

THE MICROPALAEONTOLOGY OF THE DALRADIAN

by

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Abstract

This study has involved an investigation of the micropalaeontology of the Dalradian Supergroup in Scotland and Ireland, which previously was thought to have a time range from Vendian to Arenig.

The structure, stratigraphy and metamorphism of Dalradian geology are outlined. A detailed review of Dalradian sedimentology has been undertaken and from this a new model of the depositional environment is proposed, with the emphasis being placed on the role played by block faulting and graben-like structures. A comparison is drawn with the Mesozoic and Tertiary sedimentary history of the North Sea.

The methodology is outlined and discussed, especially the morphological and statistical criteria used to establish the biogenicity of these essentially poorly preserved microfossils.

Each of the fifteen distinctive species found is discussed and compared with published material. The problem of classifying simple spheromorphs (Leiospheres) is discussed, and the problem resolved in this study by placing all simple spheres in the genus Leiosphaeridia with five different "Types" being recognised.

The pre- and post-lithification factors that affect preservation are discussed, and special emphasis placed on the role of pyrite framboids, and the pseudo-fossil morphologies they may produce. Rocks that have undergone a number of phases of deformation and some metamorphism may still contain relatively well preserved microfossils.

A biostratigraphy is erected with four informal zones. It is argued that the Maccuff Slates do not possess any unequivocal or determinable microfossils, and their Arenig age is questioned. The Dalradian Supergroup as a whole is now believed to have a time range from Vendian to uppermost Lower Cambrian.

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Chapter 1

INTRODUCTION

1.1 General Introduction

In 1893 Geikie, "for the sake of distinction and convenient reference", coined the term "Dalradian" for those rocks "East of the line of the Great Glen, which cuts the Scottish Highlands in two "where" another group of crystalline schistose rocks is largely developed". Geikie took his name from the Celtic kingdom of Dalriada in the north of Ireland that, in the 3rd century A.D. spread, initially peacefully, to the Scottish mainland, especially the Kintyre and Kilmartin areas, and to the Inner Hebrides, especially Islay (Murray 1972). Geikie's original definition was of the geographical distribution of a wide range of distinctive lithologies, all metamorphic, including "quartzites, phyllites, graphitic schists, mica schists, marbles, and various other foliated masses. With them are associated numerous eruptive rocks both (of) acid and basic". When talking about the age of the Dalradian, Geikie clearly indicates that he expected rocks of a wide age range to be found. "It is possible that in the vast mass of metamorphosed rocks constituting the wide stretch of country from the northern headlands of Aberdeen to the south-west promontories of Argyllshire, there may be portions of old Lewisian gneiss, tracts of highly altered Torridonian sandstone, belts of true counterparts of the Cambrian quartzites and limestones of Durness, and, what should not be forgotten, considerable portions of some later sedimentary series which may have followed these limestones". Geikie also describes briefly, the continuation of the Dalradian rocks into Ireland. He concludes "The Dalradian

..... may possibly mark a distinct Pre-cambrian series but it seems probable that they are only a metamorphic complex in which Archaean, Torridonian and Cambrian, or even lower Silurian rocks are included".

Thus the original definition of "Dalradian" was a geographic one of a distinctive, complex set of metamorphic rocks, and was almost identical to the modern definition of "supergroup" in that it has no time connotations (Harland et al. 1972). The Dalradian is now correctly termed the Dalradian Supergroup (Harris and Pitcher 1975).

Since 1893, the meaning of Dalradian has changed slightly. In some contexts "Dalradian" is beginning to have chronostratigraphic implications, as if the term could be regarded in the same way as Cambrian, or Vendian. This is an unfortunate trend. The time span of these rocks is not yet clear, and it is far more appropriate to restrict the term to a geographic distribution rather than a time distribution. When talking about the age of these rocks it would be better to refer to them as Rhiphaean, Vendian, Cambrian or whatever is appropriate. It is appreciated that at the moment this is rather difficult with the present lack of evidence. One of the purposes of this thesis is to add to that evidence. However it is my conviction that the phrase "of Dalradian age" should be used as little as possible.

Research into Dalradian rocks has been carried out for more than 150 years, since McCulloch (1819) first described the geology of Islay in his book "The Western Isles of Scotland". Much of this research is covered in Chapter 2 and will not be

discussed in detail here, but since 1819 research has been abundant, and has reflected the wide ranging changes in geological thought that have taken place. Initial work dealt with describing lithologies and establishing a "layer-cake" stratigraphy. By the beginning of the 1920's, the rudiments of the structural geology of the rocks had also been described. One of the major obstacles to both these lines of research in the early days, was the inability of workers to establish a true depositional succession. This stumbling block was overcome by the work of Vogt (1930) and Bailey (1930) which demonstrated that current bedding and graded bedding were acceptable way-up criteria in the Scottish Highlands.

Most research has concentrated on the structural problems in the Dalradian. These techniques have become rapidly more sophisticated over the last 15 years, but stratigraphy and sedimentology have lagged behind until Anderton (1974) produced the first truly sedimentological survey in the Dalradian. The recent work of Bradbury (Pers. Comm.) has shown that the "layer-cake" philosophy of Dalradian stratigraphy may in many cases be oversimplified.

Almost no palaeontological studies have been carried out. A very few occurrences of macrofossils from the Southern Highland Group (Upper Dalradian) (Jehu 1912, Jehu and Campbell 1917, Pringle 1940, Stubblefield 1965) have been recorded. A number of stromatolite horizons have also been identified. (Wilkinson 1930 (in Peach and Horne), Anderson 1950, Pantin 1955, Hackman and Knill 1962, Spencer and Spencer 1972, Anderton 1974). The first stratigraphic palaeontological

study of the Dalradian was the micropalaeontological work of Downie et al. (1971).

1.2 Introduction to Dalradian Micropalaeontology

Apart from a short paper by Litherland (1975) describing catagraphs and possible bryozoa, possibly Vendian or Cambrian in age from Benderloch, the only work on Dalradian micropalaeontology to date is that of Downie et al. (1971). In this work, samples, mostly of black shales/slates, from twenty-four formations were processed, by means of normal maceration followed by filtration. From this, Downie et al. found six possible chitinozoan genera (Conochitina, Desmochitina, Eremochitina, Lagenochitina, Rhabdochitina and Siphonochitina), which included nineteen species. Nine sphaeromorph acritarch genera were also found. Using these data, Downie et al. erected a preliminary biostratigraphy. The Precambrian/Cambrian boundary was placed somewhere between the base of the Tayvallich Limestone, and the base of the Portaskaig Boulder Bed. Also of importance, they suggest a possible non-sequence between the Upper Leny Grit and the Highland Border Series/Macduff Slates. The latter Formations they consider to be Arenig in age.

1.3 Purposes of this Thesis

The purposes of this Thesis can be expressed quickly and simply as follows: -

(1) To discover as many microfossil assemblages in the Dalradian Supergroup as possible, and to obtain more

information from those already discovered.

(2) To use these microfossil assemblages to erect a biostratigraphy of the Dalradian, and thus establish the age of the Supergroup as a whole and of individual formations within it. This will lead to possible correlation with other rock sequences, of similar age outside the British Isles.

(3) To investigate the effects of depositional environment, diagen^esis, metamorphism and tectonism, on the preservation of microfossils and to assess the possible effects of these factors on biostratigraphy. In order to facilitate these aims a review of all aspects of Dalradian geology has been undertaken.

Chapter 2

THE GEOLOGY OF THE DALRADIAN

It is beyond the scope and space available in this thesis to attempt an in depth review of Dalradian geology. However, sedimentology, tectonics, metamorphism and stratigraphy have a direct bearing on the microfossils. The environment in which they lived dictated, to a greater or lesser extent, the types that might be preserved, and the diagenetic, tectonic and metamorphic history that followed death and burial controlled their preservation. Thus some knowledge of all aspects of Dalradian geology is essential.

For the purposes of this thesis, emphasis has been placed on the sedimentology and stratigraphy of those low metamorphic grade areas from which samples were collected. These include: (a) Islay/Jura/Easdale; (b) Kinlochleven/Ballachulish/Appin; (c) Loch Awe/Tayvallich; (d) The Highland Border; (e) Banffshire; (f) Co. Donegal; (g) Co. Mayo (see Map 1 and Map 2).

The metamorphic and structural history has been dealt with more generally, although more detailed local structural and metamorphic data will be put forward where this has a bearing on the microfossils. The history of research will be mentioned as each area is discussed. For more detail the reader should follow up the references cited here, and in other general accounts e.g. Rast (1963), Knill (1963) and Harris and Pitcher (1975).

2.1.(a) Islay/Jura / Easdale (Map 1 and stratigraphy on Fig. 2.1)

The first descriptive account of the geology of Islay was by MacCulloch (1819). This work is best known for his

Fig. 2.1; Lithostratigraphy of the Dalradian Supergroup in Scotland. Mostly after Harris and Fletcher 1975, but with some modifications in the Southern Highland Group, (see text for discussion)

GROUPS Sub-groups		ISLAY	BALLACHULISH-TAYVALLICH	COWAL	ABERFOYLE	CALLANDER
SOUTH-ERN HIGHLAND			Loch Avich Volcanics Loch Avich Grits Tayvallich Volcanics	Beinn Beula Schists Dunoon Phyllites Bullrock Greywacke Green Beds	Highland Border Series "Psammitic Wacke" Aberfoyle Slates Green Beds	Highland Border Series Ben Ledi Grits U. Leny Grits Leny Lst & Shale L. Leny Grits Aberfoyle Slates Binnam Slates Green Beds
	Tayvallich		Kilchrenan Conglomerate Kilchrenan Grits Tayvallich Slates & Lst.			
	Crinan		Crinan Grits			
	Easdale	Scarba Conglomerate	Andrishaig/Craignish Phyll. Easdale Slates			
ARGYLL	Islay	Islay/Jura Quartzite Bonahaven Dolomite Port Askaig Tillite	Islay/Jura Quartzite Bonahaven Dolomite Port Askaig Tillite			
	Blair Athol	Islay Limestone Mullach Dubh Phyllite Ballygrant Limestone Baharradail Phyllite	Lismore Limestone Cuil Bay Slates			
	Ballachulish	Cnoc Donn Phyl/Qtzt/Lst. Cnoc Donn Quartzite (Transition) Cnoc Donn Slates Kintra Limestone	Appin Phyll & Lst. Appin Quartzite (Transition) Ballachulish Slates Ballachulish Limestone			
	Lochaber	Kintra Phyllite Maol an Fhithic Qtzt.	Leven Schists Glencoe Quartzite Binnein Schists Binnein Quartzite Eilde Schists Eilde Quartzite			
APPIN						

Fig 21

suggestion of the glacial origin of the Port Askaig Tillite and for correlating it with the Schichallion Boulder Bed. Other reports in the nineteenth century include Murchison and Geikie (1861) who correlated the Islay Limestone with the Durness Limestone, and Thompson (1875) who agreed with McCulloch's glacial interpretation of the Port Askaig Tillite. Wilkinson (1907) published a description of the lithologies on Islay, but it was Bailey (1916) who first put forward a detailed stratigraphy, based on the style of ripple marks, and his structural analysis of the Islay Anticline. Allison (1933) confirmed Bailey's succession by using current bedding as a "way-up" criteria. Bailey's sequence has only been altered in two important aspects; (i) the Mull of Oa Phyllites have been subdivided into phyllite, quartzite, and limestone formations (Basahel 1971), and (ii) the Upper Conglomerate and Lower Fine Grained Conglomerate have been included in the Port Askaig Tillite (Spencer 1971). The accepted succession on Islay and Jura is as Fig. 2.1 (after Harris and Pitcher 1975).

The Lochaber Sub-group (Fig. 2.1) is dominated by the Maolan Fhithich Quartzite. These are fine grained quartzites, notable for the occurrence of blue quartz grains (Bailey 1916). The top of the Formation is interbedded with the Kintra Phyllites, and Wilkinson (1907) considers this as evidence of a faulted contact. Bailey (1916) and Allison (1933) show that the contact is in fact stratigraphically conformable.

Until the work of Basahel (1971) all the rocks of the Ballachulish and Blair Atholl Sub-groups below the Islay Lime-

stone (Fig. 2.1) were included in the Mull of Oa Phyllites, (Wilkinson 1907, Bailey 1916 and Allison 1933). They were described as dark grey and somewhat sandy phyllites with occurrences of grey and greenish phyllites and black slates. Cream dolomites were noted as being common.

The base of the Ballachulish Sub-group consists of a sandy dolomitic limestone, passing up into a dark graphitic limestone (Kintra Limestone). This is followed by a black slate with pyrite formation (Cnoc Donn Slates), similar to the Ballachulish Slates (see Chapter 2.1.(b)), well exposed in disused quarries on Cnoc Donn, West Islay (Map reference N.R. 339 585).

The upper half of the sub-group consists of the Cnoc Donn Quartzite Formation which is a pebbly coarse sand, followed by the Cnoc Donn Phyllite/Quartzite/Limestone Formation. The latter consists of rapid changes in lithology; dolomitic limestone with evaporites (Basahel 1971), grey phyllites and coarse grained quartzites.

Sedimentation continued conformably into the Blair Atholl Sub-group (Fig. 2.1) with the deposition of the carbonaceous Baharradail Phyllites and the dark grey Ballygrant Limestone (Basahel 1971).

The Islay Limestone at the top of the Blair Atholl sub-group, lies unconformably on both the Baharradail Phyllite and Ballygrant Limestone (Basahel 1971). In the south of the Mull of Oa (Map reference NR 270 415) this unconformity is marked by a graphitic phyllite, the Mullach Dubh Phyllite.

The Islay Limestone is a grey massive, sometimes oolitic limestone, with dolomitic beds. These often contain laminar and domal stromatolites (Spencer 1971) similar to those of the Bonahaven Dolomitic Beds (Spencer and Spencer 1972). Within the dolomites, very thin beds of ironstone may occur.

The base of the Islay Sub-group (Fig. 2.1) and hence the Argyll Group is taken as the base of the Port Askaig Tillite (Harris and Pitcher 1975). This lies unconformably on the Islay Limestone (Basahel 1971).

Since the work of MacCulloch (1819) there has been considerable literature on the Port Askaig Tillite. The most important and detailed of these is Spencer (1971). The Formation crops out spasmodically for 600 km. along strike from Fordyce on the Bannffshire coast to Aeggan on the west coast of Connemara in Ireland, (MacCulloch 1819, Kilburn et al. 1965, Spencer 1971 etc.), and its distinctive character provides an invaluable lithostratigraphic marker. The type sections occur at Port Askaig on Islay (Map 1) and on the Garvellach Islands (Map 1).

Lithologically, the Formation consists of beds of mixtites separated by stratified siltstones, sandstones, conglomerates, and dolomites. The mixtites contain abundant intra- and extra-basinal boulders up to 2m in diameter. The mixtite beds almost always have conformable sharp bases and are sometimes bedded within themselves. The total thickness of the Formation (on the Garvellachs) is estimated to be 870m (Spencer 1971). Using subtle differences between mixtite beds,

Spencer (1971) has recognised 47 mixtite beds grouped into 5 members.

Boulders of intra-basinal origin are mostly sharp angular fragments of fine grained yellow or pink sandy dolomite similar to the dolomites interbedded with the mixtites. Kilburn et al. (1965) report that some of these dolomitic boulders contain stromatolite structures, although there is no report of any of the dolomitic beds interbedded with the mixtites being stromatolitic. These stromatolitic fragments may be derived from the underlying Islay Limestone Formation. Other intrabasinal boulders include dolomitic sandstone, dolomitic breccia, limestone, gritty sandstone, quartzite and argillaceous siltstone (Kilburn et al. 1965). Wilkinson (1907 p.43) has described abundant boulders of oolitic limestone from the Islay Limestone, although Bailey (1910) says he has found no evidence of this.

The extra-basinal boulders are generally more rounded and granitic.

The bedded mixtites thin laterally to zero in all cases. Soft sediment folds, indicating late ice movement (Spencer 1971) occur, and there is a strong pebble fabric in the mixtites which may in part be tectonic.

On the Garvellach Islands, varved beds occur, some with large dropstones, with evidence of deflection and penetration of sediment laminae.

Largely as a result of the detailed work of Spencer (1971) on the Port Askaig Tillite, the stratigraphy of the beds above the Tillite has altered somewhat since the work of

Wilkinson and Bailey (Table 2.1). Wilkinson (1907) erected five divisions in his Northern Series. The base was the Port Askaig Conglomerate, followed by a quartzite with a band of conglomerate which he compared closely to the Port Askaig Conglomerate. Bailey (1916) called this quartzite the Lower Fine Grained Quartzite, and made it the basal unit of his Islay Quartzite Series. Spencer (1971) recognising that the conglomerate within the Lower Fine Grained Quartzite was part of the Port Askaig Tillite removed the name of the Quartzite and included it in the Port Askaig Tillite. A summary of the changes in the stratigraphy is shown in Table 2.1.

The Bonahaven Dolomite (Fig. 2.1) is about 300m thick and is conformable on the Port Askaig Tillite. Wilkinson (1907) recognised two dolomitic units with shales, dolomitic shales and yellow dolomites. Spencer and Spencer (1972) divided the formation into five members. Lithologically the Formation consists of sandstones, pelites, dolomitic sandstones, white sandstones, dolomites and stromatolitic dolomites, and argillaceous sandstones. Evaporites have been recognised (Llewellyn 1969, MacGregor pers. comm.). Sedimentary structures are mainly sun cracks (possible "dewatering features"), which are usually contorted and corrugated due to compaction and tectonism (see Borradaile and Johnson, 1973). Wilkinson (1907) records worm trails but these have been found by no other worker. The most remarkable feature of the formation is the presence of its stromatolites. These were first recognised by Peach and Horne (1930) and subsequently described by Hackman and

TABLE 2.1		
WILKINSON 1907	BAILEY 1916	SPENCER 1971 HARRIS & PITCHER 1975
5) Sandy shales or flags with ripples & "Fucoid" Beds"	Pebbly Quartzite	Islay Quartzite Series
4) Blue and white Quartzite with ripples and "annelid" borings and "pipes".	Upper Fine- Grained Quartzite.	
3) Sandy ripple-marked and worm-tracked flags and dolomites.	Dolomitic Group.	
2) Quartzite with conglomerate.	Lower Fine- Grained Quartzite.	Port Askaig Tillite
1) Port Askaig Conglomerate.	Port Askaig Conglomerate.	

Table 2.1: Variations and correlation of Argyll Group stratigraphy on Islay, since Wilkinson 1907.

Knill (1962) and Spencer and Spencer (1972). Although no taxonomic identifications have yet been made, Spencer and Spencer (1972) recognised four different morphologies, viz. (i) stratiform lamination; (ii) closely and widely spaced, laterally linked hemispheres; (iii) rare columnar growths; (iv) irregular growth structures.

The Islay Quartzite occupies over 80% of the Islay Sub-group, and is up to 5,000m thick (Bailey 1911). The Formation thins (both tectonically and stratigraphically) to the northeast and southwest (Basahel 1971). Allison (1933) using sedimentary structures, and Bailey (1916) using ripple marks and his structural sequence demonstrated that the Islay Quartzite is younger than the Bonahaven Dolomite. Bailey (1916) divided the Formation into an upper Pebbly Quartzite Member and a lower unit, the Upper Fine Grained Quartzite. Wilkinson (1907 p.35) and Knill (1963 p.106) report worm burrows, although Bailey (1916) specifically mentioned that he did not find any, and Anderton (1974) considers that they may be synaeresis cracks.

Anderton (1974) in a detailed study of the Islay Quartzite notes that there are no mappable horizons, but that it is far from homogenous. He has recognised a coarse facies and a fine facies. Sedimentary structures are especially abundant in the coarse facies and include single deposit sets, tabular sets, trough sets, and variably orientated sets.

The Jura Slates are considered part of the Scarba Conglomerate (Harris and Pitcher 1975, and Fig. 2.1). They occur only as a thin outcrop in the south of Islay and on

Jura and have been divided into two units (Knill 1963), a lower zone of grey phyllites overlain by black phyllites.

The Scarba Conglomeratic Group is largely made up of locally derived blocks of quartzite, limestone and phyllite in a gritty matrix. The "Group" is thin on Islay and largely represented by coarse pebbly quartzites, with blue quartz pebbles and intercalated dark phyllites. Anderton (1974) has recognised two originally mud members, now slates, one of which (the Inverlussa Member) is now a dark grey/black pyritic slate.

The Scarba Conglomerate and Easdale Slates are laterally equivalent (Anderton 1974, Harris and Pitcher 1975 and Fig. 2.1). Anderson (1953) and Rast and Litherland (1970) thought the Easdale Slates equivalent to the Jura Slates. Knill (1963), Cambray (1969) and de Klein (1970) assume the Easdale Slates overlie the Scarba Conglomerate.

2.1.(b) Ballachulish/Appin/Kinlochleven Region

The oldest rocks of the Dalradian, at the base of the Lochaber Sub-group (Harris and Pitcher 1975, Fig. 2.1) occur in this region. The rocks were first described by Macknight (1811) from a Wernerian philosophy i.e. all the rocks, including the gneisses and granites were precipitated from a primitive ocean.

MacCulloch (1814) abrogated this theory by recognising that the quartzites were deposited mechanically and that the shales and quartzites were interbedded. The Wernerian hypothesis was further nullified in this region by MacCulloch

(1817) recognising the cross-cutting nature of the granites.

The stratigraphic succession of the Lochaber Sub-group in the Kinlochleven-Blackwater Reservoir area was first established by Carruthers (1913). In their Memoir, Bailey and Maufe (1916) tentatively accept this succession although they state that the repetition of quartz/schist formations that characterises the stratigraphy may be due to folding. Again Bailey and Maufe (1916) list the stratigraphical succession with the Cuil Bay youngest and the Glen Coe Quartzite oldest (the correct order). However, they consider that this may be inverted.

In an excellent paper in 1930, Bailey, using the then novel criteria of graded bedding and current bedding, established the correct stratigraphical order, and accepted Carruthers' succession at Kinlochleven as being sedimentary and not tectonic.

The succession as present accepted from the Lismore Limestone to the Eilde Flags is as in Fig. 2.1 (after Harris and Pitcher 1975).

The "Moinian" Eilde Flags is a 1000m thick formation of quartzo-feldspathic sandstone rich in biotite and muscovite, with schist intercalations. The Dalradian Eilde Quartzite is conformable above the Eilde Flags and it has been extremely difficult to separate the two. It has now been proposed, on lithological grounds that the "Moinian" Eilde Flags and Central Highlands Granulites should form a fourth Group in the Dalradian, the "Grampian Group". (Harris pers. comm.)

The Lochaber Sub-group consists of a sequence of alternating quartzite formations (Eilde, Binnein and Glencoe Quartzites) and schist formations (Eilde, Binnein and Leven Schists). The quartzite formations are all lithologically very similar being well bedded feldspathic sandstones often wedge shaped, with varying amounts of schist. All the quartzites contain abundant sedimentary structures, including cross bedding, ripple marks and slump folds.

The "schist" formations are psammitic and psammo-pelitic (Hardie 1952, Hickman 1975) with varying amounts of biotite (Bailey and Maufe 1916). The Binnein Schist Formation is notable in that it becomes carbonaceous and calcareous towards the top.

The total thickness of the Lochaber Sub-group is at maximum 5,000m thick, and on average approximately 4,500m.

The Ballachulish Sub-group (Fig. 2.1) follows conformably above the Lochaber Sub-group (Hickman 1975) and is in total approximately 1,100m thick, and consists of a limestone-slate-quartzite sequence.

The Ballachulish Limestone at the base (250m thick, Hickman 1975) consists of a lower part of a cream dolomite with thin grey-green phyllite interbeds. This passes up into thin black slates dark, fairly pure limestone and some dolomite. In the Ballachulish, and mouth of Glencoe area, the limestone is more siliceous with lenses of sweated out quartz. being common.

The Ballachulish Slate Formation follows on conformably from the Ballachulish Limestone, and is characteristically and

dramatically exposed in the old roofing slate quarries at Ballachulish (Map 1). The Formation is approximately 400m thick, and is almost entirely composed of black slate, with large euhedral pyrite cubes. Hickman (1975) has recognised black limestone intercalations in the lower part of the Formation but these die out upwards and the formation becomes pure slate. In the Loch Creran area the formation thins and dies out towards the east (Litherland 1970).

The Formation passes upwards with increasing quartzite and psammite beds, into the Striped Transition Series (Transitional Beds) (Bailey and Maufe 1916; Bailey 1960). This can be regarded as a transition zone between the Ballachulish Slates and Appin Quartzite, but Hickman (1975) has included these beds in the Ballachulish Slate Formation, maintaining that the quartzite beds represent "periodic incursions of quartz sands into an otherwise little changing environment".

300m of Appin Quartzite Formation follow conformably. This is a well-bedded, massive, white feldspathic quartzite, divided by Bailey (1960) into two members. False-bedding and detrital feldspar and quartz grains characterise the upper, while the lower is included in the Transition Series. Current bedding, ripple marks, graded bedding and slump bedding are common, and Bowes and Wright (1962) describe a washout structure.

The Appin Phyllite Formation, and Appin Limestone Formation have been combined by Harris and Pitcher (1975). The limestone is the characteristic "Tiger Rock" (Bailey and Maufe 1916). This is a dolomite, weathering to pink and black

stripes, with high Mn and low P contents when compared with other limestones in the area (Hickman 1975).

The Appin Phyllite part of the Formation is dominantly a grey phyllite, with subordinate sandstone, flags and quartzite, and is about 250m thick. Some black shale, often pyritic can also be found.

The Cuil Bay Slates, at the base of the Blair Atholl Sub-group (Fig. 2.1), are lithologically very similar to the Ballachulish Slates, being dominantly black or grey pyritic shales, with the occasional black limestone or more psammitic slate. The Formation is about 300m thick.

At the top of the Blair Atholl Sub-group is the Lismore limestone Formation. This is a complex formation about 1,000m thick that crops out on the islands of Lismore and Shuna. It is predominantly a grey limestone formation with units of blue-grey limestone and occasionally graphitic and pelitic, black shale. These units show some cyclicity. The only sedimentary structures are rare cross bedding, festoon bedding, and ^{load}~~load~~ casts.

The succession is continued in Glen Creran by the deposition of quartzites, pebble beds and black slate (Litherland 1970).

In an important paper in 1970, Rast and Litherland managed to correlate the Ballachulish succession with the Perthshire Dalradian on Islay and at Blair Atholl. Previously, Bailey (1934) had separated the Perthshire and Ballachulish Dalradian by a continuation of the Iltay Boundary Slide. Subsequently, Anderson (1948 and 1953) and Voll (1964) put

forward correlations. The former correlated the Ballachulish Limestone-Ballachulish Slate sequence with the Perthshire Dark Schist-Dark Limestone sequence. The reversal in sequence is unexplained. Voll (1964) correlated the upper Ballachulish Limestone with the Islay Quartzite and in doing so necessitated dramatic facies changes over very short distances. Both these correlations are unacceptable.

On the basis of detailed mapping in the Loch Creran area (Litherland 1970) where the presence of the Lismore Limestone on the mainland was recognised, and by a number of traverses on Islay, Rast and Litherland (1970) were able to build up the lithostratigraphic correlation (Table 2.2).

Table 2.2 Correlation of the Dalradian on Islay and in the Ballachulish Region. (After Rast and Litherland (1970), with modifications after Basahel (1971) and Harris and Pitcher (1975)):

<u>Islay</u>	<u>Ballachulish</u>
Ballygrant Limestone	Lismore Limestone
Baharradail Phyllites	Cuil Bay Slates
Cnoc Donn Phyllite/Qtzt/Lst	Appin Phyllites and Limestone
Cnoc Donn Quartzite	Appin Quartzite
Cnoc Donn Slates	Ballachulish Slates
Kintra Limestone	Ballachulish Limestone
Kintra Phyllites	Leven Schists
Maol an Fhithich Quartzite	Glencoe Quartzite

2.1.(c) The Loch Awe/Tayvallich Region (Map 1)

MacCulloch (1819) was again the first to take an interest in the geology of this region. However he did not recognise that igneous rocks were present. This was first demonstrated by Jamieson (1861). These igneous rocks have subsequently been given the term "Epidiorites". They were generally considered intrusive sills (Hill 1893) until the discovery by Peach (1903) of pillow lavas in the Tayvallich Peninsula ~~aff~~ demonstrated that some at least were extrusive. The extrusive nature of these rocks could have been appreciated earlier, when Kynaston (1897 and 1900) described pillowlavas and lavaform structures, but did not recognise them as such.

Hill (1899) first established a stratigraphy in the Loch Awe region, and grouped the rocks into the Ardisaig Series and Loch Awe Series. The Loch Awe Series consisted:

Grits and Quartzites

Black Slate

Limestone

Bailey (1913) extended this and established four formations ("groups") above the Ardrishaig Phyllites as follows:

Loch Avich Green Slate and Grits

Tayvallich Black Slates and Limestones
(with volcanics)

Crinan Quartzite and Grits

Shira Limestone

This sequence was established from structural data but

Bailey (1913) on the basis of graded bedding, and "gas-bubbles" and "pipe amygdales" at the top of lava flows demonstrated that it was also a stratigraphical sequence. This was further demonstrated by Allison (1941), although G.L. Elles (in discussion of Allison (1941)) disagreed with the reliability of graded bedding and Pipe Amygdales as "way-up" indicators.

More recent variations in the stratigraphy include a new sequence by Harris and Berridge (1969) from the Loch Nant hydroelectric tunnel (north-west corner of Loch Awe), and the subdivision of Bailey's Tayvallich Group by Borradaile et al (1971) (and Fig. 2.1), whose sequence in the Loch Awe area reads:

Southern	Loch Avich Lavas
Highland	Loch Avich Grits
Group	Tayvallich Lavas
	Kilchrenan Grits and Boulder Bed
	Tayvallich Limestone and Slates
Argyll	Crinan Grits
Group	Shira Limestone
	Ardrishaig/Craignish Phyllites

This is the present accepted stratigraphy. However it should be noted that some of the formations occur only locally, e.g. the Kilchrenan Grit and Boulder Bed only crop out around Loch Awe, and on the Tayvallich Peninsula. Volcanic rocks are well developed among the Tayvallich Slates and Limestones.

Bailey (1913) originally considered that this sequence was low in the Dalradian Supergroup. However he rescinded this during discussion of Allison (1941). Subsequently the now accepted correlation of the Tayvallich Limestone and Loch Tay Limestone (Fig. 2.1) was confirmed by Roberts (1966).

The phyllites at Ardrishaig and Craginish (Map 1) were first correlated by Hill (1885), and as such formed an important feature in his recognition of the Loch Awe Syncline. Throughout this thesis these phyllites will be considered one formation, and termed the Ardrishaig/Craginish Phyllites.

The Degnish Limestone occurs at the base of the Ardrishaig/Craginish Phyllites (Borradaile 1973), on the north shore of Loch Melfort (Map 1). It is a gritty, black, well bedded, 20m thick limestone which is internally laminated or ripple current bedded. The lithology is a mixed limestone-quartzite in which black limestone pebbles occur occasionally. This member can best be described as a partly current rippled, laminated limestone, and partly a sandy limestone with graded beds or slump fragments.

The thickness variations of the Ardrishaig/Craginish Phyllites between the west and east of the region are discussed in detail in Chapter 2.1.(f), but around Loch Awe, the Formation is some 4,000m thick, while in Craginish-Kilmelfort it is only about 2,500m thick (Knill 1959). The Formation is generally monotonous, and composed of green chloritic slates, cream sandy-limestones, and white fine-grained quartzites (Bailey 1913, Knill 1959, Borradaile 1971 and 1973). In the Loch Craginish area, they are more grey in colour (Allison

1941). The only marked change in this Formation occurs at the top, where dark slates occur. Bailey (1913) has recognised blue quartzes in the quartzitic beds. Current ripple lamination, slump folds and sole marks occur varyingly, and the cream limestones are often internally laminated.

Anderton (1975) has recognised a number of intertidal facies in the western area around Loch Melfort, Craginish and on Islay and Jura. These include laminated silt/sand; tabular sands, with erosional bases, and sole and ripple marks; sheet sands; and channel sands. The environmental significance of these facies is discussed in Chapter 2.1.(f).

Associated with the black slates at the top of the formation is the Shira Limestone. This is a discontinuous, thin black or blue limestone (Knill 1959) with some cream coloured horizons (Bailey 1913, Allison 1941 and Borradaile 1971). The limestone is occasionally gritty, and shows slump folding and current bedding (Borradaile 1971). Anderton (1974) has recognised laminated beds in this member, and has interpreted the alternate layers of degraded organic matter and carbonate as representing relict algal mat.

The base of the Crinan Grit may be slightly unconformable (Borradaile 1971). The Formation varies considerably in thickness from only about 100m thick west of Loch Awe to nearly 3,000m thick east of Loch Awe. Bailey (1916) has described the whole of the Formation as being pebbly and quartzitic, with blue and white quartzes and fresh felspar. He also notes the presence of conglomerates with slate, limestone and grit clasts and bedded slate and limestone

intercalations.

Borradaile (1971) has divided the Formation into eastern and western facies on a lithological basis, as well as differences in thickness. His eastern facies is comprised of thick bedded poorly sorted, angular coarse grained feldspathic quartzites. Graded bedding is common and channeling and erosion occurs in the lower units. Large scale (30 cm) slumps also occur.

Two other lithologies are developed. Firstly a black slate member with beds 2 - 3m thick, up to 100m thick, and secondly thin (10m) horizons of black limestone. This occurs both bedded, and massive and may be gritty. Locally it is conglomeratic, with matrix supported angular blocks of laminated black limestone, possibly from the Shira Limestone.

The western facies is comprised of thinner bedded medium grained relatively pure quartzite with rounded grains. The beds are usually well sorted, and graded bedding is rare. Very thin green and black phyllites, and a few very thin limestones also occur. The boundary of this facies has a south westerly course from Loch Awe towards Craignish.

Allison (1941) described the Crinan Grits in the Loch Craignish area. The rocks he described fit into Borradaile's (1971) eastern facies. At Craignish, the Crinan Grits are thick bedded, coarse feldspathic quartzites, often with well developed graded bedding. Black slates and limestone are also well developed, and Allison (1941) has divided the sequence into three grit members separated by two dominantly limestone members, with some shale. If the Crinan Grits at

Craignish are correlated with Borradaile's (1971) eastern facies, then the boundary separating the two facies must run northeast-southwest from Loch Craignish to the northwest corner of Loch Awe.

In the Loch Awe area, the Tayvallich Slates and Limestone formation (Fig. 2.1) is a fairly consistent thickness of 1.0 - 1.2 km. There is a local unconformity at the base of the Formation in the Kilmartin area (Gower 1973). The principle lithology is a black slate, but coarser mixtites occur in varying amounts. Bedding is most commonly massive, with a general absence of sedimentary structures, although ~~lode~~^{load} casts are quite common in the mixtites. Black and grey limestones constitute an important part of the formation, and these have been correlated with the Loch Tay Limestone (Bailey 1938, Roberts 1965). Borradaile (1971) has recognised three textures in the Tayvallich Limestone, (i) ooliths, (ii) homogeneous dark pellets, (iii) clear ovoid patches.

A minor lithology in the Loch Awe area is a thin lenticular, white, flaggy or calcareous quartzite, interbedded with the slates and limestones. The quartzite grains are usually angular, and grading occurs rarely. This lithology is comparable to the eastern facies of the Crinan Grit. On the Tayvallich Peninsula the oolitic limestone lithology dominates (Allison 1941).

The Kilchrenan Grit is a local Member of the Tayvallich Slates and Limestone Formation (Borradaile et al. 1971), occurring just north of Loch Awe. It is an arenaceous deposit which thins to the southeast, and is characteristically poorly

graded, thickly bedded, felspathic and contains abundant large and microscopic black slate shards. The coarse grains are often matrix supported.

The Kilchrenan Boulder Bed is about 30m thick and occurs locally, above the Kilchrenan Grit, north west of Loch Awe. The matrix is black slate which occasionally becomes more arenaceous or gritty. The pebbles are generally well rounded quartzites, although occasional angular gritty black limestone and black slate pebbles also occur. The Formation is consistent and continuous over some distance and locally it provides a good marker horizon.

Epidiorites occur abundantly in the Tayvallich Slates and Limestones, especially on the Tayvallich Peninsular, where Wilson and Leake (1972) have demonstrated that volcanic activity took place before the deposition of the main Tayvallich Limestone. All the epidiorites were originally considered intrusive. However Peach (1911) demonstrated by the presence of pillow lavas that some of the epidiorites at least were extrusive in character, and deposited under water (Wood 1964). Wilson and Leake (1972) on the basis of petrochemistry consider that the majority of both the extrusives and the sills originated from the same magma, and that all the epidiorites are altered basalts (Allison 1941, Borradaile 1971 and 1973, Wilson and Leake 1972).

The Tayvallich Volcanic Formation is a thick (1,000m - 2,000m) development of dominantly igneous rocks and is correlated with the Green Beds of the Highland Border region (Fig. 2.1 and Chapter 2.1.(e) (Borradaile 1971)). Some

interbedded sediments do occur, and these are confined to black slate or gritty slate lithologies, with a notable lack of sedimentary structures. The igneous rocks, which are best developed round Loch Awe are altered basalts (termed epidiorites). Both extrusive volcanics (recognised by pillow lavas etc.) and sills, occur. Borradaile (1973) considers that the sills were intruded during the volcanic activity, and are all pre-first folding.

The Loch Avich Grits are about 1,000m thick, and occur above the Tayvallic Volcanic Formation. They are dominantly chloritic, volcanogenic grits and green slates, with subordinate black slates and detrital volcanics which occur as discontinuous wedges. The grits contain very angular grains of potash feldspar, quartz and detrital epidote in a chloritic matrix. The beds are often well graded, and channelling is common.

The youngest formation in the region is the Loch Avich Volcanics, which occur north west of Loch Awe. No sedimentary intercalations are found in this formation. The rocks are similar to the Tayvallich Volcanics in that they are altered basalts, but they are consistently more acid than the latter (Borradaile 1973). Pillow lavas indicate that they are extrusives, and Borradaile (1973) considers that there are no sills.

2.1.(d) Highland Border Region

The cumulative stratigraphy of the Highland Border region, modified after Harris and Pitcher (1975) is as in

Fig. 2.1. Rocks beneath the Green Beds were not investigated due to their high metamorphic grade (see Map 1). All the formations in Highland Border region occur within the Southern Highland Group, the base of which is taken as the top of the Loch Tay/Tayvallich Limestone (Harris and Pitcher 1975). Due to extremely poor outcrop and exposure both along and across strike, the correlations presented in Fig. 2.1 must of necessity be dubious.

One of the major problems in the Southern Highland Group is the position of the Green Beds. Harris and Pitcher (1975) place this Formation above the Glen Sluan Schists/Pitlochry Schists, and below the Beinn Bheula Schists/Ben Ledi Grits/Dunkeld Grits. However there is good sedimentary younging evidence that the Beinn Bheula Schists/Ben Ledi Grits/Dunkeld Grits are high in the sequence and underlain by the older Bullrock Greywacke/Birnam Grits (see Table 2.3 for summary of younging evidence). One possible solution to this enigma is that there are two lithologically very similar "Green Beds", one of which occurs sporadically beneath the Beinn Bheula Schists/Ben Ledi Grits/Dunkeld Grits. However, I know of no direct evidence to support this.

The Green Beds are up to 1,000m thick (Roberts 1966) and crop out sporadically. They are green amphibole, epidote and chlorite rich grits (Anderson 1947, Harris and Pitcher 1975). Their green colour is attributed to a volcanic origin (Phillips 1930, Van de Kamp 1970). Borradaile (1973) has correlated them with the Tayvallich Volcanic Formation, but their sporadic outcrop (e.g. see Anderson 1947) and lack of

TABLE 2.3; Younging evidence in the Southern Highland Group.

COWAL

Beinn Bheula Schists



Dunoon Phyllites



Bullrock Greywacke

Green Beds

ABERFOYLE

Highland Border Series

"Psammitic Wacke"



Aberfoyle Slates

Green Beds

CALLANDER

Highland Border Series

U. Leny Grits



Leny Lst. and Shale



L. Leny Grits



Aberfoyle Slates



Birnam Slates

Green Beds

Ben Ledi

Grits

continuity across strike (Shackleton 1958) make them an unreliable lithostratigraphic marker (Harris and Pitcher 1975).

Roberts (1966) describes the 500m thick Bullrock Greywacke from Cowal as a pebbly and gritty greywacke with occasional blue and white quartzites. Thin grey-green slate beds do occur but are uncommon. The Birnam Grits at Dunkeld are possibly the equivalents of the Bullrock Greywacke but the type localities of the two formations are about 120 km apart, along strike and the evidence to support their correlation is very slender. Harris (1972) described the Birnam Grits in detail. They consist of medium bedded, poorly sorted, angular grained sandstones, sometimes graded. Sedimentary structures include load casts and scouring. The formation also includes bands of pale green and purple homogeneous siltstones.

The Dunoon Phyllites and Inellan Group at Cowal are considered equivalent to the Aberfoyle Slates (at Aberfoyle and Callander) and the Birnam Slates (at Dunkeld) (see Fig. 2.1).

Roberts (1966) has demonstrated at Cowal that the Dunoon Phyllites and Inellan Group are younger than the Bullrock Greywacke. The Dunoon Phyllites (approximately 2,000m thick) are predominantly dark grey, blue and purple slates. Thin bedded dark grey limestones are abundant and amongst these Bliss and Grant (unpublished data) have found evidence of algal mat (laminar stromatolites sensu. Walter 1972) (Fig. 2.2 and 2.3). Roberts (1966) also describes some well developed

Fig. 2.2 and 2,3; Probable relict algal mat from the Dunoon Phyllites at Cowal. The dark laminae consist of organic matter with layers of quartz and calcite minerals between them.

