PALAEOZOIC VOLCANOGENIC MINERAL DEPOSITS
AT PARYS MOUNTAIN, AVOCA,
AND S. E. CANADA

-

A COMPARATIVE STUDY

IN TWO VOLUMES

VOLUME I

CHRISTOPHER RICHARD POINTON

submitted for the Degree of
DOCTOR OF PHILOSOPHY

UNIVERSITY OF ASTON
IN BIRMINGHAM

DECEMBER, 1979

PALAEOZOIC VOLCANOGENIC MINERAL DEPOSITS AT PARYS MOUNTAIN, AVOCA, AND S. E. CANADA

Christopher Richard Pointon : Doctor of Philosophy : 1979
University of Aston in Birmingham

SUMMARY

The sulphide mineralisation at Avoca and Parys Mountain is intimately related to volcanism and is of volcanogenic sedimentary type. The associated volcanics are predominantly pyroclastics of rhyodacitic composition and of Upper Ordovician age. They were erupted from discrete small volcanic centres, products of single local volcanic events, whose spatial distribution was related to fractures in the sialic basement of the paratectonic Caledonides of the British Isles. These fractures resulted in linear controls on volcanic, plutonic and tectonic features; they are the result of predominantly strike-slip stresses generated in this part of the European plate during closure of the Iapetus ocean.

The mineralisation, predominantly pyritic, consists of a siliceous footwall zone containing bedded and cross-cutting sulphides and an overlying non-siliceous zone of bedded sulphides which may show vertical zoning of metal ratios. The sulphides are associated with chert and iron formation and have been affected by slumping. Mineralisation developed near the vents during intense fumarolic activity accompanying strong volcanism; at Parys Mountain, fumarolic activity commenced prior to, and continued after, the main volcanic event.

Comparison with similar deposits in Newfoundland and at Bathurst, in the Canadian Appalachians, shows that mineralisation can be associated with any discrete pulse of acid magmatism in shallow subaqueous conditions. Local features of the sulphides and associated sediments are similar, although in more distal deposits (with respect to a volcanic centre) footwall alteration and mineralisation are less well developed.

The nature of the basement and the presence or absence of earlier volcanics are not critical, although establishment of a local tensional regime at the time of ore formation may be important. The volcanics hosting mineralisation are rhyodacitic pyroclastics, generally related to a small centre and representing a single episode of volcanism.

KEYWORDS: Mineralisation; Volcanics; Caledonides; Sulphide.

ACKNOWLEDGEMENTS

I am especially grateful to Dr. J. W. Gaskarth and Dr. R. A. Ixer for their advice and assistance during their supervision of this research.

I also wish to thank Mr. J. W. Platt for his help during my work at Avoca, and the managements of Avoca Mines Limited and Cominco U.K. Limited for access to their properties, and for permission to examine and sample drillcores.

Work in SE Canada was assisted by a grant from the Bosworth-Smith Trust Fund of the Institute of Mining and Metallurgy. I should like particularly to acknowledge the help of Professor D. F. Strong of Memorial University, St. John's, Mr. E. A. Swanson, Chief Geologist, Buchans, Dr. J. G. Thurlow of Price Exploration, Mr. M. J. Collins and Mr. R. Norman, of Consolidated Rambler Mines, and Mr. J. Tuach during my visit to Newfoundland. During work in the Bathurst area, Professor A. L. McAllister, University of New Brunswick, Dr. J. L. Davies, Chief Geologist at the Mines Branch, Department of Mines and Natural Resources in Bathurst, Dr. R. N. Smith, Mr. D. Rutledge and Mr. E. Brooks of Brunswick Mining and Smelting, Mr. A. Buzas of Anaconda Limited, and Mr. W. Gates and Mr. R. Calhoun of Heath Steele Mines all kindly gave their time in discussions, in the field and on underground visits, which is gratefully acknowledged. Thanks are also offered to the respective mine managements who permitted visits to their properties.

I should also like to thank Professor D. D. Hawkes and the academic and technical staff of the Department of Geological Sciences in the University of Aston for practical help and discussions during this research. I am particularly grateful to Dr. M. A. Butterworth for her help with micropalaeontological work.

The research was funded by a research studentship from the Natural Environment Research Council.

Finally, I should like to thank Liz, my wife, not least for typing this thesis.

FOR MY FATHER

CONTENTS

VOLUME I

page
Summary ii
Acknowledgements iii
List of Contents vi
List of Figures x
List of Plates xii

CHAPTER 1. INTRODUCTION

1.1. GENERAL 2

1.2. TECTONIC SETTING WITHIN THE CALEDONIDES 4
1.2.1. The Caledonides of the British Isles 4
1.2.2. The Canadian Appalachians 9

1.3. OBJECTIVES OF THE PRESENT STUDY 11

1.4. PROCEDURE AND WORK METHODS 12
1.4.1. General 12
1.4.2. Details of Work Methods 14

1.5. TERMINOLOGY AND NOMENCLATURE 17

CHAPTER 2. MINERALISATION AT AVOCA

2.1. INTRODUCTION 20
2.1.1. General 20
2.1.2. Mining History 20
2.1.3. Previous Work 23

2.2. STRATIGRAPHY 29
2.2.1. Introduction 29
2.2.2. Ribband Group 31
2.2.3. Duncannon Group 36

2.3. INTRUSIVE ROCKS 73
2.3.1. Diorite Group 73
2.3.2. Dolerite and Microgabbro 75
2.3.3. Feldspar Porphyry 76
2.3.4. Granite 77

page

CHAPTER 2. MINERALISATION AT AVOCA (continued)

2.4. STRUCTURE 78
2.4.1. Introduction 78
2.4.2. Regional Structure 79
2.4.3. Local Structure at Avoca 85

2.5. MINERALISATION 88
2.5.1. The Avoca Mine Area 88
2.5.2. Other Mineralisation in the Avoca Volcanic Formation 98

2.6. DISCUSSION 102
2.6.1. Environment of Volcanism 102
2.6.2. Composition of the Volcanics 105
2.6.3. Age of Volcanism 106
2.6.4. Relationship to Regional Structure 106
2.6.5. Alteration Associated with the Avoca Mineralisation 107
2.6.6. Environment of Mineralisation 109
2.6.7. Genetic Model 111

CHAPTER 3. THE PARYS MOUNTAIN MINERALISATION

3.1. INTRODUCTION 115
3.1.1. History of Mining 115
3.1.2. Previous Work 117

3.2. REGIONAL GEOLOGY 119
3.2.1. Mona Complex 121
3.2.2. Ordovician 121
3.2.3. Igneous Rocks 127

3.3. STRATIGRAPHY 129
3.3.1. Parys Shales 129
3.3.2. Parys Mountain Volcanics 135
3.3.3. Silurian Shales 159
3.3.4. Dolerite 163

3.4. STRUCTURE 163
3.4.1. Introduction 163
3.4.2. Folding 165
3.4.3. Faulting 170
3.4.4. Effect of Primary Lithological Variations .. 171
3.4.5. Conclusion 171

page

CHAPTER 3. THE PARYS MOUNTAIN MINERALISATION (continued)

3.5. MINERALISATION 172
3.5.1. Introduction 172
3.5.2. Mineralisation observed in Outcrop and Drillcore 178

3.6. DISCUSSION 186
3.6.1. Scheme of Mineralisation 186
3.6.2. Age and Stratigraphic Contacts of the Parys Mountain Volcanics 189
3.6.3. Environment of Volcanism 191
3.6.4. Genetic Model 194

CHAPTER 4. MINERALISATION IN SOUTHEASTERN CANADA

4.1. NEWFOUNDLAND 198
4.1.1. Introduction 198
4.1.2. Buchans 200
4.1.3. Pilley's Island 210
4.1.4. Rambler 213

4.2. BATHURST, NEW BRUNSWICK 217
4.2.1. Introduction 217
4.2.2. Brunswick No. 12 Mine 220
4.2.3. Brunswick No. 6 Mine 222
4.2.4. Heath Steele Mines 222
4.2.5. Caribou Mine 224

CHAPTER 5. FEATURES OF COMPARISON BETWEEN THE THREE AREAS

5.1. INTRODUCTION 227

5.2. TECTONIC SETTING 227
5.2.1. Paratectonic Caledonides of the British Isles .. 227
5.2.2. The Bathurst Area 228
5.2.3. Newfoundland 229
5.2.4. Comparison of Tectonic Settings 230

5.3. VOLCANISM 231
5.3.1. Paratectonic Caledonides of the British Isles .. 231
5.3.2. Canadian Appalachians 232
5.3.3. Discussion 233

page

CHAPTER 5. FEATURES OF COMPARISON BETWEEN THE THREE AREAS (continued)

5.4 HOST ROCKS 233

5.5. SLUMPING 237

5.6. SULPHIDE MINERALISATION 238

5.7. ALTERATION 240

CHAPTER 6. SUMMARY OF CONCLUSIONS 242

REFERENCES 248

APPENDICES

APPENDIX 1. Stereographic Plots of Structural Data from the Avoca Area 256

APPENDIX 2. Chlorite Determinations 263

APPENDIX 3. Micropalaeontological Investigation - Digestion Procedure 266

VOLUME II

Map Supplement (see List of Figures)

LIST OF FIGURES

page

CHAPTER 1.

1.1. Paratectonic Caledonides of the British Isles 3
1.2. Refit map showing location of the deposits 5
1.3. Diagrammatic representation of Iapetus margins in the British Caledonides 5

CHAPTER 2.

2.1. Avoca Mines - Main areas of old workings 21
2.2. Regional Stratigraphic Correlation 24
2.3. Simplified Geological Map of SE Ireland 25
2.4. Avoca area - Stratigraphy 30
2.5. Locality Map - Avoca area 32
2.6. Avoca Area - Geology .. .. Volume II
2.7. Geological Section through Avoca-Ballymoyle Hill Area Volume II
2.8. Diagrammatic stratigraphic column for Ballymoyle Hill - Castletimon area 39
2.9 Diagrammatic stratigraphic column for Avoca area .. 50
2.10. Avoca Volcanic Formation - stratigraphic correlation with previous work 52
2.11. Correlation between the Avoca Volcanic Formation and the 'Mine Sequence' of Sheppard (in press) 53

CHAPTER 3.

3.1. Geological Map of Northeast Anglesey .. .. .. Volume II
3.2. Geology of Parys Mountain .. .. Volume II
3.3. Parys Mountain Drill Section 8600'E .. .. Volume II
3.4. Parys Mountain Drill Section 9000'E .. .. Volume II
3.5. Parys Mountain Drill Section 9800'E .. .. Volume II
3.6. Parys Mountain Drill Section 10,600'E .. .. .. Volume II
3.7. Parys Mountain Drill Section 11,000'E .. .. .. Volume II
3.8. Stratigraphic sequence in the Parys Mountain area .. 120
3.9. Lithological variations in the Ordovician of Northeastern Anglesey 123
3.10. Stratigraphic sequence on the north side of Parys Mountain 130
3.11. Parys Mountain, Geology 131
3.12. Diagrammatic E-W Section 137
3.13. Parys Mountain Structure after Greenly and Manning 164

page

CHAPTER 3. (continued)

3.14. Average assay values of ore specimens 173
3.15. Grouping of Lodes at Parys Mountain 174
3.16. Paragenetic sequence of ore minerals 177
3.17. Proposed scheme of silica paragenesis 179
3.18. Relationship of mineralisation to stratigraphy .. 180

CHAPTER 4.

4.1. Newfoundland - Tectonic Zones and Lower Palaeozoic Volcanics 199
4.2. Diagrammatic section of the Buchans Area 202
4.3. Geological map of the Buchans Area 203
4.4. Cross-section, Buchans 203
4.5. Alteration and mineralisation at Buchans 206
4.6. Spatial relationships of the Buchans orebodies .. 207
4.7. Isopach of Oriental-Sandfill-Middle Branch ore horizon 208
4.8. Simplified Geological Map - Rambler area 214
4.9. General geology of the Bathurst-Newcastle camp .. 218

LIST OF PLATES

Plate — facing page

PHOTOMICROGRAPHS OF THE BALLYMOYLE VOLCANIC FORMATION

1. Lavas 41
2. Lavas and Pyroclastics 45
3. Pyroclastics 46

PHOTOMICROGRAPHS OF THE AVOCA VOLCANIC FORMATION

4. Ballinamona Member 55
5. Ballinamona Member 56
6. Cronebane Member 64
7. Cronebane Member 65
8. Cronebane Member 66
9. Cronebane and Ballymurtagh Members 67

PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS

10. Rhyolite and Pyroclastics 140
11. Siliceous Sinter 147
12. Siliceous Sinter 148
13. Siliceous Sinter and Chert 149
14. Chert and Chloritic Chert 153
15. Chloritic Chert and Shales 154
16. Volcaniclastics 161
17. Volcaniclastics 162

COLOUR PLATES

18. Avoca Volcanic Formation - Cronebane Member 68
19. Avoca Volcanic Formation - Cronebane Member 92
20. Sulphide Mineralisation at Avoca 93
21. Parys Mountain - Rhyolite and Volcaniclastics 141
22. Parys Mountain - Siliceous Sinter 145
23. Parys Mountain - Chert and Siliceous Sinter 146
24. Parys Mountain - Volcaniclastics 160
25. Parys Mountain - Structure 168
26. Parys Mountain - Structure and Slumped Chert 169

CHAPTER 1

INTRODUCTION

1.1. GENERAL

The base metal sulphide deposits at Avoca in SE Ireland and at Parys Mountain in Anglesey, North Wales, have both had a long history of mining and are the subjects of current mining and exploration activity. The deposits lie in the paratectonic Caledonides of the British Isles, and are intimately associated with volcanic rocks of Lower Palaeozoic age (fig. 1.1).

In the northern Appalachian area of the Caledonian-Appalachian orogenic belt, important provinces of volcanogenic sedimentary sulphide mineralisation occur in Newfoundland, and in the Bathurst-Newcastle area of New Brunswick. The deposits at Rambler, Buchans and Pilley's Island in Newfoundland and the Brunswick No. 6, Brunswick No. 12, Heath Steele and Caribou deposits from the Bathurst camp are considered here as typical examples (fig. 1.2).

The environment of volcanism, the tectonic setting and details of the mineralisation and host rocks of these deposits are described. These features are used as a basis for a comparative study in which the important common features and critical factors in the location and development of volcanogenic sedimentary sulphide deposits in this part of the Caledonian-Appalachian orogen are discussed.

Fig. 1.1 Paratectonic Caledonides of the British Isles

1.2. TECTONIC SETTING WITHIN THE CALEDONIDES

1.2.1. The Caledonides of the British Isles

The Caledonides of the British Isles are commonly divided into the "orthotectonic" or "metamorphic" Caledonides, and the "paratectonic" or "non-metamorphic" Caledonides (fig. 1.2). In the orthotectonic zone, structural deformation is complex and polyphase with large horizontal movements in nappes and recumbent folds of regional scale; metamorphism reaches granulite facies, and has a well zoned gradation to lower grade assemblages (Dalziel, 1969; Winchester, 1974; Roberts, 1976).

In the paratectonic Caledonides most areas show a single dominant penetrative cleavage and one major period of folding, which was induced by strain having a dominant wrench component (Dewey, 1969a). Major nappes, thrusts and recumbent structures are not present, and the metamorphic grade lies within the lower green-schist and prehnite-pumpelleyite facies (Dewey, 1969a; Phillips et al., 1976).

The model for Caledonian plate tectonics developed by Phillips et al. (1976) showed the orthotectonic Caledonides to be composed of sediments and volcanics related to the northwestern margin of the Iapetus ocean. They suggested that the polyphase deformation and metamorphism was related to complex effects of subduction along this

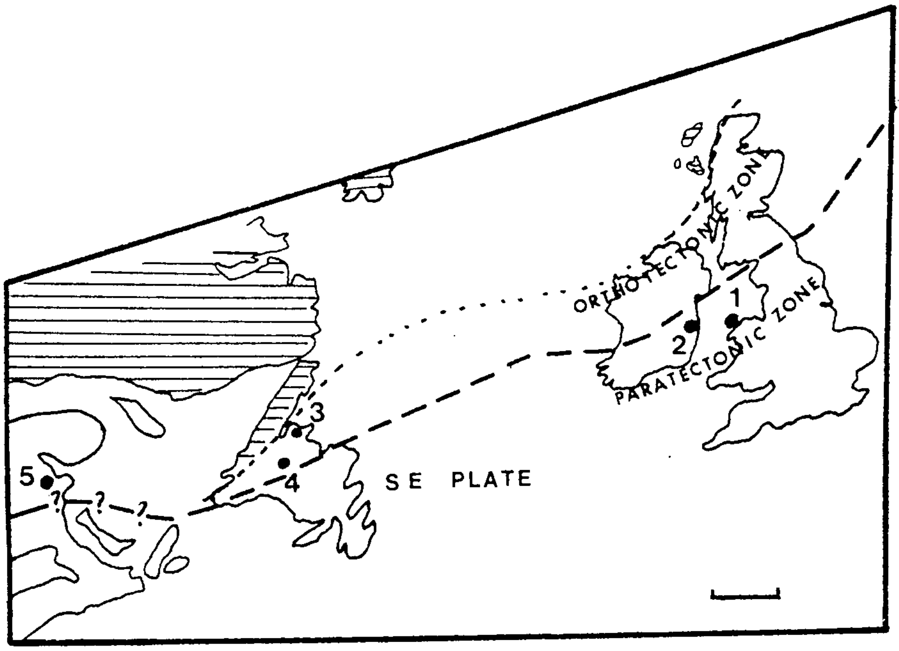
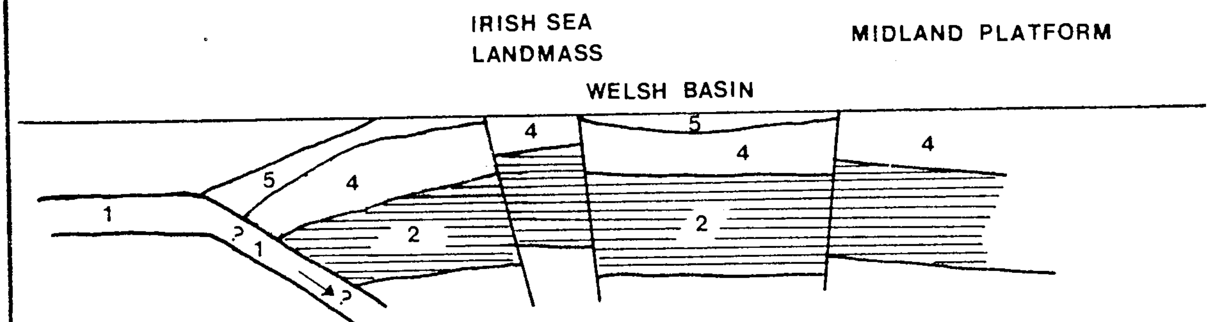


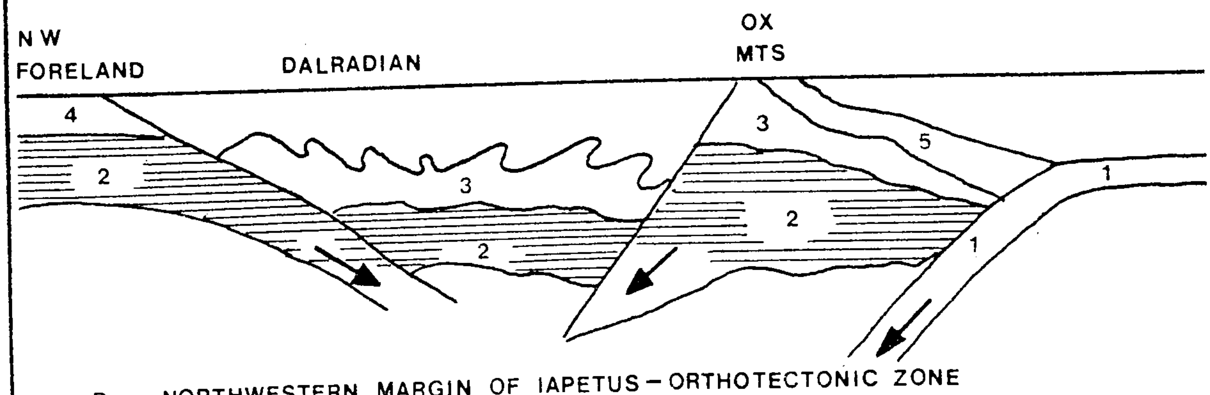
Fig 12 Refit map showing location of the deposits, the SE plate, & Grenville basement (≡)

1 Farys Mountain, 2 Avoca, 3 Rambler,
4 Buchans, 5 Bathurst.

(modified from Phillips et al 1976)



A SOUTHEASTERN MARGIN OF IAPETUS – PARATECTONIC ZONE



B NORTHWESTERN MARGIN OF IAPETUS – ORTHOTECTONIC ZONE

5 L Palaeozoic sediments & volcanics
4 Monian & Laxfordian
3 Morarian
2 Lower continental crust
1 Oceanic crust

Fig 1.3 Diagrammatic representation of Iapetus margins in the British Caledonides (modified from Phillips et al 1976) northwestern margin. The central zone consisting of Dalradian rocks represented an ensialic arc (fig. 1.3); there was attempted subduction beneath this arc of Lower Palaeozoic marginal basins (the Ox Mountains and Southern Uplands) and oceanic crust from the southeast, and, at the same time, of sialic crust of the American plate (rocks of Lewisian age) from the northwest (Phillips et al., 1976).

The Paratectonic Caledonides of the British Isles exhibit tectonics dominated by a wrench component. This, together with studies of facies distribution, volcanism, magnetics and gravity data, led Phillips et al. (1976) to propose that during the closure of Iapetus much of this zone formed a plate margin which lay at a low angle to the principal direction of plate movement. Thus much of the movement on this plate boundary was transcurrent (figs. 1.2, 1.3). Such a hypothesis is consistent with the observed features of this zone, most notably the single major penetrative cleavage, essentially upright major structures, and the northeasterly trend of both late and early Caledonian tectonic features and depositional basins. It is also consistent with the regional structural analysis of Dewey (1969a).

The major features of the paratectonic zone during the Lower Palaeozoic may be summarised as follows. During the Cambrian in SE Ireland, deep water turbiditic sediments of the Bray Group were deposited in a NE-SW elongate trough (Shannon, 1976) which lay between land to the north in County Meath (Phillips et al., 1976) and a complex horst composed of Precambrian metamorphic rocks (the Irish Sea Landmass) to the southeast (Jones, 1938; Dalziel, 1969; Shannon, 1976). Equivalent Cambrian rocks are not exposed in northern England.

In Arenig and Llanvirn times a transition to distal turbidite deposition took place in this basin. This sequence is represented by the Ribband Group in SE Ireland, the Manx Slates in the Isle of Man, and the Skiddaw Slates in the Lake District. The Irish Sea Landmass was probably still a weakly positive feature, and the distal character of the turbidite sequence may reflect low rates of supply rather than deep water conditions (Shannon, 1976).

Volcanism in the Ordovician was apparently related to regional fractures, and there is evidence of a linear control which may be related to basement structures consistent with the transcurrent stresses predicted by the plate tectonic model described above.

Lower Ordovician volcanism occurred in three belts which trend parallel to the Irish Sea Landmass. The first, consisting of basic to intermediate, mainly tholeiitic volcanics, occurs in Co. Meath, and probably extends in time into the Upper Ordovician (Stillman et al., 1974). The second, comprising intermediate and basic volcanics, occurs in the English Lake District and perhaps also includes the lower units of the volcanic succession in the Waterford area. The third volcanic sequence is developed in the Welsh Basin and consists largely of acid and intermediate volcanics.

A second major period of volcanism involving the whole of the paratectonic Caledonides, reached its maximum in Upper Ordovician (Caradocian) times. This Upper Ordovician volcanism was related to renewed fracturing and the development of fault-bounded basins in the European plate (Phillips et al., 1976). It was more widespread than the Lower Ordovician event. Large complex volcanoes were developed in the Lake District and in the Waterford area; their products grade from basalt through andesite to rhyolite in composition, with acid-intermediate volcanics being dominant. These volcanics were partly subaerial. Between these two centres, a number of small vents developed, including those in the Avoca area. The products of these vents were largely rhyodacitic pyroclastics, and their chemistry was described by Stillman et al. (1974) as calc-alkaline to alkaline and of "Andean" type.

The volcanism in Anglesey at Parys Mountain, occurring on the inner eastern flank of the Irish Sea Landmass in latest Ordovician to earliest Silurian times, represents a late example of this volcanic episode. Caradocian volcanism also occurred in the Welsh Basin where large volumes of rhyolitic pyroclastics were deposited in a subaerial environment.

No major volcanic episode is represented in the Silurian succession of the paratectonic zone. Clastic sedimentation occurred in broad basins which draped the earlier structures, indicating that the basement fractures which had controlled earlier volcanism and sedimentary basin development had a negligible influence during this period (Dewey, 1969a).

In conclusion, the paratectonic Caledonides represent the margin of the European continental plate during the closure of the Iapetus ocean. The tectonics and volcanism of the area show some similarities to a continental-oceanic plate boundary of the Andean type. However, the relative plate motions were for much of the Lower Palaeozoic oblique or parallel to the plate boundary which was therefore not strongly destructive. The major movements were transcurrent, resulting in a predominantly strike-slip stress and the development of linear fractures in the sialic basement of the European plate which exerted a strong control on volcanism and sedimentation.

1.2.2. The Canadian Appalachians

In the northern Appalachians the closure of Iapetus resulted in largely normal relative plate motions, although in Newfoundland a transcurrent component may have been important, its later effects being illustrated by, for example, the strike-slip Cabot Fault (Dewey, 1969b). Swinden and Strong (1976) have summarised recent views on the tectonic evolution of the Newfoundland Appalachians. They suggested that in Cambrian to Lower Ordovician two subduction zones existed. The southeastern margin of the Iapetus ocean was a destructive plate margin of Andean type; a second destructive margin was developed within oceanic crust, resulting in an ensimatic island arc in what is now central Newfoundland. This situation terminated with the Taconian Orogeny in Middle Ordovician time when subduction of oceanic crust ceased, as the Iapetus ocean closed.

In post-Caradocian times the early island arc and ophiolite sequences occupying central Newfoundland were covered by a flysch sequence followed by partly subaerial Silurian volcanics which reflect the final contraction of the Iapetus zone and consolidation of the crust in central Newfoundland. This culminated in the Devonian Acadian Orogeny. For a full description of the Lower Palaeozoic tectonics of the Newfoundland Appalachians, the reader is referred to Swinden and Strong (1976) and Strong (1977).

In New Brunswick the Cambrian to Lower Ordovician sequence is composed of slates, quartzites, siltstones and greywackes (Ruitenberg, 1976) which may represent a marginal basin sequence, although there is little information available on the nature of the underlying basement. These sediments are overlain by felsic volcanics and later basaltic volcanics, which were developed at a destructive plate boundary between the northwestern continental plate and oceanic crust of the Iapetus ocean (fig. 1.2).

The tectonic environment for the volcanics in the Lower Ordovician at Bathurst may thus have been an ensialic volcanic arc on the northwestern margin of the Iapetus ocean. This regime was terminated in the Middle Ordovician by closure of the Iapetus and the resulting Taconian Orogeny. Clastic sedimentation followed, accompanied by subaerial volcanism during consolidation of the crust in the central zone of the Appalachian fold belt. This consolidation culminated with the Acadian Orogeny in the Devonian.

1.3. OBJECTIVES OF THE PRESENT STUDY

The relationship between volcanism and sulphide mineralisation forms the main emphasis of this study. The first objective has been to test the validity of the volcanogenic exhalative sedimentary model for the origin of the sulphide mineralisation at Avoca and Parys Mountain, and to derive a genetic model relating mineralisation to volcanism for each of these deposits.

A stratigraphy has been derived for the volcanic rocks associated with the Avoca and Parys Mountain deposits, and this is related to the regional stratigraphy and tectonics, and also to the type, distribution and mineralogy of the ores. It is also intended to demonstrate the relationships and significance of the characteristic alteration of the volcanic host rocks, and the development of sediments of exhalative origin associated with the sulphide deposits. An attempt is thus made to relate ore formation to a volcanic stratigraphy and to deduce some of the controls on ore formation in this volcanic environment.

The comparison of features of the volcanic-sedimentary sulphide deposits within the paratectonic Caledonides of the British Isles with those of the Canadian Appalachians is intended to distinguish features of local importance in the paratectonic zone from those of more general significance.

1.4. PROCEDURE AND WORK METHODS

1.4.1. General

In the Avoca area the ore mineralogy and the distribution of the sulphide ores were described by Wheatley (1971a), who, together with Platt (1976), discussed the structure and the host rock lithologies. Wheatley (1971a, b) also discussed the broad scale tectonic setting of the mineralisation. However, the relationship of the mineralisation to the volcanic sequence in the Arklow-Wicklow areas was not known, neither were the details of the volcanic rocks and their stratigraphy.

The first part of the present study at Avoca therefore involved compilation of a geological map of the Arklow-Rathdrum area (fig. 2.6), derivation of a stratigraphy, and interpretation of the sequence of Ordovician volcanism. The second part related volcanic stratigraphy to the mineralisation at Avoca and in adjacent areas.

At Parys Mountain the ore mineralogy had been studied by Greenly (1919), Wheatley (1971a) and Thanasuthipitak (1974), and some descriptions of the volcanic rocks (Thanasuthipitak, 1974) and stratigraphy (Hawkins, 1966) had been presented. The Ordovician stratigraphy of Anglesey had been described by Bates (1972) and a 1:50,000 scale map based on the work of Greenly (1919) was available.

Field mapping for the purposes of the present study was therefore restricted to Ordovician rocks east of Parys Mountain as outlined by Greenly (1919). The lithologies mapped were related to the work of Bates (1972) to obtain a stratigraphic and structural interpretation for the setting of the Parys Mountain deposit.

At Parys Mountain itself, the host rock lithologies and structure had received limited attention and an outcrop map of the mine area was made at a scale of 1:5,000. Five cross-sections of the central part of the mine were prepared using sections with the most available drillcore. A stratigraphy and structure were derived for the mine area on the basis of outcrop, drillcore and petrographic studies, and were then related to the observed and reported occurrences of sulphide mineralisation.

In SE Canada no detailed studies were undertaken. Two weeks were spent in Newfoundland and two weeks in the Bathurst area, during which time data was collected from representative drillcores, underground visits, and from plans and sections made available by the mine managements. Outcrops were examined in the vicinity of the mines and on a limited number of traverses and at isolated exposures in both areas. The data collected during these visits amplified a study of the relevant literature.

1.4.2. Details of Work Methods

Mapping in much of the Arklow-Rathdrum area (fig. 2.6) is of a reconnaissance nature, with detailed mapping concentrated on the Avoca Volcanic Formation. A reliability diagram indicating the relative detail of coverage is inset in figure 2.6. Reconniassance mapping was based on traverses 0.5km. to 1km. wide and 1km. to 3km. apart, along which all available exposures were examined. Float, especially that in ploughed fields, was logged where evidence was available that it represented subcrop, and superficial deposits, in particular boulder clay and fluvioglacial deposits, were recorded. Float observations and outcrop areas are indicated separately in figure 2.6.

Traverse locations were planned during preliminary air photo interpretation and were designed to intersect the best exposed and geologically critical areas. For example, in the Ballymoyle Hill and Castletimon areas the traverse width was increased.

Traverse mapping data was collected on 1:10,000 scale photo-overlays (aerial photography by Vale Exploration, 1959) or onto Suirbheireacht Ordonais 1:10,560 base sheets where photographic coverage was not available. The mapping was compiled onto 1:10,560 base sheets, together with secondary air photo interpretation, using both the 1:10,000 scale photography and 1:30,000 photography (Geological Survey of Ireland, 1973). The extent of the photographic coverage is shown in figure 2.6. The reconnaissance mapping was largely completed in one field season of some two and a half months.

The area of the Avoca Volcanic Formation was outcrop-mapped on 1:10,000 scale photo-overlays in a second field season of two and a half months. This more detailed mapping was also compiled at 1:10,560. The combined results of the reconnaissance and detailed mapping are presented at 1:25,000 scale in figure 2.6.

The vicinity of the old workings at Parys Mountain was mapped at 1 : 5,000 scale using a combination of 1:10,000 aerial photography and enlarged Ordnance Survey base maps. The results are shown in figure 3.2.

Outcrop mapping of the area east of Parys Mountain used 1:10,000 scale photo-overlays (aerial photography by Meridian Airmaps Ltd., July 1971) and is presented at 1:10,000 scale in figure 3.1.

Logging of drillcore at Parys Mountain was on a conventional basis in which visual estimates of total sulphides, carbonate, sericite and chlorite were combined with hand-specimen and thin-section descriptions in tabulated form. Abbreviated descriptions are shown in figures 3.3 to 3.7. Representative samples were taken for petrographic study and existing sample material from the the collection of Thanasuthipitak (1974) was also used.

Mineral determinations on carbonates were by powder X-ray Diffraction using Cu $K\alpha$ radiation with a Ni $K\beta$ filter. Chlorite determinations were carried out by X-ray Diffraction using the Debye-Scherrer camera, the chlorites being extracted from thin-sections under the microscope to ensure that no sericite or clay minerals were included. Details of these determinations are given in Appendix 2.

1.5. TERMINOLOGY AND NOMENCLATURE

The terminology used is generally in accordance with definitions given in Gary et al. (1972). Lithological terms (such as "shale", "siltstone", "slate") are used as field names and accurate petrographic terminology is not implied. "Shale" describes fissile mudrock lacking visible grains, and "slate" is used where such rocks possess slaty cleavage; where cleavage is associated with mica flakes visible in hand-specimen, the term "phyllite" is used, and, in cases of strong development of mica, "schist".

"Siltstone" is used for rocks whose detrital granular composition is detectable but where individual grains are not readily visible in hand-specimen. "Arenite" describes epiclastic rocks with average grainsize below 2mm., and arenaceous rocks with 20% or more clay matrix are termed "greywacke". Epiclastic rocks of grainsize coarser than 2mm. are termed "rudites".

For fragmental volcanic rocks the terminology of Fischer (1966) is followed. Lithological terms for lavas are based on hand-specimen and thin-section criteria; thus "rhyolites" are siliceous lavas with quartz and alkali-feldspar phenocrysts whilst "dacites" contain plagioclase feldspar phenocrysts when porphyritic. The term "dolerite" implies some degree of ophitic fabric, and "microgabbro" is used for fine-grained equigranular intrusive rocks of intermediate composition. Other terms used are consistent with definitions in Gary et al. (1972).

In descriptions of sulphide ores, "massive sulphides" implies a rock composed of at least 70% sulphide minerals by volume. The terms "black ore" and "bluestone" refer to polymetallic sulphide ores rich in sphalerite and galena. "Yellow ore" is used for sulphide ore consisting predominantly of pyrite and chalcopyrite. The term "stockwork" implies a network of cross-cutting veins carrying sulphides.

Existing stratigraphic nomenclature has been followed where possible. Where new names have been used, the nomenclature is intended to be informal, pending erection of a recognised formal regional stratigraphy in publications of the Geological Survey of Ireland and the Institute of Geological Sciences. The stratigraphic units are referred to type areas, but type sections may be inadequately exposed for complete formal description.

Thicknesses quoted are estimated apparent stratigraphic thicknesses. Since outcrop is poor, allowance cannot be made for the effects of fold closure in many instances, and the effects of structural shortening or extension have not been taken into account. True thicknesses are not implied unless this is specifically stated. Grid references are in accordance with the appropriate National Grid.

CHAPTER 2

MINERALISATION AT AVOCA

2.1. INTRODUCTION

2.1.1. General

Avoca lies some 50km. south of Dublin in County Wicklow, in rolling farmland at an elevation of around 200m. The area is cut by the Avoca River which reaches the sea at the port of Arklow, some 10km. from the mine.

The Avoca mineralised zone has traditionally been divided into six parts, and more recently into East and West Avoca (see fig. 2.1). It has a strike length of 4km., and averages up to 100m. in width at grades of 0.3% to 0.5% Cu, and contains zones of higher grade on which mining has so far been based. Possible reserves of 100 million tonnes at 0.40% Cu have been reported by Platt (1978a), but the precarious economics of operations at Avoca in recent years have precluded systematic testing of the deposit.

2.1.2. Mining History

Mining at Avoca probably commenced in Phoenician or Roman times; although the Romans did not colonise Ireland, there was trade in gold and copper (Tigroney - ? house of the Roman). In mediaeval times, iron ores were extracted from the Avoca gossans, and probably from the other sulphide-oxide mineralisation in the area.

Fig. 2.1 AVOCA MINES - MAIN AREAS OF OLD WORKINGS

based on unpublished plans of Mianrai Teoranta

Alluvial gold has been won from gravels of the Gold Mines River (fig. 2.6); Reeves (1971) reported that, in all, 7,400oz.-9,000oz. (220-250 x 10^3g.) of gold has been won, though the bedrock source has not been identified.

Platt (1973) reported that continuous copper production at Avoca dates from the mid-18th Century, and that cementation was the main method used. Earlier, silver had been mined from the gossans at Cronebane, and this led to the discovery and extraction of the underlying copper ores. In 1787 the Associated Irish Mining Company controlled mining in both East and West Avoca; extensive underground workings were developed, with the sulphide ores being hand-sorted at the surface.

In the 19th Century, variations in commodity prices determined the profitability of the mines. For a time, the main product was sulphur when, in the 1830's, supplies from Sicily were unavailable. By 1888, co-ordinated mining operations were uneconomic and the mines were not re-opened on a commercial basis until 1945, although fossicking and tributing continued sporadically (Platt, 1973).

In the early 1950's the property was re-evaluated by Mianrai Teoranta, a company working under the auspices of the Irish Government, and large tonnage-lowgrade operations were considered for the first time, based on the West Avoca mines. From 1958 to 1962, Mogul Mining

Corporation of Canada maintained a 3,000-4,000 t.p.d. operation, with mining concentrated on remnants of ore in the 19th-Century workings.

The present phase of production commenced in 1971, after an extensive development programme based on the work of Mianrai Teoranta in West Avoca. The mine is operated by Avoca Mines Ltd., a subsidiary of Discovery Mines Ltd., of Canada. Production rate is around 3,000 t.p.d. and has been based largely on West Avoca, with both underground and surface operations. Copper concentrate is produced for export, and a pyrite concentrate is supplied to a nearby fertiliser plant. Since the 1971 fall in the copper price, the Avoca operations have been sub-economic.

Production since 1969 has totalled some 6.2 million tonnes at 0.8% Cu (Platt, 1978b). Platt (op. cit.) estimated total historical production to be around 15 million tonnes at a grade of some 1.2% Cu, mostly from massive bedded ores.

2.1.3. Previous Work

Regional stratigraphic correlation between the Avoca area and other areas in southeast Ireland is presented in figure 2.2, and a simplified regional geological map is shown in figure 2.3.

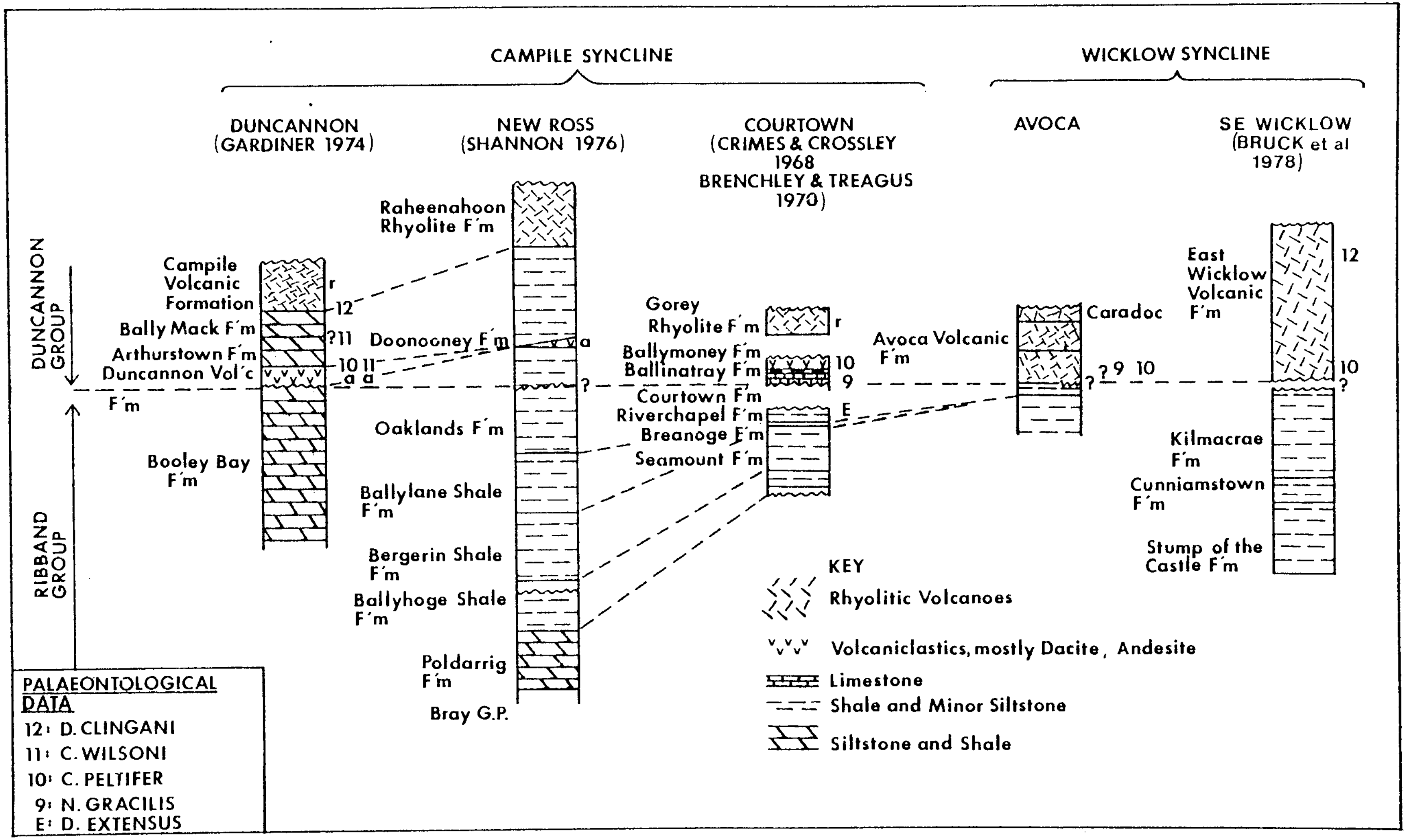


Fig. 2.2 REGIONAL STRATRATIGRAPHIC CORRELATION

Fig. 2.3

SIMPLIFIED GEOLOGICAL MAP OF SOUTHEAST IRELAND, SHOWING LOCATION OF AVOCA AREA.

Recent descriptions of the regional geology of southeast Ireland include the work of Tremlett (1959) who suggested that the structure of the area was synclinal and proposed a complex sequence of thrusts and high angle faults. Tremlett also studied the intrusions of the area and deduced some of their age relations (Tremlett, 1959). Brindley et al. (1973) distinguished early, pre-Middle Ordovician, and later, Caradocian volcanic episodes within the sediments of the Lower Palaeozoic geosyncline in SE Ireland. They showed that the volcanics occur in three major belts following the regional strike, and that, whilst in one belt the volcanics are similar, there are significant differences between the belts. The Tramore-Arklow Head and the Avoca-Rathdrum areas (see fig. 2.3) form one such belt (Brindley et al., 1973). Recent general descriptions of regional stratigraphy and structure are given by Brück et al. (1978), and regional correlations are shown in figure 2.2.

The stratigraphy and structure of the Cambrian-Ordovician sediments of the Ribband Group between Arklow and Waterford have been described by several authors, the work most relevant to the present area of study being that of Brenchley and Treagus (1970), Crimes and Crossley (1968) and Shannon (1976, 1978). Shannon concluded that the depositional environment of the Ribband Group may have been in part shallow water, and that its contact with the Duncannon Group (Upper Ordovician volcanics) was partly conformable in the New Ross area (Shannon, 1976, 1978). Crimes and Crossley (1968) and Gardiner and

Vanguestaine (1971) showed that the Ribband Group is Upper Cambrian to Arenig in age.

The Caradocian volcanism of southeast Ireland has been discussed by Stillman et al. (1974), who concluded that it was largely submarine, and consisted of a northern tholeiitic basalt-andesite belt northwest of the Leinster Granite and a calc-alkaline to alkaline belt between Waterford and Arklow (see fig. 2.3). The later more alkaline rocks of this latter belt are regarded as products of partial melting of sialic crust (Stillman et al., 1974). The products of the Caradocian volcanism were defined as the Duncannon Group by Gardiner (1974).

Stillman and Maytham (1973) studied the volcanics at Arklow Head, and concluded that they were largely pyroclastic and deposited in a shallow subaqueous environment which became emergent in the final stages of volcanism. Mitchell et al. (1972) correlated Lower Palaeozoic sequences at Courtown with those in the Waterford-Tramore area, and noted a two-fold stratigraphic division of the rhyolitic volcanics near Gorey which is similar to that between the Ballinamona and Cronebane Members of the Avoca Volcanic Formation described in this report (see figs. 2.2 and 2.4).

The structure of southeast Ireland was discussed by Gardiner (1970) who proposed a scheme of regional fold structures in which Caradocian volcanics are preserved in a number of northeast-trending synclinal zones of regional extent between Waterford and the Arklow area, to which local folds can be related (see fig. 2.3).

Mineralisation at Avoca was first described in detail by Murphy (1959) who also suggested its volcano-sedimentary origin (Prof. R. L. Stanton, pers. comm.). The geochemistry of the ores and their similarity to other Caledonian volcano-sedimentary sulphide deposits were noted by Stanton (1958). The most comprehensive description of the Avoca orebodies and their mineralogy is that of Wheatley (1971a), who developed the concept of a volcanic-sedimentary origin. Platt expanded the volcanic-sedimentary genetic model for Avoca and has established a detailed structural framework for the deposit (Platt, 1973, 1975, 1976, 1978a, b). Recently Badham (1978) has discussed the significance of slumping in the Avoca ore horizon.

Halliday (1977) provided K-Ar data which indicate ages of formation (Upper Ordovician) and deformation (Caledonian) for the Avoca mineralisation.

2.2. STRATIGRAPHY

2.2.1. Introduction

A summary of the stratigraphy is given in figure 2.4. The oldest rocks exposed in the area mapped belong to the Ribband Group, and are thought to be Upper Cambrian to Lower Ordovician in age (Crimes and Crossley, 1968; Shannon, 1976, 1978). They are overlain by rhyo-dacitic volcanics and sediments of the Duncannon Group.

Macrofossils are not common within the area studied. Reconnaissance samples from both Ribband and Duncannon Groups have been examined for microfossils but did not yield identifiable residues, although elsewhere in the Ribband Group palynological studies have met with some success (Gardiner and Vanguestaine, 1971). It is unlikely that palynology will be useful in solving local stratigraphic problems, although further sampling might provide firmer general ages for the strata.

In the absence of a biostratigraphic control, a lithostratigraphic approach has been adopted for subdivision and correlation of strata. This leads to consistent results in the Avoca area and enables useful correlations to be made with areas to the south (see fig. 2.2) where recent workers have adopted an essentially similar approach (Crimes and Crossley, 1968; Brenchley and Treagus, 1970, Shannon, 1976, 1978).

DUNCANNON GROUP (U. Ordovician)	BALLYMOYLE VOLCANIC FORMATION (?800m) rhyolitic pyroclastics, dacitic lavas, rhyolite, shale	AVOCA VOLCANIC FORMATION	BALLYMURTAGH MEMBER (> 200m) chloritic and sericitic tuff, chloritic shale, black shale, bedded sulphide
			CRONEBANE MEMBER (< 400m) rhyolite, pyroclastics, chert
			BALLINAMONA MEMBER (< 500m) tuff, quartz-eye tuff, shale, tuffaceous sediments
	partial unconformity?		
RIBBAND GROUP (Cambrian - L. Ordovician)		AVONBEG FORMATION (~200m) grey, purple, green laminated shale and siltstone	
		KILMICHAEL FORMATION (> 500m) grey laminated shale, sitlstone, sandstone	

Fig. 2.4 AVOCA AREA - STRATIGRAPHY

2.2. Ribband Group

The Ribband Group consists predominantly of argillaceous lithologies and is characterised by the presence of thinly-bedded or laminated slates and shales with thin beds and laminae of siltstone and arenite. The group is of regional extent in southeast Ireland (Gardiner, 1970; Crimes and Crossley, 1968; Brenchley and Treagus, 1970; Shannon, 1976, 1978).

Between Arklow and Courtown, three formations were defined within the Ribband Group by Brenchley and Treagus (1970) - the Kilmichael, Clones and Riverchapel Formations (see fig. 2.2.). The names Wicklow Formation, Northwestern Slates and Southeastern Slates appear on the maps of Reeves (1977a) and van Lunsen et al. (1977), but were not defined. The area of the present study (figs. 2.3, 2.5) lacks a representative coastal section, and inland exposure is poor, failing to yield sedimentological and structural data. Two lithofacies groups have been recognised:

2.	Avonbeg Formation	200m. (?)
1.	Kilmichael Formation	500m.

Correlations of these units with the stratigraphic sequences of other workers in adjacent areas are shown in figure 2.2.

Kilmichael Formation. The type section of the Kilmichael Formation is from Kilmichael Point (7km. south of Arklow) southward to

Fig 2.5 LOCALITY MAP - AVOCA AREA

[for legend and detailed geology see figure 2.6]

Clogga Strand. It has been named and described by Brenchley and Treagus (1970), and the lithofacies is well represented in the Avoca area (fig. 2.6). The formation consists of grey to black thinly interbedded mud, silt and sand. Generally there is fine lamination, averaging 1mm. - 2mm. thick. Upper and lower contacts of laminae are usually sharp, though there is some bioturbation and trace fossils have been recorded (Brenchley and Treagus, 1970).

Similar grey to black thinly-bedded and laminated sediments occur over much of the area mapped. They crop out along the coastal section from Arklow to Mizen Head, where mud and silt predominate. Intermittent outcrop along the Arklow-Woodenbridge road consists mainly of grey to dark grey thinly-bedded slate with pale silty laminae and some few interbeds of silt and fine sandstone reaching 0.3m. to 1.0m. in thickness (e.g. Loc. 16, fig. 2.6). These are commonly lensy and may show cross-lamination, some load structures and possibly trace fossils. The colour is uniformly grey to dark grey, except at Loc. 15 where they are greenish. The shaly component is dominant over most of the area and in weathered exposures the lamination is not conspicuous. Locally, the shales, while not forming outcrops, may be identified in the subcrop in freshly ploughed fields.

Avonbeg Formation. This name is suggested to include mixed purple, green, buff and grey slates, occurring throughout the area mapped. They may be correlated with the Riverchapel and possibly the Clones

Formations of Brenchley and Treagus (1970) (see fig. 2.2), but differ in that they contain grey slates and may be in part younger in age.

The name is taken from the Avonbeg River where the best exposures of this sequence of rocks occur in the area. They form a discontinuous series of outcrops along the Rathdrum-Avoca road, southwards from a point 1.8km. north of 'The Meeting of the Waters' (G.R. T 190830), and for 0.6km. along a track in the Townland of Knockanode running 300m. to 400m. west of the Avonbeg and Avoca Rivers. The sequence consists of thinly-bedded to laminated shales, often with silty laminae, coloured purple, green, buff, grey and dark grey. Silty laminae are pale grey or greenish and usually 1mm. to 2mm. thick. Bedding is of the order of 2mm. to 20mm. Locally, especially where purple colouration predominates, lamination is weak to absent.

Similar variegated slates occur in a fairly continuous band some 200m. to 300m. wide, traceable in float and sporadic outcrop along the southeastern flank of the Avoca Volcanic Formation north of Woodenbridge. To the west of the volcanics their occurrence is patchy between the Avonbeg and Aughrim Rivers. They are also developed northwest and southwest of the volcanics at Ballymoyle Hill, for about 200m. along the coast 3km. north of Arklow, and in an extensive, though poorly exposed, zone 4km. ENE of Rathdrum.

Colour variations appear to have little lateral continuity within the Avonbeg Formation. Purple colourations are at least in part secondary, since, in a number of localities, they can be seen to transgress bedding planes. It is suggested that they may reflect varying oxidation conditions, being the result of both local sedimentary conditions and of later diagenesis.

In a section westwards from Woodenbridge, along the north side of the Aughrim River valley, a conformable transition is seen from the Avonbeg Formation to the base of the Duncannon Group (see fig. 2.6). North of the Woodenbridge Hotel, purple, green and grey slates, with some few siltstone interbeds, are exposed. The siltstone interbeds are less than 1m. thick, green, and are laminated. Passing westward in intermittent outcrop, green and grey slates and siltstones occur. 750m. west of the Woodenbridge Hotel, a few layers of pale green quartz-crystal bearing dacitic tuffs occur, 0.1m. to 1.0m. in thickness, within grey laminated shales with pale silty laminae. Over the next 500m. westwards, the frequency and thickness of the tuff interbeds increases and the grey colour becomes dominant in the shales. The base of the Duncannon Group is placed at Loc. 4, where tuff beds reach 2m. in thickness and form 5%-10% of the visible sequence.

Elsewhere in the area, it appears that, whilst green and purple slates may be dominant within 50m. to 100m. of the first development of volcanics, the uppermost horizons of the Avonbeg Formation are grey in colour. In some areas, however, no significant development of green and purple shales is found, and the sequence passes through Kilmichael Formation lithologies into the Duncannon Group - for example, south of the Aughrim River and along the Avondale valley north of Rathdrum.

2.2.3. Duncannon Group

The Duncannon Group comprises volcanic and associated sedimentary rocks of Upper Ordovician age in this area of southeast Ireland. The name has been established in publications of the Geological Survey of Ireland (Gardiner, 1974).

Two major subdivisions of the Duncannon Group occur within the area mapped and these are here (informally) named the Ballymoyle Volcanic Formation and the Avoca Volcanic Formation. They are beleived to be contemporaneous, but vary in areal distribution and in component lithologies. Previous workers (Wheatley, 1971a; Platt, 1976) have regarded the two groups of volcanics as similar, including both in the unit 'Avoca Volcanics'. It is believed that the lithological differences and apparently local derivation of the volcanic rocks warrant their division into separate formations.

The Duncannon Group occupies two synclinoria trending NE-SW across the area (figs. 2.6, 2.7). Volcaniclastics dominate the sequence, but argillites and intrusive and extrusive acid lavas also occur. Exposure of lava and coarser volcaniclastics is fair, but softer lithologies are very poorly exposed.

Poorly preserved graptolites, obtained from three localities in the Avoca Volcanic Formation, suggest a Caradocian age. Brenchley et al. (1977) recorded _C. peltifer_ zone graptolites from near Rathdrum. Graptolites have been obtained from the mine sequence at Avoca and may be Caradocian, but they are poorly preserved and no definite age can be assigned (C.W. Stanworth reported by Badham, 1978; and I. Strachan, pers. comm.). Poorly preserved graptolites have also been obtained from a locality low in the Avoca Volcanic Formation north of Avoca village (G.R. T 207806) which could not be positively identified but may be _climacograptids_, and an age of Llandeilo or low Caradoc has been suggested (I. Strachan, pers. comm.).

Ballymoyle Volcanic Formation. The Ballymoyle Volcanic Formation comprises volcanic rocks in the eastern part of the area around Castletimon and Ballymoyle Hill (fig. 2.5); the latter (G.R. T 260790) is designated the type area. The nomenclature continues the use of the name Ballymoyle in the 'Ballymoyle Volcanics' of van Lunsen et al. (1977) and includes the 'Castletimon Volcanics' shown on the maps of Reeves (1977a). The formation comprises vesicular lava, rhyolitic tuff-breccia and lapilli-tuff, quartz and feldspar crystal tuff, and massive rhyolite. A diagrammatic stratigraphic column of the Ballymoyle Volcanic Formation is given in figure 2.8.

