west side of Lower Fishguard Harbour whilst along strike, it may be seen exposed in a new road cutting at Manorwen (GR 938368). In the cliff section at Lower Fishguard Harbour it is seen outcropping from Lampit Mawr towards Saddle Point. These beds conformably overlie the basaltic pillow lavas and hyaloclastites of the much thinned Strumble Head Volcanic Formation, although the upper contact of the beds, with dark pelitic sediments of possible Llandeilo age (Thomas and Thomas, 1956), appears to be faulted. The unit, some 20-30m thick, shows a gradual

FIG. 137. Elongate, dark, wispy fragments within a volcaniclastic rock from Goodwick Harbour Quarry.

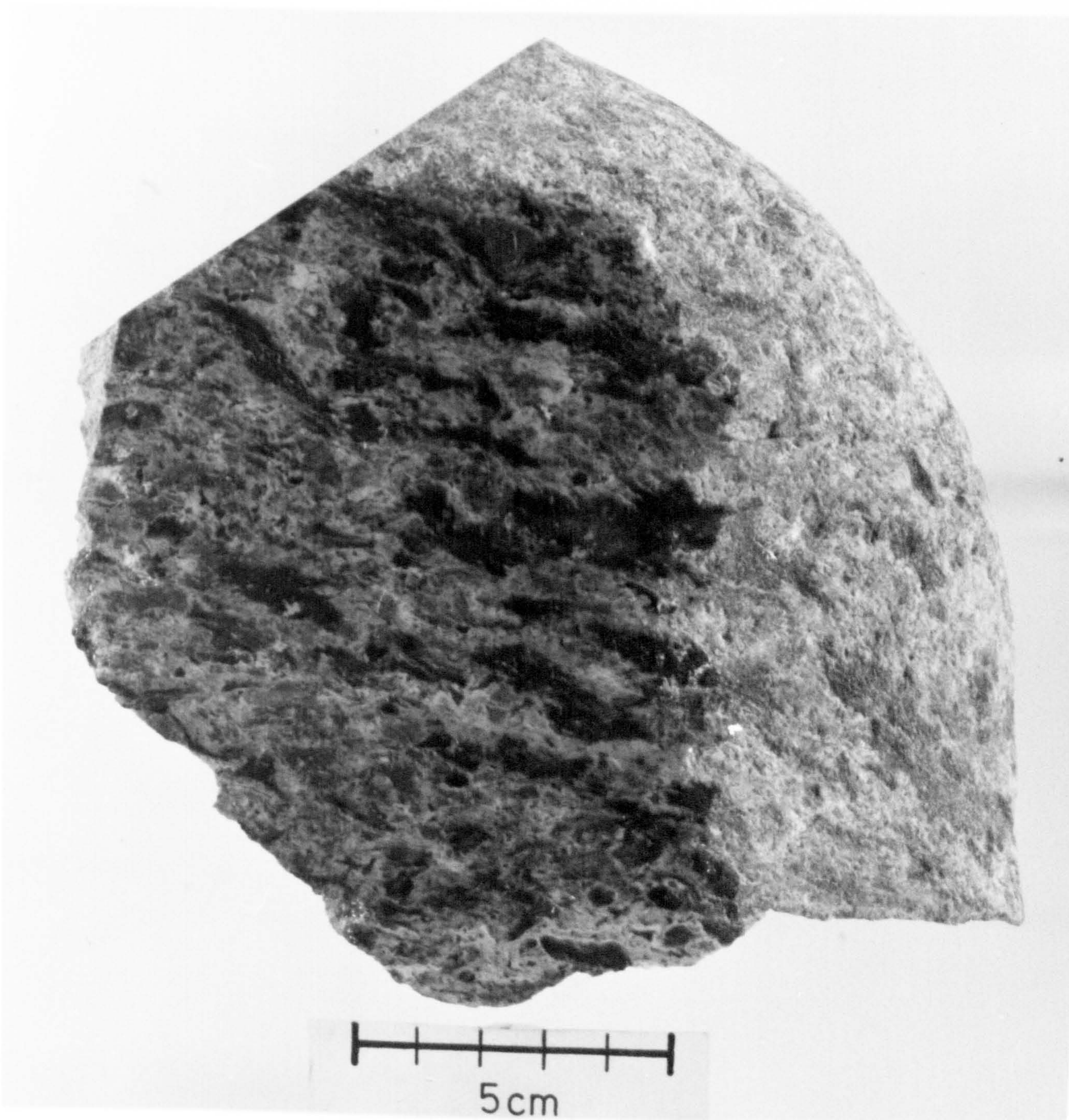
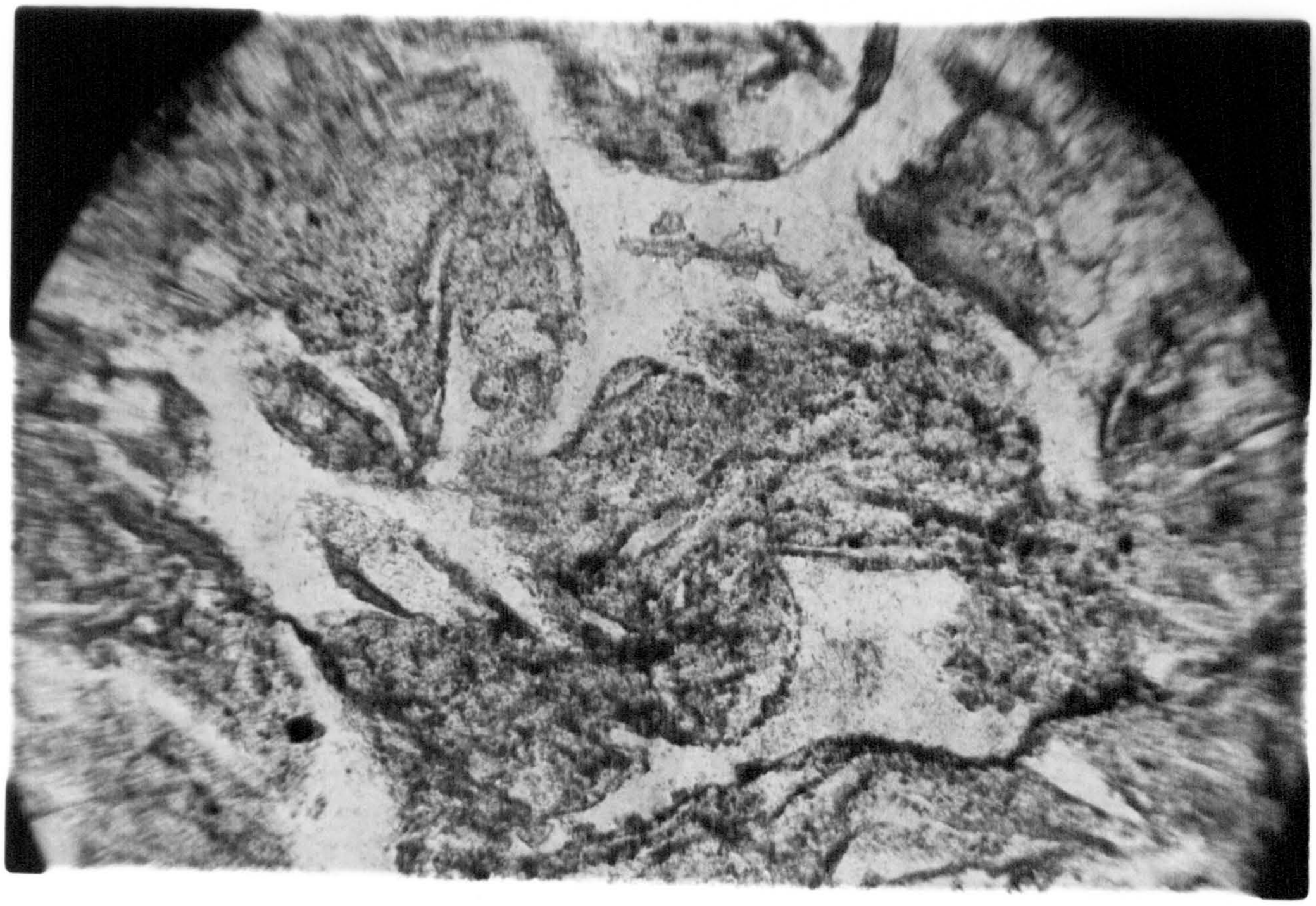