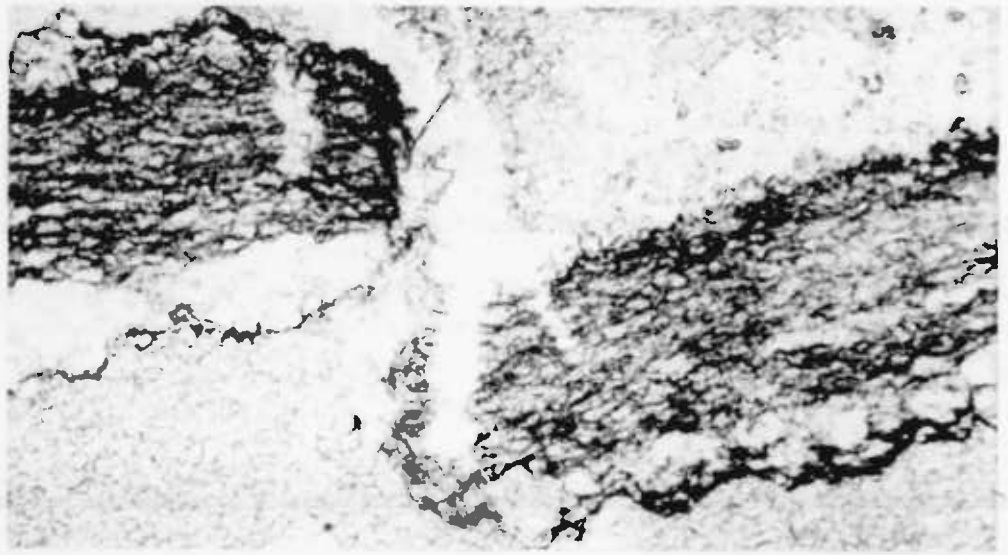


Fig. 2.2

$\overline{0.1\text{ mm.}}$

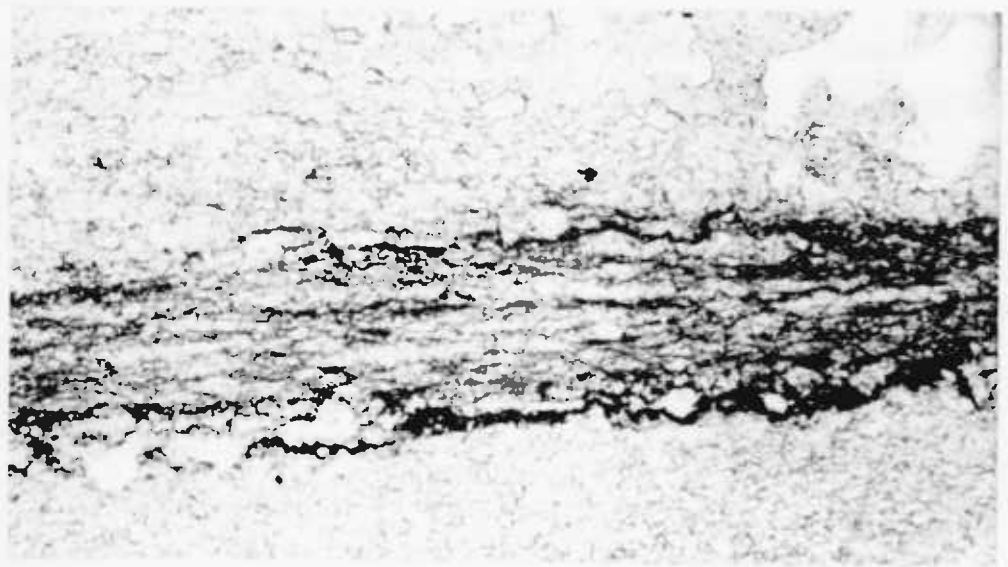


Fig. 2.3

$\overline{0.1\text{ mm.}}$

greywackes and possible "carbonated pillow lavas". The Inellan Group is similar to the Dunoon Phyllites, except that the black shales are more gritty and there is a greater proportion of greywacke.

The Aberfoyle Slates in their type locality at Aberfoyle (Map 1) are dominantly purple or red, becoming green to the north. They are approximately 400 - 900m thick (Stone 1957).

Stone (1957) demonstrates that the Aberfoyle Slates extend north east to Callander (Map 1) where they are again grey, green and purple (Harris 1962), and that there is a transitional junction between the Aberfoyle Slates and the younger Ben Ledi Grits.

Harris (1972) divides the Birnam Slates into Lower and Upper units. The lower unit is dominantly purple with pale green laminae while the upper unit is dominantly green with local purple siltstones. Grading is common and cross lamination also occurs.

The Beinn Bheula Schists (2.5 - 5.5 km thick) are part of Roberts's (1966) "greywacke affiliation" and as such, fine grained greywacke predominates with some green slate and siltstone. The possibly laterally equivalent Ben Ledi Grits are younger than the Aberfoyle Slates (Stone 1957, Harris 1962 and 1972). Stone (1957) and Roberts (1966 p.321) follow Anderson (1947) in correlating the Ben Ledi Grits with the Leny sequence (Fig. 2.1). The Ben Ledi Grits are grey-green chloritic grits (Stone 1957) with common pale grey carbonated grits. Current bedding is frequent (Harris 1962).

At Dunkeld (Map 1), the Dunkeld Grits are younger than the Birnam Slates (Harris 1972, Shackleton 1958). They are thick bedded sandstones, commonly pebbly with some green siltstones, (Harris 1972, Anderson 1947).

The Leny Group (Fig. 2.1) consists of the Upper and Lower Leny Grits, separated by the Leny Limestone (Anderson 1947, Stone 1957). Harris (1969) demonstrated on structural grounds that the Leny Limestone was part of the Dalradian. The Leny Grits are thin to medium bedded greyish-green pebbly sandstones. The pebbles are subangular. The beds are well sorted and graded (Harris 1962).

The Leny Limestone and Shale is best exposed in Leny Quarry (Map reference NN 696 095). The Formation is largely black lustrous, highly carbonaceous shale. It has been described as "anthracitic", and indeed will smoulder when put in a flame. The Leny Limestone occurs as about 50 cm beds of dark grey recrystallised carbonate. Some lamination can be found which may be relict algal mat. However the evidence is highly equivocal.

At the top of the Dalradian is the Highland Border Series which is equivalent to Jehu and Campbell's (1917) Black Shale and Chert Series. This Formation has been considered as Arenig in age (Harris and Fettes 1972), Downie 1971). The Formation consists of spilites overlain by grey cherts and black carbonaceous shales, with some interbedded cherty shales and mudstones.

2.1.(e) Banffshire

The only rocks of Banffshire that are of interest in this study are the Macduff Slates Formation (Read 1923 and 1936, Sutton and Watson 1955). Sutton and Watson (1955) estimate the thickness of the formation as about 1,300m. The rocks are dominantly grey-blue greywackes and blue, grey or greenish well cleaved slates and silts. Laminated bedding is a common occurrence as is graded bedding and intraformational conglomerates. Sutton and Watson (1955) have made a detailed study of the sedimentology of the Banffshire Dalradian in general. Many of the silts contain abundant angular quartz grains. Unstructured carbon fragments with similar size range to the quartz grains are very common. For a rock rich in carbonaceous matter it is surprising how little very fine grained organic debris there is. This is discussed in Chapter 5.2. Beds of pebbly grits with both quartz and feldspar pebbles, and calcareous grits, also occur, but less commonly.

2.1.(f) Review of the Depositional History of the Western Dalradian in Scotland

Unravelling the depositional history of the Dalradian is complex. This is partly due to the large area involved. Sedimentary compartmentation during deposition and post-depositional tectonism, has divided the basin into blocks, difficult to correlate. With the application of modern sedimentological techniques to more of the Dalradian Supergroup, it will become possible to correlate sedimentologically and accurately between these blocks. Because of the size of the

Dalradian basin and tectonic instabilities during sedimentation, local unconformities occur at least seven times (Fig. 2.4). That this does happen can be appreciated from the difficulties encountered when attempting to correlate along strike. Little detailed work on depositional environments has been carried out, and most Dalradian research has been concerned with Dalradian structure and stratigraphy. Thus the conclusions outlined below will tend to be speculative because of the limited nature of the evidence.

One major problem found in the interpretation of sedimentological data from the Dalradian is that of removing the effect of tectonism on current directions. This is a complex problem, and the cautionary words of Ramsey (1959) concerning the unfolding of non-cylindrical folds, should be borne in mind whenever dealing with current directions in the Dalradian.

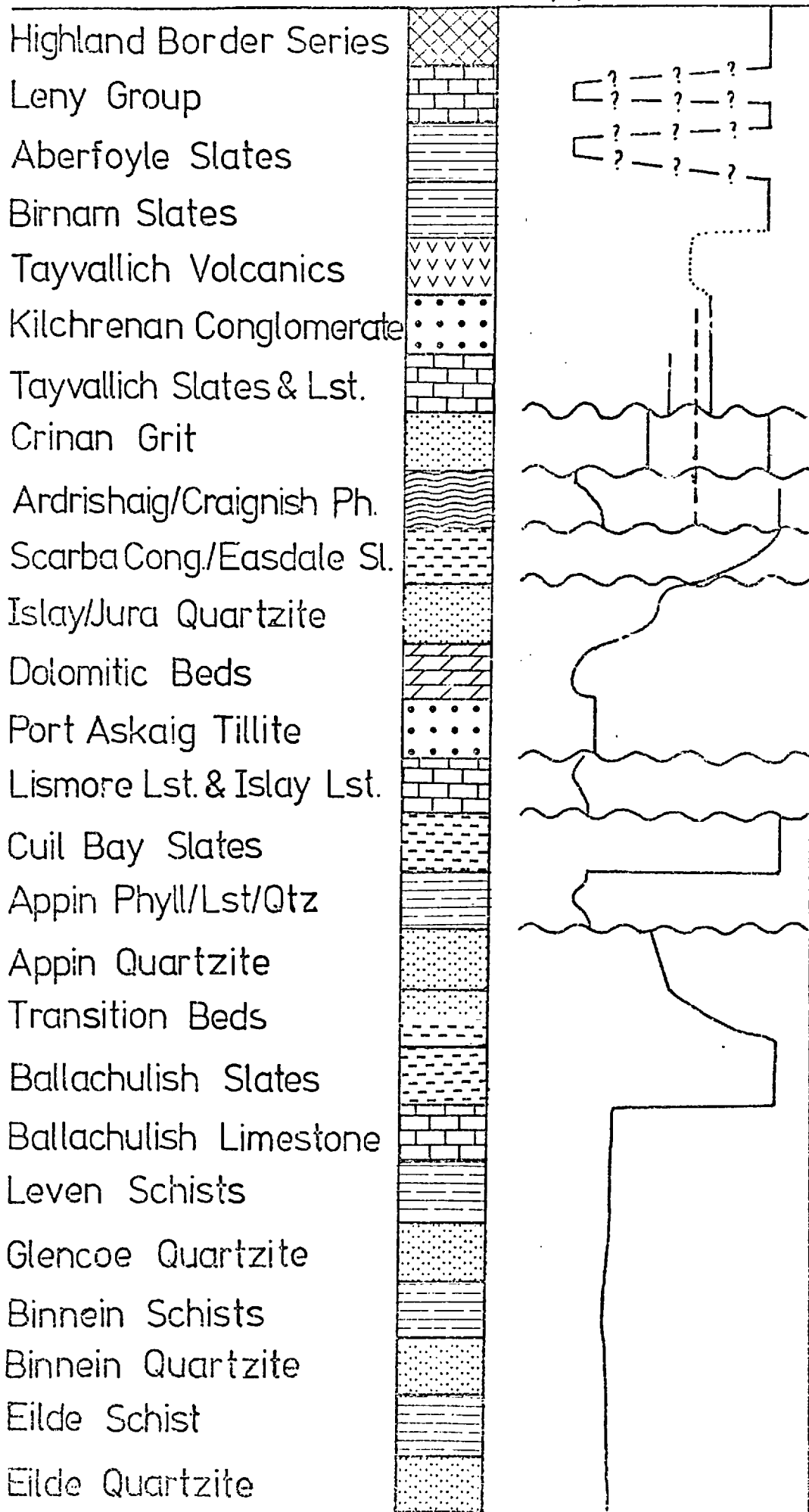
Appin Group

Lochaber Sub-group (Fig. 2.1)

In the Ballachulish area (Map 1), deposition of rocks older than the Lochaber Sub-group ended with the deposition of the immature Eilde Flags. Hickman (1975) considers this to be of shallow water coastal origin. Deposition during the Dalradian Lochaber Sub-group continued with high energy influxes of sands with abundant channelling and cross-bedding, now represented by quartzites. Quieter periods of sedimentation are represented by the interbedded schists (Fig. 2.1 and 2.4). The more turbulent conditions during the sand

Fig. 2.4; Diagram showing changes in depositional environment, during the Dalradian. This applies only to the Dalradian in the west of Scotland. The wavy line represents a local unconformity. See text for discussion.

Fig. 2.4



influxes of this time is also evident in the Maol an Fhithich quartzites on Islay (Basahel 1972). Cross-stratification is abundant in the quartzites and indicates a source to the south (Hickman 1975).

Ballachulish Sub-group (Fig. 2.1 and 2.4)

It is generally accepted that the lower part of the Ballachulish Sub-group was deposited under reducing conditions as evidenced by the black Kintra and Ballachulish Limestones and the black slates with pyrites of the Cnoc Donn Slates and Ballachulish Slates. However, Basahel (1971) considers these to be shelf sediments, deposited under relatively shallow water conditions. Hickman (1975) interprets them as initially open, deep water, low energy marine sediments, passing up into deep water turbidites, from the presence of occasional graded beds in the Ballachulish Slates. The two conclusions are difficult to reconcile, but the general appearance of the sediments in the field (monotonous and widespread lithology) suggests that they were deposited under deep water conditions.

A change in conditions took place at the top of the Ballachulish Slates. This led to an increasing influx of higher energy sands. These pebbly and cross-bedded sands are probably shallow water in origin (Hickman 1975). The cross-bedding indicates a source to the northwest or west (Basahel 1971), although the method of correction for tectonic dip is not indicated.

The Cnoc Donn Quartzite and the laterally equivalent Appin Quartzite may have been deltaic (Hickman 1975). Sedi-

mentary structures are abundant in the Appin Quartzite and indicate a source to the southwest (Litherland 1970, Hickman 1975), while ripple marks indicate a strand line to the northwest. This suggests that the Appin Quartzite was deposited by longshore currents. A similar situation occurred during Islay/Jura Quartzite times (Islay Sub-group). The Appin Quartzites are stratigraphically equivalent to the Cnoc Donn Quartzite which crops out on Islay, to the southwest and closer to the postulated shoreline to the northwest. The Cnoc Donn Quartzites are considered intertidal by Basahel (1971) with a source to the northwest or west. Thus, although the picture is slightly confusing, the evidence suggests that the Appin Quartzite was deposited by longshore currents flowing northeast, possibly on a shelf, while the Cnoc Donn Quartzite was deposited closer inshore by currents flowing directly off a land area.

A non-conformity at the top of the Appin Quartzite in the Glen Creran area (Litherland 1970) indicates local penecontemporaneous uplift and submarine erosion.

This was followed by a period of rapid facies changes at the top of the Ballachulish Sub-group, represented by the Appin Phyllite and Limestone Formation and the Cnoc Donn Phyllite/Quartzite/Limestone Formation. The dolomitic limestones show evidence of shallow water and evaporitic conditions (Basahel 1971), and Hickman (1975) considers that the sediments represent a clastic-carbonate shoreline, with an oxidizing environment. The possibility that the rapid changes in lithology are due to uplift and land emergence is

considered by Basahel (1971), but they may also represent a complex sedimentological situation with the irregular input of sediments.

Blair Atholl Sub-group (Fig. 2.1 and 2.4)

The Cuil Bay Slates and Baharradail Phyllites represent a rapid return to low energy reducing conditions, at the start of the Blair Atholl Sub-group. The lithology of the Cuil Bay Slates is very similar to that of the Ballachulish Slates and the two may have been deposited in similar environments. Hickman (1975) on the basis of a high alumina content in the Cuil Bay Slates suggests a predominance of chemical weathering, probably in a hot humid climate. This fits well with the likely low ($< 10^{\circ}$ S) palaeolatitude of the Dalradian during the late Appin Group and early Argyll Group times (Tarling 1974).

A local non-conformity on Islay at the base of the Islay Limestone represents local uplift, probably as block movements, and submarine erosion. Similar local block movements have been reported by Litherland (1970) in the Glen Creran area above the Appin Quartzite, and probably formed an important control on Dalradian sedimentation.

The Lismore Limestone appears to follow conformably after the Cuil Bay Slates but represents a marked change in depositional environment. The Lismore Limestone was probably deposited under shallow water lagoonal or restricted shelf conditions. It would be worthwhile examining the Lismore Limestone closely for evidence of stromatolites which would be

strong evidence for a shallow water origin for this Formation.

Hickman (1975) contrasts the depositional environment of the Lismore Limestones with that of the Ballachulish Limestone which was probably deposited under deeper water conditions. The Lismore Limestone has a higher concentration of "shallow water elements" (Cr Zr Nb) and also a higher Sr level. Hickman (1975) considers the latter indicative of a high salinity and shallow water conditions, although no evaporites have been reported from the Formation.

On Islay the deposition of the Blair Atholl Sub-group ended with the Islay Limestone. On the mainland there appears to be a gap between the Lismore Limestone and the Port Askaig Tillite. This may be due to penecontemporaneous erosion, but sure evidence of this is lacking. The alternative is that the Lismore Limestone was a far thicker Formation than is at present observed (1,050m, Hickman 1975) and that deposition continued unabated until Port Askaig Tillite times. The original thickness may have been reduced by tectonic thinning.

The presence of ooliths in the Islay Limestone (Bailey 1916) indicates that the formation was deposited under shallow water conditions. This is further substantiated by the occurrence of stromatolitic dolomites. If comparisons are made with modern stromatolite environments (Logan et al. 1964, Davies 1970) the Islay Limestone was deposited in a shallow well aerated and warm environment. Local uplift and erosion during this time is shown by non-conformity at the top of the Formation.

Argyll Group

Islay Sub-group (Fig. 2.1 and 2.4)

The possibility of a glacial origin of the Port Askaig "Tillite" at the base of the Islay Sub-group has caused considerable debate over the last 150 years. Thompson (1875) argued strongly for a glacial origin for the Formation, stating that he had found a striated boulder of quartzite within it. Unfortunately, this is the only report of striations and some doubt must be placed on its reliability. Bailey (1916) quoted the lack of striated boulders and the apparent "contemporaneous erosion" of the stratified beds within the formation when he questioned the necessity for a glacial origin. A non-glacial origin for the boulder beds has been suggested by Schermerhorn and Stanton (1963 and 1977) who interpreted similar beds in the West Congo as slide breccias or sub-aqueous mud flows.

Kilburn et al. (1965) considered that a slide breccia is incompatible with shallow water conditions (Klein 1970) both along and across strike for considerable distances. They also considered that a slide breccia is incompatible with the absence of ^{load} lode or flute casts, the absence of graded beds, the consistent occurrence of the boulder bed at one stratigraphical level, and the large size of the granite blocks, and the uniform assemblage of granite blocks over such a wide area. The large size of the blocks however, would not be inconsistent with a slide breccia origin, e.g. the Anglesey Melange (Greenly 1919).

In support of a glacial origin, Kilburn et al. (1965) compared the Port Askaig Tillite with the glacial tills of the Permo-Carboniferous Dwyka Tillite and with Pleistocene boulder clays. Also they point to the varved siltstones, large sand-filled polygons and involution-like structures (indicative of periglacial conditions) large boulders suggesting ice rafting and the preferred orientation of the boulders. Of these criteria, the first three, and the presence of drop-stones (Spencer 1971) are the best evidence for a glacial origin.

The source of these rocks may have been to the southeast, as Kilburn et al. (1965) found no boulders of Lewisian lithology. However it is possible that the Lewisian was not exposed at that time. A source to the southeast is also suggested by Spencer (1971) on the evidence of the orientation of elongate boulders and sedimentary folds. Spencer (1971) has demonstrated that the abundant cross-stratification and ripple marks of the interbeds show good preferred orientation in any one bed, but that this does not apply to the Formation overall. Spencer (1971) suggested that this was due to the absence of a single palaeoslope during deposition.

Dolomites are commonly interbedded with the mixtites and are well developed in the formations immediately above and below. Stromatolites form a significant part of both dolomitic formations. The presence of these apparently warm water sediments intimately associated with apparent glacial conditions is a considerable enigma. This strange relationship is widespread in the late Precambrian (Martin 1965, Olson 1966, Young 1972) and Williams (1975) has listed 28

localities, divisible into possibly three time groups, where a dolomite/glacial association occurs. These occur on every continent, but those most closely related to the Port Askaig Tillite appear to be those of Scandinavia (Banks et al. 1971, K. Bjorlykke 1967, K. Bjorlykke et al. 1976, Føyn 1938, Reading and Walker 1966 etc.).

There is palaeomagnetic evidence that the Port Askaig Tillite and similar sequences in Norway and Greenland occupied a low palaeolatitude ($< 20^{\circ}$ S.) at the time of deposition (Tarling 1974, Harland and Bidgood 1959, Bidgood and Harland 1961). Steiner (1967) and Meyerhoff (1971) attempted to explain fluctuations in the Earth's climate in terms of galactic evolution of the Solar System. However the period of 200 m.y. for this is probably too short. Roberts (1971) suggested an "anti-greenhouse" model, with CO_2 locked up in carbonates leading to a world-wide lowering of temperatures. However the presence of abundant Mesozoic and early Tertiary carbonates without accompanying glaciogenic rocks make this hypothesis unlikely, especially when compared with the relative lack of late Precambrian/early Cambrian carbonates in bulk. Williams (1972 and 1975) puts forward a novel hypothesis which relies on variations in the obliquity of the Earth's ecliptic (E). When there is a marked increase in E, (1) there would be a great intensity of global seasonality. High and low latitudes would have long hot summers, and long sunless winters. The equatorial climate would be less extreme. (2) Annual insolation would increase for latitudes greater than 43° and the ratios of pole insolation to equatorial insolation would

increase significantly. At $E = 90^{\circ}$, the equator would get less total insolation than either pole.

If during a period when E was $> 54^{\circ}$, the world entered an ice age a number of effects would take place. (1) During low insolation, continental ice sheets would develop first in low and middle latitudes ($< 43^{\circ}$) and would be confined to these latitudes. (2) Permafrost would be confined to low and middle latitudes as it would not survive the extreme summers of high latitudes. (3) The pronounced seasonality due to two solstitial freezes and two equinoctial thaws, would lead to very thin varves relative to those at high latitude. (4) Due to weak climatic zonation, local climates would be in delicate balance, and warm water could occur over wide latitudes. Short term fluctuations in insolation ($10^4 - 10^6$ years duration) would cause exaggerated oscillations in local climate, resulting in interbedding of glaciogenic beds with warm water facies.

If $E = 90^{\circ}$, then glaciation in low latitudes ($< 30^{\circ}$) would cover about 50% of the Earth's surface, whereas equivalent glaciation in high latitudes ($> 60^{\circ}$) would only cover about 14% of the Earth's surface. (The area of a symmetrical equatorial zone = $4\pi R^2 \sin L$. Area of two equal pole caps = $4\pi R^2 (1 - \sin L)$, where R = Earth's radius, and L = limiting latitude).

Therefore the widespread extent of glaciogenic rocks in the late Precambrian does not necessarily imply total glaciation. Further, the instability of climatic zones, and the short distances continents would have to drift in order

to enter and/or leave the narrow equatorial band of glaciation would lead to moderate tillite diachronism. Thus the use of late Precambrian tillites as subtle time stratigraphic marker horizons over considerable distances (e.g. Scotland, Greenland and Scandinavia) may not be justified, unless substantiated by other data e.g. palaeontological.

After the Port Askaig Tillite was laid down, the Bonahaven Dolomite was deposited under intertidal/supratidal conditions. This formation contains mudcracks (Spencer and Spencer 1972), stromatolites (Peach and Horne 1930, Hackman and Knill 1962, Spencer and Spencer 1972), and evaporite pseudomorphs (Llewellyn 1969, MacGregor pers. comm.). It is important to note that the formations both above and below the Port Askaig Tillite are abundant with stromatolitic dolomites.

From Islay/Jura Quartzite times, at the end of the Islay Sub-group through the Easdale Sub-group, and into Crinan Sub-group times sediments were deposited under environments that gradually deepened overall with time, and towards the northeast.

The Jura Quartzite was interpreted by Knill (1963) as probably deltaic, with the lenticular geometry of the formation indicating that sediment transport was from the northwest. However Anderton (1974) has carried out a far more detailed sedimentological analysis and has recognised two depositional facies. His "coarse facies" was considered to be a submarine deposit of coarse sediment deposited in a shallow marine tidal environment by high flow conditions and possibly bordered by

exposed sandy beaches, represented by the lowest strata on Jura.

The "fine facies" is interpreted as being deposited in shallow marine waters from influxes of currents carrying suspended sands. These influxes could have been tidally dispersed, storm generated suspension clouds. Anderton (1974) considers that the channel style found in this facies is unique to marine environments. There is no cyclicity in the Jura Quartzite but there is a general fining upwards (Anderton 1974, Bailey in Peach et al. 1911) and to the north. Palaeocurrent indicators consistently show flow from the south-south-west (Anderton 1971 and 1974). Anderton (1974) concludes that the Islay/Jura Quartzite was deposited by longshore currents on a continental shelf, with a land mass to the northwest. The palaeocurrent directions in the lowest strata on west Jura trend generally towards the southeast, but diverge, indicating a spot source some 20 km northwest of Jura. The sea was probably funnel shaped and for the formation to be deposited in the geometry it was, Anderton (1974) suggests a submarine barrier separated the sea from a deeper basin to the southeast.

Easdale and Crinan Sub-groups (Fig. 2.1 and 2.4)

At the end of Islay/Jura Quartzite times, the sea floor began to subside relative to the northwest and a shelf edge/slope region was established on which the Scarba Conglomerate was deposited, probably under relatively shallow water conditions (about 200m, Anderton 1974). The formation thickens

to the north and was deposited by turbidity currents flowing towards the southeast. Under these conditions the coarser sediments were probably proximal turbidites, while the mud dominant members would have been deposited under lower energy conditions.

Deepening of the ocean lead to a fining upwards of the Scarba Conglomerate and the subsequent establishment of a steeper slope. This was tectonically controlled by a basement fault running parallel to the long axis of the trough. During times of steep slope gradient, larger slumps took place in the Scarba Conglomerate with subsequent deep erosion into the Islay/Jura Quartzite. At other times deposition was restricted to settling muds and small turbidites. As tectonic activity died down and the slope decreased in gradient, gentle subsidence lead to the fining upwards of the Scarba Conglomerate into the Easdale Slates. The boundary between the two formations is strongly diachronous.

Anderton (1974) considers that most of the deposition of the Easdale Slates took place as muds from turbidity currents and nepheloid suspension in an enclosed basin. The rare sandstones and carbonates were also derived from turbidity currents. Mass flow and slide deposits at Benderloch (south of Appin) and an increase in turbidites to the north, suggests that the slope was to the north or northwest. The earlier instabilities during the Scarba Conglomerate had ceased by Easdale Slates times and the basin gradually filled. Some coarser clastics were derived from the northeast and some of the fine clastics and carbonates from the east. Anderton

(1974) suggests that there was a low relief feature to the east but with no subaerial contact with the landmass to the northwest.

The formations which lie above the Easdale Slates (i.e. the Ardrishaig/Craignish Phyllites and the Crinan Grits) are noted for a differentiation between the west of the region and the east. This is marked by a considerable difference in thickness with the eastern area being thicker, and a considerable facies difference in both formations.

At the base of the Ardrishaig/Craignish Phyllites, is the Degnish Limestone Member. Anderton (1974) interprets this pebbly Member as probably shallow water sediment derived from the east. Borradaile (1973) interprets the Member as being derived by turbidity currents from the northeast, and deposited on a southwest dipping surface. He quotes as his evidence; internal lamination, ripple current bedding, and matrix supported graded pebbles.

In the Craignish area, the Ardrishaig/Craignish Phyllites were probably deposited in an epicontinental shallow water sea (Knill 1959). Palaeocurrents flowed from the northwest (Knill 1959, Borradaile 1973, Anderton 1974). During deposition, supratidal or tidal flat conditions obtained, with gypsum pseudomorphs and tidal channels being preserved (Anderton 1974, and 1975). This section appears to fine upwards suggesting the tidal flat was regressive. Palaeocurrents in this environment indicate a source to the north or northeast. Anderton (1974) considers this is complementary to the results of Knill (1959), Roberts (1966) and Borradaile

(1973) whose results spread from northwest to northeast.

To the east (the Ardrishaig Phyllites) Borradaile (1973) found no evidence for shallow water conditions and interpreted the mechanism of deposition as turbidity currents flowing on a southwest dipping surface. The great thickness and general uniformity of the Formation suggests that sedimentation was synchronous with subsidence.

The Shira Limestone occurs in both the west and east of the outcrop of the Ardrishaig/Craignish Phyllites and on the evidence of laminar stromatolites (Anderton 1974) and current bedding (Borradaile 1973) the depositional environment may be considered shallow water or intertidal.

Crinan Sub-group

Depositional style and rate continued to be separated into east and west areas during the deposition of the Crinan Grits. In the west the Formation is less than 600m thick (Borradaile 1973) (150 - 200m Knill 1963), while in the east this increases to nearly 2,000m. The formation also becomes coarser, more pebbly and more thickly bedded eastwards, and Borradaile (1973) has divided the region into eastern and western facies. During deposition, the eastern area acted as a continually subsiding basin, into which coarse sediments were swept, while the west was a more stable block. Borradaile (1973) interprets all the formation as being derived from turbidites. On the basis of the geometry of the Formation Borradaile suggests that the source was to the northwest or southeast. Knill (1963) from palaeocurrent data at

Kilmartin, shows that in general the coarse sediments were derived from the north, while the finer grained sediments have a more variable source direction. Knill (1963) considers the sediments were deposited in a trough orientated north north east - south south west, by axially flowing density currents.

Tayvallich Sub-group

The differentiation of the area into east and west is still recognisable during the deposition of the Tayvallich Slates and Limestones Formation. The two areas are separated by a recognisable shelf break, with a slope established in the eastern region, distinguished by the presence of limestone slump breccias derived from submarine landslides (Knill 1963). The western facies is finer grained with only a few sedimentary structures (sedimentary dykes, Smith and Rast (1958)), and was deposited on a shelf. Borradaile (1973) has recognised that slump breccias are confined to the lower and northwest parts in the Loch Awe area and interprets this as the shelf edge and source retreating to the northwest. The presence of blue quartz grains in the gritty beds of the Formation may indicate a Lewisian source (cf. Sutton and Watson 1955).

Evidence of volcanism in the western Dalradian of Scotland, first occurs in this Formation with the infrequent occurrence of subaqueous lava flows, with pillow lavas in the south of the outcrop.

The greywacke of the Kilchrenan Grit was deposited under conditions of little reworking, and the paucity of grading, and preserved massive bedding suggest that this Formation was deposited as a proximal turbidite. The Formation thins to the southeast and southwest and was possibly derived from the north.

The matrix supported, pebbly, Kilchrenan Boulder Bed is interpreted by Borradaile (1973) and Kilburn et al. (1965) as a slump deposit. The nature of the formation, and its general thinness (less than 30m) has lead to its use as a local chronostratigraphic horizon. From the petrography of the pebbles, the source would have been a lithified quartzite. The most likely candidate is the Crinan Grits, as the Islay/Jura Quartzite and the Maol an Fhithic Quartzite would have necessitated an excessive amount of uplift and erosion. However, the source area may equally have been further away.

Southern Highland Group

The Southern Highland Group appears to represent a marked change in Dalradian sedimentology. Fully developed volcanic activity occurs in the Tayvallich Volcanic Formation, the thin Green Beds (equivalent to the Tayvallich Volcanics) and the Loch A'vich Volcanic Formation. It is interesting to note that volcanic activity is largely restricted to the Loch Awe and Tayvallich areas, with only the thin and very discontinuous Green Beds showing evidence of volcanism elsewhere in the Dalradian outcrop. This suggests that

volcanism was controlled by volcanic centres rather than a belt of volcanic activity.

Many of the volcanogenic rocks in the Tayvallich Volcanic Formation were deposited as subaqueous ash deposits, and subaqueous lava flows, as evidenced by the presence of pillow lavas.

The Tayvallich Volcanics are separated from the Loch Avich Volcanics by the Loch Avich Grits. The latter represent a relative increase in sediment input, with deposition taking place partly under reducing conditions (the black slates). The black slates were replaced laterally and upwards by green slates, and grits, possibly representing proximal turbidites.

The volcanic activity that returned with the Loch Avich Volcanics was totally subaqueous with abundant pillow lavas being preserved.

The green and purple slates of the Aberfoyle Slates and the slate/chert/spilite association are also not found elsewhere in the Dalradian sequence, and suggest a difference in sedimentation during the Southern Highland Group.

Due to poor exposure along and across strike in the Highland Border region, the depositional history of the Group is poorly known. At present the accepted model is one of deposition by distal turbidites in deep water. At the moment there is insufficient data to examine this model fully, but there are two points which indicate that re-examination may be necessary.

Firstly, there is considerable lateral facies change, along strike, e.g. the black slates and limestones of the

Dunoon Phyllites pass laterally into the green and red slates of the Aberfoyle Slates and Birnam Slates. Also, the "anthracitic" Leny Limestone and Shale is flanked by grits and psammitic wackes at Cowal, Aberfoyle, Callander and Dunkeld. These changes may be due to the interdigitation of turbidite fans, but they may also be due to lateral facies changes in shallow water.

Secondly, a laminar limestone in the Dunoon Phyllites at Cowal has been found that appears to represent relict algal mat. (Fig.2.2 and 2.3) If so, then this is good evidence for shallow water origin for these limestones.

Summary

The depositional history of the western Dalradian is characterised by local unconformities and breaks, often accompanied by evidence of contemporaneous erosion and sudden changes in depositional environment. Further, deposition from the start of the Ardrishaig/Craignish Phyllites until the end of the Tayvallich Slates and Limestones is characterised by a differentiation into a western area and eastern area, the dividing line trending northeast-southwest from Loch Craignish to the northwest of Loch Awe. At times, along this line evidence of shelf break and slope conditions can be found. Deposition west of this line is generally shallower than to the east. As a generalisation, deposition after the Easdale Slates was in deeper water than the underlying formations.

The local unconformities and sudden changes in depositional environment occur as follows:

- (1) Possibly a sudden change in depositional environment from shallow water to basinal sedimentation at the base of the Ballachulish Slates.
- (2) Erosion at the base of the Appin Phyllite/Limestone Formation.
- (3) Possibly a sudden change from shallow/inter-tidal sedimentation at the base of the Cuil Bay Slates.
- (4) Erosion at the base of the Islay Limestone Formation on Islay.
- (5) Probably non-deposition at the top of the Lismore Limestone Formation on the mainland.
- (6) Erosion at the top of the Islay Limestone Formation on Islay.
- (7) Contemporaneous erosion of the Islay Quartzite Formation during the deposition of the Scarba Conglomeratic Formation and the Easdale Slates Formation.
- (8) Erosion at the base of the Ardrishaig/Craignish Phyllite Formation. This forms a major unconformity that can be correlated with Donegal (see Pitcher and Berger 1972 p.38).
- (9) Erosion possibly at the base of the Crinan Grit Formation.
- (10) Erosion at the base of the Tayvallich Slates and Limestone Formation in the Kilmartin area.

- (11) Possibly a sudden change in environment during the Aberfoyle Slates Formation.
- (12) Possibly a sudden change in environment during the Leny Group.

The Appin Group is characterised by shallow water sedimentation deposited by currents often flowing from the southwest (as longshore currents) or from the northwest where a landmass existed. Shallow water sedimentation was interrupted during the Ballachulish Slates and Cuil Bay Slates by sudden deepening of the water. These conditions were followed by sudden uplift, submarine erosion, and deposition of shallow water sediments. At the top of the Islay Limestone similar submarine erosion took place before the deposition of the Port Askaig Tillite.

The Port Askaig Tillite is a unique formation in the Dalradian being glacial in origin, with a possible source to the southeast. The enigmatic association of glacial tillite and warm water dolomites may be explained by variations in the Earth's obliquity.

Deposition of that part of the Argyll Group after the Port Askaig Tillite shows a deepening upwards and towards the northeast. Starting with the supra-intertidal Bonahaven Dolomites, the sediments pass up into the Islay Quartzites, deposited on a shelf mostly by longshore currents flowing northeast. Only the lowest strata in the formation show evidence of being derived by diverging currents directly from a landmass to the northwest. Slope conditions were established

during the Scarba Conglomerate, partly due to relative uplift of the Islay Quartzite, which was deeply eroded and provided blocks and finer sediments both for the Scarba Conglomerate and the basinal Easdale Slates which followed. A continued gradual deepening is evidenced by the highly diachronous boundary between the Easdale Slates and the Scarba Conglomerate. The former was deposited in a deep restricted basin.

Uplift and erosion of the Islay Quartzite and the establishment of a tectonically active slope during the Scarba Conglomerate times was due to a basement fault, active during sedimentation. This fault had a trend approximately northeast-southwest, and can be recognised as an important feature in Dalradian sedimentation after the Easdale Slates. Before the Easdale Sub-group, this particular fault is not recognisable as such. However, the local non-conformities on Islay and the mainland and the sudden changes in depositional environment, described above, may be attributed to this major fault, or more likely, splays at an oblique angle to it. Block faulting arising from this fault pattern would have controlled sedimentation. Anderton (1974) considers a positive feature possibly existed to the southeast of the Islay Quartzite, to account for the geometry of that formation. If this is so then the depositional basin during Appin Group and early Argyll Group times appears to be graben-like.

A regional unconformity separates the Easdale Slates from the Ardrishaig/Craignish Phyllites. The syn-depositional fault trending northeast-southwest continued to be active until the end of the Tayvallich Slates and Limestones. It

divided the region into generally shallow water, relatively thin sedimentation in the west, from deep water, usually turbiditic very thick sedimentation in the east.

This fault was not continuously active, and during the deposition of the Shira Limestone at the top of the Ardrishaig/Craignish Phyllites, shallow water sedimentation prevailed over the whole area. As stated above this fault had a northeast-southwest trend, and possibly existed along a zone running from near Craignish to northwest of Loch Awe. Currents flowing from the north or northeast into the eastern area appear to have existed at times during the Ardrishaig/Craignish Phyllites, Crinan Grits and Tayvallich Slates and Limestones, and some of these have been interpreted as density currents. Assuming this was due to a positive feature to the north or northeast, this would define the 'nose' and part of the other side of a graben-like structure, assuming that the major basement fault was the northwest margin. Although there is this clear differentiation into a shallower water western area and a deeper water eastern area, there appears to be a gradual deepening with time overall.

The Southern Highland Group contains lithologies not previously encountered in the Dalradian. These include volcanics, purple and green slates, and the shale/chert/spilite association of the Highland Border Series. These new lithologies may represent a fundamental change in Dalradian sedimentation. The Southern Highland Group has been consistently thought of as deposited by turbidity currents in deep water. However, the lateral discontinuity of some of the

formations, especially the Leny Limestone and Shale, and the presence of what appears to be relict algal mat in the Dunoon Phyllites, are inconsistent with a deep water environment. Further examination of this poorly exposed Group may be necessary to fully understand its depositional history.

Block faulting and the establishment of a fault bound graben are the controlling factors in the depositional history of the western Dalradian. From Ballachulish Slate times until the end of the Easdale Slates, splay faults from a probably major basement fault aligned northeast-southwest, to the northwest of Islay and Jura, controlled vertical movement. After the Easdale Slates, a fault bounded graben was established, which trended northeast-southwest. The northwesterly faulted margin of this graben has been recognised and can be traced from Craignish to northwest of Loch Awe. The graben was mostly active during deposition, although there were periods of quiescence when shallow water sedimentation extended over a large part of the region.

Throughout the deposition of the Dalradian there is evidence that sediments were being derived from the east for periods of time. Evidence of easterly derived sediments can be found in the Port Askaig Tillite, Islay Quartzite, Easdale Slates, Degnish Limestone, and the Ardrishaig/Craignish Phyllites. The consistent presence of a positive feature to the east or southeast of the area being discussed, supports a grabenlike depositional history for these sediments. It also has considerable bearing on plate tectonic models that propose an ocean immediately to the southeast. The structural

setting discussed above, and the presence of a positive feature to the southeast, precludes any oceanic floor a short distance to the southeast of the depositional area.

This pattern of deposition is very similar to that of the post-Permian history of the North Sea. The smaller scale block faulting in the pre-Easdale Slates Dalradian is comparable to the fault pattern to the east of the East Shetland Platform, where a large number of faults lie at an oblique angle to the Viking Graben. The variation in environments found in the Dalradian is similar to the Cimmerian in the North Sea (Ziegler 1975). This comparison can be extended. Considering the large thickness of extremely organic rich shales and closely associated quartzites (which were probably originally coarse, highly porous and permeable) the Dalradian had the potential of producing enormous oil fields, similar to the North Sea, if the Caledonian orogeny had not occurred!

If the comparisons outlined above are valid, then deposition of the Dalradian took place in a rifting or tensile stress condition. A tensile stress pattern could lead to the block faulting and the establishment of a graben that is found. It is interesting to note that the northeast-southwest basement fault passes through the main development of Dalradian volcanism (Tayvallich and Loch Avich volcanics) round Loch Awe and Loch Avich. Wilson and Leake (1972) have carried out a comprehensive chemical analysis of the Tayvallich Volcanics. If these data are plotted after the fashion of Pearce and Cann (1971 and 1973) the majority of the plots fall into fields representing non-oceanic, intra-continental,

rifting type volcanism The average values for Sr and Y fall closest to values found in the Red Sea, while the average value for Nb from the Tayvallich Volcanics falls closest to an intra-cratonic value.

Thus, in conclusion, the western Dalradian was probably deposited under conditions of tensile stress and rifting, similar to that found in the post-Permian North Sea, arising from the initial rifting and spreading of the Atlantic Ocean.

2.1.(g) Ireland

Rocks of the Dalradian Supergroup occur in Ireland in four areas; Donegal, west Co. Mayo, the Ox Mountains, and Connemara. For the purposes of this study, the Dalradian of Connemara can be disregarded as the metamorphic grade is far too high (mostly above greenschist) for microfossils to be preserved. The sedimentology and stratigraphy of the other three areas will be described briefly here.

In Donegal the Dalradian is separated into two successions, divided by the Knockateen Slide, which runs northeast-southwest from Fanad to Ardara. Much of the ground to the northwest of this Slide is taken up by the Donegal Granite, but the remainder consists of the Dalradian Creeslough Succession. To the southeast of the Knockateen Slide occurs the Kilmacrenan Succession. Pitcher and Berger (1972) have correlated the Knockateen Slide with the Iltay Boundary Slide in Scotland.

The base of the Creeslough Succession (Fig. 2.5) is the Creeslough Formation, and is considered to occur at the top of the Lochaber Sub-group (Harris and Pitcher 1975).

Fig. 2.5; The lithostratigraphic correlation of the Dalradian Supergroup in Ireland, after Harris and Pitcher 1975.

Those Formations which have been sampled for microfossils, and those found to be fossiliferous are indicated.

SW MAYO

Ballytooney *+

slide

Achill Beg Psammite

Achill Beg Pelite *

Carrowgarve Psammite

Carrowgarve Pelite

Claggan

Glendaroolagh

slide

Achill Head Grits

Achill Head Schists *

Keem Limestone

Keem Schist

Keem Conglt.

Doagh Schist

Doogort Boulder Bed

Doogort Limestone

Doogort Schist

Doogort Quartzite

slide

Kildownet

Ashleam Head Psammite

Ashleam Head Pelite

Kildun Schist

Sraheens Quartzite

Cashel Psammite

Minaun Psammite

Slievmore Quartzite

SW OX MOUNTAINS

Ardvarney *+

slide

Raheenbar Quartzite

Sheeans Graph. Pelite *

Sheeans Volcanics

Barnageehy Limestone

Windy Gap Pelites

slide

NW DONEGAL

Kilmacrenan Grits

Boheolan Quartzite

Termon Pelites

Cranford Limestone

Slieve Tooley Quartzite

Dolomite

"Tillite"

L. Finn Dark Schist *

Loughros

Upper Falcarragh Pelites *+

Falcarragh Limestone

Lower Falcarragh Pelites *

Sessiagh-Clonmass

Ards Quartzite

Ards Black Schist *

Altan Limestone

Creelough

INISHOWEN-FANAD

Greencastle Green 'Beds'

Inishowen Head

Cloghan Green 'Beds'

Fahan Grits

Fahan Slates *

Culdaff Limestone

Upper Crana Quartzite

Lower Crana Quartzite

Linsfort Black Schists *

Lag Limestone

Fanad Quartzite

Upper Dolomite

"Tillite"

Fanad Limestone

Rosnakill Schists

Fig. 2.5; General Stratigraphy of parts of Ireland relevant to this thesis.
(after Harris and Pitcher 1975)
* Formations sampled
+ Formations found fossiliferous

A thick sequence of pyritous black shales, the Ards Pelites follows the Altan Limestone in the middle of the Ballachulish Sub-group. Towards the top the Formation includes semi-pelites, impure calcareous bands and cherty beds. Sedimentary structures include graded bedding, load casts, washouts and sedimentary dykes (Pitcher and Berger 1972).

A transition about 60m wide leads into the succeeding homogenous feldspathic sandstone of the Ards Quartzites (McCall 1954). Lenses and beds of pebbles occur.