The vesicular lava occurs as several horizons of greenish, very fine-grained, commonly rather siliceous, vesicular lava, intercalated in rhyolitic pyroclastics. Individual flows vary from 1m. to more than 10m. in thickness. The lava is best developed at Ballymoyle Hill, where up to four individual horizons are present. To the north of Ballymoyle Hill, and at Castletimon, only one horizon of lava was distinguished, but near the coast at Jack's Hole (G.R. T 320854) a series of flows is observed.

One horizon exposed on the coast north of Jack's Hole consists of autoclastic lava breccia, composed of round blocks generally less than 0.5m. across in a sparse green, fine, probably hyaloclastic, matrix. Blocks have chilled, often oxidised, margins, and show some evidence of soft deformation. Inclusions of shale in the breccia confirm its deposition in a subaqueous environment.

In thin-section (see plates 1 and 2) the lavas are seen to be amygdaloidal porphyritic dacites, typical examples being 1107 and 1108, 1111, 1113 and 1114, 1120, 1148, 1150, 1154 and 1156. Phenocrysts form a minor proportion of the rocks, generally less than 10% and often less than 1%. In some specimens (e.g. 1111, 1114) up to 5% of clear subhedral quartz phenocrysts, $\leqslant$0.4mm. in diameter, are

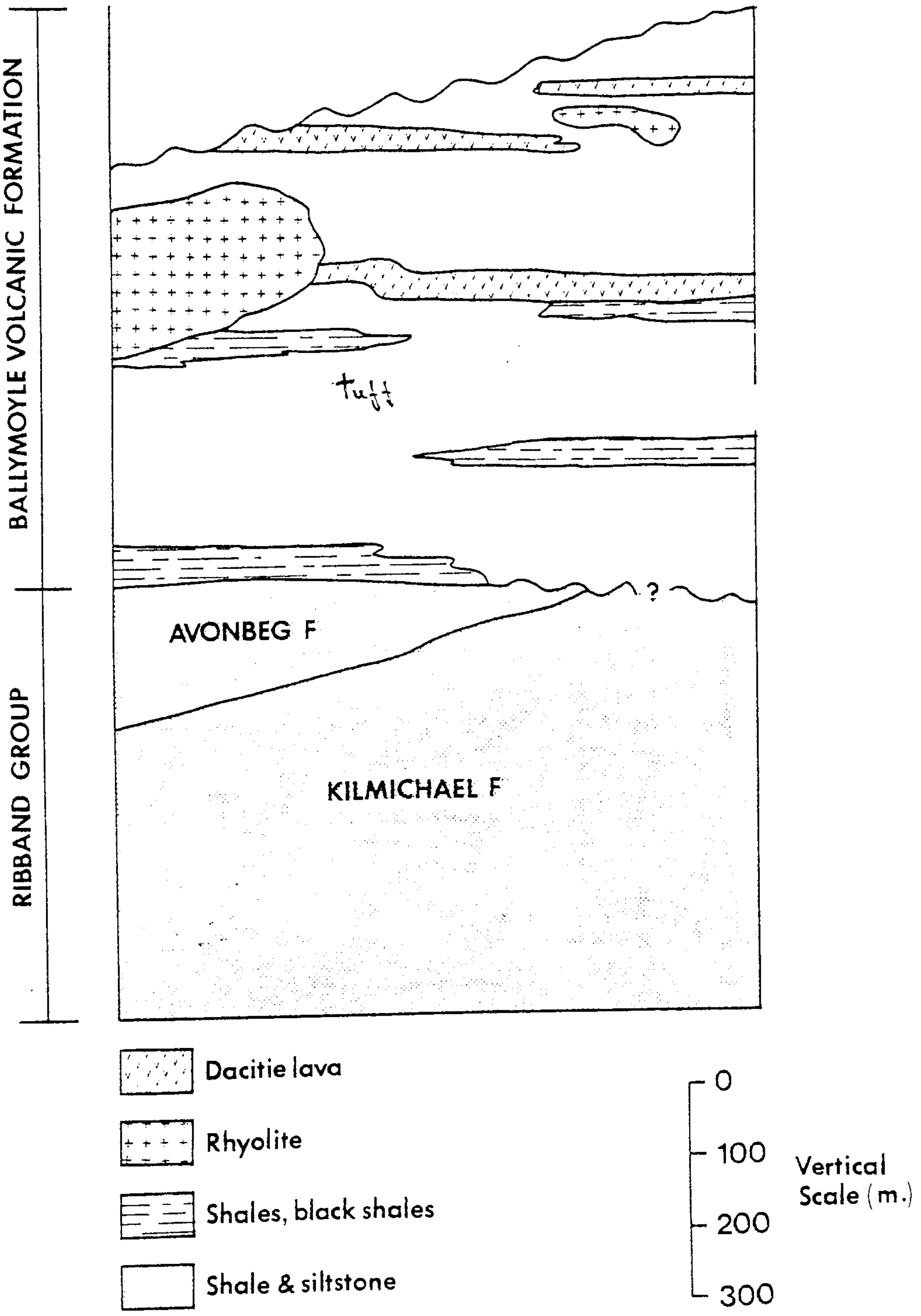


FIG. 2.8
DIAGRAMMATIC STRATIGRAPHIC COLUMN FOR BALLYMOYLE HILL ~ CASTLETIMON AREA

present. The most common phenocrysts are of albite, or of slightly cloudy alkali feldspar, up to 2mm. in size. In some specimens the feldspar phenocrysts appear broken or corroded. Rare intensely altered calcic plagioclase feldspars occur as aggregates of albite, quartz and calcite.

The groundmass contains feldspar laths, either orthoclase or albite, dusty opaques, chlorite, minor epidote and occasional prehnite. Often the groundmass is partly recrystallised with quartz porphyroblasts poikilitically enclosing groundmass feldspars.

Amygdules are very common, ranging in size from 0.5mm. to 3mm., and the proportion of amygdules to matrix varies widely. In many specimens there is little or no flattening, especially where they are small. They generally show concentric zoning with a quartz-rich outer zone and a core of quartz + chlorite ± epidote, but also consist of a single phase of quartz ± chlorite or, more rarely, chlorite ± epidote. In some instances, chalcedonic silica forms a final phase in the core, and in rare cases some albite (?) was observed. In several specimens, small fracture-filling veinlets of quartz + chlorite ± epidote ± carbonate cut the lava, postdating the amygdules.

A trachytic texture is observed locally, and perlitic textures are common and well preserved (see plate 1). In some examples,

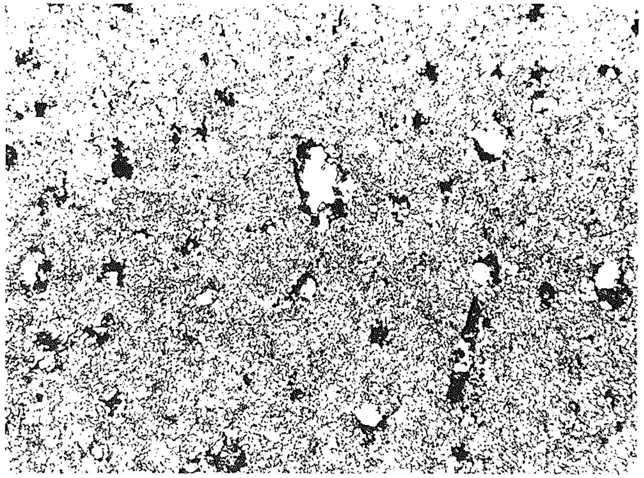
PLATE 1

PHOTOMICROGRAPHS OF THE BALLYMOYLE VOLCANIC FORMATION - LAVAS

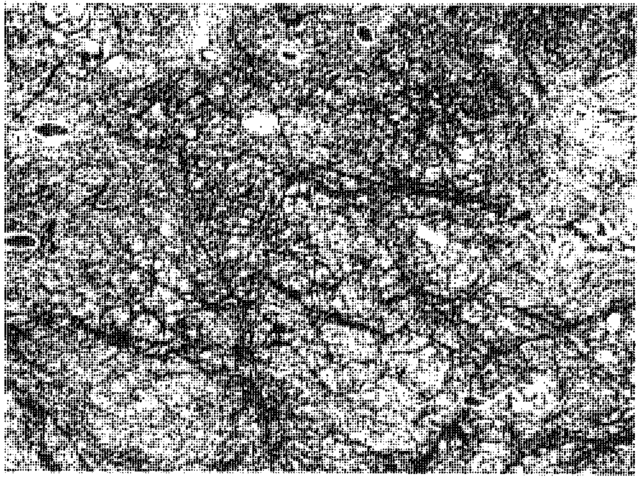
(scale bar = 0.5mm.)

1. 1120 - Amygdaloidal rhyolitic lava (ppl)
2. 1108 - Perlitic amygdaloidal lava (ppl)
3. 1198 - Rhyodacite lava with perthitic feldspar phenocrysts (ppl)
4. 1119 - Amygdaloidal rhyolitic lava, amygdules of quartz and chlorite (ppl)
5. 1108 - Perlitic amygdaloidal lava (ppl)
6. 1113 - Amygdaloidal dacitic lava, flattened amygdules (ppl)

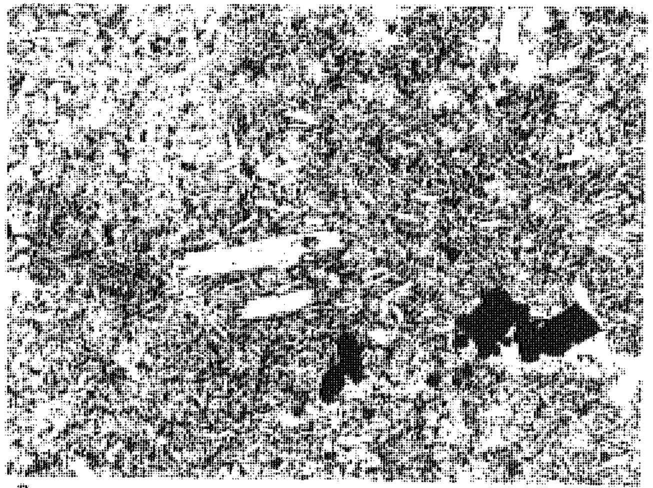
ppl = plane-polarised light



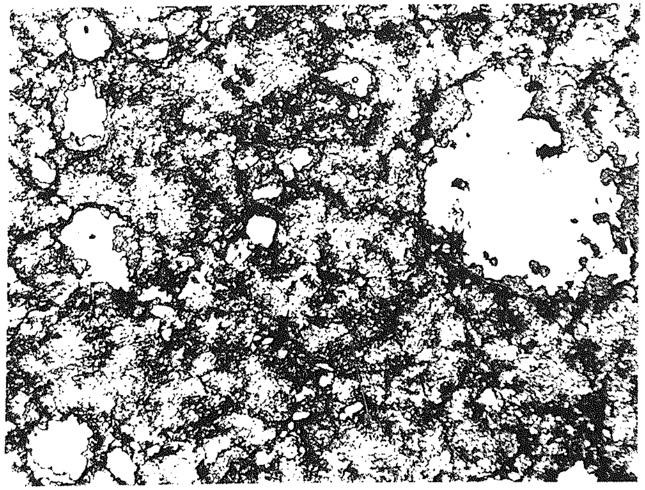
1



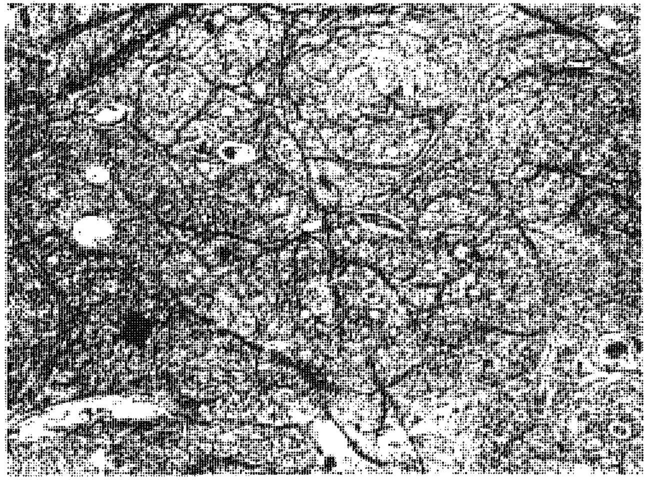
2



3



4



5

6

PLATE 1

development is so strong that the rocks consist of nodules of lava separated by seams of chalcedonic silica and chlorite.

Rhyolitic tuff-breccias and lapilli-tuffs are exposed on the west side of Ballymoyle Hill in the lower part of the sequence, although the base of the Formation is not exposed. These pyroclastics are generally crystal-lithic tuffs varying from ash to lapilli grade, but contain blocks of ash, very fine rhyolite and grey to purplish slate as angular to subrounded clasts up to 50mm. x 20mm. (typical examples near Loc. 28), and locally larger blocks of rhyolite up to 1m. in diameter. Bedding is rarely observed in outcrop, but is seen in scree blocks.

In the Castletimon area (figs. 2.5, 2.6) the lower pyroclastics of the sequence are subaqueous, with black shale interbeds seen near the mouth of Potter's River and along the coast north of Jack's Hole. Tuffaceous mudstones, tuffs and tuff-breccias are intercalated with dacitic flows, and flows, sills and plugs of rhyolite; and a few thin (50mm.) cherty mudstone bands. Alteration varies from perfectly preserved matrices to strong sericite and carbonate development, but tectonic flattening is weak to absent and the characteristic fabric of the coarser volcanics at Avoca is not seen.

Near the mouth of the Potter's River, fine tuffaceous mudstones and lapilli-tuffs with fragments larger than 10mm. in a fine matrix are seen. The fragments are mostly rhyolite with a few quartz and feldspar crystals. Possible glass shards are seen in the matrix in thin-section. To the north, these rocks and crystal tuffs are intercalated with horizons of tuff-breccia with blocks of rhyolite up to 3m. across. The presence of large blocks of rhyolite in a fairly thinly-bedded tuff sequence suggests they may be derived from the massive and brecciated flows in the sequence. Locally there are indications of a shallow-water environment with cross-cutting relationships which may represent channelling.

In thin-section, lithic fragments are seen to consist of fine tuff, devitrified glass, rhyolite, aggregates of altered plagioclase feldspar, fresher untwinned feldspar and quartz (e.g. 1127).

Quartz and Feldspar Crystal Tuffs are more important in the middle and upper parts of the sequence at Ballymoyle Hill. Between Potter's River and Jack's Hole they are intercalated with lavas and coarser pyroclastics, and they are well represented north of Jack's Hole.

At Ballymoyle Hill these tuffs are composed of a fine matrix containing subhedral quartz and feldspar crystals 1mm. to 2mm. in diameter. The feldspars are mostly perthites with subordinate K-feldspar and albite. Lithic clasts of similar size are less abundant, and are mostly of rhyolite. Preservation of matrix textures is variable, but glass shards around 0.5mm. in size, some few relict fiamme and some eutaxitic textures (see plates 2 and 3) indicate that this is a sequence of ash-flow tuffs with a significant degree of welding (examples 1112, 1115 and 1116). Similar features of matrix support and eutaxitic fabric can be seen near Potter's River (examples 1184, 1185 and 1186).

To the north of Jack's Hole, excellently preserved part-welded tuffs are exposed (samples 1159, 1191); these are composed largely of glass shards with 10% of euhedral feldspars (orthoclase, perthite and rare albite), some quartzes and 10% - 20% of a fine ashy matrix.

They are recrystallised but the textures of the glass shards are well preserved, with virtually no flattening, and the preservation of fine fragments of bubble wall indicates that the rocks are undoubtedly pyroclastic (see plate 3). The matrix support and local eutaxitic fabric indicate an ash-flow origin, and these vitric tuffs are intercalated with clearly welded ash-flow tuffs with eutaxitic texture, fiamme, and corroded quartz and minor feldspar crystals (1196). Grain sizes are 0.3mm. - 0.7mm. for glass shards, and 0.5mm. - 2mm. for crystal clasts.

Whilst a cleavage is commonly developed in these rocks, it is not intense; primary textures are well preserved, delicate shards show

PLATE 2

PHOTOMICROGRAPHS OF BALLYMOYLE VOLCANIC FORMATION - LAVAS AND PYROCLASTICS

(scale bar = 0.5mm.)

1. 1191 - Part-welded tuff with alkali feldspar crystals (ppl)

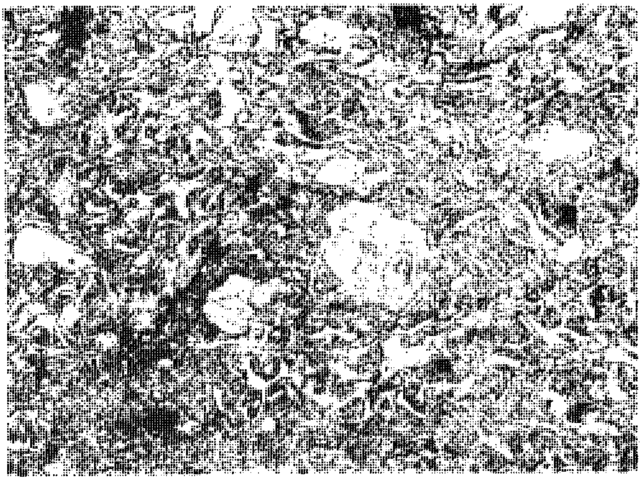
2. 1191 - Showing local flattening and welding of glass shards (ppl)

3./4. 1197 - Non-welded vitric-crystal tuff (?ash-flow) with well preserved shards (ppl)

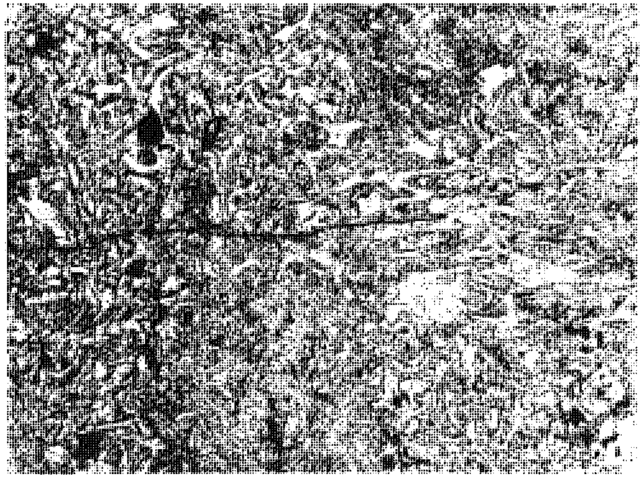
5. 1106 - Aphyric amygdaloidal rhyodacitic lava with quartz amygdules carrying minor opaques (ppl)

6. 1177 - Amygdaloidal rhyolite with quartz amygdules (crossed nicols)

ppl = plane-polarised light

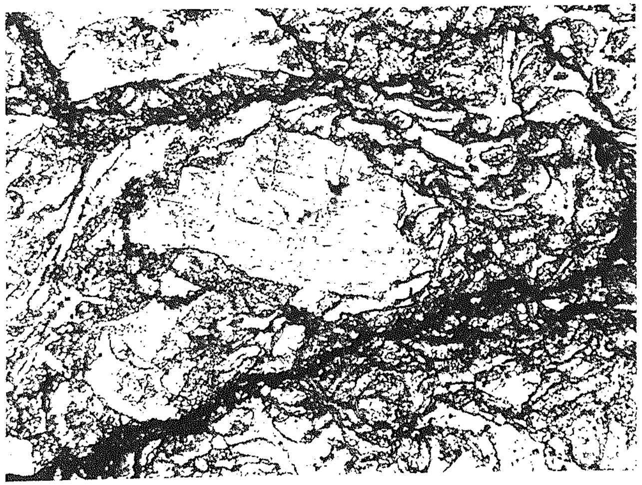


1

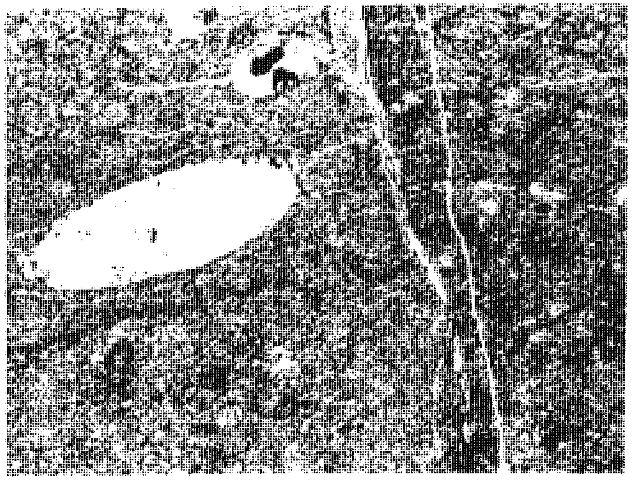


2

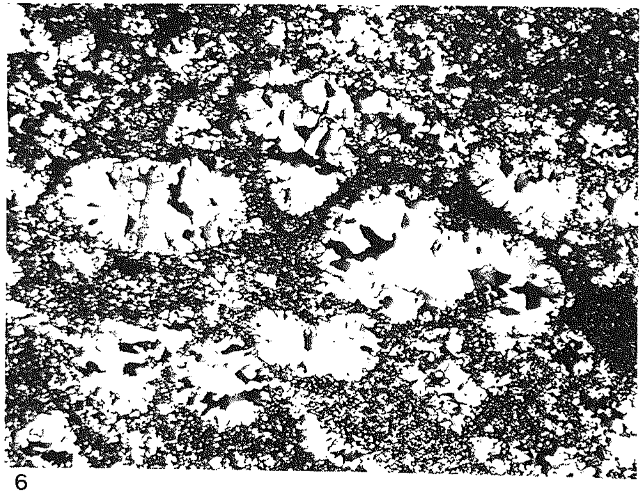
3



4



5



6

PLATE 2

PLATE 3

PHOTOMICROGRAPHS OF BALLYMOYLE VOLCANIC FORMATION - PYROCLASTICS

(scale bar = 0.5mm.)

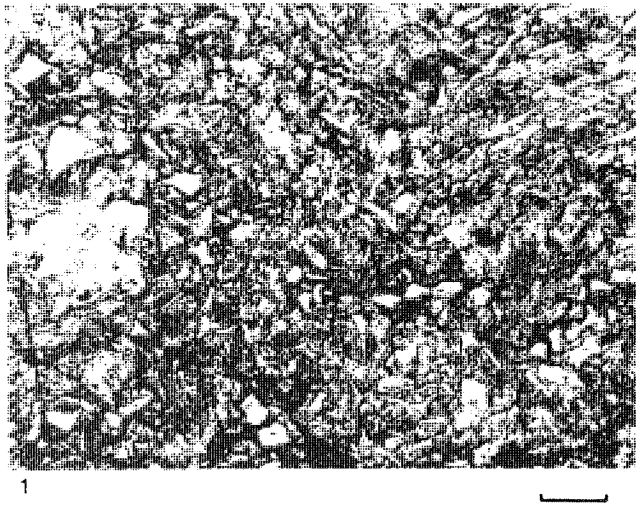
1./2./3. 1159 - Vitric-lithic tuff with well preserved glass shards (ppl)

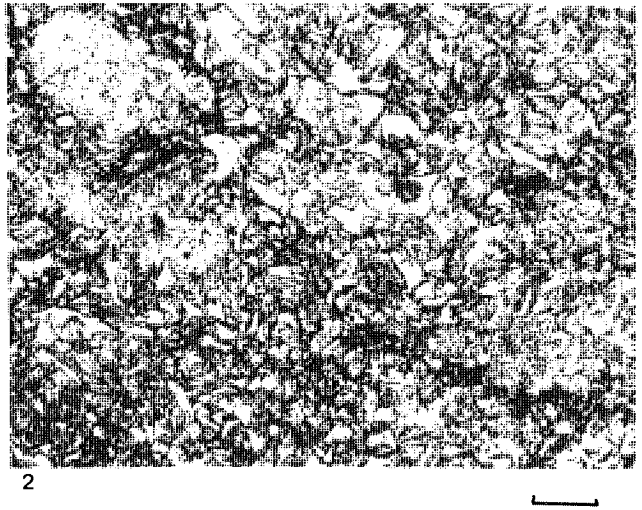
4. 1195 - Non-welded vitric tuff (ppl)

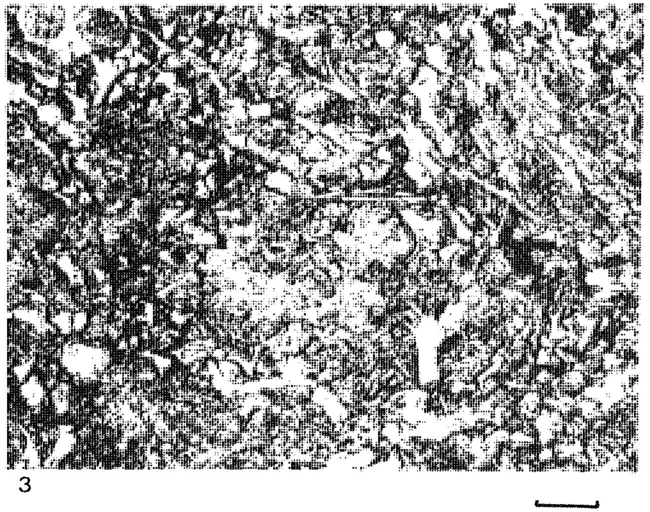
5. 1186 - Crystal tuff, ash-flow, with embayed quartzes (crossed nicols)

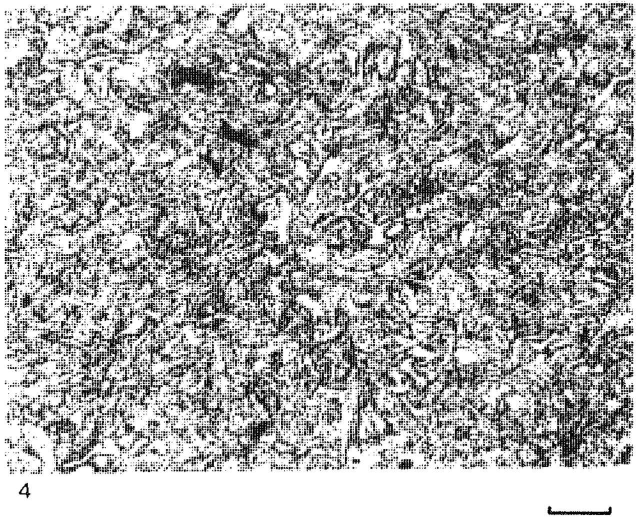
6. 1115 - Ash-flow tuff with feldspar crystals (ppl)

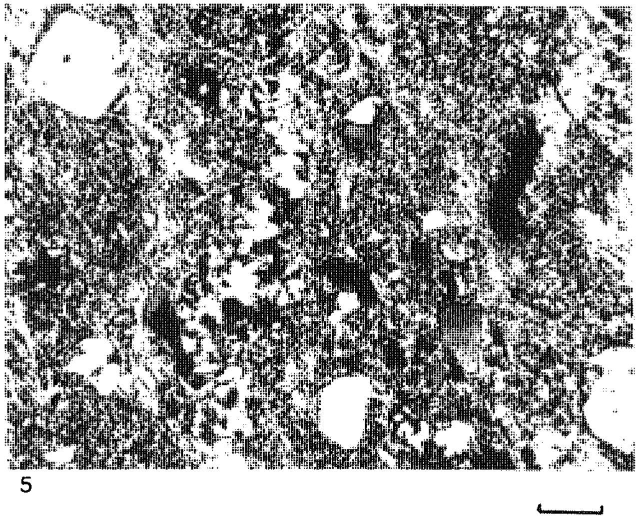
ppl = plane-polarised light


1


2


3


4


5

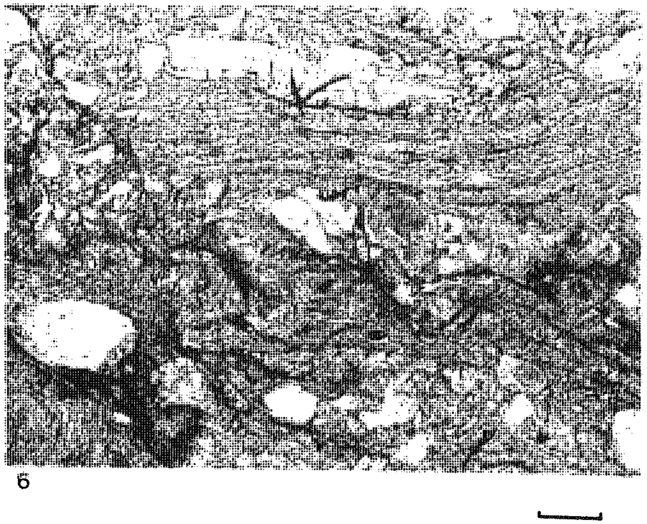

6

PLATE 3

little tectonic flattening. This is in strong contrast to the textures in the Avoca Volcanic Formation.

The rhyolites are mostly very fine-grained massive siliceous rocks, commonly brecciated and annealed by fine quartz veinlets. Locally they are altered with bleaching, development of sericite and clay, and pyrite in veinlets and also finely dispersed.

Rhyolites at Ballymoyle Hill occur as lensy bodies and are probably flows. At Castletimon, small bodies of rhyolite are intercalated with tuffs in the coastal section and are probably flows a few metres thick. The presence of blocks of rhyolite in the tuffs suggests they are extrusive. Inland only larger bodies of rhyolite have been mapped because of the reduced level of exposure and the reconnaissance nature of the mapping. These bodies are mostly plug-like, although partly conformable with the lava horizon.

The rhyolites contain up to 5% of phenocrysts of quartz (0.1mm. - 0.3mm.) and, less frequently, of untwinned feldspar which may be corroded. Mafics are generally absent; a little chlorite and epidote (?) occur in samples 1125 and 1126, but this could be a result of their position in the roof of the quartz-diorite intrusion. The matrix is finely recrystallised; recognisable flow textures are uncommon. Quartz amygdules (0.1mm.) are not flattened. Rectilinear quartz veining and annealed brecciation are common, often associated with traces of sulphide.

Autobrecciation is well developed in sample 1152, which has a coarse fragmental texture on a scale of around 5mm. and a matrix of rhyolite. Both fragments and matrix contain amygdules up to 1mm. across, but the larger and better defined amygdules are in the matrix phase. This rhyolite is unusual in that its phenocrysts are mainly of feldspar, reaching 2.5mm. long, but mostly smaller, of sanidine (?), perthite and sodic plagioclase.

Avoca Volcanic Formation. The Avoca Volcanic Formation comprises Upper Ordovician volcanic rocks between Croghan Kinshella (G.R. T 130730) northeast to the Kilbride area (G.R. T 288882) and includes volcanics around the Avoca mine, which is considered the type area. Also included here within the formation are volcanics around Rathdrum ('Rathdrum Volcanics' on geochemical maps of Reeves, 1977a); lithologies are broadly similar in both areas, as are geochemical background values for Cu, Pb and Zn from stream-sediment surveys (see section 2.6.2), but more detailed work may reveal differences requiring their designation as a separate formation. The Avoca Volcanic Formation contains rocks referred to as the 'Upper Volcanic Series' of Wheatley (1971a) and 'Avoca Volcanics' of Platt, 1976.

The Avoca Volcanic Formation is subdivided into three members on the results of the present mapping; these are informally named as follows:

3. Ballymurtagh Member.

2. Cronebane Member.

1. Ballinamona Member.

A diagrammatic stratigraphic column is shown in figure 2.9. Correlation with the stratigraphy of the mine area derived by other workers is given in figures 2.10 and 2.11.

With the exception of Quaternary glacial, glacio-fluviatile and raised beach deposits, the Avoca Volcanic Formation contains the youngest rocks in the area. It rests with at least partial conformity on slates of the Ribband Group, and its top is not exposed. Its estimated apparent thickness is 1km. and it has an erosional top.

Ballinamona Member. The type section is in the Townland of Ballinamona, 1km. west of Woodenbridge at G.R. T 177777 (see fig. 2.6). Whilst isolated exposures of this member are common, continuous sections are seldom of any length, but the type section contains most of the important lithologies. The Ballinamona Member represents the basal and distal parts of the Avoca Volcanic Formation. It consists of sericite-rich tuffs, with black shales, grey and, in places, laminated slates, and tuffites (see plates 4 and 5).

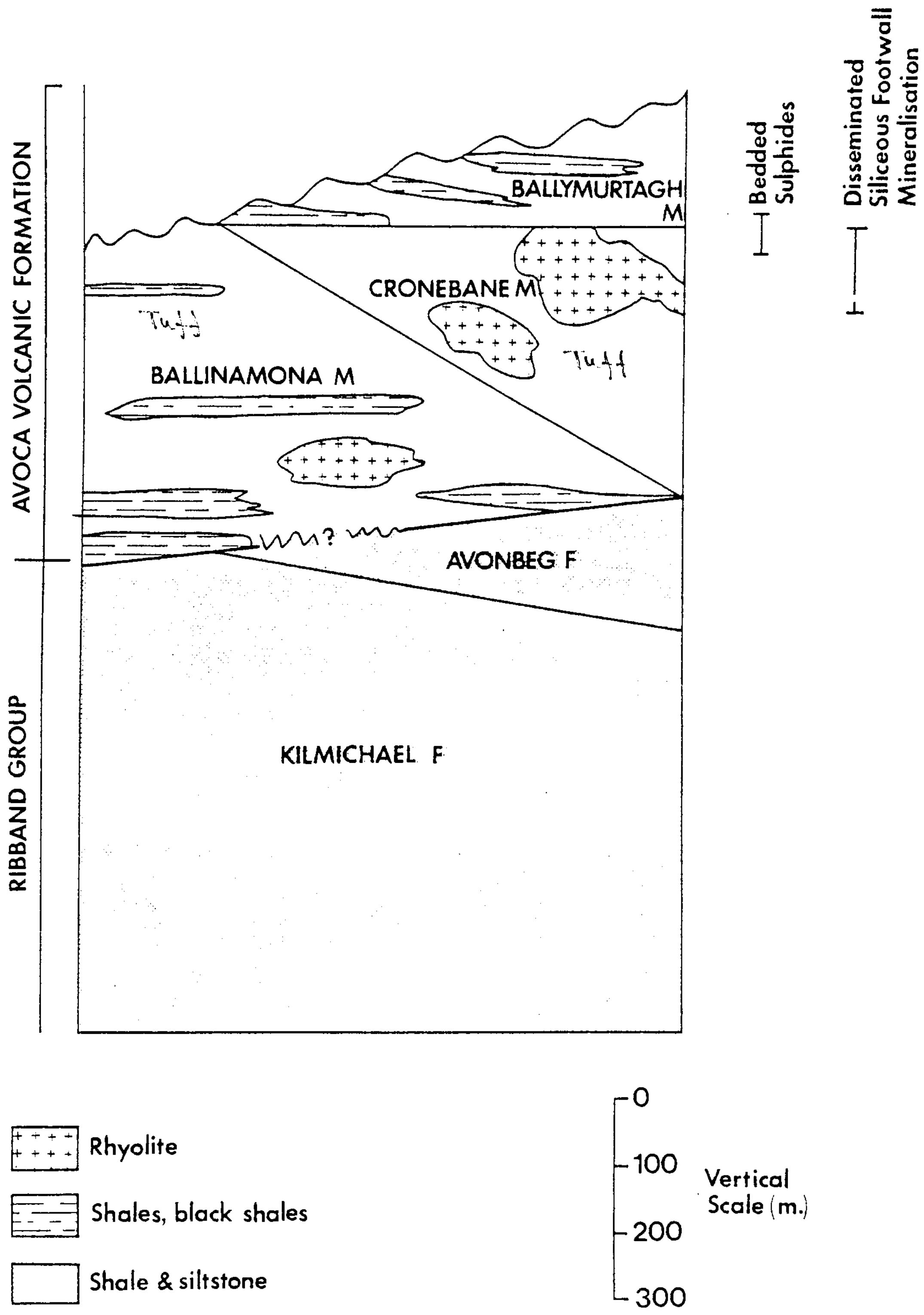


FIG. 2.9
DIAGRAMMATIC STRATIGRAPHIC COLUMN FOR AVOCA AREA (SHOWING RELATIONSHIP OF MINERALISATION TO STRATIGRAPHY)

The conformable contact of the Duncannon Group (Ballinamona Member) with the Ribband Group has been described in section 2.2.2, with the base of the Ballinamona Member being placed at Loc. 4, in the type section (see fig. 2.6). Passing westwards from Loc. 4 to Loc. 5, the lower part of the Ballinamona Member consists of grey to dark grey slates with pale silty laminae in places but becoming less common, intercalated with black pyritic shales with pyrite cubes up to 3mm. and increasing numbers of volcaniclastic interbeds. These consist of washed tuffs and tuffaceous siltstones of rhyolitic and dacitic composition; they are strongly cleaved, in part sheared, with grains of quartz, alkali feldspar, sodic plagioclase and rhyolite, generally grain-supported with a matrix of sericite and white mica, quartz, and, in some cases, a substantial proportion of chlorite (e.g. 1032, 1034).

Passing westwards, shales become less important, outcrops being mainly of crystal and crystal-lithic tuffs. The tuffs are matrix-supported, with clasts of subhedral perthite (sometimes zoned), quartz and minor sodic plagioclase with some rhyolite. The matrix comprises 70% - 80% of the rock and is dominated by white mica and quartz with minor chlorite and epidote group. Cleavage is generally strong and the matrix substantially recrystallised, and tuffs locally

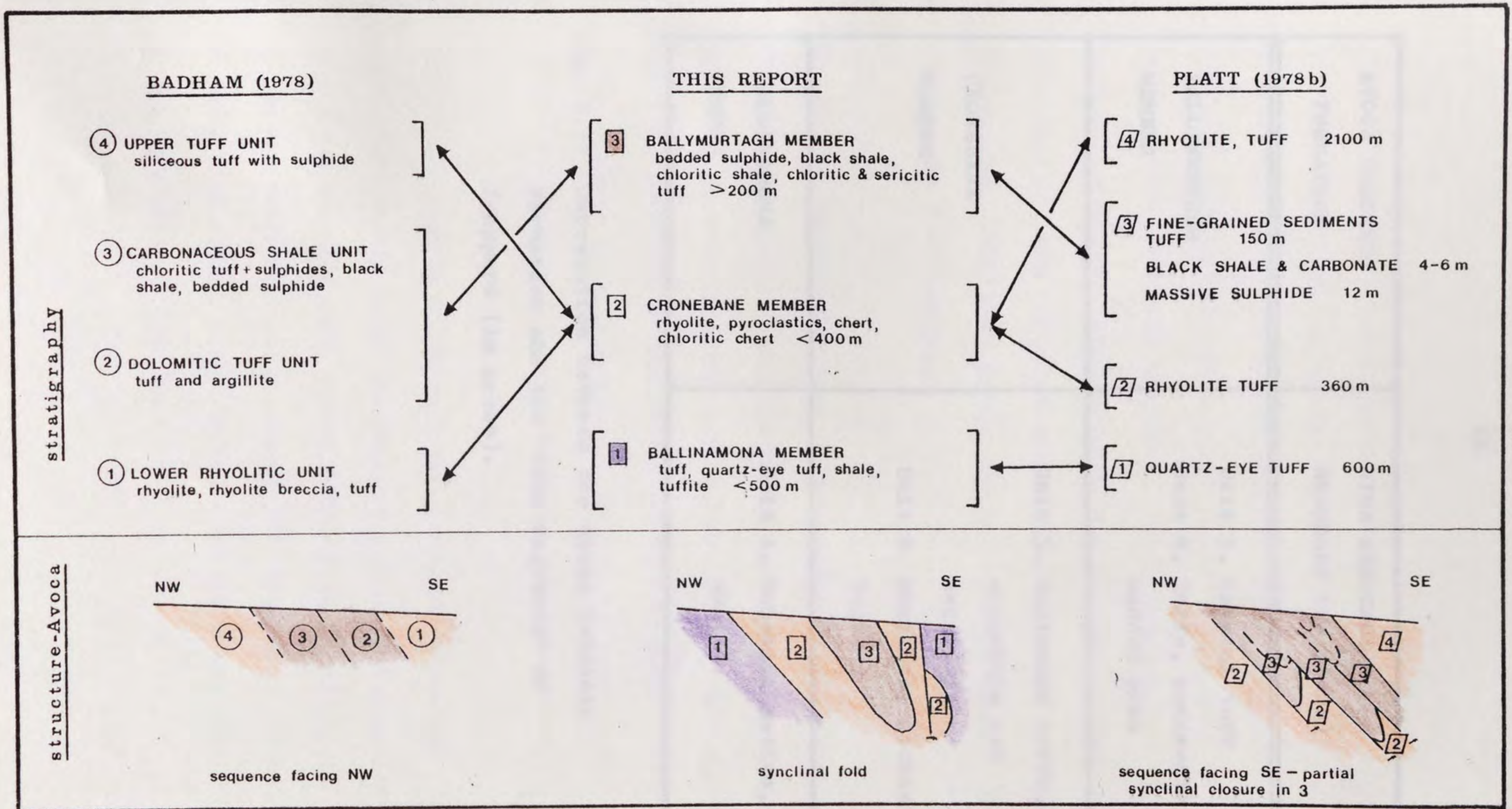


Fig.2.10 AVOCA VOLCANIC FORMATION – STRATIGRAPHIC CORRELATION WITH PREVIOUS WORK

AVOCA VOLCANIC FORMATION	MINE SEQUENCE Sheppard (in press)
BALLYMURTAGH MEMBER	Unit 5. Crystal tuff Unit 4. Tuffs, sediments, bedded ores
CRONEBANE MEMBER	Unit 3. Siliceous tuffs, chloritic and sericitic Unit 2. Rhyolite, lithic tuff
BALLINAMONA MEMBER	Unit 1. Volcaniclastics, shales.

Fig. 2.11 Correlation between the Avoca Volcanic Formation and the 'Mine Sequence' of Sheppard (in press).

developing an augen fabric (quartz-eyes) around primary clasts and secondary quartz-aggregates (see plate 5). In some specimens (e.g. 1036) a remnant eutaxitic fabric suggests that the tuffs were at least in part ash-flows. Interbedded (?) fine tuffs occur as sericitic phyllites. Pre-cleavage quartz + carbonate ± sulphide veinlets occur, and carbonate is also developed as augen and in the matrix of more altered tuffs and shales (e.g. 1039, 1062, 1070). Local variations noted in the mapping are described below.

Ballinamona Member lithologies extend southwestwards along the eastern margin of the volcanics, outcrop being poor except along forestry tracks near Ballinasilloge. Outcrops are more common on the western side of the volcanics in this area. Coarser tuffs are uncommon, the dominant lithologies being fine sericite tuffs and phyllites, and grey slates.

Between the Aughrim and Avoca Rivers, coarser quartz-eye tuffs occur mainly on the southeastern side of the volcanics except for the area north of West Avoca where sericitic quartz-eye tuffs are well developed. The lower part of the sequence with slates, sericitic tuffs and tuffaceous siltstones is exposed at Loc. 33.

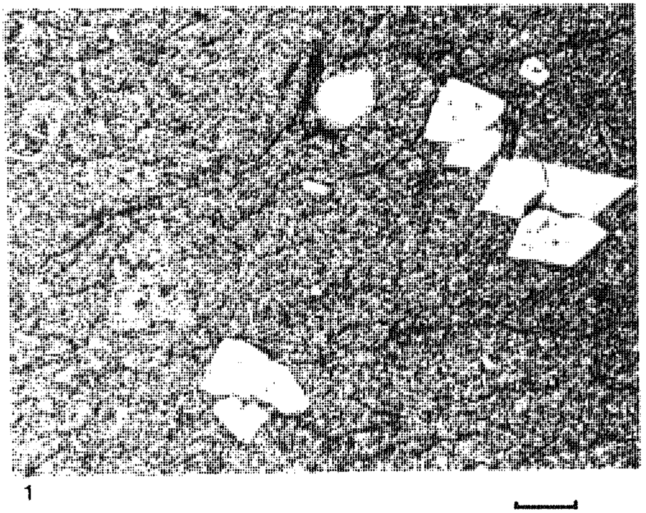
PLATE 4

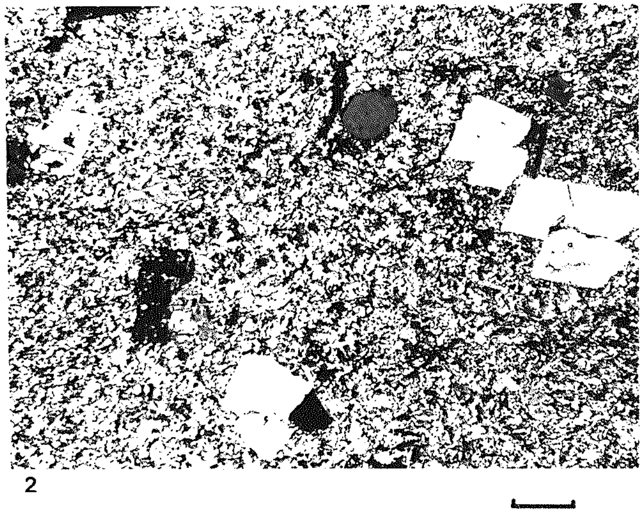
PHOTOMICROGRAPHS OF AVOCA VOLCANIC FORMATION - BALINAMONA MEMBER

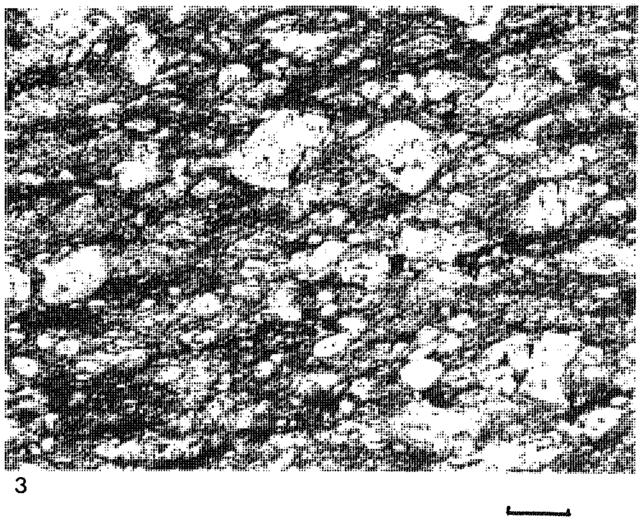
(scale bar = 0.5mm.)

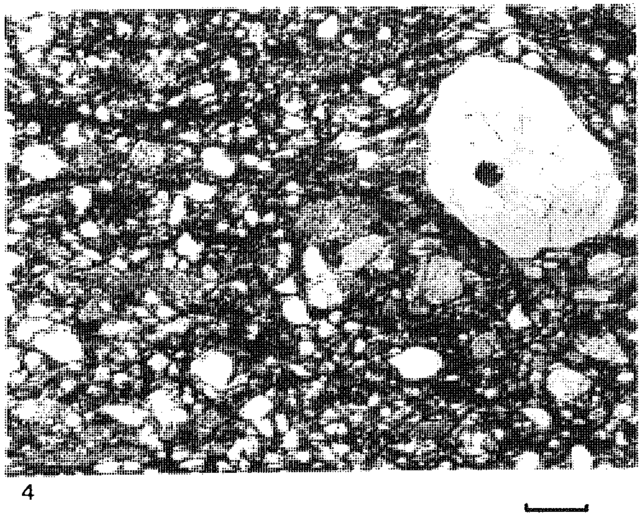
1. 1043 - Rhyolite, finely recrystallied matrix, quartz and perthitic feldspar phenocryss (ppl)
2. 1043 - As above (crossed nicols)
3. 1038 - Cleaved crystal tuff with cludy alkali feldspar and small clear quartz crystls (ppl)
4. 1034 - Cleaved poorly sorted rhyoliic tuffaceous sandstone - grain supported (ppl)
5. 1087 - Embayed quartzes in probableash-flow tuff (ppl)
6. 1027 - Crystal tuff with alkali feldspar (crossed nicols)

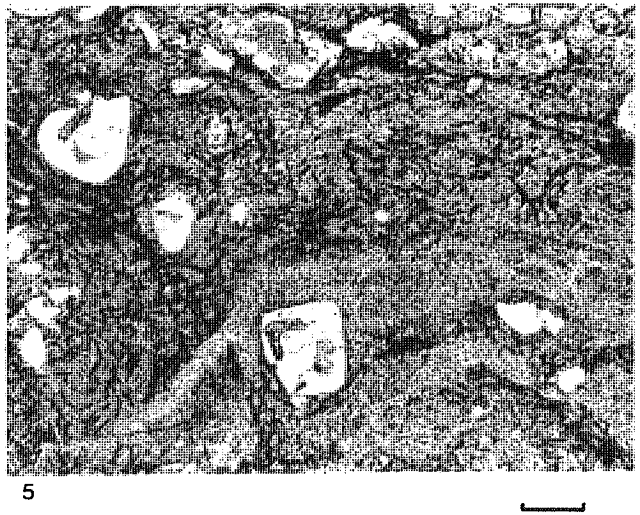
(ppl = plane-polarised light)


1


2


3


4


5

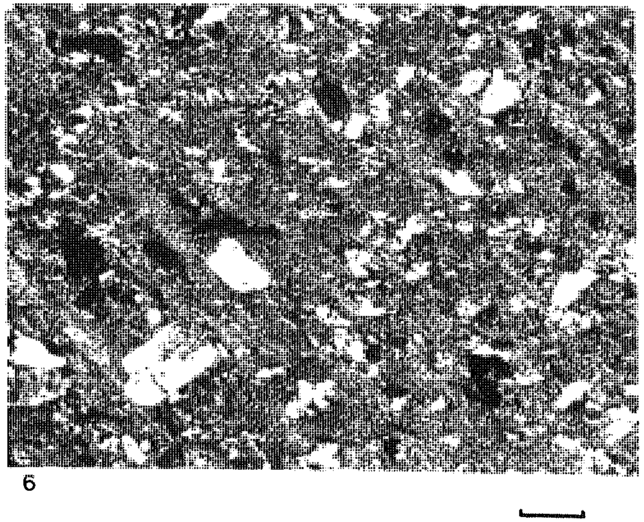

6

PLATE 4

PLATE 5

PHOTOMICROGRAPHS OF AVOCA VOLCANIC FORMATION - BALLINAMONA MEMBER

(scale bar = 0.5mm.)

1. 1027 - Feldspar crystal tuff (ppl)

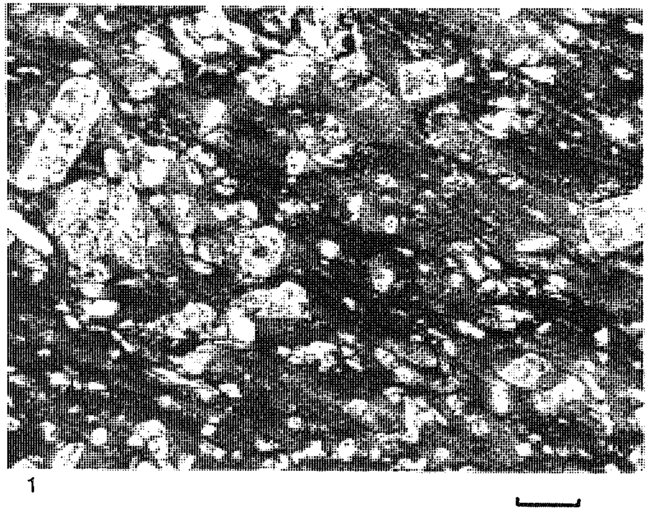
2. 1028 - Dacitic crystal-lithic tuff with incipient augen development (ppl)

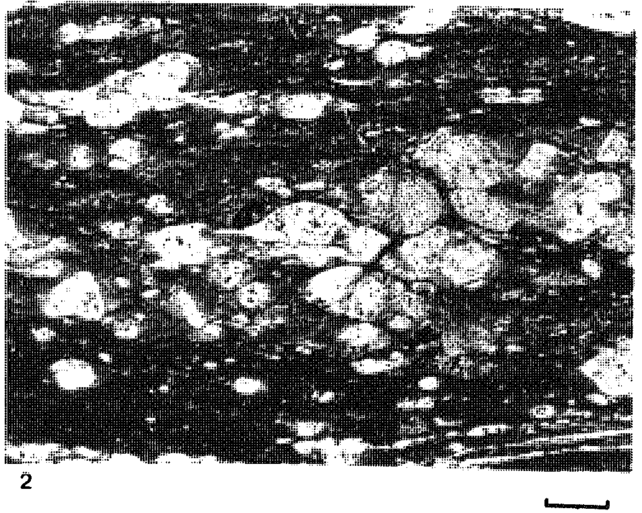
3. 1028 - As above (crossed nicols)

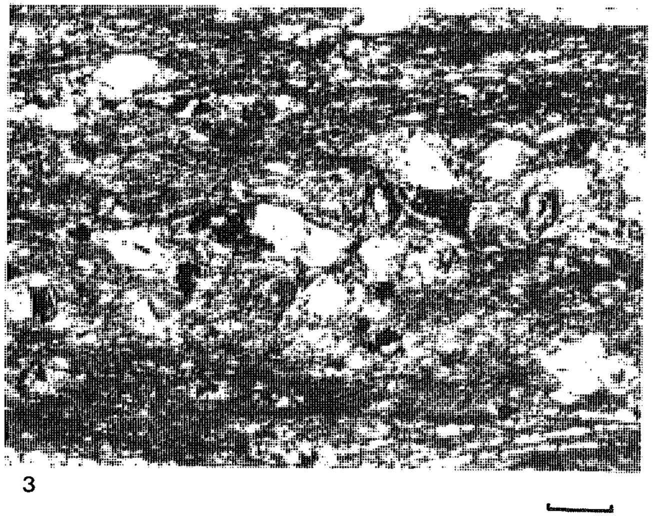
4./5. 1223 - Incipient augen development in original crystal tuff (with embayed quartzes). Augen develop from overgrowths on single crystals, crystal aggregates, or in intergranular areas, and cleavage becomes undulating (ppl)

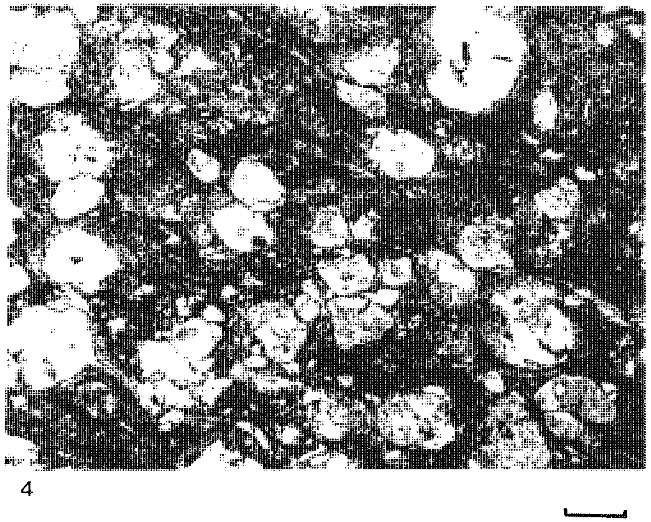
6. 1066 - Augen development in tuff. Cleavage passes around augen with recrystallised quartz, both around original crystal clasts and in intergranular areas (crossed nicols)

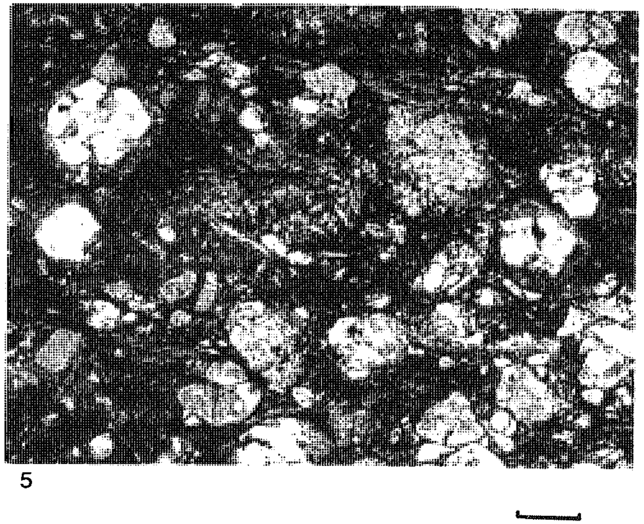
ppl = plane-polarised light


1


2


3


4


5

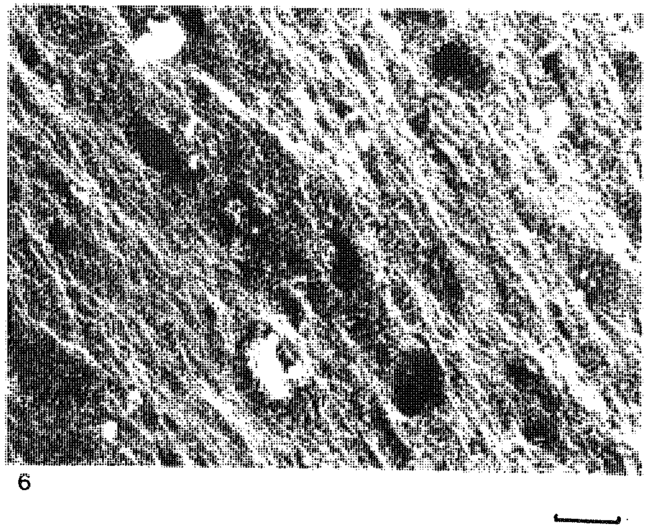

6

PLATE 5

Northeast of the Avoca River the base is again exposed just north of Avoca village; in this zone small bodies of massive rhyolite, probably intrusive, occur in the lower part of the volcanics (see plate 4). Outcrop is very poor on the eastern side of the volcanics in this area, but locally float observations in freshly ploughed fields indicate the lithologies in subcrop.