5 cm

FIG. 138a and b. Coarser horizons in volcaniclastic rocks from the Goodwick Harbour area. Angular clasts are chiefly of rhyolitic lava.

FIG. 139. Tubular pumice in subaqueous ash-flow tuff from Lower Fishguard Harbour. PPL. x120.

FIG. 140. Cuspate glass shards in subaqueous ash-flow tuff exposed in road-cutting at Manorwen. PPL. x400.



fining upwards. At the base, lithic fragments, both acidic lava and sedimentary clasts, up to 5cm in diameter, are associated with crystal and glassy debris. Both quartz and feldspar crystals are present and commonly show an angular outline. The glassy volcanic debris is composed of tubular pumiceous fragments (Fig. 139) as well as cuspate or irregular fragments showing well formed vesicles (Fig. 140). These fragments are set within a fine-grained, recrystallized groundmass. Upwards the size of the lithic clasts decreases and sedimentary clasts disappear, but, in contrast, the amount and size of pumiceous and vitric fragments increases. A reverse grading of pumiceous material in subaqueous deposits is common and is considered to be due to the buoyancy of pumice. During the settling out of debris within a column of water, pumiceous material tends to be found associated with the finer fraction. The origin of the unit under consideration here is not clear, although it is suggested that it represents the deposits of a subaqueous ash-flow and the fact that none of the vesicles show collapse structures suggests that it was cold at the time of its emplacement. The presence of a coarse base containing mudstone clasts supports the contention that the unit represents an ash-flow, similar to others identified in the area.

The presence of abundant vitric material in the unit described above and also within the lowermost volcaniclastic unit exposed at Lower Fishguard suggests that debris from explosive eruptions may be important in the ground to the east of Fishguard. In this context, it is important to consider that the nature of material within the acidic volcaniclastic units changes across the Goodwick Syncline.

It appears likely that the units on either side of the syncline had different source provenances, and the amount of shortening due to the fold may be considerable.

Within the Strumble Head Volcanic Formation, thin, bedded, siliceous horizons are occasionally seen, for example north of Carn Melyn (at GR 88904064) and also near Carn Helen (at GR 93334054). They are composed principally of recrystallized quartz and feldspar aggregates, although rarely shardic and pumiceous clasts are observed. It is possible that these represent fall accumulations from distant eruptions.

In conclusion, it is apparent that many of the acidic volcaniclastic horizons of the Strumble Head-Fishguard area contain significant quantities of sedimentary material, particularily in the basal parts of these deposits, in addition to the volcanically-derived material. This testifies to the fact that these horizons resulted from deposition from gravity-driven flows, such as debris flows, which were capable of eroding and incorporating the partly-lithified or unlithified substrate. Naturally the flows were cold and derived from the unconsolidated carapaces of the rhyolitic flows or domes. The examples described here may thus represent a variety of ash-flow whose importance has hitherto been largely unrecognized.