At the top of the Ballachulish Sub-group is the Sessiagh-Clonmass Formation. This is a highly variable sequence with marked lateral facies changes (Iyengar et al. 1954, McCall 1954, Pulvertaft 1961, Knill and Knill 1961 and Rickard 1962). Five members (three dolomitic limestones and two quartzites) occur in the type area. The Formation also includes sandy shales. Abundant sedimentary structures indicate that the formation was deposited under shallow water conditions, and this is further substantiated by the discovery of relict algal mat, described by Bliss et al. (in press) (Fig. 2.6).

The base of the Blair Atholl Sub-group consists of the thick, widely spread Lower Falcarragh Pelites Formation. It consists of 600m of grey and black striped carbonaceous pelites with some semi-pelitic and calcareous beds occur. In the Maas district, the pelites become more purple.

Rickard (1962) and Pitcher and Berger (1972) describe a blue or grey limestone, with some pelitic partings, the Falcarragh Limestone, separating the Lower Falcarragh Pelites

Fig 2.6; Algal mat at Maas. (see Bliss et al. in press for detailed discussion). The dark laminae represent organic matter, and the paler layers, minerals, mostly calcite and chlorite.

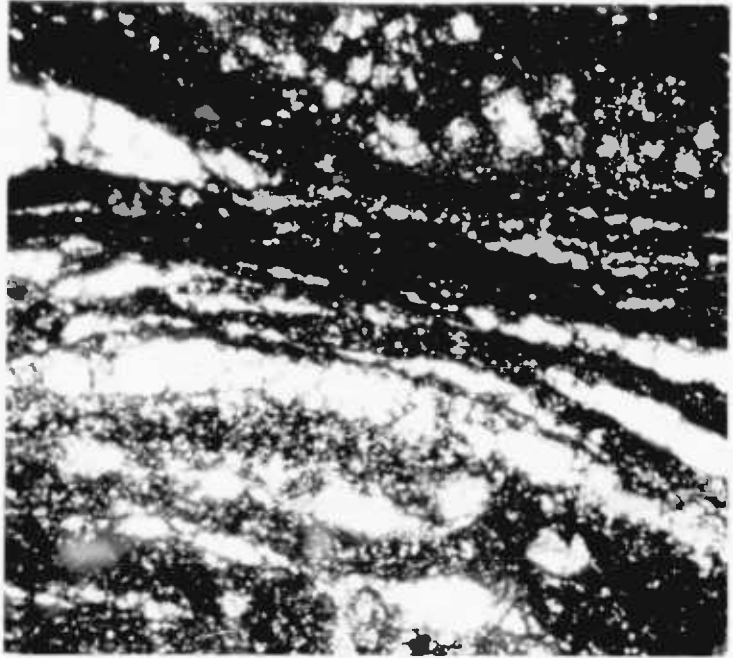


Fig. 2.6; Algal mat at Maas. (see Bliss et al. (in press) for detailed discussion.)

from the Upper Falcarragh Pelites, over a wide area. The latter formation follows gradationally from the Falcarragh Limestone, and consists of striped pelites (Rickard 1962) with discontinuous pale sands and silts. Carbonaceous matter is less abundant than the Lower Falcarragh Pelites.

The top of the Creeslough Succession is the Loughros Formation. This has sporadic outcrop and rather variable lithology, including quartzite and banded semi-pelites, and calc-flags, and limestones (Rickard 1962, Knill and Knill 1961, Pitcher and Berger 1972).

The base of the Kilmacrenan Succession is taken as the Glencolumbkille Formation (Pitcher and Berger 1972). This is correlated with the Loughros Formation (Harris and Pitcher 1975). The Glencolumbkille Pelites (Howarth et al. 1966) consist of black graphitic pelites with psammitic beds and some graphitic limestone. This is followed, without a break, by the Glencolumbkille Limestone, with a lower part of light grey marble, and an upper part of cream or grey dolomitic marble. The upper part may be stromatolitic in origin (Muir in press).

The Glencolumbkille Boulder Bed follows the Glencolumbkille Limestone. Kilburn et al. (1965) have correlated this with the Port Askaig Tillite in Scotland. In Donegal, the thickness varies from about 100m in the west to 525m in Fanad (Pitcher and Berger 1972). The lithology in Scotland and Ireland is very similar, and as this formation has been described and discussed in some detail in Chapter 2.1.(a) and 2.1.(f) it will be discussed no further here.

The dominantly quartz arenite Slieve Tooley Quartzite overlies the Glencolumbkille Boulder Bed. Subordinate feldspathic arenite and occasional calcareous beds also occur. Sedimentary structures include crossbedding and ripple marks. The Slieve Tooley Quartzite is the topmost formation of the Islay Sub-group.

At the base of the Easdale Sub-group is the Termon Formation which starts with the Cranford Limestone. This 240m thick member consists of a lower yellow dolomite with some coarse grit followed by grey limestone interbedded with pelites.

The pelites overlying the Cranford Limestone constitute the thickest part of the Termon Formation, being about 2440m thick (Pitcher and Berger 1972). The lower section of these rocks consist of dark garphitic pelites with some thin dolomites and green psammities. The dark pelites become green upwards, and lenses of pale calcareous psammities are quite common.

At the base of the Crinan Sub-group occurs the Crana Quartzite, and this is more than 1500m thick (Pitcher and Berger 1972). The Formation is interpreted as turbiditic in origin. McCallien (1937) has divided the Formation into three Members, the lowest of which is fine grained with interbedded fine psammities and striped semi-pelites. This is followed by the "Killygarvan Flags" which consist of striped psammities and thin limestones. The upper division consists of graded pebbly grits and forms the uppermost unit of the Kilmachrenan Succession.

To the south of Donegal, Dalradian rocks crop out in the Ox Mountains, and western County Mayo (Achill Island and Westport Bay).

In the southwest Ox Mountains, a major fault running north-northeast-south-southwest, to the north of Castlebar, cuts the Dalradian outcrop in two. Currall (1963) has mapped the area to the west of this fault and has placed the rocks there in the Southern Highland Group. The succession as outlined by Currall (1963) is as follows:

Ardvarney Formation

----- Slide

Raheenbar Quartzite

Sheeans Graphitic Pelite

Sheeans Volcanic Formation

Barnageehy Limestone

Windy Gap Pelites

The Windy Gap Pelites are predominantly feldspar and tourmaline rich mica schists, with some grit bands. To the south, the Formation becomes more garnetiferous.

The Barnageehy Limestone Formation, which follows, is a 15m thick white, pure recrystallised limestone with some micaceous beds.

Correlation of this sequence with the Southern Highland Group of Scotland is based largely on the similarities of petrography and sporadic outcrop between the Sheeans Volcanic Formation and the Green Beds of Scotland (Phillips 1930). The Sheeans Volcanics are mainly tuffaceous.

The Raheenbar Quartzite Formation is a 100m thick sequence of white and grey micaceous flaggy quartzites. The top 60m are dark, often containing abundant graphite. At the top of the formation, thinly bedded graphite schists occur.

A thrust separates the Ardvarney Grits and Phyllites from the sequence below. This Formation is about 300m thick. The grits are poorly sorted often with pebbly bottoms. Many of the grits have a distinct green colour due to the presence of chlorite rich lenses. Interbedded with the grits are green and purple-grey phyllites.

To the northeast of Castlebar, the rocks have been described as Moine or pre-Moine (Harris and Pitcher 1975; Johnstone 1975, Phillips 1973). Taylor (1968) and Long (1974) have suggested they are Dalradian on the basis of lithological structural comparisons with known Dalradian rocks in Ireland.

Long (1974) describes four Dalradian formations in the area as follows:

Cappagh Formation	
Garraghill Formation	Argyll Group
Tawnyshane Pelite Formation	Appin Group
Tawnyshane Marble Formation	

The Tawnyshane Marble Formation is a very poorly exposed white tremolitic marble, 90m thick, that passes up transitionally into the Tawnyshane Pelite Formation. This is a "vaguely" banded pelite with some marble towards the top. There is an increase in quartzite towards the top of the Formation, which

passes through a transition zone into the Garraghill Formation.

The Garraghill Formation is a 1750m thick sequence of white quartzites overlain by feldspathic psammites and rare pelites and semi-pelites. Near the top of the Formation, feldspathic bands occur. This Formation is characterised by extensive veining by granitic and pegmatitic sheets.

Taylor (1968) records a sharp transition at the base of the Cappagh Formation. This is 650m thick and consists of pelites, semi-pelites and psammites, at the base, overlain by the amphibolitic Newantrim Member.

Long (1974) uses the amphibolitic Newantrim Member to correlate with Taylor's (1968) "volcanic amphibolite" in the Slieve Gamph area (central Ox Mountains), and also the Garraghill Formation with Taylor's (1968) Leckee Quartzite. Taylor (1968) tentatively correlates this with the Termon Formation in Donegal.

On Achill Island, Co. Mayo, the Dalradian rocks are separated into two areas, one at the northern end and the other at the southern end of the island, by a large expanse of Moinian (Max 1972). The rocks in the north are of too high metamorphic grade to warrant collection. However, one formation, the Doogort Limestone is of interest, as relict algal mat has been recognised in the limestone at Doogort (Muir in press).

Rocks of lower metamorphic grade occur on the south end of Achill Island (south of Ashleam Bay), and on the tiny island of Achill Beg. A succession from the Moine, southwards to Achill Beg is almost complete.

Fig. 2.7; Sketch map of the major structures in Scotland.

- 1; Islay Anticline
- 2; Loch Awe Syncline
- 3; Ardrishaig Anticline
- 4; Tarbert Monoform
- 5; Ben Ledi Monoform
- 6; Aberfoyle Anticline (synform)

Fig. 2.8; Sketch map of the major structures in Ireland.

Fig 2.7

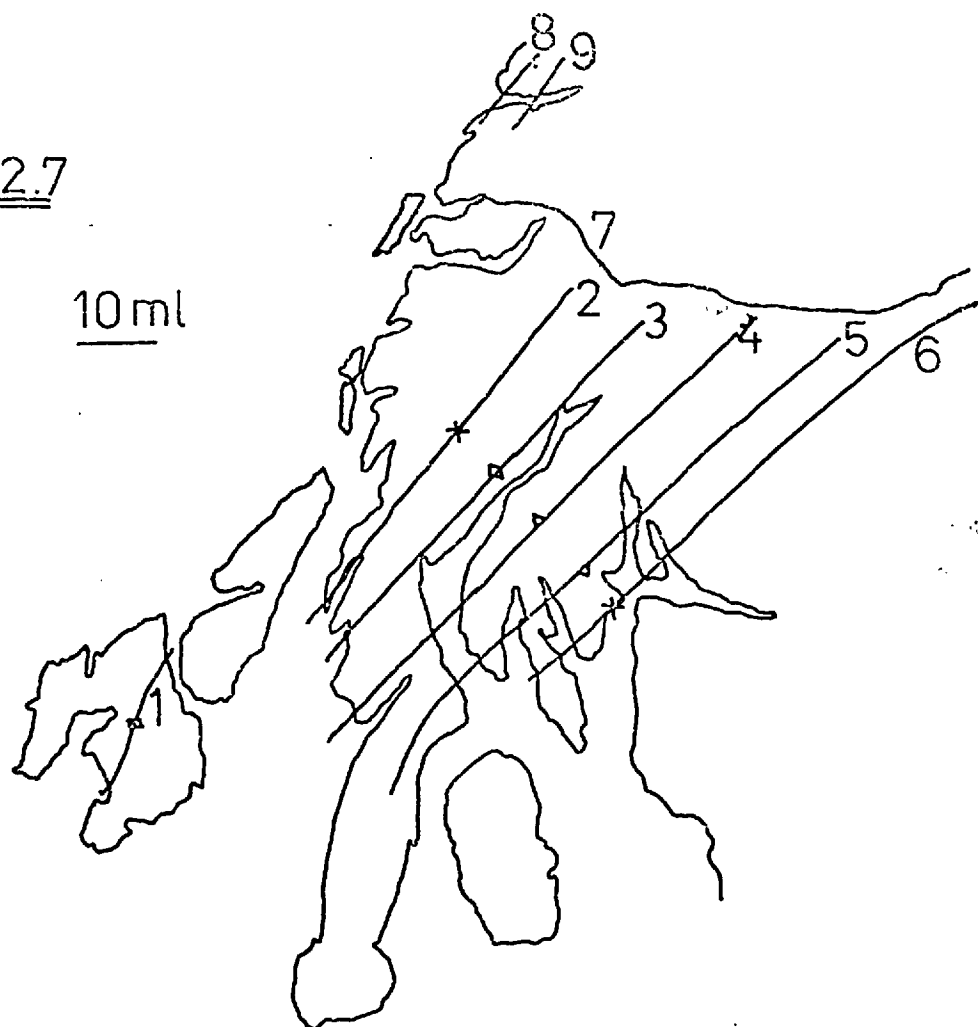
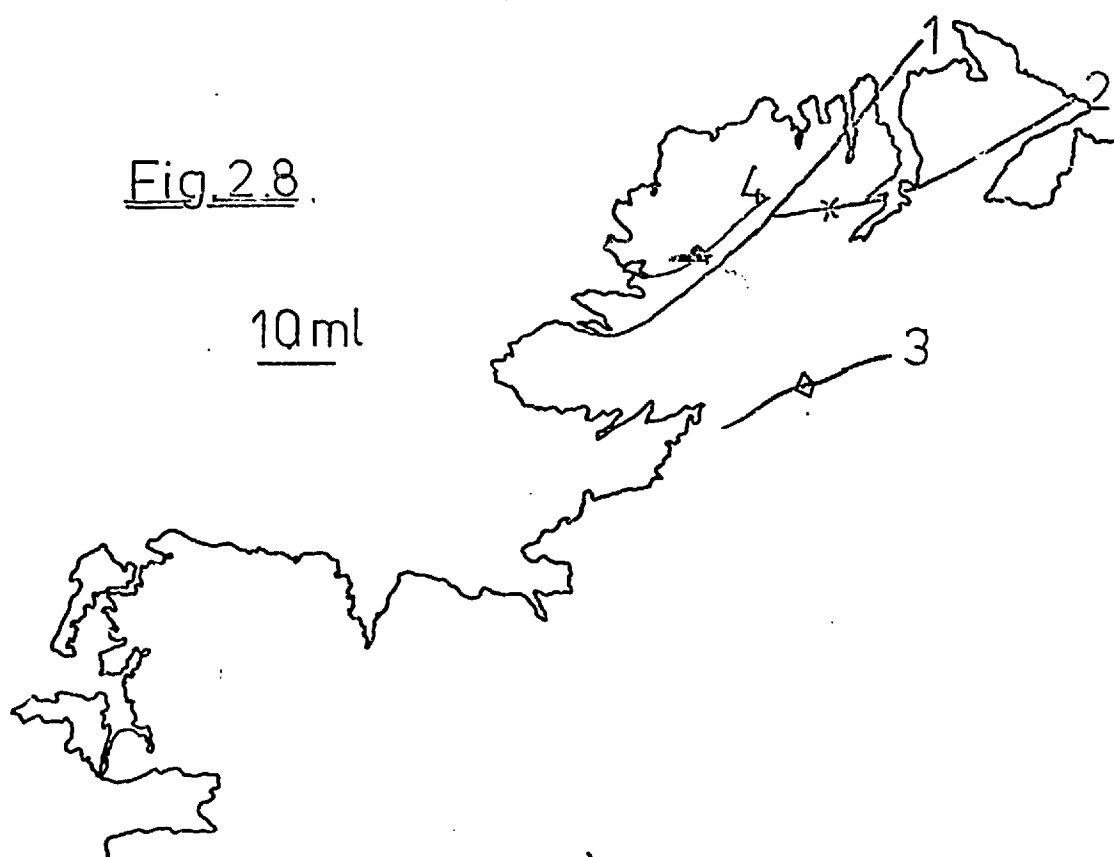


Fig 2.8.



The lowermost formation (Inver "Group") consists of graphitic black schists, pelitic calcareous beds and interbedded grey quartzites. There is a transition upwards between this and the Corslieve "Group" of the Argyll Group (Max 1972). The Corslieve "Group" consists of white quartzites passing up into muscovite-chlorite schists.

Max (1972) has recognised a diachronous base for the Southern Highland Group in south Achill Island, and the base is taken as a distinctive quartzite-clast slump conglomerate.

On Achill Island the Southern Highland Group is mostly gritty schists, graphitic schists, poorly graded and ungraded gritty quartzites, with subordinate and local conglomerates and volcanics. The volcanics consist of finely laminated tuffs and relic bombs (Max 1972) or pillows (Trendall and Elwell 1963).

2.2 Dalradian Structure in Scotland and Ireland

The Dalradian Supergroup in Scotland and Ireland has undergone polyphase deformation, and the interpretation of the large scale structures has historically been closely linked with the interpretation of the stratigraphy. Thus the large scale structures which are found will be briefly discussed here, while the minor structures (especially cleavage) which play a more important part in microfossil preservation, will be discussed in Chapter 5.1.

The major structures in Scotland and Ireland (Fig. 2.7 and 2.8) are dominated by large recumbent folds and nappe structures with amplitudes of many kilometres. The structures

recognised in Scotland can be traced into Ireland, although some complications do arise, especially in the Connemara Dalradian.

In Scotland the large scale structures are found in two tectonically separated areas (Fig. 2.7): (i) the area south of the Iltay Boundary Slide between Appin and the Highland Boundary Fault (Map 1), and (ii) the Lochaber Region (Map 1). In the former, the structure is dominated by large nappes facing north west and south east. In the north of the area (Fig. 2.7) is the Islay Anticline (Bailey 1916). This is a northwest-facing isoclinal fold, the lower limb of which is partly cut out by the Loch Skerrols Thrust on Islay. The axial plane of the fold trends northeast-southwest on Islay and dips towards the southeast (Fig. 2.9) steepening as it approaches the Loch Awe Syncline (Roberts 1974).

The next structure to the southeast is the Loch Awe Syncline (Fig. 2.7 and 2.9). First recognised by Hill (1893), this has subsequently been described in detail by Bailey (1922), Borradaile (1973), Borradaile et al. (1971), and Harris and Berridge (1969). The Loch Awe Syncline is a complex of folded bedding and cleavage, the axial plane of which is near vertical and trends northeast-southwest (Fig. 2.7 and 2.9), along Loch Awe (Map 1).

From Loch Awe to the Highland Boundary Fault in Scotland, the dominant structure is the Tay Nappe. This is composed of three major structural areas: the Knapdale Steep Belt to the north, the Cowal Flat Belt further south, and the Aberfoyle Steep Belt near the Highland Boundary. The southeast facing

Fig. 2.9; Structural cross-section of the Scottish Dalradian.

A: South of the Iltay Boundary Slide

1st; Loch Skerrols Thrust

ia; Islay Anticline

las; Loch Awe Syncline

aa; Ardrishaig Anticline

tm; Tarbert Monoform

cfb; Cowal Flat Belt

bls; Ben Lui Syncline

blm; Ben Ledi Monoform

aa'; Aberfoyle Anticline (synform)

B: North of the Iltay Boundary Slide

fws; Fort William Slide

tma; Tom Meadhain Anticline

as; Appin Syncline

bs; Ballachulish Syncline

sbs; Stob Ban Syncline

basl; Ballachulish Slide

kac; Kinlochleven Anticline

msc; Mamor Syncline

kaf; Kinlochleven Antiform

bws; Blackwater Syncline

bwa; Blackwater Anticline

----- Axial Trace of secondary fold

—————> Facing on primary folds

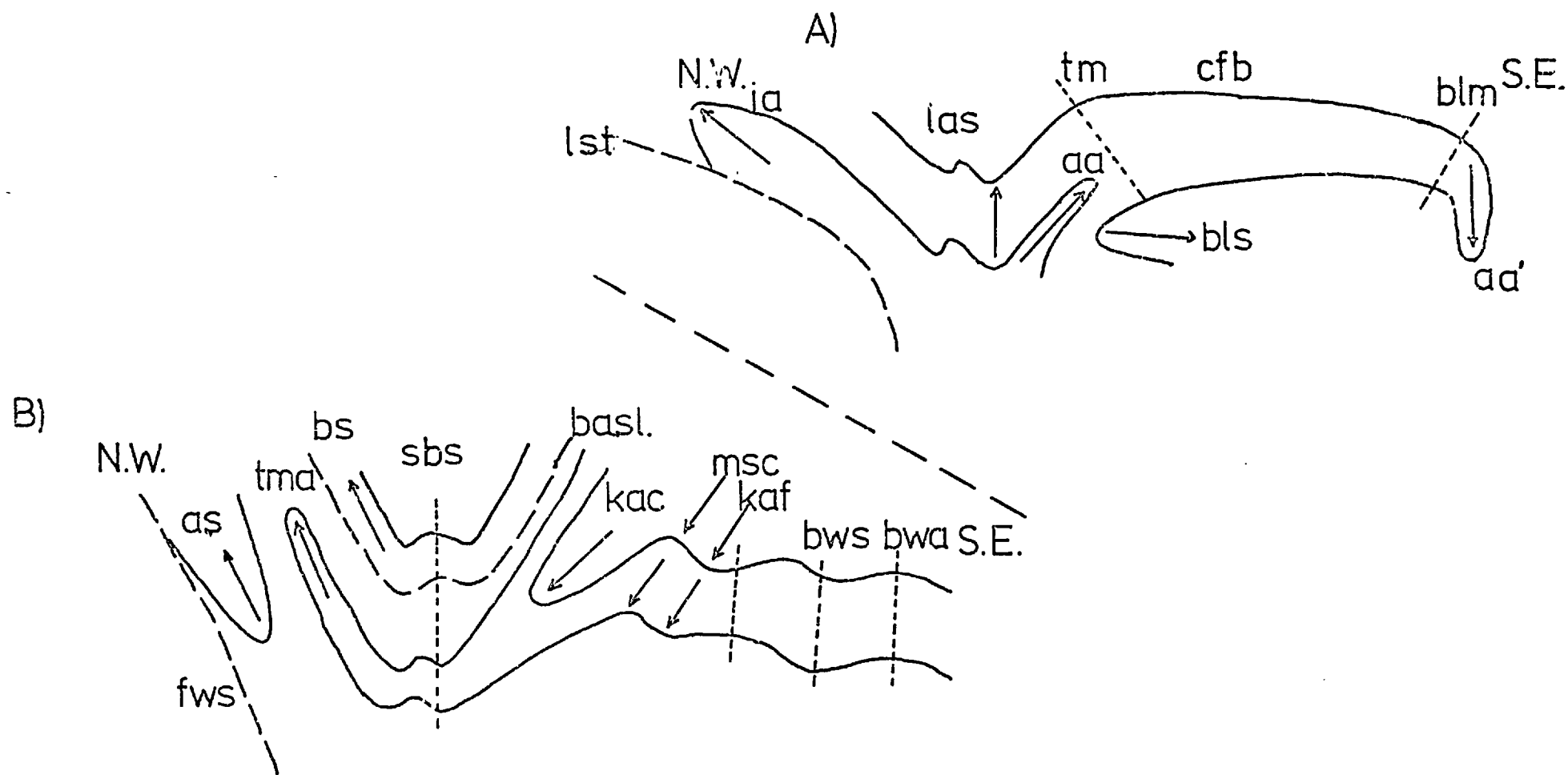


Fig.2.9 Structural cross-section of area, A); south of, and B); north of, the Iltay Boundary Slide.

Tay Nappe roots in the northern Steep Belt in the upward facing isoclinal Ardrishaig Anticline, whose axial plane dips steeply to the northwest (Fig. 2.9). The southeast limb of the Ardrishaig Anticline is folded into the Ben Lui Syncline (Cummins and Shackleton 1955), a southeast facing fold (Fig. 2.9) closing to the northwest and whose axial plane dips gently to the southeast.

Southeast of the Ardrishaig Anticline, and structurally above the Ben Lui Syncline, the rocks are bent over the Tarbert-Kilmelford Monoform (Borradaile 1973) and onto the Cowal Flat Belt (Fig. 2.9), where the bedding is consistently flat lying. Further southeast still, the beds pass over the Ben Ledi Monoform and into the Aberfoyle Steep Belt, where the rocks dip generally steeply to the southeast. The major structure consisting of the Tarbert-Kilmelford Monoform - Flat Belt - Ben Ledi Monoform, is termed the Cowal Antiform (Clough 1897, Roberts 1966).

Close to the Highland Boundary Fault and in the core of the Highland Border Steep Belt is the synformal Aberfoyle Anticline. This is recognised as the nose of the Tay Nappe, and faces downwards to the southeast. As such it is the continuation of the Ardrishaig Anticline.

Between the axial traces of the Ardrishaig and Aberfoyle Anticlines, the flat-lying beds belong to the lower limb of the Tay Nappe, and as such are constantly inverted.

The Lochaber/Appin region is separated from the area just described by the Iltay Boundary Slide (Bailey 1910). This is a major structural feature, and also separates the

central Dalradian from the Central Highland Granulites. The idea that the stratigraphy on either side of this slide could not be correlated (Bailey 1922) was shown to be incorrect by Rast and Litherland (1970), (see Chapter 2.1b).

The rocks of the Ballachulish-Kinlochleven area lie structurally below the Iltay Boundary Slide (Rast 1963) and the southwest Highlands. The structures are recumbent synclines and anticlines whose axial traces now dip southeast and northwest (Fig. 2.9) and are best exposed along Loch Leven from Appin to the Blackwater Reservoir. In the west the folds face upwards to the northwest and consist of the Appin Syncline, Tom Meadhoin Anticline and Ballachulish Syncline. East of Callert House (NS 110595) the folds generally face downwards to the northwest, and consist of the Kinlochlevel Anticline, Mamore Syncline and Mamore Anticline (Fig. 2.9).

All the folds named above are primary folds and have been refolded by the Stob Ban Synform and Blackwater Antiform (Roberts 1974, Treagus 1974). The axial planes of these secondary folds dip nearly vertically and strike approximately north-south.

Two major slides occur in this area, the Fort William Slide, and the Ballachulish Slide (Bailey 1910). These are both lags. The former, in the west (Fig. 2.9), cuts out the lower limb of the Appin Syncline, and separates the Dalradian Appin Group from the Eilde Flags in the west. The Ballachulish Slide cuts out part of the lower limb of the Ballachulish Syncline. Closely associated with, and parallel to the Ballachulish Slide is Sgurr a Choise Slide (Bailey and

Maufe 1916). Slides are an important feature in Dalradian structural geology, and can best be described as pre-deformation lag or thrust faults that have been subsequently deformed.

Bailey (1910 and 1922) divided the deformation of the Dalradian into primary and secondary phases. His primary folds were the Loch Awe "nappe", Iltay nappe and Ballapel Foundation (structures in Ballachulish/Appin area), in descending structural order. Bailey (1922) considered that these were subsequently deformed by a secondary phase of deformation which lead to the Loch Awe Syncline, Islay Anticline, Glen Orchy Anticline, and Ben Lawers Syncline. Work since then has confirmed that two dominant fold phases are present throughout most of the Scottish Dalradian. In Ballachulish and Appin, these are D_1 and D_3 (Roberts 1974, Treagus 1974). The D_1 folds have been described above, and these are refolded by the D_3 Stob Ban Synform, Kinlochleven Antiform, Blackwater Synform and Blackwater Antiform (Fig. 2.9) (Roberts 1974, Treagus 1974). A D_4 structure in this area, the Loch Leven Antiform, whose axial trace runs east-west along Loch Leven is responsible for the arcuate outcrop pattern in that area.

In the Southwest Highlands the pattern is a little more complex. Clough (1897), King and Rast (1956) and Rast (1963) recognised four major fold phases ($F_1 - F_4$): Roberts (1974) also recognised four "kinematic" phases (after Voll 1960) and termed his: B_1 , B_{2a} , $B' \perp B_1$, and B_{2b} . He correlated this with those of Rast (1963) and Clough (1897) as follows:

$$\begin{aligned}
 B_1 &= F_1 \\
 \left. \begin{array}{l} B_{2a} \\ B' + B_1 \end{array} \right\} &= F_2 \\
 B_{2b} &= F_3
 \end{aligned}$$

The Islay Anticline, Loch Awe Syncline, Ben Lawers Syncline and Cowal Antiform (Fig. 2.7 and 2.9) are now regarded as primary (D_1) folds (Borradaile et al. 1971, Borradaile 1973, Roberts 1966, 1974). Borradaile et al. (1971) report finding no evidence to support a pre-cleavage fold phase for the Loch Awe region as suggested by Knill (1960) and Harris and Berridge (1969). Secondary deformation (D_3) is taken up by the Tarbert Monoform and Ben Ledi Monoform. An apparently common D_4 deformation is recognised in the Loch Leven Antiform (Treagus 1974) and the downbending of the Tay Nappe nose to form the synformal Aberfoyle Anticline (Stone 1957, Shackleton 1958, Harris et al. 1976).

The evolution of the Tay Nappe has been a matter of some discussion. Cummins and Shackleton (1955) suggested that the Nappe was the result of deep reaching gravitational flow. Roberts (1974) disagreed with this and considered that it was due initially to lateral compression at depth, initiating the primary structures. These remained constant, while gravity collapse at a high structural level formed the Tarbert and Ben Ledi Monoforms. Harris et al. (1976) have studied the nose of the Tay Nappe in the Dunkeld region. They have found that structural complexity increases downwards, and suggest

that simple shear played an important part in the Nappe's formation.

Although four main phases of folding are recognised throughout most of the Scottish Dalradian, more than four phases of deformation have taken place. Thus, in Kinlochleven, Treagus (1974) has described five phases and in the Southwest Highlands, Roberts (1974) accounts for eight phases of deformation in total. However, most of these minor phases occur only locally, on a microtextural scale, as variously orientated planar cleavages, kink bands, crenulation cleavages etc., and while they form a part of the structural history, they have little effect on the stratigraphy. The local microstructure however is more important in the preservation of microfossils and the effect of this is discussed in Chapter 5.1.

The major structures recognised in the Dalradian of western Scotland can be followed into Ireland. They can best be correlated in Donegal. The Iltay Boundary Slide continues as the Knockateen Slide, which separates the Creeslough Succession to the northwest from the Kilmacrenan Succession (see Chapter 2.1.(g)). To the northwest of the Knockateen Slide, a series of north facing recumbent folds occur. To the southeast of the Slide, the Ballybotey Antiform corresponds to the Islay Anticline. Further southeast, the Lough Foyle Syncline is the continuation of the Loch Awe Syncline. The root of the Tay Nappe in Ireland is the Claudy Anticline which faces upwards to the southeast and strikes northeast-southwest. No continuation of the Aberfoyle Anticline, the

nose of the Nappe is found in Ireland, as the Highland Boundary Fault cuts it out (Fig. 2.10).

Four regional deformational events are recognised in Ireland as well as in Scotland. In Ireland, there appears to be a deformation phase prior to major recumbent folding (F_1 in Scotland, $D_2 - D_3$ in Ireland, Pitcher and Berger 1972). The D_1 phase has been recognised in Ireland as consisting of major slides, "bedding schistosity" and lack of folding.

In Scotland, there appears to be an absence of the equivalent of the Irish D_3 , i.e. regional intensification and local refolding of the S_2 cleavage. The D_4 phase in Ireland (i.e. minor open folds trending northeast-southwest) can be correlated with F_3 in Scotland (Rast 1963).

Thus although there is some discrepancy between the fold phases in Ireland and Scotland, this is largely due to the absence of a pre-nappe phase in Scotland (but see Knill 1960), and overall a reasonable correlation can be made.

2.3 Regional Metamorphism

Because of the importance of metamorphism in microfossil preservation, a brief description will be given of the regional metamorphism of the Dalradian. Initial work was undertaken by Barrow (1893 and 1912) in the North east Highlands, and Clough (1897) in the Southwest Highlands. Barrow (1912) was the first to produce a map of metamorphic zoning in the Dalradian (in the Loch Deeside area), based on a number of index minerals. His index minerals consisted of

Fig. 2.10; Sketch map and cross-section, correlating the major Caledonian structures in Scotland and Ireland. (after Pitcher and Berger 1972)

gg; Great Glen Fault

mt; Moine Thrust

lf; Leannan Fault

ibs; Iltay Boundary Slide-Knockateen Slide

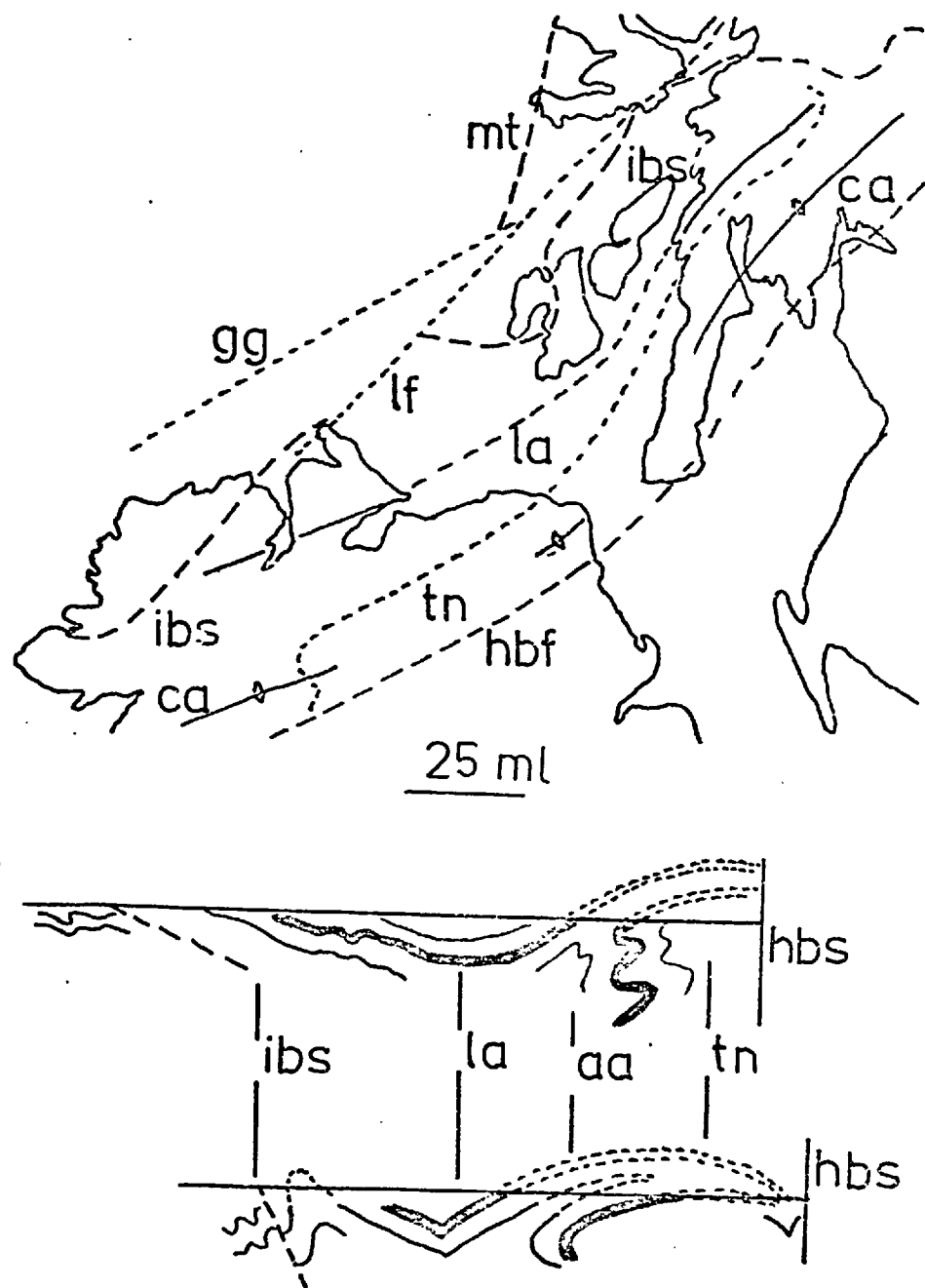
la; Loch Awe Syncline-Lough Foyle Syncline

ca; Cowal Anticline-Lough Derg Anticline

tn; inverted limb of the Tay Nappe

hbf; Highland Boundary Fault

Fig.2.10



- (i) clastic mica
- (ii) digested mica
- (iii) almandine and other higher temperature forms

The first two were combined by Tilley (1925) into the "chlorite" zone, and McNamara (1964) subdivided this again into low temperature and high temperature subzones.

Similar maps of metamorphic zonation in the Scottish Dalradian have been produced by Kennedy (1948), Dewey and Pankhurst (1970) and Winchester (1974). The metamorphic zoning on Map 1 follows these authors.

An initial conflict sprang up between the theories of Clough (1897) who related metamorphic zoning to structure by illustrating the decrease in metamorphic grade either side of the Cowal Antiform, and Barrow (1912) who, working in the Northeast Highlands related metamorphic zoning to igneous intrusion. Bailey (1923), Tilley (1925) and Elles and Tilley (1930) have also discussed the relationship of metamorphism to structure. Harry (1958), Chinner (1960), Rast (1958) and Sturt and Harris (1961) have demonstrated that metamorphism took place in several episodes. Rast (1963) suggests that three phases of metamorphism (M_1 , M_2 and M_3) took place and relates these to fold phases as follows:- M_1 ; syn- F_1 ; M_2 , post- F_2 ; M_3 , syn- F_3 . In a similar fashion, Pitcher and Berger (1972) have related phases of metamorphism to fold phases in Donegal.

From Map 1 and Map 2 it can be seen that the low grade (chlorite) grade rocks suitable for preserving microfossils

are restricted in Scotland to the west of the Dalradian outcrop, and a thin band along the Highland Boundary Fault, and in Ireland to the Ox Mountains parts of northwest Mayo, and parts of Donegal. Recent research into Dalradian metamorphism has mainly been concerned with the more "interesting" higher grade rocks in the northeast Dalradian. However, recent detailed work by McNamara (1964) has investigated low grade rocks in Cowal, from the Highland Boundary Fault, northwards into the biotite zone. This is the most useful work with respect to the present study as it examines the sort of rocks that are most important for a study of microfossils in metamorphic regimes.

The rocks north of the Highland Boundary Fault are all recrystallised and belong to the quartz-albite-muscovite-chlorite sub-facies of the lower greenschist facies. The characteristic mineral assemblage described by McNamara (1964) in Cowal is: quartz+albite+phengite+chlorite+calcite+dolomite+anatase. The more green slates possess a greater amount of chlorite, and sericite and rutile needles are also common. The lustrous cleavage planes encountered in many of these rocks are usually due to the orientation of sericite. Pressure solution, and redeposition of quartz occurs commonly. McNamara (1964) makes the interesting comment that "reaction between the organic matrix and silica in solution in the intergranular pore fluid occurs in preference to reaction between the matrix and quartz", although he does not expand on this.

McNamara (1964) considers that the physical conditions at the Highland Boundary Fault, during metamorphism were at

a temperature of about 220°C and pressure of 2.2 kb. (depth 7 - 8 km), while at the northern boundary of the Dunoon Phylites the conditions may have been of a temperature of 300°C, pressure 3.3 kb. and depth of 11 km.

2.4 The Age of the Dalradian Supergroup

One of the major problems associated with the Dalradian Supergroup is the determination of its age. It has long been suspected that rocks of a wide age range would be found in the Supergroup. However, although, with the aid of isotopic dating, considerably more is known about the time of deformation and metamorphism than previously, there is still very little data relating to the age of deposition of the sediments. It is one of the major purposes of this thesis, to put forward and discuss new micropalaeontological evidence bearing on this problem. However the available geological evidence relating to the age of the Dalradian must be discussed first.

2.4.(a) Isotopic data

Over the last fifteen years (since Gilletti et al. 1961) a large number of radiometric dates have been published. The early confusion of wildly differing dates from the same rock mass is gradually being overcome as understanding is developed of sampling and experimental techniques, and the role radiogenic elements play in the rock system. Unfortunately, due to the metamorphic events that have affected the Dalradian, it is

impossible to obtain an age of deposition of the sediments. Instead a minimum "restricting" age must be obtained from igneous bodies, in their geological setting. In conjunction with these the dates of metamorphism of the sediments can also be calculated.

(i) Granites and Newer Gabbros

The granite bodies distributed in Scotland and Ireland, occur traditionally in two groups, the "older" and "newer" granites (Barrow 1893). The "older" granites are syn-oregenic and the "newer" granites, post-orogenic.

In north-east Scotland, the Ben Vuirich, Meall Gruaim and Glen Tilt granites are post-D₂, pre-D₃ bodies (Bradbury et al. 1976, Pantin 1962), and, in addition, the Keith and Portsoy granites were intruded pre-main metamorphism (Read 1961 and Pankhurst 1974). Gilletti et al. (1961) consider the main Dalradian metamorphism to have been about 475m.y. ago. There has been a wide variety of ages on the Ben Vuirich granite: 480 ± 36 m.y., Bell 1968, Rb/Sr whole rock (includes data for Keith and Portsoy granites): 564 ± 25 m.y. Pankhurst and Pidgeon 1976, Rb/Sr whole rock, 8 best points (Pankhurst and Pidgeon are "doubtful whether this has any geological meaning"): 437 ± 7 m.y., Gilletti et al. 1961, Rb/Sr on biotite. Bell gives a date of 511m.y. and Pankhurst 609 ± 11 m.y., as reported by Dunning (1972). However probably the best date is a 6 point U-Pb isochron of $514 \pm 6/-7$ m.y. by Pankhurst and Pidgeon (1976). The Portsoy Granite is a pre-main metamorphism body. Pankhurst (1974) reports a 5 point Rb/Sr

whole rock isochron of 669 ± 17 m.y. while Bell (1968) gives a date of 560 m.y.. Late and post-metamorphic granites include: Kenneth Mont, 463 ± 4 m.y. (4 point Rb/Sr whole rock), Aberchirder 454 ± 9 m.y. (5 point, Rb/Sr whole rock), Longmanhill 480 ± 50 m.y. (5 point Rb/Sr whole rock), Strichen 462 ± 22 m.y. (7 point Rb/Sr whole rock (Pankhurst 1974)).

In Ireland similar work has been undertaken. The post-tectonic granites in the Galway complex have been dated variously in the range 384 ± 1 m.y. to 428 ± 10 m.y. (Leggo et al. 1966, Pidgeon 1969 and Leggo and Pidgeon 1970).

The Donegal Granite is a post D_2 body and has been dated as 498 ± 5 m.y. (10 point Rb/Sr whole rock isochron, Leggo and Pidgeon 1970). Similarly the Ox Mountains Granodiorite is syn-orlate D_2 and has been dated at 500 ± 18 m.y. (9 point Rb/Sr whole rock, Max et al. 1976).

The newer Gabbros of north-east Scotland are post- D_2 and possibly syn D_3 (Pankhurst 1974), and were intruded at 501 ± 17 m.y. (Pankhurst 1974), or 510 ± 13 m.y. (Rb/Sr, whole rock on Inch Gabbro by Pankhurst 1969). In Ireland the Connemara Ultrabasic body post-dates F_1 , but pre-dates M_3 and F_2 , and has been dated as 515 ± 15 m.y. (U-Pb, Pidgeon 1969).

Thus on the evidence of radiometric dates of igneous bodies, Dalradian sedimentation had finished, and the first two phases of deformation had been completed by about 500 - 520 m.y. ago, i.e. Upper Cambrian times.

(ii) Metasediments

Because of metamorphism, an accurate radiometric date on the deposition of Dalradian sediments, is not possible.

Leggo et al. (1969) report a 572 ± 20 m.y. Rb/Sr whole rock isograd from unmetamorphosed Islay siltstones which resulted either from diagenesis or possibly very weak greenschist metamorphism. Bell (1968) has produced an 11 point Rb/Sr whole rock 670 ± 30 m.y., and uses this as an approximate and maximum deposition age. Using his data Bell (1968) concludes that deposition took place between 530 m.y. and 830 m.y. ago.