In the area around G.R. T 213833 the dominant lithologies exposed in ditches and in float are green sericitic and grey slates. Typical Ribband Group lamination is absent, but so also are coarser sericitic tuffs. These lithologies have been provisionally placed within the Ballinamona Member, since their interpretation as a facies change within the volcanics provides the simplest interpretation of the data. Outcrop is insufficient to indicate any structural or palaeotopographic complications in this area.

South and southeast of Kilbride, outcrop is again poor, and mapping of the Ballinamona Member is largely inferred from float. Rhyolite and fine sericitic slaty tuffs occur in outcrop and float at Loc. 45. The feldsparphyric rhyolite of sample 1128 is quite strongly veined by quartz, pyrite and (?) stilpnomelane.

North of East Avoca the Ballinamona Member occupies an inferred anticlinal zone, in the core of which Ribband Group lithologies may reach the surface, though no definitive exposures were found. Near the contact with the Cronebane Member sericitic quartz-eye tuffs are well developed, passing downwards into finer tuffs and slates.

West of Kilbride, pale to dark grey or locally pale green non-laminated slates occur between Cronebane Member tuffs and a dioritic intrusion. The slates lack the typical bedding, lamination and colour variation of Ribband Group; however, no evidence of a tuffaceous component is visible in the available outcrops. Though here provisionally placed within the Ribband Group, they could represent a local volcanic-free development of the Ballinamona Member.

Along the Avondale River, Ballinamona Member lithologies are exposed in railway and track cuttings. Near Rathdrum a sequence of rhyolitic ash-flow tuffs, often with much secondary carbonate, shales and dolomitic siltstones are assigned to the Ballinamona Member (e.g. samples 1070, 1079, 1080, 1084).

Cronebane Member. The member is named after the Townland of Cronebane in East Avoca where it is exposed north and south of the Cronebane open pit, in contact with the Ballymurtagh Member. Normal contacts with the Ballinamona Member are not exposed but can be located to within 25m. in much of this area.

The Cronebane Member represents the proximal facies of the Avoca Volcanic Formation and is generally restricted to the central part of the belt. It consists of three main lithologies: rhyolite, pyroclastics, and chert and siliceous chloritic mudstones; and is generally characterised by an intense alteration in which quartz, chlorite, sericite and sulphides are developed.

Massive rhyolites (see plates 6 and 7) are abundant near the Avoca Mine, particularly east of the north-south fault which cuts the mine sequence. The major bodies are shown in figure 2.6. The rhyolites appear to be both in the form of plugs and conformable flows or sills; in hand-specimen and thin-section both types of body are similar, having a hard, very fine-grained, more or less recrystallised granular groundmass with sparse alkali-feldspar and rare sodic plagioclase and quartz phenocrysts. Devitrification textures are absent, except for perlitic cracks which occur in some examples.

Amygdules less than 1mm. across and sub-circular in section are common, and are filled with silica. Spherulites are also common, especially occurring in bands in flow-banded examples (e.g. 1166 and 1016, a reconnaissance sample from near 1102). Pumiceous zones occur (e.g. 1016, 1093, 1094 and plates 6 and 7) and locally the rhyolite grades into strongly welded tuff. Textures are insufficiently well preserved for rheomorphic effects to be detected; field and petrographic evidence suggest that these welded zones are scoriaceous parts of rhyolite flows rather than welded ash-flow units.

Brecciation is common and involves coarse and fine breccia with angular fragments from several centimetres to less than 1mm. across. These are annealed either by quartz or by rhyolite, the latter case indicating flow-brecciation or early de-gassing (1015, 1097).

Quartz veining is ubiquitous, commonly in several directions. Quartz + chlorite veining, generally with pyrite, is found in parts of the rhyolites northeast of East Avoca and west of Kilbride. Traces of epidote also occur (1097, 1098, 1102).

Chlorite and pyrite are also dispersed in the rock; further from mineralisation, sericite + pyrite is more common. Where quartz + chlorite ± sulphide veining is intense, as at Cronebane, angles of rotation of rhyolite fragments in the accompanying brecciation are small.

The pyroclastic rocks of the Cronebane Member (plates 7 and 8) are of coarser grainsize than those of the Ballinamona Member (up to 3mm.). They are strongly altered and cleaved, but fresher examples may show features of deposition from ash-flows (see plate 7).

The coarser tuffs and lapilli-tuffs crop out well around the mines and sporadically towards Kilbride; they also occur south of Rathdrum near Avondale House, and in a zone north of Cronebane. In the mine area the tuffs pass upwards into cherts and siliceous chloritic mudstones which form the immediate footwall and partial hostrock to the bedded pyrite and chalcopyrite mineralisation. Southwest of West Avoca, Cronebane Member lithologies, originally flanking rocks of the Ballymurtagh Member to the north and south, progressively thin, initially on the north side and subsequently on the south, beyond Ballymoneen.

In outcrop and hand-specimen these coarser tuffs show a characteristic cleavage development, for which the term 'pseudo-imbrication' has been suggested (see plates 8, 9 and 18). Cleavage is not planar but has a lensy or augen-like development which is surprisingly regular. These augen develop from original fragments or, where these are absent, from recrystallisation of quartz aggregates, and are distributed in a regular 'en-echelon' structure (1134, 1100), and a similar pattern is developed in both matrix and grain-supported tuffs (1169).

Recrystallisation of the Cronebane Member pyroclastics is generally intense, associated with silicification and propylitisation, with the destruction of the original fabrics. Less altered specimens have clasts of quartz, perthitic feldspar and rhyolite, generally supported in a variably recrystallised fine matrix of quartz (+ feldspar ?), sericite and chlorite. Traces of pumpelleyite occur in specimen 1165.

The cherts and siliceous chloritic mudstones are exposed in workings in the mine sequence, but were not recognised elsewhere (probably because of the quality of exposure). They are well bedded and cleaved. Silicification is intense, falling off rapidly at the contact with the Ballymurtagh

Member. The cherts have recrystallised as lensy bodies of white quartz.

The sequence in the mine area is highly altered. The few relict textures present indicate that a significant proportion of it is of tuffaceous origin (1002, 1003) but in many cases all primary fabric has been obliterated. The finer chloritic mudstones and cherts are believed to represent iron formation (Wheatley, 1971a).

In this bedded sequence, which may be of the order of 20m. thick, intercalated lenses of bedded sulphides (pyrite + chalcopyrite) are common, increasing into the Ballymurtagh Member. Quartz + chlorite + sulphide veins cut the bedding at shallow angles. There has also been substantial remobilisation of quartz, sulphide (especially chalcopyrite) and minor chlorite during tectonism.

Ballymurtagh Member. The name is taken from the Townland containing the West Avoca mine, the type section being taken as the west end of the open pit. This section is not ideal as it does not exhibit all the lithologies within this member, and is subject to mining activity, but it contains the best exposures of this unit in the Avoca area. The

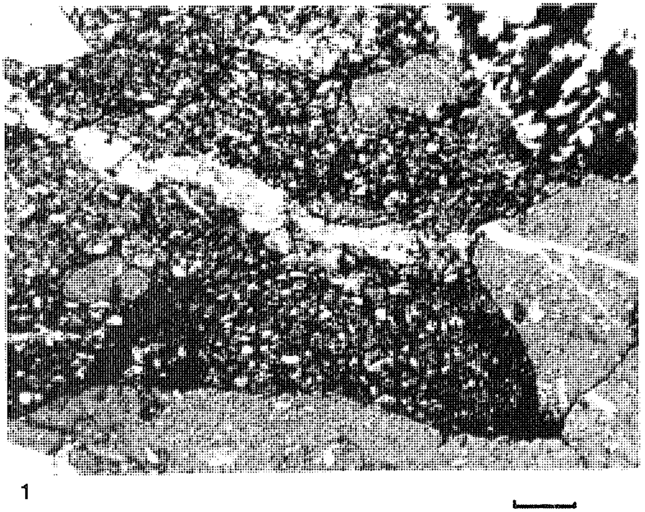
PLATE 6

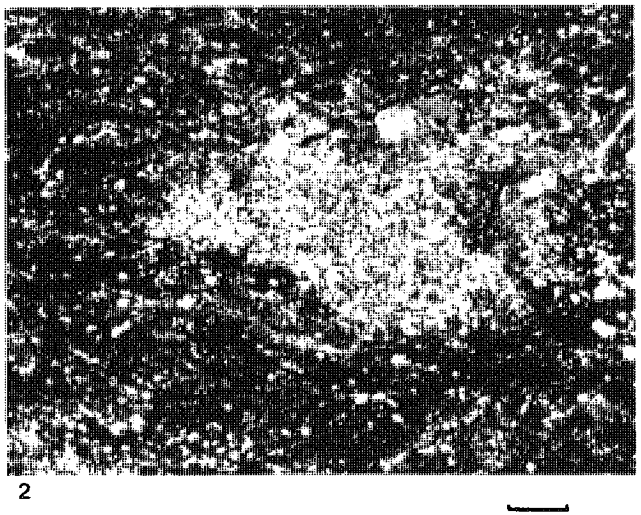
PHOTOMICROGRAPHS OF AVOCA VOLCANIC FORMATION - CRONEBANE MEMBER

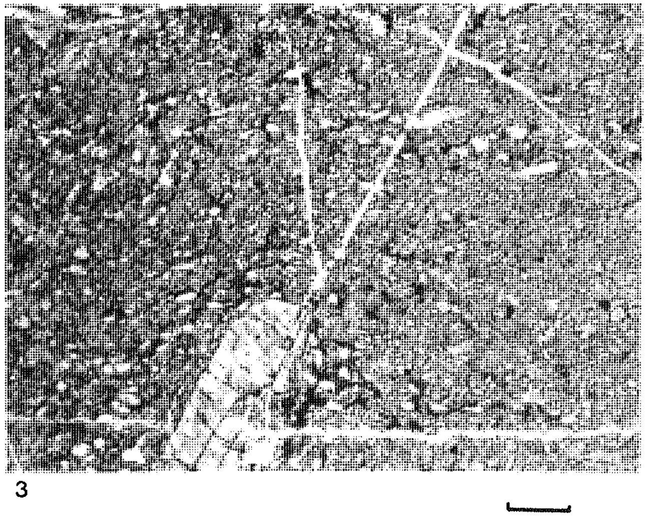
(scale bar = 0.5mm.)

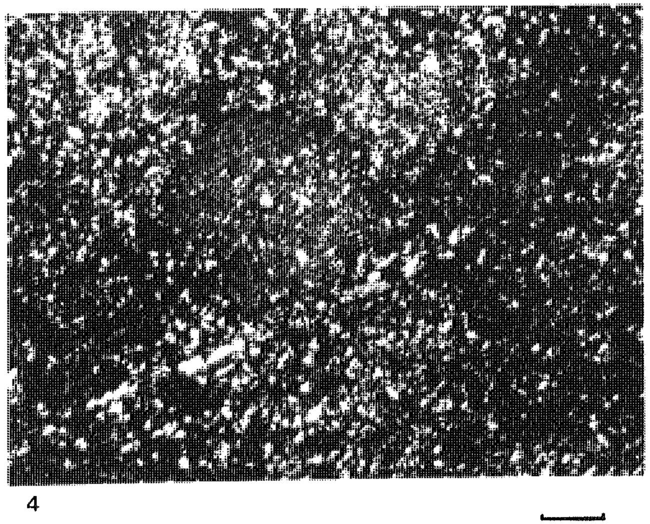
1. 1015 - Autobrecciated rhyolite (ppl)
2. 1016 - Spherulitic patches in rhyolite, with feldspar phenocryst (crossed nicols)
3. 1013 - Trachytic flow texture and feldspar phenocryst in rhyolite (ppl)
4. 1012 - Spherulitic patches and amygdule in partly recrystallised glassy rhyolite (crossed nicols)
5. 1097 - Rhyolite with quartz + chlorite amygdule (ppl)
6. 1103 - Weak flow texture in rhyolite (ppl)

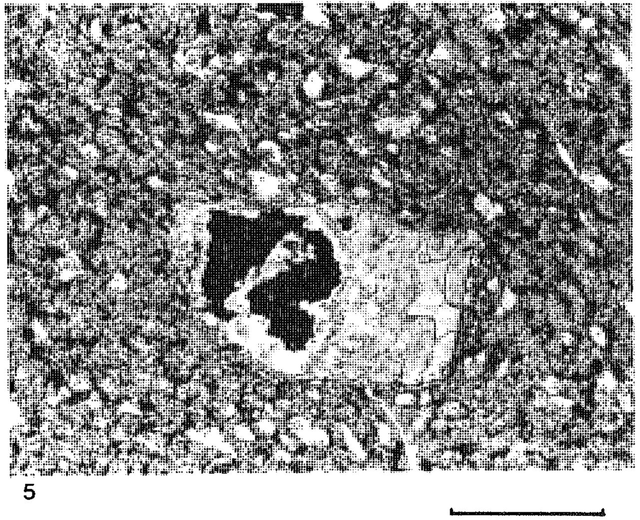
ppl = plane-polarised light


1


2


3


4


5

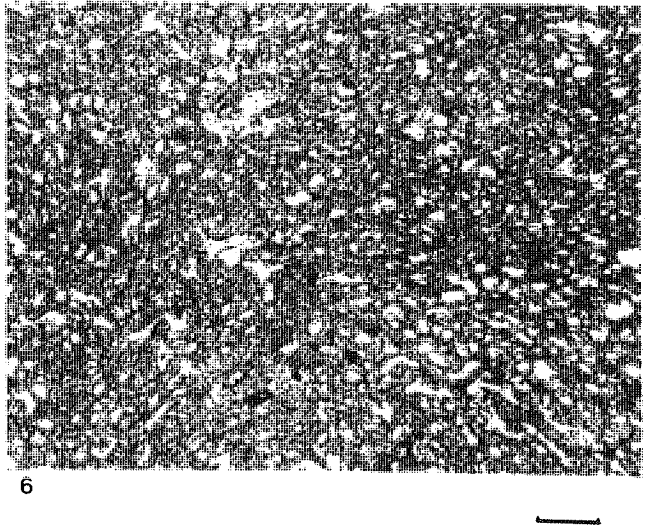

6

PLATE 6

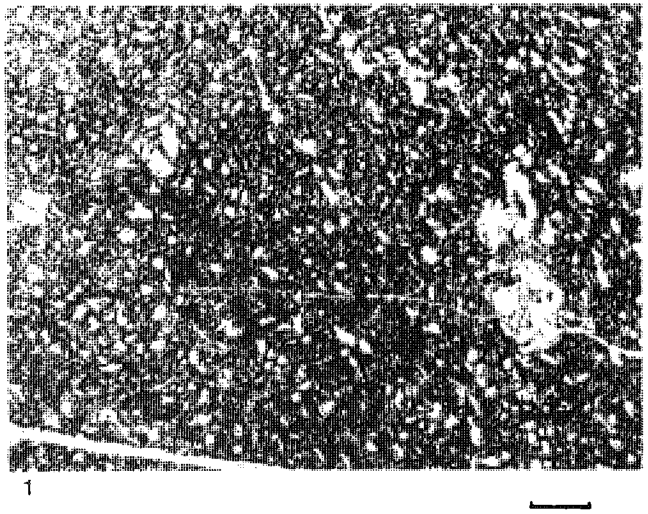
PLATE 7

PHOTOMICROGRAPHS OF AVOCA VOLCANIC FORMATION - CRONEBANE MEMBER

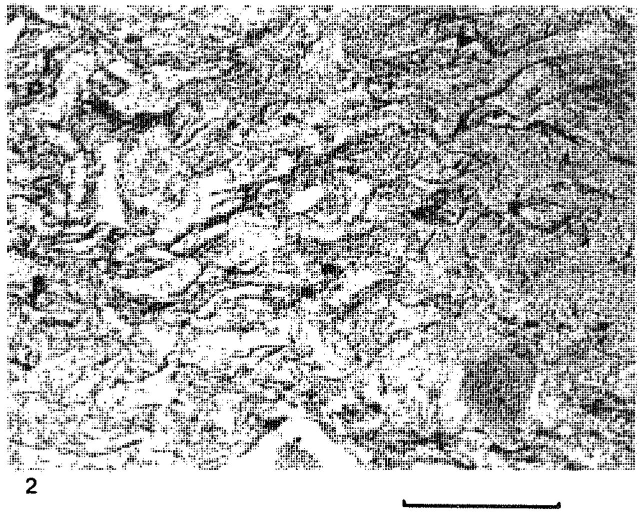
(scale bar = 0.5mm.)

1. 1103 - Feldspar phenocrysts in rhyolite (ppl)
2. 1093 - Part-welded tuff (ppl)
3. 1096 - Remnants of welded textures in recrystallised tuff (ppl)
4. 1094 - Devitrified rhyolite (fragment in coarse lithic tuff) (ppl)
5. 1094 - Remnants of partially welded fabric (ppl)
6. 1010 - Altered tuff with remnants of lithic fragments (ppl)

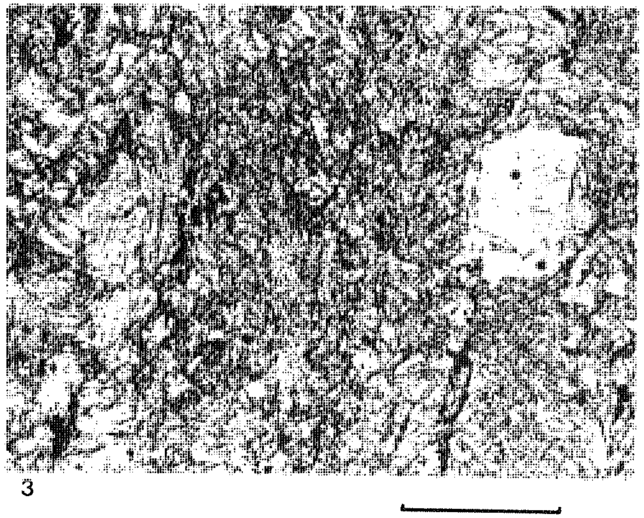
ppl = plane-polarised light



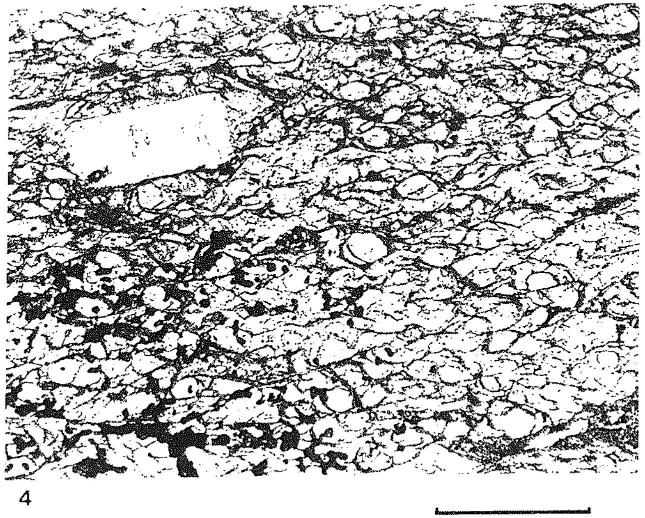
1



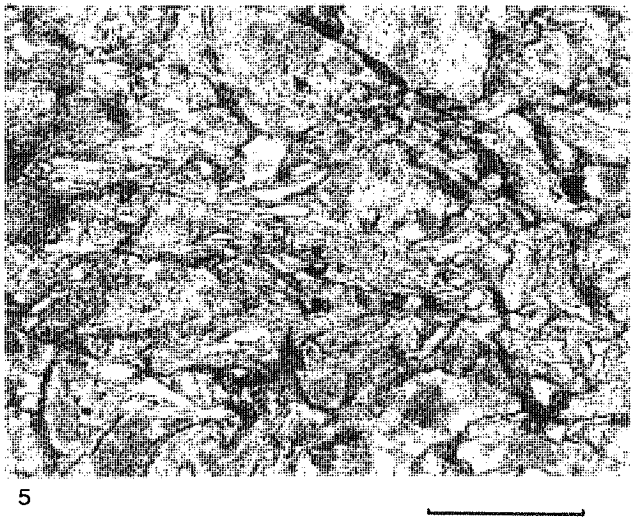
2



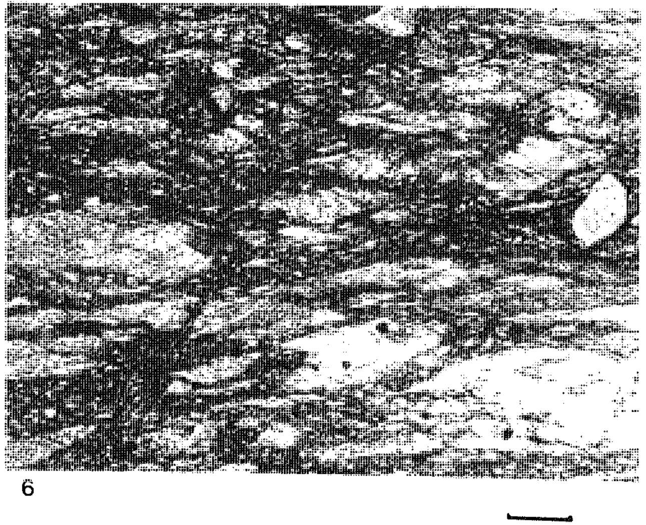
3



4



5



6

PLATE 7

PLATE 8

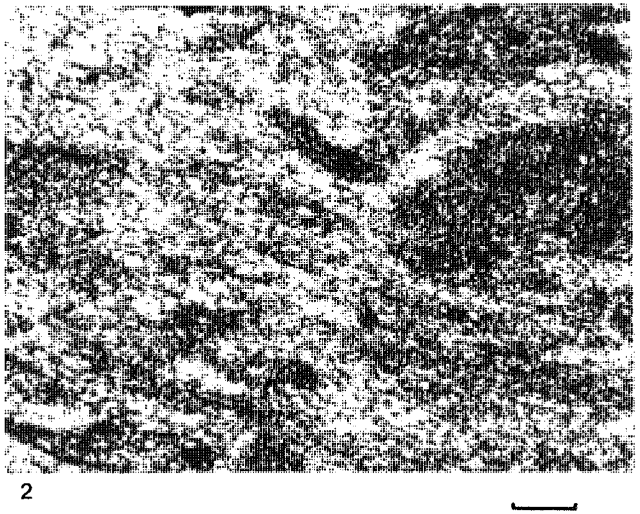
PHOTOMICROGRAPHS OF AVOCA VOLCANIC FORMATION - CRONEBANE MEMBER

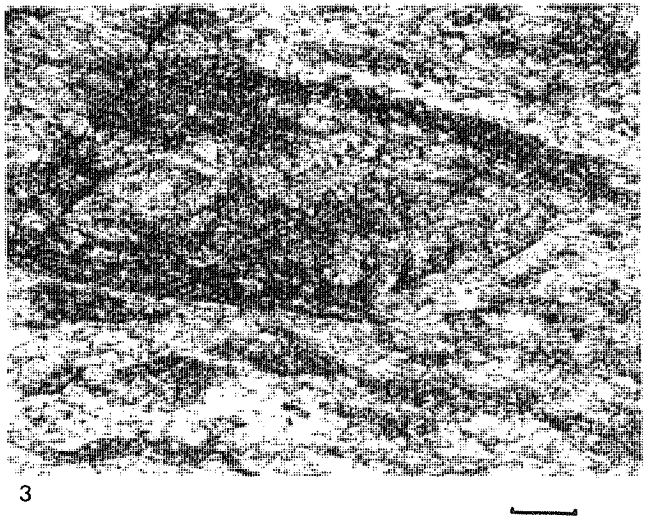
(scale bar = 0.5mm.)

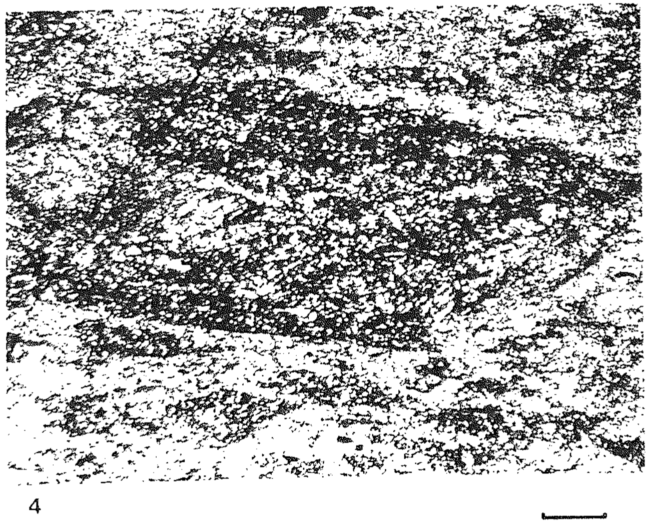
1. 1008 - Relict fragmental texture in strongly altered tuff (ppl)
2. 1008 - As above (crossed nicols)
3. 1007 - Relict fragmental texture in altered tuff (ppl)
4. 1007 - As above (crossed nicols)
5. 1134 - Altered tuff with development of augen texture, lensy cleavage and overgrowth of quartz on original clasts (ppl)
6. 1099 - Altered crystal tuff, with strong development of lensy cleavage and augen fabric (ppl)

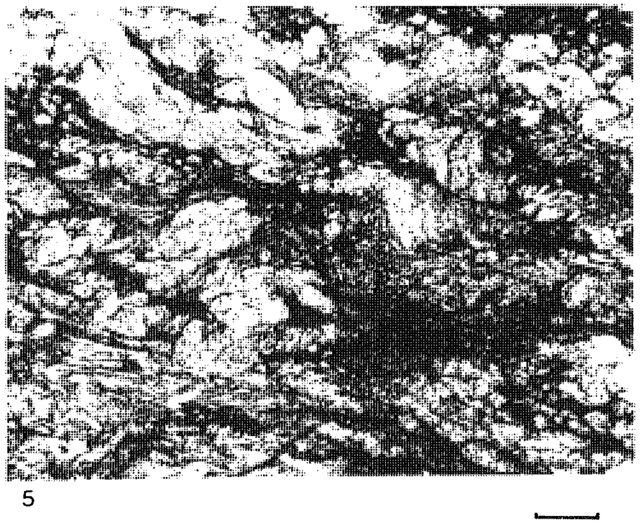
ppl = plane-polarised light


1


2


3


4


5

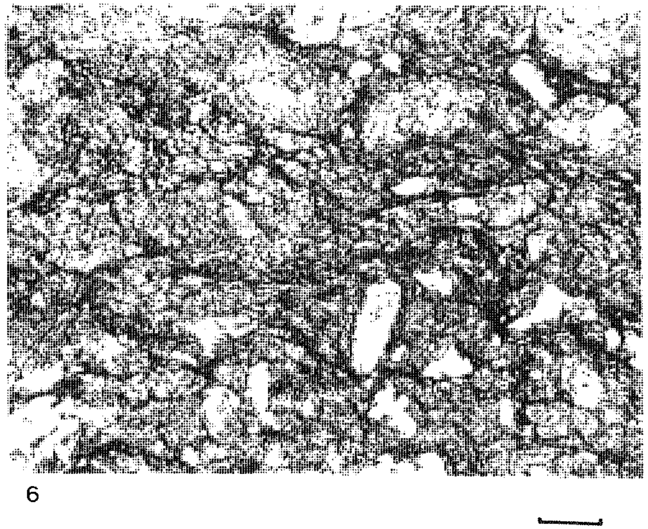

6

PLATE 8

PLATE 9

PHOTOMICROGRAPHS OF AVOCA VOLCANIC FORMATION - CRONEBANE MEMBER

(scale bar = 0.5mm.)

1. 1003 - Porphyroidal quartz augen in recrystallised quartz sericite matrix (in original tuff) (ppl)

2. 1003 - As above (crossed nicols)

3. 1100 - Incipient augen formation in tuff: overgrwoth on original clasts and in intergranular areas (ppl)

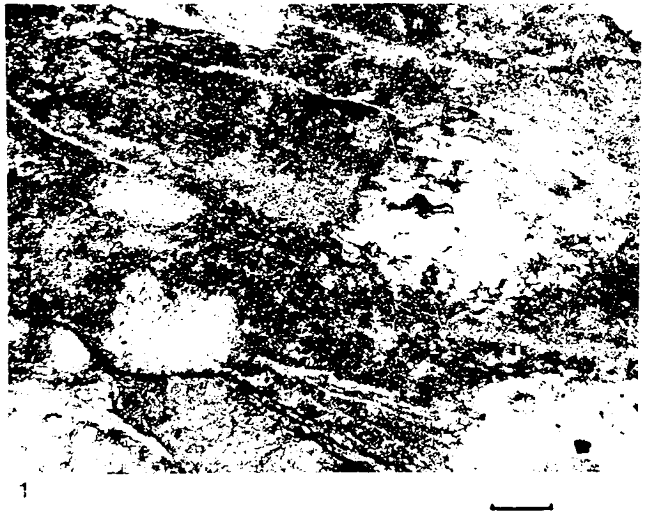
PHOTOMICROGRAPHS OF AVOCA VOLCANIC FORMATION - BALLYMURTAGH MEMBER

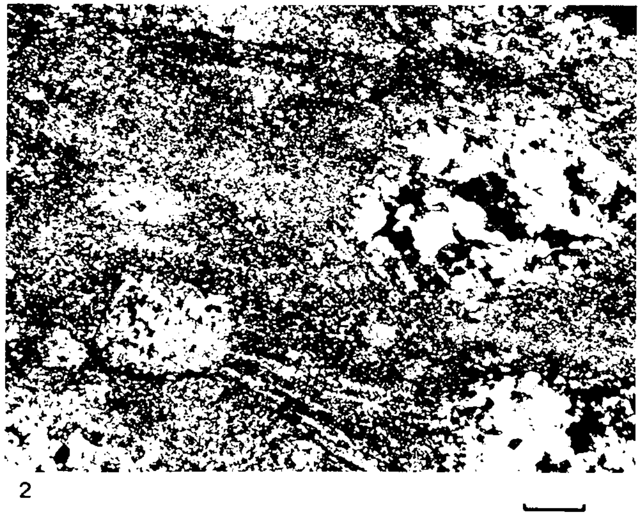
(scale bar = 0.5mm.)

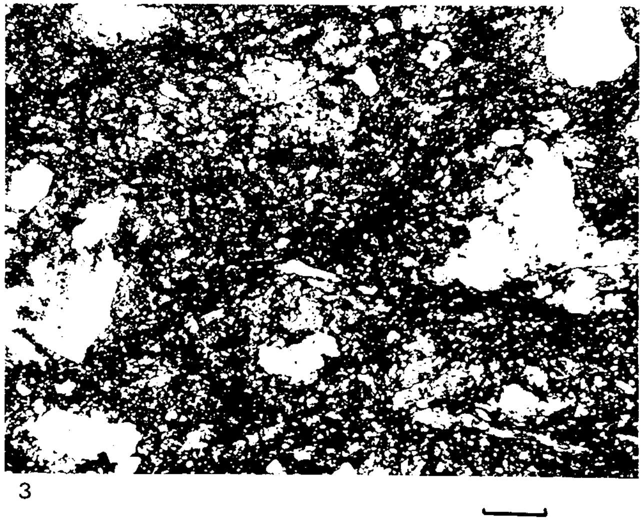
4. 1215 - Tuffaceous, chloritic iron-formation with bands of magnetite (ppl)

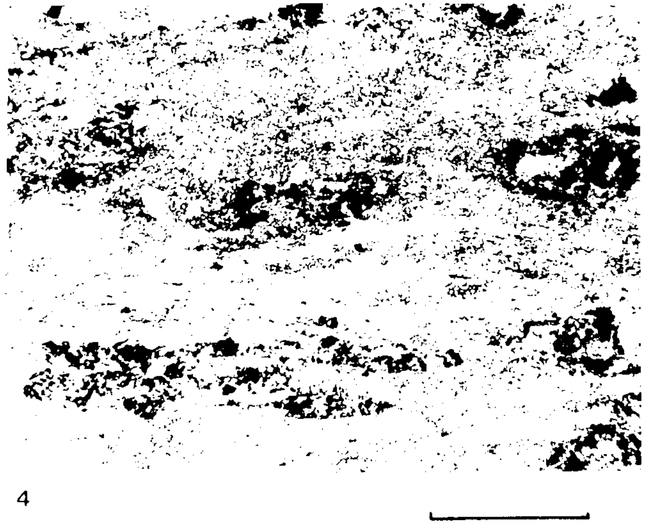
5./6. 1217 - As above with pyroclastic quartz crystals (ppl)

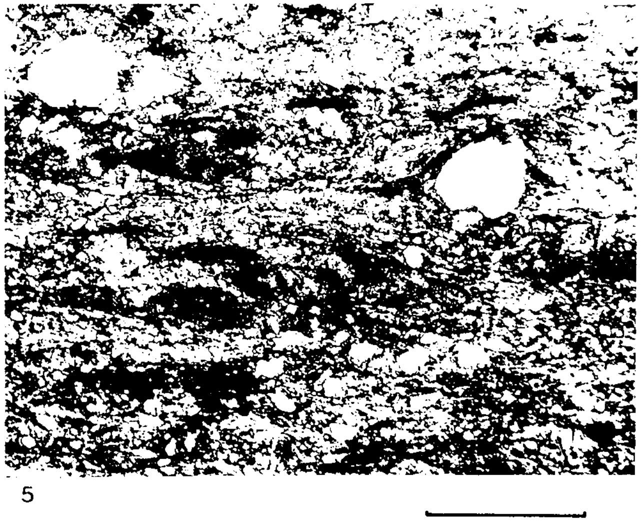
ppl = plane-polarised light


1


2


3


4


5


6

PLATE 9

PLATE 18

AVOCA VOLCANIC FORMATION - CRONEBANE MEMBER

1. Coarse pyroclastic with lensy cleavage ('pseudo-imbrication') fabric.

   North of Cronebane open-pit.

2. Fragment of siliceous footwall material in bedded pyrite - result of slumping.

   Cronebane open-pit.

1

2

PLATE 18

Ballymurtagh Member comprises sericitic tuffs (often with carbonate), chloritic shales, black shales, bedded sulphides and chloritic tuffs.

In the mine area, siliceous lithologies of the Cronebane Member are overlain essentially conformably by a sequence of non-silicified sericitic tuff ('Magnesian Tuff' of Platt, 1976), carbonaceous shales and chloritic shales ('chlorite schist') with interbeds of bedded, in part massive, sulphides.

Slumping in this unit has been described by Badham (1978) at Cronebane where the slumped unit within the Ballymurtagh Member contains both Ballymurtagh and Cronebane Member lithologies (see below).

The sequence can be traced south and westwards to Moneyteige (G.R. T 140750); the black shales are not seen in outcrop and the member is apparently composed mostly of chloritic tuffs and chloritic shales. The presence of the Ballymurtagh Member east of the Avoca River has not been confirmed except in the Cronebane open pit and adjacent areas along strike, although outliers may be present in the poorly exposed areas within the Cronebane Member outcrop area.

Lithologies similar to those of the Ballymurtagh Member are found near Avondale House (G.R. T 142868). An area of poor outcrop mapped as Ballinamona Member near Kilbride on the east bank of Potter's River contains an outcrop of carbonate-bearing black shale, and it is possible, though unlikely, that it has been wrongly assigned.

The component lithologies of the Ballymurtagh Member are described below.

The sericitic tuffs include the 'Hangingwall Pyroclastics', 'Hangingwall Tuff' and part of the 'Dolomitic Sediments and Tuffs' of Platt (1976), 'Magnesian Tuff' of Avoca Mines reports, and the 'Dolomitic Tuff Unit' of Badham (1978) (see fig. 2.10). They are best developed in West Avoca and south of Rathdrum (1120, 1057, 1071, 1072) and are generally intercalated with black shales, grading into tuffs in which chlorite, rather than white mica, is dominant.

The sericitic tuffs comprise fine-grained non-silicified tuffs and tuffaceous sediments, and are strongly altered. The only primary textures seen are small subrounded or subangular quartz grains and relics of recrystallised shards and feldspar crystals. Generally in thin-section the rocks consist of very fine quartz + white mica ± clay aggregates in lensy shapes which are separated by large plates of pale chlorite or sericite, or in some cases a clay-rich matrix. Talc has also been reported (Platt, 1976; Wheatley, 1971a) and specks of sulphide are common. Significant amounts of carbonate occur locally as pervasive replacements (together with fine-grained calc-silicate phases, mostly epidote where identifiable optically) as secondary augen and in quartz veins with associated sericite, chlorite and traces of (?) prehnite.

Chloritic shales ('chlorite schist') occur associated with bedded sulphides at West Avoca. They consist of fine-grained bedded rocks dominated by chlorite, with fine quartz and mica, and grade into fine chloritic tuffs with which they appear to be interbedded to the southwest (see plate 9). These rocks have been discussed by Wheatley (1971a) who considered that they represent iron formation.

Black shales include black and dark grey carbonaceous shales exposed at East and West Avoca, and also south of Rathdrum. Carbonate is generally associated with them as lensy re-crystallised interbeds up to 0.5m. thick, nodular replacements up to 10mm. across, as irregular patches and in veins. The beds of carbonate may show slump fold structures. The carbonate is a ferroan dolomite, with some later overgrowths of calcite, in a variety of replacement habits of coarse crystallinity. Petrographic examination of ten thin sections and XRD scans of six samples give no indications of remnants of pseudomorphs of evaporite minerals associated with this carbonate. At Cronebane, interbeds of fine sericitic tuffs are present.

Bedded sulphides occur in black and chloritic shales at Avoca and to the southwest where mixed sulphide-oxide ores occur. At Ballymoneen, 1.5km. SW of West Avoca, lenses of siliceous magnetite and bedded sulphides occur, and further to the southwest magnetite rich lenses are present at Ballycoog and Moneyteige (fig. 2.6). These occurrences are described further in section 2.5.2.

Chloritic tuffs consist of non-siliceous feldspar and quartz bearing tuffs and associated tuffaceous sediments which dominate the Ballymurtagh Member southwest of Ballymoneen (see plate 9).

The tuffs are best exposed along the Aughrim River and in the Ballycoog-Moneyteige area. They are generally fine grained with subhedral to anhedral grains of sodic plagioclase, untwinned feldspar, minor quartz and some lithic fragments. These may be grain- or matrix-supported in a matrix of green chlorite, with variable amounts of mica, stilpnomelane, fine quartz, magnetite, apatite and epidote. In some cases, grains appear to be pyroclastic (1041, 1042), but in others there is probably a strong epiclastic component (1174).

2.3. INTRUSIVE ROCKS

2.3.1. Diorite Group

Extensive intrusions of diorite and quartz diorite occur in the Arklow-Rathdrum area. They have been described by Reeves (1976). The diorite occurs in a zone of northeasterly trend from the area of Avondale House south of Rathdrum to Kilbride (figs. 2.5, 2.6). Smaller intrusions of dioritic rocks occur, for example to the south-west of West Avoca, but the majority of the other intrusions in the area are of dolerite or microgabbro. The diorite intrudes Ribband Group and the lower zones of the Avoca Volcanic Formation.

No intrusive contacts have been observed but the author concurs with Reeves (1976) that the diorites probably predate the main Caledonian deformation. Reeves (1976) cites evidence of deformed crystals, crushing and cleavage in the diorite, and cleavage postdating spotting in hornfelsed contact zones; orientation of chlorite in thin section can also be seen. Furthermore, the diorites are intruded by dolerite dykes (with chilled margins) and the dolerites also show a cleavage in the orientation of their chlorite (see below).

Reeves (1976) documents gradational changes in composition from diorite to quartz-diorite and granodiorite in the 'Carrigmore Intrusion' northwest of Kilbride (fig. 2.6). Diorite occurs in a central zone, surrounded by quartz-diorite, and granodiorite is locally developed as a marginal phase.

The rocks are phaneritic and are medium to coarse-grained. The diorite contains augite and biotite (alteration to chlorite is common, but uralitisation less so) with plagioclase (An_{48}), and K-feldspar which occurs as large crystals poikilitically enclosing all earlier minerals. The plagioclase is strongly sericitised. Quartz forms less than 5% of the rock (Reeves, 1976).

In the quartz-diorite, hornblende is developed from alteration of pyroxene and also occurs as free hornblende crystals. Quartz exceeds 5% and the feldspar is sericitised andesine overgrown by K-feldspar (Reeves, 1976). In the granodiorite (CI less than 30) pyroxene is absent, the mafics being hornblende and biotite.

The intrusives show moderate to strong alteration. Uralitisation occurs (1140) with development of some hornblende, but Reeves (1976) regarded the compositional zoning of the rock types as primary.

Propylitic alteration is widespread and commonly intense near the margins. Mafic phases are destroyed, as is plagioclase feldspar, and an assemblage of chlorite + epidote + quartz + albite + carbonate + opaques is developed (1089, 1092, 1135). Chloritic veinlets are also common with some quartz, and locally pumpelleyite and possibly prehnite (1064, 1065).

2.3.2. Dolerite and Microgabbro

Dolerite and microgabbro occur throughout the area, intruding Ribband Group, Volcanics and Diorite as dykes (up to 5m. thick) and as larger laccolithic or sill-like bodies which most commonly occur near the Ribband Group-Volcanics contact. They are fine-grained, dark green-grey rocks; ophitic texture is commonly but not invariably developed, and contacts are chilled.

The dolerites have been described by Hatch (1889) and recently by Reeves (1977b), who concluded that they predate the main regional deformation, this conclusion being supported by observations of cleavage in altered dolerites in outcrop and thin-section during the present study.

Although alteration is strong, the primary mineralogy of these rocks comprises augite and intermediate plagioclase feldspar (An_{54} determined by Reeves, 1977b); in a few specimens olivine is present (e.g. specimen 1180). The texture is ophitic to sub-ophitic in most cases (e.g. 1151, 1129). Original matrices are usually not preserved.

Alteration is complex, and intense. Uralitisation is the early phase (1123, 1157), followed by chloritisation and propylitisation. Feldspars are saussuritised, or in some cases albitised, and original mafics (and secondary amphibole) completely altered to chlorite and opaques. More calcic plagioclase feldspars are in some cases largely altered to carbonate. The matrix is generally completely recrystallised to an assemblage containing some or all of the following: chlorite, quartz (e.g. 1081), albite (e.g. 1110, 1123), epidote group (e.g. 1081, 1110), pumpelleyite (1091), opaques and (?) prehnite (1129, 1151).

2.3.3. Feldspar Porphyry

Some few dykes of feldspar porphyry occur within the Ribband Group slates. They are less than 10m. wide and are not shown in figure 2.6. They are pale grey rocks with phenocrysts up to 2mm. of feldspar showing fine normal or less commonly oscillatory zoning (1045) which are inclusion-rich and may show polysynthetic twinning indicating a sodic composition, although Carlsbad twinning is more common. Most are fresh but some are strongly sericitised. Quartz phenocrysts are abundant, and are clear, subhedral, locally showing some corrosion at their boundaries with the groundmass. Ragged green chlorite patches

(0.5mm.) pseudomorph mafics in some specimens. The matrix is a fine xenomorphic granular intergrowth of quartz, alkali feldspar, white mica, opaques and apatite.

An intensely argillically altered body of feldspar porphyry occurs in the Cronebane open pit as a narrow cross-cutting feeder with several sill-like bodies up to 3m. thick and some tens of metres in length branching off it. It postdates mineralisation, but its relationship to deformation is uncertain.

2.3.4. Granite

The Ballinaclash granite is a medium-grained phaneritic intrusive with a hypidiomorphic texture, consisting of perthitic and oligoclase feldspars, anhedral quartz and biotite. Minor amounts of sphene and zircon are present. Wheatley (1971a) recorded granophyric phases at the margins; a hornfelsed zone up to 30m. wide is developed in the country rocks, notably on the eastern side.

The granite is believed to be a marginal body to the syntectonic Leinster batholith (Brindley, 1954; Brindley and Connor, 1972; BrÜck and O'Connor, 1977; BrÜck et al., 1978).

2.4. STRUCTURE

2.4.1. Introduction

Tremlett (1959) proposed that the structure north of Avoca consists of a tight syncline overturned towards the west. Wheatley (1971a) stated that the Avoca district straddled a monoclinal structure overturned to the northwest, and Platt (1976) referred to an overturned recumbent syncline, refolded into an antiformal structure of northeasterly plunge. The interpretation proposed here (see fig. 2.7) is that the Duncannon Group occupies two synclinal zones, separated by an anticline of Ribband Group. The plunge of the synclines is irregular but on average is shallow to the southwest. This interpretation is consistent with the regional fold structures proposed by Gardiner (1970) for southeast Ireland.

Resolution of structural problems in the Avoca area is limited by the lack of a representative well-exposed coastal section, and by the sparsity and poor quality of inland exposure. In addition, traceable marker horizons are absent, and the lithostratigraphic subdivisions which are the major field-mappable units represent facies which are in part lateral equivalents. Local areas such as West Avoca have abundant surface exposure, permitting detailed structural analysis, but in attempting to extend such analyses to the regional scale several constraints should be noted. Firstly the mine sequence includes rocks of widely differing competencies; secondly the relative importance of slumping and tectonic transposition of rock types is still debated (Badham, 1978, and subsequent discussions, 1979); and thirdly the mine sequence consists largely of altered fine-grained clay-rich rocks which will show imprints of variations in stress which may not substantially affect the distribution of rock types on the regional scale.

2.4.2. Regional Structure

Folding. A geological section through the area is given in figure 2.7. The main structural elements for three areas of Ribband Group outcrop and for the Avoca and Ballymoyle Volcanic Formations are shown as stereographic plots in Appendix 1. These results are taken from reconnaissance traverses, except for those in the Avoca Formation where results from more detailed mapping are included. Appendix 1 also includes results of Brenchley and Treagus (1970) from the Ballymoney area south of Arklow.

The structural data plots indicate that the main structural elements are consistent between the two volcanic formations and the three areas of Ribband Group rocks. The data from north of Arklow compare well with those of Brenchley and Treagus (1970). The first cleavage (S_1) shows a point distribution which indicates that there has been only one major period of folding postdating the volcanism. The main cleavage (S_1) strikes 055°, dipping on average 65° to the southeast. Subsequent minor folding has a locally visible cleavage which dips northwest; it is most commonly associated with kink-bands or small-scale folds of the order of 1m. in wavelength, but it is not widely developed. The second cleavage observed at Ballymoney (Brenchley and Treagus, 1970) which dips NNE, is not obvious north of Arklow, although there are faults of this trend.

The L_1 lineation defined by the trend of axes of minor first generation folds shows a complete range of attitude within the plane of the first cleavage. This feature was noted by Brenchley and Treagus (1970) at Ballymoney, and can be demonstrated over short distances, for example in the coastal section north of Arklow.

The minor folds of the first generation are tight to isoclinal with wavelengths from a few millimetres to 10m. They are best developed in laminated tuffs and slates, and are well exposed on the coast in Ribband Group lithologies. Their presence must qualify the significance of facing determinations in the finer-grained rock units.

Folds of wavelength 100m. - 1,000m. are not seen, except at the Avoca Mine, probably as a result of the sparsity of exposure and lack of variation in lithology. Lithological contacts traced out between the Ballymurtagh and Ballinamona Members south of the

Aughrim River (fig. 2.6) suggest that such folds are present in this area, but exposures provide little structural information.

The results of mapping (figs. 2.6, 2.7) indicate large folds of wavelength 1km. - 2km. with an axial trend (040°) divergent from the main regional cleavage, S_1 (055°). This divergence between regional synclinal axes and the main cleavage may be the result of strike-slip stresses during the Caledonian orogeny as indicated by Phillips et al. (1976) and Phillips (1978).

The regional synclines preserve the Caradocian volcanics, and their axes commonly coincide with developments of massive rhyolite which suggest proximity to original vents. It is believed that a direct relationship exists between volcanic vent distribution, regional fold axes and the location of later intrusives (see section 2.6.4). The existence of these major folds is supported by a number of lines of evidence.

The Avoca Volcanic Formation has yielded poorly preserved fauna, suggesting an Upper Ordovician age (see section 2.2.3); fossil ages for the Ribband Group range from Upper Cambrian to Lower Ordovician (Brenchley and Treagus, 1970; Crimes and Crossley, 1968; Shannon, 1976) and lithostratigraphic correlations with the Avoca area are considered to be reliable (fig. 2.2). The volcanics are therefore flanked on either side by older strata and thus occupy synclinal zones within the Ribband Group. This relationship occurs to the south in areas studied by Brenchley and Treagus (1970) and Shannon (1976, 1978) and in work summarised by Gardiner (1970).

Kilmichael and Avonbeg Formation lithologies crop out to both east and west of the Ballymoyle Volcanic Formation and to the west of the Avoca Volcanic Formation. This provides good lithostratigraphic correlations for the Ribband Group in these areas and provides further evidence of a synclinal distribution of the stratigraphy.

The results of geological mapping (fig. 2.6) show that, particularly southwest of the Avoca River, the distribution of lithologies is symmetrical about an axial zone occupied by the Ballymurtagh Member. This is consistent with a synclinal structure with the Avoca Volcanic Formation in its core.

The distribution and outcrop pattern of the dacite lava units within the Ballymoyle Volcanic Formation suggest synclinal fold closures, notably at Ballymoyle Hill (figs. 2.6 and 2.7). The reconnaissance nature of mapping in the Ballymoyle Hill-Castletimon area should be noted, however; further detailed mapping may lead to modification of the suggested structure although it is doubtful if conclusive proof of structural closure is possible from the present quality of outcrop.

The structural interpretation proposed here - that the volcanics occupy two synclinal zones within the Ribband Group - is consistent with the evidence presented above and with the presence of a single major regional cleavage. The preservation of delicate primary petrographic fabrics (see plates 1 - 3) and weakness of the main cleavage in unaltered volcanics of the Ballymoyle Volcanic Formation do not suggest the intensity of deformation required to produce major refolded isoclinal overfolds. The simpler style of folding proposed here is more consistent with the style of deformation typical of the paratectonic Caledonides (Dewey, 1969a).

Faulting. Faulting followed folding in the area, and has a significant effect on rock distribution. The limited extent and quality of exposure precludes detailed fracture analysis, but mapped and inferred faults shown in figure 2.6 have the following major orientations:

North-South Faults - this fault set forms a series of major fractures; in the southwest the direction is NNE, becoming more strictly northerly in the northern and eastern parts of the area. The fault separating East and West Avoca is perhaps the best demonstrated since it displaces the mineralised horizon. The throw is oblique with the strike-slip component exceeding the vertical. The fault planes, where seen, mostly near the mine and on the coast, are steeply dipping.

East-West Faults - this fault set is well exposed on the coastal section, but is strongly developed throughout the area, displacing lithological contacts and influencing topographic features. Where exposed, the fault-planes are vertical, and the inferred throws are those of normal faults.

Northeast Faults - these faults are apparently less common, but this may result from non-recognition because they are sub-parallel to the strike. Fault planes which are exposed on the coast, and, for example, in the Aughrim River valley, are steep but throws cannot be determined because of lack of exposure.

Southeasterly Faults - a minor set of southeasterly trending steep faults causes displacements of lithological units, especially in the area between the Avoca Mine and the Aughrim Valley. Their positions are mostly inferred from geomorphological features, and the resultant offsets of geological boundaries suggest that the displacements on these faults are largely vertical.

Metamorphic Grade. Few specimens have yielded diagnostic assemblages, but the few occurrences of pumpelleyite and prehnite, mainly in the intermediate intrusive rocks (e.g. 1091, 1045?), suggest that the grade is within the prehnite pumpelleyite and the low greenschist facies.

2.4.3. Local Structure at Avoca

The detailed structure of the mine area has been much discussed (Platt, 1978b; McArdle, 1979; Badham, 1979). Badham (1978) showed that slumping is important in redistributing rock types at Cronebane but Platt (1976, 1978b) demonstrated that the main local structural feature is isoclinal folding with accompanying axial plane shear (see fig. 2.10).

During the present study, the mine area was considered only on a broad scale as part of the regional sequence, and little detailed structural work was done within it. A detailed structural analysis was carried out by Wheatley (1971a), and additional work forms part of a study presently being undertaken by Sheppard (Trinity College, Dublin, Ph.D. in progress).

Wheatley (1971a) recorded a major penetrative cleavage, S_1, which is axial planar to the main fold set, and corresponds to the regional S_1 cleavage noted above. He also recorded a second, non-penetrative cleavage (S_2) striking 130° with steep dips to NE and SW.

Faults were classified by Wheatley as minor, major, and breccia zones. The minor faults of northerly trend dip steeply and comprise both normal and reverse faults with minor sinistral components; those of southeasterly trend are steep normal faults, and those of northeasterly trend are shears which merge into the main schistosity. The major faults are sinsitral oblique strike-slip faults with either normal or reverse dip-slip components; they strike north-northeast (026°). Open fissures and breccia zones of mean trend 169° also occur. Wheatley recorded mineral elongation in the plane of S_1 trending 212° and plunging 38° SW, which coincides with the plunge of the mineralisation, and also some minor F_1 drag folds with a mean trend of 078° plunging 22°E. For further details, the reader is referred to Wheatley (1971a).

The gross structure of the Avoca Mine area is believed to be a syncline overturned to the SE with a shallow plunge to the southwest (figs. 2.7 and 2.10), and this is supported by the following features observed during mapping:

1. It lies within a regional syncline whose axial zone is occupied by the Ballymurtagh Member, and passes through the mine area.
2. Silica + chlorite + sulphide alteration of the Cronebane Member occurs on the north (over the entire length of the mine zone) and on the south (notably at Cronebane) of the Ballymurtagh Member.
3. Identical Cronebane Member tuff lithologies occur both north and south of the bedded sulphide zone, though on the south side massive rhyolites are more common.

4. Both rhyolite and chloritised tuffs of the Cronebane Member occur as phacoids in slump breccias within the Ballymurtagh Member at Cronebane, indicating that the latter is the youngest unit in the sequence; thus the youngest unit occupies the axial zone.
5. An overall southwesterly plunge is indicated by the pinching out of the Ballymurtagh Member to the northeast, indicating a closure in this direction.