Harper (1967) puts forward a large number of new K-Ar dates for Dalradian metasediments and discusses them in the light of a cooling theory. Basically, the Argon "clock" is set as the rock cools below the Argon Curie point. Thus the youngest and structurally highest units reach this point earlier, and are therefore "older" than stratigraphically and structurally lower units. Harper relates 13 slates from the Middle Dalradian and the Ballapel Foundation, that yield dates 447 m.y. - 436 m.y.. Two Upper Dalradian rocks from Loch Awe give dates of 455 m.y. and 440 m.y.. A Macduff slate yielded a 439 m.y. date. Harper suggests that these rocks lay over the centre of a regional heat source and show that the northeast took longer to cool. Twelve whole-rock K-Ar results from Loch Awe and the Highland Border yield dates of 484 m.y. - 462 m.y.. Harper regards 470 m.y. as an average minimum age of the main metamorphism in the Dalradian. High temperature metamorphism was preceded by a low temperature event, and six K-Ar results from the Aberfoyle Slates and Dunoon Phyllites at the Highland Border have yielded dates of 508 - 496 m.y.. These probably lost some radiogenic argon during M_2 but Harper (1967) believes an average age of 505 m.y.

can be regarded as the minimum age for initial fold movements and metamorphism.

2.4.(b) Palaeontological dating

Macropalaeontological data are rather rare in the Dalradian. The only common occurrences are stromatolites, including algae mat (Hackmann and Knill 1962, Spencer and Spencer (1971), Wilkinson 1930, Anderson 1950, Anderton 1974, Bliss et al. (in press)). The only report of macrofossils from the Irish Dalradian is one specimen of Protospongia hicksi Hinde, a sponge, from the Upper Dalradian of Clare Island, Clew Bay, Co. Mayo, (Rushton and Phillips 1973). This gives a possible age of Middle Cambrian.

In Scotland, there are a number of pieces of macropalaeontological evidence. The first is Hugh Miller's graptolite from the Macduff Group in 1858. These were identified as Monograptus priodon Brown, with a range, late Llandovery - Mid Wenlock. However, as no other examples of graptolites from the Macduff Group have been found, and there is considerable confusion as to the exact locality of Miller's samples, some doubt must be placed on the reliability of this age.

From the Highland Border region, Pringle (1940) reported a trilobite, identified as Pagetia in the Leny Limestone. This identification has been confirmed by Stubblefield (in discussion of Brown 1965), and on this basis the Leny Limestone is upper Lower Cambrian in age..

Jehu and Campbell (1917) also report macrofossils from the Highland Border Series in the Aberfoyle area. They record graptolitoidea and brachiopoda from the Lower or Black Shale and Chert series. From the limestone of the Margie Series, G.J. Hinde (in Jehu and Campbell 1917) has identified probable calcareous algae. From this assemblage, Jehu and Campbell conclude that the Highland Border Series is probably Upper Cambrian to Ordovician in age, although some of the brachiopods may be Middle Cambrian. Bulman (1963) and Rowell (1963) consider that Jehu and Campbell's fossils are not fossils at all.

The most detailed palaeontological study to date is the micropalaeontological work of Downie et al. (1971). From this, they conclude that the base of the Cambrian may lie between the Port Askaig Tillite and the Tayvallich Limestone, and that the Highland Border Series and Macduff Slates are Arenig in age. Downie et al.'s paper will be discussed in greater detail later.

Thus although there is some evidence relating to the age of the Dalradian, much of it is confusing and contradictory. The need for new data is considerable.

Chapter 3

MATERIALS AND METHODS

3.1 Sample Collection

As this project is primarily concerned with setting up a biostratigraphy, samples were collected from as many stratigraphical levels in the Dalradian as possible. This necessitated concentrating on collecting fine grained black shales/slates lithologies of low metamorphic grade, as these were considered to be the most likely to produce microfossils (see Downie et al. 1971). Thus there is a bias in sample lithology. Work by Vidal (1976b), who has examined a wide range of lithologies from one formation (Visingsö formation, Sweden), has shown that both paler and coarser unindurated rocks (when compared with my samples), contain preserved microfossils. The examination of microfossil assemblages from different lithologies within a short time span would be a useful extension of work in the Dalradian.

Sampling initially concentrated on the thicker continuous black slate formations within the Dalradian. This was subsequently extended to also collecting from black shale beds and intercalations within dominantly non-shale formations, e.g. Crinan Grit and Bonahaven Dolomite.

The sample pattern has also been biased, geographically. Only rocks below biotite grade (apart from the Ballachulish slates) have been collected. These areas are concentrated in the South-west Highlands and along the Highland Boundary Fault in Scotland (see Map 1), and in North Donegal, and in certain parts of Mayo in Ireland (see Map 2).

During collection, care was taken to collect material that was fresh to minimise recent contamination at this stage.

This was especially difficult in Ireland, where exposure is often poor and weathering is often deep. One of the criteria used to collect fresh samples was the state of the pyrite. Any samples that had pyrite that was turning rusty-brown were considered unsuitable. However, although considerable care was taken to collect unweathered rocks, even the apparently best material may contain recent contamination in microfractures or between laminae. Care was taken to recognise and appreciate this problem when looking for microfossils.

The geographic localities and their position in the established stratigraphy are listed in Appendix Table 1.

3.2 Sample Preparation

In the laboratory, samples were examined using thin sections, polished sections and acid digested residues, (Macerates) with a Zeiss photomicroscope.

The thin sections were cut approximately 30µm thick at a low angle to bedding and slaty cleavage. Thus the plane of section was approximately parallel to the principle^{al} plane of compression. A number of samples were sectioned and polished and used in combined reflected and transmitted light microscopy. Thin sections were used extensively as they provide a rapid means of examining microfossil assemblages, guarantee the "insitu" nature of the microfossils, and provide evidence of the inter-relationships between the individual microfossils and between microfossils and mineralogy. It has also been found, both in this study and in others (Spjeldnaes, pers. comm.), that during maceration, poorly

preserved often brittle microfossils that can be recognised in thin section, disintegrate and are unrecognisable.

All samples were macerated as follows: About 30 - 40gm of sample were used which would initially comprise of one or two large blocks. The sides of these blocks were ground off with a diamond rotary lap, in order to remove surface weathering, and ensure that the material used would be as fresh as possible. The blocks were then washed with distilled water, wrapped in "Kimwipe" cloth, and broken into fragments less than 1cm^3 in volume. The particle size then ranged from dust up to 1cm^3 fragments. All these fragments were put into a 100ml polypropylene beaker closed with a petri dish. The hydrochloric acid was used to remove carbonates from the samples, a process which could take up to a week, but usually only about three days. During this time the acid was changed daily. At the end of this period most of the hydrochloric acid was decanted off, leaving a small amount just covering the sample, and cold 40% hydrofluoric acid was added.

The samples were left in cold 40% hydrofluoric acid for up to six weeks. The length of time needed to break down the rock, varied quite considerably from a week for chert and soft shales, up to six weeks for the hardest and most metamorphosed slates. Cold hydrofluoric acid was used as it was found that heating did not significantly reduce preparation time.

After the samples had been broken down to organic residues, these were washed with distilled water until neutral. Initially the residues were washed by decanting the excess liquid, filling the beakers with distilled water, gently

agitating by hand until the residue was in suspension, and then letting the residue settle. This action was repeated until neutrality was reached. Due to the length of time it took some residues to settle, the 15 - 20 washes necessary to reach neutrality could take up to 2 weeks. To overcome this problem, equipment (Fig. 3.1) was built which could wash, automatically and continuously up to six residues at a time. One of the major advantages of this is that once started, no more attention need be paid to the washing, which continued 24 hours a day.

The equipment (Fig. 3.1) consists of six cylindrical cells, through which distilled water passes continuously at a rate of 0.2l/hr for each cell. The source of the distilled water is a perspex header (5cm x 15cm x 11cm) tank, mounted on the side of a fume cupboard, which is fed direct from a still. Six pipes (internal diameter 0.6cm) pass from the tank through the side of the fume cupboard and one into the base of each cell. The rate of flow through the cells is controlled by a screw tap on each pipe. The cells are mounted on a single perspex base. Each cell is a perspex cylinder, 13cm high and 6cm internal diameter. The inlet pipe is at the base of the cell and there is a drain pipe (internal diameter 0.9cm) at the top. In the cell is suspended a tubular bag approximately 10cm long and 3cm in diameter, of semi-permeable dialysis membrane, which is tied at the bottom. The tube is held at the top of the cell by a circular "groove and tongue" method (Fig. 3.2). This unit can be lifted free from the remainder of the cell to facilitate placing the bag in and out of the cell.

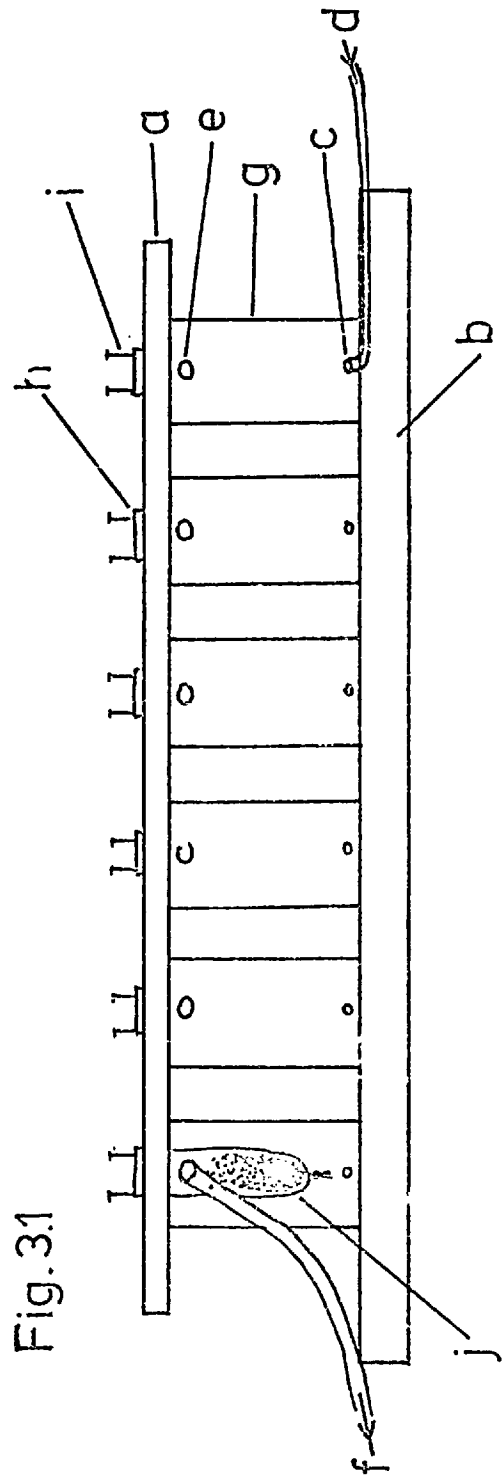
Fig. 3.1 and 3.2; Mechanism used to wash macerate residues.

Fig. 3.1; Vertical cross-section of equipment, showing the six cells in position, inlet and outlet pipes, and one dialysis bag in position.

- a; top plate length 70cm. thickness 0.75cm.
- b; base plate length 80cm. thickness 2cm.
- c; inlet pipe diameter 0.6cm.
- d; from header tank
- e; outlet diameter 0.9cm.
- f; to sink
- g; cylindrical cell, diameter 6cm. height 10cm.
- h; groove-and-tongue ring to hold dialysis bag
- i; lifting pegs, to aid removal
- j; dialysis bag in position

Fig. 3.2; Detail of groove-and-tongue (h; in 3.1) for holding dialysis bag.

- a; dialysis bag



During operation residue is poured into the dialysis bag and the bag topped up with distilled water. The space outside the bag is filled with distilled water from the tank, and is replaced completely every $1\frac{1}{2}$ hours. Neutrality is reached by hydrogen ions passing from the more concentrated solution in the dialysis bag to the weaker surrounding solution and then passed out through the outlet. This method reduced washing time to 40 hours.

During all stages of maceration, no filtration or centrifugation was used as these would have biased assemblages and probably damaged the microfossils. The dangers of filtration are illustrated in Vidal (1976b). In this paper he has used a $20\mu\text{m}$ filter. The bias this can lead to is clearly shown in his description of Pterospermopsimorpha densicoronata. He gives this a size range of $20\mu\text{m}$ to $45\mu\text{m}$ and a major mode at $20\mu\text{m}$ to $35\mu\text{m}$. Again he states that Synsphaeridium sp. has a size range of $20\mu\text{m}$ to $30\mu\text{m}$ and a mode at $19\mu\text{m}$ to $20\mu\text{m}$. Clearly in both these examples, part of the size distribution is missing. After the residues had been neutralised, strew mounts fixed in glycerine jelly were prepared, using 3" by 1" glass microscope slides and 2" x 1" glass cover slips. Usually eight or more slides were made of each residue, and care was taken to use material from the top, middle and bottom of each residue in order to avoid bias due to possibly different densities of the microfossils.

Macerates were used consistently in close conjunction with thin sections, for a number of purposes, macerates show distinct advantages. As the fossil is not cut by a plane of

section, the complete morphology of the fossil can be seen in maceration. If the fossil assemblage in a rock is sparse, then maceration will concentrate this. Likewise, if the assemblage is very dense, with few details visible in thin section, then maceration will "spread" the assemblage out.

At all stages of preparation, care was taken to avoid contamination by keeping containers firmly covered and by using distilled water only. However, it is appreciated that however much care is taken, contamination might occur. This was taken into account when examining the residues.

3.3 Biogenicity Criteria

All the microfossils from the Dalradian Supergroup come from rocks that have undergone quite intense deformation and have often been metamorphosed to a relatively high grade (for organic matter). Gutjahr (1966) and Sengupta (1974 and 1975) have shown that organic microfossils darken considerably and lose important morphological features during heating and pressure. With the higher levels of metamorphism and deformation it becomes increasingly difficult to differentiate between microfossils and fragments of organic debris. An example of this is the recognition of genuine spines on microfossils as opposed to small fragments and flakes of organic debris attached to a smooth sphaeromorph. In order to set a consistent standard when considering the biogenicity or not of these essentially very simple microstructures, and in order to allay the fears of those who may consider that microfossils could not be preserved under these geological conditions, a

set of morphological and statistical criteria have been developed. The morphological criteria are based on those of Cloud and Licari (1963). The statistical criteria have been used rarely in this study, but are based on those outlined by Schopf (1976). These criteria have also been discussed by Muir et al. (in press) in the context of microfossils from 3.355×10^9 years old Onverwacht Group, the Dalradian Easdale Slates and the Ordovician Ballantrae Group.

The morphological criteria used are as follows:

(1) The microstructure should be of similar colour to the surrounding organic debris. If this is so, then it is probable that the microstructure and organic debris underwent the same geological history. It should be remembered however, that a sphaermorph with a wall only $1\mu\text{m}$ - $2\mu\text{m}$ thick will be a lot paler than a dense clump of organic debris $10\mu\text{m}$ - $20\mu\text{m}$ thick.

Reworked organic microfossils in the Phanerozoic can often be recognised by their considerably darker colour when compared with the remainder of the assemblage. This does not apply in the Dalradian, as all the microfossils are dark brown to black in colour due to metamorphism.

(2) The microstructure should be of distinctive and consistent morphology, and should occur abundantly throughout a sequence of rocks. Distinctive morphologies that appear only very rarely should be treated with circumspection. Hughes and Moody-Stuart (1967) are of the opinion that one should have at least 100 individuals before creating a new species. However, a few (10) individuals have been used in some cases

to describe a species. It is felt that although rare, these individuals are of distinctive enough morphology and are so similar to other microstructures undoubtedly biogenic, that they may also be considered biogenic.

(3) The microstructure should be demonstrably of organic matter. Although this should ideally be confirmed by chemical means (e.g. by using X.R.D.) this is impossible when it comes to considering each individual microstructure seen down the microscope. Instead the polarising properties of a petrographic microscope can be used. Under crossed polars carbonised organic matter is opaque, and can thus be distinguished from many minerals that are likely to be encountered. The only common mineral with which there are problems is pyrite, as this is also opaque under the microscope. This difficulty can be overcome by using reflected light in conjunction with transmitted light. It is therefore useful to have a microscope that can be changed from transmitted to reflected light without moving the stage. Ideally, polished thin sections should be used, but normal thin sections will usually be flat enough for simply recognising pyrite. Under conditions of high transmitted luminosity, some reflected light can occur, and an experienced worker can sometimes use this to recognise pyrite.

(4) There should be no mineralogical distortion of the microstructure. The growth of disruptive minerals can begin during or after deposition and can occur as a response to diagenesis and metamorphism any number of times during a rock's history. New crystal growth can distort the micro-

structure producing a morphology different from the original micro-organism. However, crystal growth need not necessarily distort the microstructure, as for example, in the case of permineralisation, and/or replacement. The effects of new mineral growth on microfossils is discussed in greater depth in the section on preservation.

(5) The microstructure should occur in what is demonstrably a rock of sedimentary origin, and be syndepositional with the sediment. No samples from post-depositional cracks and joints were used. It is important that the rock should be fresh and collected as far away from present and palaeo-weathering surfaces as possible. In many samples this was aided by their being rich in euhedral pyrite. Rocks in which these were turning brown were considered too badly weathered (see section sample collection Chapter 3.1).

These morphological criteria were used continuously when examining samples. All the microstructures that were considered microfossils (i.e. biogenic) fulfill all these criteria.

The statistical tests are those outlined by Schopf (1976) and are as follows:

(i) The fit of the assemblage to a normal distribution or combination of such distributions by means of a probability plot. This is a plot of the diameter of spheroids measured versus the percent of spheroids in the population larger than a given diameter (Fig. 3.3). Thus a monospecific population, with a Gaussian ("normal") distribution will plot as a straight

line, while a polyspecific population will produce a curved plot. Statistically, it should be possible to break down (or "deconvolute") a curved plot into its constituent normal distributions, (i.e. its individual "species"). Work by myself and P.R. Grant, has shown that while this is statistically possible in simple cases, it is doubtful whether this process has any real biological meaning. If a curved probability plot is deconvoluted into its constituent normal distributions, then these "statistical species" must be confirmed by observing complementary morphological variations in the microfossil with a microscope. In the case of the Easdale Slates using simple thin walled sphaeromorphs, its size distribution produced at least five "statistical species". Only one morphology, the simple thin walled sphaeromorph was recognised down the microscope.

Schopf (1976) and Muir et al. (in press) use this test by comparing the plot of these assemblages in question with modern algal species and undoubtedly biogenic fossil populations (e.g. Gunflint unicells) (Fig. 3.3) and use their similarities to judge biogenicity. It is interesting to note that treating the Easdale Slate assemblage in the same fashion, produces a curve parallel to the Gunflint unicells. This suggests that the two populations are made up of similar "statistical species". But there is no evidence to suggest that there is any relationship between the biological species of the two assemblages, and the Easdale slate microfossils are notably larger than those of the Gunflint unicells.

Fig. 3.3;Hyberbolic probability/size plot (from Muir et al. in press).

c; Chlorella

gl; Gloeocapsa

g; Gunflint unicells

t; Tetraspora

b; Bitter Springs 'spot cells'

o; bedding plane 1 Onwerwacht microfossils (see Muir et al.)

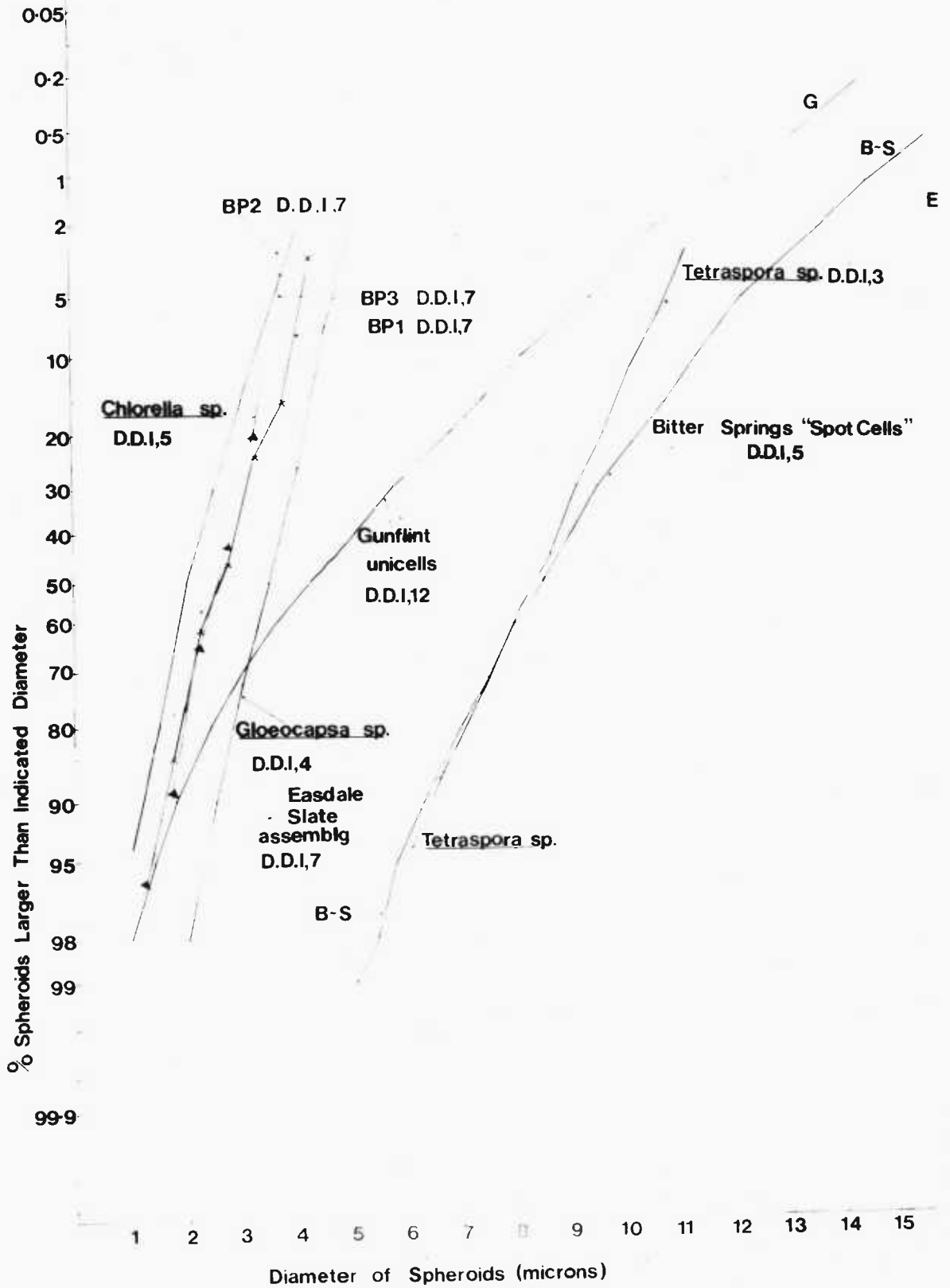
o'; " " 2 " ' "

o''; " " " " "

bh; Ordovician Bennanne Head Ballantrae Group

e; Easdale Slates (Leisphaeridia Type 1 only.)

PROBABILITY PLOTS OF SIZE DATA (modified after Schopf 1975c)



(ii) Divisional Dispersion Index (D.D.I.)

This is the "number of cell divisions, the least number of sequential divisions required to mathematically "reduce" the largest cell of a population to the smallest cell of that population"

The number relates the division of the largest cell into two equal halves and the division of those, and subsequent daughters into halves themselves. It is "mathematical" division and assumes no growth of the daughter cell before division. Thus the D.D.I. inter-relates the end members of otherwise unrelated populations, e.g. populations with size ranges $45\mu\text{m}$ to $100\mu\text{m}$, $8\mu\text{m}$ to $20\mu\text{m}$ and $1\mu\text{m}$ to $2.5\mu\text{m}$, all have a D.D.I. of 4. Schopf, using published size data of "11 modern cyanophytes" and "140 species of spheroidal unicellular algae" concludes that to be biogenic a population should have a low D.D.I. (less than 7 or 8), and that populations with a high D.D.I. (9 or 10) are probably abiogenic. Again it is uncertain whether the D.D.I. has any biological meaning. The high D.D.I. of the Gunflint population (12) has been explained as being due to the complex nature of the population (Schopf 1976). However, the Easdale slates population is equally complex according to the probability plot, and yet its D.D.I. is only 4 (highly biogenic!).

(iii) Standard Deviation

The third method used by Schopf is the standard deviation. However, this is directly related to the D.D.I. and if a population is biogenic according to the D.D.I. the standard deviation will also show it to be biogenic.

CHAPTER 4
PALAEONTOLOGY

4.1 Descriptions and Systematics

The acritarch descriptions below follow the systematic principles outlined by Downie, Williams and Sarjeant (1961), Evitt (1963), Downie, Evitt and Sarjeant (1963) and Downie (1973). The problems encountered with classifying simple sphaeromorphs ("Leiospheres") are described and discussed.

The locality of each specimen illustrated is by the following scheme.

e.g. B37(M₃) 108.4/5.3

B37: Sample number (see appendix for detailed stratigraphical and geographical locality).

(M₃): Macerate residue, mount number 3.

108.4/5.3: Coordinates of specimen on Zeiss photomicroscope 004 at Imperial College. (Bottom lefthand corner of 3" x 1" microscope slide has coordinates 145.4/0.0, and the coordinates are graduated in millimetres.)

e.g. E45(TS) 93.0/15.4

E45: Sample number

(TS): Thin section

93.0/15.4: Coordinates as above.

GROUP: ACRITARCHA Evitt 1963

Sub-group: ACANTHOMORPHITAE Downie Evitt and Sarjeant 1963

Genus: MICRHYSTRIDIUM

(Deflandre 1937) emend. Downie and Sarjeant 1963

Type Species:- Micrhystridium inconspicuum (Deflandre 1935)
Deflandre 1937.

Diagnosis: Hystrichosphere with spherical or oval test not divided into fields or plates, bearing processes with closed tips, most often simple, rarely branching or ramifying, without distal connections of any kind. The processes are generally of one type. Mean and modal diameter of test less than 20 μm .

Remarks: Staplin (1961) emended the diagnoses of Micrhystridium to exclude the upper size limit of 20 μm for this genus, and to specify that the spines were closed. Downie and Sarjeant (1963) argue strongly for the differentiation of Micrhystridium and Baltisphaeridium on a size basis as originally established by Deflandre (1937). However, they agree with Staplin (1961) on specifying the closed nature of the apical ends of the processes.

Micrhystridium cf. lanatum
Volkova 1969 (Pl. 1, Fig. 1 - 6)

Description: Outline of test generally circular, and characterised by an abundant covering of short hair-like spines. All the spines are of equal length ($< 3 \mu\text{m}$) and appear to be evenly distributed, are closed apically, are narrow based and sharp pointed or blunt. The spines occur all over the surface of the test, and do not form clusters or polygonal groups, or define polygonal or circular areas.

Dimensions: Diameter of test 8 μm to 11 μm
Length of spines 1 μm to 3 μm .

Remarks: The major difficulty in recognising poorly preserved Micrhystridium cf. lanatum in these rocks is the possibility that they are clusters of radiating crystals. However, after examining these in considerable detail, I have concluded that these microstructures are genuine representatives of M. cf. lanatum for a number of reasons. Firstly the general outline of the body is regularly circular without the marked angular and lath-like irregularities that would be expected if this were a cluster of radial crystals. Secondly the spines are of consistent size and occur abundantly over the whole surface of the test. In a radial cluster of crystals more than one order of crystal size would be expected, with a number of longer and probably thicker lath-like crystals, dominating and protruding beyond the others. Thirdly, although the spines cover the surface of the test densely, they can be resolved and the surface of the test can be recognised between spines. Many of the spines can be recognised as being hair-like without blunt ends. Fourthly, these forms are not locally restricted to one stratigraphical horizon, within the Highland Border Series. The formation of radial crystals would be expected to be confined to local conditions.

Micrhystridium cf. lanatum differs from all other species of Micrhystridium by the presence of a dense covering of very short spines as opposed to longer and more sparse spines on other species.

Rudavskaya (1971) illustrates a possible M. lanatum

under the name ?Tasmanites sp. from the Cambrian Mottled strata in East Siberia. In this it would appear that the spines had been misinterpreted as pores by Rudavskaja (1971). Vidal (1976a) also illustrates a possible M. lanatum from the Tillite Group, Ella Ø., East Greenland, and calls it Bavlineella faveolata (Shepeleva). However B. faveolata is characterised by a more fram-boidal structure (see Volkova 1974 and Chapter 5.1).

Occurrence: Highland Border Series,

?Lough Feagh Group, Clare Island.

Other recorded occurrences: Gaskin's Leap formation, Howth, Ireland, Lower Cambrian (Smith in press): Hollyrock Quartzite, Malvern Lower Cambrian (Potter, unpublished Ph.D. Thesis): Vergal'sk Horizon, Atdabanian Stage, Lower Cambrian: Holmia kjerulfi zone (Volkova 1969), Booley Bay Formation, Co. Wexford Ireland, ?Lower-Middle Cambrian (Gardiner and Vanguetaine 1971): ?Downie Zone 5 (as reported by Potter 1974).

Genus: SOLISPHAERIDIUM

Type Species:- Solisphaeridium stimuliferum (Deflandre) Staplin, Jansonius & Pocock 1965.

Synonymy: Micrhystridium stimuliferum Deflandre 1938

Baltisphaeridium stimuliferum (Deflandre) Sarjeant 1961.

Diagnosis: Vesicles spherical, wall relatively firm and rigid, several to numerous firm spines, hollow or solid, relatively long and slender tapering continuously towards

the closed tips. Spines have a tendency to reduce their cavity through secondary deposition of wall material, but if present the cavity communicates freely with the vesicle.

Solisphaeridium sp.

(Pl. 1, Fig. 8 - 10; Pl. 2, Fig. 1 - 4)

Description: Outline of test circular to elliptical and regular. Tests occur singly. Body hollow. Wall single, slightly thicker than is normal and uniform. Folds may occur in the wall, but these are rare. Where they do occur they are narrow and straight. The surface is smooth or slightly granular.

The test is characterised by three processes. All three processes occur on one side of the ellipse only. One process is situated at the equator while the others are situated either side of the equator, about halfway between the equator and the pole of the test.

The processes are short, with a wide base and a rounded pointed apical end. Because of the preservation of the Dalradian material, it is impossible to determine whether the processes are hollow or solid. They are unornamented.

Dimensions: Diameter of test 4 μ m to 13 μ m

Length of processes 1 μ m to 2 μ m.

Remarks: This species found here is closely similar to Solisphaeridium sp. illustrated by Konzalova (1974 Pl VI, Fig. 3), from the Middle Cambrian (Acadian) of the Jince Formation of Czechoslovakia. This has processes re-

stricted to one side of the test, and the processes appear to be hollow.

Solisphaeridium stimuliferum Staplin et al., (1965) has longer spines, and is generally more rounded. However, the distribution of spines on one side of the test only may be due to preservation.

Occurrence: Easdale Slates

Crinan Grits

Highland Border Series

Cappagh Formation

Loch Feegh Group (Clare Island)

Other recorded occurrences: Middle Cambrian (Acadian) of the Jince Formation (Skryje Shales), Barrandian area, Czechoslovakia (Konzalova 1974).

Genus: ALLIUMELLA

Vanderflit 1971

Type Species:- Alliumella baltica Vanderflit 1971 p.69
Figs. 42 - 48.

Diagnosis: Test rounded, dense; diameter 12 - 24 μ m with processes characteristically throat-like of variable length. A tip variably pointed depending on individual and curved in a different fashion. Colour dark brown. Lacking ornament.

Remarks: The genus Pirea Vavrdova 1972 has a clavate tip to the single process and may be synonymous with Alliumella Vanderflit. Deunffia Downie 1960 differs in possessing a more slender, often curved apical process that may be

ornamented at its apical end.

?Alliumella sp.

(Pl. 2, Fig. 5 - 10; Pl. 3, Fig. 1 - 10; Pl. 4, Fig. 1 - 3)

Description: Outline circular and regular, with a single tube-like process. Body and process hollow, with continuous wall. Wall is single, thin and uniform. Occasionally surface is randomly granular, probably due to metamorphism.

The process is hollow, cylindrical, except where it joins the main body, and walls diverge. Simple union between process and central body. Apical end of process, open, straight edged. No specimens have been found on which the process has clearly not been broken. One specimen seems to have a bulbous termination of the process. Process shape is variable, being either long and thin, or short and appearing stubby. Width of process usually about 2 μ m.

Dimensions: Diameter of central body 4 μ m to 17 μ m

Width of process 2 μ m to 4 μ m

Length of process 1 μ m to 32 μ m

Remarks: This form differs from all species of Deunffia Downie 1960 and Domasia Downie 1960, by possessing a far wider and heavier process, and lacking any ornamentation on the apical end of the process.

Although no termination to the process has been recorded, the fact that the apical end of the process is almost always rectilinear and has not broken diagonally or in a ragged fashion may indicate that the style of "break" of the process is natural to the species and not

a feature of preservation. It may be part of the reproductive stage in an algal life cycle.

Alliumella sp. differs from species of Balti-sphaeridium with one process, and not possessing a constriction of the process as it reaches the central body.

Timofeev (1970) described microfossils morphologically similar to Alliumella sp. as Phycomycetes.

Occurrence: Cnoc Donn Slates

Appin Transition Beds

Bonahaven Dolomite

Easdale Slates

Tayvallich Slates and Limestones

Highland Border Series.

Other recorded occurrences: Alliumella baltica, Piritas Series, Byelorussia and Latvia, Lower Cambrian, (Vanderflit 1971), Huermeda Schist, Spain, Lower Cambrian (Potter 1974), Black Forest, Lower part of Middle Cambrian (in Potter 1974). St. Tudwal's and Tremadoc area, Zone SLA, Lower Cambrian, (Potter 1974).

Sub-group: NETROMORPHITAE Downie, Evitt and Sarjeant 1963

Genus: DEUNFFIA

Downie 1960

Type Species:- Deunffia monospinosa Downie 1960 pl. 1, Fig. 8.

Diagnosis: Shell hollow, elongate ellipsoidal, more or less smooth, less than 100 μ m in length. Body composed of thin pale yellow to brown organic membrane. Ornament consisting of a single hollow spine situated at one end.

Spine terminates in a point or branches in various ways.

Deunffia flagellata Jankauskas 1975

(Pl. 4, Fig. 6 - 10; Pl. 5, Fig. 1 - 10; Pl. 6, Fig. 1 - 3)

Description: Outline of test sub-circular to elliptical, generally regular, but may be irregular under poor preservation conditions. Test hollow and occurs singly. Wall is single and consistently thin and uniform. Surface of test smooth and without ornament. Test is characterised by a process at one pole. This may be long and hair-like, or shorter and slightly wider at the base. Many processes are short and narrow, and appear to be broken. Process may be straight or slightly curved especially towards the apical end. The process appears to be hollow, and in simple contact with the main body.

The pole where the process occurs is usually more pointed than the other which is characteristically smoothly rounded. No opening or pylome has been found at the pole opposite to the process.

In one specimen the process appears to join the main body via a flat cylindrical collar 1 μ m in diameter and 1 μ m high. However this may be a preservational feature.

Remarks: Deunffia conifera Jankauskas 1975 differs from D. flagellata in that the latter has a longer process with a narrower base. Also D. conifera is usually ornamented with small turbercles and possesses a pylome. These do not occur in D. flagellata. Further, D. flagellata

differs from D. conifera in lacking a thickening at the end of the process.

The process of D. monospinosa Downie, is much longer than those observed from D. flagellata, and D. brevispinosa differs in that the process may be divided into partitions, and granules occur at the distal part of the test. Both these species have wider processes.

Potter (1974 unpublished thesis) has illustrated a form which appears similar to D. flagellata and is described as Leiofusa sp.. None of the specimens in the Dalradian can be put in the genus Leiofusa.

Konzalova (1974) illustrates (Plate I, Figs. 6 and 7) an "apparent organic remain" looking very similar to D. flagellata with a short hair-like process, from the Bohemian Upper Proterozoic of Czechoslovakia.

Deunffia dentifera Volkova 1969 has a longer process than D. flagellata.

Occurrence: Mullach Dubh Phyllites

Easdale Slates

Bonahaven Dolomites

? Crinan Grits

Falcarragh Pelites

Lough Feagh Group (Clare Island)

Ardvarney Formations

Other recorded occurrences: Vergal'skiy and Rauvenskiy horizons,

Lower Cambrian, Baltic region, (Jankauskas 1975);

?Bohemian, Upper Proterozoic, Czechoslovakia (Konzalova 1974).

Sub-group: HERKOMORPHITAE Downie, Evitt and Sarjeant 1963

Genus: PLICATOSPHERA

Potter 1974

Type Species:- Plicatosphaera elementaria Potter 1974.

Diagnosis: Body hollow, outline circular to polygonal, wall single layered, smooth to granular divided into polygonal areas by sutures. Line of suture usually indicated by folds of body wall formed by overlapping margins of the polygonal plates; no thickening at the angles of the polygons, apart from a possibly granular surface texture; no ornament sutural or otherwise.

Remarks: Potter (1974) has discussed the relationship between the genera Plicatosphaera, Cymatiosphaera (Wetzel) Deflandre 1954, Retisphaeridium Staplin, Jansonius and Pocock 1965, and Comtofaciesphaera Potter 1974, in the Cambrian of Britain. All these are characterised by polygonal fields formed by sutures on the sphaeromorph surface. The genus Plicatosphaera is the simplest without ornament on the sutures, and is characteristic of the Lower Cambrian. The other genera occur in younger rocks, and in these the sutures become more complex. For example, the genus Comtofaciesphaera possesses short elements on the suture. The more complex genera are considered to have arisen from the genus Plicatosphaera.

Plicatosphaera cf. elementaria Potter 1974

(Pl. 6, Fig. 5 - 10)

Synonymy: 1968 Retisphaeridium n.sp. Slavikova

1969 Cymatiosphaera div. spp. Volkova

1972 Cymatiosphaera sp.l. Crarier-Diez.

Description: Outline circular to subcircular, and generally regular. Body is hollow. Wall appears to be thin and single. Surface ornamented by "sutures". These may be flat or protrude from the surface or indent the inner surface. These are interconnected and define polygonal fields, generally five-sided. The fields may be regular pentagons or more irregular, and approach sub-circular. Field size may vary slightly on one specimen. Number of fields varies, largely due to poor preservation, from 10 - 30. Sutures are simple and straight, with no ornamentation on individual sutures.

Surface of fields smooth and without ornamentation.

Dimensions: Diameter of test 11 μ m to 12 μ m

Diameter of fields approximately 1.5 μ m.

Remarks: These specimens of P. cf. elementaria are a little smaller than those described by Potter (1974). Both the body and individual fields are considerably smaller than P. voluminosa Potter and P. sp. A Potter. The sutures are not enhanced by folding. Specimens of Cymatiosphaera sp. in Gardiner and Vanguetaine (1973) are larger, with larger and more irregular fields than P. elementaria. Dictyotidium cambriense Slavikova 1968, is also larger, and the ridges are ornamented with short spines.

Vidal (1976b) illustrates an "enigmatic spheromorph" (Fig. 23 A-H p.41) which has polygonal fields developed on its surface. Scanning electron micrographs of this specimen show that the "sutures" are in fact wall-like

structures protruding inwards from the inner surface of the test wall.

Occurrence: Easdale Slates

Other recorded occurrences: ?Visingsö Formation,

Upper Vendian (Vidal 1976b): Comley area,

Nuneaton area, ?Malvern area, St. Tudwal's peninsula;

Zones 1, N3 and N4 of Potter (1974).

Sub-group: DISPHAEROMORPHITAE Downie, Evitt and Sarjeant 1963

Genus: ARCHAEOSACCULINA

Naumova 1968

Type Species:- Archaeosacculina baltica Naumova 1968
pl. II, Fig. 9.

Diagnosis: Outer membrane round, thin smooth or with ornament.

Innerbody round or oval strong or thin. Diameter 10 -

50 µm. Inner body $\frac{1}{2}$ - $\frac{3}{4}$ size of outer membrane.

Remarks: Pterospermopsimorpha Timofeev 1966 is larger than Archaeosacculina, the membrane may be ornamented and the outer wall is possibly thinner. Nucellosphaeridium Timofeev 1966 has a larger membrane and a considerably smaller inner body.

Archaeosacculina cf. baltica Naumova 1968

(Pl. 7, Fig. 1 - 10; Pl. 8, Fig. 1 and 2)

Description: Test consists of outer membrane and inner body.

Outer membrane hollow, circular to sub-circular in

outline, and may be irregular. Wall single, thin and

uniform. Surface smooth and without ornament. Slight

random granular texture may occur on some specimens due to low grade metamorphism.

Outline of inner body circular on slightly angular, regular or slightly irregular. One specimen has been found in which the inner body consists of four very small hollow spheres in contact. Generally inner body considerably darker and stouter than outer membrane, probably due to thicker wall. Surface of inner body smooth with no visible ornamentation.

Tests always occur singly. Inner body always sits in centre of test and is usually $\frac{1}{2}$ - $\frac{3}{4}$ diameter of test.

Dimensions: Diameter of test 8 μ m to 17 μ m

Diameter of inner body 4 μ m to 11 μ m

Inner body/whole test %; 62.5% to 82%.

Remarks: The relationship between the size of the inner body and test as a whole (62% to 82%) distinguishes this from other Disphaeromorphitae e.g. Nucellosphaeridium Timofeev. The angularity of some inner bodies may be due to growth of pyrite crystals.

Occurrence: Mullach Dubh Phyllites

Easdale Slates

Tayvallich Slates and Limestones (only 1 poorly preserved specimen that may be a bubble).

Ardvarney Formation

Other recorded occurrences: Lontovas suite, Estonia, Lower Cambrian (Naumova 1968). Vosmoye Complex, Northern Siberia, Lower Cambrian (Iltchenko 1973); Zone 1-2 (Torridonian), Downie (1974); Hell's Mouth Grits,

Lower Cambrian, Zone S1A (Protolenid/Strenullid zone) (Potter 1974); St. Tudwal's Peninsula, Lower Cambrian, Zon SIC (Paradoxides oelandicus and part of P. paradoxissimu zone) (Potter 1974).

Archaeosacculina sp.A.
(Pl. 8, Fig. 3 - 10)

Description: Test consists of outer membrane and inner body.

Outer membrane circular, usually pale, with regular indentations spaced approximately 1 μm apart, and < 0.5 μm deep. No evidence of the spatial distribution of these indentations on the test surface. Outer membrane wall is single and thin. At the indentations, "septa" radiate inwards, towards the inner body. One "septum" occurs at each indentation. The "septa" are < 1 μm wide and about 2 μm long. They appear to connect the inner body to the wall of the outer membrane.

The inner body is circular to slightly angular in outline, and may be irregular. Inner body dark, and central. Surface of inner body smooth with no ornamentation.

Dimensions: Diameter of test 9 μm - 22 μm

Diameter of inner body 4.5 μm - 12 μm

Inner body to test %: 48% - 74%

Remarks: This form differs from Archaeosacculina cf. baltica, by the presence of radiating "septa" connecting the Inner body to the outer membrane wall.

The only species described, which I have found similar to Archaeosacculina sp. A is Cymatiosphaera baikitica Timofeev 1966, from the Middle Ordovician and Lower Silurian of the Siberian Platform. The two species are superficially very similar, although C. baikitica is considerably larger, and the spines are distinct entity radiating from the inner body, rather than a feature connecting the inner body to the outer membrane wall. A number of spines in C. baikitica do not appear to reach the periphery of the test.

Sub-group: SPHAEROMORPHITAE Downie, Evitt and Sarjeant 1963

Genus: LEIOSPHAERIDIA

Eisenack 1958

Type Species:- Leiosphaeridia baltica Eisenack 1958.

Diagnosis: Vesicles spherical to subspherical, without processes; with or without pylomes; wall smooth, punctate, granulate or with minute sculpture, thin to proportionally moderately thick, without pores or radial canals.

Remarks: There has been some considerable discussion over the years concerning the classification of the simplest spheromorph acritarchs and although the work of Downie and Sarjeant (1963) and Staplin et al. (1965) have clarified the position to some extent the naming of simple spheromorphs still appears to lack order.

In 1938 Eisenack described the genus Leiosphaera and designated as its type species Leiosphaera solida. Sub-

sequently Eisenack (1958) recognised that Leiosphaera solida was conspecific with Tasmanites huronensis (Dawson 1871) and abandoned the name Leiosphaera. All species originally assigned to Leiosphaera that did not possess the characteristics of Tasmanites Newton 1875, i.e. thick wall and radiating pores, were transferred to the new genus Leiosphaeridia Eisenack 1958, the type species of which is Leiosphaeridia baltica.

Staplin et al. (1965) note that some confusion has arisen due to Eisenack's diagnosis of Leiosphaeridia indicating that a pylome had to be present, and that this had not yet been found on the type species. Downie and Sarjeant (1963) have broadened the diagnosis to include forms with or without a pylome. However Downie and Sarjeant (1963) point out that Eisenack (1958) did not consider a pylome to be present in every species or that it had specific value.

Timofeev introduced the name "Leiosphaeridium" in 1956 under the new sub-family, Leiosphaerideae. However Leiosphaeridium was invalid as it appeared only as a caption to an illustration, without a diagnosis or designation of type species. Timofeev (1959) validated the genus Leiosphaeridium by describing its type species Leiosphaeridium eisenacki. However Timofeev (1959) clearly attributed Leiosphaeridium to Eisenack (1938) and intended it as an alternative to Leiosphaera Eisenack. As an alternative, it is not valid however. Staplin (1961) attempted to validate Leiosphaeridium by amending the diagnosis, but as a rejected name cannot be re-used,

(I.C.B.N. Rules), this also is invalid and Downie and Sarjeant (1963) suggest that the name should be abandoned. The validity of Leiosphaeridium is brought into further doubt by vagaries in the size range of this genus. Timofeev (1959) states that the size range of the genus Leiosphaeridium 200 - 300 μm , while the type species L. eisenacki has a quoted size range of 100 - 125 μm (Timofeev 1959).

Timofeev (1959) validly proposed the genus Protoleiosphaeridium, although the type species P. conglutinatum was not designated by Timofeev until 1960. Again there is a discrepancy of size range. The genus has a quoted size range of 20 - 30 μm while the six described species have a size range 20 - 50 μm , (Timofeev 1959). Protoleiosphaeridium is small, thin walled, without pores and without pylomes. However, this does not differ significantly from Leiosphaeridia Eisenack 1958 and Downie and Sarjeant (1963) suggests that Protoleiosphaeridium is a junior synonym to Leiosphaeridia.

Timofeev (1966) proposed a new genus Protosphaeridium with the type species P. densum. Timofeev (1966) equates this with Protoleiosphaeridium (Timofeev 1959), although there is no indication that all the species under Protoleiosphaeridium are transferred to Protosphaeridium. The type species of Protosphaeridium (P. densum) is invalid, as the type species of Protosphaeridium should be "Protosphaeridium conglutinatum nov. comb."

The description of this genus: "spherical, 5 - 60 μm , smooth or slightly sculptured, with or without folds, with or without pylome", is not significantly different to Leiosphaeridia, and as such Protosphaeridium Timofeev 1966 can be considered a junior synonym of Leiosphaeridia.

The position is further complicated by such descriptions of simple spheromorphs as the genus Huroniospora Barghoorn 1965 from the early Proterozoic Gunflint Iron Formation and many other Precambrian formations. These are described as spheroidal cells with smooth or minute sculpture, possibly with a small pylome occasionally present and a size range of 1 - 16 μm . In a similar fashion to Protosphaeridium Timofeev 1966, Huroniospora Barghoorn 1965 may best be described as a subgenus to Leiosphaeridia Eisenack 1958.

As can be seen from the discussion above, the genus Leiosphaeridia Eisenack 1958 can include all simple spheromorphs with smooth or minutely ornamented surfaces. This is an unwieldy and inconcise concept. As has been illustrated by many authors (and see below) distinctive and separate simple spheromorph morphologies can be recognised, and yet be accommodated in the genus Leiosphaeridia. However unless criteria can be established that are consistent over a wide range of preservational conditions, the splitting of Leiosphaeridia into a number of new genera may not serve a useful purpose.

Amongst the physical features of a spheromorph that can be observed are: shape, size, colour, ornamentation,

folding, wall thickness. For the classification of spheromorphs outside a single sample, (where depositional and preservational conditions would be fairly homogenous) the criteria used must reflect the original spheromorph and be consistent during variable preservational conditions. Such features as colour, folding, and to some extent ornamentation (granulate textures can arise from metamorphism see Chapter 5.1), size and shape (see Knoll & Barghoorn 1975), are variable under different preservational conditions. Folding for example would be highly reduced under conditions of slow sedimentation and early cementation (almost non-existent in very early diagenetic chert), but would be increased under conditions of fast sedimentation and late cementation. Different styles of folding under similar preservational conditions could be an important feature for classification, and different fold styles could represent different "species". However, there is insufficient information about the mechanism of the folding of spheromorph walls, and whether a unique fold style is confined to spheromorphs with unique properties e.g. wall structure.

Schopf (1968) has attempted to classify simple spheromorphs by means of their method of reproduction (e.g. Myxococcoides Schopf 1968). However, this needs extremely well preserved material, and the ability to recognise a reproductive phase.

With the discussion above, I have decided, for the purposes of this study, to classify all simple sphero-

morphs in the Dalradian under the genus Leiosphaeridia Eisenack. As more than one form of spheromorph can be recognised, these will be described as Type 1, Type 2 ... etc.. The similarities of each Type to published species will be discussed in the section "Remarks" pertaining to that Type.

Genus: Leiosphaeridia Type 1

Description: Outline circular to elliptical, usually regular, but irregular under conditions of poor preservation. Wall single, thin, 0.5 μ m or less, uniform; surface smooth or slightly granular, without ornamentation or processes. Very rarely do folds occur on the surface. No evidence of pylome found. Tests occur singly.

Dimensions: Diameter of test 3 μ m to 18 μ m

Major mode 5 μ m to 6 μ m

Remarks: This type bears a close similarity to Huroniospora psilata Barghoorn 1965. There is some similarity with the the genus Myxococcoides Schopf 1968, in that both have no outer membrane. Protosphaeridium parvulum Timofeev (1966) and Protosphaeridium pusillum Timofeev (1966) also bear a close similarity to Type 1, although folds in Type 1 are rarer than is suggested by Timofeev's descriptions. Apart from the absence of any evidence of a triradiate mark in any specimens of Type 1 there is little of difference between Type 1 and Leioligotritileum minutissimum (Naumova) Timofeev. Likewise Trachyoligotritileum minutum (Naumova) Timofeev, although both these species

have higher size ranges than Type 1 (15 - 40 μ m and 10 - 40 μ m). Konzalova (1974) illustrates a Leiosphaeridium sp. comparable to Type 1 from the Bohemian Upper Proterozoic. Polyporata nidia Pychova 1967 differs from Type 1 in possessing openings. Leiopsophosphaera rotunda Pychova 1967 appears to be similar to Type 1, although the size range of L. rotunda (12 μ m - 15 μ m) is much less than Type 1.

Occurrence: Cnoc Donn Slates

Mullach Dubh Phyllites

Bonahaven Dolomites

Easdale Slates

Crinan Grits

Highland Border Series

Ardvarney Formation

Loch Feegh Group (Clare Is.).

It is almost certain the Leiosphaeridia Type 1 occurred throughout the Dalradian, although in a number of formations the spheromorphs are too dark to determine if the wall is thin and the surface unornamented.

Other recorded occurrences: Leiosphaeridia Type 1 spheromorphs occur from the late Archean onwards.

Leiosphaeridia Type 2

(Pl. 10, Fig. 7 - 10, Pl. 11, Fig. 1 - 6)

Description: Outline circular to elliptical, generally regular.

Tests occur singly. Wall single, relatively thick (0.8 μ m to 1.2 μ m), and usually more irregular than

Leiosphaeridia Type 1. Surface of test smooth or slightly granular. No evidence of pylome found.

Dimensions: Diameter of test 6 μ m to 12 μ m.

Remarks: Leiosphaeridia Type 2 differs from Trachysphaeridium laminaritum (Timofeev) Vidal 1976b, in the absence of short spines and in being considerably smaller. The genus Menneria Lopukhin is considerably larger and more granulate than Type 2. Leiosphaeridia Type 2 probably bears closest resemblance to Protosphaeridium densum Timofeev or Protosphaeridium rigidulum Timofeev, although it is towards the lower end of the size range, and a little smaller than both of these.

Occurrence: Mullach Dubh Phyllites

Crinan Grits

?Tayvallich Slates and Limestones

Highland Border Series

Other recorded occurrences: Lower Precambrian to Upper Cambrian of Russia, Scandinavia, Europe, Australia, China, and Antarctica.

Leiosphaeridia Type 3

(Pl. 11, Fig. 7 - 9)

Description: Outline circular, regular. Tests occur singly.

Wall single, usually thin, uniform. Surface of test ornamented by latitudinal dark parallel striae apparently centred on one pole. The striae may be preservational, but their regularity suggests they are original. Spacing between striae about 0.4 - 0.7 μ m. Up to 11 striae have

been observed on the surface of test. No evidence of pylome found.

Dimensions: Diameter of test 9 μm - 12 μm

Width of striae $\approx$ 0.5 μm .

Remarks: Leiosphaeridia Type 3 differs from the genus

Stictosphaeridium Timofeev in having straight as opposed to sinuous striae, and in being smaller. The striae of this form are only clearly visible on one specimen, but the regularity of those striae suggest that this is an original feature. No other genus similar to Type 3 has been found.

Occurrence: Easdale Slates

?Highland Border Series.

Other recorded occurrences: None known

Leiosphaeridia Type 4

(Pl. 12, Fig. 1 - 2)

Description: Tests occur singly, outline of test circular.

Wall single, thin. Surface of test covered with minute, often arcuate? rugulae, forming an irregular mesh work.

The fields are of irregular shape and size.

Dimensions: Diameter of test 8 μm to 11 μm .

Remarks: Leiosphaeridia Type 4 is most similar to Favoso-

sphaeridium Timofeev 1966. It differs in being considerably smaller than any of the species described by Timofeev (1966), and having more irregular "fields".

However the illustrations of this genus by Timofeev (1966) e.g. Plate VIII fig. 3, show tests with irregular fields

of varying size. Vidal (1976b) illustrates specimens of F. favosum Timofeev, which show considerable similarity to Leiosphaeridia Type 4. The minute ?rugulae show considerable irregularity. However, the size illustrated by Vidal (1976b) are considerably larger than Leiosphaeridia Type 4 found here. The small species F. variabilis described by Cloud and Germs (1971), while appearing to be very similar to F. favosum Timofeev, are more similar in size to that of L. Type 4 found here (13.2 μ m to 26 μ m as opposed to 8 μ m to 11 μ m).

Leiosphaeridia Type 4 differs from the genus Plicatosphaera Potter (1974) in that its ornament is minute and indefinite and forms fields of irregular shape and size, as opposed the more distinct and regular pentagonal fields of Plicatosphaera Potter.

Occurrence: Easdale Slates

Other recorded occurrence: Favososphaeridium variabilis,

Stoer Formation, Stoer Bay, Scotland, Vendian (Cloud and Germs 1971); Favososphaeridium favosum, Visingsö Beds, Sweden, Vendian, ?Lower Cambrian (Vidal 1976b); Favososphaeridium favosum, N. China, late Precambrian, Russia and S. Sweden, Cambrian (Timofeev 1966).

Leiosphaeridia Type 5

(Pl. 12, Fig. 3 - 7; Pl. 12A, Fig. 1 - 5)

Description: Irregular three-dimensional clusters, on chains, of simple Type 1. Leiospheres. Individuals are circular in outline, regular; with thin single wall. Surface is

smooth or occasionally granular, and unornamented.
Individuals in a cluster show some size variation
(5 μm - > 12 μm). Usually 10 or less individuals in
a cluster. Individuals in a straight chain are usually
of more comparable size.

Dimensions: Diameter of individuals 5 μm - 12 μm

Size of cluster: up to 35 μm .

Remarks: Leiosphaeridia Type 5 is very similar to Synsphaeridium
conglutinatum Timofeev (1966) (Protoleiosphaeridium
conglutinatum Timofeev 1959). It differs in the
individual vesicles being smaller than in S. conglutinatum.
Also the vesicles of S. conglutinatum appear to be more
uniform in size in any one cluster (although this is
not stated in the diagnosis) than Leiosphaeridia Type 5.
Unfortunately Synsphaeridium conglutinatum Timofeev (1966)
is invalid, as the genus Synsphaeridium (type species
S. gotlandicum) was validly proposed by Eisenack (1965).
However the two species described by Eisenack (1965) are
different from Leiosphaeridia Type 5 in being ornamented.

Occurrence: Mullach Dubh Phyllites.

Other recorded occurrence: Abundant in the late Precambrian
and Lower Palaeozoic (Timofeev 1966).

SPHEROIDAL MORPHOLOGIES Incertae Sedis

Form "A"

(Pl. 16, Fig. 1 - 10, Pl. 17, Fig. 1 - 8)

Description: Outline similar to that of a peanut shell. Test
characterised by two, or rarely three spheres or ellipses

in contact, which are joined at a neck. A single organic wall is continuous around the test, and very rarely does an organic wall occur across the neck. Clearly this form can be differentiated from simple leiospheres which have come in contact fortuitously or otherwise. At the neck, opposite walls rarely touch.

Outline is generally regular. Surface smooth or granular under different preservational conditions. Test is always hollow, with single wall which is thin, and occur singly. The two spheres are generally different in size, but may be equal.

Dimensions: Length of test 10 μm to 26 μm

Diameter of individual spheres 5 μm to 18 μm .

Remarks: No formal description of Form A has yet been made.

However specimens morphologically similar to Form A have been illustrated by a number of authors. Potter illustrates a Granomarginata squamacea that has a gross morphological similarity to Form A. However C. squamacea is a Disphaeromorphitae with a poorly defined outer membrane, and is clearly not comparable to Form A.

Konzolova (1974) has illustrated (Plate II Fig. 4) a specimen of Form A from the Upper Proterozoic Bohemian of Czechoslovakia, under "opaque organic fragments".

Vidal (1976b) similarly illustrates reasonably well preserved specimens of Form A from the Visingsb Formation of Sweden, and classifies them as Pterosperopsimorpha densicoronata Sin and Liu 1973.

Moorman (1974) illustrates Form A type microstructures from the late Precambrian Hector Formation of west Canada and ascribes them to the genus Sphaerocongregus Moorman. Many of the specimens illustrated by Moorman (1974) are distorted by pyrite framboid growth.

Darby (1974) has made a detailed study of forms comparable to Form A from the Gunflint Formation of Ontario. He attributes them to a budding stage in the life cycle of Huroniospora microreticulata Barghoorn 1965, and compares their morphology to that of the extant fungus Mucor rouxii, which reproduces by budding under a CO₂ atmosphere (Bartnicki-Garcia and Nickerson 1962). Darby (1974) uses this evidence to suggest that the atmosphere during Gunflint Formation times ($\approx$ 2,000 m.y. B.P.) was rich in CO₂.

The morphology of Form A is very similar to the budding stages of many yeast fungi and has been described in a general fashion by Matile et al. (1969). Budding occurs in many genera of the sub-families Cryptococcoideae, Rhodotoruloideae, and Saccharomycetoideae, and these are not all restricted to CO₂ rich conditions. Without further evidence regarding the affinity of Form A microfossils, or independent sedimentological evidence, few inferences can be drawn from this morphology with regard to the atmosphere when they existed.

Occurrence: Ballachulish Slates

Cnoc Donn Slates

Mullach Dubh Phyllites

Bonahaven Dolomite

Easdale Slates

?Highland Border Series

Other recorded occurrence: Bohemian Upper Proterozoic Czechoslovakia (Konzolova 1974), Vendian Visingsö Formation, Sweden (Vidal 1975b), Early Proterozoic, Gunflint Formation, Ontario (Darby 1974). Late Precambrian Hector Formation, western Canada (Sphaerocongregus, Moorman 1974).

Form B

(Pl. 13, Fig. 1 - 8, Pl. 14, Fig. 1 - 10; Pl. 15, Fig. 1 - 10)

Description: Outline of test varies from circular to elliptical and hemispherical. Three morphological forms are included under Form B, but as they occur as a continuum (see Remarks below) they will be discussed here under a common heading.

(i) Outline of test circular or sub-circular, generally regular, but may be irregular under conditions of poor preservation. Test appears to be hollow in better preserved material but this is often difficult to assess due to darkness of test. Wall single and thin and is uniform. Surface is smooth. Tests occur singly.

This form is characterised by a split in the edge of test. The split usually occurs about three-quarters of the way up the circumference. The angle between the two sides of the split varies between 50° and 90° and in plan view the split penetrates the test for up to three-quarters of the length of the chord parallel to the equator.

Splits never occur radially, but always propagate parallel to the equator.

Dimensions: Diameter of test 4 μm to 16 μm .

(ii) Outline of test sub-circular, generally regular except under poor preservation. Test hollow. Wall single, thin and uniform. Surface of test smooth and without ornament. Tests occur singly.

This form is characterised by the presence of a circular opening or pylome, approximately halfway between the test's equator and pole. The wall at the circumference of the pylome is thin and shows no evidence of collar, ridge, suture or other structure which may define its position.

The form is also characterised by a "cap", which can be termed an operculum, that is attached to one point of the circumference of the pylome. The circumference of the operculum appears to be the same as that of the pylome in any one specimen, and clearly the operculum has split away from the remainder of the test. Again there is no evidence of collar, ridge, suture or other structure that the operculum has split away from a predetermined position.

Dimensions: Diameter of test 5 μm to 20 μm

Diameter of pylome 3 μm to 15 μm

(iii) Outline of test sub-hemispherical, to sub-hemi-elliptical outline, the straight edge is always parallel to the minor axis of the ellipse. In both cases the straight edge forms the rim of a pylome which occurs

approximately halfway between the equator and pole. The test is hollow and the pylome edge can be seen in three-dimensions in better preserved samples. The pylome allows entry to and from the centre of the test. The test's wall is single, thin and uniform. The surface of the test is smooth and without ornamentation. Tests occur singly.

In a small number of specimens (see Pl. 15, Fig. 4) the pylome appears to be stellate.

No collar, ridge, suture or other structure occurs around the circumference of the pylome that might indicate that occurs at a predetermined position. However, in a number of specimens the edges of the pylome, as seen in plan curve inwards. This may be a preservational feature, but as the remainder of the test may be undamaged in specimens where this occurs, and this feature is thought to be original.

Dimensions: Diameter of test 5 μm to 17 μm

Diameter of pylome 4 μm to 12 μm .

Remarks: These three forms constitute a continuum. Starting at Form B (i) a split develops on the edge of sphere about halfway between the equator and the pole. As no evidence of a structure that might indicate the position where the split should start, has been found on simple leiospheres the stage before Form B (i) cannot be clearly recognised. However the stage previous to Form B (i) was almost certainly a spheromorph.

Once the split has been initiated, it spreads across

a chord parallel to the equator and an operculum splits off the main body. A decrease in the anchorage of the operculum to the test can be observed until the operculum breaks away. These stages can be seen in Form B (ii).

After the operculum has broken away, the test is hemispherical to hemielliptical in outline, with an open circular pylome. This is stage B (iii).

The purpose of an operculum breaking away from the test and leaving a pylome, is in most acritarchs to release an inner cyst. However, amongst Dalradian specimens of Form B, none have been found showing evidence of possessing an inner body. No Disphaeromorphitae have been found in the process of forming a pylome or with evidence of where one could start. Possibly the Form B acritarchs never had an inner cyst. More likely as Form B specimens are rather rare, there is insufficient material available at present to observe the moment of release of the cyst. Also many specimens are opaque, and the presence or absence of a cyst cannot be determined.

Kildinella magna Timofeev (1973) and the genus Dichasphaira Potter (thesis 1974) are larger than Form B, and split along the equator, forming two equal hemispheres which often roll up. Volkova (1969) illustrates (Plate XLVIII figs. 8 & 9) specimens of Leiosphaeridia type B which split similarly, and C.J. Peat (pers. comm.) has found abundant split Leiospheres from the Proterozoic Roper Group of Australia. However all these forms are

Leiospheres which split equatorially to produce equal hemispheres. Form B differs in splitting halfway between equator and pole and producing a distinct operculum.

Form B differs from the Genera Priscogalea and Cymatiogalea by being smaller and lacking any surface ornamentation or processes.

Occurrence: Cnoc Donn Slates

Mullach Dubh Phyllites

Appin Transition Beds

?Easdale Slates (1 poorly preserved specimen)

Crinan Grits

?Highland Border Series

Lough Feagh Group

Ardvarney Formation

ALGAE

Incertae Sedis:

Filaments

(Pl. 18, Fig. 1 - 3; Pl. 19, Fig. 1 - 4)

Description: Filaments long (up to 400 μm) and very thin

($\approx 2 \mu\text{m}$), parallel walled. Walls very thin. Filaments non-septate, sheath-like. They are coated with ? organic debris. Filaments very wiggly. Branching occurs occasionally, and junction is often thickened. The width of the filaments are generally consistent but may undulate slightly.,

Remarks: These filaments differ from many that have been described by being extremely thin relative to their length. Their non-septate nature suggests that they may be algal sheaths.

Occurrence: Easdale Slates: Kerrera Island only

Other recorded occurrences: Fossil filaments which may be similar to these have been described frequently through the Precambrian and later.

CHAPTER 5

DISCUSSION

5.1 Preservation

The physico-chemical processes which operate on a microorganism from its death until its examination as a microfossil have a marked effect on its state of preservation.

In exceptional circumstances, e.g. very early diagenetic silicification, the microfossil may maintain an extremely good state of preservation. However at any stage of its post-mortem history, its state of preservation may either stay constant, or as is more usual deteriorate. It is therefore important to have some understanding of the processes of preservation. This is especially so in the Dalradian, where tectonism and metamorphism are added to the usual factors which include death, deposition, diagenesis etc.

The physico-chemical processes which effect a sediment, and the associated organic matter after deposition have been divided into "diagenesis" and "metamorphism". However, as these two phenomena form a continuum, in which with increasing temperature and pressure (which may be due to increase in depth of burial), diagenesis passes into metamorphism, it is more convenient to divide preservation processes into "pre-lithification" and "post-lithification". The former concerns a situation where mechanical movement of grains is still possible, compaction is greatest, and pore fluids are most mobile. Post-lithification processes occur after cementation, where pore fluid influences decrease, and pressure and temperature phenomena are of more importance, especially where these result in the re-orientation of minerals (formation of cleavage)

and growth of new metamorphic minerals.

Pre-lithification processes:

The first factor controlling final preservation, is the range of species available. This depends both on the age of the rocks and the depositional environment, the latter becoming a more important factor in the case of benthic micro-organisms.

On death, and the immediate post-burial stage (very early diagenesis), the preservation of a microfossil is controlled by the environment in which it is buried, and the rate of burial, and depends on the chemical, biological and physical characteristics of that environment.

An oxidising environment will destroy organic matter, and for microfossils to be preserved it is necessary for there to be sufficient organic matter in the sediment to use up all the available oxygen and thus create a reducing environment. This situation is found in many recent depositional environments rich in organic matter, e.g. the Black Sea (Deuser 1971), the California Borderlands (Hülsemann and Emery 1961) and Christchurch Harbour England (Love and Murray 1963). The biological destruction of organic matter is the result of the microbial destruction of macromolecules, and the feeding habits of larger burrowing and sediment-dwelling organisms. Although there is no direct evidence for such organisms from the Dalradian (but see Wilkinson 1907, and Knill 1963), at present, the presence of abundant trace fossils in rocks of similar age in Scandinavia and Greenland (Cowie and Spencer 1970, Banks

1970 , Banks et al. 1974), indicates that worm-like browsers probably did exist in Dalradian seas.

Microbial activity appears to decrease rapidly with depth, such that at about 1m depth, this activity has almost stopped (Degens 1967). Microbial and chemical activity (hydrolysis) at the surface lead to alteration of proteins, polysaccharides, fats etc. into soluble amino acids, sugars etc.. After the cessation of microbial activity, diagenetic alteration of organic matter is largely restricted to polymerisation and condensation, redistribution of pre-existing organic molecules, and thermal degradation leading to the formation of kerogen. However, many of these processes appear to have little effect on the gross morphology of the microfossil once it has been buried. The very early loss of internal structure and organelles can be expected, but the presence of small blebs or spots inside some extremely well preserved Precambrian material (e.g. Schopf 1968, Hofmann 1976, Diver 1974, Muir 1976) may be the remnants of these organelles (Golubic and Hofmann 1976). However the evidence to support this equivocal and in the case of Dalradian microfossils, all the small spots inside spheromorphs are either fragments of organic matter of unknown origin, or pyrite microcrysts (Fig. 5.1). However, beyond that if a microfossil survives being eaten, then these early diagenetic chemical processes appear to have little effect on its gross morphology.

The original lithology plays an important part in pre-lithification preservation. In the situation where coarse silts and sands are being deposited, a number of factors

Fig. 5.1; Leiosphaeridia ?Type 2 showing small central dark spot of uncertain origin. Possibly degraded cell organelles?

Fig. 5.2; Diagram showing microfossils sitting in a relatively protected fashion in a loosely packed silt.



Fig. 5.1

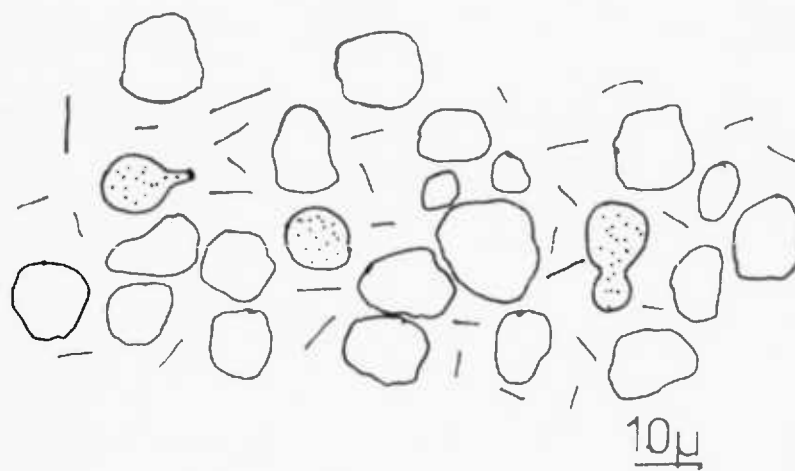


Fig. 5.2

combine to reduce the likelihood of microfossils being preserved.

The environments of deposition of many coarse grained sediments e.g. beach sands, are strongly oxidising, and hence very unsuitable for microfossil preservation. Rate of deposition is likely to be high, with a consequent low concentration of organic matter. The grain size of the sediment is by itself not a factor that should cause excessive damage to microfossils. If a silt or sand was deposited from suspension, without any grinding, then however the grains settled, even in the most compact hexagonal packing there would still be sufficient pore spaces for microorganisms to fall into and remain undamaged (Fig. 5.2). More damage is caused in coarse grained sediments by the grinding between grains that takes place under the higher energy environments associated with these sediments. This results in mechanical breakdown of the microfossils. The preservation of microfossils in pore spaces is more likely to be successful in silt grade sediment, deposited at a lower energy. This occurs in the silts of the Roper Group (C.J. Peat pers. comm.) (Fig. 5.3). Vidal (1976) has shown that relatively well preserved microfossils can occur in unindurated siltstones. One of the factors that may be important in this context is the degree of compaction, and also whether cementation takes place early or not. Greater compaction would lead to a closer packing of the grains and a reduction in pore space, thus helping to destroy microfossils. In the Dalradian it has been found that silt grade and coarser rocks are generally

unsuitable for the preservation of microfossils.

These negative features are perhaps best illustrated in the case of turbidites. The sediment is deposited quickly with much attrition between grains. A considerable time span would be necessary at the end of each cycle to allow for a sufficiently thick layer of organic rich, fine grained sediment to be deposited, and not eroded by the subsequent turbidity flow. The role of organic matter in turbidites is illustrated in the Macduff Slates (see Chapter 5.2) where the organic matter is clearly acting as grains of sediment. There is no organic "dust", and the organic matter occurs as angular grains of similar and larger size range and angularity as the quartz grains (Fig. 5.4). The generally larger size of the fragments of organic matter is a reflection of the difference in specific gravity between organic matter and quartz, with smaller fragments being carried further on by the current. Clearly the organic matter has been swept in with the sediment and there appears to be no organic matter that has not been reworked.

Microfossils are best preserved in fine grained (argillaceous) sediments. Slow rates of deposition lead to a relatively high organic matter/sediment ratio, and slow or stagnant bottom waters combine with this to produce a reducing environment.

On deposition, argillaceous sediments possess a porosity of 70 - 90% and an initial water content of 50 - 80% (Müller 1967). In this situation microfossils can float with little contact with surrounding grains. Little attrition occurs

Fig. 5.3; Well preserved acritarch in a silt from the Roper Group (1300 m.y.) of Northern Australia (photo C.J.Peat).

Fig. 5.4; Photomicrograph from the Macduff Slates (B66), showing the close similarity of grain size between quartz and graphite in a turbidite environment.

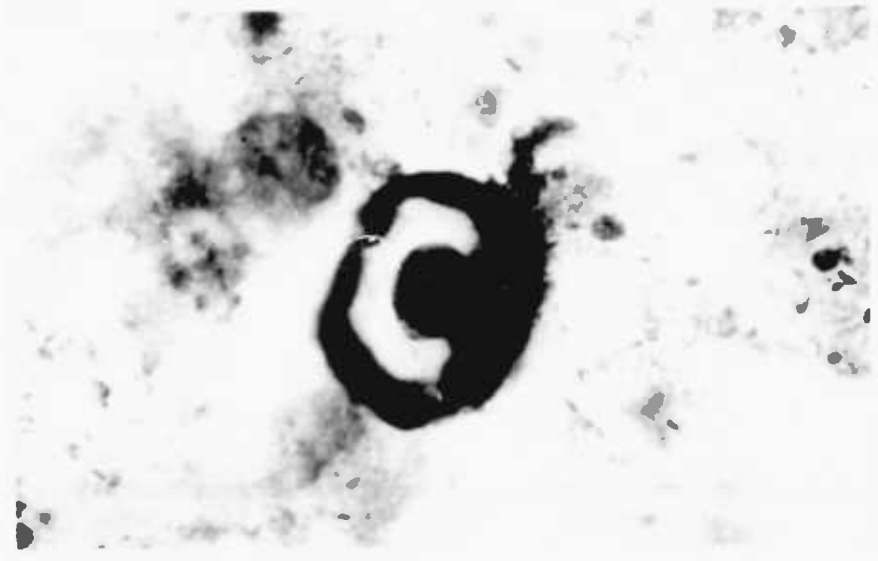


Fig.5.3

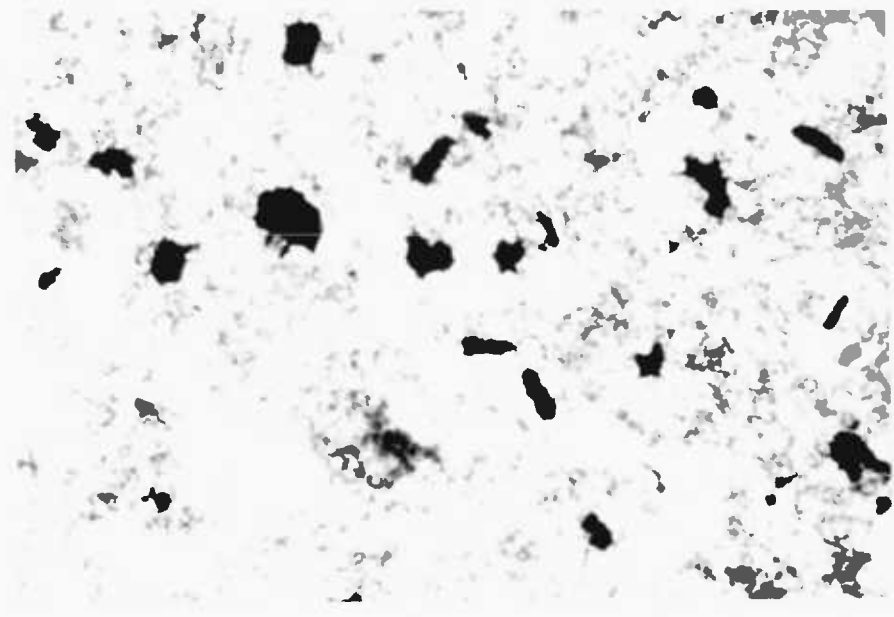


Fig.5.4

between grains at this stage. The initial structure is a sub-random orientation of grains, usually as edge to surface fashion, due to negative charges on surfaces and positive charges on broken ends. It is possible for aggregates of crystals to collect with large spaces between them, in which microfossils may lodge (Müller 1967) (Fig. 5.5).

On compaction the grains become more dense, and there is consequent decrease in porosity. Only a small amount of overburden is necessary to produce a marked change in porosity (8m of overburden can produce a 30% decrease in porosity (Müller 1967 after Zülig 1956)). At the same time there is an increasing sub-parallel alignment of the clay flakes. During this time microfossils, especially the larger ones can undergo flattening and folding. However the damage caused by compression need not be excessive, as at the same time, the muds become mechanically stronger ("stiffer"). This may be due to bonding between clays (Rittenberg et al. 1963). If there is a high electrolyte content in the mud, then the degree of orientation on compression can be decreased (Von Engelhardt and Gaida 1963).

With increasing depth of burial, clay mineral transformations take place. Illite is formed at the expense of montmorillonite, and chlorite (and illite) at the expense of kaolinite. Although these transformations in themselves probably play little part in the preservation of microfossils, they do lead to an increase in the amount of SiO_2 present. The SiO_2 is also increased by the breakdown in feldspars. This increase is important in cementation, and its effects

Fig. 5.5; Diagram showing the way in which pores arising from the aggregation of clay minerals in sediment prior to compaction can accomadate microfossils.

Fig. 5.6; The Aberfoyle Slates; a very fine grained shale, high in mica, but relatively very poor in organic matter and microfossils.

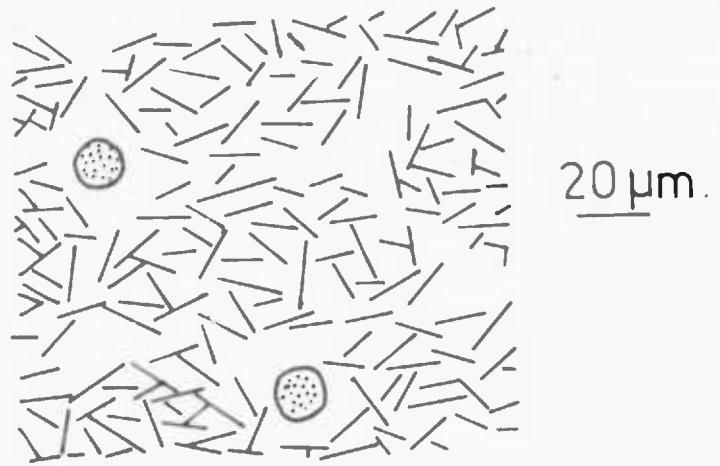


Fig.5.5



Fig.5.6

will be discussed in greater detail later.

During the pre-lithification stage, pore waters can circulate relatively freely through the sediment. If these remain reducing, then the organism should remain largely intact. However, if there is a change in depositional environment, say due to block uplift, and sediments are deposited on the muds under oxidising conditions, then oxidising pore waters could reach down into the underlying muds and break down organic matter, including microfossils. It is interesting to examine this concept in the light of Dalradian sediments. The Transition Beds at Ballachulish, consist of thin (≤ 10 cm) dark shale beds interbedded with thicker (20 - 30 cm) sandstone beds. These shales contain abundant organic matter and preserved microfossils, while the quartzites are white, medium to coarse grained, and were probably deposited under oxidising conditions. Clearly percolating pore waters did not oxidise underlying organic matter in that case. In contrast, the Aberfoyle Slates are a thick sequence of massive purple and green slates almost totally devoid of organic matter (Fig. 5.6). Their general lithology, is not sufficiently different from other organic rich slates to explain this difference. It would be unreasonable to suggest that organic matter was not present during deposition. It is almost certain that oxidative pore waters circulating during diagenesis broke down the organic matter that did exist.

During pre-lithification processes, mineralisation plays an extremely important part in preservation. This mostly takes the form of pyrite. Because microcrystalline pyrite has

such a marked affect on preservation of microfossils, and on creating pseudomorphs, a special study has been undertaken to examine the relationships between microcrystalline pyrite and organic matter in the Dalradian. This is presented at the end of this section.

In addition to pyrite, preservation in iron oxides also occurs. Preservation by primary iron oxides has been recognised by Barghoorn and Tyler (1965) in the Gunflint Chert, and Walter, Goode and Hall (1976) from the Nabberu Basin. In the Dalradian most of the iron oxides appear to be secondary, in many cases pseudomorphing pyrite. A similar situation has been reported by McConnell (1974) from the Mescal Formation.

Cementation links the pre-lithification preservation processes with those that occur post-lithification, and may be a great aid to preservation or destruction of microfossils. Calcite and silica are the most common cementing agents, and as most argillaceous sediments contain some initial carbonate and silica, cementation can occur both at an early and late stage in diagenesis. In the Dalradian, those shales which are the most siliceous contain, as a general rule, the best preserved microfossils. In these siliceous shales, e.g. Mullach Dubh Phyllites and the Easdale Slates, microfossils with good three-dimensional preservation occur (Fig. 5.7). Examination has shown that silica infills the fossil as well as surrounds it (Fig. 5.7), thus preserving the fossil in a rigid mould. Very few of these fossils show folds, such as are common amongst other microfossils of similar age. From this it appears that they were infilled before appreciable

Fig. 5.7; Good three-dimensional preservation in siliceous shales;

Leiosphaeridia Type 1 Easdale Slates E36(TS) 115.9/4.5

a; upper surface view

b, equatorial view

The distance between 'a' and 'b' is approximately 7 μ m. to 8 μ m. The section is cut approximately parallel to the plane of major compression (i.e. bedding plane and bedding plane cleavage)

Fig. 5.8; Photomicrograph under crossed-nicols, showing the relatively large size of quartz crystals in comparison with the microfossil (approximately 7 times the size in this plane). The microfossil is the small dark circle in the middle of the photo.



Fig.5.7

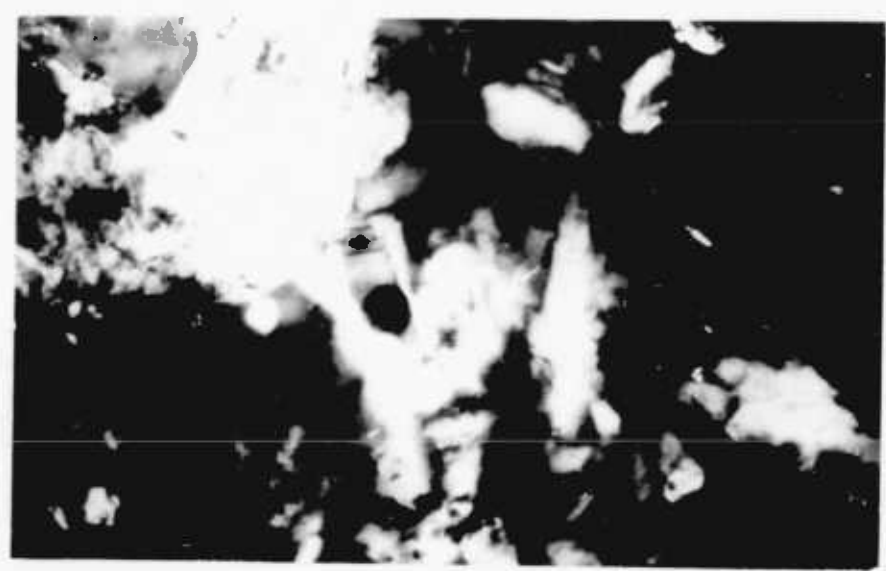


Fig.5.8

50 μm

compression could take place. The additional silica necessary could originate from the breakdown of clays and feldspars during burial (Müller 1967). Dapples (1967) considers this an important feature in forming siliceous shales.

The silica is not extremely fine grained as occurs with well preserved fossils in chert (e.g. Schopf 1968), but it is rather coarse (Fig. 5.8). This may indicate that the original cement was fine grained, but has subsequently recrystallised without disturbing the microfossil. At a pre-cementation stage when silica rich fluid entered the microfossil, the microfossil wall must have been semi-permeable, to an extent that the silica ions could pass through. Whether or not this permeability was destroyed when the organic matter was polymerised under higher pressure/temperature conditions is not known, but is thought likely.

Where the cement is carbonate a different situation can be observed, and as a rule preservation is less good. It appears that in this case it is difficult for a fossil to sit "within" a carbonate grain, as it does with silica cement. Instead carbonate crystals have broken through the fossil wall, crushing it (Fig. 5.9). The result is commonly that unrecognizable organic matter occurs around carbonate grain boundaries (Fig. 5.9) and few well preserved microfossils remain. However, this effect may be more due to recrystallisation during metamorphism. The worst preservation occurs in recrystallised black carbonaceous limestones.

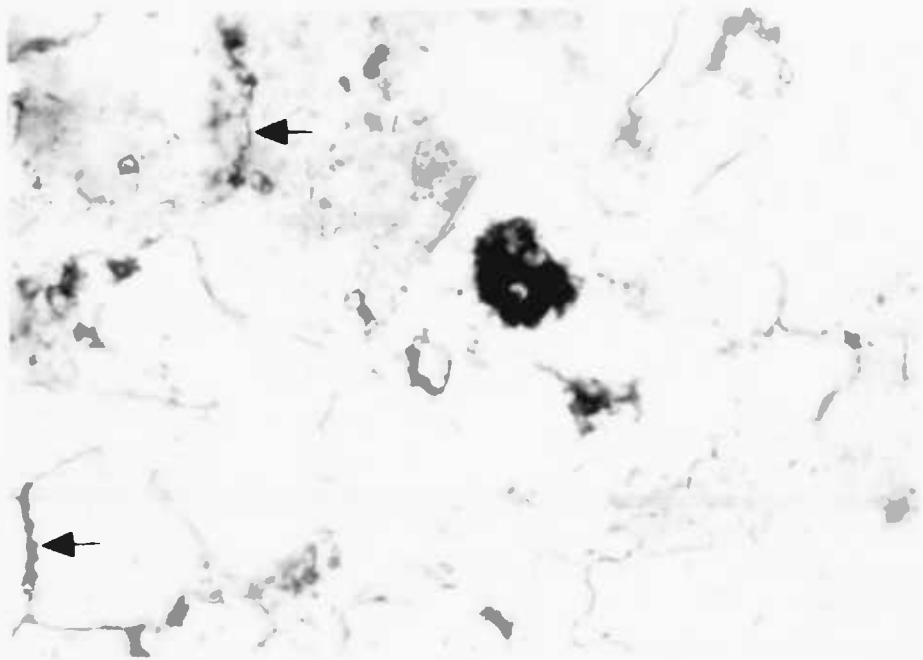


Fig 5.9; Very poor preservation of possible acritarch in the Tayvallich Limestone. Poor preservation due to crushing of acritarch by diagenetic and metamorphic calcite growth. Note also the concentration of organic matter at grain boundaries, arrowed.