Compilation of mapping and drilling results by Platt (1976, 1978b and unpublished data) are consistent with this interpretation indicating minor folding of a single ore horizon to form a series of synclines of shallow southwesterly plunge which are complicated by axial plane shear on the limbs (fig. 2.10). It is considered that these minor folds occur within the regional fold structure and that the sequence within the Avoca Mine area contains the closure of the upper part of the sequence.

The fold structure suggested is consistent with the mineral elongation lineation described by Wheatley (1971a) and visible in the open pit of West Avoca. The northeasterly-plunging minor "F_1 drag-folds" in ore noted by Wheatley are suggested to be a similar feature to the rapid variations in plunge of minor folds exhibited by Ribband Group Laminites (see section 2.4.2).

2.5. MINERALISATION

2.5.1. The Avoca Mine Area

The mineralogy of the Avoca ores has been described by Wheatley (1971a) who derived a comprehensive paragenesis for the ore minerals. The major sulphide mineral at Avoca is pyrite which accounts for 90% of the total sulphides, and Wheatley (1971a) described framboidal, colloform and zoned and unzoned crystalline types. The subsidiary sulphide phases are chalcopyrite, sphalerite and less commonly galena. Chalcocite is common in the Cronebane open pit. Wheatley (1971a) also recorded tetrahedrite-group, arsenopyrite, pyrrhotite, bismuth sulphosalts and other minor phases. Iron oxides are associated with bedded non-siliceous ores hosted by chloritic shales in West Avoca. Wheatley (1971a) recorded that chalcopyrite, sphalerite and galena frequently show replacement textures with respect to pyrite, and that their crystallisation therefore post-dated that of most of the pyrite.

Sulphide mineralisation at Avoca may be divided on a macroscopic scale into three types:

1. Siliceous footwall mineralisation.
2. Non-siliceous cupreous pyrite mineralisation.
3. Polymetallic bedded mineralisation.

Historically at Avoca these are referred to as the South Lode type, Pond Lode type and Kilmacooite respectively, although within the 'Lodes' ore types may merge. The first two names are nomenclature generally restricted to West Avoca, although the ore types also occur in East Avoca.

Siliceous footwall mineralisation. This type occurs stratigraphically at the top of the Cronebane Member. It consists of a host composed largely of quartz and chlorite representing intensely altered iron-formation, chert and fine tuff, with abundant quartz and chlorite veins which commonly cut the bedding at shallow angles. The sulphides occur as dispersed grains and small aggregates in the bedded host, within the cross-cutting quartz chlorite veins, and as massive conformable lenses of the order of 10mm. to 0.1m. in thickness and of variable lateral extent (up to 5m.).

The sulphides are predominantly pyrite, with chalcopyrite, giving average grades for the better sections of this mineralisation of the order of 0.7% to 1.25% Cu. Sphalerite is a minor constituent at West Avoca (0.25% Zn - Murphy, 1959) but at East Avoca it is more important, and grades in this zone may average up to 1% Zn (e.g. drillhole E.C.4 quoted by Platt, 1976). Galena follows sphalerite, but grades are generally below 0.5% Pb. In the conformable lenses of ore, the chalcopyrite:pyrite ratio is generally higher than for the non-siliceous pyritic ore; Murphy (1959) quoted values of 1.25% Cu with only 5% to 8% S for the South Lode in West Avoca, whereas for the non-siliceous pyritic ore of the Pond Lode grades were 0.9% to 1.0% Cu with 25% S, again in West Avoca.

Sulphide distribution and grade are subject to strong stratigraphic control. Mineralisation is most intense near the contact with the Ballymurtagh Member. This is true for all three forms of sulphide occurrence but most marked for sulphide in conformable lenses. Copper grade and sulphide content fall off rapidly within 10m. of this contact within the Cronebane Member from an average of 0.7% to 1.25% Cu to around 0.3% Cu (Avoca Mines Ltd., unpublished data). This lower grade mineralisation extends for up to 100m. into the footwall.

The best development of this mineralisation type occurs in the South Lode at West Avoca (plate 20) where Murphy (1959) recorded widths of up to 50m. of the higher grade of mineralisation. The South Lode zone occurs at the top of the Cronebane Member in an apparently en-echelon relationship to the non-siliceous Pond Lode. The local term 'South Lode' includes both siliceous footwall and non-siliceous cupreous pyrite ore, but it is in this zone that the former is best developed. Pyrite and chalcopyrite occur disseminated in the siliceous chloritic rocks, in discordant veinlets of quartz and sulphide and as lenticular beds commonly associated with fine pale green chert. In some of these beds, galena and sphalerite occur together with pyrite and chalcopyrite. In addition to the above, irregular patches of coarse crystalline white quartz, minor chlorite and chalcopyrite occur, with little associated pyrite. These resemble metamorphic exudation veins and are believed to be the result of remobilisation during metamorphism. They cut all other forms of mineralisation.

The 'North Zone' at West Avoca, which shows extensive quartz-chlorite alteration, contains low-grade mineralisation (?0.2% Cu) of the siliceous footwall type. The zone is exposed adjacent to two small old open pits to the north of the present West Avoca workings.

In East Avoca, siliceous footwall mineralisation forms the major part of the Tigroney mine, and is well exposed in the Cronebane pit. The host rock at Cronebane is a green siliceous altered tuff with recrystallised cherty and chloritic bands. Abundant quartz veins occur parallel, sub-parallel and discordant to the bedding. Pyrite and minor chalcopyrite are present in the veins, and also occur dispersed in the rocks, and in thin, laminated beds. Towards the contact with the Ballymurtagh Member the amount of bedded sulphide increases, and subrounded, commonly elongate slabs of mineralised, quartz-veined, siliceous, chloritic lithologies are observed disturbing the sulphide layering. These are interpreted as blocks of the footwall slumped into the bedded sulphide (plate 18) and are further described in the following section.

PLATE 19

AVOCA VOLCANIC FORMATION - CRONEBANE MEMBER

1. Altered, mineralised rhyolite, brecciated with matrix of pyrite.

   East end of Cronebane open-pit.

2. Rhyolite as above, showing crackle-brecciation.

   East end of Cronebane open-pit.

1

2

PLATE 19

PLATE 20

SULPHIDE MINERALISATION AT AVOCA

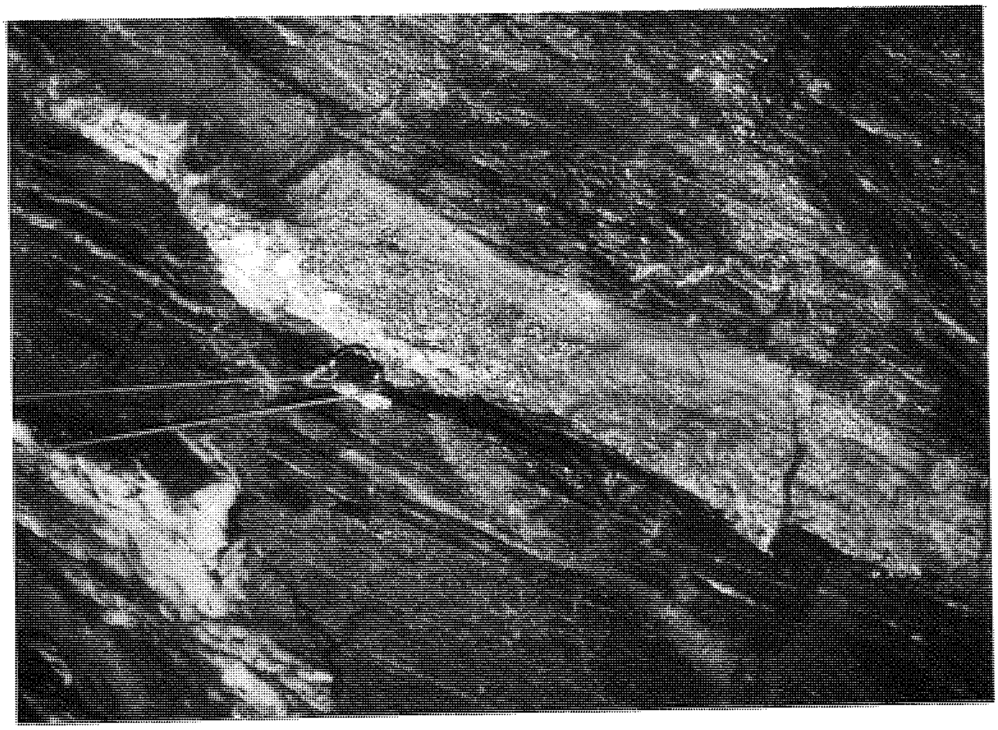
1. Pond Lode - bedded pyrite in chloritic host showing discontinuous 'scalloped' bedding.

   West Avoca.

2. South Lode - bedded pyrite in siliceous chloritic host with mobilised chalcopyrite and white quartz.

   West Avoca.

1



2

PLATE 20

In this upper part the silicification becomes patchy and the beds of sulphide thicker and more coherent. The base of the Ballymurtagh Member is formed by non-siliceous well laminated ± massive pyritic sulphides with grey-green sericitic tuff and black shale.

At the north end of the Cronebane pit is a body of rhyolite, argillically altered, forming a breccia with a pyritic sulphide matrix (plate 19). Contacts with the enclosing fine tuffs and black shales are sheared, but the rhyolite is cross-cutting and probably intrudes the sediments. It has been described by Badham (1978) and Platt (1978a). The breccia is at least in part a crackle breccia, the fragments having suffered rotation of the order of 10° only. At the contact with the shale, disruption is more severe.

Non-siliceous bedded cupreous pyrite mineralisation. This ore type occurs at the base of the Ballymurtagh Formation at Avoca. It consists of bedded pyritic ore hosted by chloritic shale or in part by black carbonaceous shale. The sulphides are predominantly pyrite, with minor chalcopyrite and only traces of sphalerite and galena. Average copper grades are 0.8% to 1.1% Cu (Murphy, 1959) and the pyrite:chalcopyrite ratio is high (see above). The mineralisation varies between massive (90% sulphide) and more dilute (as low as 10% - 20% sulphide overall) but is invariably bedded; pyrite commonly has a grainsize of up to 1mm. Wheatley (1971a) recorded colloform and spheroidal in addition to crystalline textures. Chalcopyrite is generally interstitial to, or replacing, pyrite (Wheatley, 1971a).

The main body of the non-siliceous bedded pyrite mineralisation at West Avoca is the Pond Lode (fig. 2.1 and plate 20). It consists of well bedded pyrite, in part massive, in a host of chloritic shale, passing at the hangingwall into black graphitic shale.

The bedded sulphides exhibit a lenticular bedding structure consisting of individual bedded units of laminated or thinly-bedded pyrite and chloritic shale which may show slumped, graded or simple bedding on a scale of millimetres or tens of millimetres. Sedimentologically consistent units reach 10mm. to 1m. in thickness and can be traced laterally over distances of from 0.1m. to 2m. or more. At the junction between these coherent units the laminae and thin beds overlap in a scalloped structure giving the whole a lenticular-bedded appearance (plate 20). It is suggested that the depositional environment was subject to disturbance, but there is no evidence of large-scale slumping in the Pond Lode at West Avoca such as has been observed at Cronebane (see below).

At West Avoca, similar mineralisation occurs in thin horizons in the locally named 'Mernagh' and 'Keating' zones.

At East Avoca, non-siliceous bedded pyritic ores occur in the Tigroney mine in a narrow zone south of the 'Tigroney adit'. Old stopes are seen in this zone underground but it was not observed in outcrop. It is bounded to north and south by Cronebane Member lithologies and may represent the sheared-out keel of a syncline.

In the Cronebane area of East Avoca the bedded pyritic mineralisation is well developed but differs in several respects from the equivalent zone at West Avoca. The contact with the Cronebane Member (which hosts siliceous footwall mineralisation) is not simple: blocks, subrounded to subangular and tabular in shape, up to 1m. in length and 0.1m. thick, of chert, silicified chloritic tuff and rhyolite occur as clasts in bedded non-siliceous sulphides (plate 18). The clasts themselves carry typical siliceous footwall mineralisation. The frequency of these blocks decreases upwards towards black shales of the polymetallic ore zone horizon, which has been shown by Badham (1978) to be an extensively slumped zone (see below).

The presence of clasts of Cronebane Member lithologies in the non-siliceous pyritic ores is believed to be the result of contemporaneous disturbances similar to those which produced the overlying slumped zone in the black shales. The fragments appear to be locally derived and the distance of transport small since the lithologies involved occur in the immediate footwall.

Some enrichment of the non-siliceous pyritic ores has occurred at Cronebane. The host rock is partly or totally converted to a white clay, the pyrite is generally coarser in grainsize (1mm. - 2mm.) and the main copper sulphide is covellite. This enrichment is probably the result of supergene processes.

There is little data available for the Connary area, though this was extensively mined in historic times.

Polymetallic bedded mineralisation. Non-siliceous bedded polymetallic mineralisation occurs within the Ballymurtagh Member in the horizon immediately overlying the non-siliceous pyritic ores. The ore varies from fine-grained pyrite with beds and laminae rich in chalcopyrite or composed of fine sphalerite and galena to pods of massive galena with sphalerite and the finely bedded 'Kilmacooite'. This last is a typical 'black ore' consisting of a dense intergrowth of galena, sphalerite, pyrite and minor chalcopyrite assaying up to 30% or more Pb + Zn (Wheatley, 1971a).

At West Avoca finely layered polymetallic sulphides overlie the bedded pyrite horizon with a sharp conformable contact. They are of finer grainsize than the pyrite mineralisation and represent a true massive sulphide horizon with 80% - 90% sulphides but probably only around 1m. thick. Discontinuous lenses of galena and sphalerite up to 2m. thick overlie the Pond Lode horizon within the carbonate rich sections of the Ballymurtagh Member.

At East Avoca the bedded polymetallic ore is developed in the Cronebane area and remnants of it are present in the open pit. At the east end of the open pit a thin horizon, less than 0.5m. thick, of grey, very fine-grained, banded 'Kilmacooite' occurs in a black shale host overlying the pyritic ore horizon. In the central part of the open pit the bedded pyritic ore horizon is overlain by an extensive slump breccia unit, up to 50m. or more in thickness, hosted by black carbonaceous shales and containing fragments of siliceous footwall mineralised material, altered rhyolite, 'Kilmacooite', siliceous chalcopyrite ore and pyritic ore. This unit has been described in detail by Badham (1978) who recognised its slumped origin.

To the east 'Kilmacooite' is found in the dumps at Kilmacoo (its type area) east of Connary, but no exposures or workings are accessible.

2.5.2. Other Mineralisation in the Avoca Volcanic Formation

A comprehensive list of minor mineral occurrences in the Avoca area is given by Wheatley (1971a). Many of these are in cross-cutting veins and are represented by small amounts of spoil, and no additional information to that presented by Wheatley is available. Four of the occurrences are worthy of mention in the light of further field evidence and their relationship to the volcanic stratigraphy presented above.

Ballymoneen. At Ballymoneen, Loc. 34, some 1.5km. SW of West Avoca (fig. 2.6), iron and perhaps copper were worked in the 19th Century. According to Wheatley (1971a), to the west of the fault passing near Loc. 34 two en-echelon lenses of siliceous magnetite, with minor pyrite and veined by later carbonates, are conformable in green chloritic phyllite. East of the fault, Wheatley (1971a) described a series of ore lenses with a layered pyritic zone stratigraphically overlying a siliceous copper-rich zone. These are also conformable within green chloritic phyllite, and their mineralogy comprises pyrite, chalcopyrite and sulphosalts (Wheatley, 1971a). In addition, pale brown sphalerite occurs as veinlets and bands in some layered pyrite specimens in the mine dumps.

The present mapping shows that the Ballymoneen mineralisation occupies a similar stratigraphic position to that of the Avoca mineralisation - the junction between the Cronebane and Ballymurtagh Members. The host-rock of the layered pyritic ores is a similar chloritic mudrock. Wheatley (1971a) commented on the similarity of the mineralisation types, with both siliceous footwall and non-siliceous cupreous pyrite types being present. Wheatley (1971a) reported that some drilling had been undertaken but the prospect has not been effectively evaluated (J. Platt, pers. comm.). The presence of this mineralisation indicates potential for both copper and lead-zinc ores in the area southwest of Avoca.

Ballycoog. The mineralisation at Ballycoog (G.R. T 157772) at Loc. 47, 5.5km. SW of West Avoca, lies within the Ballymurtagh Formation. The mineralisation was worked around 1769 (Cole, 1922). According to Wheatley (1971a), the mineralisation consists of "two en-echelon lenses, a northern lode of siliceous magnetite with disseminated chalcopyrite and a southern lens of banded pyrite with minor chalcopyrite". The lenses which wedged out in depth were broadly conformable with the regional trend, and grab samples graded 1.5% - 2% Cu (Wheatley, 1971a).

The host rocks are chloritic mudrocks with large plates of dark chlorite and chloritic tuffs. The western outcrops in the area are of tuffs and buff slates veined by quartz, chlorite and limonite, but there is little pervasive silicification in outcrop. The spoil dump material consists of quartz veined chloritic tuff with white quartz + green chlorite + magnetite and traces of galena in the veins, and a largely non-siliceous chlorite schist with layers up to 0.1m. thick of massive magnetite with slugs of recrystallised chalcopyrite. Wheatley (1971a) also recorded layered pyrite.

The Ballycoog mineralisation thus appears to contain both oxide and sulphide as bedded ores in chloritic mudrocks and a stringer zone. Nearby to the east is a local development of siliceous Cronebane Member type altered tuffs.

Moneyteige. The Moneyteige workings consist of two shallow shafts, two trenches and an adit at Loc. 49 (G.R. T 140759), some 8.5km. SW of West Avoca. Production of iron ore was recorded by Weaver (1821). Wheatley (1971a) reported that outcrops indicate two seams of siliceous magnetite up to 5m. (15ft.) thick and 100m. (300ft.) in length, and that the dump material graded about 1.5% Cu.

The host rocks are chlorite schists of the Ballymurtagh Member. Mineralisation on the spoil dumps consists of massive magnetite with traces of chalcopyrite in veins of quartz and dark green chlorite with randomly orientated growth in somewhat silicified chlorite schists.

Between Ballycoog and Moneyteige are several shallow surface workings and one shaft (Loc. 48) at Ballinasilloge, which Wheatley (1971a) recorded as being sunk to work a series of siliceous veins with sphalerite, galena and minor chalcopyrite. The host rocks are chlorite schists and tuffs of the Ballymurtagh Member. Little sign of mineralisation is present at surface except for sparse gossanous quartz veins less than 0.1m. across. The dump material at the shaft is mostly vein quartz and carbonate with a little pyrite. Anomalous levels of zinc were found in a soil geochemical survey in this area (Platt, unpublished reports, Avoca Mines Ltd.).

Ballard. A small body of rhyolite and dacite at G.R. T 266876 shows in part propylitic alteration and contains cross-cutting veins of pyrite, quartz and chlorite. The mineralisation is weak and patchy. Nearby (Loc. 46) some signs of old workings are present and 1km. to the southwest is a series of old shafts from which magnetite was worked in historic times. The area was investigated by Mianrai Teoranta (unpublished reports) and appears to consist of a thin zone of siliceous magnetite. Wheatley (1971a), quoting Murphy (Mianrai Teoranta data), reported assay values of 55% Fe over 2m. (6ft. to 8ft.) in an old stope. The workings have recently collapsed. The mineralisation occurs within the Cronebane Member but there is little evidence concerning its nature.

2.6. DISCUSSION

2.6.1. Environment of Volcanism

Shannon (1976) suggested that the Ribband Group represents a distal turbidite suite and that its distal nature may reflect low rates of supply from an eroded source area rather than a deep water depositional environment. This is supported by the red and purple colouration in its upper units which is believed to be the result of oxidation during sedimentation or diagenesis. Stillman and Maytham (1973) in a study of volcanics at Arklow Head, 3km. south of Arklow, concluded that volcanism commenced in a shallow subaqueous environment, with the cone becoming emergent in the later stages of volcanism.

That the Ballinamona Member was deposited in subaqueous conditions is shown by the conformable contact with the Ribband Group in the Aughrim River section, by the intercalations of grey and black shales higher in the sequence, and the tuffaceous sediments found within it. Subaqueous conditions persisted at least locally because black shales with graptolites overlie ore at Avoca in the Ballymurtagh Member.

The base of the Ballymoyle Volcanic Formation also contains shale intercalations, and there are shales higher in the sequence in lava breccia and interbedded with tuffs north of Jack's Hole. Horizons of welded ash-flow tuffs in the sequence suggest that the depth of water was not great.

It is concluded that the Duncannon Group in the Arklow-Rathdrum area was deposited in a shallow subaqueous, at least partly marine environment, and that local emergence may have taken place.

The volcanics, which are largely composed of pyroclastics, contain rhyolite masses, many of which are plug-like in form. The rhyolites were probably emplaced at high level because they are amygdaloidal, show flow layering in some cases, and commonly are autobrecciated. These rhyolites are believed to represent areas proximal to original vents, since they are commonly grouped together and mostly occur within the coarser and more strongly hydrothermally altered Cronebane Member.

The Ballinamona Member, containing finer, partly reworked pyroclastics and argillites, is considered to represent more distal and earlier volcanism. It also occupies the lower parts of the stratigraphic section. The Ballymurtagh Member post-dates the intense alteration and mineralisation phase and represents a return to quieter conditions of fine tuff and shale deposition during the waning phase of the volcanic cycle.

Volcanism in the area occupied by the Avoca Volcanic Formation was thus related to a number of small centres now represented by concentration of rhyolite and surrounded by a proximal volcanic unit, the Cronebane Member. The quieter, earlier and more distal volcanics are represented by the Ballinamona Member and the products of the waning stages of volcanism by the Ballymurtagh Member which overlies both the above.

In the Ballymoyle Volcanic Formation a less detailed picture is available but the rhyolitic and dacitic lava concentrations at Castletimon and Ballymoyle Hill are considered to represent original volcanic centres and the environment was probably similar to that of the Avoca Volcanic Formation.

2.6.2. Composition of the Volcanics

Petrographic information from less altered specimens indicates that the volcanics are rhyolitic to dacitic in composition. In the Ballymoyle Volcanic Formation the lavas are dacitic; quartz phenocrysts are commonly present although some andesitic compositions are probably present.

The results of stream-sediment surveys by Reeves (1977a) and van Lunsen et al. (1977) show that geochemical background values for volcanics in the Rathdrum and Avoca areas correspond well, but differ from those in the Castletimon and Ballymoyle areas:

	Cu ppm		Pb ppm		Zn ppm	
	mean	threshold	mean	threshold	mean	threshold
Avoca Volcanics	37	114	137	497	163	336
Rathdrum Volcanics	27	62	171	647	156	329
C/timon & *B/moyle Volcanics	16	32	49	87	93	183

* (Ballymoyle Volcanic Formation)

Data from Reeves (1977a); van Lunsen et al. (1977)

Statistical analysis by Reeves (1977a) indicated homogeneity within the groups. These background values for Cu, Pb and Zn in stream sediments imply some real geochemical distinction between the Avoca and Ballymoyle Volcanic Formations. The similar values in the Avoca and Rathdrum groups also support the inclusion of volcanics near Rathdrum in the Avoca Volcanic Formation.

2.6.3. Age of Volcanism

The age of volcanism is probably Upper Ordovician (Caradocian) on the palaeontological evidence of Brenchley et al. (1977) and the poorly preserved graptolites reported in section 2.2.

2.6.4. Relationship of Volcanism to Regional Structure

The volcanics are related to vent areas indicated by concentrations of massive rhyolite, as described above. The rhyolite occurrences have a strong linear trend (fig. 2.6) which is roughly parallel to the axes of the regional folds. A similar relationship can be seen on the regional geological maps (e.g. Brindley et al., 1973) to continue through the Enniscorthy and New Ross areas.

The linear trend is also followed to a large extent by the post-volcanic but pre-deformation dioritic intrusive bodies, and is reflected not only in their shape (which may be tectonically modified) but in their spatial distribution. A similar observation applies to the syn-tectonic granite and granodiorite intrusions related to the Leinster Batholith, of which the Ballinaclash granite is an example within the area mapped. Thus volcanic centres, location of two phases of later intrusives and regional synclinal fold axes all follow a single linear trend. This recurrent linear control may reflect deep structural weakness in this zone of the crust at least since Ordovician times, and Shannon (1976), discussing the sedimentology of the Lower Cambrian Bray Group, suggested that the Cambrian depositional basin in this area may have been elongate in a NE-SW direction.

2.6.5. Alteration associated with the Avoca Mineralisation

The Cronebane Member of the Avoca Volcanic Formation shows the effects of widespread alteration which is most intense in the immediate footwall of the Avoca mineralisation. This alteration involves the destruction of lithic fragments, feldspars and mafic mineral phases, and the deposition of an assemblage quartz + chlorite ± pyrite. Where alteration is less intense, silification is weaker and sericite occurs in preference to chlorite. Such weak alteration is also found in the Ballinamona Member in mineralised areas. Associated with this alteration are some petrographic features. Where sericitic alteration is strong 'quartz-eyes' may develop. These are formed in most cases by recrystallisation and overgrowth of primary crystal clasts in tuffs, but where alteration is intense they commonly lack visible nuclei and are porphyroblastic (see plates 5, 8 and 9).

In the Cronebane Member where quartz + chlorite ± pyrite alteration is strong, the rocks develop a lensy cleavage which may resemble a gneissic fabric in places and elsewhere is similar to a coarse eutaxitic fabric (see plates 8 and 9). In thin-section such rocks appear intensely altered, particularly their matrices. Original clasts are overgrown with quartz or recrystallised, and an undulating cleavage wraps around them to give the lensy appearance. Where clasts are absent, the symmetry of this cleavage is in some cases maintained by the growth of fine quartz aggregates.

Such features of strong cleavage and intense recrystallisation in the Cronebane Member contrast with the delicately preserved vitric and welded textures described from the Ballymoyle Volcanic Formation (plates 2 and 3). It is suggested that these fabrics result from alteration of pyroclastics prior to lithification. Volcanic glass and pumiceous fragments are altered to clay by hydrothermal solutions passing through the permeable volcanics in fumarolic areas, and collapse to give similar fabrics to those found in vapour-phase welded ash-flow tuffs. Silica and iron may be deposited in the mineralised areas and the primary feldspars and mafic minerals destroyed. Subsequent imposition of a cleavage results in the fabric described as'pseudo-imbrication' in section 2.2.3.

Such rocks form much of the stratigraphic footwall of the Avoca deposit where they contain low-grade mineralisation and are interbedded with recrystallised chert and chloritic iron-formation (see below). The alteration, in a less intense form, extends along strike away from the Avoca mine.

2.6.6. Environment of Mineralisation

The bedded sulphide mineralisation at Avoca occurs within the upper part of, and immediately overlying, the Cronebane Member. The footwall and lower parts of this bedded ore zone are affected by the strong silica + chlorite + sulphide alteration described above and are believed to have originally comprised pyroclastics, cherts and chloritic mudrocks, although subsequent recrystallisation is intense. The upper part of the bedded ore zone, within the Ballymurtagh Member, is not siliceous and is hosted by chloritic shales and black shales.

Wheatley (1971a) sampled the chloritic rocks associated with the bedded sulphides and concluded that the chlorite was iron-rich, comparable with thuringite, and that horizons composed of such iron-rich chlorites represented original sedimentary iron formation.

Wheatley's conclusions were supported by his identification of a phosphate-rich horizon within this sequence (Wheatley, 1971a).

In addition to sulphide, carbonate (mostly a ferroan dolomite) is common in the Avoca mine area in an horizon overlying sulphide in the Ballymurtagh Formation. It is present in beds, which have slump-folds, and as nodules and patches replacing shales and sericitic tuffs. The close spatial relationship between carbonate and sulphide, and the concentration of carbonate in the strata immediately overlying the sulphides, suggest that there may be a genetic relationship between the two phases. It is believed that carbonate may have been deposited by the latest stages of the same hydrothermal system which deposited the sulphides.

Badham (1978) demonstrated the effects of slumping at East Avoca. The lensy bedding features observed in the Pond Lode indicate that some syn-sedimentary disturbance also took place at West Avoca. However, the well bedded section of the Pond Lode, with lateral continuity for distances in excess of 10m. indicates that, in at least the upper parts of the mineralised sequence at West Avoca, large scale transposition of material did not occur. Thus, whilst there is local disruption of thin bedding, movement of material for more than a few centimetres, and mixing of yellow ore, black ore and mineralised footwall lithologies by slumping, is not believed to have taken place.

Wheatley (1971a), in his paragenetic scheme for the Avoca mineralisation, noted that chalcopyrite, sphalerite and galena replace pyrite, and proposed a time gap between pyrite and the later sulphides. He suggested that pyrite was a primary sedimentary component, and the later sulphides were epigenetic, with the replacements occurring between sedimentation and later folding (Wheatley, 1971a). The occurrence of distinct phacoids of yellow ore, black ore, and bedded pyritic sediments in slumps at East Avoca (Badham, 1978) indicates that the time gap between the main pyrite and the polymetallic sulphides was short, and that deposition of both phases occurred essentially within the sedimentary environment.

2.6.7. Genetic Model

The volcano-sedimentary nature of the Avoca mineralisation was first suggested in the 1950's by G. J. Murphy (in private correspondence with Professor Stanton, pers. comm.), and discussed by Stanton (1958). The detailed work of Wheatley (1971a) and Platt (1976) further developed this concept, which is again supported by the results of the present study.

The mineralisation at Avoca is the largest known occurrence of sulphide mineralisation within the Avoca Volcanic Formation. Volcanism, of Caradocian age, was associated with a series of small rhyolitic vents whose distribution was probably controlled by temporally persistent linear zones of crustal weakness. The volcanism, which occurred as a single phase of activity, was predominately subaqueous. It commenced with a fairly widespread sequence of fine tuffs, and tuffaceous sediments, which were interbedded with shales. Local vents then built up with deposition of coarse proximal pyroclastics, local flows of rhyolite, and small shallow plugs. Towards the end of this stage, strong hydrothermal activity developed around the vents resulting in local fumarolic exhalations, which gave rise to volcanogenic sediments comprising chert, iron formation and sulphides. The passage of large volumes of hot water through the unconsolidated pyroclastics resulted in alteration of their glassy and pumiceous components with silicification, chloritisation and sulphide deposition. Thus 'stockwork' mineralisation in the strict sense is not common at Avoca, but the bedded sulphide zones are underlain by altered volcanics with dispersed sulphides and some quartz, chlorite and sulphide veins.

The main horizon of sulphide deposition developed at the conclusion of this vent-building volcanism, which was followed by a return to quieter conditions in which fine tuffs, and shales, were deposited. Fumarolic activity continued, giving rise to deposits of iron formation and locally carbonate.

The main zone of bedded sulphides shows a crude zonation from cupriferous pyrite to polymetallic pyritic ore (Kilmacooite) with time. In part the ore zone is extensively slumped, but elsewhere, though local disturbance is evident, little transposition of material has occurred.

Several other areas of hydrothermal activity were developed along strike from Avoca, for example at Ballymoneen, Ballycoog and Moneyteige, where sulphides, chloritic iron formation and magnetite are associated with local zones of altered pyroclastics.

The altered volcanics in the mineralised zones exhibit a more intense degree of deformation than less altered volcanics of the same age in the area. Despite the appearance of the volcanic rocks at Avoca, metamorphic grade is low and deformation simple in the area as a whole. Mineralisation and volcanism probably ceased in the Upper Ordovician, although younger strata are not exposed in the area. Caledonian folding produced synclines whose axes generally follow the same linear features as the original volcanic centres.

CHAPTER 3

THE PARYS MOUNTAIN MINERALISATION

3.1. INTRODUCTION

3.1.1. History of Mining

Parys Mountain is situated 3km. south of Amlwch in north-eastern Anglesey. It forms an east-northeasterly trending ridge 2.5km. long and up to 150m. above sea level.

Copper has been mined at Parys Mountain since 1768, following its discovery by Alexander Frazier, traditionally held to have been shipwrecked on the Anglesey coast whilst fleeing from Scotland to escape a charge of manslaughter. Frazier, under the protection of Sir Nicholas Bayley, owner of the land an an ancester of the Marquis of Anglesey, initiated mining in 1762, but the workings were abandoned. Roe & Co., of Macclesfield, then took up a lease in 1765, and in 1768 struck ore in the central part of the mountain (Greenly, 1919).

The area was probably worked in Roman times - old plans record 'Roman workes', and cakes of copper of Roman origin have been discovered in the vicinity (Manning, 1959). The main period of production was from 1768 to 1883 and for a substantial part of this period the deposit was Europe's major producer. The yearly output of copper metal for the first twenty years was 3,000 tons (Greenly, 1919) and the overall production has been estimated at over

130,000 long tons of copper metal from 2.6 to 3.7 million tons of ore (Manning, 1959).

Hard rock mining virtually ceased in 1883, but minor amounts of 'bluestone ore' continued to be taken from the opencasts (Greenly quotes more than 600 tons mined in 1912), and recovery of ochre and copper by precipitation continued until the 1950's. Attempts to re-open the mine in 1920 and the 1950's failed because no ore zones were found above the former working level, 200m. - 250m. below surface (Thanasuthipitak, 1974).

Diamond drilling has been carried out intermittently since 1961, when Northgate Exploration commenced a series of eleven holes (prefix M) on the northern side of the property. This programme was continued by Canadian Industrial Gas and Oil in 1966. Intermine Ltd. carried out geochemical and geophysical surveys and diamond drilling up to 1973. Since that time, Cominco Ltd., with a controlling interest in the property, have carried out extensive diamond drilling. Over one hundred and ten holes have now been drilled, the deepest being about 600m.

3.1.2. Previous Work

The deposit was briefly described by Ramsay (1881), but the first comprehensive account was by Greenly (1919). Manning (1959) described the results of investigations of workings down to the Dyffryn Adda level (Parys 45fm or 5th level), about 75m. below surface, and of old records and plans. Hawkins (1966) described the results of drilling by Northgate Exploration on the northern side of Parys Mountain and recognised that much of the 'felsite' consisted of sediments. Bates (1966) presented mapping and faunal evidence that the structure is a single synclinal fold. Wheatley (1971a) examined a limited range of ore specimens and proposed a paragenetic scheme for the ore minerals. Thanasuthipitak (1974) described the relationship of mineralisation to petrology, identifying the major volcanic lithologies and carrying out analytical programmes for trace elements and major oxides. He described the volcanics as calc-alkaline, and presented various statistical correlations of trace element values.

The origin of the mineralisation has been a subject of debate. Greenly (1919) described the various ore zones as lodes, but noted that only the North Discovery Lode and its associates were typical fissure veins, other zones having diffuse margins and cherty quartz gangue. He concluded that the mineralisation was post-deformation but pre-Carboniferous. Manning (1959) believed the mineralisation to be associated with a forked dyke of felsite.

Wheatley (1971a) distinguished primary bedded pyrite from polymetallic sulphides which he described as cross-cutting and epigenetic. The epigenetic mineralisation was considered to be pre-deformation, having been deposited by hydrothermal solutions related to the volcanic activity which produced the Parys Mountain Volcanics, but was believed to post-date the Silurian Shales. Some remobilisation of mineralisation was recognised.

Thanasuthipitak (1974) proposed that hydrothermal mineralisation was related to volcanism and was essentially syngenetic, occurring at or near surface with little separation in time between early pyrite and polymetallic sulphides. Like Wheatley, he described metamorphic remobilisation. Mineralisation was suggested to be pre-Silurian Shales. Ixer and Gaskarth (1976) developed the model of Thanasuthipitak (1974), relating it to Ordovician plate-tectonics. They compared Parys Mountain with the Kuroko deposits of Japan. Sivaprakash (1977) carried out further studies of the ore mineralogy, describing the sulphosalts. On the basis of geochemical studies of the sulphosalts, he concluded that the mineralisation formed at high temperatures.

Marengwa (1973) compared the mineralisation with that in the Llanrwst area and concluded that the mineralisation was epigenetic. Nutt et al. (in press) also rejected a syngenetic origin on the basis of K-Ar age determinations (between 340ma and 410ma), and of field evidence of cross-cutting relationships of ore to host rocks, and suggested that the mineralisation is epigenetic and post-metamorphic.

The most detailed account of the regional geology remains that of Greenly (1919), although Greenly's Precambrian stratigraphy has been revised by Shackleton (1969) and is the subject of current debate (e.g. Barber and Max, 1979). The Ordovician stratigraphy has been revised on the basis of recent palaeontological studies and mapping by Bates (1972).

3.2. REGIONAL GEOLOGY

The results of reconnaissance geological mapping of part of northeastern Anglesey are shown in figure 3.1, and the stratigraphy is summarised in figure 3.8. This section describes the geology of northeastern Anglesey with an emphasis on the Ordovician strata, and for detailed accounts of the geology of Anglesey as a whole, the reader is referred to the work of Greenly (1919) and Bates (1972).

	NORTHEASTERN ANGLESEY	PARYS MOUNTAIN		
UPPER PALAEOZOIC	CLASTICS (sandstone, limestone, conglomerate)			
LOWER PALAEOZOIC	SILURIAN SHALES	SILURIAN SHALES	grey and black shales	> 60m
	PARYS MOUNTAIN VOLCANICS	PARYS MOUNTAIN VOLCANICS	black shales, chert, chloritic chert and shale, tuff, volcaniclastics, siliceous sinter, rhyolitic and dacitic lavas, massive rhyolite	200m
	CARADOCIAN CLASTICS (shales, sedimentary breccias)			
	? disconformity	?		
	ARENIG-LLANVIRN CLASTICS (shales, conglomerates)	PARYS SHALES	Southern Shales Grey Shales Shales with Breccia Interbeds	> 250m 150m 180m
	unconformity			
PRECAMBRIAN	MONA COMPLEX (schist, gneiss, quartzite, granite)	MONA COMPLEX	chloritic schist and gneiss	?

FIG. 3.8 STRATIGRAPHIC SEQUENCE IN THE PARYS MOUNTAIN AREA

3.2.1. Mona Complex

The Mona Complex is a series of metamorphic rocks including feldspathic, chloritic schist and gneiss, quartzite, granite, marble and metavolcanics, which forms the basement on which the Lower Palaeozoic strata were laid down. A late Precambrian age has been given for the metamorphism (Fitch et al., 1969); this is of variable intensity in the greenschist to lower amphibolite facies and includes polyphase deformation. Fragments in Lower Palaeozoic conglomerates indicate that its grade was essentially the same then as now and that Caledonian overprinting has had little effect on gross lithologies. Caledonian faulting is important and some contacts with the Lower Palaeozoic are tectonic breccias.

3.2.2. Ordovician

General. Major Lower Palaeozoic sedimentation commenced in the Arenig. In southwest Anglesey 300m. of Mona-derived breccias and conglomerates were deposited (Greenly, 1919), but the basal sequence thins rapidly northwards, and in the northeast is represented by the Foel Formation (Bates, 1972) which near Nebo is 15m. to 20m. thick, composed of pebbly grit and flaggy arenites with shale or siltstone partings. Bates (1972) recorded D. extensus from the Foel Formation.

In southwest Anglesey the basal Arenig is overlain by coarse clastics with shaly interbeds (Triorwerth and Nantannog Formations) with faunal assemblages of D. hirundo and D. murchisoni (Bates, 1972). In the northeast, shales overlie the Foel Formation. Bates (1972) identified a pre-Caradoc disconformity throughout Anglesey and demonstrated that Ordovician deposition basins are, subject to tectonic shortening, approximately reflected by the present day subcrop of the Ordovician rocks. He suggested that faults such as the 'Carmel Head Thrust' were probably active during sedimentation, having relatively small, largely vertical displacements. Since stratigraphic relationships are uncertain in much of the area of the map (fig. 3.1), the Ordovician rocks are described by areas. A summary is given in figure 3.9.

Dulas Bay. On the coast at Dulas Bay, along the southern margin of figure 3.1, a series of black shales crops out, from which Greenly (1919) obtained graptolites of D. murchisoni and D. bifidus zones. The shales are black, massive or with traces of bedding and lamination in the form of sparse silty layers. They commonly contain fine pyrite (1% or more), and concretions ($\leqslant$0.5m.) of black siliceous pyritic material. Some few lenses of massive pyrite occur, up to 50mm. thick and 1m. long.

Fig. 3.9 LITHOLOGICAL VARIATIONS IN THE ORDOVICIAN OF NORTHEASTERN ANGLESEY

AREA	LITHOLOGIES	AGE
northeast of Ogof Fach fault	Fresh Water Bay Conglomerate green - grey cleaved siltstones shales	? Caradoc
Mynydd Eilian to Porth-y-Gwichiaid	grey laminated shales and siltstones black to grey shales with calcareous and pyritic beds grit and conglomerate	unknown
Dulas Bay	Dulas Formation black shales	unknown Arenig-Llanvirn

To the north of the black shales and separating them from the Precambrian to the north, is a siltstone-shale sequence referred by Bates (1972) to the Dulas Formation. Their contact with the shales is faulted, and that with the Precambrian is a high-angle reverse fault (the 'Nebo Thrust' - Greenly, 1919). The sequence consists of inter-bedded coarse siltstones and fine quartz arenites (0.1m. to 1m.), and shale ($\leqslant$0.5m.); the shale is grey-black, the siltstone green or grey with chloritic or carbonaceous laminae, and shows grading (rarely), lenticular or convolute lamination, cross-lamination, troughs, and other small-scale features suggesting shallow-water deposition. The age of the Dulas Formation is uncertain (Bates, 1972).

<u>Mynydd Eilian</u>. North of the Precambrian in the area between Mynydd Eilian and Porth y Gwichiaid (fig. 3.1) three main lithological groups are present. Their inter-relationships are uncertain, and palaeontological sampling has had little success except to suggest that part of the sequence may be Caradocian (Bates, 1972). The area is bounded on the northeast by the Ogof Fach Fault, named by Bates (1972).

On the south side of Porth y Gwichiaid, a sequence of black to grey shales contains sparse green silty beds up to 0.5m. thick, lensy calcareous beds up to 1m. thick, massive pyrite lenses 0.1m by 20mm., and several beds of intraformational conglomerate. Washouts in silty layers show that the sequence both dips and youngs north. The contact with the Precambrian is a tectonic breccia some 10m. thick, cut off by later, north-dipping faults. Bates (1972) suggested that this breccia represents a thrust plane on which the Precambrian was thrust northward over the shales. Cataclastic deformation is intense in the Precambrian rocks near the contact, but decreases southwards away from the contact. The shales are also cataclastically deformed near the contact.

On the north side of Porth y Gwichiaid are grey laminated to thinly bedded shales and siltstones with some few hard, non-calcareous nodular concretions (composed mostly of quartz and chlorite). This lithology forms most of the outcrop between the coast and Mynydd Eilian. A poorly exposed, thin (less than 10m.) horizon of an arenaceous lithology which crops out in the cliffs may be tuffaceous.

Inland on Mynydd Eilian, reddish grits and gritty or pebbly shales overlie the picrite sill (fig. 3.1). These pass eastwards into grits, conglomerates and shales, and southwards into grey shales, nodular in part. Observations are consistent with the opinion of Bates (1972) that the coarser sediments occur in an anticlinal structure trending and plunging northeast with the gritty and pebbly shales being the lowest stratigraphically.

A northeasterly trending fault (probably an extension of the faulted southern contact of the Parys Shales), running southeast of Mynydd Eilian, cuts out this sequence. The gritty beds which crop out northeast of Ty-canol Farm may represent a second similar anticline south of the fault. The folding is distorted by subsequent faults of northerly trend.

Northeast of the Ogof Fach Fault. Between Ogof Fach and Ogof Fawr (fig. 3.1) are well cleaved green-grey, sericitic shales in which bedding and lamination are not seen, and whose age is unknown. At Ogof Fawr they pass northward into a sequence of grey shales with interbeds of siltstone, sandstone and gritty shales. On the south side of Fresh Water Bay, beds of slumped breccias enter the sequence, at first discontinuous and infrequent, but becoming more important northwards. This sequence has been named the Fresh Water Bay Conglomerates by Bates (1972). The rudaceous beds contain fragments of a siliceous cherty laminate, quartz, vein quartz, altered feldspar and quartzite or rhyolite. It cannot be stated with certainty that all the clasts are derived from the metamorphic basement and that none are of volcanic origin. The clasts are commonly supported by a grey shaly matrix. Sorting is very poor, with blocks up to 0.5m. Beds vary in thickness up to 3m. In addition, isolated subangular to subrounded boulders up to 1m. across, and of similar composition to the clasts in the breccias, occur in the shales.

Bates (1972) reported this sequence, which extends for some 600m. north of the limit of mapping in figure 3.1, as inverted, dipping north but younging south. Some sedimentary structures (grading, scouring) in the section mapped in this work suggest younging to the north 150m. - 200m. north of Ogof Fawr. The local structure thus remains uncertain. Glyptograptus teretiusculus was collected by Greenly (1919) from slates in the Tyllau Duon quarries on the north side of Fresh Water Bay, and Bates (1972) suggested that this indicates a Caradocian age.

3.2.3. Igneous Rocks

Basic and Intermediate Intrusives. At Mynydd Eilian, a large sill of hornblende picrite is intruded along the contact of the Ordovician and the Mona Complex. It is described in detail by Greenly (1919), who indicated a Palaeozoic age.

Numerous sills and dykes of dolerite crop out between Parys Mountain and the coast. They are most commonly altered to some degree with development of chlorite, calc-silicates, albite, quartz and carbonate.

A small plug-like body of coarse-grained intermediate intrusive crops out near Bryn-mor.

Intermediate sills composed of medium-grained granular intergrowth of plagioclase feldspar (albitised), with minor untwinned feldspar and interstitial patches of green chlorite (up to 25%) and quartz (5%), occur in the Dulas section and along Afon Goch. They are more feldspar-rich than the dolerites.

Acid Igneous Rocks. Between Mynydd Eilian and the Ogof Fawr-Ogof Fach coast section, small irregular plugs, sills and dykes of rhyolitic composition are present in the shales on both sides of the Ogof Fach Fault but are more abundant to the northeast. Individual bodies are small, usually less than 30m. wide; contacts are irregular and commonly steep. The rhyolite is itself silicified with strong quartz veining, and silicification also affects the host rocks. Showings of sulphides are not common, but trial workings were found at two localities.

The rocks are fine-grained crystalline rhyolites with phenocrysts (1mm.) of euhedral to subhedral Carlsbad-twinned K-feldspar, minor perthite and albite, and rare subhedral clear quartz crystals. The matrix is a fine crystalline intergrowth of quartz, minor untwinned feldspar, and tiny laths of albite. The untwinned feldspar in a few instances shows remnant spherulitic fabric. Incipient seritisation of feldspars occurs throughout, and the rocks are cut by late coarse quartz veins.

The major occurrence of rhyolitic rocks other than at Parys Mountain is at Rhosmynach, where a rhyolitic complex similar to that of Parys Mountain is seen (Greenly, 1919; Wheatley, 1971a). The rhyolite has associated sulphide mineralisation, consisting of pyrite and chalcopyrite with minor sphalerite and galena. Wheatley (1971a) identified native bismuth and bismuthinite, and the deposit gives anomalous arsenic values in soil (Intermine, unpublished data). The deposit was worked early in this century; the workings reportedly extend to 40m. (120ft.) depth (Dewey and Eastwood, 1925), and its strike length is some 200m. Three lodes were worked (Dewey and Eastwood, 1925) but no reliable grades or production records are available.

The host rocks are dark grey shale, a central zone of massive rhyolite, and shale breccias with clasts of clear subangular unstrained quartz, rhyolite, sulphides and fine sericitic rock.

3.3. STRATIGRAPHY

3.3.1. Parys Shales

The local stratigraphy at Parys Mountain is given in figure 3.8. The shales underlying the Parys Mountain Volcanics were divided by Hawkins (1966) into three units (see fig. 3.10). The black shales of Hawkins are here described with the Parys Mountain Volcanics because they

AGE	LITHOLOGY			THICKNESS (feet)
SILURIAN (Llandovery)		Grey shales with graptolites		-
Presumed ORDOVICIAN		Fine-grained sediments with a few occurrences of tuff	wholly or partially within the 'felsite' zone of silicification	600+
	Parys Shales	Black shales		
		Grey shales quickly weathering to brown and green	Parys Green Shales of Greenly	720
		Grey micaceous shales with beds of sedimentary breccia		1200+
		Carmel Head Thrust		
PRE-CAMBRIAN		Amlwch Beds	Pale green phyllites	

Fig. 3.10 Stratigraphical Sequence on the north side of Parys Mountain (from Hawkins, 1966)

Fig. 3.11 Parys Mountain, Geology. (For details see Figs. 3.2-3.7) occur interbedded with them. In this account, shales on the south limb of the structure (the 'Southern Shales') are included with the Parys Shales.

Shales with sedimentary breccia interbeds. This unit is stratigraphically the lowest, and is only seen in drillcore to the west of about 9800'E (fig. 3.2). It consists of dark grey micaceous shales, bedded and well cleaved, containing interbeds of polymictic sedimentary breccia. These interbeds vary from less than 0.1m. up to 20m., and contain angular fragments of chloritic schist and gneiss, quartzite, white quartz and grey and black shale. The rock grades from a breccia with a shale matrix to a grit. Clast size varies from less than 5mm. to several metres. Hawkins (1966) also reported beds of greywacke from drillhole M10, approximately on section 7800'E on the mine grid.

The thickness given for this unit is tentative, because it is uncertain if any of the boreholes logged cut an unfaulted contact between Mona Complex rocks and the Ordovician. Hole A3A (section 9000'E, fig. 3.4) cuts a breccia at the contact between Mona Complex rocks and Parys Shales which has in part a shale matrix, but it is not certain that this is a basal sedimentary breccia. A minimum thickness of 150m. is present between 8600'E and 9800'E, and in hole M1 (8200'E), logged by Hawkins (1966), it may be 180m. Thicknesses are estimated normal to bedding angles in core and are less that those given by Hawkins (1966) and Thanasuthipitak (1974).

Within this sequence, sparse interbeds of pyroclastics are present, for example in hole A3A at 121.9m. (400ft), as are some massive dacitic and rhyolitic rocks (e.g. hole 43 at 70m. (200ft.) depth and in hole M10).

Grey Shales. The upper unit of Parys Shales consists of grey or greenish-grey shales, weathering to green or buff. Bedding is less frequently seen, although interbeds of pale buff-weathering siltstone, weak colour banding, and some few beds of intraformational breccia with clasts up to 30mm. of siltstone and black shales, occur. Local irregularity of the bedding indicates the presence of slump structures.

Lamination and thin bedding are obscured as chlorite development and intensity of cleavage increase towards the contact with the volcanics. At the contact between the Parys Shales and the volcanics on the northern limb, a few metres of grey to black pyritiferous shales are present locally, though generally alteration is too intense to distinguish them from the underlying grey shales.

The thickness of this upper unit varies from 150m. on section 8600'E to more than 250m. on section 11,000'E where the base is not seen in drillholes. This thickness variation may represent an erosional upper contact, since the lower contact of the Grey Shales with the Shales with breccia interbeds is gradational.

Southern Shales. In outcrop and in drillcore, underlying the Parys Mountain Volcanics to the south, are grey micaceous, generally well cleaved shales, thinly bedded to laminated in part, with dark and paler grey or silty bands. They differ slightly in colour from the Grey Shales, and do not weather to the typical green and buff colours. Similar shales crop out at the west end of Parys Mountain.

The Southern Shales show slump and plastic fold structures in core. They contain nodules and veinlets of iron carbonate and several per-cent of pyrite. Chlorite, however, is rarely developed except at depth, where an intersection in hole A15 shows shales with chloritic alteration and quartz + chlorite + sulphide veins typical of the stockwork zone to the north.

Interpretation of the contact of Southern Shales and volcanics is hampered by scarcity of drill intersections. It is possible that a thin horizon of younger dark grey shales may locally overlie the Arenig-Llanvirn shales in this area, though their presence cannot be established with certainty. In such intersections as do exist (see figs. 3.3 to 3.7), the contact may be sheared (hole A12), transitional (IM6, IM9), or be a zone of intraformational breccia (hole A17). Shearing is generally present near the contact, but may be entirely within the shales. For example, hole IM6 on 8600'E cuts an apparently normal contact between cherty chloritic shales and dark grey shales, followed by a 60m. intersection of gneiss with sheared contacts, before re-entering grey shales. On the surface, at approximately 11,400'E; 9000'N on figure 3.2, thin tuff or cherty breccia bands occur in shales within 3m. of the contact with Parys Mountain Volcanics.

Age of the Parys Shales. Early work on graptolites by Ellis, reported by Greenly (1919), suggested that while shales on the north side were Lower Ordovician, the Southern Shales were Silurian. Bates (1966) concluded that both were Ordovician in age and this is supported by unpublished micropalaeontological work from the Institute of Geological Sciences (M. J. C. Nutt, pers. comm.). The Parys Shales in both northern and southern outcrops are thus considered to be Arenig to Llanvirn in age.

3.3.2. Parys Mountain Volcanics

General. This unit occupies the western end of Parys Mountain, and two zones north and south of the main workings (fig. 3.2). It was called the 'felsite' by Greenly (1919) and later writers, but the term Parys Mountain Volcanics is preferred here since the unit is intimately related to volcanism and contains both volcanic and sedimentary components. The main lithologies are listed in figure 3.8; they are wholly or in part lateral equivalents of one another, but a crude stratigraphy exists with cherty lithologies at the top and base of the unit and a central zone of coarse volcaniclastics. This sequence is traceable along strike and from the northern to the southern limb of the structure, though the subdivisions are poorly defined and vary in thickness. The spatial relationships are illustrated in figure 3.12, and detailed lithological descriptions follow. Cherts and volcaniclastics form the central part of the Parys Mountain Volcanics, passing to the west into rhyolitic flows and flow breccias, and eastward into pyroclastics and rhyolitic flows in the Pen y Sarn area (figs. 3.2, 3.12).

Rhyolitic and Dacitic Lavas. Rhyolitic and dacitic lavas were described by Thanasuthipitak (1974); they occur in four thin horizons at the western end of Parys Mountain, two within the Parys Shales, a third at the base of the volcanics and a fourth at the top of the volcanics (Thanasuthipitak, 1974). The dacite at the base of the volcanics persists on the northern contact as far east as section 9800'E, but the upper horizon has not been identified in drillcore or outcrop between 8600'E and 11,000'E.

Thanasuthipitak divided the dacites into a rare porphyritic type with plagioclase feldspar phenocrysts up to 10mm. in diameter, and a more common aphanitic type consisting of lath-shaped plagioclase feldspars (up to 45% of the rock) in a fine-grained aggregate of quartz. The groundmass commonly shows devitrification features (Thanasuthipitak, 1974). Observations during the present study are consistent with the description by Thanasuthipitak (1974).