Post-lithification processes:

After cementation the processes which effect preservation are tectonism and metamorphism. There is a wide transition between diagenesis and metamorphism. Müller (1967) considers that the critical transition temperature is 300°C is at a depth of 10,000m, and this agrees closely with McNamara (1964), who considers that the lowest grade rocks in the Dunoon Phyllites were metamorphosed at 220°C and a depth of 8,000m, while conditions at the northern boundary of the Dunoon Phyllites may have been 300°C and a depth of 11,000m. (It should be noted that the Dunoon Phyllites are considerably less than 3,000m thick!) Metamorphism affects microfossils in two ways: (i) the effect of pressure and temperature on the chemistry and subsequently the morphology of microfossils, and (ii) the mechanical effect of the growth of new metamorphic minerals.

Tectonism in this context is concerned with mechanical rotation of micas along aligned planes (cleavages), and the effect of a locally imposed stress pattern on the rock and microfossils. This includes not only rotation and growth of micas, but pressure solution, and shearing as well.

Tectonism and metamorphism in reality cannot be separated in this fashion, especially when the regional metamorphism in the Dalradian is largely tectonic in origin (Bailey 1923, Tilley 1925, Elles and Tilley 1930, Rast 1963, McNamara 1964).

Any rotation or growth of micas during tectonism and metamorphism such as the imposition of cleavage is likely

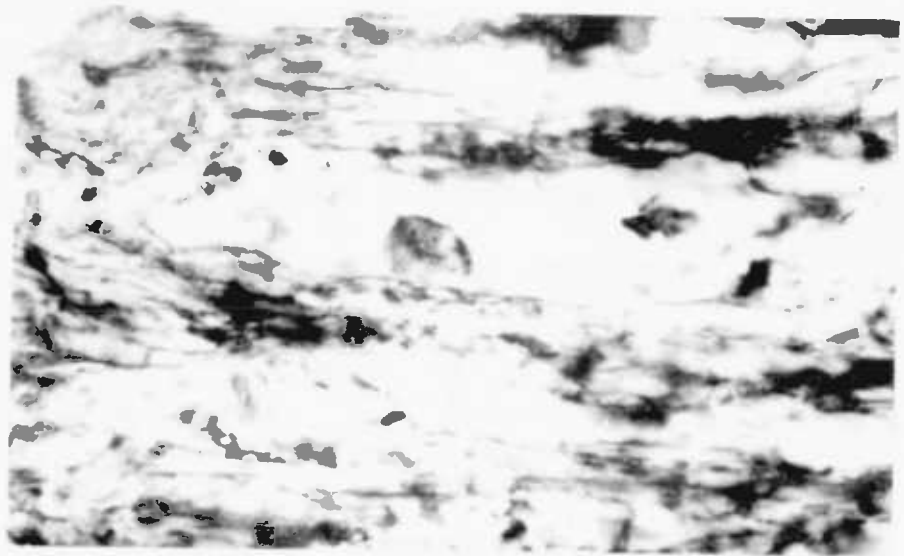


Fig. 5.10; Photomicrograph from the Fassele Slates of acritarch being destroyed by imposition of a cleavage. Note how the cleavage lamella has cleanly broken the acritarch. Compare this with Fig. 5.14, which shows a similar phenomenon in the Tayvallich Slates and Limestones. (X1500)

mechanically to damage microfossils (Fig. 5.10). Thus those slates with the fewest micas, and therefore the most complete silica cementation, will suffer least during tectonism. In micaceous slates however, there are areas of null stress where preservation can be expected to be better than in areas of high stress with much rotation and recrystallisation. On a macro-scale, this can occur in the hinges of minor and meso folds in interbedded pelites and psammites. Knipe and White (1977) have shown that in this area (see Fig. 5.11) the axial planar cleavage is reduced to almost zero, with the original rock fabric being maintained. Away from this area, the diverging axial planar cleavage becomes more intense. These areas on the hinges of folds, are potential areas of relatively good microfossil preservation.

On a microscopic scale, in micaceous rocks, the preservation is controlled by the distribution of cleavage. Cleavage consists of discrete zones of strain with a concentration of reorientated micas and new mineral growth. These zones are areas of high microfossil destruction. Cleavage planes are separated by areas of low strain, usually of the order of 5 - 30 μm wide (White and Knipe 1977, Knipe and White 1977). In these areas of low strain, although there is some growth of new minerals (especially at higher grades), the micas are orientated at a high angle to the cleavage, and maintain something of their original orientation with little rotation (Fig. 5.12). These areas of low or zero strain contain the best preserved microfossils in a cleaved rock with abundant micas. With increasing stress the cleavages close together,

Fig. 5.11; Diagram illustrating the area 'A' on the crest of a fold of interbedded shales and sandstones, where the intensity of the axial planar cleavage is minimal, and microfossils may stand the best chance of being preserved. (after Knipe and White 1977)

Fig. 5.12; Photomicrograph from the Appin Phyllites, showing the distribution of cleavage lamellae. These are the long white streaks. Between these are areas of lower stress, where micas can be seen at a high angle to the cleavage, and show a relatively random orientation.

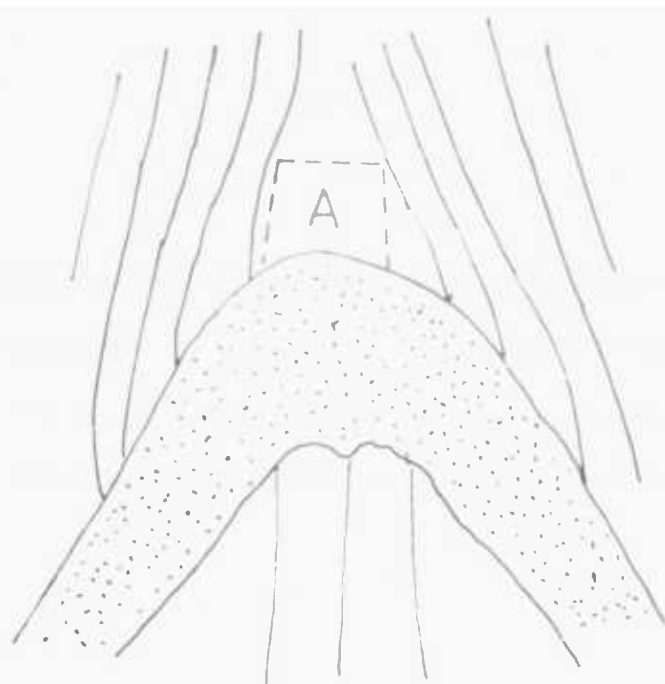


Fig. 5.11

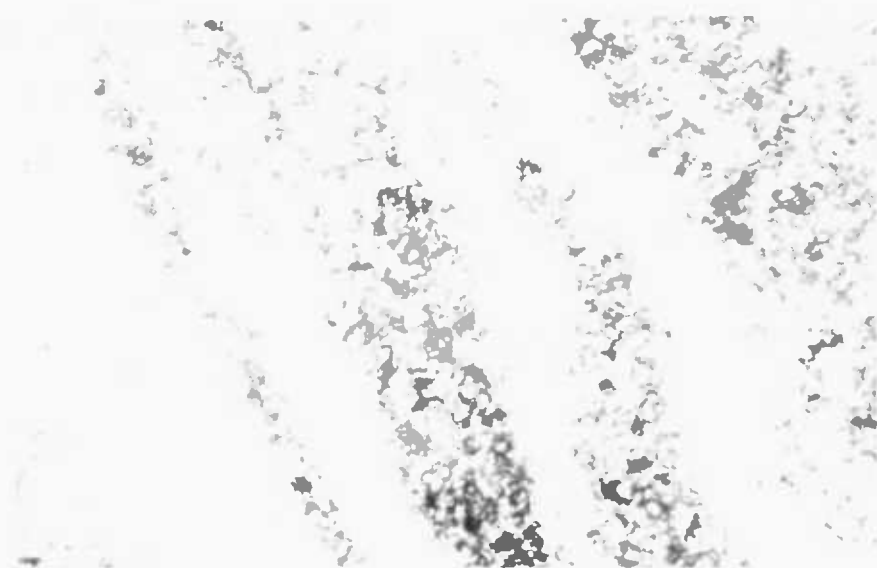


Fig. 5.12

120µm

reducing the width of low strain areas. With increasing number of cleavages the size of these areas also decreases. However, even in rocks affected by say, four cleavages, some of these areas will still remain, and may possibly contain reasonably well preserved microfossils (Fig. 5.13).

Another way in which microfossils may be preserved in strongly cleaved rocks is in pressure shadows. This is most dramatically shown in samples of the Tayvallich Slates from the Loch Nant area. In these rocks, the cleavage and deformation are amongst the most intense of all the Dalradian rocks examined for microfossils. The cleavage is strongly developed, and closely spaced throughout the rock, with few areas of low strain (Fig. 5.14). Within this there are no microfossils preserved. However the rock also contains relatively large quartz grains (50 μm - 100 μm). As stress was applied to the rock these quartz grains formed pressure shadows normal to the principle stress. In a few of these, microfossils occurred, which were protected and preserved in these low strain areas (Fig. 5.15). Also, at an early stage of this deformation, quartz migration began to take place along the quartz grain boundaries, and into the pressure shadows. This migrated quartz encapsulated the microfossils in the pressure shadows and protected them from subsequent strain (Fig. 5.15). This fortunate occurrence is comparable to the remarkable preservation of flies in amber.

As discussed above the preservation of microfossils in strongly cleaved rocks with high mica content is largely dependant on the spacing of the cleavage planes, and therefore

Fig. 5.13; Diagram illustrating how the crenulation of a first cleavage (S1) to form a secondary cleavage (S2), can still leave areas of low strain with randomly orientated micas, in which microfossils might be preserved.

Fig. 5.14; Typical cleavage in the Tayvallich Slates, with abundant quartz grains.

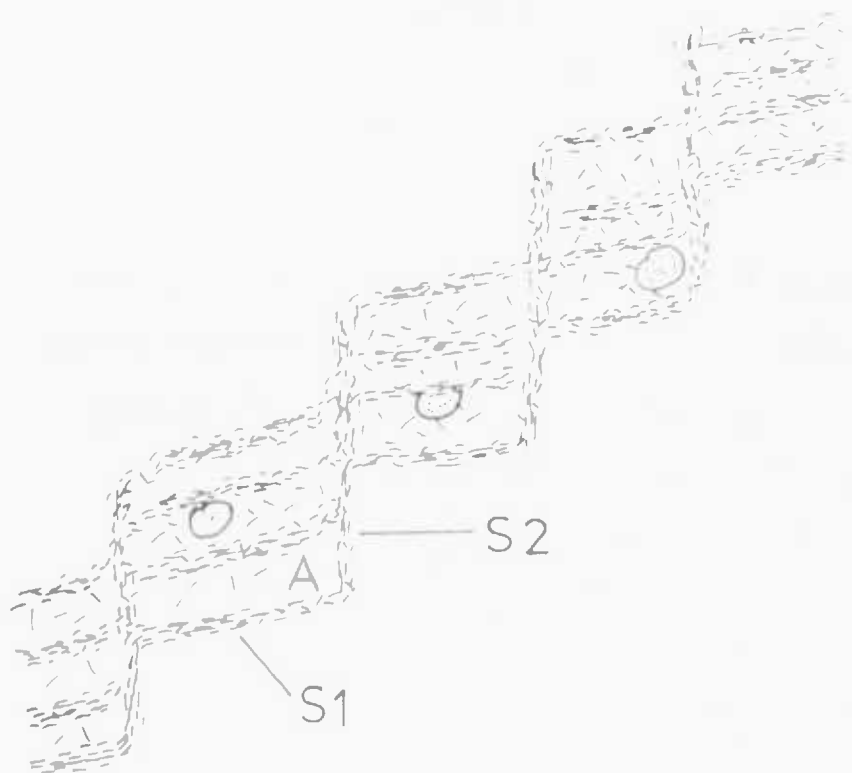


Fig. 5.13

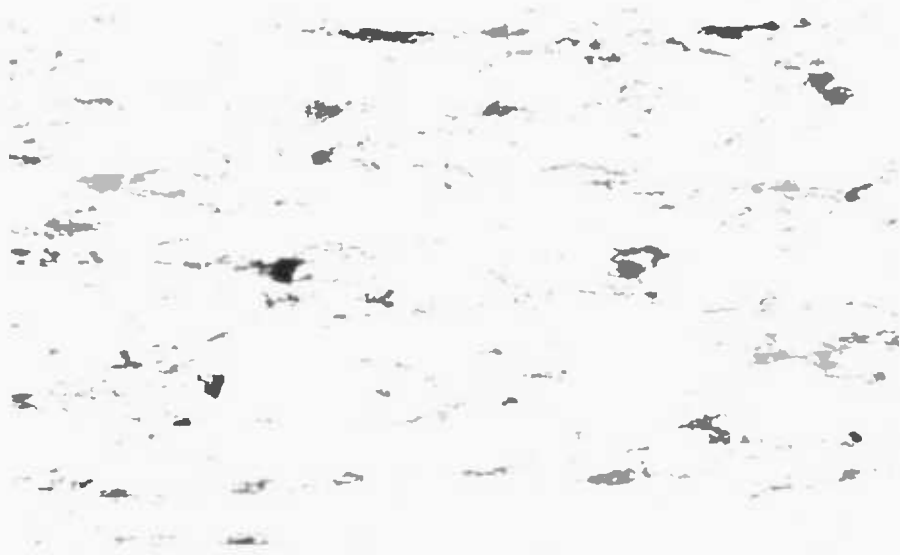


Fig. 5.14

Fig. 5.15; Preservation of microfossils in quartz filled pressure shadows in the Tayvallich Slates and Limestones:

a and b; Alliumella sp. preserved in pressure shadow.

Note the closely spaced cleavage around the lens.

'a' and 'b'; B4(TS) 105.3/9.6 'a' X380

'b' X1200

c; A Leiosphaeridia sp. similarly preserved in a quartz filled pressure shadow. Note that the lower half of the microfossil has not been protected and has been destroyed by the imposition of a cleavage.

'c': B4(TS) 106.5/9.2 X1500

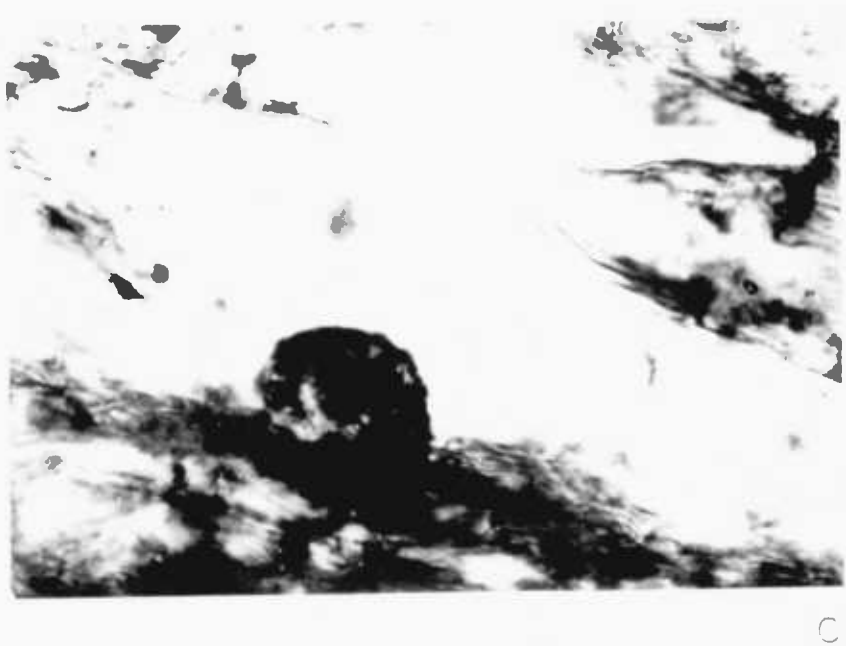
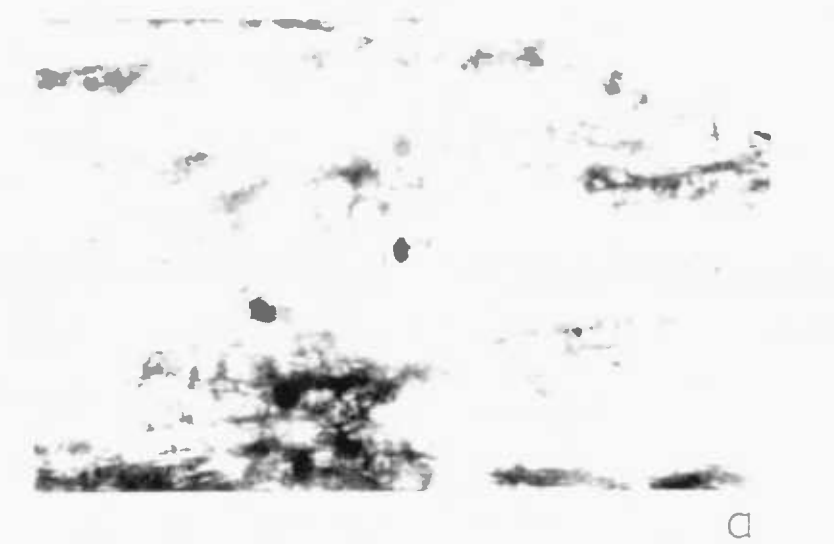


Fig 515

the width of the areas of low strain where microfossils might be expected to have a chance of being preserved. Thus this spacing controls the size of microfossils that might be reasonably well preserved. This is possibly one explanation for the generally small size of microfossils in the Dalradian when compared with assemblages from less deformed rocks of similar age which contain microfossils that are often larger (50 μm - 200 μm).

Acicular and flaky metamorphic minerals, e.g. sericite, muscovite, rutile, phengite etc. often radiate from the centres of spheromorphs. Many of these are 2 μm or less in diameter and 5 μm - 10 μm long and often pierce the walls of the spheromorph (Fig. 5.16). It is often difficult to differentiate these from genuine organic spines.

In the context of this study I am primarily concerned with the metamorphic effects of temperature and pressure on microfossils. Gutjahr (1966) and Sengupta (1974 and 1975) have published results on the experimental carbonisation of spores, and review previous work on this subject. It is apparent that time has little effect on spores, but they darken, go black, often decrease in size and lose morphological detail on the application of temperature and pressure. Sengupta (1975) has observed that at atmospheric pressure the inner contents of spores of Lycopodium clavatum become dark brown-black at 225°C, while the exine undergoes a similar colour change at 225°C. It is very interesting that with increase in pressure (to 1k bar pressure) both the inner contents and exines become black at higher temperatures,

between 250°C and 350°C. These temperatures and pressures show a marked similarity to the conditions in the lowest grade Dalradian, as established by McNamara (1964) from metamorphic minerals i.e. 220°C and 2.2k bar pressure.

Grayson (1973) has examined the changes in translucency of Carya in Louisiana oil wells. He has shown that there is a consistent non-linear decrease in translucency with depth, and this is shadowed by a corresponding decrease in oxygen and increase in carbon content. Grayson (1973) also makes the important point that to be meaningful these studies must be carried out on a single species. Different species with different wall thickness, size and wall ornamentation could produce markedly different results. This may explain the variations in darkness in the lowest metamorphic grade Dalradian rocks, where dark fossils are different species from paler ones. However as there is often no morphological difference between the two groups, the variations in colour may be due to these fossils passing through a transition zone, so that the colour changes have not reached an equilibrium state.

In the Dalradian, nearly all the microfossils have reached a stage where they are black. However, in a few areas of lower grade metamorphic regimes e.g. the extremewest of Scotland, microfossils are paler, being only dark brown in colour (Fig. 5.17). In the Easdale Slates the initiation of darkening due to metamorphism can be examined. The first stages are a dark speckling on spheromorphs (Fig. 5.18). The speckles are very small, and randomly spread over the

Fig. 5.16; Microfossil. showing the growth of an acicular crystal through the microfossil's wall. This example is relatively clear but if the crystals are more abundant and smaller, difficulties may arise in separating them from spines.

Easdale Slates E36(TS) 98.5/14.9 X1500

Fig. 5.17; Typical low metamorphic grade, dark brown spheromorph.

Easdale Slates E40(TS) 102.8/4.7 X1500

Fig. 5.18; Development of dark, randomly distributed speckles on the surface of a spheromorph at low metamorphic grade.

Mullach Dubh Phyllites D19(TS) 97.4/21.8 X1500

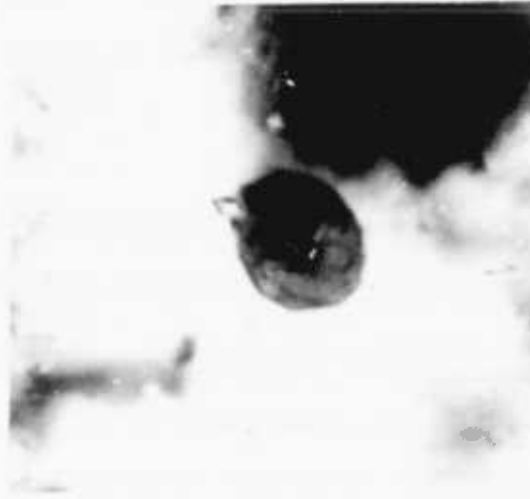


Fig.5.16



Fig.5.17

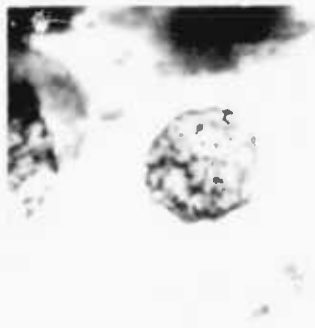


Fig.5.18

surface of the spheromorph. There appears to be no stage obviously connecting this with the totally black spheromorphs. No fossils are found with large black blotches that may be an intermediate stage between the speckles and total blackness. It appears that there is a sudden change in colour at a certain stage probably related to a chemical change. In the Easdale Slates, dark spheres, paler ones and intermediate, speckled ones all occur in the same sample (Fig. 5.19). Part of these differences may be due to variations in wall thickness, but as samples further east, in higher metamorphic grades are examined, evidence of paler microfossils disappears.

As the microfossils become metamorphosed, the walls become brittle, and quite often fractured while remaining as one entity in the rock. This can be illustrated by the brittle fracture of microfossil walls by metamorphic minerals (Fig. 5.20) as opposed to the more plastic type of deformation as illustrated by wall deformation arising from the growth of framboidal pyrite from inside microfossils (Fig. 5.21). This brittle fracture is the cause of many microfossils breaking apart during maceration.

Although the effects outlined above apply generally to microfossils in tectano-metamorphic regimes, study of Dalradian microfossils has shown that in many cases local conditions are of more importance than the regional setting. The prime example of this is the preservation of microfossils in the Ballachulish Slates and Transition Beds. Both formations occur within a few hundred metres of each other on the south side of Loch Leven. Both formations are found just

Fig. 5.19; Three specimens from the same sample (E36) in the Easdale Slates.

a; very pale brown

Leiosphaeridia Type 1 E36(TS) 113.6/18.5 X1500

b; dark brown

Leiosphaeridia Type 1 E36(TS) 109.5/14,7 X1500

c; very dark brown

?Leiosphaeridia Type 1 E36(TS) 98.6/13.7 X1500

Fig. 5.20; Rupture of brittle spheromorph wall by growth of metamorphic mineral.

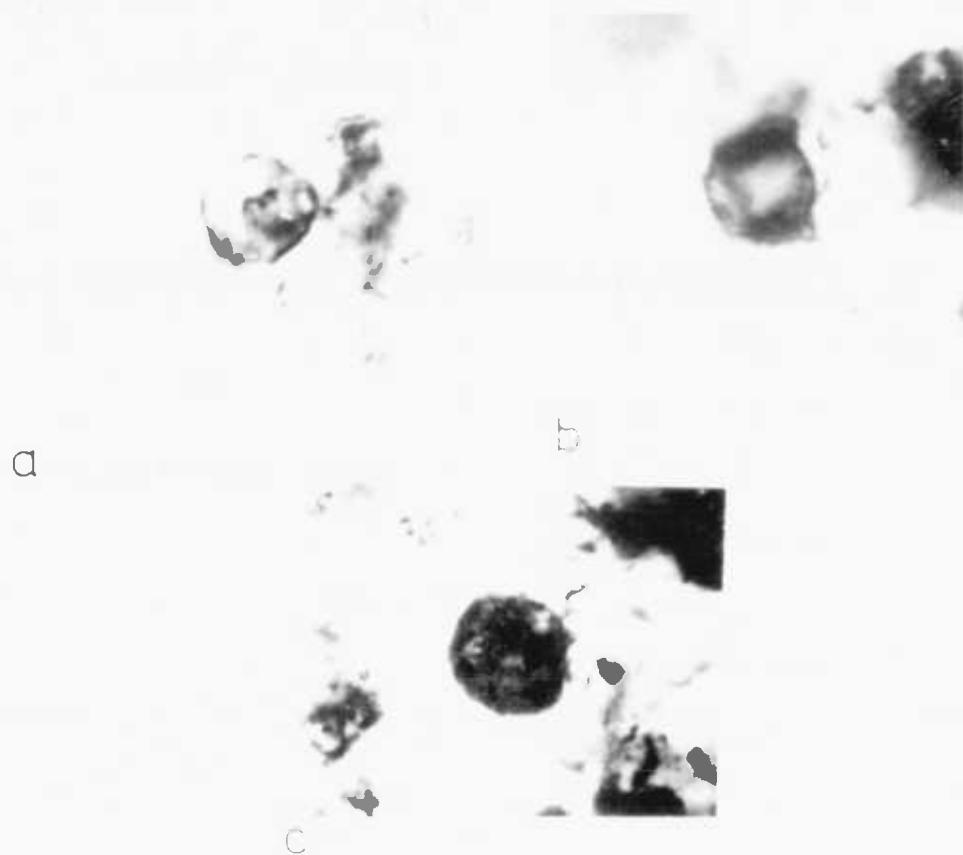


Fig. 5.19

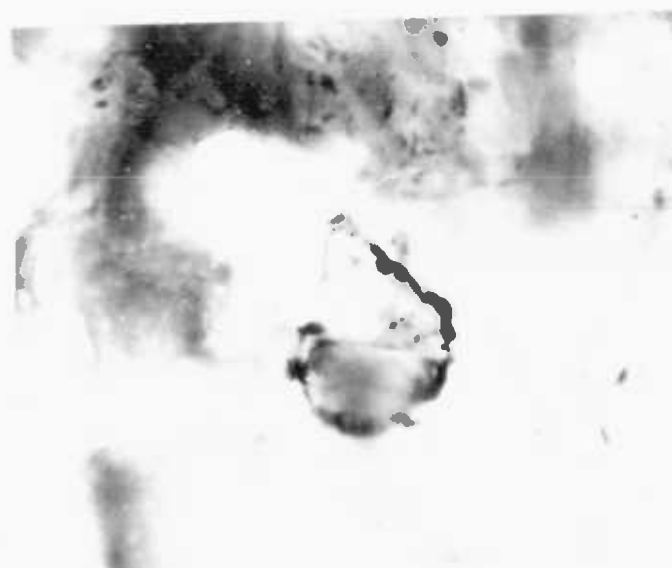


Fig. 5.20

within the biotite isograd (Map 1) and as such are at the highest regional metamorphic grade of all Dalradian microfossils found in this study. In the Ballachulish Slates, few recognisable microfossils are found and these are all very dark and damaged (Fig. 5.22) and fall apart on maceration. On the other hand, microfossils in the Transition Beds are much better preserved and are often paler (Fig. 5.23). The lithological differences are that the Ballachulish Slates is a massive thick slate formation, while the Transition Beds are interbedded shales and quartzites. During tectonism the quartzitic beds of the Transition Beds appear to have protected the shales. This would be better achieved if deformation had as little bedding plane shear as possible, i.e. large scale folding. As far as heating is concerned, the presence of the quartzitic beds also appears to have protected the shale.

Pre-lithification pyrite mineralisation:

A study has been made of the interrelationships between microfossils and pyrite framboids from the Easdale Slates (Chapter 2.1.(a)), by comparison of morphologies and size distributions. Assessment of the association of fossils and framboids may give some indication of the genesis of framboids. The possibility that some of the raspberry textured microstructures described in the literature, as microfossils, actually have an abiogenic origin, is reviewed.

The Easdale Slates (Chapter 2.1.(a)) were extensively sampled on the island of Seil (Map 1). Two samples, E36 and

Fig. 5.21; Plastic deformation of an acritarch by growth of framboidal pyrite. Compare this with the fracturing of a brittle acritarch wall shown in Fig. 5.20 and Fig. 5.16.

E50(TS) 96.5/14.0 X1500

Fig. 5.22; Poor preservation of a possible acritarch from the Ballachulish Slates (B44(TS) 97.5/17.3 X1500). This is one of the most 'acritarch-looking' microstructures found in the Ballachulish Slates.

Fig. 5.23; Considerably better preserved acritarch (Form B(i)), from the Appin Transition Beds (B49(TS) 120.5/20.8 X1500). This form is not only paler than those of the Ballachulish Slates, but also has a recognisable morphology.

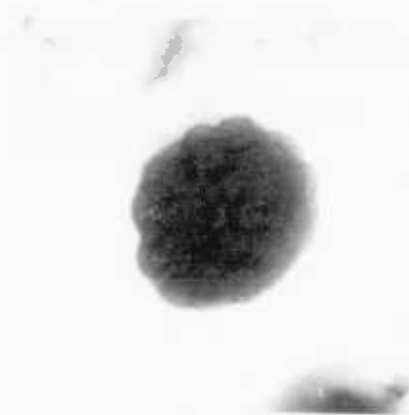


Fig. 5.21



Fig.5.22



Fig.5.23

E50, were chosen for detailed examination as they contain the most abundant, best preserved, fossils and framboids respectively. To make these comparisons valid statistically or biologically, it is necessary to use the best preserved material available. E36 is from near the base of the succession at Easdale village (Map 1, NM 747173), and contains the most abundant and well preserved microfossils found in my study so far. Throughout the succession, preservation of the fossil assemblages is variable, although there is little change in assemblage structure. Framboids occur only at the top of the succession, first in E49, where they are not abundant and are generally of indistinct morphology. However, in the topmost sample, E50, they are abundant and possess distinctive framboidal morphologies.

In the Easdale Slates a number of fossil forms have been found. By far the most abundant are leiospheres. In addition to these the following forms have been found (Chapter 4.1 and Fig. 5.24): (i) Form B (leiospheres possessing pylome and operculum, but without ornamentation), (ii) Deunffia flagellata Jankauskas, (iii) Plicatosphaera sp. Potter, (iv) Alliumella sp. Vanderflit, (v) Archeosacculina sp. A (vi) Archeosacculina cf. baltica Naumova, (vii) Form A (smooth form shaped like a peanut shell), (viii) Solisphaeridium sp. Deflandre.

Because of the rarity of the other species, only simple leiospheres, Form A and Alliumella sp. have been used in this study.

Fig. 5.24; Typical microfossils from the Easdale Slates. For complete assemblage see Table 5.1.

a and b; Leiosphaeridia Type 1

c and d; Form A

e and f; Alliumella sp.

g; Deunffia flagellata

h; Solisphaeridium sp.

i; Archaesacculina cf. baltica

Scale bar represents 10µm.

Fig. 5.25; Diagram of relationships between framboids and microfossils in the Easdale Slates.

a; framboids infill the spheromorph microfossil, but do not distort the wall

b; similar to 'a', but in this case, the spheromorph is infilled with both massive and microcrystalline pyrite. The wall is again undistorted

c; a framboidal texture has been imposed on the microfossil due to outgrowth of microcrysts

d; a similar texture due to organic debris encasing individual microcrysts

Fig 5.24

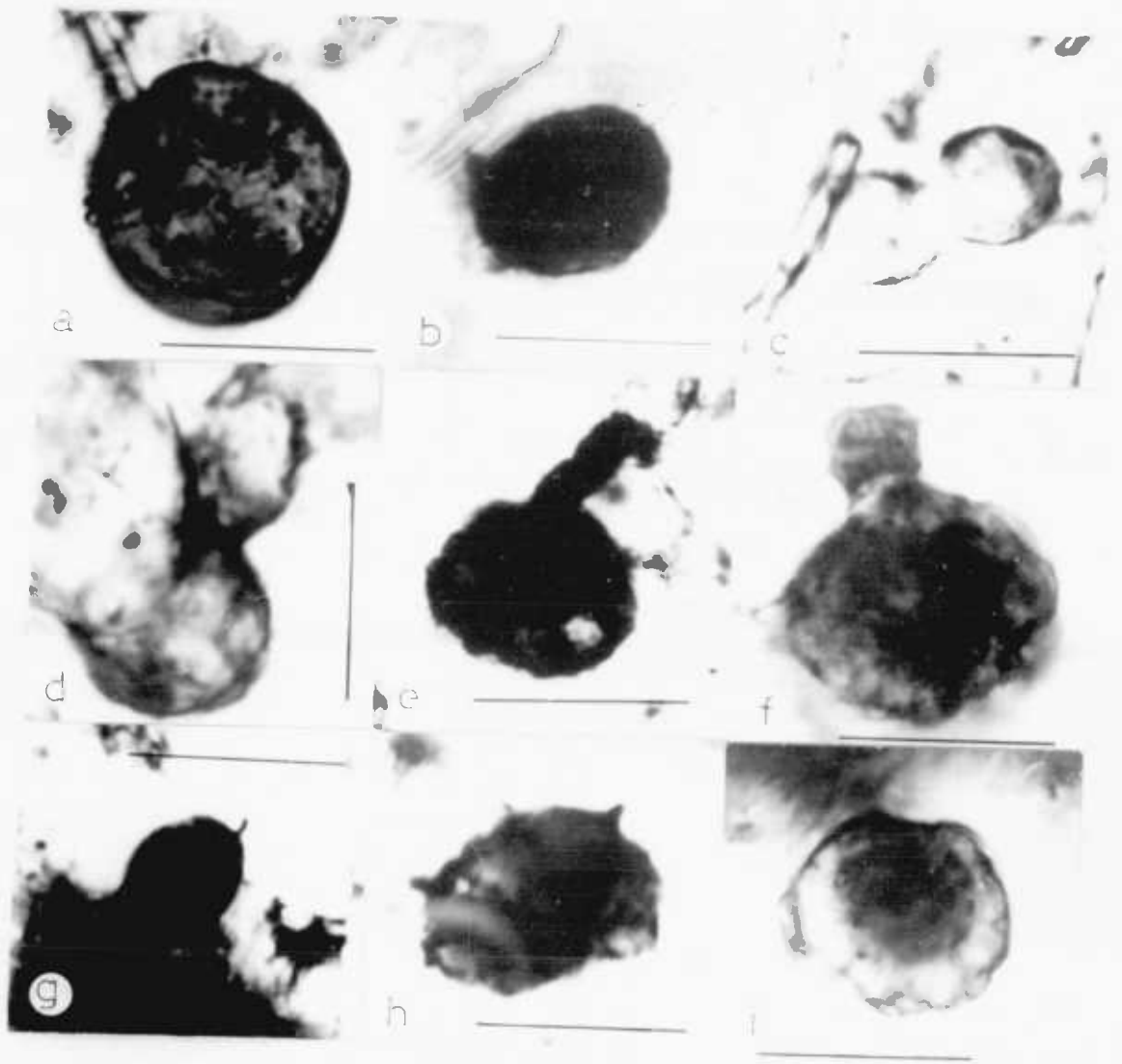
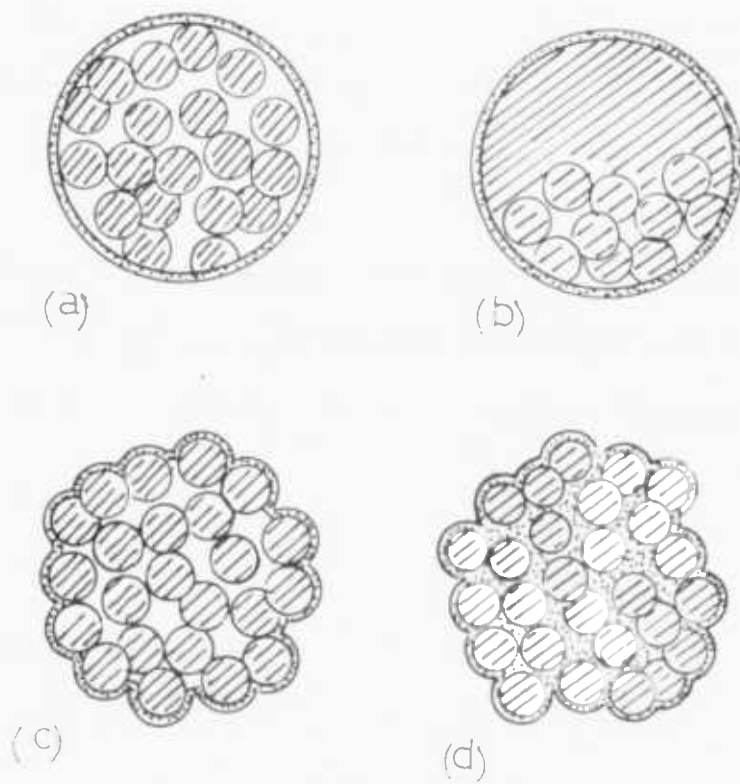


Fig.5.25



Rickard (1970) defines framboids as "Discrete spheroidal aggregates of micro-crystallites. They normally consist essentially of pyrite, although magnetite, greigite and limonite have been identified All framboids are spheroids or modifications of spheroids". The framboids that occur in E50 show a high degree of sphericity, and consist of pyrite that is either massive, or occurs in the form of microcrysts (Fig. 5.25). Both microcrystalline and massive pyrite may appear in the same framboid (Fig. 5.25). The microcrysts have a consistent diameter of $1\text{ }\mu\text{m}$ - $2\text{ }\mu\text{m}$ in any one framboid, and are sub-spherical to polygonal in section, (see Love and Amstutz (1966) for a review of framboidal textures). Groups of microcrysts are occasionally ordered, although only in microdomains. If more than one microdomain occurs in a framboid, there appears to be no ordered relation between them.

Only a few rare framboids occur apparently unassociated with organic matter, and in the majority of cases the framboids are intimately associated with organic matter in one of three ways. Firstly, the organic matter may form a thin wall around the framboid, with the framboid's outermost microcrysts abutting against the organic wall without distorting it. In this case the surface of the microstructure is smooth and not modified by the crystal texture (Fig. 5.25 and Fig. 5.26). These outermost microcrysts may be spherical or hexagonal, or their shape may be modified so that the outer surface of the microcryst has a curvature concentric with that of the confining organic wall. Secondly, organic matter again

Fig. 5.26; Photomicrographs in transmitted and reflected light, of the morphology of framboids and their relationship to organic matter, 'a'-'j' are thin sections of E50, 'k' and 'l' are macerate residues from the Deer Park Schists.

a and b; transmitted and reflected light micrographs of framboidal infilling of Leiosphaeridia ?Type 1, without distorting the organic wall

c and d; similar to 'a' and 'b', although 'd' clearly shows good framboidal texture not imposed on the organic wall

e and f; transmitted and reflected light micrographs of pyrite infilling Form A microfossils, without distorting the fossil's wall. Note the 'all-encompassing' organic wall in 'e'

g and h; similar to 'e' and 'f', except the pyrite is infilling a Alliumella sp.

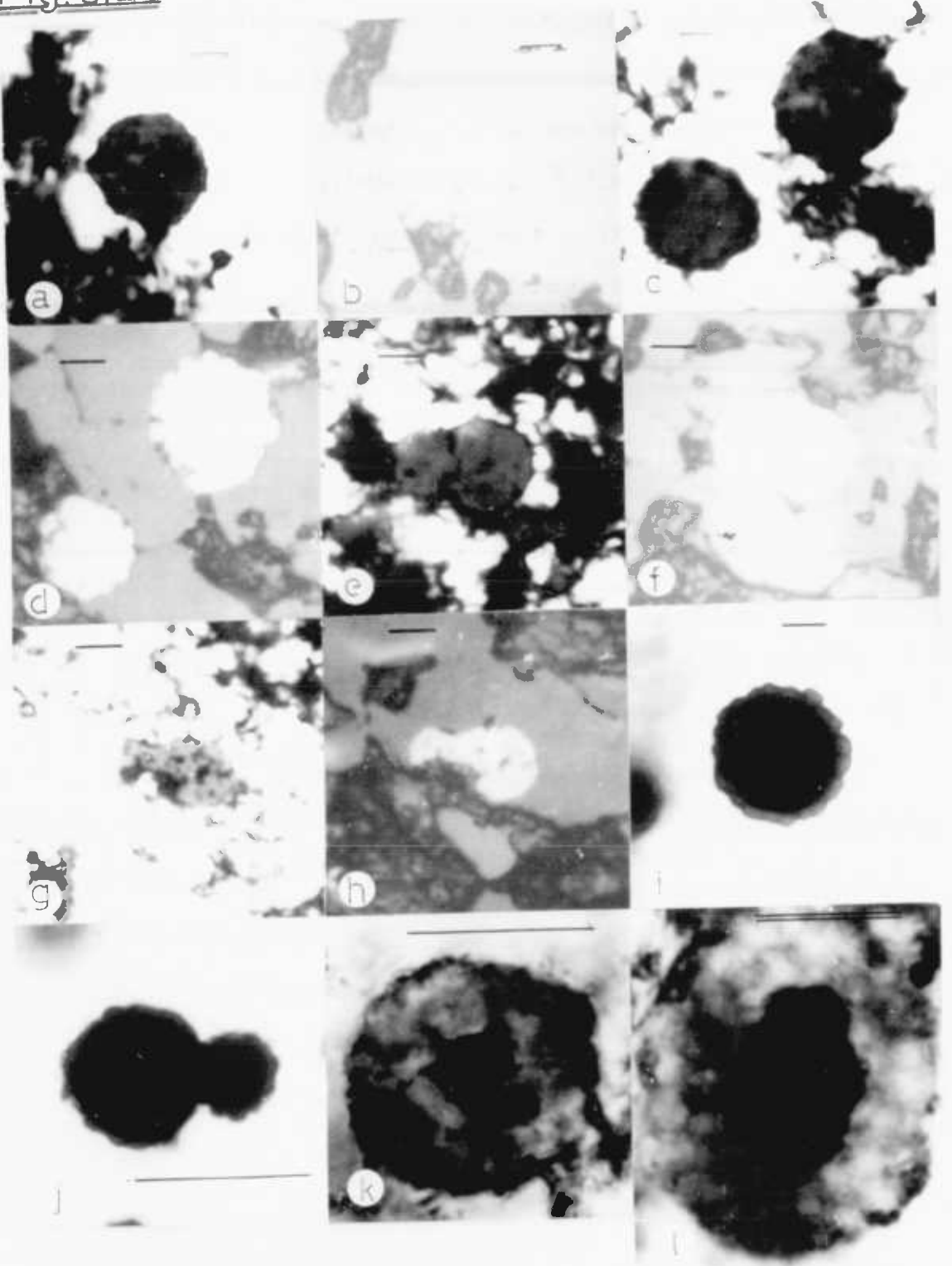
i and j; transmitted and reflected light micrographs of Leiosphaeridia sp. ('i') and Form A ('j') infilled with framboidal pyrite, in which the outer microcrysts have distorted the organic wall

k and l; transmitted light micrographs of structures of organic matter after macerating hematitic framboids from the Deer Park Schists. Note the remnant framboidal pyrite cores.

Single bar line represents 10µm.

Double bar line represents 5µm.