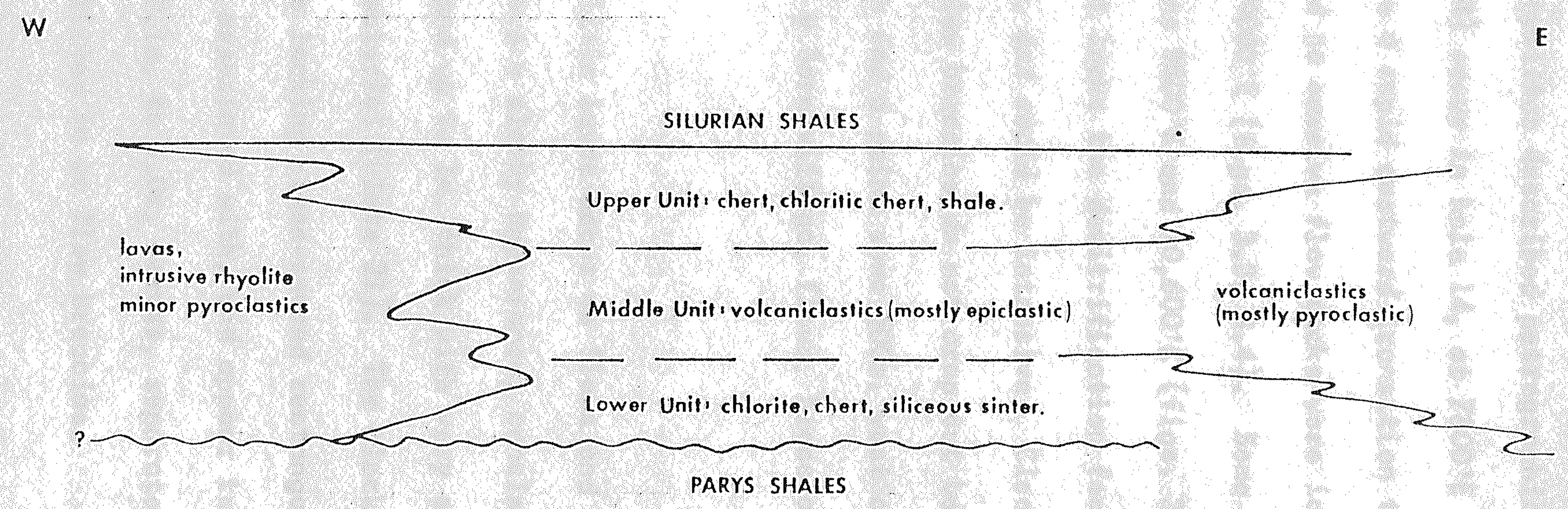


Fig. 3 12

DIAGRAMMATIC E-W SECTION ILLUSTRATING DISTRIBUTION OF DOMINANT LITHOLOGIES IN THE PARYS MOUNTAIN VOLCANICS (NOT TO SCALE)

Rhyolitic lavas crop out at the western end of Parys Mountain. The majority of glassy rhyolites described petrographically by Thanasuthipitak (1974) occur in hole 14, at 7800'E on the mine grid (fig. 3.2). There is a rapid eastward transition to a predominantly clastic sequence, and no massive flow rocks were identified on sections 8600'E and 9000'E (figs. 3.3, 3.4). Some massive rhyolite is present on sections 9800'E and 10,600'E (figs. 3.5, 3.6) in the southern limb, but it lacks the devitrification features seen in the samples from hole 14, and could be intrusive. Clearly identifiable rhyolite flows and flow breccias do not crop out between the western end of Parys Mountain and a point some 500m. west of Pen y Sarn (fig. 3.2); near Pen y Sarn village, flows, breccias and welded tuffs may be seen.

In outcrop, the rhyolitic lavas occur as flows and flow breccias. The flows commonly have a slabby appearance, consisting of blocks several metres long and up to 1m. thick with very sparse ashy or rubbly interstitial material (plate 21). The blocks are composed of fine-grained rhyolite lacking close-spaced rectangular jointing. Such rocks are intimately associated with, and appear to pass into, breccia with blocks of lava 0.1m. to 1.0m. across, separated by an ashy matrix, which are believed to be flow breccias.

The rhyolitic lavas commonly show abundant well developed spherulites and perlitic cracks and contain weakly to moderately flattened amygdules, features described by Thanasuthipitak (1974). Phenocrysts, generally less than 1mm. across, are of quartz and feldspar. The latter are variably altered to illite or sericite, and where silicification is strong, polycrystalline quartz aggregates appear to pseudomorph phenocrysts. The matrix, forming 90% or more of the rock, has a fine xenomorphic-granular texture of quartz, with minor sericite and less chlorite. Some examples show possible flow layering. Intense silicification may obscure primary textures but the criteria of abundant spherulites, perlitic cracks, amygdules, presence of interstitial sericite, presence of phenocrysts, and a coarser xenomorphic-granular texture with clear quartz, allow distinction of these rocks from the other volcanics.

Intrusive Rhyolite. At Morfa-du (fig. 3.2) a body of massive rhyolite crops out. It has close rectangular jointing and, locally, autobrecciation; it lacks the slabby appearance and flow-brecciation of the lavas. In hand-specimen the rock is fine-grained and highly siliceous, and lacks textural features except for rectilinear quartz veins.

Its outcrop pattern, though strongly influenced by faulting, suggests that the rhyolite is intrusive; it appears discordant with respect to the volcaniclastics and siliceous sinter. No drillholes from Morfa-du have been logged in this study, and thus no comment can be

PLATE 10

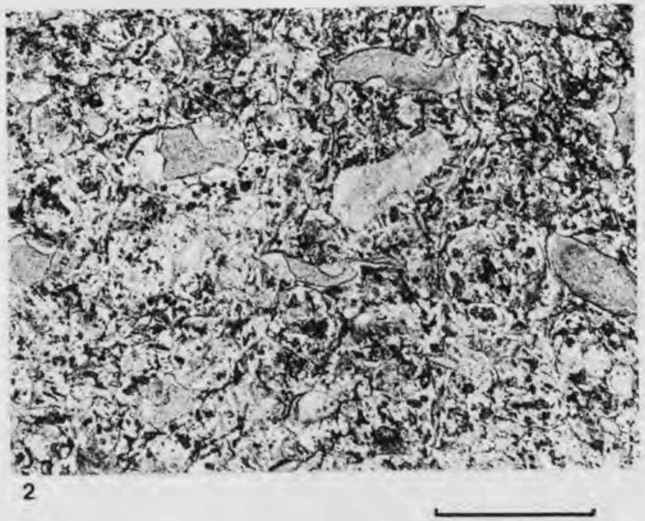
PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - RHYOLITE AND PYROCLASTICS

(scale bar = 0.5mm.)

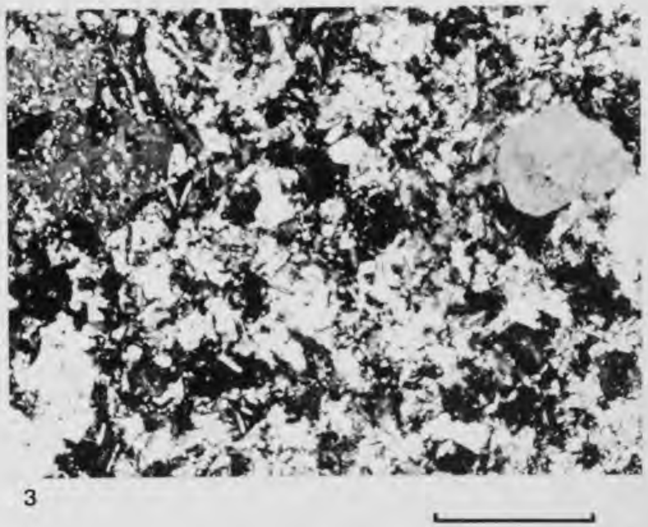
1. A 125 - Rhyolitic lava with alkali-feldsapr phenocryst and chloritic amygdules (ppl)
2. A 125 - As above, showing perlitic texture (ppl)
3. A 159 - Quartz and feldspar porphyritic rhyolite (ppl)
4. Drillhole A3A - 121m. (397') Ash-flow tuff with embayed quartz and feldspar crystals (ppl)
5. Drillhole A15 - 299.9m. (984') Remnant welded texture in silicified ash-flow tuff (ppl)
6. Drillhole A15 - 313.6m. (1029') Remnant welded texture in ash-flow tuff (ppl)

ppl = plane-polarised light

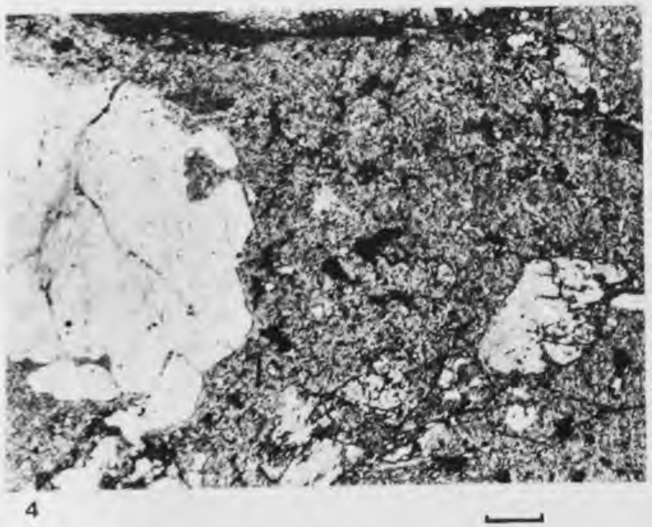
1



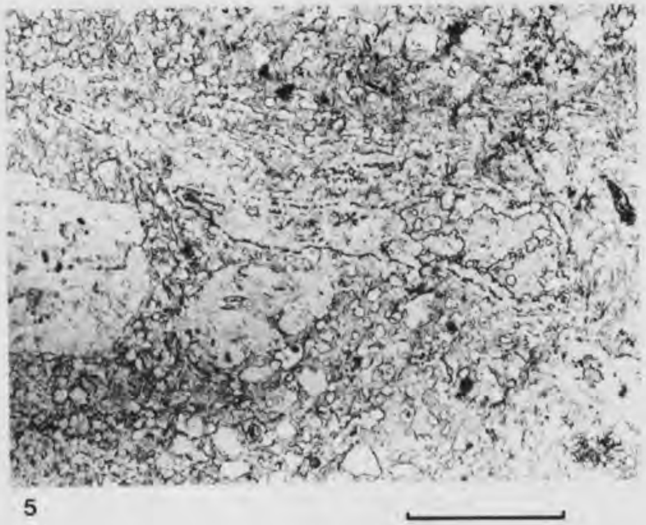
2



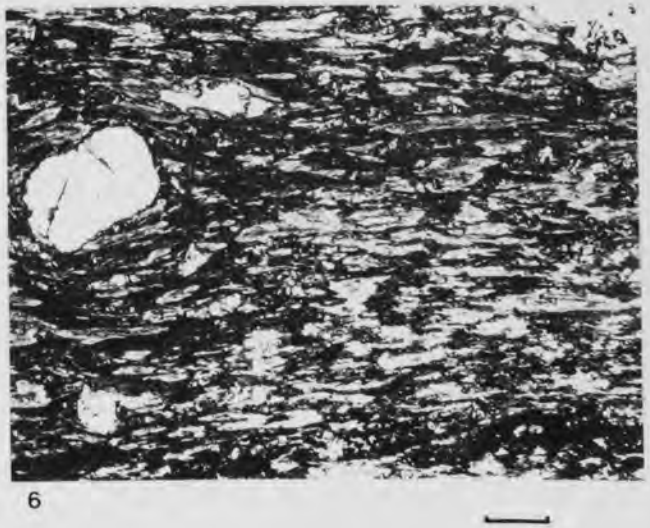
3



4



5



6

PLATE 10

PLATE 21

PARYS MOUNTAIN - RHYOLITE AND VOLCANICLASTICS

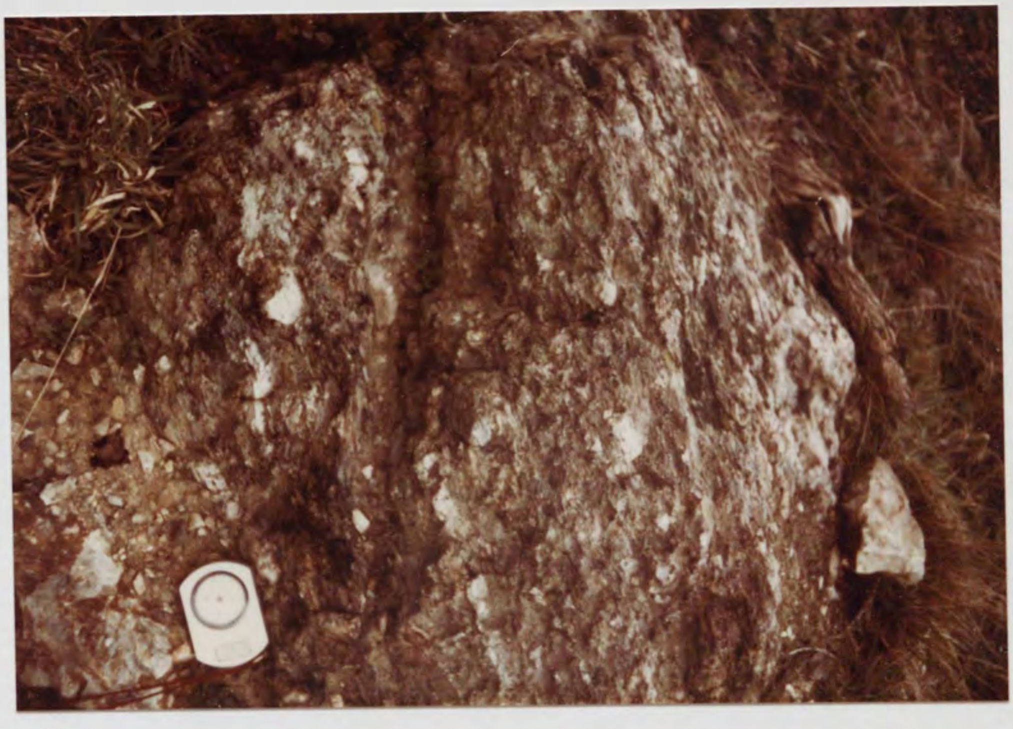
1. Rhyolite flows - Parys Mountain Volcanics.

   West end of Parys Mountain, near Morfa-du.

2. Lapilli-tuff with blocks of rhyolite - Parys Mountain Volcanics.

   Near Pen-y-sarn War Memorial.

1



2

PLATE 21

made on the behaviour of the body at depth, but relationships are believed to be complex (B. B. Young, pers. comm.).

In thin section (e.g. A120), the rock has a fine xenomorphic-granular texture and consists of quartz with some interstitial sericite and a trace of pyrite. It is aphyric but contains veinlets and irregular patches of coarsely crystalline quartz, probably resulting from partial recrystallisation. No flow features are seen.

Siliceous Sinter. This rock name was first used at Parys Mountain by Thanasuthipitak (1974) to describe a lithology found at the base of the volcanics on the northern side of their outcrop, consisting almost entirely of quartz. It is a very fine-grained rock, varying in colour from pale bluish grey to white or cream.

In outcrop, the most characterisitic feature of the siliceous sinter is an irregular layering shown by variations in colour or by the presence of variable proportions of voids, which are either leached or filled with white chalcedonic silica. The layering forms arcuate or curved lenticular patterns, which appear to be primary, unrelated to structure, and are traceable for distances only of the order of 1m. - 2m. Polyphase brecciation is also characteristic, in which variously coloured fine-grained quartz phases are brecciated and annealed by subsequent phases of similar composition. Three phases of fracturing and silica deposition were identified in several outcrops. This feature is best seen at Morfa-du. In some outcrops and in drillcore, the rock may simply appear as a massive white quartz rock with a faint granular fabric. The close jointing of rhyolites and the characteristic features of the lavas are absent. Quartz and quartz + sulphide veining are commonly intense, cutting the features described above.

In underground exposure, approximately on section 9000'E, the rock varies from massive to layered white quartz with festoons of lenticular curved bands, up to 0.5m. thick and 2.0m. in length, of massive pyrite with chalcopyrite and encrustations of secondary copper salts (see also section 3.5).

The Siliceous Sinter forms the Carreg-y-doll lode zone, up to 50m. wide, between Parys Shales and the northern outcrop of volcanics, extending from the Corwas Fault in the east to north of the Great Opencast (fig. 3.2). It crops out again at Morfa-du in a similar stratigraphic position. The outcrop pattern, examination of drillcore, and underground mapping by Manning (1959) indicate that the Carreg-y-doll lode is a largely stratiform body, passing down into a stockwork of quartz + chlorite + sulphide veins in altered Parys Shales in a transitional zone up to 20m. thick. The polyphase brecciation seen at surface and the spatial relationships indicated by drill intersections show that the basal contact is locally crosscutting, and that the lower contact where stockwork mineralisation is intense, may consist of a non-stratiform root zone (see figs. 3.3 to 3.7). Typical intersections are in drillholes IM19 and A15.

Siliceous Sinter also occurs in outcrop and drillcore on the southern side of Parys Mountain, for example on section 10,600'E (fig. 3.6), and is intersected by holes IM9 and IM10. It is developed in both the upper and lower cherty zones of the Parys Mountain Volcanics.

In thin section, Siliceous Sinter has a very fine matrix of quartz, clay and sericite. Quartz is generally dominant as an extremely fine-grained xenomorphic aggregate. The matrix contains varying proportions of quartz-filled voids - this quartz phase being either chalcedony or recrystallised polycrystalline quartz preserving the axial junction and radial boundaries of the original sheaves of fibrous chalcedony. The chalcedony and secondary quartz both have bands of inclusion trails parallel to the void margins. The voids are generally around 0.2mm. in diameter, but locally reach 5mm., and are both circular and elliptical in section, both shapes being presen in the same thin-section (plates 11, 12, 13). Where they are elliptical (axial ratio <10:1) the longer axis is in the plane of any layering present. The proportion of voids ranges from 10% to 50% of the rock. In a specimen from hole IM9 at 15.3m. (50ft.) depth, collo form pyrite coats a void margin and is overgrown by quartz (plate 11)

PLATE 22

PARYS MOUNTAIN - SILICEOUS SINTER

1. Siliceous Sinter - void-rich and massive bands.

   Morfa-du.

2. Siliceous Sinter - banding and brecciation.

   Morfa-du.

1

2

PLATE 22

PLATE 23

PARYS MOUNTAIN - CHERT AND SILICEOUS SINTER

1. Bedded grey cherts with some sulphide and cross-cutting white quartz veins.

   Hillside Opencast.

2. Siliceous Sinter, showing irregular banding and annealed brecciation.

   Morfa-du.

1

2

PLATE 23

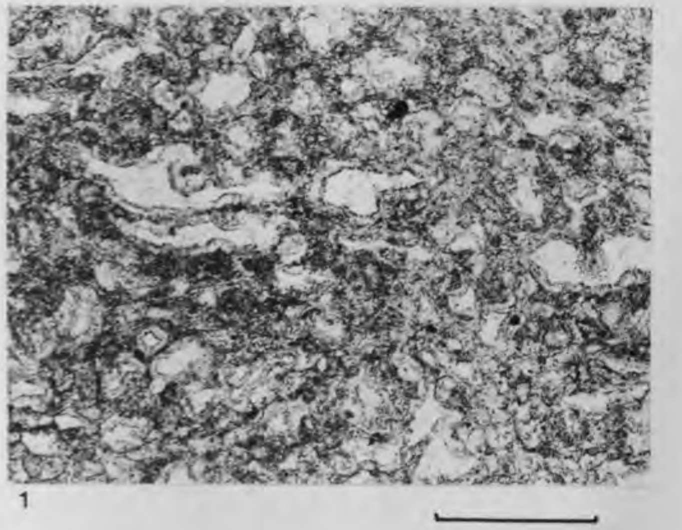
PLATE 11

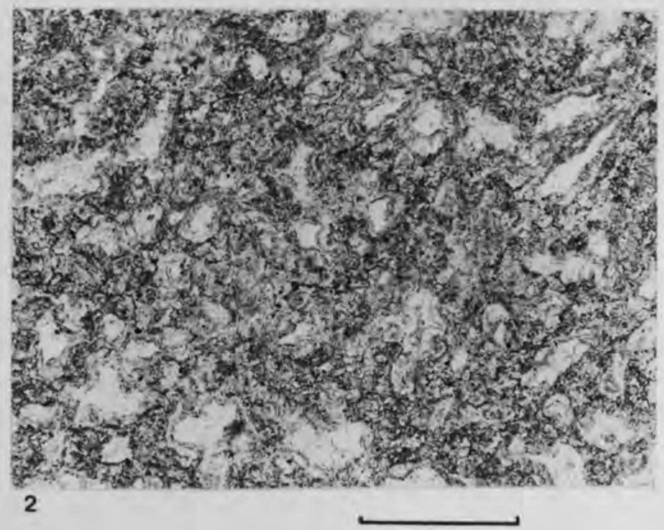
PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - SILICEOUS SINTER

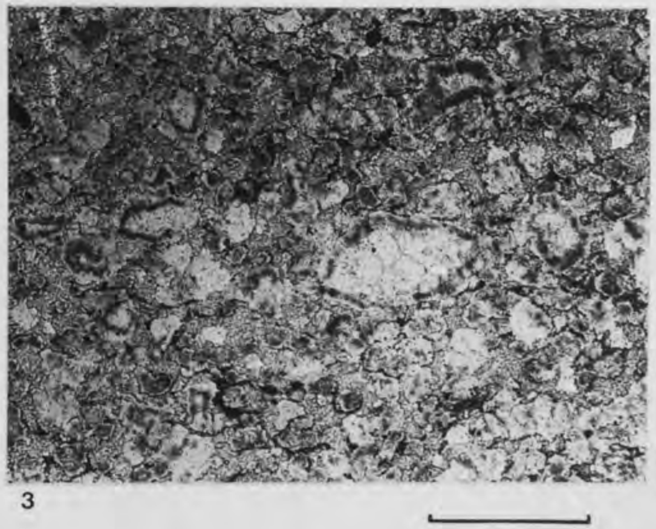
(scale bar = 0.5mm.)

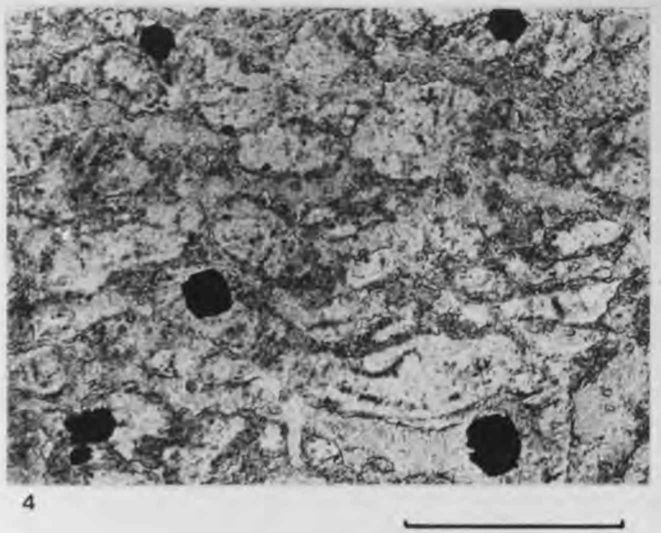
1. A 140 - Siliceous sinter with irregularly shaped voids containing bands of inclusions (ppl)
2. A 140 - As above, but orientation of voids more irregular (ppl)
3. Drillhole IM10 - 213.4m. (700') Siliceous sinter: void-filling quartz with inclusions bands (ppl)
4. Drillhole IM9 - 15.3m. (50') Siliceous sinter (ppl)
5. Drillhole IM9 - 15.4m. (50' 6") Siliceous sinter with quartz-filled voids of varied shape (ppl)
6. As 5. above, but showing axial junction of quartz in voids, probably ater original chalcedony (crossed nicols)

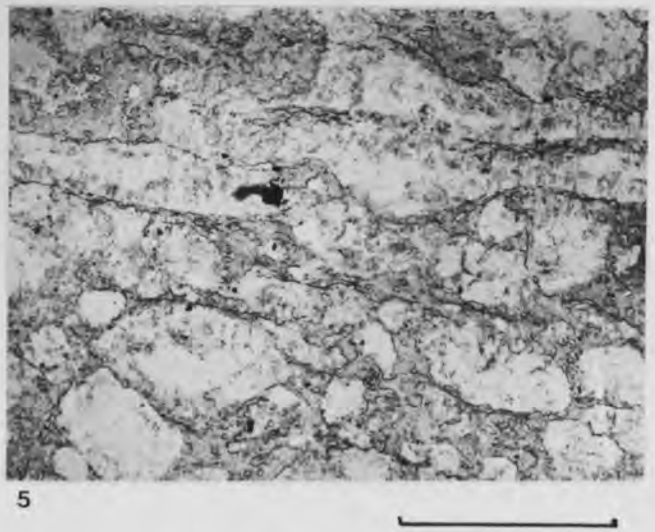
ppl = plane-polarised light


1


2


3


4


5

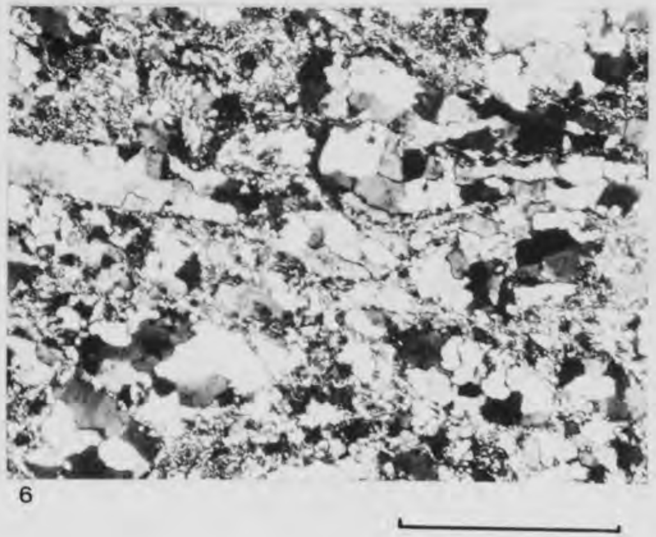

6

PLATE 11

PLATE 12

PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - SILICEOUS SINTER

(scale bar = 0.5mm.)

1. A 140 - Quartz-filled void in silicous sinter showing boundaries of quartz grains (pseudomorphig original chalcedony?) and parallel bands of inclusions (crossed nicols)

2. Drillhole IM9 - 16.1m. (53') Siliceus sinter showing detail of void-flling quartz (ppl)

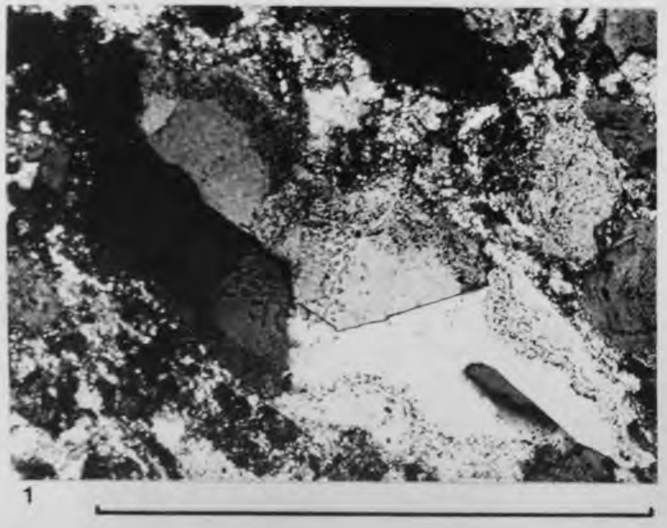
3. As 2. above, with crossed nicols, sbwing contrast with matrix

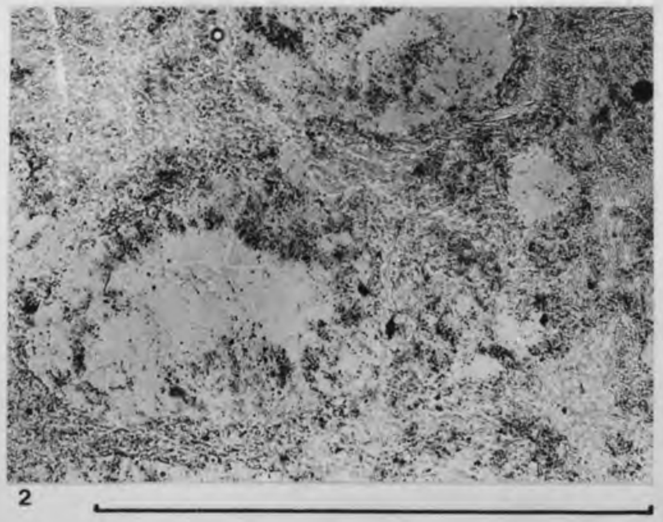
4. Drillhole IM9 - 15.4m. (50' 6") Silceous sinter - detail of quartz in voids (psudomorphing chalcedony) and quartz + clay matix (crossed nicols)

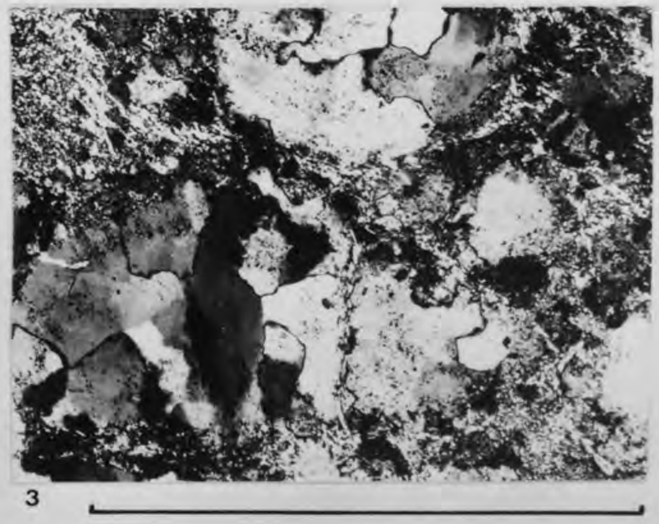
5. Drillhole IM19 - 87.5m. (287') Silieous sinter cut by later coarsely crystalline quarz vein with sulphide, showing contrast of the quarz phases (ppl)

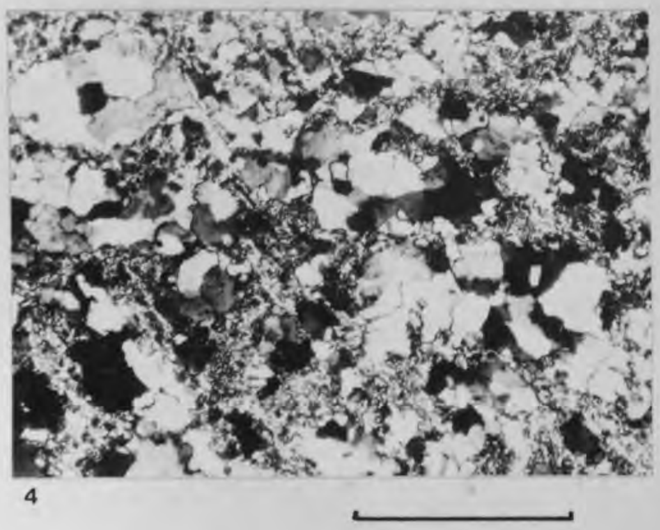
6. As 5. above, with crossed nicols

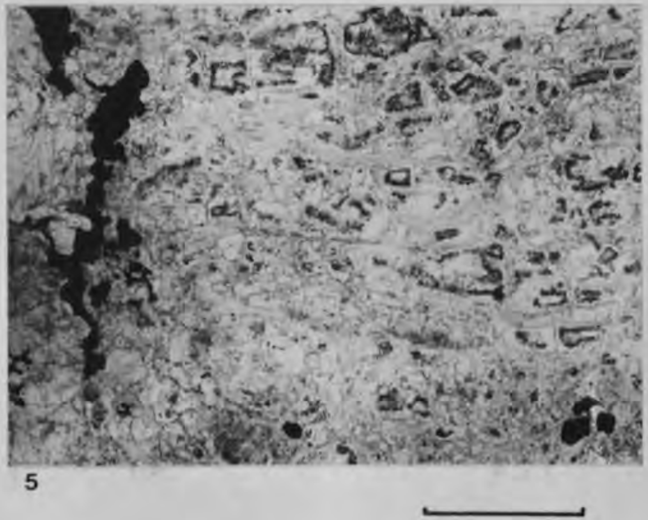
ppl = plane-polarised light


1


2


3


4


5

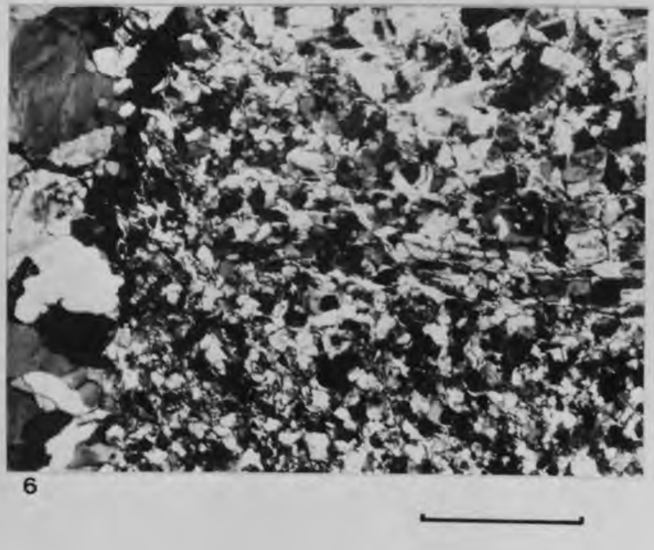

6

PLATE 12

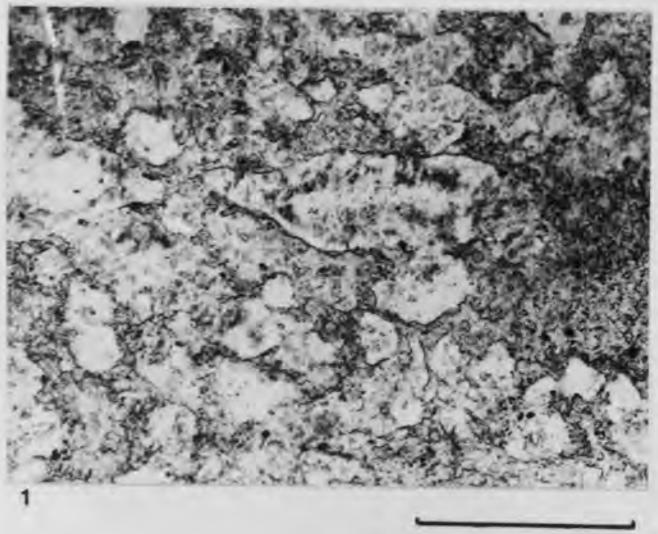
PLATE 13

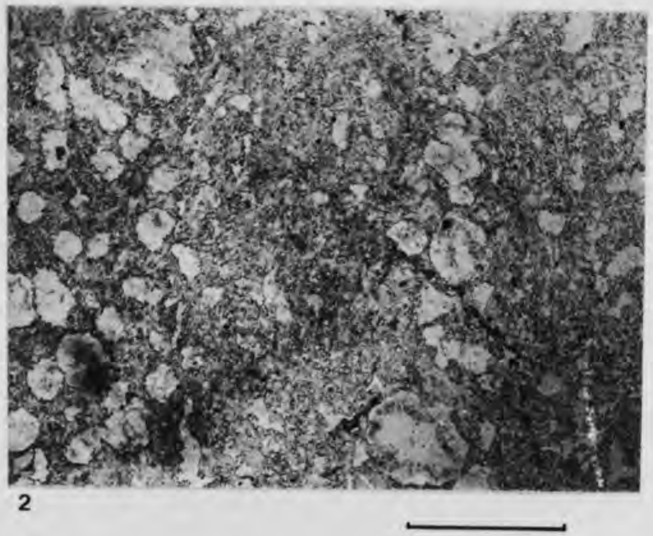
PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - SILICEOUS SINTER AND CHERT

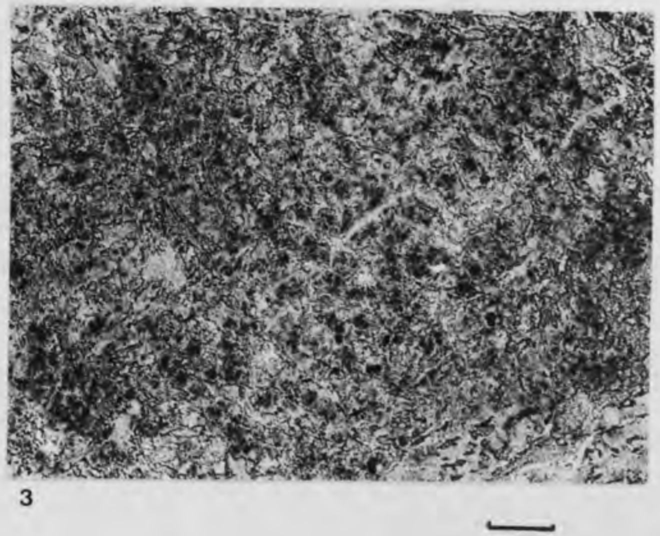
(scale bar = 0.5mm.)

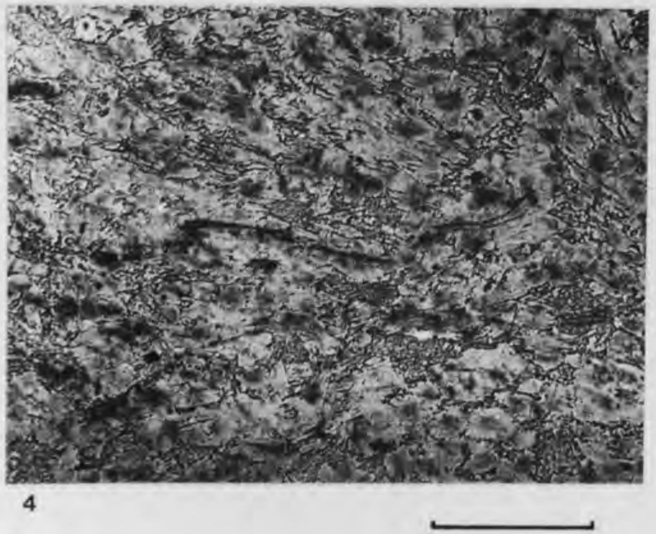
1. Drillhole IM9 - 15.5m. (51') Siliceous sinter with void-filling quartz after chalcedony (ppl)
2. Drillhole IM9 - 29.7m. (97' 6") Siliceous sinter with void-rich bands (ppl)
3. Drillhole IM6 - 143.3m. (470') Chert with typical brownish patchy very fine-grained quartz and sericite (ppl)
4. Drillhole IM6 - 197.2m. (647') Chert with some banding of brownish quartz and sericite (ppl)
5. Drillhole 32 - 419.7m. (1377') Very fine brownish cherty quartz (ppl)
6. Drillhile IM6 - 136.5m. (447' 10") - Sericitic chert (ppl)

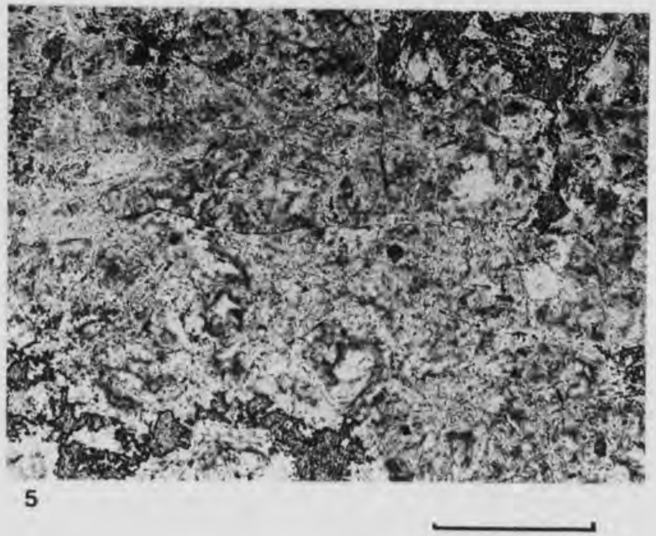
ppl = plane-polarsied light


1


2


3


4


5

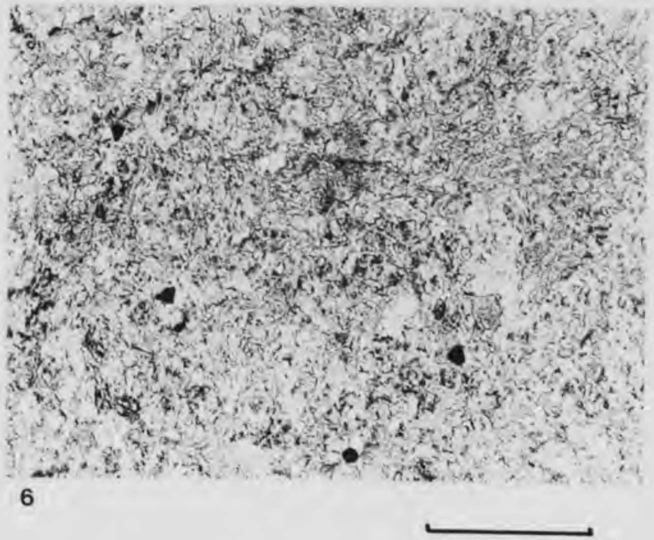

6

PLATE 13

In a few instances minor amounts of iron carbonate and/or anhydrite form cores to quartz-filled voids.

The rocks commonly have a crude layering, of the order of 2mm. thickness, consisting of parallel void-rich, void-poor, or massive cherty layers. This layering is disturbed and discontinuous, being interrupted by irregular veinlets and patches of extremely fine cherty quartz-aggregate. Later rectilinear veins of coarsely crystalline quartz are common, and distinct from the above. Where sulphides are seen in thin-section, it appears that their distribution is parallel to the layering.

Chert. This lithology is present throughout the Parys Mountain Volcanics and consists of quartz ($>$ 90%) with minor sericite or clay and, in some instances, some chlorite. It is generally layered, the layering being parallel and regular except where slumping has occurred. It is distinguished from siliceous sinter by the more regular layering and lack of void-filling chalcedony, and from the chloritic cherts and shales by lack of chlorite. All three lithologies are, however, intimately related, and intermediate types do occur.

In outcrop, the chert is grey to cream, extremely fine-grained, and generally layered. Interbeds of massive sulphide and black pyritic shales occur. Massive and slumped cherts are both seen in the

Great Opencast. Massive bedded cherts are exposed on the north and east sides, but in the central and southern parts of the pit, balls and rafts of chert are seen slumped together with black shales and massive pyrite. Some features are shown in plates 13, 14, 23 and 26. The massive cherts may have sharp or gradational contacts with black mudstones and shales. Chert is also an important component of the volcaniclastics.

In drill sections, chert is seen to be spatially related to zones of sinter, probably as their lateral equivalents (figs. 3.3 to 3.7). It is more abundant than chloritic chert in the upper part of the Parys Mountain Volcanics, chloritic rocks being more common in the stratigraphically lower parts of the unit (fig. 3.12).

In thin-section the chert consists of very fine-grained ($\leqslant$0.01mm.) to cryptocrystalline quartz-aggregate with up to 5% sericite, clay or chlorite, and a similar proportion of opaques. The quartz is commonly pale brownish in colour (in contrast to the clear, coarsely crystalline quartz of later cross-cutting veins), and it locally contains small, rounded, darker brown patches (0.1 mm.) which may be crystallisation nuclei. The brown colour is believed to be caused by submicroscopic inclusions. Spherulites are rare, and when present occur as isolated examples composed of radiating fibres of (?) chalcedony: layers and trains of spherulites, typical of rhyolites, are not seen.

Clasts may occur in the cherts, either as small quartz crystals, or as polycrystalline quartz grains; a few altered feldspars (?) are also observed. The presence of these clasts is considered to indicate a tuffaceous component. The cherts are laminated in part, laminae being distinguished by varying grainsize, a variable tuffaceous component, or, most commonly, by variations in sericite content - layers varying from pure chert to cherty sericitic mudstone.

Cross-cutting veins of quartz and quartz + sulphide + chlorite are common, and locally replacive growth of siderite ± anhydrite nodules is seen (e.g. IM10 at 312m./1024ft.).

Chloritic Cherts and Shales. These rocks form a major component of the Parys Mountain Volcanics. They occur as massive and layered rocks or as breccia, and as a matrix for the volcaniclastics. These lithologies have not been distinguished from cherts in outcrop (fig. 3.2) for two reasons, firstly because outcrops are so strongly leached that all micaceous minerals are altered to clay, and secondly because exposure is poor in areas where, on the basis of drill intersections, the chloritic rocks are expected at the surface.

Drillhole intersections show that at depth there is a poorly-defined gradation between pervasively altered Parys Shales and chloritic cherty sediments, both being well mineralised. Chloritic chert forms the matrix to much of the volcaniclastics ('Middle Unit' of fig. 3.12);

PLATE 14

PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - CHERT AND CHLORITIC CHERT

(scale bar = 0.5mm.)

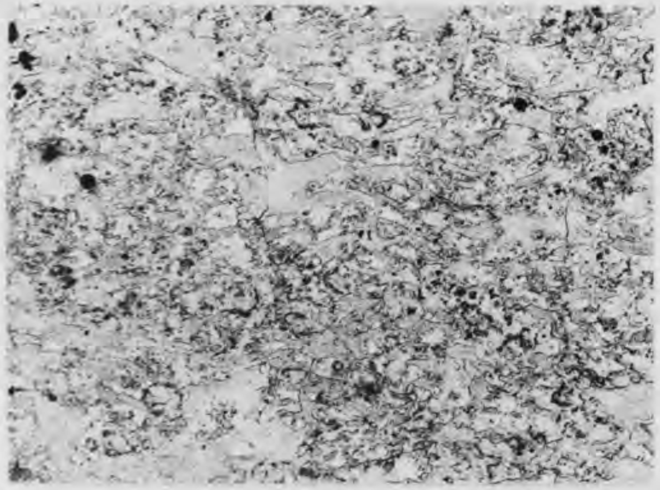
1./2./3. Drillhole IM6 - 126.8m. (416') Chert with weak foliation and compositional banding (ppl)

4. Drillhole IM6 - 245.4m. (805') Chloritic chert with weak compositional banding (ppl)

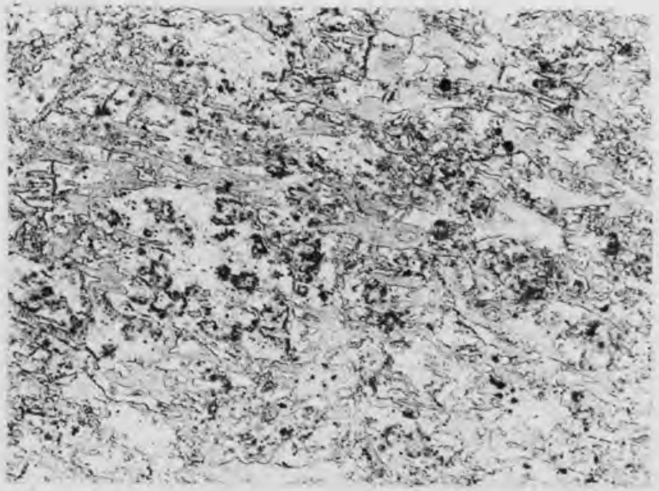
5. Drillhole IM6 - 336.5m. (1104') Chloritic chert with patchy brownish fine quartz (ppl)

6. Drillhole IM6 - 406.1m. (1332' 4") Chloritic chert with some pyrite and fine patchy quartz (ppl)

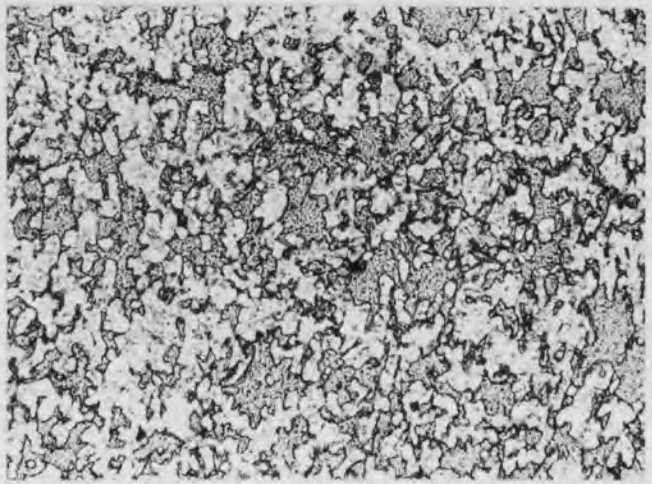
ppl = plane-polarised light


1


2


3


4


5


6

PLATE 14

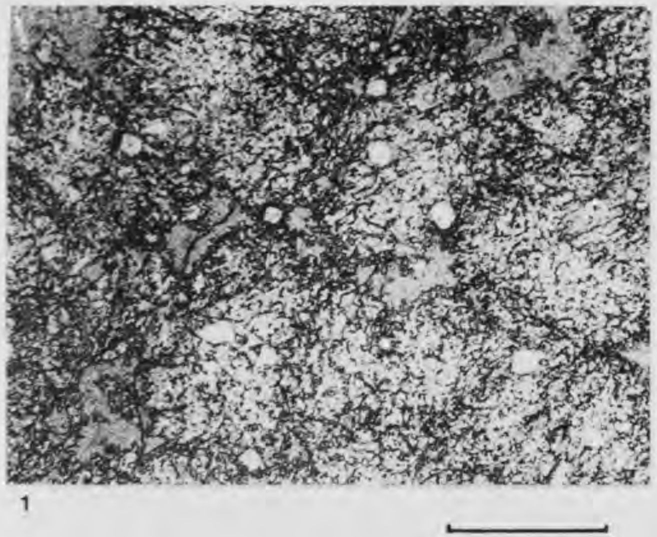
PLATE 15

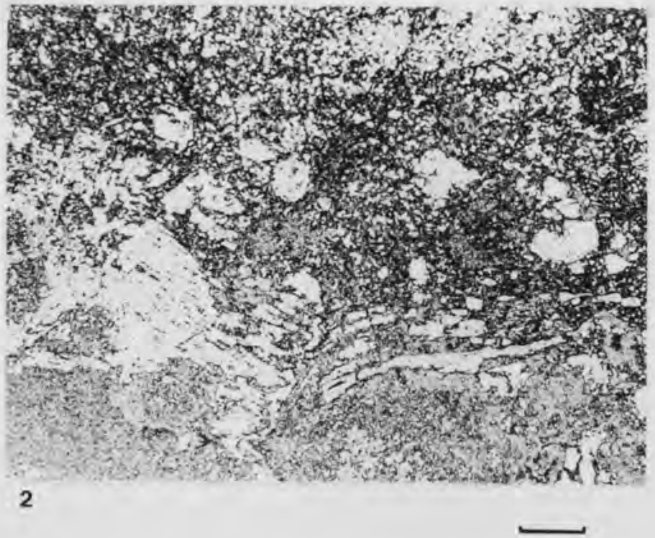
PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - CHLORITIC CHERTS AND SHALES

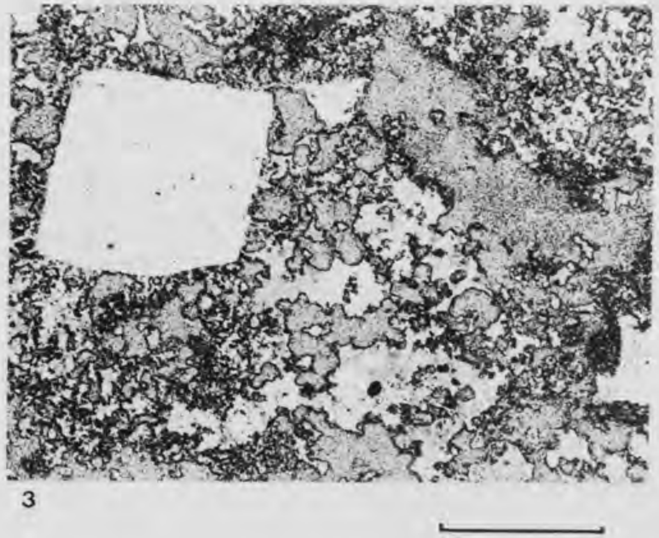
(scale bar = 0.5mm.)

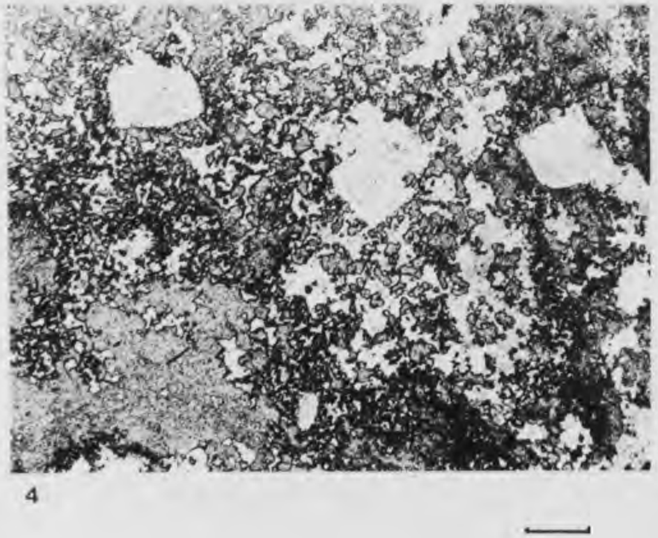
1. Drillhole IM6 - 312.4m. (1025') Chloritic chert with small pyroclastic quartzes (ppl)
2. Drillhole IM6 - 341.4m. (1120') Lamination and tuffaceous component in chloritic chert (ppl)
3. Drillhole IM6 - 411.5m. (1350') Cherty chloritic shale with pyroclastic quartz (ppl)
4. Drillhole IM6 - 411.5m. (1350') Pyroclastic quartzes partly overgrown by quartz (ppl)
5. Drillhole IM6 - 377.9m. (1240') Replacive growth of quartz nodule in chlorite rock (ppl)
6. As 5. above, but under crossed nicols

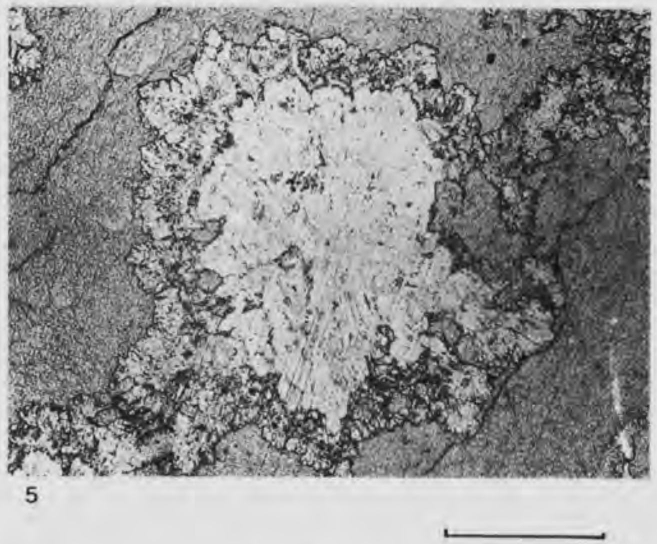
ppl = plane-polarised light


1


2


3


4


5

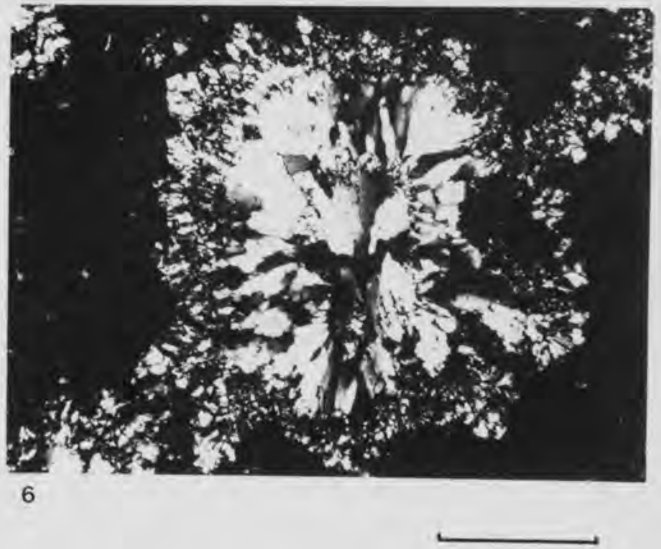

6

PLATE 15

it is the dominant lithology in the 'Lower Unit' and also occurs extensively in the lower part of the cherty 'Upper Unit'.

In drillcore the chloritic cherts are siliceous blue-grey rocks with an irregular fine granular fabric or a diffuse patchy appearance of paler and darker areas. There is a continuous gradation with decreasing silica to dark green chloritic mudstones with siliceous patches. A characteristic intermediate type has a chlorite matrix with variable proportions of round quartz nodules up to 2mm. in diameter. The chloritic rocks contain veins, bands and nodular clots of sulphide (pyrite and chalcopyrite) or of iron carbonate.

In thin-section the rocks consist of chlorite (15% - 90%), quartz (up to 85%) and pyrite or carbonate (up to 30%). The chlorite is very pale green, essentially non-pleochroic with a very low birefringence, lacking anomalous interference colours. Its habit is of aggregates of small plates which lack a strong cleavage orientation unless the rock is sheared. Its character contrasts markedly with that of the chlorite of the altered dolerites and dacites.

The quartz occurs as the extremely fine xenomorphic-granular intergrowth typical of the cherts described above, with similar brownish colour and nuclei. The cherty quartz occurs as patches which in places appear to replace chlorite, but elsewhere the reverse relationship is indicated.

Quartz nodules in chloritic shales often have a radial structure and are also brownish and cloudy; they clearly replace chlorite. Carbonate occurs as veins, patches or nodules replacing chlorite; pyrite has a similar habit or is associated with quartz nodules.

The rocks show varying degrees of layering with the beds or laminae having different proportions of quartz and chlorite. The presence in some layers of angular quartz grains, fragments of rhyolite and possibly altered feldspar (pseudomorphed by quartz-aggregates) may indicate a tuffaceous component. Such clasts, and the quartz nodules, are in some cases overgrown by a clear, inclusion-free quartz phase.

Shales. Grey to black shales with layers and nodules of pyrite or of carbonate occur as interbeds up to 1m. thick in the volcanics. They may be chloritic or sericitic, or similar to the Silurian Shales described below. They are more common in the upper part of the Parys Mountain Volcanics in the central and eastern parts of the area (e.g. hole IM10).

Tuffs. Tuffs occur as thin interbeds in chert and volcaniclastics throughout the sequence. The presence of minor tuffaceous bands within cherts and chloritic rocks has been described above. In drill-core, minor intervals of pyroclastics are observed on most sections, but in the central part of Parys Mountain they have not been distinguished in outcrop where weathered surfaces shown by pyroclastics are similar to those of epiclastic lithologies in the volcaniclastics.

Welded ash-flow tuffs are present in hole A15 (section 8600'E) between 290m. (950ft.) and 336m. (1100ft.) depth. They contain clasts of vesicular rhyolite, altered feldspar and quartz; the lithic fragments are mostly of lapilli grain size. Thanasuthipitak (1974) described welded tuffs from drillholes to the west of this section.

In the central part of Parys Mountain (between 9000'E and 11,000'E on the mine grid - fig. 3.2) the matrix of the tuffs is strongly altered and primary textures are destroyed; the rocks contain fragments of similar composition and grainsize to those in the welded tuffs described above in a matrix of shale or sericite and quartz. There is a gradation into tuffaceous chert.

Volcaniclastics. Volcaniclastics form a major part of the Parys Mountain Volcanics; they consist of polymictic rudaceous to arenaceous rocks containing fragments of rhyolite, chert, chloritic chert, chloritic and sericitic shales, and of sulphides. The matrix varies from pure chert through cherty shale to shale, and contains either chlorite or sericite. Grainsize varies up to a maximum of 100mm.

These rocks form the majority of outcrops in the central part of Parys Mountain outside the opencasts. They vary from cherty rocks with a weak undulating cleavage whose fragmental nature is not easily discernible, to rocks with a more shaly matrix in which angular blocks of rhyolite are clearly seen on faces normal to the cleavage. In drillcore the rocks are distinguished by their breccia fabric and polymictic character.

The volcaniclastics occur throughout the Parys Mountain Volcanics, but predominate in the 'Middle Unit' (fig. 3.12). This stratigraphic variation, though imprecisely defined, continues along strike between 8600'E and 11,000'E, and is recognised in both limbs of the structure, though its thickness varies (see figs. 3.3. to 3.7).

In thin-section the compositions of the clasts are seen to comprise all the component lithologies of the Parys Mountain Volcanics described above, and in addition include mineralised chert and shale, and banded siliceous sulphides. Textures are best preserved in shaly matrices. Both grain and matrix support are present.

In drillhole IM9 the volcaniclastics, overlying a zone of bedded chert, shale and sinter, consist of a 60m. thickness of breccias, rudaceous to arenaceous, containing clasts of shale, sinter, rhyolite, chert and sulphides. Twenty thin-sections and polished thin-sections have been examined from this zone. The transported sulphides are massive, siliceous and banded, or in a shale matrix. The breccia is sedimentary, having a cherty or cherty shale matrix and showing a post-depositional cleavage (plates 16 and 17).

3.3.3. Silurian Shales

Grey to black well cleaved and laminated shales and mudstones occur as remnants in the opencasts at Parys Mountain. Graptolites from these shales indicate that their age is Llandovery (Elles, in Williams, 1907 and in Greenly, 1919; Lapworth in 1882, recorded by Hawkins, 1966; Bates, 1966 and 1972). This age has been confirmed by micropalaeontological work carried out for the Institute of Geological Sciences (M. J. C. Nutt, pers. comm.).

Recent drillcores show the Silurian Shales to be a sequence of grey to black, buff or rarely greenish shales, commonly laminated, and containing up to 10% pyrite and/or iron carbonate as beds, nodules or veinlets. Thin lensy interbeds up to 10mm. thick of hard pale pyritic siliceous silty material occur, and some thin tuff beds are present (e.g. in drillholes A6 and IM10).

Towards the base of the shales, near the contact with the Parys Mountain Volcanics, slumped breccias of shales and siliceous rocks

PLATE 24

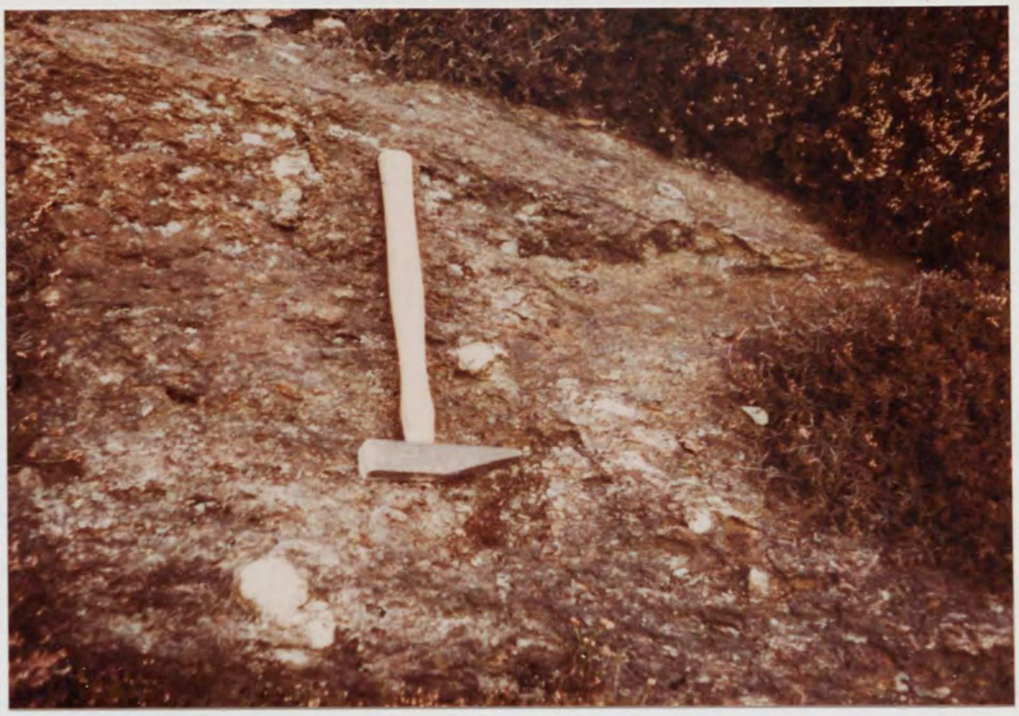
PARYS MOUNTAIN - VOLCANICLASTICS

1. Lapilli tuff with blocks of rhyolite - Parys Mountain Volcanics.

   South of east end of Great Opencast.

2. Tuff-breccia with blocks up to 20cm.

   North-West of Great Opencast.



1

2

PLATE 24

PLATE 16

PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - VOLCANICLASTICS

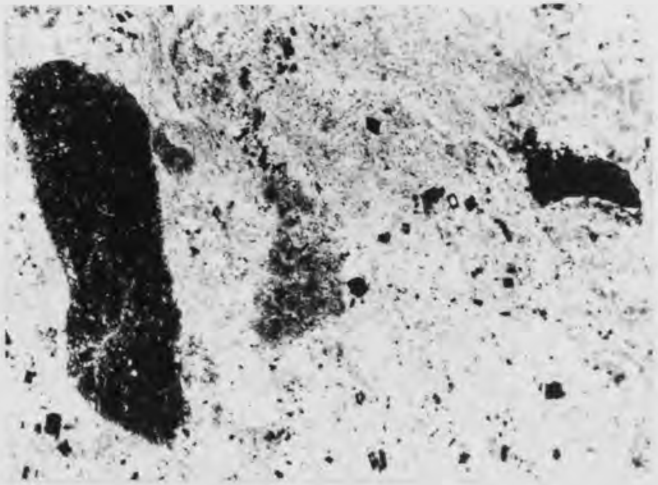
(scale bar = 0.5mm.)

1. Drillhole IM9 - 36.4m. (119' 6") Fragments of chert, siliceous sinter and sulphide (pyrite) in shaly matrix (ppl)
2. Drillhole IM9 - 59.3m. (194' 6") Fragments of chert, shale and sulphide in cherty matrix (ppl)
3. As 2. above, showing the mineralised fragments (ppl)
4. Drillhole IM9 - 36.4m. (119' 6") Fragments of chert, rhyolite and banded siliceous sulphide in shaly matrix (ppl)
5. Drillhole IM9 - 36.4m. (119' 6") Detail of mineralised fragment (ppl)
6. Drillhole IM9 - 65.7m. (215' 6") Sulphide-rich clast in cherty volcaniclastic (ppl)

ppl = plane-polarised light

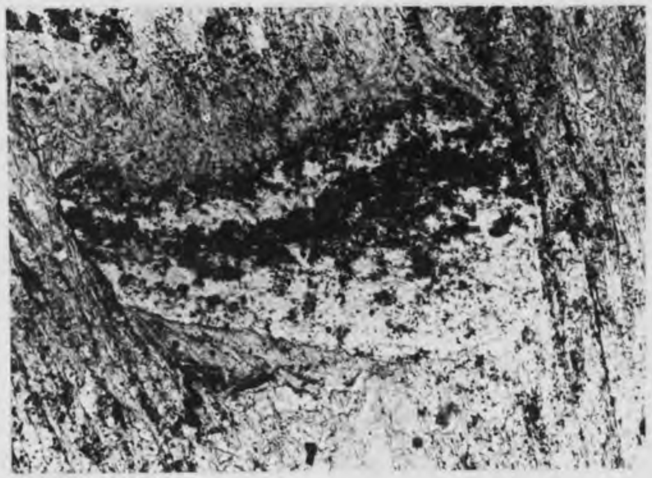
1

2

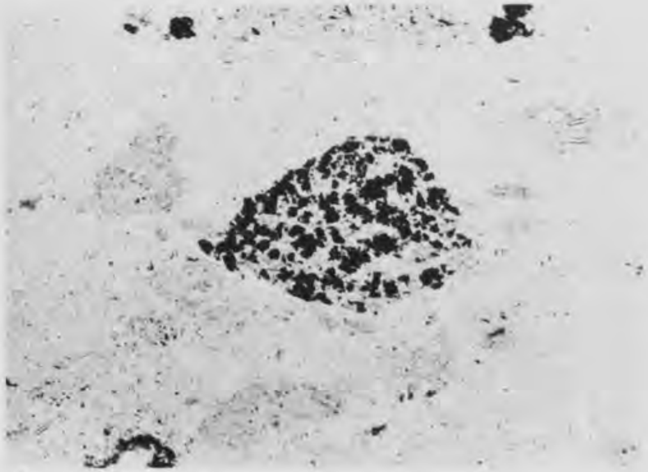


3

4



5



6

PLATE 16

PLATE 17

PHOTOMICROGRAPHS OF THE PARYS MOUNTAIN VOLCANICS - VOLCANICLASTICS

(scale bar = 0.5mm.)

1. Drillhole IM9 - 59.3m. (194' 6") Cherty volcaniclastic with fragments of shale, chert and sulphide (ppl)

2. Drillhole IM9 - 60m. (197') Banded volcaniclastic with quartz, sulphide and chert in a cherty matrix (ppl)

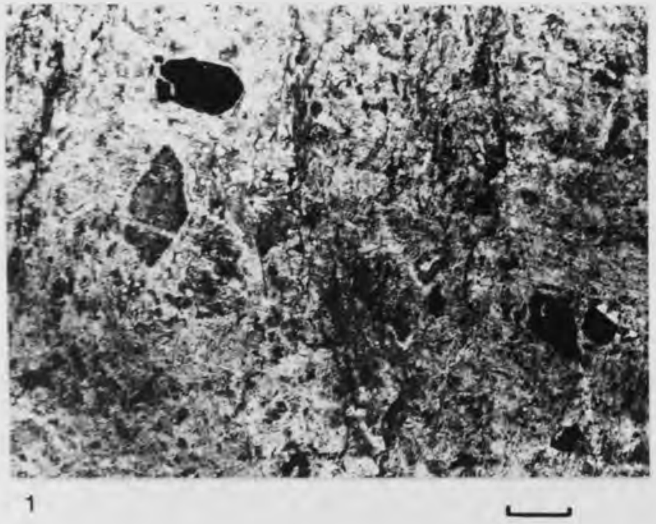
3. Drillhole IM9 - 44.2m. (145') Chert, shale and rhyolite fragments in cherty matrix (ppl)

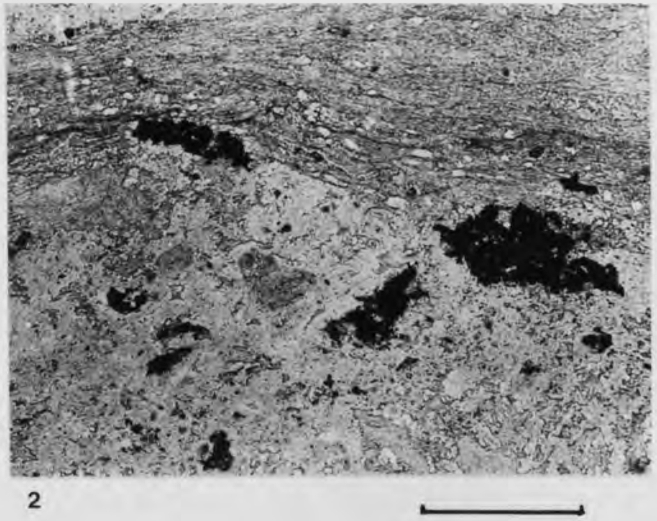
4. Drillhole IM9 - 60m. (197') Detail of mineralised clast in cherty volcaniclastic (ppl)

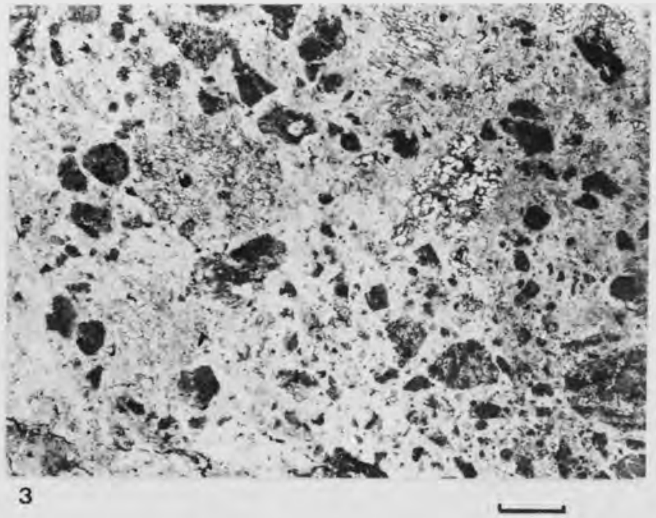
5. Drillhole IM9 - 63.1m. (207') Mineralised clast in chert (ppl)

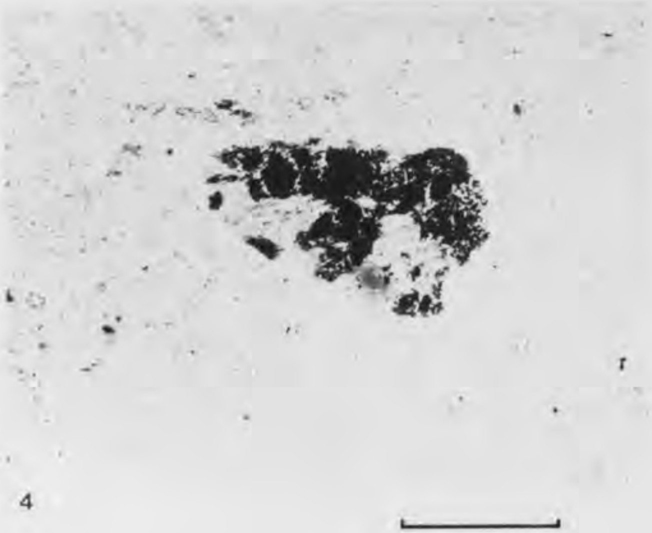
6. Drillhole IM9 - 59.3m. (194' 6") Detail of mineralised clast in chert matrix (ppl)

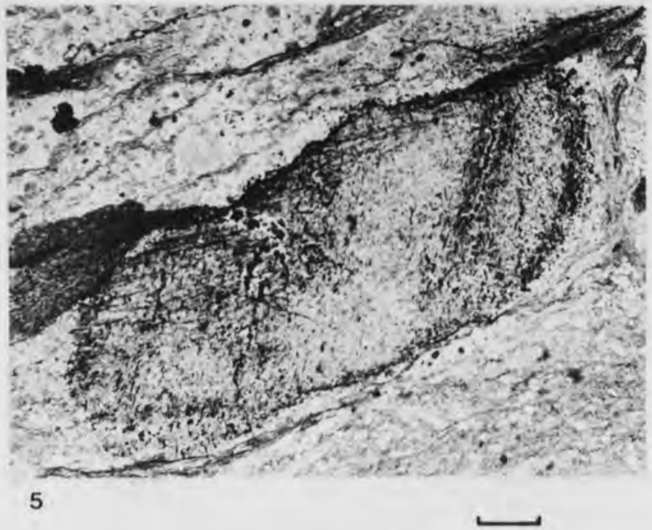
ppl = plane-polarised light


1


2


3


4


5

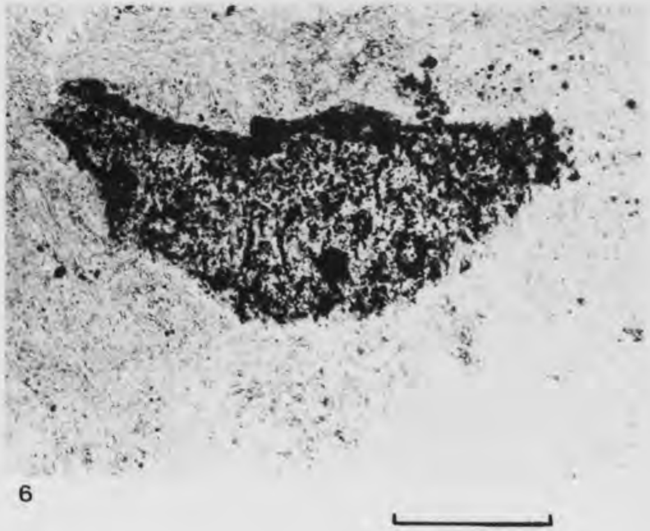

6

PLATE 17

are common. The contact itself, where unsheared, is commonly sharp and apparently conformable, with minor interbeds of chert in the shale and vice versa. An example of such a contact occurs in drill-hole IM10, and hole 2 also probably cuts a transitional contact. This contact is discussed in section 3.6.2.

3.3.4. Dolerite

Sills of dolerite occur within Parys Shales and the Parys Mountain Volcanics. They are altered to an assemblage of chlorite, quartz, albite, carbonate and epidote, though remnants of ophitic texture remain.

3.4. STRUCTURE

3.4.1. Introduction

Greenly's (1919) interpretation of the structure (fig. 3.13), partly based on the incorrect identification of Silurian graptolites in the Southern Shales, shows the 'felsite' as stratiform and places synclinal axes both to the north and to the south of its southern outcrop. Greenly regarded low angle thrusting as important. Manning (1959) considered that the 'felsite' was a dyke and that the succession was overturned and dipping north-northwest with no major

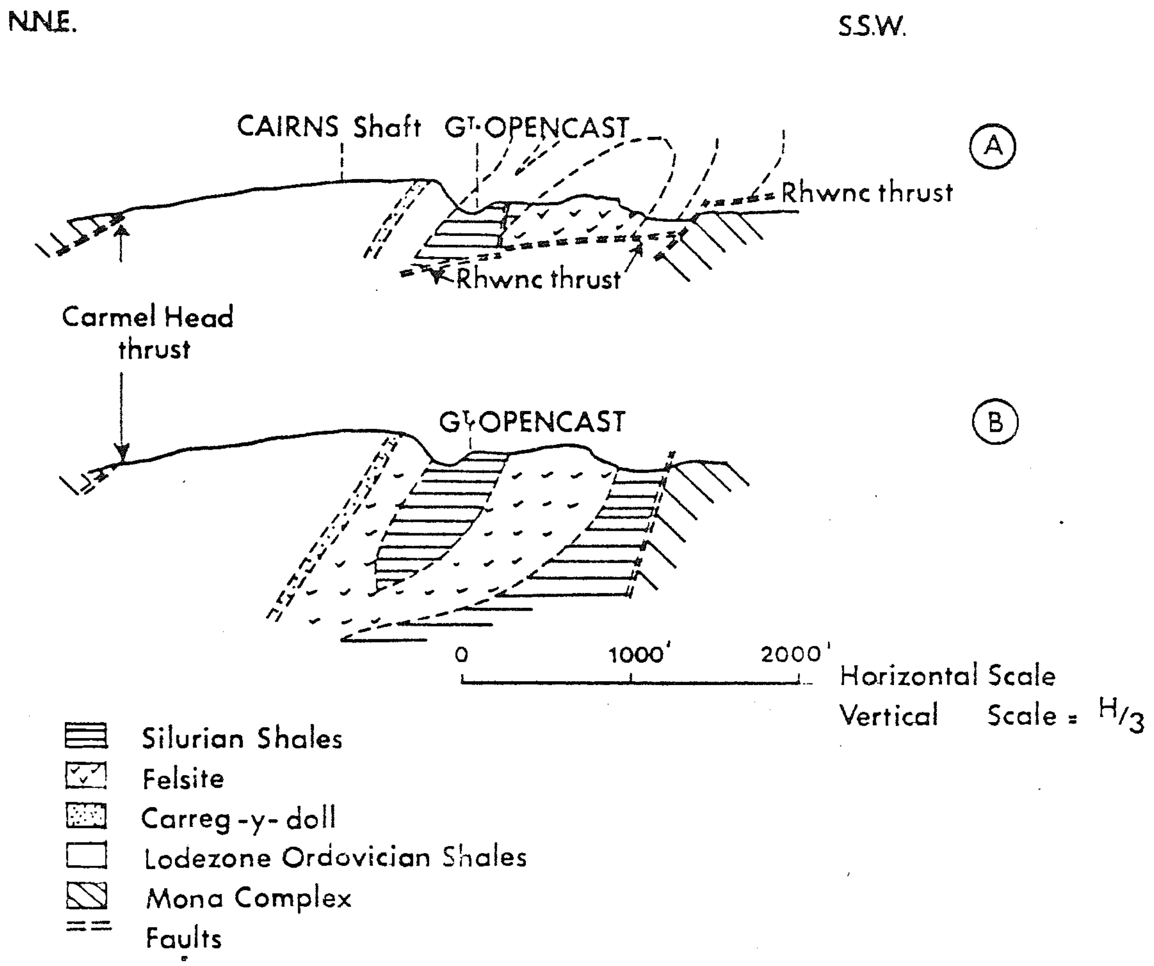


Fig.3.13 PARYS MOUNTAIN - STRUCTURE Ⓐ after Greenly (1919)
Ⓑ after Manning (1959)

fold closure at Parys Mountain (fig. 3.13). He reported that no significant thrusting could be observed at Parys Mountain.

Hawkins (1966) also found no evidence of the thrusting suggested by Greenly, though such structures have been proposed by exploration geologists working in the area (Intermine, unpublished reports). Bates (1966), on the basis of a revision of the graptolites from the Southern Shales and of structural data, suggested that the structure is a single syncline, a view supported by the results of the present study.

3.4.2. Folding

Structural information presently available at Parys Mountain may be summarised as follows:

a) It has now been established that shales on the north, west and south sides of Parys Mountain are Ordovician in age and that Silurian rocks are apparently restricted to the core of the structure between the two outcrops of volcanics. Contacts between volcanics and shales are commonly sheared; no indisputable way-up data has been obtained from them. Diamond-drilling indicates that the Silurian Shales do not continue in depth.

b) Bedding is commonly sub-parallel to the main cleavage, except at the western end of Parys Mountain, where an area of northeasterly dips occurs, and in the Great and Hillside Opencasts (fig. 3.2). At the eastern end of the Great Opencast, shallow to horizontal dips occur in chert. On the southern side of both opencasts, thinly-bedded Silurian Shales are found overturned and dipping 60° - 80° to the NNW. Bedding angles from diamond drill cores are generally consistent with boundaries drawn on sections (figs. 3.3. to 3.7); bedding is generally not seen in the volcaniclastics, but occurs in cherts and chloritic rocks and is common in less altered shales.

c) The main cleavage (S_1) dips at 50° - 60° towards 340°. A minor cleavage (S_2) is seen in thin section but only in a few outcrops.

d) Minor folding in the Silurian Shales is common; folds plunge between 10° and 25° ENE and the main cleavage is axial planar to them. No reliable linear structural data has been obtained from the volcanics.

e) Deep drilling on the north side of Parys Mountain has encountered siliceous chloritic rocks up to 600m. below surface (hole 38, fig. 3.3), and no hole has yet been drilled in which altered and mineralised rocks have not been intersected, although deep holes to the north would have been expected to have passed, entirely within Ordovician shales, beneath the keel of a synclinal structure.

f) Although a well developed zone of stockwork mineralisation, grading into pervasive chloritisation, silicification and mineralisation, is present in the Parys Shales on the northern limb, especially at depth, the stratigraphically equivalent shales on the southern limb are largely unchloritised, although they carry quartz and carbonate veins. An exception occurs at depth in hole A15 (fig. 3.3) where silicified and chloritised shales are found. However, the few holes which have intersected the Southern Shales have not penetrated them for any distance.

A synclinal structure is indicated by the symmetry of the stratigraphy at outcrop and by the failure of the Silurian Shales to continue in depth, and is consistent with the information listed in points a) to d) above. Details of the structural interpretation are given in the five drill-sections (figs. 3.3 to 3.7). The reliability of the detailed interpretation is dependent on the density of drilling; control is particularly poor on the southern limb.

The evidence summarised in points e) and f) above suggests that at depth the synclinal structure is not simple. It is believed that

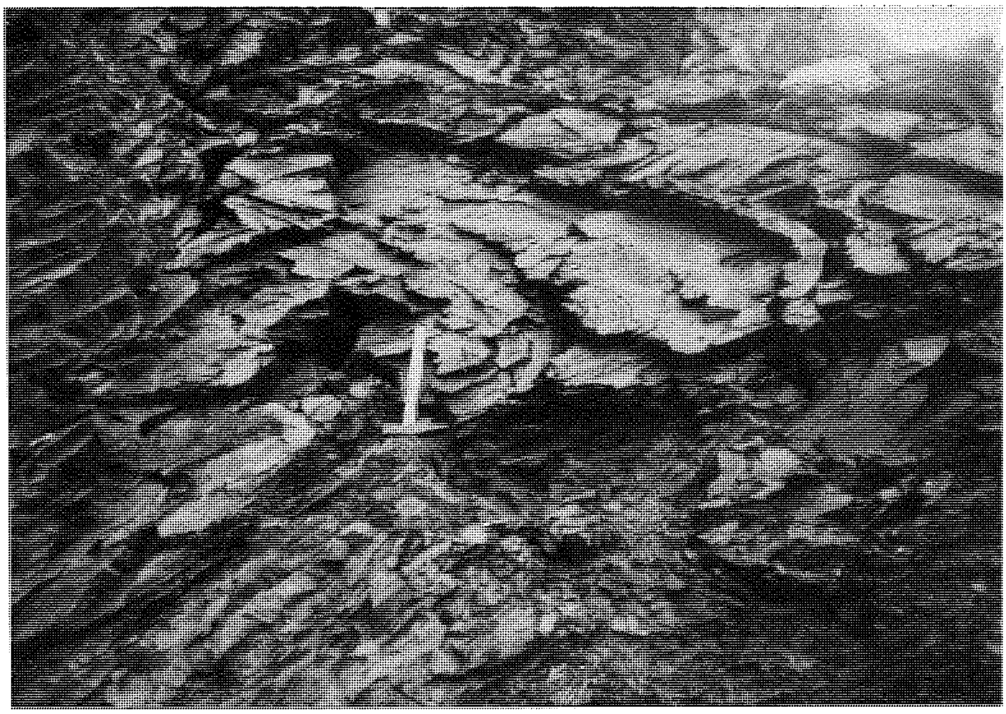
PLATE 25

PARYS MOUNTAIN - STRUCTURE

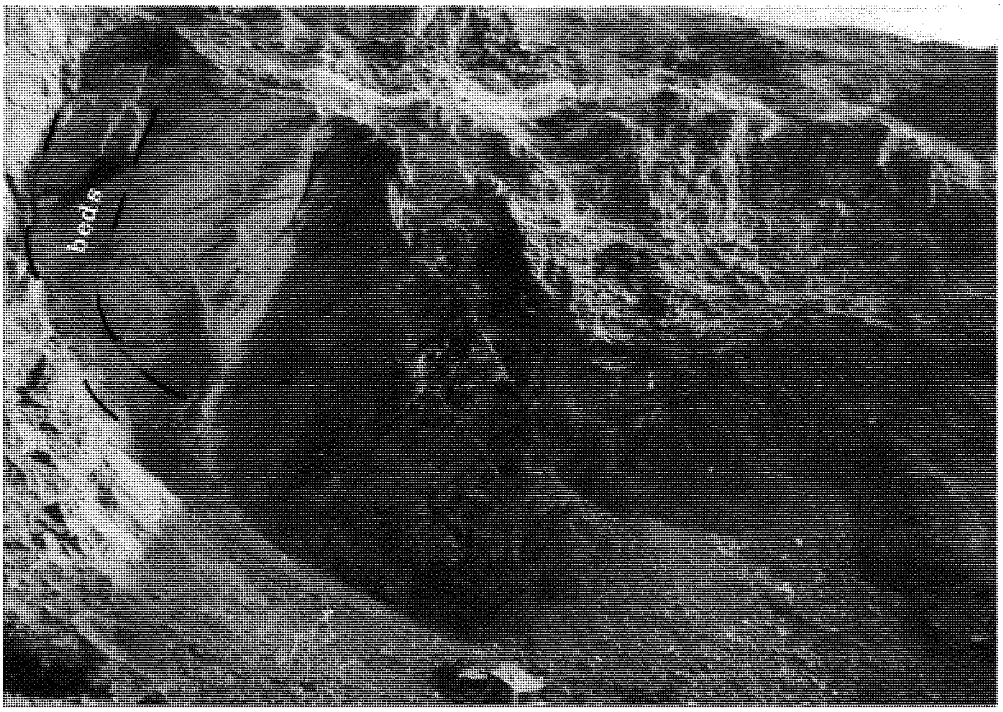
1. Fold closure in Silurian Shales.

   East end of Great Opencast.

2. As above, from a distance, showing
   Parys Mountain Volcanics enclosing
   Silurian Shales at left.
   (Curved surface at left is bedding.)



1



2

PLATE 25

PLATE 26

PARYS MOUNTAIN - STRUCTURE AND SLUMPED CHERT

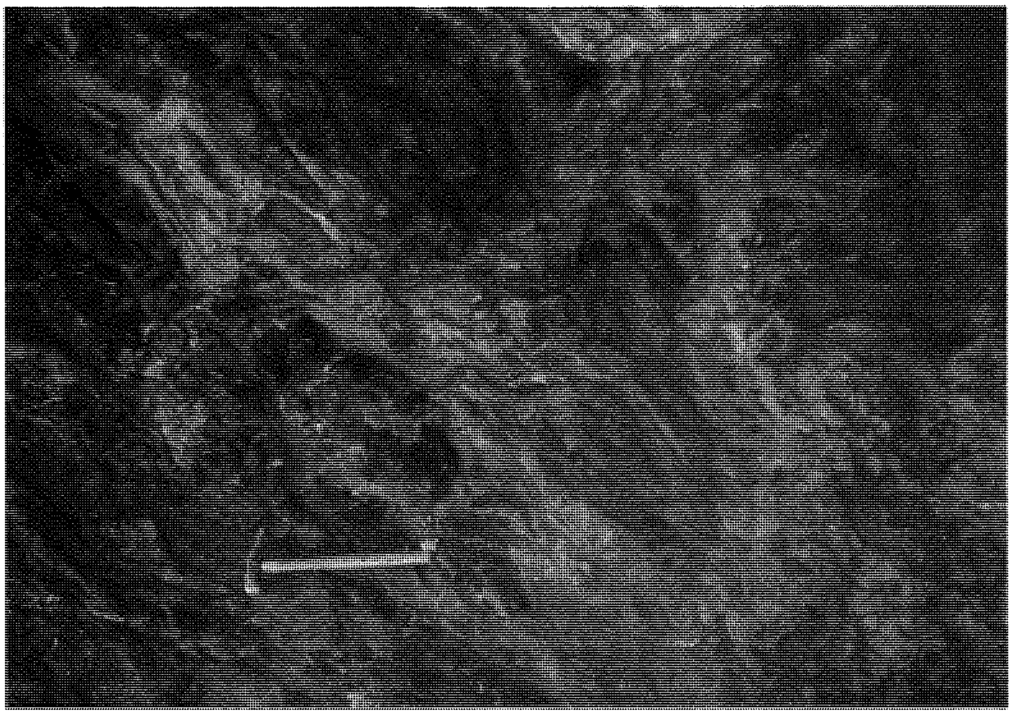
1. Fold closure in Silurian Shales.

   West end of Great Opencast.

2. Slumped chert. Rafts and blocks of chert in sulphide and shale matrix.

   Great Opencast.

1



2

PLATE 26

faulting and primary lithological variations may contribute to the apparent complexity of distribution of rock types within the synclinal structure.

3.4.3. Faulting

The most conspicuous faults at surface are a NNE to NNW trending series of which the Great and Carreg-y-doll Crosscourses are the best known. Movement on the Great Crosscourse was estimated by Manning (1959) as west side 60m. south and 100m. down. That on the Carreg-y-doll Crosscourse is similar in sense and magnitude. On the intervening Cairns Fault, movement is apparently similar in magnitude but in the reverse sense. Thus net displacement on this fault set is probably not large, though it is locally important and hampers correlation.

A series of steep reverse faults, probably pre-dating the crosscourses, dipping northwards at 60° - 80° and striking E to ENE, is suggested by intersections of fractured zones in drillcore. Such faults may be related to the Corwas Fault and possibly to parts of the 'Carmel Head Thrust'. Those in the central parts of the mine have apparent vertical displacements of 100m. or less.

A third fault set, involving axial shear parallel to the main cleavage is also indicated in drillcore but the evidence is not conclusive and no estimate of displacements can be made.

3.4.4. Effect of Primary Lithological Variations

Lithological variations may affect the structural interpretation in two ways. Firstly, the western end of Parys Mountain consists largely of intrusive rhyolite and massive flows - competent lithologies with partly non-stratiform primary contacts which are surrounded by relatively incompetent shales. Secondly, the zone of stockwork and pervasive alteration at the top of the Parys Shales may be expected to be non-stratiform, and is perhaps related to pre-deformation fractures (see section 6.3).

3.4.5. Conclusion

Although a detailed structural analysis of Parys Mountain is not possible from the available information, there is sufficient data to establish the presence of a synclinal fold with a core of Silurian Shales, although at depth the detailed picture is not clear. The fold may have been subject to axial shear, and has certainly been disrupted by later high-angle reverse faulting and a final phase of oblique-offset steep normal faults.

The major folding and development of S_1 are of Caledonian age (Ineson and Mitchell, 1975; Nutt et al., in press). The age of S_2 and of the reverse faults and crosscourses is not known and could be late Caledonian or Variscan.

3.5. MINERALISATION

3.5.1. Introduction

Greenly (1919) described two main types of ore from Parys Mountain: 'bluestone' and 'pyrite-chalcopyrite' (fig. 3.14). The former is a fine-textured intergrowth of sphalerite, pyrite, chalcopyrite, galena and chalcocite, showing banding. It is similar to the Kilmacooite of Avoca (Manning, 1959). The pyrite-chalcopyrite ore was described as a mixture of idiomorphic pyrite with later anhedral chalcopyrite in a fine quartz matrix 'not unlike that of quartzite'.

The lodes described by Greenly are grouped in five associations based on location and ore and gangue mineralogy, as shown in figure 3.15. Much of Greenly's evidence came from mine dumps, old plans and local knowledge, as much of the workings had been exhausted by the end of the 19th Century. His account does, however, provide a useful basis for further descriptions, and is summarised below.

Fig. 3.14 AVERAGE ASSAY VALUES OF ORE SPECIMENS FROM PARYS MOUNTAIN

(after Greenly, 1919)

	BLUESTONE (3 samples)	CHALCOPYRITE-PYRITE (2 samples)
Pb	14%	0.1%
Zn	30%	less than 1%
Cu	1.6%	5%
S	27%	25%
SiO_2	15%	41%
Fe	13%	24%

Fig.3.15 GROUPING OF LODES AT PARYS MOUNTAIN

(modified from Greenly, 1919)

1	GREAT LODE	Clay Shaft Lode Great Opencast Lode Black Rock Lode Golden Venture Lode
2	CARREG-Y-DOLL LODE	
3	MORFA-DU	
4	NORTH DISCOVERY LODE	North Branch Lode North Discovery Lode South Branch Lode Charlotte Lode
5	CROSSCOURSES	

The Great Lode lay in the upper part of the volcanics and base of the Silurian Shales, and was mainly worked in the Opencasts. The group consisted of a 'series of lenticular impregnations' in a fine-grained quartz and chlorite matrix. Though the lode was largely worked out, Greenly (1919) stated that it did not have the appearance of a true fissure vein, that it died out sharply in depth in a complex of small veins, and that a rough zoning of ores had been recorded with pyrite on the north (within the 'felsite') followed by chalcopyrite-rich ore, and bluestone on the south at the Silurian Shales contact.

The Carreg-y-doll Lode was described as a single body 1.6km. ('1 mile') long and up to 21m. (70ft.) wide at the contact of the 'felsite' and Parys Shales to the north. Again Greenly (1919) reported that this was not a true fissure vein, but consisted of fine quartz rock with 'wandering banded structures' and 'drusy cavities' (siliceous sinter). The ore consisted of pyrite + chalcopyrite occuring 'in lenticular seams' up to 7m. (24ft.) thick. Grades were 2.5% to 3% Cu.

The North Discovery Lode and its associates (fig. 3.15) were described as more typical fissure vein lodes with sharp footwalls and hangingwalls (North Discovery Lode) or comprised quartz stringers with minor chalcopyrite, galena and sphalerite (North and South Branch Lodes). The gangue was coarse venous quartz, unlike that of the other lodes, with chlorite and some wall rock fragments in it. The

North Discovery Lode was the richest zone at Parys Mountain; it ran on the north side of the 'felsite', 0.4km. ('$\frac{1}{4}$ mile') west from the Great Crosscourse, and had a cross-cutting relationship with the Carreg-y-doll Lode. Its mineralogy was chalcopyrite with subordinate pyrite; grades are not certain but Greenly recorded that the spoil banks when reworked yielded 3% to 5% Cu.

Greenly (1919) reported minor mineralisation from the crosscourses in the area of the Carreg-y-doll zone. Pyrite occurred in the Great Crosscourse and possibly chalcopyrite in the Carreg-y-doll Crosscourse. Manning (1959) stated, however, that the Great Crosscourse was unmineralised.

The Morfa-du Mine consisted of a series of ill-defined 'bluestone impregnations' with a little pyrite and quartz, but the mineralisation was commonly coarser than in the Great Lode. Greenly (1919) gave few details of ores or host rocks.

The sulphide mineralogy has been described by Wheatley (1971a), Thanasuthipitak (1974) and Sivaprakash (1977). Pointon and Ixer (in press) derived a scheme of paragenesis shown as figure 3.16. This indicates three main stages of opaque mineral formation; the ore minerals fall into a number of associations:

a) Minor quantities of iron-titanium oxides associated with the crystallisation of the volcanics; these are now

Fig. 3.16 Paragenetic sequence of ore minerals at Parys Mountain (after Pointon and Ixer, in press) pseudomorphed by polymorphs of TiO_2 and haematite; TiO_2 polymorphs and graphite are present as detrital grains in the sediments.

b) A major phase of pyrite, associated with later chalcopyrite, sphalerite and galena, with minor quantities of arsenopyrite, tetrahedrite group minerals and lead-bismuth sulphosalts.

c) Small discrete crystals associated with quartz-chlorite or quartz-carbonate veining that cuts the main sulphide mineralisation; within these veins, small discrete inclusion-free pyrite euhedra and framboids, arsenopyrite and marcasite, are accompanied by chalcopyrite, galena and inclusion-free sphalerite.

It is believed that the last association phase represents remobilisation during metamorphism.

3.5.2. Mineralisation observed in Outcrop and Drillcore

The Great Lode. Little ore remains in the opencasts; however, sulphides, commonly massive, are present as thin layers in chert and also in slumped chert and shale units where both pyrite and some chalcopyrite are associated with shales. Pyritic sulphide seams, mostly following the bedding, occur in chert and shale near the volcanic-shale contact. In these outcrops pyrite is the dominant

Fig. 3.17 PROPOSED SCHEME OF SILICA PARAGENESIS AT PARYS MOUNTAIN

	1	2	3	4
brownish very fine-grained to cryptocrystalline quartz (chalcedonic)	—			
fibrous chalcedony - void filling in siliceous sinter	—			
pale brown to clear very fine quartz aggregate in irregular often cross-cutting veinlets	—	—		
silicification: polycrystalline quartz aggregates (coarse grained) and nodules with carbonate and anhydrite	—	—	—?	
quartz + sulphide veins with chlorite selvages	—	—		
quartz + sulphide + chlorite veins (often chalcopyrite-rich)			—	
barren white quartz veins				—

1 Early - sedimentary

2 Early - pre- or syn- Silurian Shales

3 Main regional deformation (Caledonian)

4 Post Caledonian (?)

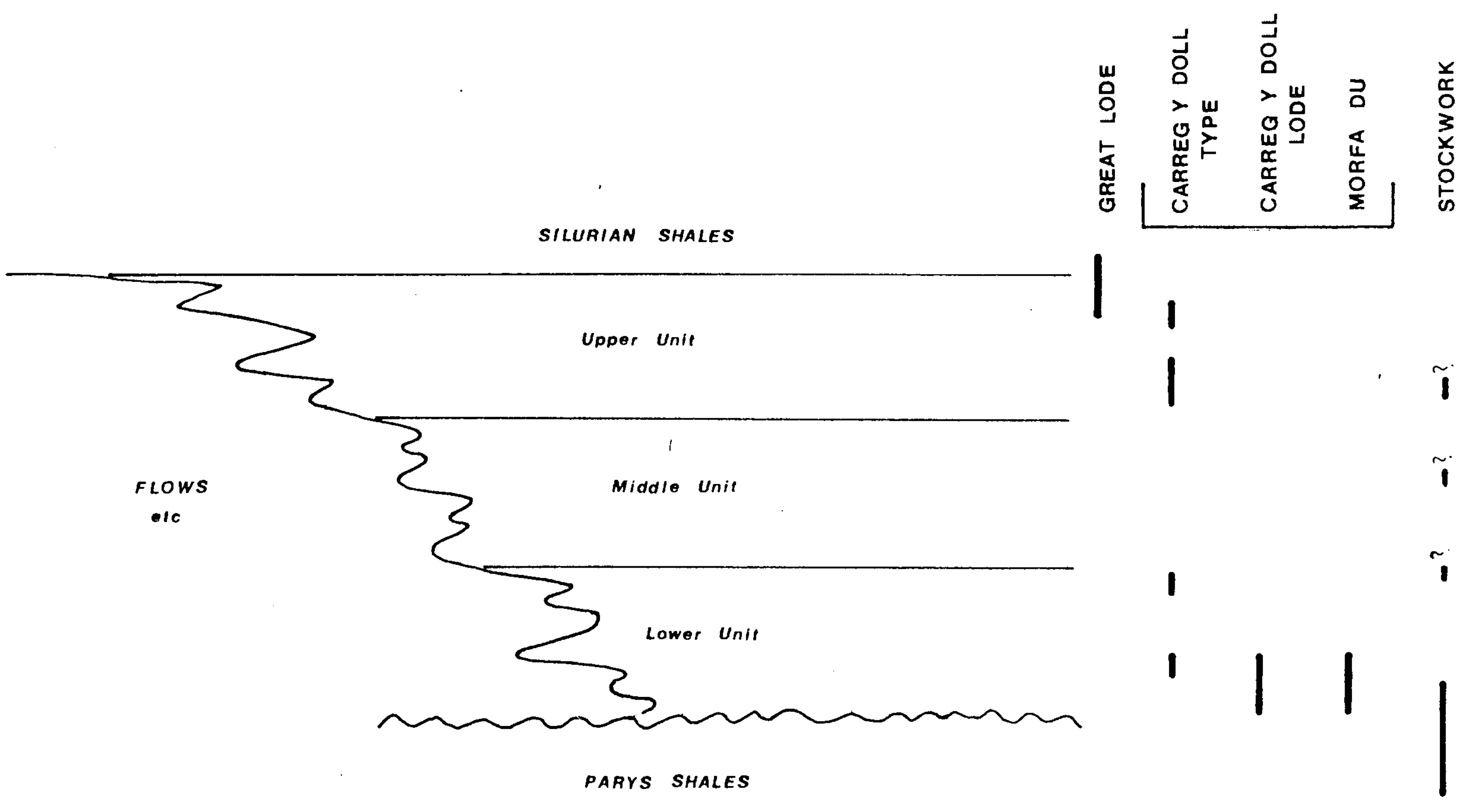


Fig 3.18 RELATIONSHIP OF MINERALISATION TO STRATIGRAPHY in the PARYS MOUNTAIN VOLCANICS

not to scale

sulphide, but minor copper sulphides are present and secondary copper salts are seen on weathered faces. Quartz, pyrite and chalcopyrite veins up to 30mm. wide cut cherts and slump breccias and locally occur in the basal Silurian Shales.

In cherty mudstones on the north side of the Great Opencast, pyrite, with some chalcopyrite, galena and sphalerite, occurs in three main associations. Firstly, dispersed in the sediment; secondly, as discrete conformable lenses; thirdly and probably most abundantly, as cross-cutting quartz + sulphide veins up to 50mm. wide forming a network with little apparent preferred orientation. A weak later set of white quartz veins dips S to SW at low angles, but does not carry sulphides.

Hole A7 (section 9000'E) cuts the chert sequence conformably underlying Silurian Shales. This consists of massive grey chert with layers of siliceous massive sulphides (pyrite, chalcopyrite, galena and (?) sphalerite), mineralised slump breccia with chert, shale and siliceous ± massive sulphide fragments in a cherty matrix, and interbeds of shale and cherty mudstone having layers of massive pyrite + chalcopyrite up to 150mm. thick. The above sulphides are pyrite-dominated though they are polymetallic. All rocks are cut by white quartz + sulphide veins in which chalcopyrite is commonly dominant. In the Silurian Shales, pyrite beds up to 20mm. thick occur in the first 5m. - 10m., above which both iron carbonate and pyrite are present.

On sections to the east, the situation is similar. Grey cherts, containing patches and lenses of massive pyritic sulphides up to 10mm. thick, have shaly interbeds carrying up to 30% pyritic sulphides; slumped breccias of chert, shale and sulphides are also present, and all these lithologies are cut by white quartz veins carrying chalcopyrite, pyrite and locally galena and sphalerite. The quartz veins die out within a few metres in the Silurian Shales. In hole M19 (section 10,000'E) the cherts are rather chloritic and patches of coarsely crystalline chalcopyrite and quartz are conspicuous. The sequence again passes into dark grey shales with lenses of pyrite and minor associated chalcopyrite, sphalerite and galena. On section 11,000'E the contact is marked by a sulphide-bearing intraformational breccia, and this, too, is cut by quartz + sulphide veins.

In the above sequences a distinction can be drawn between sulphides, generally of fine grainsize, occurring in lenses and beds in the cherts and shales, and a cross-cutting association of sulphides, quartz, and some chlorite. The latter association is of coarser grainsize and occurs in irregular patches and cross-cutting veins. In many cases chalcopyrite is the dominant sulphide, intimately associated with coarse-crystalline white quartz and green chlorite.

This association is believed to be composed of constituents which have been remobilised during metamorphism and have crystallised locally either as patchy segregations or in fractures as vein fillings. They are identified with association c) in the paragenetic scheme of Pointon and Ixer (fig. 3.16). This distinction between fine-grained primary sulphides and the remobilised association is found throughout the mineralised sequence.

<u>The Carreg-y-doll Lode</u>. In outcrop this zone consists of siliceous sinter with a network of gossanous limonite veins and lenses. Underground it appears as a white quartz rock with lenses of massive pyrite with minor chalcopyrite (see also section 3.2). The massive sulphides are encrusted with secondary copper salts which are commonly concentrated parallel with the bedding.

In drillcore the Carreg-y-doll Lode is largely siliceous sinter with a few percent of dispersed pyrite, and with chlorite dispersed or as chloritic shale layers. Sulphides occur as disseminations, as patches and nodules of coarse pyrite and chalcopyrite in chloritic zones, as massive sulphide layers or irregular patches. In all cases the Lode contains cross-cutting veins of quartz + sulphide ± chlorite, and later barren milky quartz veins. The vein sulphides are pyrite, chalcopyrite and, in some instances, galena and sphalerite (e.g. IM23, section 11,000'E). The Lode varies in thickness from 0m. to 30m.

Other Mineralisation associated with Siliceous Sinter. Mineralisation similar to that of the Carreg-y-doll Lode is developed locally within both the upper and lower cherty units.

In the 'Upper Unit' (fig. 3.18) the mineralisation generally occurs in the lower part, but locally rises towards the Great Lode zone. Mineralised zones, which occur on most sections (figs. 3.3 to 3.7), consist of siliceous sinter, with layers or lenses of chloritic chert and shale, containing sulphides dispersed, as massive layers (?beds) and in quartz veins. Commonly the last is the dominant habit, but layers up to 0.1m. thick are present, for example in IM6 (8600'E). Pyrite predominates and in the irregular layers of sulphide it is fine-grained with minor associated chalcopyrite. The sinter passes laterally into interbedded chloritic chert and chloritic and sericitic shales containing layers of fine chlorite + pyrite + quartz + chalcopyrite. Patches of coarse, recrystallised chlorite + chalcopyrite + pyrite and quartz + sulphide ± chlorite veins are common.

In the 'Lower Unit', mineralisation on the southern limb is irregular in distribution and may lie at or above the contact with the Southern Shales. It is similar to that above with abundant white quartz + sulphide veins, and dispersed and layered sulphides commonly occurring in the more shale-rich zones. Chalcopyrite is most commonly observed in the remobilised association with white quartz and chlorite. In the layered and dispersed sulphides, pyrite dominates, but chalcopyrite, galena and sphalerite are also present. These zones have some strike continuity, for example between sections 8600'E and 9000'E, and are at least partly stratabound (figs. 3.3, 3.4). On section 10,600'E, hole IM9 intersects siliceous sinter and chert with interbeds of sericitic and grey shale with pyrite, chalcopyrite and sphalerite; this is overlain by a breccia containing clasts of chert, sinter, mineralised shale and siliceous banded sulphides (see section 3.3.2).

At Morfa-du, shafts have been sunk adjacent to outcropping siliceous sinter in the same stratigraphic horizon as the Carreg-y-doll Lode. Drillcore from this area was not examined in the present study, and Greenly (1919) stated only that the mine consisted of a series of ill-defined bluestone impregnations. Blocks collected from the mine dumps show finely banded polymetallic sulphide-bearing sinter with layering which is often disrupted on a millimetre scale, and autoclastic brecciation which is annealed by similarly banded sinter and sulphide. The appearance is similar to that of the siliceous sinter in outcrop at Morfa-du. In addition, polymictic brecciation occurs with clasts of mineralised sinter up to 50mm. x 50mm. in size, and fine-grained pyritic sulphide clasts up to 20mm. across in a matrix of fine quartz and sulphide. This is itself cut by barren white quartz veins; a final phase of coarse bladed baryte and coarse crystalline galena occurs as crosscutting veins and irregular patches.

Stockwork. In Parys Shales on the northern limb of the structure, low grade mineralisation is present, stratigraphically below the Carreg-y-doll Lode on all sections (figs. 3.3 to 3.7). It consists of chlorite + quartz + pyrite + chalcopyrite veins with well developed chlorite selvages which pass stratigraphically upwards into pervasively chloritised shale with intense stringers of sulphide and quartz, commonly having a gradational contact with siliceous sinter. The predominance of chlorite over quartz distinguishes these veins from later veins in the Great Lode and Carreg-y-doll Lode.

This is a stockwork zone; it is thin to absent at surface but increases with depth to a thickness of around 50m. at 300m. depth, and within it, sulphides, including chalcopyrite, exceed 2% of the rock. The zone has been intersected by all deep holes on the northern side, but it does not extend beneath the southern limb of the structure. A substantial tonnage of mineralisation is represented but grades are below 1% Cu.

3.6. DISCUSSION

3.6.1. Scheme of Mineralisation

The mineralisation is divided into primary and secondary types:

Primary Mineralisation. The primary mineralisation is believed to be contemporaneous with the Parys Mountain Volcanics. It is thus Ashgill to Lower Llandovery in age, on the basis of palaeontological evidence and the conformable contact between the volcanics and the Silurian Shales (evidence for which is discussed in the succeeding section). Primary mineralisation can be divided into three types:

1) The Great Lode. This occurs in the contact zone of Parys Mountain Volcanics and Silurian Shales, and is hosted by cherts, slumped breccias of chert and shale, cherty mudstones, and shales. Mineralisation consists of beds and lenses of fine-grained sulphides. If the sources of Greenly (1919) are correct, then it was zoned stratigraphically from a pyrite-rich base through a zone richer in chalcopyrite, to an upper zone of bedded polymetallic bluestone ore.

2) Carreg-y-doll - type Mineralisation. This is associated with siliceous sinter and occurs in several areas, the best development being the Carreg-y-doll Lode itself (fig. 3.18). The mineralisation consists of pyrite + chalcopyrite, with minor galena, though locally galena and sphalerite are abundant, as at Morfa-du. It occurs within the siliceous sinter as dispersed sulphides and as massive lenses, but is commonly richer in intercalations of grey or chloritic shale. Cross-cutting mineralisation is present, particularly at the base

where it grades into a stockwork zone, but the mineralisation generally is in stratiform zones which, though thin (up to 30m. in most cases), are laterally extensive.