Fig. 5.26



occurs only as a thin wall round the outer surface of the microstructure but the typical framboidal texture is imposed on it by the outward growth of microcrysts (Fig. 5.25 and 5.26). The whole microstructure then has a framboidal texture. The third form is superficially very similar to the second, except that organic matter is wrapped around each microcryst, instead of being only a thin surface wall around the whole framboid (Fig. 5.25 and 5.26).

In order to test whether the size distribution of the microfossils and that of the framboids were of the same statistical population, a number of statistical tests were made on measurements of 432 microfossils from E36, and 130 framboids from E50.

The fossils were photographed in thin section in transmitted light using a Zeiss photomicroscope. The negative (mag. X160) were then enlarged in a photographic enlarger to a total magnification of X1600, and the images measured to an accuracy of ± 0.5 mm with a transparent grid. The framboids were photographed in a polished thin section with the same microscope in reflected light. Due to poor contrast in the negative the same measuring method could not be used. Instead each negative (mag. X160) was mounted in a photographic transparency binder and projected using a horizontally mounted slide projector. The image was projected onto a mirror fixed at an angle of 45° and reflected down onto the same transparent grid used to measure the fossils' dimensions. In order to determine the magnification used in this method, a portion of the grid was thus mounted, projected and measured.

The aggregate magnification was X1920.

Three common statistical tests (F-test, t-test and Kolmogorov-Smirnov test), and statistical comparison (a probability curve) have been applied to these data in order to test their statistical similarity and to determine whether they may belong to the same statistical 'population'. These tests are briefly outlined below.

(i) F-test: This test determines the equality of variances of the two populations. The F distribution is the theoretical distribution that would be expected by randomly sampling a normal distribution and calculating for all possible pairs of sample variances, the ratio $F = S_1^2/S_2^2$, (where S_1 and S_2 are the sample standard deviations).

(ii) t-test: This tests the hypothesis $H_0: u_1 = u_2$, (where u is the sample mean), which states that the mean of the population from which the first sample was obtained is equal to the mean of the population from which the second sample was obtained, against the hypothesis $H_0: u_1 \neq u_2$.

(iii) Kolmogorov-Smirnov test: This test is one of the most powerful general procedures to test the hypothesis that two sample distributions are not the same. The test is sensitive to any difference of form or locality between the two populations. To carry out this test the individuals of each sample are arranged in order of magnitude, the scale of the variable (in this case micrometres), being divided into 0.5 μm intervals. The frequency of each interval is found, and also the cumulative frequency at each interval. As there

is a different number of individuals in each sample, the cumulative frequencies are divided by its appropriate total sample size. This provides cumulative proportional frequencies in the range 0-1. At each interval the difference in the cumulative proportional frequencies is calculated. The highest value obtained (in this case 0.12) is the test statistic.

(iv) The final statistical comparison is the cumulative probability plot described by Schopf (1976), (see Chapter 3.3). One important feature of this is that distributions of similar statistical construction, but not necessarily of biologically related origin produced parallel curves. If the framboids and microfossils from the Easdale Slates are plotted on a probability plot, the curves are very close, and parallel to each other (Fig. 5 28). The framboids plot smaller than the microfossils (i.e. the framboid curve is to the left of the microfossil curve) as a result of measuring techniques. The framboids were measured under reflected light, and the planes of reflection would rarely pass through the framboids' greatest diameters. In the case of transmitted light the plane of section is less important as the greatest diameter of the microfossil will be measured as long as the plane of section is above the microfossil's equator. The closeness and parallelism of the two curves further suggests that the two distributions are statistically very similar. Two other framboid pyrite distributions (from the Chattanooga Shale (Love and Amstutz 1966), and a Scottish oil shale of the Lower Carboniferous (Love 1957), have been plotted on the

Fig. 5.27; Histograms showing the size distributions of;

- a; microfossils from sample E36 (Easdale Slates)
- b; framboids from E50 (Easdale Slates)
- c; framboids from the Chattanooga Shale (after Love and Amstutz 1966)
- d; pyrite spheres from a Scottish Lower Carboniferous oil shale (after Love 1958)

Note the broad similarity between the four distributions. The differences are brought out in Fig. 5.28.

Fig. 5.27

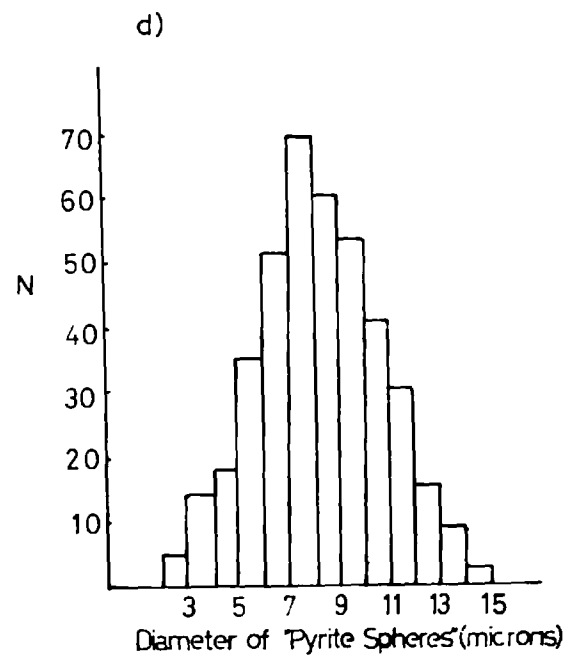
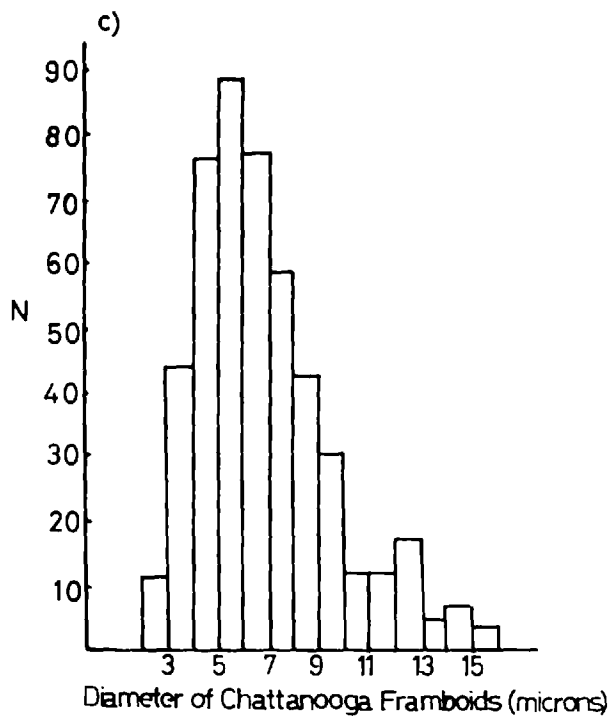
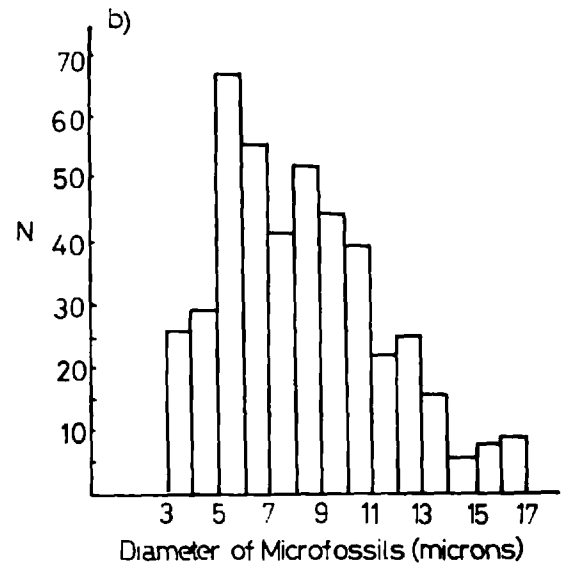
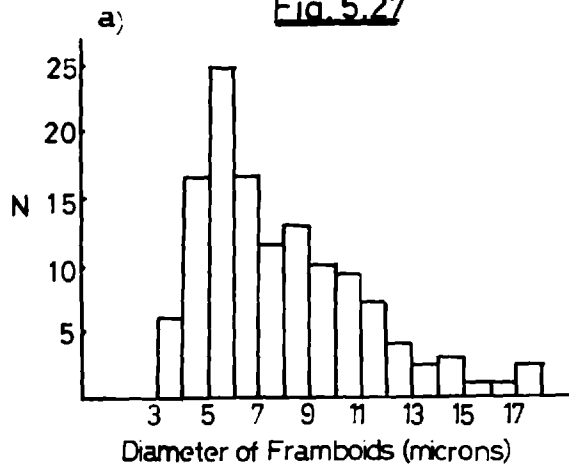


Fig. 5.28; Probability curve similar to Fig. 3.3, showing the statistical similarities between the size distributions of a number of framboid assemblages. (after Schopf 1976)

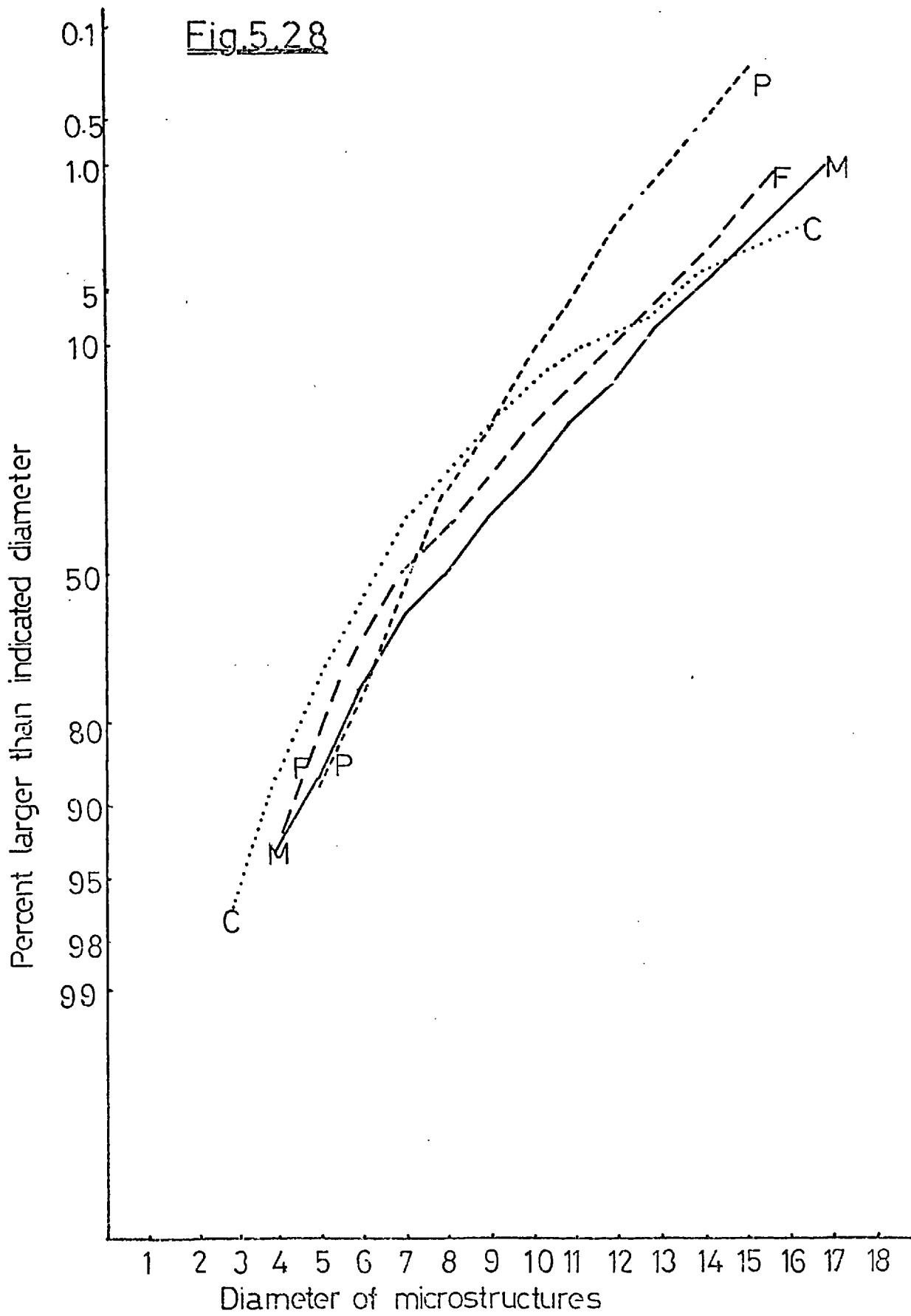
F, framboids from the Easdale Slates

M, microfossils from the Easdale Slates

C, framboids from the Chattanooga Shales (after Love and Amstutz 1966)

P, pyrite spheres from a Lower Carboniferous oil shale (after Love 1958)

Note the close parallelism between the framboids and microfossils from the Easdale Slates, compared with the widely divergent plots from the other two distributions. The Easdale Slates framboids plot to the left of the microfossils (i.e. they appear to be smaller) due to measuring techniques. See text for discussion.



same probability graph. Although on initial examination by eye of their histogram distributions (Fig. 5.27) they appear to be similar to each other and the Easdale Slate framboids, the probability plot shows them to be clearly different.

The statistical tests outlined above, clearly indicate that there is a strong similarity in size distribution between the framboids and fossils of the Easdale Slates. Specifically the first three tests indicate that the two distributions are not different at a 95% level of confidence. Although the statistical tests indicate a close relationship between the size distributions of the framboids and microfossils in the Easdale Slates, it is necessary to examine the gross morphologies of the fossils and framboids, as well as the relationship of framboid and organic matter, and to determine this relationship. Also it is important to see if the undistorted fossil morphologies are reflected among the framboids. In a synthetic environment, without the mold influence of organisms, framboids are spherical (Sweeney and Kaplan 1973), i.e. this is the "natural" shape of framboids. In the Easdale Slates, the most common fossil form is a simple sphere, therefore to be confident that framboidal pyrite has developed inside fossils, the framboids must have a definitive morphology that can be clearly associated with a fossil morphology. Thus a search was made in E50 for framboids with Form A and Alliumella sp. morphologies, and both were found (Fig. 5.26). In both of these the component parts are filled with microcrystalline pyrite, and the whole microstructure has an encircling wall of organic matter. The

Form A microfossils show the characteristic morphology of large and small spheres in contact with a thin enveloping wall. The Alliumella sp. forms have the characteristic parallel sided tubular process, about 4 μ m in diameter and of varying length (Fig. 5.26). These are undoubtedly fossils that have been infilled with microcrystalline pyrite. An important feature of many of these fossils is that the organic wall is not distorted or punctured.

The association of pyrite with microfossils has often been reported elsewhere. It has been demonstrated that microcrystalline pyrite can infill the rigid chambers of the tests of foraminiferida and diatom frustules (Love and Murray 1963), while Wicander and Schopf (1974) showed pyrite infilling the cells of Devonian blue-green and other algae from New York, while Kobluk and Risk (1977) have illustrated the infilling of algal borings in brachiopod shells by microcrystalline pyrite. Gustadt and Schopf (1969) have shown cells from the late Precambrian Beck Springs Dolomite being replaced by haematite pseudomorphing pyrite. Neves and Sullivan (1964) have illustrated the geometric effects of the deformation of spore walls by the growth of pyrite crystals. But the Easdale Slate assemblage from the late Precambrian contains fossils that are not easily comparable with modern organisms, and it may be argued that the simplest framboïd morphologies are not infillings of microfossils but only infillings, for example, of hydrocarbon globules, (Rickard 1970). It is for this reason that the search for evidence of the pyritic infillings of microfossils using comparative morphologies has

been restricted to those microfossils of complex morphology and undoubted biogenicity.

It can therefore be inferred that if fossils with elaborate morphologies have been infilled, this can have happened to the simple spheres also. Framboids are associated with organic matter in a number of ways. The organic matter can form a uniform thin walled "rigid" case against which the microcrysts may abut, but which they do not distort (Fig. 5.26) or the organic matter may drape the outer microcrysts in a manner that produces a framboidal texture (Fig. 5.26). A large number of framboids of recognisable fossil morphology have an organic matter/microcryst relationship of the first type. As no microfossils have been found in E36 or any other samples from the Easdale Slates, with a framboidal type texture, but not infilled with pyrite, then where this texture occurs in E50 it must be assumed to be secondary, arising from either the plastic distortion of an originally spheroidal fossil by the microcrysts or from the microcrysts becoming wrapped in organic debris during growth. In such cases, where there is distortion, it is extremely difficult to determine if the microstructure is a fossil, unless there are other features, such as spines that can convince the observer that it is a genuinely altered fossil. The microstructures illustrated by Allison and Moorman (1973) come under this category. In that paper many of the "microfossils" illustrated show classical, three dimensional framboidal textures. Figure 1B shows "a type 'A' colony treated with nitric acid to remove pyrite". This texture is exactly as

would be expected from the growth of framboids in organic debris. Many of the illustrations, e.g. Fig. 1H, are very similar to Pyritosphaera sp., Love (1957), which Love now considers to be "a small blob of organic matter amongst which the sulphide has crystallised" (Love 1962). Similar morphologies have been illustrated by Neves and Sullivan (1964) and Volkova (1974). Likewise caution should be expressed concerning the late Precambrian microstructure, Sphaerocongregus variabilis (Moorman 1974), which again, in a number of illustrations, has a classical framboidal morphology. In all cases where there is the possibility that the microstructure has been affected by the growth of pyrite framboids (Javor and Mountjoy 1976), a most stringent and careful examination must be made before the microstructure is considered biogenic. Cloud, Moorman and Pierce (1975) have published more details on the Sphaerocongregus variabilis Moorman assemblage. Many of the morphological descriptions of the microstructures are almost identical to descriptions of framboids e.g. "2/Membrane bound aggregates 7 μ m - 20 μ m in diameter with spherical or polygonal (my emphasis) sub-units 0.5 μ m - 1 μ m in diameter". In a rock containing abundant pyrite, the probability that these are either framboids in organic debris or framboid-deformed microfossils, must be very high. Similar comments can be made concerning the genus Bavlinella Shepeleva, which also has a highly framboidal morphology.

Microstructures morphologically identical to Love's Pyritosphaera sp. and to Allison and Moorman's (1973) Fig. 1, F, H, I, and K, have been found by macerating Upper Dalradian

(? Mid Cambrian) black shales from Western Ireland. These rocks occur on the south side of Clew Bay, near the village of Kinsallagh, and belong to the Deer Park Schists (Phillips et al. 1969). These rocks are deformed black shales and sandstones and have been thrust over less deformed Ordovician sediments to the south.

No recognisable microfossils have been found to date, but there are abundant well preserved haematitic and pyritic framboids. Many of the haematitic framboids have pyritic cores, indicating that the haematite is secondary after pyrite, probably due to oxidation, possibly during weathering. They show a size range and morphology similar to that of the framboids from the Easdale Slates. After normal maceration, without the use of nitric acid to remove the pyrite, the haematite had dissolved leaving an organic framboidal microstructure (Fig. 5.26) identical to Love's Pyritosphaera, to Allison and Moorman's (1973) figures and to Moorman's (1974) figures of Sphaerocongregus sp. The original morphology and position of each microcryst in the Deer Park Schists framboids is defined by the undissolved wall of organic matter that had originally encased the microcryst. Many of these macerated microstructures contain clearly framboidal pyrite in their cores. There is no doubt that these microstructures have an abiotic origin, and that the morphology of the organic matter is due to wrapping of organic debris around pyritic microcrysts.

The origins of framboids have been the subject of investigations by Rickard (1970), Love and Amstutz (1966), and

Sweeney and Kaplan (1973). From this work it is clear that although there is not yet a complete understanding of the origin of framboids, a number of general points can be made:

(i) The vast majority are found in marine sediments (virtually always in black muds indicating reducing conditions) e.g. Sweeney and Kaplan (1973), Love and Murray (1963).

(ii) It is thought that the necessary excess sulphur is produced by the action of sulphate reducing bacteria under reducing conditions, although framboidal pyrite can also be produced under synthetic conditions in the absence of bacteria, (Sweeney and Kaplan 1973, Rickard 1969).

(iii) Pyrite framboids are intimately associated with organic matter. This often takes the form of infillings of foraminiferids (Love and Murray 1963), diatoms (Sweeney and Kaplan 1973) and algal cells (Wicander and Schopf 1974).

From these general points, it may be postulated that the interior of cells of dead microorganisms in the black mud of the Easdale Slates acted as microenvironments, producing reducing conditions, suitable for the growth of pyrite framboids. The same sort of conditions would have existed in clumps of organic debris lying on the sea floor.

5.2 Discussion of Macduff Slates

In Downie et al.'s (1971) study on Dalradian micropalaeontology, one of the most important conclusions was the Arenig age of the Macduff Slates and Highland Border Series.

These formations were considered in that study to be among the most fossiliferous, being especially abundant in "fragments of possible chitinozoa". There has been some problem in equating the Arenig age for the youngest part of the Dalradian with geological evidence, especially the radiometric ages of syn-tectonic granites (see Chapter 2.4). This has led, amongst other things to an age of 530 m.y. being suggested for the base of the Arenig (Bradbury et al. 1976).

In this present study, I have had considerable difficulty in reproducing the results of Downie et al. (1971) from the Macduff Slates and Highland Border Series. Initial examination of macerate residues and thin sections from a small number of samples from the Macduff Slates did not produce any microstructures that could, with confidence be referred to as microfossils. A further suite of samples were collected from Macduff (Map 1), but none were collected from further east along the coast at Gamrie Bay, where a number of the samples of Downie et al. were collected from. However, again after maceration, no microfossils were found. Organic matter is plentiful, but this is all black, carbonised, often plate-like and lustrous under high magnification. The fragments are irregular in outline, and often angular, with many re-entrant angles (Fig. 5.29). A small number of fragments possess more regular smoother, often suboval outline (Fig. 5.30), but none of these show any clear evidence of a neck which would indicate that the fragment was derived from a chitinozoan. Fragmented tubular structures 30 μ m to 70 μ m long and 5 μ m to 10 μ m wide (Fig. 5.31), also occur frequently.

Fig. 5.29; Typical graphitic matter in the Macduff Slates. (B68(TS)
121.7/14.8 X400)

Fig. 5.30; More rounded bodies in the Macduff Slates.

a; B65(TS) 113.9/11.3 X400

b; B68(TS) 121.7/8.7 X400

Fig. 5.31; Tubular organic structures in the Macduff Slates,
showing crystals protruding from within.

a; B66(TS) 113.7/14.6 X400

b; B66(TS) 110.3/15.4 X400

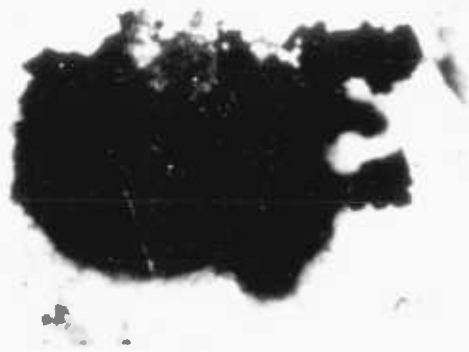


Fig.5.29

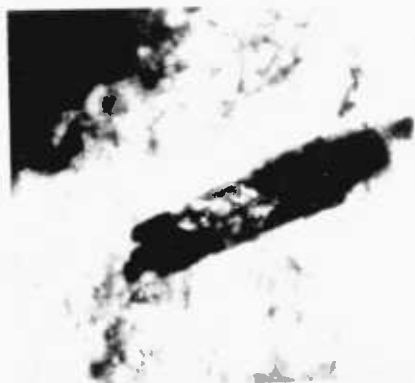


a



b

Fig.5.30



a



b

Fig. 5.31

All the organic matter occurs as fragments of discernable size, and there is a marked lack of organic "dust", which forms a prominent part not only of fossiliferous organic rich sediments, but also those which although they contain no preserved microfossils, are rich in organic matter that was clearly indigenous to the sediment.

The Macduff Slates show evidence of being turbiditic in origin. Quartz is the most abundant mineral, and quartz grains are usually angular, poorly sorted and with little evidence of preferred orientation. The slaty cleavage that can be seen in hand specimen is found to be not penetrative in thin section. The organic matter that occurs has a similar size range and distribution to the quartz grains (Fig. 5.32) and the angular nature of the organic fragments is very similar to that of the quartz.

The common feature with all the organic fragments in the Macduff Slates is that they are intimately associated with very fine grained "clay minerals" (Fig. 5.33). So far these have been unidentified. The clay minerals form clumps often covered by organic matter. At suitable places, e.g. re-entrant angles, the clay minerals can be seen protruding from beneath the organic fragments (Fig. 5.33). In all cases, the shape of the organic fragment is defined by that of the "clay mineral" clump. In the case of organic tubes, the same very fine grained clay minerals can be seen protruding from the ends of the organic tubes (Fig. 5.33). Clearly in these cases organic matter has enveloped a clay mineral rod and subsequently part of the organic tube has broken away.

Fig. 5.32; Size distribution of quartz grains and carbonaceous fragments from the Macduff Slates Formation (B66). Both distributions were measured in the same thin section. Note the considerable similarity in style between the two distributions. The carbonaceous fragments are generally slightly larger than the quartz fragments. This is probably due to a difference in density (see text for discussion)

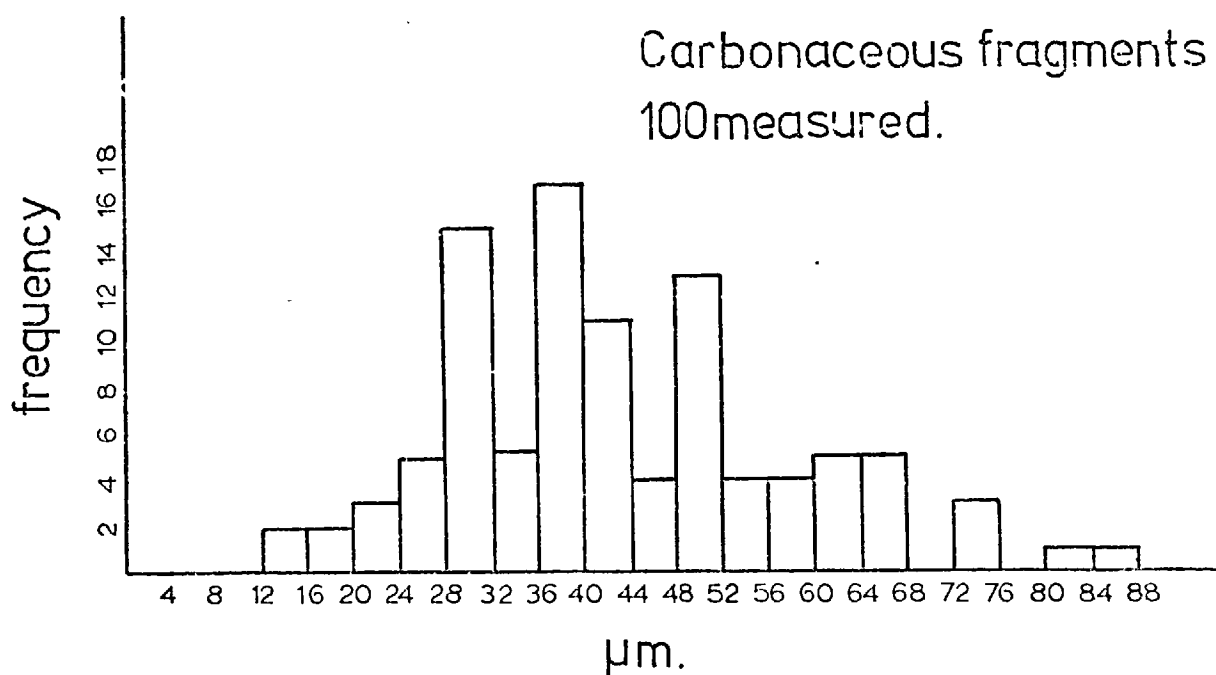
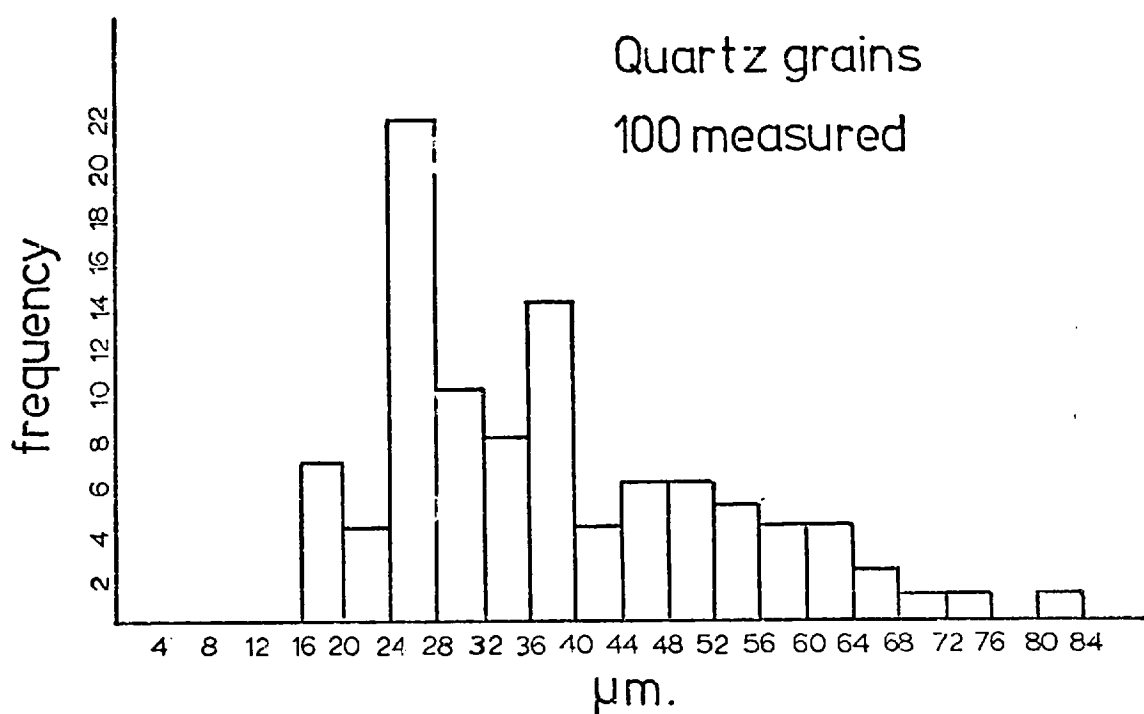


Fig.5.32. Size distribution of quartz grains & carbonaceous fragments in the Macduff Slates.

Fig. 5.33; Association of organic matter and fine grained "clay minerals" in the Macduff Slates. The organic matter appears to 'wrap round the clay minerals.

a; B68(TS) 117.2/13.8 X400

b; B68(TS) 97.2/9,2 X400

Fig. 5.34; Rounded organic body in the Highland Border Series.

Note the lack of any noticeable 'neck.

PL4(TS) 93.7/14.8 X400

Fig.5.33

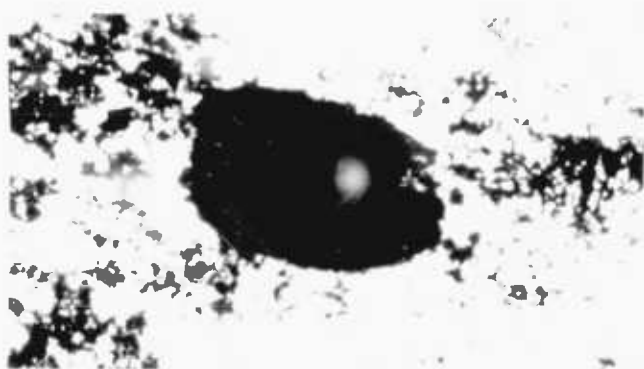
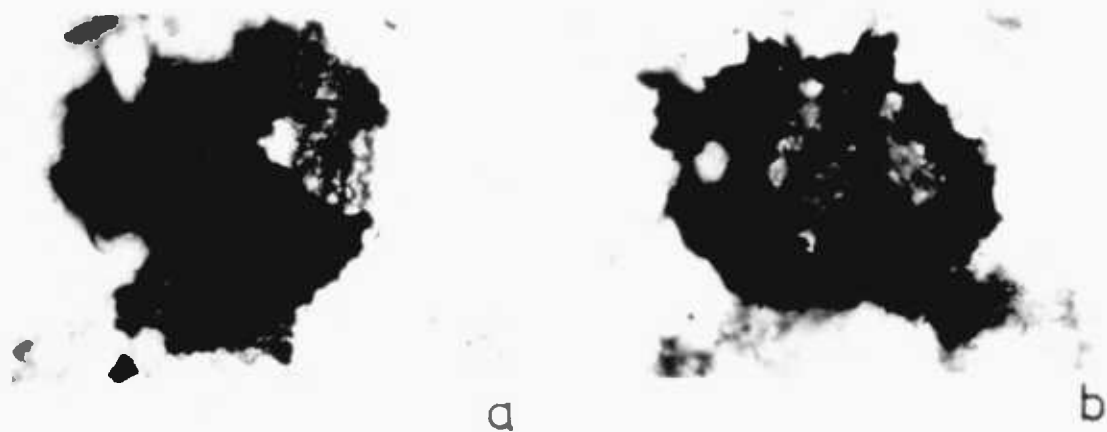


Fig.5.34

The rocks of the Highland Border Series, show a similar relationship between organic matter and very fine grained "clay minerals". The lithology of this formation is generally finer grained, and less quartz rich than the Macduff Slates. The organic fragments are commonly ellipsoidal in outline (Fig. 5.34) and the highly irregular and angular fragments found in the Macduff Slates do not occur. Also there is an abundance of organic "dust" and well preserved microfossils occur. Overall the Highland Border Series shows evidence of being deposited in quieter conditions than the Macduff Slates.

A number of ellipsoids in the Highland Border Series show no evidence of "clay minerals" in thin section, and only an elliptical body of organic matter can be seen. Many other ellipsoids are totally devoid of organic matter and consist totally of "clay minerals". Between these two extremes, a number of stages occur, where the organic ellipse has fractured along strips usually parallel to the minor axis of the ellipse and clay minerals are revealed beneath. A complete sequence can be found between the two end members, with larger and larger splits occurring and a subsequent decrease in organic matter (Fig. 5.35). The splits and the sequence described above illustrates that the morphology of the organic ellipse is controlled by the underlying ellipsoidal "clay mineral" clump. From these observations I conclude that in the Highland Border Series ellipsoidal balls of "clay minerals" occur, many of which have been enveloped by a layer of organic matter and that these ellipsoidal organic micro-

Fig. 5.35; Breakdown of ellipsoidal organic bodies similar to

Fig. 5.34, to reveal clay minerals beneath...

a; PL4(TS) 129.6/ 3.6 X400

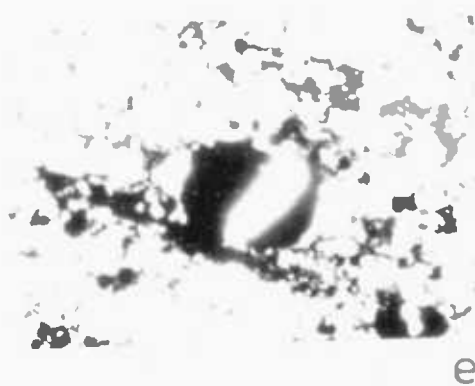
b; PL4(TS) 121.5/ 11.9 X400

c; PL4(TS) 108.5/ 8.5 X400

d; PL4(TS) 118.6/ 15.9 X400

e; PL4(TS) 98.6/14.6 X400

Fig. 5.35



structures are mechanical in origin and not related directly to organisms. Their origin was possibly the wrapping of organic matter around clay balls in a relatively high energy source area, probably by a rolling action, similar to that postulated for ooliths. These were then carried into the depositional area and buried. They were probably near spherical on deposition, but subsequent sedimentary and tectonic compaction has compressed them into ellipsoids. The plane of section in which they were examined is at right angles to the axis of principle stress. It is interesting to note that the organic envelopes appear to have fractured in a brittle fashion and that the fractures run perpendicular to the axis of principle strain. Possibly the main period of compression did not occur until the organic matter had carbonised and become brittle. One cause of carbonisation is metamorphism, although the very low grade necessary could be reached merely by shallow burial.

These well preserved microstructures from the Highland Border Series, can be related to the Macduff Slates. There is a similar relationship between organic matter and "clay minerals", where the former wraps around the latter. The difference between the two formations is that in the Macduff Slates the "clay balls" have been more severely damaged, and instead of being regular and sub-spherical with smooth outlines, they are angular, irregular in outline, and have obviously suffered attrition, and appear to have been swept into the depositional area by relatively high energy currents (c.f. Fig. 5.33, 5.34 to Fig. 5.28, 5.30). The angular and

immature nature of the quartz grains supports this. The absence of fine grained organic "dust" is explained in the same way as the absence of very fine grained minerals: they have both been carried further away by the decreasing turbidity currents.

The organic matter in the Macduff Slates has also undergone brittle fracture, but this is not the regular pattern of the Highland Border Series, which depends on a compactional stress pattern, but rather due to attrition.

The source area for both these formations is not known. But as they are both interpreted as turbidites, it can be assumed that the source was in much shallower water. The source of the organic matter is also not known, for certain. It would appear that there was a quantity of degraded organic matter on the sea floor possibly as sheets of amorphous matter, or the source may have been degraded algal mat.

5.3 Biostratigraphy

Most of the work on late Precambrian and Cambrian acritarchs, and their use in biostratigraphy has been carried out by Russian and Eastern European workers. Major problems for the worker in the West that have arisen from this bias are language and accessibility of material. One of the results of this is that Russian material has almost certainly not been used to its full potential in this study. Another problem is the lack of macrofossil control. Where this is available, macrofossil provincialism also poses a problem when attempting to correlate over large distances. Andreeva (1966) has published an historical account of research into Precambrian and Cambrian microfossil assemblages of the U.S.S.R. up to 1966.

Outside the U.S.S.R. similar research has not been on the same scale. Downie and Ford (1966), Downie and Tremlett (1968), and Downie (1974) have published results from Britain, Norway and Greenland. Potter (1974) has carried out research into acritarchs from Britain and Spain, while Vidal (1976a and b) has contributed results from Sweden and Greenland. In addition to these workers, others have described late Precambrian and Cambrian assemblages from Scotland (Cloud and Germs 1971), from Ireland (Smith 'in press', Gardiner and Vanguestaine 1971), Belgium (Vanguestaine 1967, 1970) and from Norway (Manum 1967, and Spjeldnaes 1967).

From this study a scheme of four informal acritarch zones is proposed for the Dalradian (Table 5.1).

The zonal system is based primarily on the first appearance of species, although the last appearance of Archaeosacculina cf. baltica can be used to mark the upper boundary of zone 'c'. There is an insufficient number of many of the species characteristic of a particular zone to allow the proportion of a species to the whole assemblage to be used statistically to define a zone.

Most of the species continue through subsequent zones after they have first appeared. There are a number of possible explanations why some do not. The first factor is preservation. Species with fine sculpture, e.g. Plicatosphaera elementaria, Archaeosacculina sp A, and Leiosphaeridia Type 4 might not survive under the poorer preservational conditions of e.g. the Highland Border Series. However their appearance in the Easdale Slates is believed to mark their earliest occurrence, as the species are not found in the older Bonahaven Dolomite or Mullach Dubh Phyllites where assemblages are equally well preserved. However, this does not explain the absence of Form B from the Bonahaven Dolomite (and possibly the Easdale Slates), or the absence of Leiosphaeridia

Table 5.1: Distribution of microfossils in the Dalradian of Scotland.

* Species definitely present.

+ Species probably present.

(Note: The stratigraphic column on the left is a composite one for the Scottish Dalradian. For the relevant lithostratigraphic equivalents, see Fig. 2.1).

SPECIES	FORMATION	Acritarch Zones		Approximate age
		This study	Downie (1974)	
<u>Microhystridium</u> cf. <u>lanatum</u>				
<u>Leiosphaeridia</u> Type 4				
Form C				
<u>Archaeosacculina</u> sp. A				
<u>Solisphaeridium</u> sp.				
<u>Plicatosphaera</u> cf. <u>elementaria</u>				
<u>Leiosphaeridia</u> Type 3				
<u>Leiosphaeridia</u> Type 5				
<u>Archaeosacculina</u> cf. <u>baltica</u>				
<u>Dennifia</u> <u>flagellata</u>				
<u>Leiosphaeridia</u> Type 2				
<u>Allumella</u> sp.				
Form A				
Form B				
<u>Leiosphaeridia</u> Type 1				
Highland Border Series	*	*	*	upper
Leny Limestone and Shale	+			75
Birnam Grits				
Birnam Slates				
Ben Ledi Grits			d	Lower Cambrian
Dunoon Phyllites/Aberfoyle Slates				
Bullrock Greywacke				
Tayvallich Volcanics	?	?	?	
Tayvallich Slates and Limestones	+	+	+	lower
Crinan Grits	*	*	*	
Craignish Phyllites			c	
Easdale Slates	*	*	*	
Islay Quartzite				
Bonahaven Dolomite	*	*	*	
Port Askaig Tillite				
Islay Limestone			b	73-4
Mullach Dubh Phyllites	*	*	*	Approximate position of Precambrian/Cambrian boundary
Lismore Limestone				
Cuil Bay Slates/Baharradail Phyllites	+			
Appin Phyllites			a	1-2
Appin Quartzite				Vendian
Appin Transition Beds	*	*	*	
Ballachulish Slates/Cnoc Donn Slates	*	*	*	
Ballachulish Limestone				
Lochnagar Sub-group				

Type 5 from all formations except the Mullach Dubh Phyllites. The explanation for this may lie in the depositional environment.

The zones, with their respective acritarch assemblages, and a discussion of their possible stratigraphic ages, are described below. This, and the occurrence of acritarch species in the Dalradian are illustrated in Fig. 5.1.

Zone 'a': The base of this zone cannot be clearly defined because no microfossils have been found in the Lochaber sub-group, but the first appearance of microfossils in the Ballachulish Slates/Cnoc Donn Slates is taken as the base of Zone 'a'. The top of Zone 'a' occurs at the base of the Mullach Dubh Phyllites.

Characteristically the acritarchs of this zone are simple and smooth walled, lacking in ornamentation. Four species occur:

Leiosphaeridia Type 1, Form A, Form B, and Alliumella sp. All these species occur abundantly in each zone, and Zone 'a' is distinguished more by the absence of species characteristic of other zones, than by any positive feature.

Zone 'b': The base of Zone 'b' is taken as the base of the Mullach Dubh Phyllites, and the top is the base of the Easdale Slates. Only two fossiliferous formations occur in this zone, the Mullach Dubh Phyllites, and the Bonahaven Dolomites.

The species: Leiosphaeridia Type 1, Form A, Form B, and Alliumella sp. continue from Zone 'a'. However it should be noted that Alliumella sp. is absent from the Mullach Dubh Phyllites, and Form B has not been found in the Bonahaven Dolomite.

Four new species are introduced, and hence define the base of this zone. These are: Leiosphaeridia Type 2, Deunffia flagellata,

Archaeosacculina baltica and Leiosphaeridia Type 5. Archaeosacculina baltica and Leiosphaeridia Type 2 do not occur in the Bonahaven Dolomite, but do occur in younger formations. Leiosphaeridia Type 5 is restricted to the Mullach Dubh Phyllites.

Zone 'c': The base of Zone 'c' is at the base of the Easdale Slates, where six species make their first appearance. The top of the zone is poorly defined, as no microfossils (apart from dubious biogenic structures in the Dunoon Phyllites, and Leny Limestone and Shale) have been found between the Tayvallich Slate and Limestone, and the Highland Border Series. The top of the Tayvallich Slates and Limestone could be taken as the upper limit of Zone 'c' with the last occurrence of Archaeosacculina baltica, if the specimens found are genuine examples of acritarchs, and not artefacts.