3) Stockwork Mineralisation. This occurs within chloritic and silicified Parys Shales, passing up into the base of the Carreg-y-doll Lode horizon. Pyrite and chalcopyrite are present in quartz veins with chlorite selvages; the grade is below 1% Cu.

Secondary Mineralisation. The secondary mineralisation consists of remobilised sulphides in quartz veins with chlorite. These are believed to have been redeposited locally during metamorphism. Chalcopyrite commonly exceeds pyrite (as in the North Discovery Lode). The associated quartz is invariably coarsely crystalline, and the mineralisation is generally in veins which cut the bedding, though some irregular patches of coarsely crystalline quartz and chalcopyrite are also considered to be of secondary origin. The age of this remobilisation is probably late Caledonian, forming during and after the main deformation.

3.6.2. Age and Stratigraphic Contacts of the Parys Mountain Volcanics

The features of the contacts of the volcanics with Parys Shales and Silurian Shales are described in sections 3.3.1, 3.3.2 and 3.3.3 above. The interbedding of chert and shale within a sharp contact zone, and the mixing of chert, shales and sulphides in the slumped breccias in the Great Opencast described in section 3.3.2, are taken to show that the cherts are primary. This conclusion is supported by their appearance in thin-section. If the cherts are primary, then the evidence of interbedding of chert and shale (see section 3.3.3) also indicates that the contact between the Parys Mountain Volcanics and Silurian Shales is conformable. This conclusion is consistent with the occurrence of the thin tuffaceous bands noted in the lower parts of the Silurian Shales.

Greenly (1919) and Wheatley (1971a), however, concluded that the silicification, including the formation of the cherts, post-dates the Silurian Shales, a conclusion disputed by Thanasuthipitak (1974). Greenly (1919) described bedding planes passing from siliceous to non-siliceous mudstones. On the basis of the evidence referred to above, formation of the cherts by post-Llandovery pervasive silicification is rejected, and it is proposed that the Parys Mountain Volcanics - Silurian Shales contact is a normal conformable sequence of chert, cherty mudstones and shales.

Thanasuthipitak (1974) proposed that the base of the Silurian Shales was unconformable, but, although intraformational breccias do occur in this zone, the evidence from the cores of drillholes IM10 and 2 (see section 3.3.3) suggests that the Silurian Shales are conformable with the volcanics.

Palaeontological evidence indicates that the Parys Mountain Volcanics, with a maximum thickness of 200m., overlie Llanvirn strata and are overlain by Llandovery strata. Because of this, it is most probable that there was a period of non-deposition in the sequence. It is proposed that this disconformity, or unconformity, lies at the base of the volcanics for the following reasons. Firstly, the upper contact, discussed above, is apparently conformable. Secondly, the Grey Shales at the top of the Parys Shales show marked variations in thickness along strike (see section 3.3.1). Thirdly, intraformational breccias occur at the base of the Parys Mountain Volcanics on the southern limb of the structure (see figs. 3.3 to 3.7). Whilst this evidence is not conclusive, it indicates the probability of a stratigraphic break at the base of the volcanics. It is therefore concluded that the age of the Parys Mountain Volcanics is Ashgill to Lower Llandovery.

3.6.3. Environment of Volcanism

The host rocks at Parys Mountain have a major proportion of cherty and chloritic rocks, and the criteria for their classification have been described in the text. They have a characteristically extremely fine brownish inclusion-rich quartz, commonly show a regular layering, and have local tuffaceous horizons. The cherts, intimately related to the volcanic rocks, are believed to be the product of siliceous exhalations associated with volcanism, reprecipitated under subaqueous conditions.

The chloritic cherts and shales have similar quartz phases and textural features to those of the cherts. They are considered to be of similar origin, that is, chemically precipitated sedimentary rocks. They differ from the cherts in that their non-silica phase is chlorite, and that it is more abundant than the non-silica phase in the cherts. The optical properties of this chlorite differ from those of the chlorites found in the altered igneous rocks in the sequence, and though recrystallisation has taken place, its intimate relationship to the cherty quartz suggests that it is a primary component.

X-ray diffraction studies on seven specimens of this chlorite show greater relative intensities for the 002 and 004 reflections, and weaker intensities for 001, 003 and 005 reflections, indicating that they are iron-rich in composition (Brindley, 1961). Their diffraction patterns suggest that the chlorites are thuringite, an Fe-Al-rich variety. Results are given in Appendix 2.

Stanton (1976) discussed the association of iron- and aluminium-rich sedimentary units associated with stratiform and related sulphide deposits, and showed that this association is common to deposits in New Brunswick, Japan, Cyprus and Broken Hill, N.S.W. It is believed that the chloritic cherts at Parys Mountain fall into this association and represent chemically precipitated ferruginous cherts (i.e. an iron formation) associated with fumarolic activity during volcanism.

The Siliceous Sinter is associated with the cherty rocks. Occurrences are largely conformable and most have a considerable lateral extent, particularly along strike, though some are only local in development. Its irregular layering is believed to be of colloform origin. The abundant chalcedony-filled voids are of variable shape in the same thin-section, and were presumably of that shape when filled by the chalcedony. The Siliceous Sinter carried irregular veins of an extremely fine-grained silica phase resembling cherty or chalcedonic quartz. This quartz is quite distinct from later coarse quartz in veins, and the brecciated rock is annealed by this early silica phase. These features distinguish it from volcanic lithologies, and from later vein deposits; they are considered to be consistent with an interpretation as a surficial proximal fumarolic deposit.

Spatial relationships of lithologies within the Parys Mountain Volcanics (fig. 3.12) show that rhyolitic flows are restricted to the western end of Parys Mountain where they are associated with a small body of intrusive rhyolite. The nearest recurrence of flows and welded tuffs in outcrop is near Pen-y-sarn village (fig. 3.2), again associated with massive rhyolite. The intervening zone is dominated by cherty sediments, minor shale and an accumulation of volcaniclastics. This last lithology is composed of polymictic rudite and arenite containing clasts of all major lithologies in the Parys Mountain Volcanics, and also siliceous banded sulphides and mineralised shales. It is interpreted as the product of slumping of previously deposited volcanics and sediments from the flanks of one or more small rhyolitic vents.

The distribution of massive rhyolite in northeastern Anglesey is as a series of small plugs (up to 500m. across) occurring in a linear zone, roughly parallel to the 'Carmel Head Thrust'. This is a fault zone considered by Bates (1972) to have been active in the Upper Ordovician, forming the margin of a sedimentary basin. Within the Parys Mountain Volcanics, zones of Siliceous Sinter, and perhaps also the underlying stockwork, have their maximum lateral extent along this trend which, though due in part to metamorphic deformation, probably reflects a primary distribution. These features are believed to indicate a control on volcanism and fumarolic activity by a fault system active in the Upper Ordovician.

3.6.4. Genetic Model

The timing of mineralisation is critical to any discussion of ore genesis. The occurrence of fragments of mineralised rock, siliceous sinter, and siliceous banded sulphides in sedimentary breccias which show a post-depositional S_1 cleavage (section 3.2, plates 16, 17), clearly indicates that a primary phase of mineralisation occurred during the deposition of the Parys Mountain Volcanics. Additional evidence comes from the lenticular layers of massive sulphides in the Siliceous Sinter which are not cross-cutting and show no evidence of being replacements. Sulphides in cherts and shales are also generally parallel to the lithological banding. Remobilisation of sulphides with recrystallised quartz and chlorite can be recognised on the basis of both macroscopic and microscopic features. Both primary and secondary stages are polymetallic (Pointon and Ixer, in press).

The model of ore genesis proposed for the Parys Mountain deposit is as follows:

Volcanic activity in late Ordovician times occurred as a series of small vents along a line parallel and close to one of the marginal fault systems of an Upper Ordovician sedimentary basin (the 'Carmel Head Thrust').

At Parys Mountain, the first products of volcanism were local rhyolitic and dacitic flows adjacent to the vent, and fumarolic activity which gave rise to siliceous exhalite (the Siliceous Sinter) with associated sulphides, and cherty iron formation. As vent activity with proximal flows, flow breccias and small volumes of pyroclastics, reached its maximum, possibly coinciding with the intrusion of a small plug of rhyolite, pyroclastic rocks, cherts, shales and sulphides slumped off the flanks of the vent and accumulated, forming an horizon overlying the early formed sinter and cherty iron formation. Volcanic activity then decreased and slumping became less frequent, but fumarolic activity continued, producing an accumulation of chert, shale, iron formation and massive sulphides in the upper part of the Parys Mountain Volcanics. The cherts and cherty shales at the top of the sequence were overlain, apparently conformably, by Silurian Shales, as volcanic activity in the region died out.

Thus, at Parys Mountain, fumarolic activity preceded, or accompanied, the onset of active volcanism, and continued through to its waning stages. Centres of fumarolic activity varied with time, being represented by bodies of siliceous sinter.

The morphology of the siliceous sinter, and probably also of the underlying stockwork zone, is believed to indicate that the locus of fumarolic activity was controlled by fractures parallel to the line of vents and to the 'Carmel Head Thrust' described above. This implies the action of the same structural control on volcanism, sedimentation and fumarolic activity.

Primary sulphide mineralisation, associated with the early fumarolic activity, was partly destroyed and reworked during the major phase of slumping, but the ensuing return to more stable conditions enabled the series of lenses forming the Great Lode to be deposited. If the sources available to Greenly (1919) are correct, these lenses showed a zoning of ore types from yellow ore to black ore (Kilmacooite type) comparable with that of many volcanic-sedimentary sulphide deposits, including Avoca and the Japanese Kuroko deposits (Ixer and Gaskarth, 1976).

The deposit was folded and sheared in the Caledonian orogeny, during which time remobilisation of quartz, chlorite, chalcopyrite and pyrite, galena, sphalerite, arsenopyrite and carbonate is believed to have occurred. Later cross-faulting caused minor disruption of the structure.

CHAPTER 4

MINERALISATION IN SOUTHEASTERN CANADA

4.1. NEWFOUNDLAND

4.1.1. Introduction

Newfoundland occurs at the northern end of the Appalachian fold belt and contains many known volcanogenic sulphide deposits including those of Buchans, Pilley's Island and Rambler, some features of which are described here. Newfoundland can be considered to be made up of three major geological zones (fig. 4.1) - the Western Platform, the Central Mobile Belt and the Avalon Platform (Williams et al., 1972; Swinden and Strong, 1976). The Western Platform consists of Precambrian (Grenville) basement overlain by klippen of obducted ophiolites and Palaeozoic platform carbonates. The Avalon Platform is formed by rocks lacking Grenville trends which suffered a late Precambrian orogeny (Strong et al., 1977). The mineralisation considered below occurs in the Central Mobile Belt which consists mostly of Lower Palaeozoic rocks, and this zone will therefore be described in more detail.

Strong (1977) identified two volcanic sequences in the Central Mobile Belt, the first being Lower Ordovician (pre-Caradocian) and the second post-Caradocian. The first is submarine, with a chemistry overlapping the tholeiite and calc-alkaline fields, and compositions ranging from basalt through andesite to dacite. It contains thick pyroclastic units, and Strong (1977) considered it to represent an

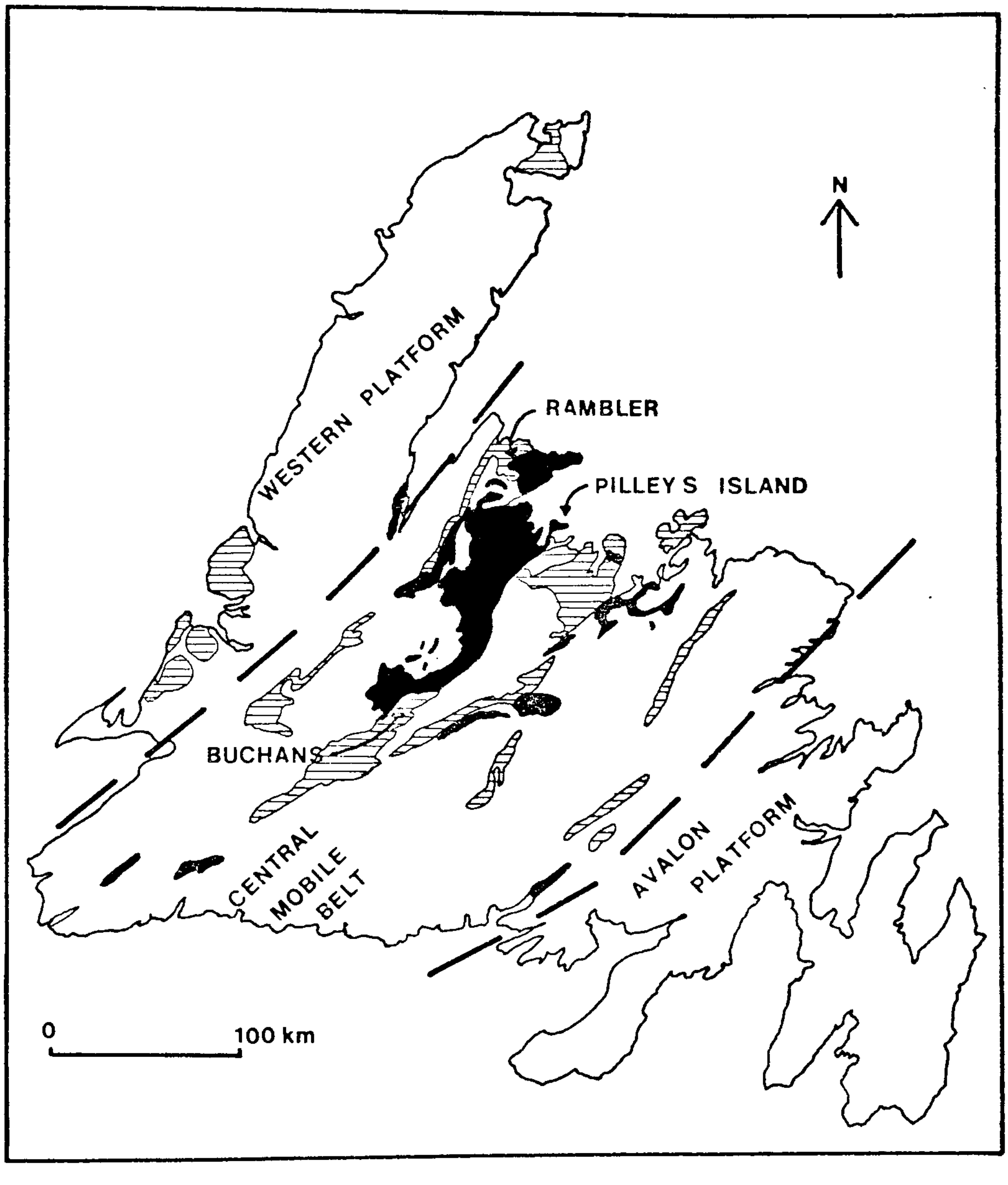


Fig 4 1 NEWFOUNDLAND – Tectonic zones (after Williams et al 1972) ; Lower Palaeozoic volcanics (after Strong 1977)

■ Post Caradoc
▤ Pre Caradoc

early arc sequence. This Lower Ordovician volcanic suite is overlain by a Caradocian black shale unit, locally followed by a thin flysch sequence. Following this sedimentary interval is a bimodal volcanic suite of Silurian age, consisting of basalt and rhyodacite. This unit hosts the Buchans and Pilley's Island mineralisation. It is considered by Strong (1977) to represent late arc, post subduction volcanic activity which was calc-alkaline to alkaline in character.

4.1.2. Buchans

Introduction. The Buchans deposit consists of at least six discrete orebodies within an area approximately 3km. x 2km. Known reserves are now virtually exhausted; the total tonnage mined since 1928 is approximately 16 million tonnes averaging 14.9% Zn, 7.7% Pb, 1.4% Cu, 110g/T Ag and 1.2g/T Au (Thurlow et al., 1975). The most significant feature of the geology is the transported ore. Interpretation of the stratigraphy has changed radically since that of Thurlow et al. (1975) and the following description is largely taken from unpublished data of, and discussion with, Thurlow and Swanson, together with personal observations of outcrop, drillcore and mine plans of ASARCO.

Stratigraphy. The deposits are hosted by the Buchans Group, part of the 'post-arc' volcanics of Strong (1977). The metamorphic grade of the Buchans group is low, and the rocks are not strongly folded, although some major thrusts occur in the area.

The Buchans Group is divided into Upper and Lower Subgroups (figs. 4.2 - 4.4). The lowest member of the Lower Buchans Subgroup is the Footwall Basalt - a thick unit composed of mounds of amygdaloidal basaltic pillow lava with flanking pillow breccias and mafic volcaniclastics; its apparent thickness is 3km. - 8km. but there may be repetition by thrusting.

The Footwall Arkose conformably overlies the Footwall Basalt (fig. 4.2); its thickness apparently varies rapidly with a maximum of 2km. in the eastern part of the area. It consists of poorly sorted, probably reworked, rhyolitic lithic tuff and is massive with little trace of bedding. Rare interbeds of siltstone, chert and conglomerate are present. The composition is of rhyolite fragments, large white quartzes and feldspar set in a fine volcaniclastic matrix.

The Intermediate Footwall lies conformably on, and is in part interbedded with, the Footwall Basalt (fig. 4.2). Away from mineralisation the rocks grade from basaltic at the base to andesitic at the top (J. G. Thurlow, pers. comm.). Near mineralisation the unit consists of silicified, chloritised and sericitised breccias, pyroclastics and flows. In the vicinity of mineralisation this unit rapidly thickens and a strong topography was apparently developed on its surface (fig. 4.4, and Thurlow et al., 1975). Swanson and Thurlow (pers. comm.) conclude that as the volcanics of the Intermediate Footwall were deposited, alteration and mineralisation were continuously

Fig. 4.2 Diagrammatic Section of the Buchans Area

(E. A. Swanson & J. G. Thurlow, unpublished results)

Fig, 4.3 Geological Map of the Buchans Area

(E. A. Swanson & J. G. Thurlow, unpublished results)

Fig. 4.4 Cross-section, Buchans

(E. A. Swanson & J. G. Thurlow, unpublished results)

taking place at shifting loci. The alteration (silicification, chloritisation) is patchy and is associated with the development of volcanic siltstones and lenses of massive pyrite where there were minor breaks in volcanism. The most intense alteration occurs below the ore horizon itself. The alteration zones are roughly conformable and alteration is pervasive with irregular stringers of quartz, sulphide and chlorite rather than fracture related as in a conventional stockwork.

The top of the Intermediate Footwall appears to represent an hiatus in volcanism, and is overlain by the Ore Horizon. Palaeotopographic depressions in the Intermediate Footwall contain beds of volcanic derived siltstone-wacke which contain fractured and subrounded detrital pyrite grains, and have anomalous values of Ba, Cu, Pb, Zn (Thurlow et al., 1975). The ore occurs on the slopes of palaeotopographic highs in the Intermediate Footwall above zones of intense chlorite + silica + sulphide alteration and mineralisation ("in situ ore"), and in palaeotopographic depressions overlying the pyritic siltstone-wackes ("transported ore").

The orebodies are overlain by the Ore Horizon Pyroclastics which consist of rhyodacitic pyroclastics with some few lenses of siltstone. Some massive rhyolites are present near the base and there are several intercalations of andesitic or basaltic flow rocks. The ore horizon is also overlain in part by the Lake Seven Basalt, consisting of pillow lava, breccia, some felsic pyroclastics, and elsewhere by the Upper Arkose which is similar in hand-specimen to the Footwall Arkose but has graded bedding (fig. 4.2). These are believed by Swanson and Thurlow (pers. comm.) to be members of the Upper Buchans Subgroup - essentially a bimodal unit of basaltic and rhyolitic volcanics. The allocation of these rocks to the Upper Buchans Subgroup is based on the existence of the thrust shown in figure 4.2. This is a revision of the cyclical model proposed by Thurlow et al. (1975). The revised model also applies to the Ski Hill Sequence which may be a thrust repetition of the Intermediate Footwall (fig. 4.2). The Prominent Quartz Sequence consists of pumiceous rhyolitic vitric-lithic and reworked tuffs with large white quartz crystals and resembles the Footwall Arkose.

The thrusting mentioned above is not proven but if it exists then Thurlow (pers. comm.) proposes that in figure 4.2 the Prominent Quartz Sequence + Ski Hill Sequence are equivalent to the Footwall Arkose + Intermediate Hangingwall.

Mineralisation. The distribution of the orebodies at Buchans is shown in figures 4.5, 4.6 and 4.7. Ore is divided into "in situ" and "transported" types.

In situ massive sulphide ore overlies footwall mineralisation which may reach ore grade and which consists of disseminated and vein

Fig. 4.5 Alteration and Mineralisation at Buchans

(E. A. Swanson & J. G. Thurlow, unpublished results)

Fig. 4.6 Spatial Relationships of the Buchans Orebodies

(E. A. Swanson & J. G. Thurlow, unpublished results)

stipple = transported ore

solid = in situ ore

Fig. 4.7 Isopach of Oriental - Sandfill - Middle Branch ore horizon (E. A. Swanson & J. G. Thurlow, unpublished results) sulphide in a chlorite and quartz rich altered volcanic host rock (Thurlow et al., 1975). The relative tonnage of footwall ore-grade material is small (about 155,000 tons at approximately 5% Zn, 2.5% Pb and 1.5% Cu - ASARCO data) but the altered zone is more extensive. The massive sulphide ore overlying this footwall zone consists of massive bedded sulphide with barite and quartz gangue. The layering is commonly well preserved as alternations of pyrite and fine-grained sphalerite + galena, with some coarse blebs of recrystallised chalcopyrite, and some tetrahedrite. Vertical zoning is not marked, but chalcopyrite-rich ore occurs as lenses at the base of the sulphide bodies and a capping of barite is developed locally. Brecciation, slumping and the occurrence of pyroclastic blocks with sag structures in the surrounding bedded sulphides were observed at the margins of the bodies of in situ ore (E. A. Swanson, pers. comm.).

Transported sulphide ore does not directly overlie ore-grade footwall mineralisation and may not overlie altered footwall. The ore consists of a breccia composed of clasts up to 1m. across of black and less commonly yellow ore in a matrix of black ore. There is no vertical or lateral zoning. The gangue is mostly barite and grades are similar to those of in situ ore. The host rock of transported ore is a coarse volcanic breccia which consists of sub-angular blocks of all volcanic lithologies and sulphides in a fine volcaniclastic matrix. The blocks are commonly matrix-supported. The ore is overlain in some places by a barite capping, which appears in part to post-date the main sulphide mineralisation, and by a second conglomerate unit containing subrounded blocks of volcanics and some few exotic blocks (mostly granite) in a sparse fine matrix.

The transported ore and its host breccias occur in palaeotopographic trough-like depressions in the Intermediate Footwall surface, above a layer of pyritic siltstone-wacke (Thurlow et al., 1975). These troughs have been defined by detailed drilling (Swanson, pers. comm., and fig. 4.7). Along the axes of the troughs, orebody contacts are gradational with varying proportions of ore clasts in the conglomerate, but laterally cutoffs are very sharp. Both the ore and the host conglomerate are regarded as debris-flow deposits.

4.1.3. Pilley's Island

At Pilley's Island, mineralisation occurs in volcanics which are correlated with the Buchans Group (Strong, 1977). The mineralisation has several similarities to that at Buchans, notably the occurrence of in situ massive sulphide above an altered footwall, and also of transported ore associated with breccias.

The host volcanics (the Roberts Arm Group - Strong, 1977) consist of a lower basaltic sequence of pillow lavas, overlain by felsic volcanics. The latter are rhyodacitic comprising an interlayered pile of flows and pyroclastics. Lenses of massive sulphide occur in this upper unit. They are overlain by a dacitic lithic breccia - a heterogeneous assemblage of subrounded to angular clasts of variably altered dacite with a small percentage of massive sulphide fragments in a fine siliceous groundmass with disseminated sulphides. The uppermost part of the Roberts Arm Group is a local laharic horizon.

Massive sulphides are known in three showings in the local area. One supported a small mining operation in the past, but there is no current production. The largest showing (the Old or Main Mine) consists of a lens of massive sulphide overlying a locally developed stockwork zone. The stockwork consists of quartz-pyrite veins in a quartz + chlorite + sericite altered massive felsic volcanic. The stockwork passes laterally into very fine grained silicified chloritic pyritic rhyolite - probably a plug - with some few sulphide + quartz veins, and massive dacite.

Two other small showings of mineralisation occur in the immediate area. The first, the Henderson showing, occurs in dacitic breccias near the top of the felsic volcanic sequence. It consists of a breccia with subrounded to subangular blocks of massive sulphide (mostly pyrite with some chalcopyrite and sphalerite with a siliceous gangue); and angular blocks of fine grained silicified rhyolite or dacite, in a fine silty matrix which is pyritic. The sulphide clasts range from 1mm. to 20cm. in diameter. The sulphide bearing breccia overlies unaltered volcanic breccia and a sequence of dacitic flows and small plugs of glassy rhyolite, comprising the felsic volcanics of the Roberts Arm Group. The Henderson showing bears a strong resemblance to the transported ore at Buchans.

The second minor showing, the Bull Road showing, is also hosted by breccias. The ore is of higher grade, consisting of one or more lenses of fine-grained sphalerite, pyrite, chalcopyrite and galena with little gangue. Sulphide fragments occur within a poorly sorted, dacitic lithic breccia, which shows some chloritisation and sericitisation. The alteration is not intense although there is local, patchy, pervasive silicification and development of quartz + sulphide veinlets. Some exposures of ore are finely layered and show little evidence of disruption, but blocks of banded ore in a sulphide matrix are also present.

The mineralisation at Pilley's Island, though of small scale, shows similarities to the environment for the Buchans mineralisation proposed by Swanson and Thurlow as described in the preceding section. Lenses of massive sulphides, some showing evidence of disruption in the sedimentary environment, overlie altered and weakly mineralised volcanics, and a brief field investigation suggests these may be adjacent to a plug of rhyolite which is itself altered and contains some stockwork mineralisation. Sulphide-rich debris flows occur a short distance away from this "in situ" mineralisation, underlain by unaltered, unmineralised volcanics. In both cases, mineralisation is associated with local centres of felsic volcanism developed above a sequence of basaltic pillow lavas.

4.1.4. Rambler

The Rambler deposit, near Baie Verte in north central Newfoundland, was described by Tuach and Kennedy (1978). This brief account follows that of Tuach and Kennedy and includes information provided in discussion by M. J. Collins and R. Norman, together with personal observation. The mineralisation occurs within volcanics of the Pacquet Harbour Group which have been tentatively correlated with the Caradocian early arc sequence although this correlation is uncertain because of the lack of detailed information (Strong, 1977). The Pacquet Harbour Group consists of a lower mafic sequence of pillow lavas and volcaniclastics and an upper unit of mixed mafic volcaniclastics and local felsic pyroclastics and plugs. The uppermost part of the sequence is largely epiclastic, composed of reworked volcanic material. The mineralisation is related to a local centre of acid volcanism, whose products are largely coarse dacitic breccias and lithic pumiceous tuffs.

In the immediate mine area, some finer tuffs occur. The footwall, for at least 30m. below the horizon of the Ming orebody, consists of chlorite, sericite and pyrite - altered tuffs which commonly show a

Fig 4.8 Simplified Geological Map — Rambler Area after Tuach and Kennedy 1978 well developed augen fabric resembling the 'pseudo imbrication' in the Avoca and Parys Mountain footwalls.

The mineralisation at Rambler occurs in several orebodies whose original relationships have not yet been established. Current production is from the Ming orebody, which consists, in the upper levels of the mine, of three horizons of massive sulphide separated by quartz sericite schist (Tuach and Kennedy, 1978). The upper two horizons are layered and consist mostly of pyrrhotite. The lowest horizon is of higher grade and has a breccia fabric with pyrite and pyrrhotite blocks in a matrix of chalcopyrite. This fabric is believed to be the result of recrystallisation of the chalcopyrite during metamorphism rather than a debris flow, and it is not polymictic. Down dip the lenses merge and this breccia ore type becomes dominant to give a body 10m. thick grading 8% Cu and 2% Zn overlain by a layer of lower grade bedded sulphides grading 2% Cu, which is variable in thickness and which locally is absent.

The immediate footwall of the Ming orebody in the upper levels of the mine is a sericitic schist (? altered fine tuff) several metres thick, which is underlain by a chlorite-altered zone. At depth the sericite horizon dies out and the ore rests directly on a chloritic footwall with dispersed sulphide. The lateral equivalent of sulphide ore along strike is a chert horizon.

The main Rambler deposit (fig. 4.8) was a small lens of lower grade massive sulphide, now mined out (Tuach and Kennedy, 1978). The East Mine consisted of 2.1 million tonnes grading 1.04% Cu (Tuach and Kennedy, 1978) in a disseminated, stratabound body consisting of pyrrhotite, pyrite and chalcopyrite in a quartz chlorite schist zone up to 35m. thick. The ore consisted of sulphide lenses and veinlets dominated by pyrite; chalcopyrite was recrystallised and remobilised, occurring mostly as patches and veinlets. The East Mine contained no extensive massive sulphide bodies (Tuach and Kennedy, 1978); its broadly conformable morphology described on mine plans, and its appearance in drillcore, has strong similarities with the Cronebane Member in the footwall at Avoca, but no bedded sulphides have been found stratigraphically overlying it.

Examination of some drillcores from the Ming orebody area showed that carbonate nodules similar to those at Avoca and Parys Mountain are present, but no information is available on their spatial relationship to ore.

4.2. BATHURST, NEW BRUNSWICK

4.2.1. Introduction

In the Bathurst area the oldest rocks are the (?) Lower Ordovician Tetagouche Group, comprising sedimentary and volcanic rocks deformed in the Middle - Upper Ordovician Taconian Orogeny. They are unconformably overlain by Silurian sediments and a bimodal Siluro-Devonian basalt-rhyolite volcanic suite. The Tetagouche Group contains several major volcanogenic sedimentary sulphide orebodies, some of which are described below. An outline of the geology and the location of the deposits considered here are shown in figure 4.9.

The stratigraphy of the Tetagouche Group has been described and discussed by several authors, including Smith and Skinner (1958), McAllister (1960), Davies (1972a) and Whitehead and Goodfellow (1978), and there has been some controversy as to the sequence. The results of recent mapping (Davies, 1977) show the sequence to be:

1. Metasediments. Argillites with areanceous interbeds, commonly laminated and probably representing a turbidite sequence, having a gradational contact with the overlying Felsic Volcanics.

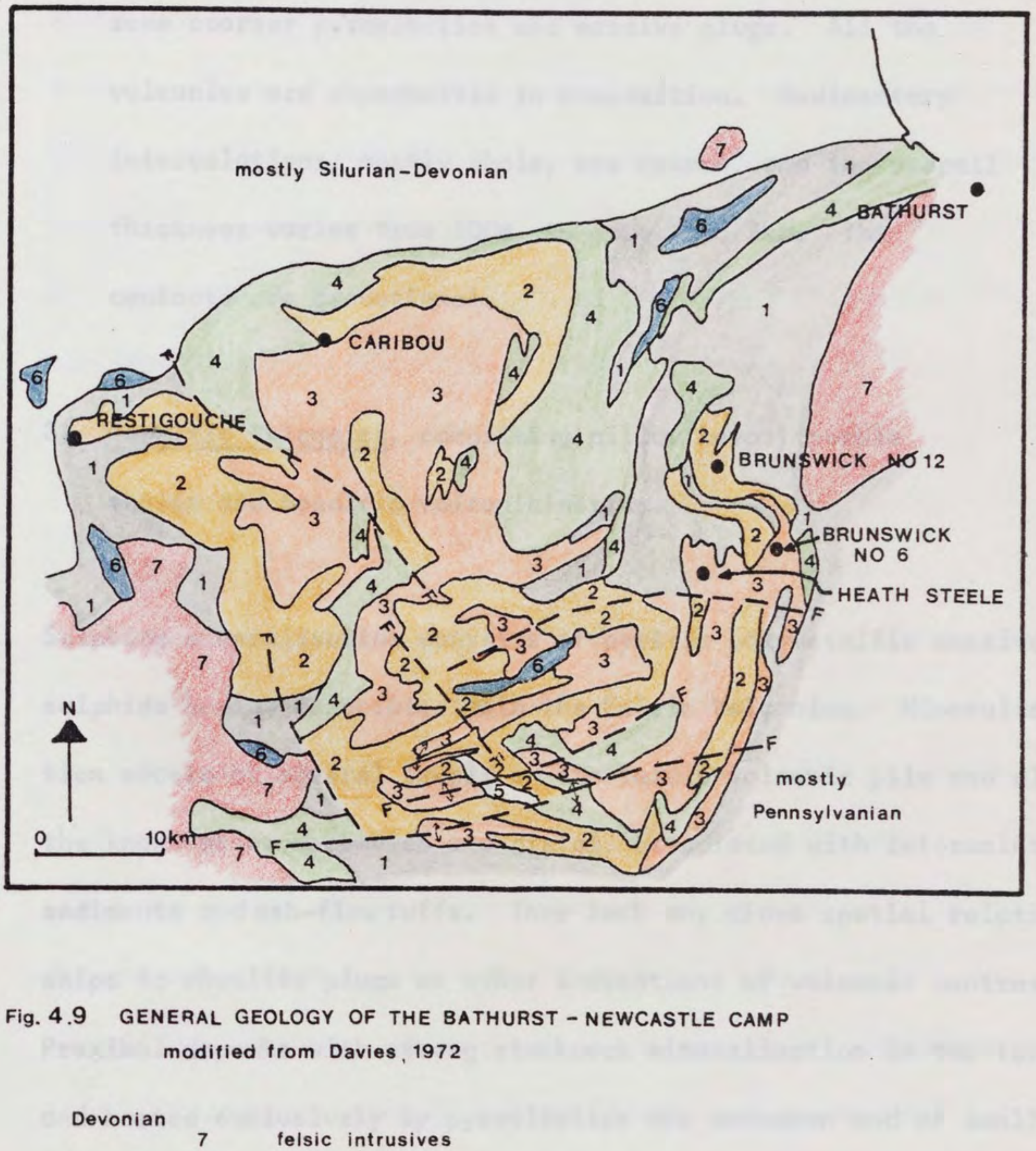


Fig. 4.9 GENERAL GEOLOGY OF THE BATHURST – NEWCASTLE CAMP
modified from Davies, 1972

Devonian		
	7	felsic intrusives
	6	mafic intrusives
	5	cataclastic intrusive rocks
Ordovician		
	4	mafic metavolcanics
	3	felsic metavolcanics
	2	augen schist
	1	metasediments

2. Felsic Volcanics, consisting predominantly of ash-flow tuffs, mostly feldspar and quartz crystal tuffs, with some coarser pyroclastics and massive plugs. All the volcanics are rhyodacitic in composition. Sedimentary intercalations, mostly shale, are common, and the overall thickness varies from 100m. to more than 1km. The contacts are gradational.

3. Basaltic Volcanics, comprising pillow lavas, purple shales and basaltic volcaniclastics.

Sulphide mineralisation consists of pyritic polymetallic massive sulphide bodies associated with the Felsic Volcanics. Mineralisation occurs at several levels in the felsic volcanic pile and all the known major orebodies are distal, associated with intercalated sediments and ash-flow tuffs. They lack any close spatial relationships to rhyolite plugs or other indications of volcanic centres. Proximal deposits with strong stockwork mineralisation in the footwall and hosted exclusively by pyroclastics are uncommon and of small size but are known in the area (the Restigouche deposit is an example).

The distal massive sulphides, though lacking extensive footwall stockwork mineralisation, have a more or less well defined, chlorite-bearing, altered footwall which contains minor quantities of sulphide.

Locally they may have crosscutting stockwork zones which are small in comparison with the volume and lateral extent of the massive sulphide. The massive sulphides are conformable, bedded, generally contain 10% or less of quartz and chlorite gangue, and tend to be zoned stratigraphically from Cu-rich at the base to Pb+Zn-rich at the top. Lateral zoning may also be present (Lusk, 1969). Tonnages of individual bodies vary from a few thousand to more than 100 million tonnes.

4.2.2. Brunswick No. 12 Mine

The mineralisation occurs within a sequence of interbedded argillites and ash-flow tuffs - mostly quartz and feldspar crystal tuffs. The immediate footwall ('Footwall Metasediments') is predominantly a green argillite commonly strongly chloritic and locally siliceous (Luff, 1977). Iron Formation is present as a capping and lateral equivalent of ore. It consists of laminated chlorite and magnetite with traces of sulphide in places, or of a carbonate facies of interlaminated siderite-chlorite and magnetite. Laminated pyritic chert is also present. The Iron Formation is locally slumped with fragmentation to give debris flowbreccias (Luff, 1977). Above the ore horizon, the sequence consists of argillite with local horizons of lithic and crystal tuffs and associated volcanic breccia, followed by further tuffs of the Felsic Volcanics.

The massive sulphide consists of fine-grained pyrite, sphalerite, galena, chalcopyrite, pyrrhotite and minor tetrahedrite. The gangue, 10% - 20% of the total, is quartz, carbonate and chlorite. Published reserves are 98 million tonnes grading 9.22% Zn, 3.79% Pb, 0.30% Cu and 80g/T Ag (Luff, 1977). Structural deformation of the orebody is intense and complex (Luff, 1977), and in some areas (the ' West Zone'), recrystallisation and remobilisation effects are pronounced. In the 'Main Zone' these effects are weaker and primary features of the ore zone can be distinguished. Vertical zonation of the ore is indicated by a Cu-rich zone at the base, overlain by a zone up to 20m. thick richer in sphalerite and galena. This is followed by a low grade zone, some 10m. - 15m. thick, of essentially massive pyrite, grading below 6% (Zn + Pb). Above this is a second 20m. thick horizon of lead-zinc ore, grading 13% (Zn + Pb). Locally this sulphide sequence is capped by a zone of layered pyrite with some colloform textures.

Extensive stockwork mineralisation is not present in the footwall. A local development of cross-cutting veins of chalcopyrite and pyrrhotite occurs at the south end of the Main Zone, but it is limited in extent and may not be primary. Elsewhere the chloritic footwall contains beds, lenses and disseminations of pyrite patchily developed from a few metres to tens of metres into the footwall.

4.2.3. Brunswick No. 6 Mine

This deposit lies some 10km. along strike from the No. 12 deposit and is in the same stratigraphic horizon (fig. 4.9). As at the No. 12 deposit, structural deformation is intense and complex. A similar stratigraphic zoning occurs in the massive sulphide, with enrichment of copper towards the base, while the main part of the massive sulphide consists of pyrite, sphalerite, galena and chalcopyrite, generally finely layered and delicately folded. The footwall is chlorite schist and tuff with disseminations and lenses of pyrite, pyrrhotite and chalcopyrite, the latter up to 3m. thick. The width of this footwall zone varies from 3m. to 60m., and it contains no strongly cross-cutting features. As at No. 12, the ore is generally overlain by iron formation, composed of magnetite and chlorite, and is commonly well banded. At the stratigraphic top of the iron formation a continuous bedded pyrite horizon occurs, varying in thickness from 1cm. to more than 3m. (McAllister, 1960; McAllister and Lamarch, 1972).

4.2.4. Heath Steele Mines

The mineralisation at Heath Steele lies, like the Brunswick No. 12 ore zone, within the Felsic Volcanics of the Tetagouche Group, probably towards their base, in a mixed tuff and argillite sequence. The stratigraphy is similar to that at Brunswick No. 12, and the structure equally complex. The deposit consists of several steeply plunging lenses of massive sulphide.

The footwall at Heath Steele consists of 'Chlorite Tuff' - a thick unit of chloritic argillite with interbeds of a chloritic quartz-crystal tuff. No massive volcanic lithologies are known in the footwall (W. Gates, pers. comm.). Quartz and quartz-feldspar crystal tuffs form the hangingwall, and pass upward into the main part of the Felsic Volcanics consisting mostly of crystal-lithic rhyolitic tuffs.

All the sulphide bodies at Heath Steele (at least four are known) lie in the same horizon (Archibald, 1971), but this can only be defined imprecisely (to within 50m. or so) where ore is absent. The massive sulphides have a sparse gangue of chlorite and quartz, and lensy developments of commonly finely layered magnetite, chlorite and pyrite iron formation occur above, below and within the massive sulphide (Archibald, 1971).

The footwall Chlorite Tuff contains low grade mineralisation consisting of chalcopyrite as sparse blebs and veinlets, and beds and lenses of pyrite. There is a sharp increase in sulphide content (from $\leqslant 10\%$ to $> 75\%$) at the footwall contact of the orebodies. The massive sulphide of the 'B-Zone' consists of a lower zone of coarsely crystalline pyrite, pyrrhotite and chalcopyrite with minor chlorite and some intercalations of fine sericitic tuff. This lower part of the orebody is massive and layering is uncommon. The stratigraphically higher parts of the orebody consist of commonly finely layered pyrite with ruby sphalerite, minor galena and a little chalcopyrite, and contain intercalations of iron formation.

The massive sulphides are stratiform and commonly bedded. Current mining is in the 'B-Zone'; previous mining and additional reserves occur in three further zones about 1km. along strike. Within each sulphide body there is a vertical upwards zonation from copper to lead and zinc enrichment. Lateral zoning of metal values also occurs, and has been related to variations in alteration and mineralisation in the footwall to suggest the direction of the source of mineralisation (Lusk, 1969). The average grade of the massive sulphide in the 'B-Zone' is 1.55% Pb, 4.24% Zn, 1.17% Cu and 53g/T Ag.

4.2.5. Caribou Mine

This deposit is in the north of the Bathurst district (fig. 4.9). No primary ore has been worked although a secondary enrichment zone up to 30m. thick was mined as a small open pit. This zone averaged 3% Cu as chalcocite and covellite (A. Buzas, pers. comm.). The geology of the deposit was described by Cavalero (1970, 1972) and Roscoe (1971).

The mineralisation at Caribou occurs toward the top of the Felsic Volcanics of the Tetagouche Group (J. L. Davies, pers. comm.). The host sequence consists of acid volcaniclastics, ash-flow tuffs and sediments, passing upwards into pillow lavas, basic volcaniclastics and shales of the 'Basalitic Volcanics'. It has been folded into a syncline (Cavalero, 1972).

The footwall consists of a grey sericitic phyllite and chlorite schist (Cavalero, 1972) with up to 10% pyrite disseminated and in lenses, but generally no base metal sulphides (A. Buzas, pers. comm.). This is underlain by graphitic argillite, and no clear tuffaceous rocks are encountered until some 30m. stratigraphically below the ore horizon. The sulphides occur as several en-echelon lenses with phyllite layers between them, and are finely layered in the upper parts of the ore horizon.

The sulphides consist mainly of pyrite with sphalerite, galena and chalcopyrite. Roscoe (1971) described zoning with chalcopyrite enrichment in the footwall, and sphalerite and galena in the hangingwall. The hangingwall contact is sharp, with sulphides overlain by felsic lithic and crystal tuffs (Roscoe, 1971).

CHAPTER 5

FEATURES OF COMPARISON BETWEEN THE THREE AREAS

5.1. INTRODUCTION

The mineralisation at Avoca and Parys Mountain, and the deposits in the Newfoundland and Bathurst areas of SE Canada, can be compared on the basis of a number of generalised features. These include the tectonic setting and type of volcanism associated with the mineralisation, and more detailed aspects of the deposits such as alteration and the nature and distribution of the sulphide minerals. Detailed genetic models have been derived for the mineralisation at Parys Mountain and Avoca in previous chapters, and the intimate temporal, stratigraphic and genetic relationship between sulphide mineralisation and volcanism has been established. The work of Thurlow et al. (1975) at Buchans, Tuach and Kennedy (1978) at Rambler, and Stanton (1959) and McAllister (1960) at Bathurst has also established the volcanic-sedimentary origin of these deposits.

5.2. TECTONIC SETTING

5.2.1. Paratectonic Caledonides of the British Isles

The Parys Mountain and Avoca deposits both formed in an ensialic setting in the paratectonic Caledonides near a continental margin where plate movement was largely transcurrent and the tectonics were dominated by a wrench component (Dewey, 1969a). Volcanism and sedimentation were controlled by temporally persistent linear structures throughout the Lower Palaeozoic.

In SE Ireland this control began in the Lower Cambrian with the development of an elongate trough bounded to the east by a major horst - the Irish Sea Landmass. The control persisted through Ordovician times when the location of fault-bounded depositional basins (Phillips et al., 1976) and volcanic centres were apparently related to basement structures, and through later Caledonian time when intrusive activity and tectonism followed similar linear controls. Dewey (1969a) showed that the structure was consistent with a predominantly wrench strain.

Similar controls by basement faults can be demonstrated in Anglesey, which lay on the eastern flank of the Irish Sea Landmass. In both Anglesey and SE Ireland the volcanics with which mineralisation is associated occur as a series of isolated centres located along linear zones which reflect this basement structural control.

5.2.2. The Bathurst Area

In the Bathurst area the oldest rocks exposed are those of the Tetagouche Group, and the nature of the crust underlying the Ordovician volcanics is not certain. The volcanics are older than those associated with the Avoca and Parys Mountain mineralisation, being of Lower Ordovician age, and were deformed in the Middle Ordovician Taconian orogeny.

The tectonic environment differed from that of the paratectonic Caledonides of the British Isles in that volcanism and sedimentation were not subject to linear controls. Furthermore, subsequent deformation occurred in two orogenic episodes (Taconian - Middle Ordovician, and Acadian - Devonian) and involved the development of large scale recumbent folds. This is similar to the orthotectonic zone in the British Isles, and indicates the presence of a stronger component of normal plate motion during orogeny in this part of the Caledonian-Appalachian belt. The tectonic environment during volcanism in the Tetagouche Group is not yet clear (Dr. J. L. Davies, pers. comm.).

5.2.3. Newfoundland

In Newfoundland, Swinden and Strong (1976) and Strong (1977) related earlier pre-Caradocian volcanism directly to subduction during closure of the Iapetus ocean. They refer these volcanics to an ensimatic early arc environment. This volcanic episode ended with obduction of ophiolitic rocks westward onto the Grenville basement of the Western Platform, and the deposition of a Caradocian black shale unit and flysch sediments in central Newfoundland.

The Rambler deposits are associated with this pre-Caradocian volcanism, but their precise tectonic setting is not clear. Swinden and Strong (1976) discussed two interpretations for the Rambler area: firstly, that the volcanics hosting the Rambler deposits are a normal calc-alkaline suite generated directly by subduction; secondly, that the acid volcanics at Rambler represent a local modification of this suite by a period of rifting, because of the bimodal basalt-rhyolite association and the lack of andesites in the area as described by Tuach and Kennedy, (1978).

The post-Caradocian volcanics of Newfoundland are regarded by Strong (1977) as having been erupted in a post-subduction island arc environment. Their chemistry is calc-alkaline to alkaline and they show a tendency to bimodality between basaltic and rhyodacitic compositions (Strong, 1977). The Buchans deposit is hosted by this late arc sequence.

5.2.4. Comparison of Tectonic Settings

The occurrence of Avoca and Parys Mountain near a continental margin which was subject to mainly transcurrent stress suggests that a tectonic regime which did not involve strong compression, and may have involved local tensional zones, proved favourable for development of volcanogenic-sedimentary mineralisation. Whether similar conditions existed in the northern Appalachians at the time of mineralisation is not certain. It is possible that the Rambler deposit was associated with a brief period of rifting, and this is also possible in the case of Buchans where the volcanics post-date the main subduction-related events.

The nature of the crust underlying the volcanics with which mineralisation is associated is apparently not a critical factor. In the case of Avoca and Parys Mountain, it was sialic crust, but Rambler was formed in an ensimatic arc. For Buchans, which formed in a post-subduction late arc setting, the underlying crust was intermediate between these two. At Bathurst the nature of the pre-Lower Palaeozoic basement is not certain but may have been sialic crust.

5.3. VOLCANISM

5.3.1. Paratectonic Caledonides of the British Isles

At both Parys Mountain and Avoca the volcanism associated with mineralisation was the first major volcanic event in the Lower Palaeozoic at that site. The volcanics at Avoca overlie a substantial thickness of Lower Palaeozoic sediments, whilst at Parys Mountain they are close to the underlying sialic basement.

The volcanics associated with mineralisation represent a single volcanic episode and consist of a limited volume of predominantly pyroclastic material. Their composition is rhyodacitic; it is unimodal, and basaltic volcanics do not occur at either locality, although minor outcrops of basic-intermediate post-volcanic intrusions are present in both areas. At Parys Mountain the maximum thickness of the volcanics is some 200m. and at Avoca it is around 1km.

5.3.2. Canadian Appalachians

In SE Canada the volcanism was more extensive and complex. In the Bathurst area the acid volcanics of the Tetagouche Group are of rhyodacitic composition and consist of crystal tuffs, in part ash-flows, and intercalated sediments. They are now believed to be the earliest volcanic rocks in the observed stratigraphy, although the base of the Group is not seen. They vary from 100m. to more than 1km. in thickness (Dr. J. L. Davies, pers. comm.).

In Newfoundland mineralisation in both pre- and post-Caradocian volcanic suites is related to small centres of acid volcanics, consisting largely of pyroclastics, overlying a thick accumulation of basaltic pillow lavas. The pre-Caradocian volcanics are reported by Strong (1977) to grade from basalt through andesite to rhyolite, although in the vicinity of the Rambler deposits andesites are absent.

The post-Caradocian volcanics are generally of bimodal basaltic-rhyolitic composition (Strong, 1977).

5.3.3. Discussion

Although unimodal suites of acid volcanics are associated with mineralisation in the paratectonic Caledonides of the British Isles and are found also in the Bathurst area, in the Buchans and Rambler areas the volcanics are bimodal. The volcanics with which Rambler is associated show a normal range of compositions from basalt to rhyolite when considered on a regional scale.

The general conclusion to be drawn is that mineralisation is associated with a discrete pulse of acid magmatism which in some instances followed extensive basaltic volcanism but in others had no preceding extrusive volcanic phase. The major features common to all deposits are their association with a single event of rhyodacitic volcanism, the general relative scarcity of andesites, and the predominance of pyroclastic lithologies.

5.4. HOST ROCKS

The host rocks of mineralisation consist of acid volcanics and associated sediments. The volcanics are predominantly pyroclastic for all the deposits studied. They consist of ash-flow tuffs, tuffs and lapilli-tuffs which in all cases, except for the more distal deposits at Bathurst, are closely related to a centre indicated by the occurrence of tuff-breccias (the "mill-rock" of Sangster, 1972) and massive rhyolite as flows or small high-level plugs. The pyroclastics are generally altered, and this is discussed in a succeeding section. The pyroclastics grade, away from the centre, into tuffaceous sediments, a feature well displayed at Avoca.

Sediments also occur intercalated with the volcanics and are best developed stratigraphically close to the ore horizon. These sediments consist of chert and various facies of iron formation, and are considered to be of exhalative origin. The common association of iron formation with stratiform base metal mineralisation was noted by Stanton (1976), and the association of iron formation with bedded sulphides at Bathurst was described by Stanton (1959), McAllister (1960) and Davies (1972b). No distinct iron formation has been recorded at Buchans or Rambler.

The cherts are best developed at Parys Mountain where they make up a significant proportion of the volcanic sequence. They also occur at Avoca and at Rambler. They are less common in the deposits examined in the Bathurst area where there appears to be less silica associated with minerlisation generally. Cherts are not recorded at Buchans.

The iron formation is developed as sulphide, oxide, silicate and carbonate facies; in some cases the facies are discrete, but commonly they are interbedded with one another. Sulphide iron formation is, by definition, present in all these exhalative-sedimentary sulphide deposits, and consists of bedded pyrite with associated chlorite, quartz and base metal sulphides.

Silicate facies iron formation in these deposits consists largely of iron-rich chlorite with variable amounts of quartz. At Avoca the iron-rich nature of the chlorite was demonstrated by Wheatley (1971a) and the chlorites determined in the present study from Parys Mountain are similar (see Appendix 2). They are comparable with thuringite. At both Parys Mountain and Avoca the chlorite is the host for, and the lateral equivalent of, bedded sulphides. Wheatley (1971a) recorded an associated phosphatic horizon at Avoca which might be compared with, for example, the Banded Iron Formation at Broken Hill described by Stanton (1976). Chloritic rocks are developed near the ore horizon at Rambler, and the lateral equivalents of ore are cherts and chloritic pyroclastics. However, no detailed studies have been undertaken and the rocks have not been positively identified as iron formation.

Iron carbonate occurs interbedded with chlorite, magnetite and pyrite in iron formation overlying the Heath Steele, Brunswick No. 12 and Brunswick No. 6 orebodies. Extensive development of carbonate is not recorded from Buchans (where, however, barite commonly overlies the sulphide ores), but at Rambler drillcores showed dispersed carbonate nodules in chlorite schist and pyroclastics near the ore horizon. At Avoca, carbonate, mostly ferroan dolomite, is found in horizons immediately overlying bedded sulphides at West Avoca. The most common habit is as replacive nodules, but beds of coarsely crystalline carbonate also occur. At Parys Mountain, discrete beds of carbonate have not been recorded, but nodules and veins of siderite are common, and visual inspection of drillcores indicates that the carbonate has a mutually exclusive distribution with respect to sulphide.

Oxide iron formation, in the form of magnetite, is common in the Bathurst area (Stanton, 1959 ; McAllister, 1960; Davies, 1972b) where it is intimately associated with chlorite, sulphide and carbonate. At Avoca little magnetite is seen in the mine area but, to the southwest, stratiform bodies of magnetite occur at Ballycoog and Moneyteige; they contain a little chalcopyrite and lie within a chlorite schist host rock.

In all the deposits studied, with the possible exception of Buchans, iron formation is intimately associated with sulphides. It consists of silicate, oxide and carbonate facies which are in many cases interbedded, and in others intimately mixed as a chlorite mudrock with lenses, nodules or scattered grains of carbonate, magnetite and sulphide.

5.5. SLUMPING

Slumping with associated debris flows occurs in and near the ore horizon at Parys Mountain, at Avoca (Badham, 1978) and at Buchans (Thurlow et al., 1975). No extensive slumping has been recorded from the Brunswick No. 6 and No. 12 and Heath Steele deposits. At Caribou and Rambler, no slumping has been recorded, but less detailed information is available for these deposits.

With the exception of Rambler, the deposits which lack significant slumping are distal with respect to volcanic centres. The slumping reflects slope instabilites in unconsolidated sediments and pyroclastics in active volcanic terrain. The observed mixing of pyrite + chalcopyrite "yellow ore" and polymetallic "black ore" in debris flows shows that the observed mineral parageneses for such deposits (e.g. for Avoca by Wheatley, 1971a), which show early pyrite replaced by later base metal sulphides, were completed within a very short time, because the distinct ore types form angular clasts in penecontemporaneous debris flows.

Sulphides when slumped and redeposited are not necessarily dispersed but can remain as bodies with economic metal grades. Swanson (pers. comm.) has shown that at Buchans isopach maps of the ore horizon reveal that transported ore is confined within well defined channels in the surface of the footwall rocks (see fig. 4.7).

5.6. SULPHIDE MINERALISATION

At Avoca and Parys Mountain mineralisation occurred throughout the period of maximum volcanic activity. This is well shown at Parys Mountain where fumarolic exhalations and sulphide sedimentation accompanied the onset of volcanism and persisted through until its waning stages. At Avoca traces of bedded mineralisation are found some tens of metres below the main ore horizon in the stratigraphic footwall, but significant accumulations of bedded sulphide were built up only when pyroclastic activity subsided.

In Bathurst a similar feature occurs in that ore is developed at more than one horizon in the camp but its accumulations are associated with a pause in volcanism during which time sulphides and iron formation were not diluted by simultaneous pyroclastic activity. At Brunswick No. 6, beds of pyrite from 10mm. to 3m. thick occur in the footwall of the massive sulphide in a zone varying from 3m. to 60m. thick (E. Brooks, pers. comm.).

At Rambler, the East Mine, described by Tuach and Kennedy (1978), may represent a "diluted" sedimentary sulphide deposit. It consists of a stratiform zone of pyroclastics and chloritic schists containing beds, lenses and veinlets of pyrite, pyrrhotite and chalcopyrite. The zone is up to 35m. thick and yielded 2.1 million tonnes of ore at 1.04% Cu. The footwall zone at Avoca is considered to have a similar origin. In contrast, the Ming orebody at Rambler is thought to represent a discrete period of sulphide deposition uninterrupted by additions of volcanic material.

True stockwork mineralised zones are less common. Where they are present, for example at Parys Mountain and in the Cronebane area at Avoca, they are relatively small compared with the extent of the overlying bedded mineralisation.

The bedded sulphides of these deposits commonly show some stratigraphic zoning of base metal contents. Most, for example Buchans, Avoca and Heath Steele, show the typical zonation from copper-rich at the base to polymetallic at the stratigraphic top, as described for the Kuroko deposits of Japan by Tatsumi and Watanabe (1971). In other deposits, such as Brunswick No. 12 and Parys Mountain, the zoning is less regular. At Brunswick No. 12 two zones of richer lead + zinc mineralisation are separated by a central layer of essentially massive pyrite. At Parys Mountain copper-pyrite and polymetallic zones occur as lenses in both the upper and lower mineralised horizons, although the old plans studied by Greenly (1919) suggested that the upper ore horizon was zoned from copper through to lead + zinc rich ore.

5.7. ALTERATION

Alteration characterised by the development of quartz, chlorite and sericite was described in Chapter 2 as being characteristic of the pyroclastics immediately underlying ore. The altered rock type has a regular augen fabric, with an undulating lensy cleavage separated by augen of siliceous material. Some of these augen develop into true "quartz-eyes", and others remain as quartz + chlorite intergrowths.

Petrographic studies show that this fabric is developed by a modification of the original pyroclasts, which are in some cases recrystallised, and in others overgrown by quartz to form the siliceous augen. Augen are produced from single clasts or aggregates of original fragments. The augen also form by recrystallisation of quartz in the matrix in places where original fragments are not present so that a regular undulating cleavage fabric is formed.

The fabric, referred to in Chapter 2 as "pseudo-imbrication", probably results from the passage of large volumes of hot aqueous fluid through unconsolidated pyroclastics; pumice and glass fragments would be destroyed, being altered to clays, and silica, iron and alumina would be mobilised. The subsequent imposition of a cleavage on these altered rocks would lead to the development of the characteristic regular fabric.

This fabric is well developed in the footwall zones of the deposits at Rambler, Buchans, Avoca and Parys Mountain. These deposits are more proximal, relative to volcanic centres, than those studied in the Bathurst area where in the more distal deposits, such as Heath Steele and Brunswick No. 6 and No. 12, it is present only locally.

CHAPTER 6

SUMMARY OF CONCLUSIONS

The main features of the deposits considered in this study are presented below in a tabulated form. All the deposits considered have an intimate relationship with their volcanic host rocks, and have been shown to be of volcanogenic exhalative-sedimentary origin.

For the deposits considered in the paratectonic Caledonides of the British Isles and SE Canada it is concluded that sulphide mineralisation can be associated with any small discrete pulse of acid magmatism developed in shallow subaqueous conditions. The nature of the underlying basement, whether sialic, simatic or intermediate, is not a critical factor, neither is the general tectonic environment, although it is suggested that the establishment of a local tensional regime at the time of ore formation is important.

The size of the deposits varies widely from small (less than 1×10^6 T) sub-economic bodies to those of more than 100 million tonnes. Grades vary from less than 1% (Cu+Pb+Zn) to in excess of 20% base metals.

The volcanics with which mineralisation is associated are rhyodacitic, largely pyroclastic, and are generally related to a small centre. In the deposits formed in an ensialic environment, basement structure appears to control the location of these centres. The volcanics represent a single episode of volcanism which is either unimodal

	AVOCA	PARYS MOUNTAIN	BUCHANS	RAMBLER	BATHURST
Tectonic Setting	Continental margin, transcurrent stress, local tension ?	Continental margin, transcurrent stress, local tension ?	Post active subduction; possibly tensional	Subduction, possibly local tension	Continental margin
Underlying Basement	Sialic (metamorphic + sediments)	Sialic (metamorphics)	Island arc	Simatic	? Sialic
Size (approximate) & Grade	Historical production: 15 million tonnes at 1.2% Cu Possible reserves of 100 million tonnes at 0.4% Cu	3.5 million tonnes at 4% Cu mined. Low grade reserves remain (30 million tonnes at 0.76% Cu)	16 million tonnes at 14.9% Zn, 7.7% Pb, 1.4% Cu At least six bodies	4 million tonnes in several bodies with grades varying from 8% Cu + 2% Zn to 1% Cu	Several bodies - largest >100 million tonnes at 6% Pb + Zn
Volcanism	Unimodal rhyodacitic. Small centres aligned along basement fractures ?	Unimodal rhyodacitic. Small centres aligned along basement fractures	Bimodal. Isolated acid centre overlying thick basaltic pile	Bimodal. Isolated acid centre overlying thick basaltic pile	Unimodal rhyodacitic overlying clastic sediments. Original distribution of centres uncertain
Chemistry of Volcanics	? calc-alkaline	? calc-alkaline	calc-alkaline to alkaline	alkaline to sub-alkaline	? calc-alkaline
Composition of Volcanics	Pyroclastics related to rhyolitic centre with some proximal flows and breccias	Rhyolite, welded tuffs, pyroclastics related to small centre	Pyroclastics related to small centre	Pyroclastics, including breccias, related to small centre	Ashflow tuffs and tuffs/tuffites
Situation relative to Volcanic Centre	Proximal	Proximal	Proximal	Proximal	Mostly distal
Thickness of Volcanics	< 1km.	< 200m.	? 1km. approximately	? 1km. approximately	100m. - 1km.

	AVOCA	PARYS MOUNTAIN	BUCHANS	RAMBLER	BATHURST
Post mineralisation Igneous Activity (pre-metamorphic)	Post-volcanic dioritic intrusives	Dolerite/microgabbro, granophyres and ultrabasic intrusions	Bimodal volcanics basalt-rhyodacite	Late are bimodal volcanics basalt-rhydocite	Mafic volcanics mostly basaltic pillow lavas
Associated Sediments	Cherts, chloritic iron formation, some carbonate Magnetite + chlorite iron formation on strike	Chert, chloritic chert, some chloritic mudstone (iron formation) Some dispersed carbonates Debris flows	Pyritic wackes and debris flows with transported ore; bedded barite	Chert; possibly chloritic iron formation	Chlorite, magnetite and carbonate-bearing iron formation
Sulphides	Pyrite, minor chalcopyrite, and less sphalerite and galena	Pyrite, minor chalcopyrite, and less sphalerite and galena	Sphalerite, galena with chalcopyrite, pyrite	Pyrrhotite,pyrite; with chalcopyrite	Pyrite, with sphalerite, galena and less chalcopyrite
Vertical Zoning of Sulphides	Yes Cu → Pb, Zn	Not overall Perhaps locally in upper ore zone	Yes, in 'in situ' orebodies	No, but little Pb, Zn present	Yes, but copper low overall, and central zone of low grade present
Slumping	Present	Important	Important	--	--
Alteration	Quartz+chlorite +sericite, 'pseudo-imbrication' in footwall extensive	Quartz+chlorite +sericite, including 'pseudo-imbrication' throughout	Quartz+chlorite +sericite, including 'pseudo-imbrication' in footwall of 'in situ' orebodies	Quartz+chlorite +sericite, strong quartz-eye development in footwall and ore horizon	Local quartz+chlorite alteration in footwall

rhyodacitic, or part of a bimodal basalt-rhyolite suite in which andesites are uncommon.

All the deposits contain bedded sulphides, in most cases pyrite being dominant. The sulphides are commonly stratigraphically zoned with an upward increase in the ratio (Pb+Zn):Cu. In some deposits, however, such as Rambler, there are commonly only small amounts of lead and zinc and in such cases zoning is weak to absent. Other exceptions occur at Brunswick No. 12 where upper and lower zones rich in lead and zinc are separated by a layer of essentially barren pyrite.

The footwalls of the deposits show a characteristic alteration, with strong development of quartz, chlorite and sericite. In deposits which are more distal, with respect to a volcanic centre, the footwall alteration is weak but in proximal deposits it is intense and may affect the entire sequence of acid volcanics.

Sulphide deposition and pyroclastic activity commonly overlapped so that footwalls consist of altered volcanics and sediments with beds and lenses of sedimentary sulphides. In the main ore horizon, sulphides accumulated undiluted by contemporaneous pyroclastics, and the sulphides are associated with iron formation and chert which form the host, hangingwall and lateral equivalents to ore. The chert and iron formation, like the sulphides, are considered to be sediments of volcanic exhalative origin. Their accumulation in the ore horizon reflects a period when pyroclastic activity was less intense, whilst strong fumarolic activity was maintained.

Instability in the volcanic environment during and immediately following ore formation is reflected in the common occurrence of slumping and debris flows in the ore horizon. Slumping may disperse previously deposited sulphides, as at Parys Mountain, but at Buchans a significant proportion of the ore reserves occurred as sulphide-rich debris flow deposits. The recognition of such debris flows and the strong control on their distribution by the basement topography may be important in the search for ore within known mineralised areas.

REFERENCES

ARCHIBALD, D.E. 1971. Geology and grade control technique at Heath Steele Mines (Paper presented at C.I.M.M. meeting, Bathurst, N.B., July 1971).

BADHAM, J.P.N. 1978. Slumped sulphide ores at Avoca, Ireland, and their significance (Trans. I.M.M. 87, B 21-26).

BADHAM, J.P.N. 1979. Discussion of Badham (1978) (Trans. I.M.M. 88, B 69-74).

BARBER, A.J. & MAX, M.D. 1979. A new look at the Mona Complex (Anglesey, North Wales) (J.G.S. 136, 407-423).

BATES, D.E.B. 1966. The Geology of Parys Mountain (Welsh Geol. Quarterly V.2. No. 1. 27-29).

BATES, D.E.B. 1972. The Stratigraphy of the Ordovician rocks of Anglesey (Geol. J. 8, 29-58).

BRENCHLEY, P.J. & TREAGUS, J.E. 1970. The Stratigraphy and structure of the Ordovician rocks between Courtown and Kilmichael Point, Co. Wexford (Proc. R. Irish Acad. 69B, 83-102).

BRENCHLEY, P.J., HARPER, J.C., MITCHELL, W.I. & ROMANO, M. 1977. A re-appraisal of some Ordovician successions in eastern Ireland (Proc. R. Irish Acad. 77B, 65-85).

BRINDLEY, G.W. 1961. Chlorite Minerals. In The X-Ray Identification and crystal structures of clay minerals, G. Brown, ed. (Min. Soc. London) p. 489-516.

BRINDLEY, J.C. 1954. The Geology of the Northern end of the Leinster Granite, Part I - Internal Structural Features (Proc. R. Irish Acad. 56B, 159-190).

BRINDLEY, J.C. & CONNOR, 1972. The minor acid intrusions of the Aughrim-Ballinaclash area, Co. Wicklow (Proc. R. Irish Acad. 72B, 166-183).

BRINDLEY, J.C., McARDLE, P. & SCHIENER, E.J. 1973. The Lower Palaeozoic volcanic rocks of south-east Leinster, Ireland (Sci. Proc. Roy. Dublin Soc. 4A, 431-438).

BRUCK, P.M. & O'CONNOR, P.J. 1977. The Leinster Batholith : geology and geochemistry of the Northern Units (Geol. Surv. Irl. Bull. 2, 381-393).

BRUCK, P.M., GARDINER, P.R.R., MAX, M.D. & STILLMAN, C.J. 1978. Field Guide to the Caledonain & pre-Caledonian rocks of south-east Ireland (Geol. Surv. Irl., Guide Series No. 2).

CAVALERO, R.A. 1970. Geology of the Caribou deposit, Restigouche County, N.B. (Paper presented to Can. Inst. Min. Met. A.G.M. Toronto).

CAVALERO, R.A. 1972. Caribou Deposit - Summary Geology (Anaconda Canada Ltd. unpub. rept.).

COLE, G.A.J. 1922. Memoir and map of localities and minerals of economic importance and metalliferous mines in Ireland (Mem. Geol. Surv. Irl. 154 pp).

CRIMES, T.P. & CROSSLEY, J.D. 1968. The stratigraphy, sedimentology, ichnology and structure of the Lower Palaeozoic rocks of part of NE Co. Wexford (Proc. R. Irish Acad. 67B, 185-215).

DALZIEL, I.W.D. 1969. Pre-Permian History of the British Isles - A Summary. In North Atlantic Geology and Continental Drift, M. Kay, ed. (Am. Assoc. Petrol. Geol. Mem. 12) p. 5-31.

DAVIES, J.L. 1972a. The Bathurst-Newcastle Area (XXIV I.G.C. Field Guide A-58, p. 50-58).

DAVIES, J.L. 1972b. Geology and geochemistry of the Austin Brook Area, Gloucester County, N.B. with special emphasis on the Austin Brook Iron Formation (Unpub. Ph.D. Thesis, Carleton Univ. Ottawa).

DAVIES, J.L. 1977. Geological Map of Northern New Brunswick (Dept. Nat. Res., Govt. of N. Brunswick).

DEWEY, H. & EASTWOOD, T. 1925. Copper ores of the Midlands, Wales, Lake District & the Isle of Man (Mem. Geol. Surv. Gt. Brit. Min. Res. 30).

DEWEY, J.F. 1969a. Structure and Sequence in the Paratectonic British Caledonides. In North Atlantic Geology & Continental Drift, M. Kay, ed. (Am. Assoc. Petrol. Geol. Mem. 12) p. 309-335.

DEWEY, J.F. 1969b. Evolution of the Appalachian-Caledonian Orogen (Nature, 222, 124-129).

FISCHER, R.V. 1966. Rocks composed of volcanic fragments and their classification (Earth Sci. Rev. 1, 287-298).

FITCH, F.J., MILLER, J.A., EVANS, A.L., GRASTY, R.L. & MENEISY, M.Y. 1969. Isotopic age determinations on rocks from Wales and the Welsh Borders. In The Precambrian & Lower Palaeozoic Rocks of Wales, A. Wood, ed. (Univ. Wales Press, Cardiff) p. 23-46.

FITTON, J.G. & HUGHES, D.J. 1970. Volcanism & Plate Tectonics in the British Ordovician (Earth & Plan. Sci. Lett. 8, 223-228).

GARDINER, P.R.R. 1970. Regional Fold Structures in the Lower Palaeozoic of south-east Ireland (Geol. Surv. Irl. Bull. 1, 47-51).

GARDINER, P.R.R. & VANGUESTAINE, M. 1971. Cambrian & Ordovician microfossils from S.E. Ireland and their implications (Bull. Geol. Surv. Irl. 1, 163-210).

GARDINER, P.R.R. 1974. The Duncannon Group : an Upper Ordovician unit in S.W. Co. Wexford (Bull. Geol. Surv. Irl. 1, 429-446).

GARY, M., McAFEE, R., WOLF, C.L. (eds.) 1972. Glossary of Geology (American Geological Institute, Washington, D.C. 805 pp).

GREENLY, E. 1919. The Geology of Anglesey (Mem. Geol. Surv. Gt. Brit. 980 pp, 2 vols.).

HALLIDAY, A.N. 1977. Isotopic age studies of mineralisation in Western Europe (Unpub. Ph.D. Thesis, Univ. of Newcastle-upon-Tyne).

HATCH, F.H. 1889. Notes on the Wicklow Greenstones (Geol. Mag. 6, 261-265).

HATCH, F.H. 1889. On the Lower Silurian Felsites of S.E. Ireland (Geol. Mag. 6, 545-549).

HAWKINS, T.R.W. 1966. Boreholes at Parys Mountain, near Amlwch, Anglesey (Bull. Geol. Surv. Gt. Brit. No. 24, 7-18).

INESON, P.R. & MITCHELL, J.G. 1975. K-Ar Isotopic age determinations from some Welsh Mineral localities (Trans. I.M.M. 84, B 7-16).

IXER, R.A. & GASKARTH, J.W. 1975. Parys Mountain - a possible Kuroko-style deposit (Min. Dep. Studies Gp. Meeting, Leicester, abstracts).

JONES, W.R. 1947. The mining district of Avoca, Co. Wicklow (private Rept. to Mianrai Teoranta).

LAPWORTH, 1882. In On the Geology of Anglesey, T. McK. Hughes (Q.J.G.S. 38).

LUFF, W.M. 1977. Geology of Brunswick No. 12 Mine (Can. Min. Met. Bull. June 1977).

van LUNSEN, H.A., REEVES, T.J. & BRUCK, P.M. 1977. Stream sediment base metal geochemistry of One-Inch Sheet 139 (Geol. Surv. Irl. Rept. Series RS77/1, 29-31).

LUSK, J. 1969. Base Metal zoning in the Heath Steele B-1 Orebody, New Brunswick, Canada (Econ. Geol. 64, 509-518).

MANNING, W. 1959. The Parys and Mona Mines in Anglesey. In The Future of Non-ferrous Mining in Great Britain and Ireland (London, I.M.M.) p. 313-328.

MARENGWA, B.S.I. 1973. The mineralisation of the Llanrwst area and its relation to mineral zoning in North Wales with reference to the Halkyn-Minera area and Parys Mountain (Unpub. Ph.D. Thesis, Univ. of Leeds).

McALLISTER, A.L. 1960. Massive sulphide deposits in New Brunswick (Can. Min. Met. Bull 53, 88-98).

McALLISTER, A.L. & LAMARCH, R.Y. 1972. Mineral deposits of Southern Quebec & New Brunswick (XXIV I.G.C. Excursion A58-C58 Guide).

McARDLE, P. 1979. Discussion of Badham (1978) (Trans. I.M.M. 88, B 72).

MITCHELL, W.I., CARLISLE, H., HILLER, N. & ADDISON, R. 1972. A correlation of the Ordovician rocks of Courtown (Co. Wexford) and Tramore (Co. Waterford) (Proc. R. Irish. Acad. 72B, 83-89).

MURPHY, G.J. 1959. The Avoca enterprise - 2 : The geology of the mineralised area (Mine & Quarry Engineering 25, 330-338).

NUTT, M.J.C., INESON, P.R. & MITCHELL, J.G. in press. The age of mineralisation at Parys Mountain, Anglesey (Proceedings of conference 'Caledonides Reviewed' I.G.C.P. Dublin 1978).

PHILLIPS, W.E.A., STILLMAN, C.J. & MURPHY, T. 1976. A Caledonian plate-tectonic model (J. Geol. Soc. Lond. 132, 579-609).

PHILLIPS, W.E.A. 1978. Strain adjacent to the Iapetus Suture (Proc. I.G.C.P. Conference - The Caledonides of the British Isles Reviewed, Dublin 1978, in press).

PLATT, J. W. 1973. Avoca (Mining Ireland, 72-91).

PLATT. J.W. 1975. New light on Avoca ore potential (Mining Ireland, 78-81).

PLATT, J.W. 1976. Volcanogenic mineralisation at Avoca, Co. Wicklow, Ireland, and its regional implications (Geol. Soc. Lond. Spec. Pub. No. 7, 163-170).

PLATT, J.W. 1978a. The Avoca Mines (In Prospecting in Glacial Terrain, I.M.M.).

PLATT, J.W. 1978b. Contributed Remarks on Badham (1978) (Trans. I.M.M. B 184-188).

POINTON, C.R. & IXER, R.A. in press. The Parys Mountain mineral deposit, Anglesey : Geology and ore mineralogy (Trans. I.M.M. in press).

RAMSAY, A.C. 1881. The Geology of North Wales (Mem. Geol. Surv. Gt. Brit. HMSO, 611 pp).

REEVES, T.J. 1971. Gold in Ireland (Geol. Surv. Irl. Bull. 1, 73-86).

REEVES, T.J. 1976. Some diorites in eastern Co. Wicklow (Geol. Surv. Irl. Bull 2, 15-26).

REEVES, T.J. 1977a. Stream sediment base metal geochemistry of One-Inch Sheet 130 (Geol. Surv. Irl. Reprt. Series RS77/1, 1-13).

REEVES, T.J. 1977b. The dolerites in part of eastern Co. Wicklow (Geol. Surv. Irl. Bull. 2, 159-165).

ROBERTS, J.L. 1976. The structure of the Dalradian rocks in the SW Highlands of Scotland (J. Geol. Soc. 130, 1-93).

ROSCOE, W.E. 1971. Geology of the Caribou Deposit, Bathurst, New Brunswick (Can. Jour. Earth Sci. 8, 1125-1136).

RUITENBERG, A.A. 1976. Comparison of volcanogenic mineral deposits in the Northern Appaijachians and their relationship to tectonic evolution. In Stratabound Sulphide Deposits, Wolf, ed.

SANGSTER, D.F. 1972. Precambrian volcanogenic massive sulphide deposits in Canada : A Review (Paper 72-22, Geol. Surv. Canada).

SHACKLETON, R.M. 1969. The Precambrian of North Wales. In The Precambrian and Lower Palaeozoic rocks of Wales, A. Wood, ed. (Univ. of Wales Press, Cardiff) p. 1-22.

SHANNON, P.M. 1976. The petrology and structural relations of some Lower Palaeozoic rocks in southeast Leinster (Unpub. Ph.D. Thesis Nat. Univ. Ireland).

SHANNON, P.M. 1978. The stratigraphy and sedimentology of the Lower Palaeozoic rocks of southeast Co. Wexford (Proc. R. Irish Acad.).

SHEPPARD, W. in press. Aspects of the geology of Avoca Mines, Co. Wicklow, Ireland (Proceedings, Symp. Caledonian-Appalachian Stratabound Sulphides, Trondheim, Norway, 1979).

SIVAPRAKASH, C. 1977. Geochemistry of some sulphides and sulphosalts from Parys Mountain, Anglesey (Unpub. M.Phil. Thesis, Univ. of Aston).

SMITH, C.H. & SKINNER, R. 1958. Geology of the Bathurst-Newcastle Mineral District, N.B. (Bull. Can. Inst. Min. Met. 51, 150-155).

STANTON, R.L. 1958. Abundances of copper, zinc and lead in some sulphide deposits (J. Geol. 66, 484-502).

STANTON, R.L. 1959. Mineralogical features and possible mode of emplacement of the Brunswick Mining and Smelting orebodies, Gloucester County, New Brunswick (Trans. Can. Inst. Min. Met. 62, 339-351).

STANTON, R.L. 1976. Petrochemical studies of the ore environment at Broken Hill, N.S.W. 1 - constitution of 'banded iron formation' (Trans. I.M.M. 84 B 33-46).

STILLMAN, C.J. & MAYTHAM, D.K. 1973. The Ordovician volcanic rocks of Arklow Head, Co. Wicklow (Proc. R. Irish. Acad. 73B, 61-77).

STILLMAN, C.J., DOWNES, K.M. & SCHEINER 1974. Caradocian volcanic activity in east and southeast Ireland (Sci. Proc. Roy. Dublin Soc. 5 No. 6,).

STRONG, D.F. 1977. Volcanic regimes of the Newfoundland Appalachians (Geol. Ass. Can. Spec. Paper 16).

STRONG, D.F., O'BRIEN, S.J., TAYLOR, S.W., STRONG, P.G. & WILTON, D.H. 1978. Aborted Proterozoic rifting in eastern Newfoundland (Can. J. Earth Sci. 15, 117-131).

SWINDEN, H.S. & STRONG, D.F. 1976. A comparison of plate tectonic models of metallogenesis in the Appalachians, the North American Cordillera, and the East Australian Palaeozoic (Geol. Ass. Can. Spec. Paper 14).

TATSUMI, T. & WATANABE 1971. Geological Environment of formation of the Kuroko-type deposits (Soc. Mining Geol. Japan Spec. Issue 3, 216-220).

THANASUTHIPITAK, T. 1974. The relationship of mineralisation to petrology at Parys Mountain, Anglesey (Unpub. Ph.D. Thesis, Univ. of Aston).

THURLOW, J.G., SWANSON, E.A. & STRONG, D.F. 1975. Geology & lithogeochemistry of the Buchans polymetallic sulphide deposits, Newfoundland (Econ. Geol. 70, 130-144).

TREMLETT, W.E. 1959. The structure of the Lower Palaeozoic rocks of the Arklow district (Ireland) (Q.J.G.S. Lond. 115, 17-40).

TUACH, J. & KENNEDY, M.J. 1978. The geologic setting of the Ming and other sulphide deposits, Consolidated Rambler Mines, Northeast Newfoundland (Econ. Geol. 73, 192-206).

WEAVER, T. 1821. The geological realtions of the East of Ireland (Trans. Geol. Soc. Lond. 5, 117-304).

WHEATLEY, C.J.V. 1971a. Economic geology of the Avoca mineralised belt, S.E. Ireland, and Parys Mountain, Anglesey (Unpub. Ph.D. Thesis, Imp. Coll. Lond.).

WHEATLEY, C.J.V. 1971b. Aspects of metallogenesis within the Southern Caledonides of Great Britain and Ireland (Trans. I.M.M. 80, B 211-223).

WHITEHEAD, R.E.S. & GOODFELLOW, W.D. 1978. Geochemistry of volcanic rocks from the Tetagouche Group, Bathurst, N.B., Canada (Can. Jour. Earth Sci. 15, 207-219).

WILLIAMS, H., KENNEDY, M.J. & NEALE, E.R.W. 1972. The Appalachian Structural Province. In Variations in Tectonic Styles in Canada, R.A. Price & R.J.W. Douglas, eds. (Geol. Ass. Canada Spec. Paper II) p. 181-262.

WILLIAMS, G.J. 1907. Note on the geological age of the shales of Parys Mountain, Anglesey (Geol. Mag. 4, 148-150).

WINCHESTER, J.A. 1974. The zonal pattern of regional metamorphism in the Scottish Caledonides (J. Geol. Soc. 130, 509-524).

APPENDIX 1

STEREOGRAPHIC PLOTS OF STRUCTURAL DATA FROM THE AVOCA AREA

(stereograms, lower hemisphere, equal area)

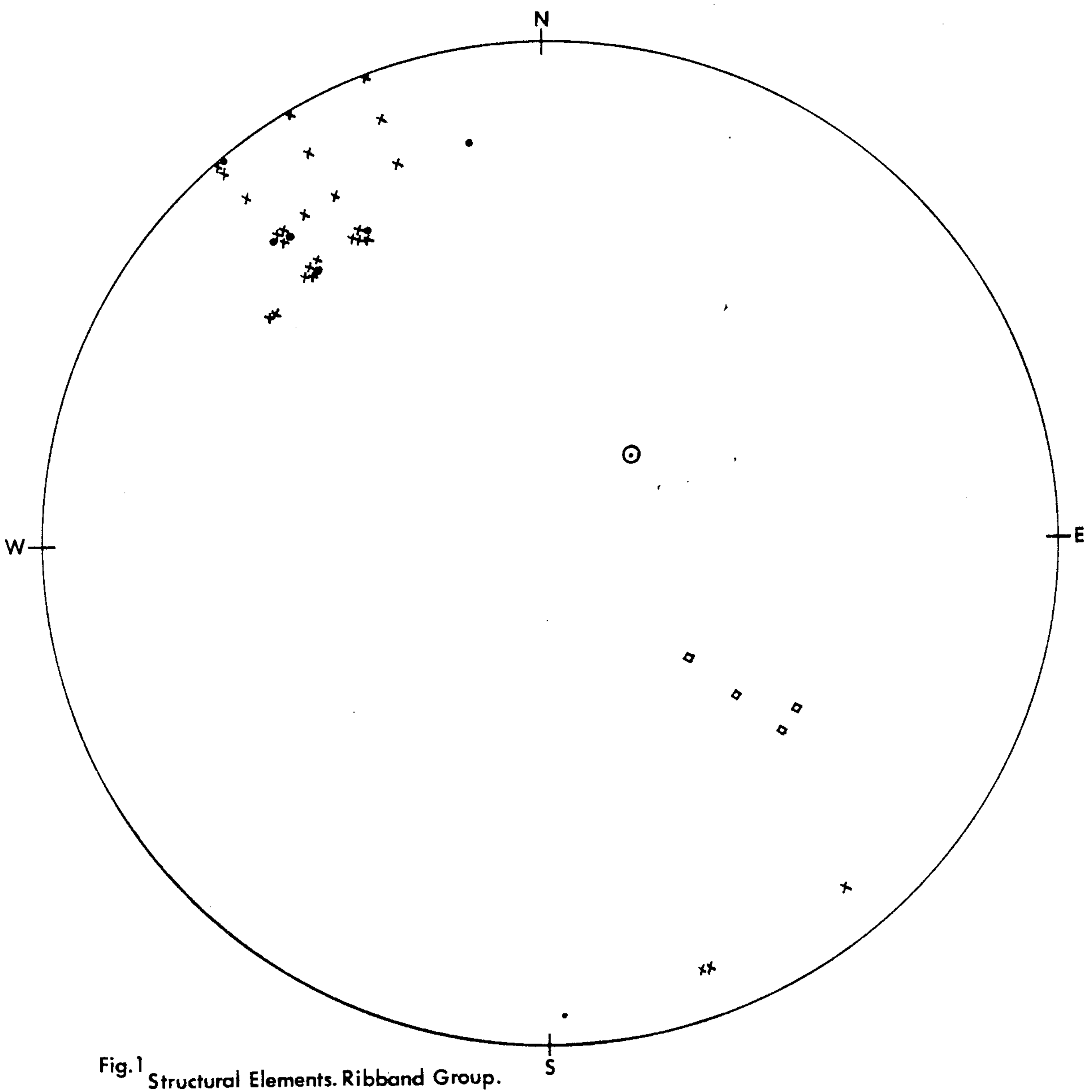


Fig. 1 Structural Elements. Ribband Group. Area 1 (west of Avoca Formation)

- × Poles to main cleavage (S_1)
- □ Poles to second cleavage (S_2)
- • Poles to bedding
- ⊙ Lineation (L_1)

(Lambert Equal-Area Projection)

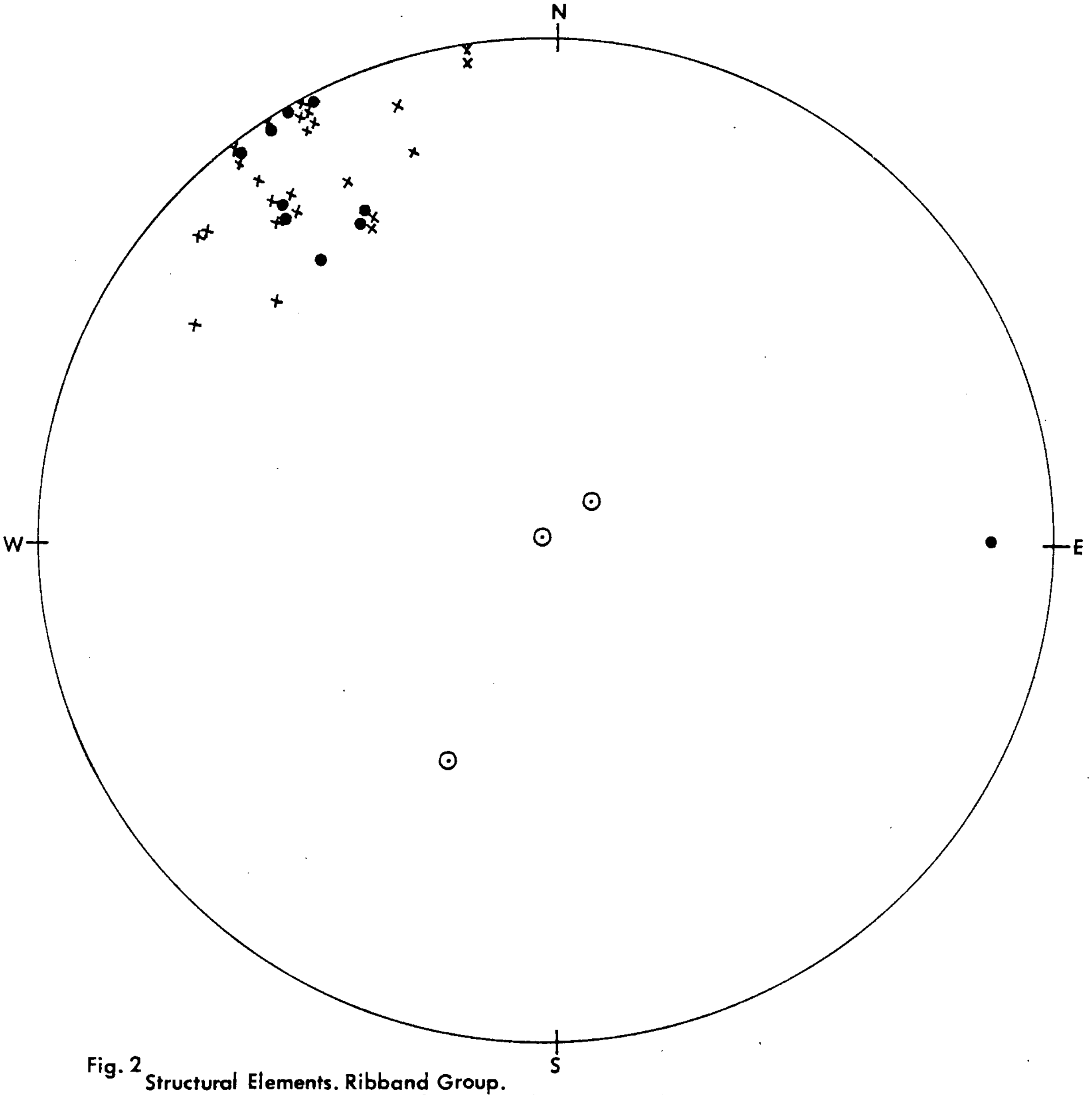


Fig. 2 Structural Elements. Ribband Group.
Area 2 (Between Avoca and Ballymoyle Formation)

- x Poles to main cleavage (S_1)
- ☐ Poles to second cleavage (S_2)
- ● Poles to bedding
- ⊙ Lineation (L_1)

(Lambert Equal-Area Projection)

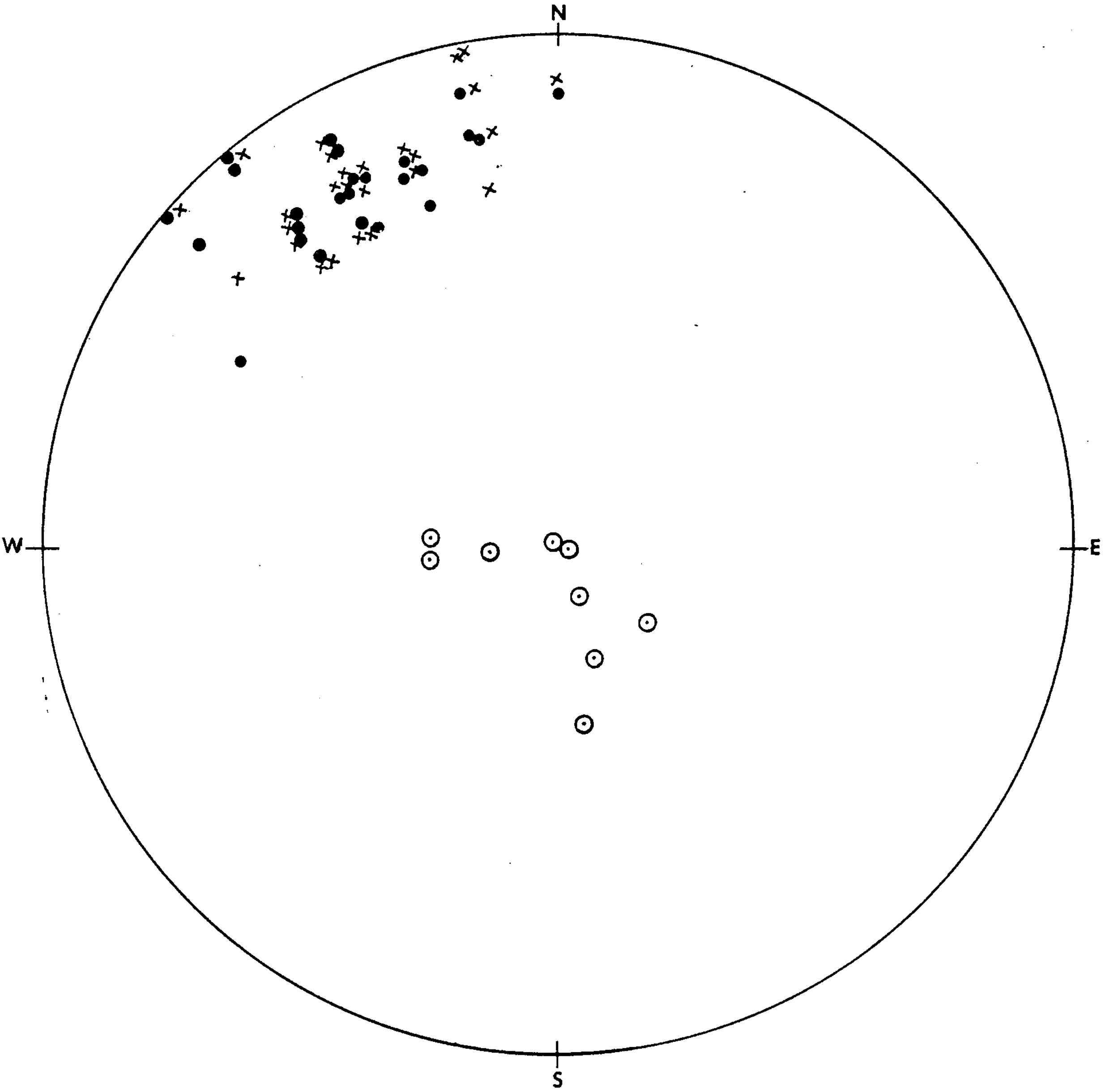


Fig. 3 Structural Elements. Ribband Group
Area 3 (east of Ballymoyle Formation)

- X Poles to main cleavage (S_1)
- ☐ Poles to second cleavage (S_2)
- ● Poles to bedding
- ⊙ Lineation (L_1)

(Lambert Equal-Area Projection)

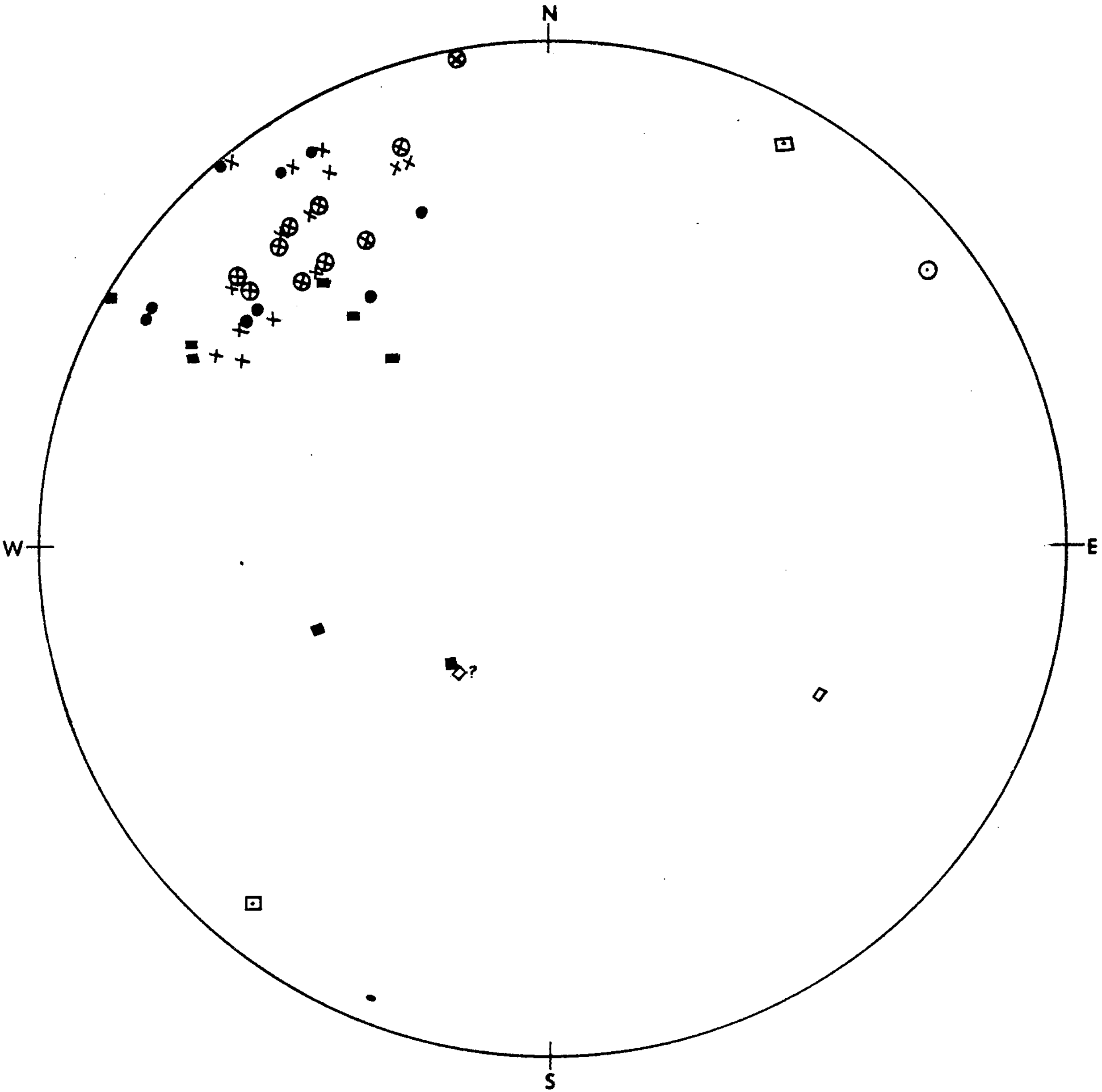


Fig. 4 Structural Elements. Ballymoney Group.

Ballymoyle Formation	Avoca Formation
⊗ Pole to(S_1)	× Pole to(S_1)
■ Pole to bedding	□ Pole to(S_2)
⊡(L_1)	● Pole to bedding
	⊙(L_1)

(Lambert Equal-Area Projection)

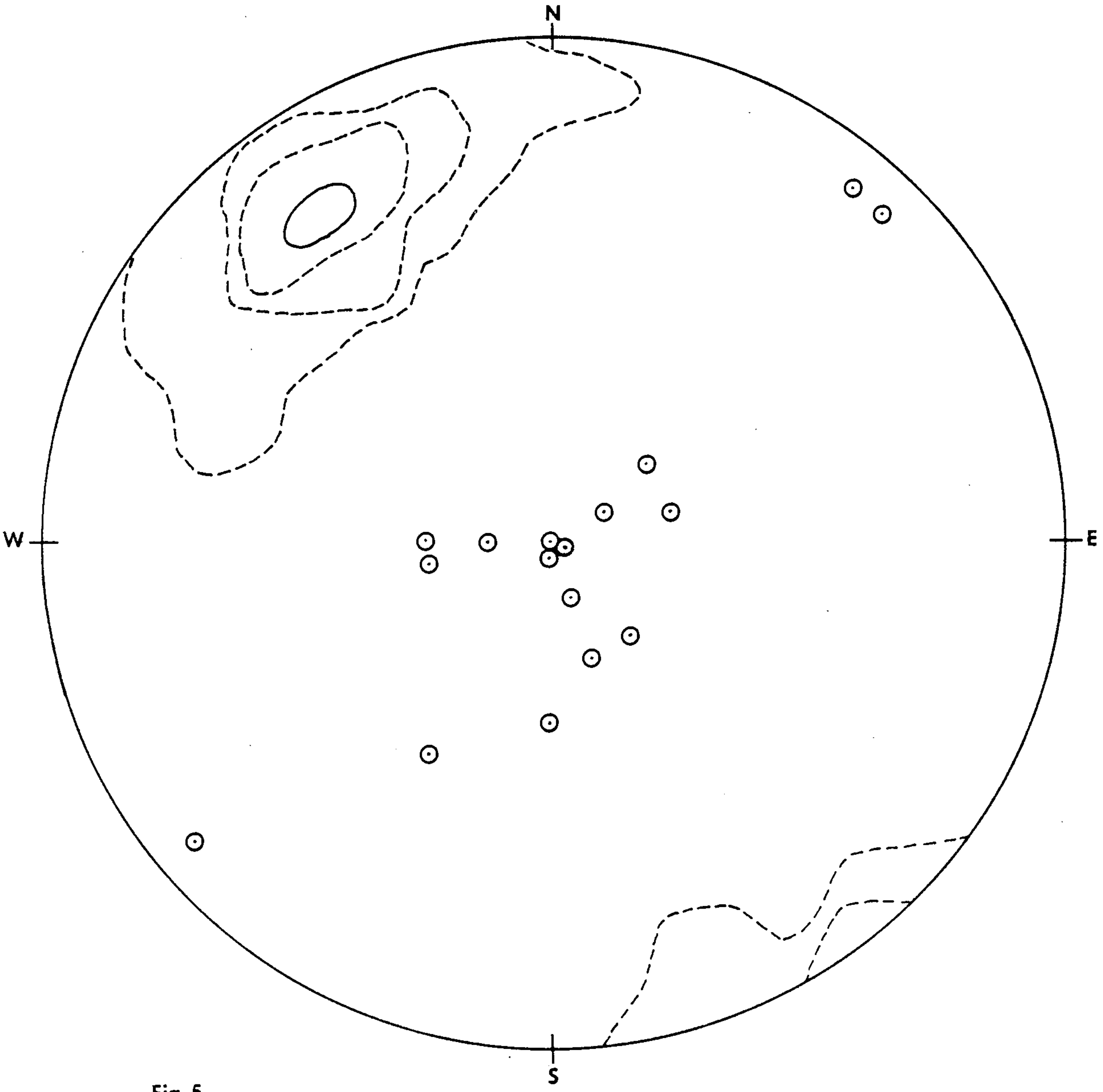


Fig. 5 Arklow - Wicklow Area

---Contours to 104 poles to cleavage (S_1) (contour interval 10%)

⊙ Bedding - cleavage lineation (L_1)

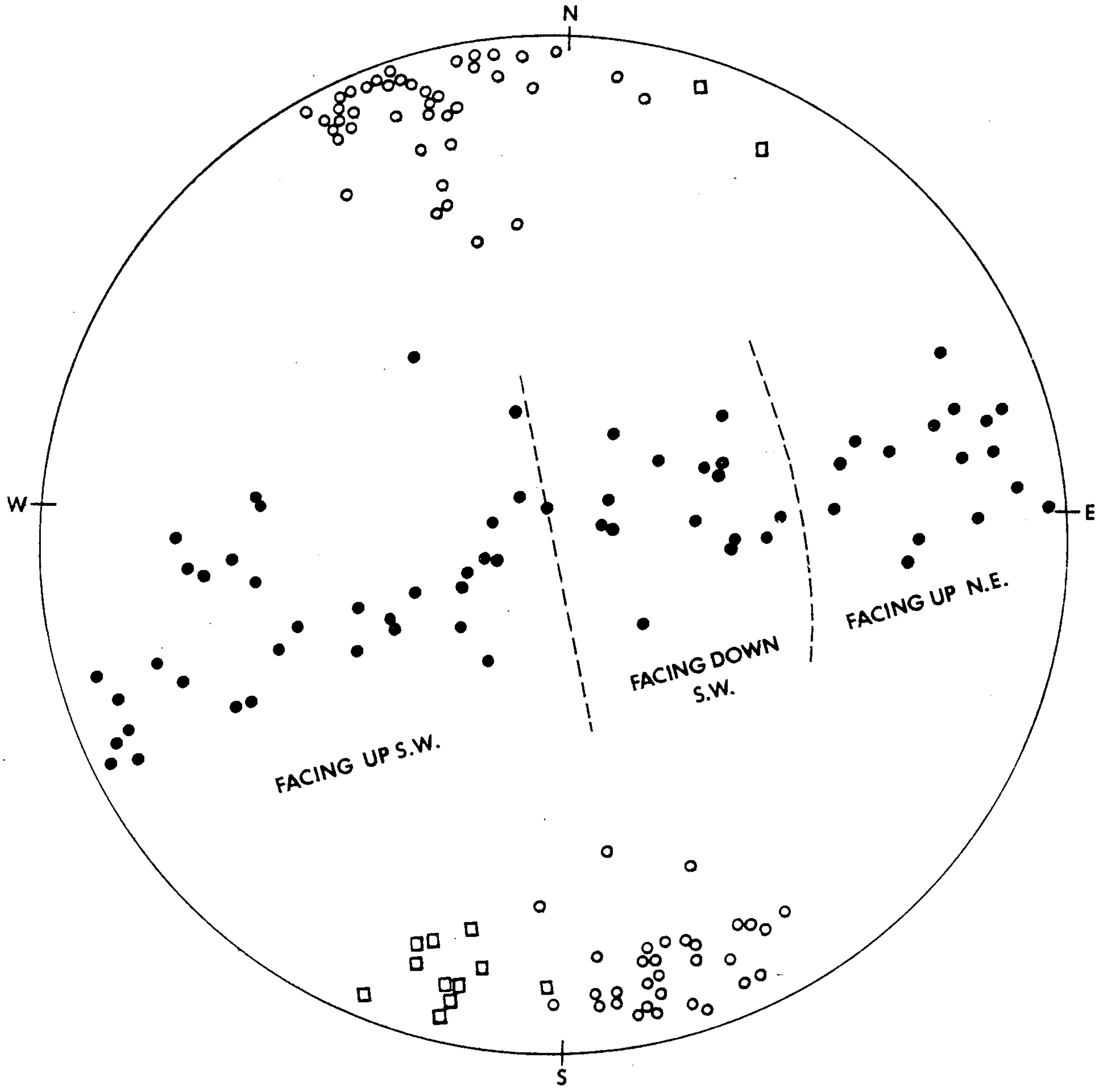


Fig 6 Results of Brenchley and Treagus (1970) for the Ballymoney area.

o pole to 1st cleavage
o bedding/1st cleavage intersections, first fold axes
□ pole to 2nd cleavage

APPENDIX 2

CHLORITE DETERMINATIONS

'd'-spacings of chlorites determined from chloritic shales and cherts at Parys Mountain are shown below, and compared with standard results for thuringite and the results of Wheatley (1971a) from Avoca. Determinations were made using a Debye-Sherrer camera on samples mounted on a glass fibre. The samples were extracted from thin-sections under the microscope to ensure that impurities other than quartz were excluded. Samples were irradiated for 90 to 105 minutes with Co Kα radiation using an Fe Kβ filter and fine collimators.

PARYS MOUNTAIN CHLORITES

'd'-spacings (relative intensities)

	1	2	3	4	5	6	7
(001)	13.83(5)	14.37(8)	14.18(8)	14.25(8)	14.58(8)	14.56(6)	14.31(7)
(002)	6.97(6)	7.09(10)	7.08(10)	7.07(10)	7.10(10)	7.07(10)	6.96(10
(003) (020)	4.69(4)	4.71(6)	4.65(4)	4.70(6)	4.70(4)	4.68(4)	4.67(6)
							4.22(3)
(004)	3.52(10)	3.54(6)	3.53(5)	3.52(9)	3.54(6)	3.51(6)	3.50(2)
					3.01(1)	3.01(1)	3.00(2)
(005)	2.82(1)	2.84(2)	2.81(2)	2.82(2)	2.83(1)	2.82(2)	2.79(1)
		2.65(2)					
	2.57(1)	2.58(4)	2.57(3)	2.58(5)			
	2.53(1)	2.54(4)		2.53(5)	2.54(4)	2.55(1)	2.55(3)
				2.43(4)	2.43(3)		2.43(2)
	~2.36(1)	2.38(4)	2.38(2)	2.37(3)	2.37(2)	2.39(1)	2.37(1)
		2.12(1)		2.25(2)	2.26(2)		2.26(2)
	1.99(1)	2.00(3)	2.00(4)	2.00(4)	2.00(4)	2.01(3)	2.00(4)
	~1.88(1)	1.88(1)	1.88(1)	1.88(2)	1.88(2)		
				1.81(2)	1.82(2)		1.81(2)
		1.66(2)	1.66(1)	1.66(1)		1.66(1)	1.66(1)
	1.56(1)	1.56(1)	1.56(1)	1.56(2)	1.56(1)		1.56(1)
				1.54(4)	1.53(4)		1.53(6)
	1.50(1)	1.51(2)	1.51(1)	1.50(2)	1.50(1)		1.50(1)

1 = Drillhole A12 - 191.1m. (627')
2 = " A12 - 323.4m. (1061')
3 = " 32 - 440.4m. (1445')
4 = " IM6 - 306.3m. (1005')
5 = " 43A - 605.3m. (1986')
6 = " 35 - 344.4m. (1130')
7 = " IM19 - 46.6m. (153')

	1	2	3	4	5
(001)	13.6(7)	14.1(9)	14.1(4)	14.1(7)	14.02(4)
(002)	6.90(10)	7.07(10)	7.05(10)	7.05(10)	7.07(10)
(003) (020)	4.63(8)	4.73(3)	4.71(4)	4.67(5)	4.70(4)
(004)	3.49(10)	3.54(6)	3.53(8)	3.52(10)	3.53(7)
(005)	2.80(6)	2.84(3)	2.84(3)	2.81(3)	2.82(1)
			2.70(1)	2.66(4)	
	2.61(7)	2.58(3)		2.60(9)	
		2.53(3)	2.52(5)	2.55(7)	2.55(4)
	2.46(7)	2.43(3)		2.45(7)	2.45(5)
	2.39(7)	2.37(2)		2.39(8)	2.39(5)
	2.26(7)	2.25(1)		2.27(7)	2.27(1)
			2.15(4)		2.16(1)
	2.00(8)	2.00(2)	2.02(1)	2.01(7)	2.01(4)
	1.88(5)	1.88(1)		1.88(4)	1.88(2)
	1.81(4)	1.82(1)			1.82(1)
			1.78(3)		
	1.72(2)	1.74(1)		1.75(10)	
	1.66(4)	1.66(1)		1.66(1)	1.66(1)
					1.57(1)
	1.55(8)	1.56(1)	1.56(4)	1.55(9)	1.55(4)
	1.52(1)	1.53(3)	1.52(2)	1.51(6)	1.52(1)
		1.50(1)	1.48(3)	1.50(1)	

1 Thuringite File no. 3-67*
2 " File no. 7-78*
3 " File no. 13-29*
4 " File no. 21-1227*
5 Chlorite sample from Avoca (Wheatley, 1971a)

* Selected Powder Diffraction Data for Minerals; Joint Committee on Powder Diffraction Standards, Publication DBM-1-23, 1974.

APPENDIX 3

MICROPALAEONTOLOGICAL INVESTIGATION - DIGESTION PROCEDURE

Fresh samples of shale were collected from outcrop. A minimum of 1kg. of sample was obtained. The sample was crushed to less than 4mm. (approximately) in a jaw crusher. Digestion was carried out as follows, on some 10g. of sample:

1. Immersed in 40% Hydrofluoric Acid for approximately 10 days, stirred occasionally.
2. Decanted and refilled with distilled H_2O at least 5 times at intervals of at least 6 hours. EXAMINED
3. Small amount of black residue placed in sintered funnel (porosity 3), and fuming HNO_3 added. Left for between 1 hour and 3 days.
4. Washed with conc. HNO_3, dil. HNO_3 and distilled water. EXAMINED
5. Immersed in 5% KOH for 24 hours. EXAMINED
6. Washed and treated with conc. HNO_3 for times up to 3 days.
7. 1g. $KClO_3$ added to conc. HNO_3 in funnel. Left for 3 days.
8. Washed in distilled H_2O and 5% KOH. EXAMINED

In some cases, conc. HNO_3 was substituted for fuming HNO_3 in stage 3.

No identifiable residues were obtained, although black shapes were noted in several samples.