The species found in Zones 'a' and 'b', with the exception of Leiosphaeridia Type 5, continue through into Zone 'c'. Three fossiliferous formations occur in this zone: the Easdale Slates, Crinan Grits, and Tayvallich Slates and Limestones.

The new species which occur in the Easdale Slates at the base of this zone are: Leiosphaeridia Type 3, Plicatosphaera elementaria, Solisphaeridium sp., Archaeosacculina sp.A, Form C, and Leiosphaeridia Type 4. Of these Archaeosacculina sp.A, Form C, and Leiosphaeridia Type 4 only occur in the Easdale Slates. This is not suprising, as these forms are characterised by delicate ornament, and the preservational conditions in formations younger than the Easdale Slates are not good enough for this ornamentation to be preserved. However, Leiosphaeridia Type 3, Plicatosphaera elementaria, and Solisphaeridium sp. are found in younger rocks.

Zone 'd': The base of this zone cannot be clearly defined, although it is taken as the top of the Tayvallich Slates and Limestones. Only one fossiliferous formation, the Highland Border Series, occurs in this zone.

Those species without delicate ornament continue from Zone 'c' and these include: Leiosphaeridia Type 1, Form A, Form B, Alliumella sp., Leiosphaeridia Type 2, Deunffia flagellata, Leiosphaeridia Type 3, and Solisphaeridium sp.

One new species occurs, Michrystidium cf. lanatum and this characterises the zone.

The geological age of these four zones will now be assessed, using both the age range of these acritarchs as known at present, and other comparative age data from the Dalradian and possibly equivalent rocks in Scandinavia and Greenland, including acritarch zonal schemes proposed by Downie (1974) and Potter (1974).

Within the Dalradian itself, other palaeontological data are scarce. Downie et al. (1971) ascribed an Arenig age to the youngest Dalradian (Macduff Slates and Highland Border Series). Older rocks in the southern Highland Group have been considered upper Lower Cambrian or Middle Cambrian in age on the basis of the trilobite Pagetia from the Leny Limestone (Pringle 1945; Stubblefield 1965), and the discovery of Protospongia in the Lough Feagh Group of Clare Island (Rushton and Phillips 1973). Litherland (1975) recorded the presence of oncolites, catagraphs and ?bryozoa from the Easdale Slates at Benderloch, and suggested that the oncolites and catagraphs could be compared to similar Vendian and Riphean material from Spitsbergen and Russia. Litherland (1975) noted that in Spitsbergen this assemblage occurs below the main tillite, while the Easdale Slates occur above the Port Askaig Tillite. This result would not markedly contradict the conclusion of Downie et al. (1971) in placing the Precambrian/Cambrian boundary between the Port Askaig Tillite and the Tayvallich Limestone. However, it should be noted that the oncolites and catagraphs from the Easdale Slates are relatively long-ranging, and the Vendian age assigned to them is not conclusive.

Thus the sparse palaeontological age data available for comparison in the Dalradian can be summarised as follows:

Southern Highland Group	Macduff Slates	Arenig ¹	
	Highland Border Series		
	Lough Feagh Group	Middle Cambrian ²	
	Leny Limestone	upper Lower Cambrian ³	
Tayvallich Limestone			
Easdale Slates		Vendian ⁴	Precambrian/ Cambrian ¹ Boundary
Port Askaig Tillite			
pre-Port Askaig Tillite		Vendian ¹	

Sources: 1 Downie et al. (1971)
 2 Rushton & Phillips (1973)
 3 Pringle (1940) and Stubblefield (1965)
 4 Litherland (1975)

As discussed in Chapter 5.2, I consider that the possible chitinozoa used to establish the Arenig age of the Macduff Slates and Highland Border Series are not acritarchs, and as such the age of the youngest Dalradian is brought into question.

The lithological similarity between the British Dalradian and the Caledonides of Scandinavia and Greenland has often been remarked upon, largely because of the occurrence of tillites in each area. Often (e.g. in Finnmark, and East Greenland) the tillite formation is associated with dolomites, in a similar fashion to the Dalradian, although this is not always the case. These tillites have been broadly correlated, and their combined use as a chronostratigraphic marker has been suggested (Harland 1964). On this basis, Harland (1974) suggested that they should be used to mark the Precambrian/Cambrian boundary. However, although there are strong lithostratigraphic similarities between the tillite sequences, their chronostratigraphic value has not yet been systematically confirmed, using either radiometric or palaeontological evidence. Williams (1975) on theoretical grounds, and Morris (1977)

from palaeomagnetic results, expressed caution concerning the widespread synchronicity of late Precambrian glaciations.

Some evidence of the age of these comparable Caledonian sequences does exist and can be used in assessing the age of Dalradian acritarch zones. Pringle (1972) obtained a Pb/Sr whole rock date of 646 ± 23 m.y. (i.e. upper Riphean to lower Vendian) from shales associated with the Varanger Tillite of Finnmark. In the same late Precambrian/Cambrian sequence an evolving succession of trace fossils occurs (Banks 1970). The first traces appear less than 200m above the upper of two tillites. Banks (1970) suggested tentatively that glaciation ceased in Finnmark about 15-43 m.y. before the beginning of the Cambrian (i.e. middle or late Vendian).

In the Kong Oscars Fjord region of East Greenland, Vidal (1976a) recovered a number of acritarch assemblages from the Eleanore Bay Group and the Tillite Group. The latter disconformably overlies the former. On the basis of this material, Vidal (1976a) suggested a late Riphean age for the Eleanore Bay Group and a Vendian age for the Tillite Group. The Vendian age is largely based on the occurrence of Bavlinella faveolata. It has been argued in Chapter 5.1. that this species is probably framboidal pyrite in origin, and as such cannot be used biostratigraphically. Protosphaeridium laccatum (Timofeev) Vidal and Trachysphaeridium timofeevi Vidal, are the only other species found by Vidal (1976a) in the Tillite Group. The former ranges from the Lower Proterozoic to Lower Palaeozoic. The latter may have a restricted range in the upper Vendian, although it is only known from the Tillite Group, the possibly Vendian Visingsö Beds of southern Sweden, and the Tornetrask Group of uncertain age from northern Sweden (Vidal 1976b).

Microfossils also occur above the tillite in East Greenland in the Canyon Formation and Bastion Formation (Downie 1974). The Canyon Formation contains microfossils of Downie's (1974) zone 3 and is considered Vendian in age, whereas the Bast^tion Formation is placed in zone 4 and zone 5. Both zones are Lower Cambrian in age. Zone 4 represents the Tommotian stage and zone 5 the succeeding Atdabarian stage. Body fossils and trace fossils from the Bastion Formation confirm its Lower Cambrian age (Cowie and Spencer 1970).

In southern Norway the tillite is overlain unconformably by rocks of Downie's (1974) zones 4 and 5, i.e. Lower Cambrian in age.

From the evidence outlined above and summarised in Table 5.2, most of the Caledonian tillites can be considered Middle or Late Vendian in age. This evidence must be compared with the results obtained from this study.

Zone 'd' is almost certainly Lower Cambrian in age (probably upper Lower Cambrian) in that it is characterised by Micrhystridium cf. lanatum, which is also characteristic of the Atdab^arian stage of the Lower Cambrian of Estonia. This species has also been reported from the upper Lower Cambrian of Ireland (Smith in press, Gardiner & Vanguetaine 1971) and from the Durness Limestone of Scotland, as part of Downie's (1974) zone 5. Gower (1973) correlated the Durness Limestone with the Dalradian Tayvallich Slates and Limestone (zone 'c'). Potter (1974) considered that the genus Micrhystridium is characteristic of the Lower and Middle Cambrian in Britain.

Zone 'a' appears to be Vendian in that it is characterised by very simple, long-ranging forms. Only Alliumella sp., appears to be more restricted to the late Precambrian (Riphean) and Cambrian (Timofeev 1973).

TABLE 5.2

<u>GREENLAND</u>	<u>NORWAY</u>	<u>SCOTLAND</u> (outside Dalradian)	<u>DALRADIAN</u> (this study)
(tb) Ella Ø Frm LCA	(bm) Holmia Shale LC	(bm) Durness Lst. LC?A (base)	(m) Highland Brdr. LCA Series
(tbm) Bastion Frm. LCT	(t) Stappogiede Frm. LC	(m) Salterella Grits LCA	(?mb) Leny Limestone LC?A
(m) Canyon Frm. V(?LC)		(m) Fucoid Beds LCA	(m) Tayvallich Sl LC and Lst.
Tillite V	Tillite V*		(m) Easdale Slates LC
(m) Eleanore Bay Gp. V			Port Askaig LC-V Tillite
			(m) Mullach Dubh LC-V Phyllites
			(m) Appin Group V

Notes: Correlations are only tentative.

t::Trace Fossils
b: Body Fossils
m: Microfossils

LCA: Lower Cambrian, Atdabanian Stage
LC: Lower Cambrian, uncertain stage.
LCT: Lower Cambrian, Tommotian Stage.
V: Vendian.
*: Rb/Sr age of 686 +/- 23 m.y.

For Dalradian palaeontology outside this study, see discussion and table in text.

Thus zones 'b' and 'c' must be examined in order to determine the position of the Precambrian/Cambrian boundary in the Dalradian. It should be noted that the Port Askaig Tillite occurs in zone 'b' and if the Caledonian tillites do form a chronostratigraphic level, then zone 'b' would appear, on external evidence, to be Vendian in age.

In zone 'b' Leiosphaeridia Type 2 and Leiosphaeridia Type 5 are long-ranging forms, with occurrences from the Lower Precambrian through to the Lower Palaeozoic. Archaeosacculina baltica, however, has a more restricted record. This species occurs in the Torridonian in Downie's (1974) zones 1 and 2, and also throughout the Lower Cambrian, including the Lontovas suite of Estonia (Naumova 1968), the Vosmoye Complex of Northern Siberia (Il'tchenko 1973), and the Protolenid/Strenuellid zone (Hell's Mouth Grits) and the Middle Cambrian Paradoxides oelandicus zone (St. Tudwal's Peninsula) (Potter 1974). Also within zone 'b' occurs Deunffia flagellata. This form has only been previously recorded from the Lower Cambrian Vergal'skiy and Rauvenskiy horizons of the Baltic region (Jankauskas 1975). With only this one published record of Deunffia flagellata, it is impossible to assess the importance of this species with regard to a possible Cambrian age for zone 'b'. Unfortunately, neither of the two distinctive species of this zone has been reported from rocks associated with other Caledonian tillites. Thus a direct comparison of material is not possible. However, the presence of two species known to occur in the Cambrian (in one case predominantly through the Lower Cambrian), associated with indirect evidence that the tillite is late Vendian in age would indicate that zone 'b' lies close to and possibly spans the Precambrian/Cambrian boundary.

Of the six new occurrences in zone 'c', only Plicatosphaera elementaria is of biostratigraphic use, as the others are either long-ranging, or else their identification with recorded species is only

tentative.

Plicatosphaera elementaria is the type species of Potter's (1974) zone SLA which corresponds to the upper Lower Cambrian Protolenid/Strenuellid zone. Potter (1974) discussed at some length how the simple nature of the sutures defining the fields on the surface of this species is a Lower Cambrian characteristic with more complex sutured forms occurring later in the Cambrian. Again this is the only record of Plicatosphaera elementaria, and therefore its range is not known. However, from the complex nature of its surface texture it would appear to be a Cambrian rather than a Vendian form.

Thus, on the evidence of the microfossils, zone 'a' appears to be Vendian and zone 'd' upper Lower Cambrian. Zone 'c' may be Lower Cambrian in age, although this cannot be stated with certainty until more is known of the range of Plicatosphaera elementaria. On both internal evidence, and using comparative material from other Caledonian tillite sequences, zone 'b' probably spans the Precambrian/Cambrian boundary. Again, this cannot be stated with certainty until more is known of the range of Deunffia flagellata and more detailed work can be carried out on microfossils from other Caledonian tillite sequences.

Chapter 6

CONCLUSIONS

Conclusions

The conclusions that have been reached from this study can be outlined under a number of headings.

1. Methods.
2. Depositional environments of the Dalradian.
3. Palaeontology.
4. Preservation.
5. Biostratigraphy.
- ~~6. Further work.~~

1. Methods

(a) Biogenecity criteria. The poor preservation of many of the microfossils in the Dalradian has necessitated the establishment of and continuous use of a set of morphological criteria based on those of Cloud and Licari. These are: (i) a similar colour to the surrounding organic debris; (ii) distinct and consistent morphology; (iii) demonstrably consist of organic matter; (iv) no mineralogical distortion; (v) the microstructure should occur in a demonstrably sedimentary rock.

The use of statistical techniques outlined by Schopf (1976) has also been discussed but it is concluded that the biological significance of the statistical methods is by no means unambiguous, and they have not been used extensively in this study.

(b) Techniques. All samples have been examined using both petrological thin sections and macerations. A number of polished thin sections have also been used.

This has permitted the greatest amount of information to be obtained from the material.

2. Depositional Environments

A review of the depositional environments of the Dalradian has been undertaken. From this, it can be shown that Dalradian sediments were deposited on an ensialic basement under conditions similar to those operating during the Mesozoic and Tertiary history of the North Sea. Sedimentation was initiated in a number of relatively small basins, controlled by block faulting. The faults were oblique to a major basement fault northwest of Jura, which probably trended northeast - southwest. At the base of the Ardrishaig/Craignish Phyllites is a major unconformity which can also be recognised in Ireland (see Pitcher and Berger 1972 p.381). After the formation of the Ardrishaig/Craignish Phyllites, deposition in the western Dalradian was limited by a graben-like feature whose northwest margin was probably controlled by a major basement fault trending northeast - southwest from northwest of Loch Awe to near Craignish. This major feature, which can be recognised as a shelf break separates generally shallow water sedimentation to the west from deep water turbidites etc. to the east. At times e.g. during the deposition of the Shira Limestone, shallow water sedimentation prevailed over the whole area.

During the whole of this time there appears to have been a landmass to the northwest from which material was supplied. In Appin Quartzite and Islay Quartzite times, currents flowed longshore towards the northeast depositing

sediments on a shelf. During Dalradian sedimentation, however, there is considerable evidence of sediments being derived from the southeast, east and northeast, indicating that throughout this period, a positive feature existed to the east of the area of deposition.

The tectonic setting of these events is a taphrogenic, probably rifting phase, similar to that of the post Permian North Sea. This, plus the abundant evidence of a positive area to the east gives little support for the existence of an extensive ocean during this time. Sedimentation appears rather to have taken place mostly on a continental basement. Only the marked change in sedimentation and the introduction of volcanics during the deposition of the Southern Highland Group indicates deeper water and possibly more oceanic sedimentation.

3. Palaeontology

Fifteen distinct and recognisable species based on morphological differences have been recognised from the Dalradian. It is likely that more are present, but the generally poor preservation of most of the microfossils has led to the loss of distinctive ornament and in many cases only gross morphology remains. The most common morphology is simple spheroids. A number of species previously unrecognised in the Dalradian have been described. These include: Form A, Form B, Deunftia flagellata, Plicatosphaera cf. elementaria and Micrhystridium cf. lanatum.

The problem of the classification of simple spheromorphs with no, or only minute, ornament is discussed. The generic name Leiosphaeridia Eisenack 1958 is shown to have precedence over other genera of simple spheres, many of which are invalid. To bypass the confusion, all the simple spheromorphs with little or no ornamentation in this study have been placed in the genus Leiosphaeridia 1958. Using such criteria as variations in wall thickness, and minute wall features, a number of different morphologies have been recognised. These have been given the names "Type 1", "Type 2" etc. Five different simple spheromorph morphologies have been recognised in this study.

4. Preservation

This has been recognised as an important feature in Dalradian micropalaeontology. The factors relating to preservation have been described and discussed. It has been shown that pre-lithification stages, including early cementation are important in creating good preservation, with microfossils possessing good 3-dimensionality in thin section. Siliceous shales in which early diagenetic cementation has taken place contain fossils better preserved than shales with a high mica content, even though the latter may be extremely fine grained.

The other major diagenetic feature that effects preservation is the growth of pyrite. This usually takes the form of microcrystalline framboids. It has been shown that this pyrite can be related to organic matter in three different ways: (i) framboidal pyrite in-filling spheromorphs acritarchs, without distorting the wall; (ii) the

frambooid in-fills the spheromorph and distorts its walls giving the whole microstructure a frambooidal texture; (iii) the individual microcrysts grow in organic debris which wraps around the microcrysts, producing again a frambooidal texture. The recognition of these effects by pyrite is important, and the close relationship between microfossils and frambooids has been tested both by morphological comparisons and by a number of statistical tests. Many microstructures with "raspberry" morphologies have been recognised as physical distortions of acritarchs, and it is suggested that similar microstructures that have been termed "microfossils" in the literature are probably abiological in origin. The most important of these are Spherocongregus Moorman and Bavlinella Shepeleva. From the evidence outlined and discussed in Chapter 5.1, these two genera cannot be considered microfossils.

The post-lithification factors which control preservation are tectonism and metamorphism, although metamorphism is an ongoing process overlapping with diagenesis. Metamorphism is largely concerned with the effects of pressure and temperature. It has been recognised in this study that with increase in metamorphism, acritarchs darken in a similar fashion to that shown by others to occur in spores and pollen. Most of the microfossils are black, although those in the lowest grade rocks of western Scotland, especially the Easdale Slates and Mullach Dubh Phyllites

are paler. In these formations, the microfossils are thought to be in a transition stage with pale brown spheromorphs, those with an irregular dark speckling and those totally dark, occurring in the same sample.

It is interesting to note that the work of McNamara (1964) estimated conditions of lowest grade Dalradian metamorphism at about 200°C - 300°C and a pressure of about 2 k.bar. This compares favourably with the experimental work of Sengupta (1975), which illustrated Lycopodium spores turning dark brown to black at similar temperatures.

Tectonism has been restricted to the mechanical effects of rotation and growth of mica. It has been shown that this generally has a destructive effect on microfossils, largely resulting in the rupture of brittle acritarch walls. However both on a large scale and micro-texturally, there are areas where relatively good preservation can occur on the crests of folds in psammite/shale sequences, in places where cleavage is minimal. On a microscale cleavage lamellae with high strain are separated usually by areas $5\text{ }\mu\text{m}$ to $30\text{ }\mu\text{m}$ across of low strain and microfossils can be preserved in these areas.

Pressure solution, resulting in quartz mobilisation can be shown to be a rare contributor to the preservation of microfossils. Where these occur in pressure shadows associated with quartz grains and have been in-filled with grain boundary migrated quartz, their preservation is relatively good.

From these studies it has been shown that microfossils can be relatively well preserved in conditions that might have been considered unsuitable. A low metamorphic grade is preferable, but microfossils have been found in rocks up to low biotite grade regionally (Appin Transition Beds). These occur in thin shales in a dominantly quartzitic formation. Similarly, rocks without cleavage have a greater chance of having well preserved microfossils than those that are cleaved. However, the latter are worth examining for microfossils as both on a macro- and micro-scale areas of low strain are found.

5. Biostratigraphy

One of the major aims of this study has been to use the microfossils found to erect a biostratigraphy. On an internal basis, within the Dalradian, four acritarch zones ('a'-'d') have been erected. The base of each zone has been defined by the introduction of new species. The zones are as follows:

'a' : Lochaber Sub-group - Lismore Limestone.

'b' : Mullach Dubh Phyllites - Islay Quartzite.

'c' : Easdale Slates - Tayvallich Slates and Limestones.

'd' : Tayvallich Volcanics - Highland Border Series.

An estimate of the geological age of these zones has been made by comparing the known age-range of these acritarchs with other age data from within the Dalradian, and from similar Caledonian tillite sequences in Scandinavia and Greenland. No conclusions have been reached concerning the chronostratigraphic value of these tillites, but the cautionary words of Williams (1975) and Morris (1977) are noted.

On the basis of this evidence, zone 'a' is considered to be Vendian in age; zone 'b' probably spans the Precambrian/Cambrian boundary; zone 'c' is lower Lower Cambrian, and zone 'd' upper Lower Cambrian. In

order to achieve a more accurate positioning of the Precambrian/Cambrian boundary in particular, and also the age of zone 'c', more data concerning the age-ranges of Deunffia flagellata and Plicatosphaera elementaria are necessary. Both of these species have only one other recorded occurrence.

The Port Askaig Tillite occurs in zone 'b' and as such has a probable latest Vendian to possibly lowest Cambrian age. This contradicts some of the age evidence of other late Precambrian tillites which appear to span an age of latest Riphean to latest Vendian. Further work on the correlation of these tillites is now necessary. This spread in ages may indicate that marked glacial diachronism took place under unusual geological conditions.

On the basis of the acritarch assemblages described above, there is no evidence to support the hypothesis of Cummins (1966 and 1974) that the Leny Limestone is equivalent to the Loch Tay Limestone.

In Ireland, acritarch assemblages have been discovered in only three formations: the upper Falcarragh Pelites, Lough Feagh Group (Ballytooey Formation) of Clare Island, and the ^dArdvarney Formation in the Ox Mountains. On the basis of the assemblages found, the Falcarragh Pelites would occur in zone 'b', and the Lough Feagh Group in zone 'd'. These agree with present lithostratigraphical correlations. The Ardvarney Formation has been considered part of the Southern Highland Group. However, the absence of Micrhystridium cf. lanatum may exclude it from zone 'd' and the formation may be older than previously thought.

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PLATE 1

- Fig. 1 Michrhystridium cf. lanatum; Highland Border Series
PL4(b) 121.9/7.1 X1500
- " 2 Michrhystridium cf. lanatum; Highland Border Series
PL4(b) 96.3/14.9 X1500
- " 3 M. cf. lanatum; Highland Border Series
HB27(M3) 102.6/15.8 X1500
- " 4 M. cf. lanatum; Highland Border Series
HB27(M4) 102.2/14.9 X2500
- " 5 M. cf. lanatum; Highland Border Series
PL4(TS) 125.0/14.8 X1500
- " 6 M. cf. lanatum; Highland Border Series
PL4(TS) 125.0/14.8 X2500
- " 7 M. cf. lanatum; Highland Border Series
PL1(M6) 108.3/13.0 X2500
- n" 8 Solisphaeridium sp.; Easdale Slates
D29(M1) 118.5/5.4 X2500
- " 9 Solisphaeridium sp.; Easdale Slates
D29(M1) 118.5/5.4 X2500
- " 10 ?Solisphaeridium sp.; Crinan Grit
HB43(TS) 107.3/13.5 X2500

Plate 1



1



2



3



4



5



6



7



8



9



10

PLATE 2

Fig. 1 Solisphaeridium sp.; Easdale Slates

D29(TS) 107.3/14.6 X1500

" 2 ?Solisphaeridium sp.; Easdale Slates

E36(TS) 117.0/12.3 X1500

" 3 ?Solisphaeridium sp.; Highland Border Series

PL4(TS) 112.8/7.4 X1500

" 4 ?Solisphaeridium sp.; Lough Feagh Group (Ballytooney Formation)

1180(TS) 103.4/18.0 X2500

" 5&6 Alliumella sp.; Easdale Slates

E45(TS) 120.2/13.3 X2500

" 7 Alliumella sp.; Easdale Slates

E36(TS) 117.0/12.1 X1500

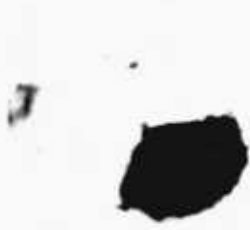
" 8 Alliumella sp.; Easdale Slates

E36(TS) 116.9/12.0 X1500

" 9&10 Alliumella sp.; Bonahaven Dolomite

D19(M1) 93.4/17.2 X2500

Plate 2



1



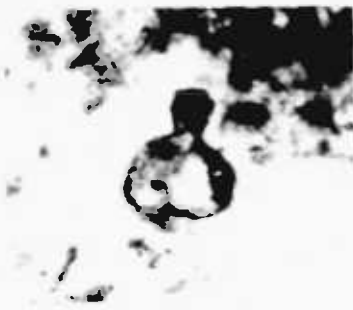
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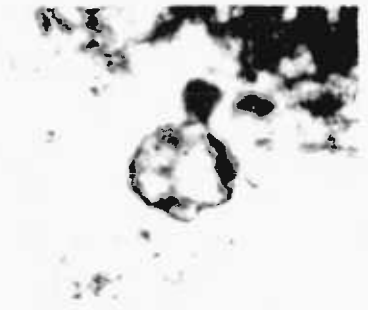
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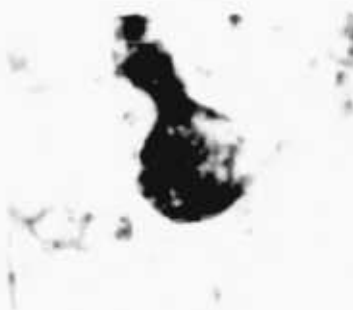
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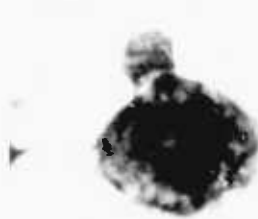
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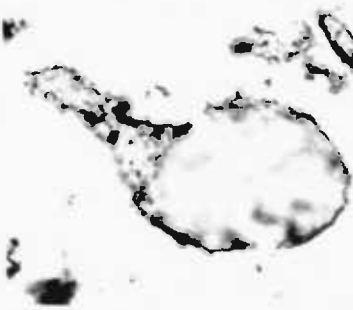
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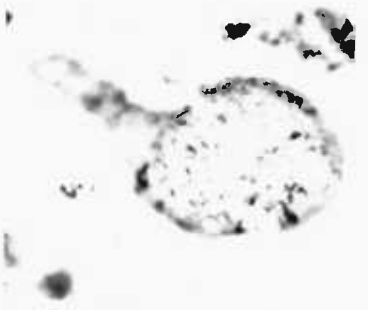
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8



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PLATE 3

Fig. 1 ?Alliumella sp.; Appin Transition Beds

B49(TS) 94.0/10.1 X1500

" 2&3 Alliumella sp.; Appin Transition Beds

B49(TS) 94.0/11.6 X1500

" 4 ?Alliumella sp.; Highland Border Series

PL4(M3) 115.5/15.6 X1500

" 5 Alliumella sp.; Highland Border Series

PL4(M12) 113.5/4.2 X2500

" 6 Alliumella sp.; Lough Feagh Group (Ballytooley Formation)

1180 (TS) 106.6/18.9 X2500

" 7&8 Alliumella sp.; Easdale Slates

E40(TS) 106.1/18.4 X1500

Plate 3



1



2



3



4



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8

PLATE 4

Fig. 1 Alliumella sp.; Easdale Slates

D29(M1) 127.6/22.7 X1500

" 2 Alliumella sp.; Bonahaven Dolomite

D19(M1) 119.8/13.1 X1500

" 3 Alliumella sp.; Appin Transition Beds

B49b(TS) 98.8/7.2 X1500

" 4 Alliumella sp.; Mullach Dubh Phyllites

D18(M1) 112.6/5.9 X1500

" 5 Deunfria flagellata; Mullach Dubh Phyllites

D18(M1) 104.6/11.1 X1500

" 6 D. flagellata; Bonahaven Dolomite

D19(M1) 119.1/21.2 X1500

" 7 D. flagellata; Bonahaven Dolomite

D19(M1) 119.5/15.9 X1500

" 8 D. flagellata; Bonahaven Dolomite

D19(M1) 103.9/10.1 X1500

" 9 D. flagellata; Easdale Slates

D29(M1) 132.5/10.1 X1500

" 10 D. flagellata; Highland Border Series

PL4(M3) 115.5/17.3 X1500

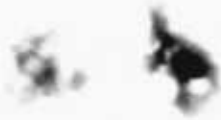
Plate 4



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PLATE 5

Fig. 1 Deunffia flagellata; Lough Feagh Group (Ballytooney Formation)

1183(TS) 93.6/23.0 X2500

" 2 D. flagellata; Lough Feagh Group (Ballytooney Formation)

1180(TS) 105.6/19.0 X1500

" 3 D. flagellata; Ardvarney Formation

BL5b(YS) 116.4/3.2 X1500

" 4 D. flagellata; Ardvarney Formation

BL5b(TS) 116.4/3.2 X2500

" 5 D. flagellata; Upper Falcarragh Pelites

I13(TS) 106.1/11.3 X2500

" 6 ?D. flagellata; Mullach Dubh Phyllites

D18(M1) 85.3/14.9 X1500

" 7 ?D. flagellata; Crinan Grits

HB43(TS) 114.2/12.1 X2500

" 8 D. flagellata; Highland Border Series

PL4(M12) 110.3/19.1 X1500

" 9 D. flagellata; Highland Border Series

PL4(M3) 106.3/18.1 X1500

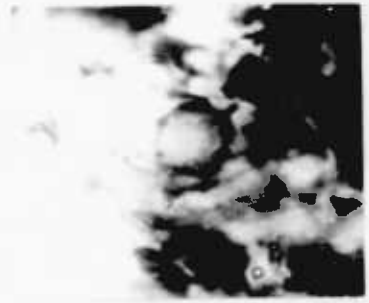
" 10 ?D. flagellata; Lough Feagh Group

1183(TS) 95.9/2.4 X2500

Plate 5



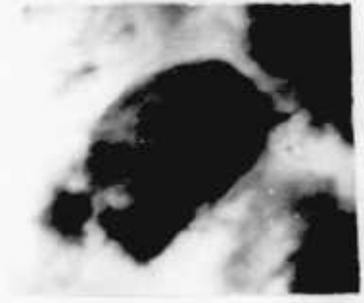
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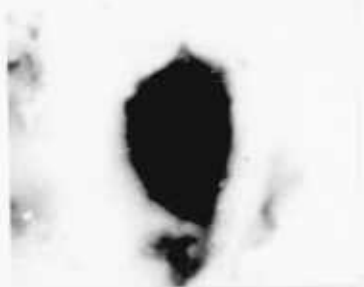
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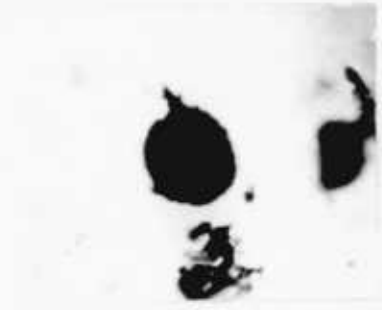
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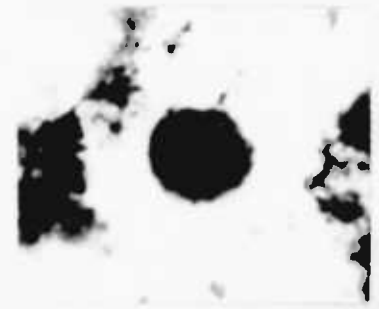
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PLATE 6

Fig. 1 ?Deunffia flagellata; Lough Feagh Group (Ballytooey Formation)

1169(TS) 121.3/17.2 X1500

" 2 ?Deunffia flagellata; Ardvarney Formation

BL5b(TS) 96.6/16.5 X2500

" 3 ?Deunffia flagellata; Ardvarney Formation

BL5b(TS) 103.5/15.6 X1500

" 4-7 Plicatosphaera elementaria; Easdale Slates

E36(TS) 96.7/10.6 X2500

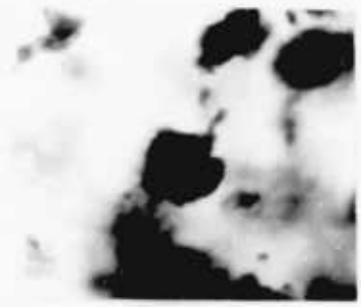
" 8&9 P. elementaria; Easdale Slates

E36(TS) 117.1/7,8 X2500

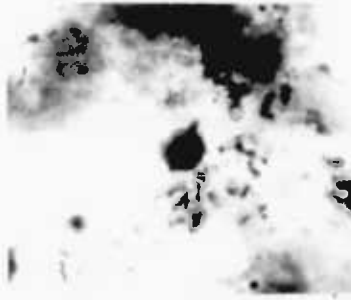
Plate 6



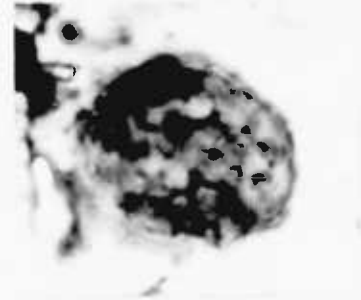
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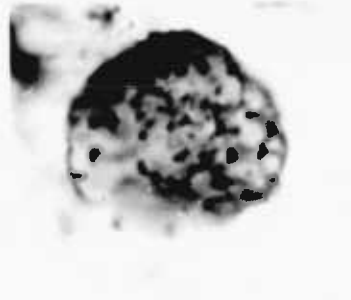
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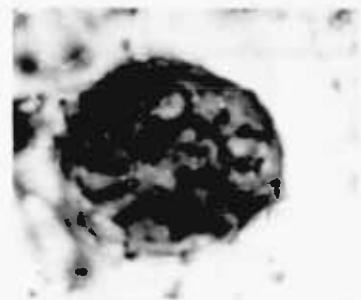
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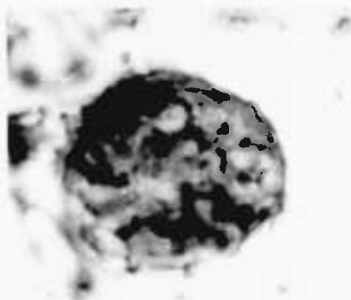
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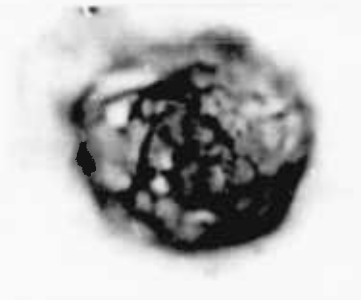
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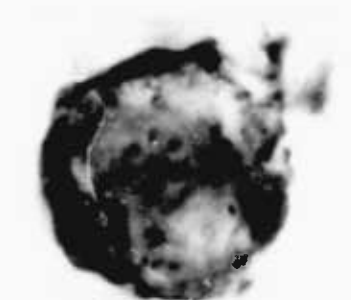
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PLATE 7

Fig. 1 Archaeosacculina cf. baltica; Mullach Dubh Phyllites

D18(TS) 108.4/5.7 X1500

" 2&3 A. cf. baltica ; Mullach Dubh Phyllites

D18(TS) 117.5/12.8 X2500

" 4 A. cf. baltica; Bonahaven Dolomites

D19(TS) 116.0/10.4 X1500

" 5 A. cf. baltica; Easdale Slates

D29(M1) 118.5/6.9 X2500

" 6&7 A. cf. baltica; Easdale Slates

E36(TS) 121.0/11.6 X1500

" 8&9 A. cf. baltica; Easdale Slates

D29(TS) 127.7/22.0 X2500

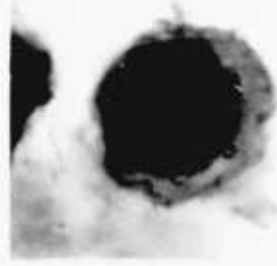
" 10 A. cf. baltica; Easdale Slates

E36(TS) 115.0/15.3 X1500

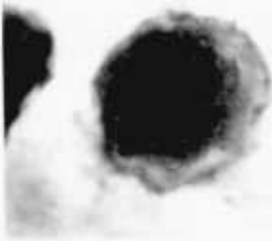
Plate 7



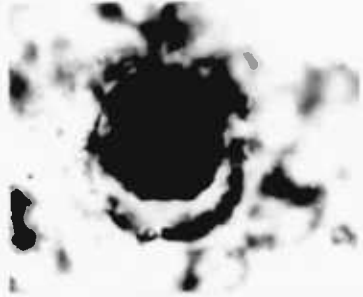
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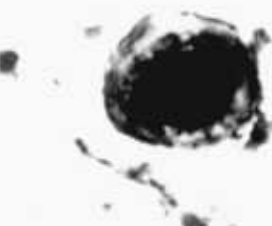
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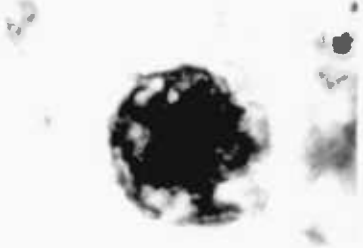
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PLATE 8

Fig. 1 ?Archaeosacculina cf. baltica; Tayvallich Slates and Limestones

B4(TS) 93.7/18.4 X1500

(possibly a bubble)

" 2 A. cf. baltica; Tayvallich Slates and Limestones

B4(TS) 103.5/5.8 X1500

" 3&4 A. sp. A; Easdale Slates

E36(TS) 84.7/15.3 X1500

" 5-7 A. sp. A; Easdale Slates

E36(M1) 108.9/4.9 Fig. 5 X1500

Fig. 6&7 X2500

" 8 ?A. sp. A; Easdale Slates

E36(M3) 112.6/21.6 X2500

" 9&10 A. sp. A; Easdale Slates

E36(M2) 97.2/10.2 X2500

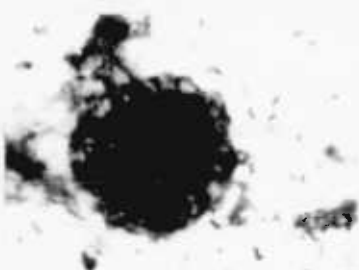
Plate 8



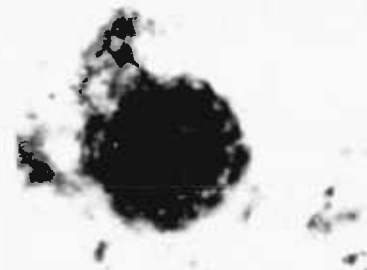
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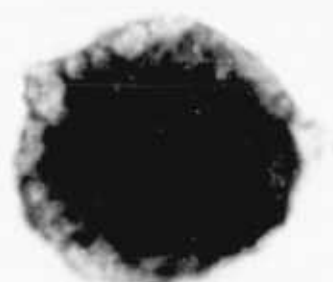
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4



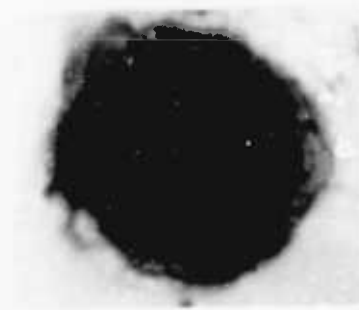
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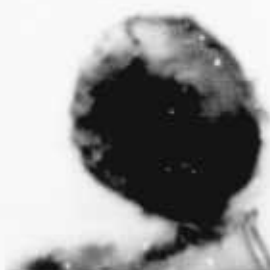
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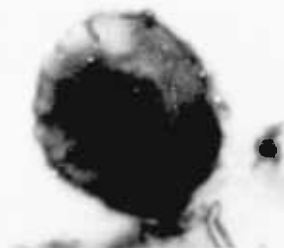
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PLATE 9

Fig. 1 ?Leiosphaeridia Type 1; Appin Transition Beds

B49(TS) 94.3/15.7 X1500

" 2 L. Type 1; Appin Transition Beds

B49(TS) 121.2/5.8 X1500

" 3 L. Type 1; Easdale Slates

F36(TS) 103.4/20.6 X1500

" 4 L. Type 1; Easdale Slates

E36(TS) 102.9/21.9 X1500

" 5 L. Type 1; Easdale Slates

E40(TS) 106.0/12.8 X1500

" 6 L. Type 1; Easdale Slates

E36(TS) 95.3/3.0 X1500

" 7 L. Type 1; Easdale Slates

E42(TS) 95.8/14.6 X1500

" 8 L. type 1; Crinan Grits

HB43(TS) 112.4/12.9 X1500

" 9 L. Type 1; Crinan Grits

HB43(TS) 112.6/13.7 X1500

" 10 L. Type 1; Crinan Grits

HB43(TS) 104.1/13.8 X1500

Plate 9

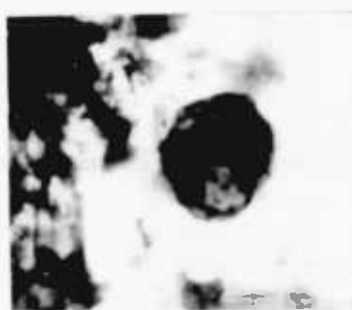
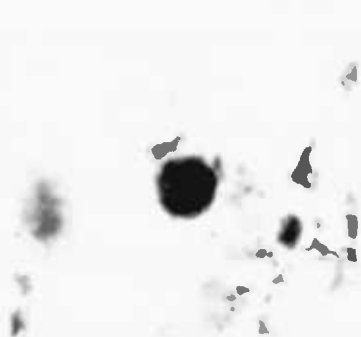


PLATE 10

Fig. 1 Leiosphaeridia Type 1; Highland Border Series

PL4(TS) 124.4/13.9 X1500

" 2 L. ?Type 1; Highland Border Series

PL4(TS) 103.7/9.2 X2500

" 3 L. Type 1; Highland Border Series

PL4(TS) 97.3/18.1 X1500

" 4 L. Type 1; Lough Feagh Group (Ballytooney Formation)

1180(TS) 107.2/18.1 X1500

" 5 L. Type 1; Lough Feagh Group (Ballytooney Formation)

1183(TS) 96.3/27.7 X1500

" 6 L. Type 1; Lough Feagh Group (Ballytooney Formation)

1183(TS) 94.6/22.9 X1500

" 7&10 L. Type 2; Bonahaven Dolomite

D19(M1) 115.1/17.2 X2500

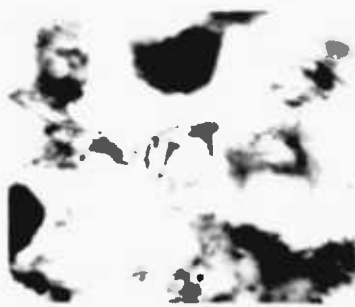
" 8 L. Type 2; Bonahaven Dolomite

D19(M1) 97.0/3.2 X1500

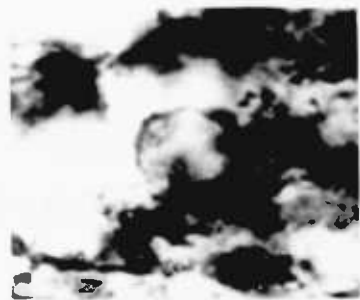
" 9 L. Type 2; Bonahaven Dolomite

D19(M1) 107.9/5.0 X1500

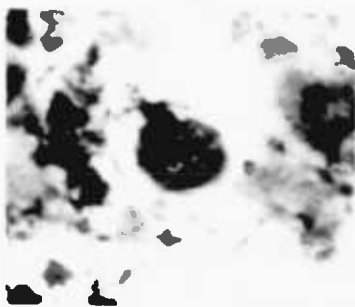
Plate 10



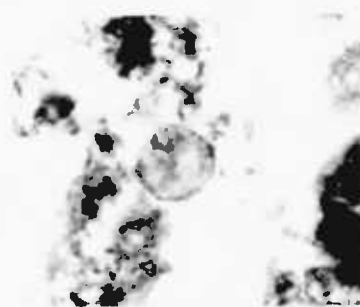
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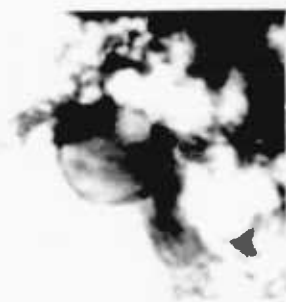
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PLATE 11

Fig. 1 Leiosphaeridia Type 2; Mullach Dubh Phyllites

D18(M1) 105.3/17.0 X1500

" 2 L. ?Type 2; Crinan Grits

HB43(TS) 115.8/14.4 X1500

" 3 L. ? Type 2; Crinan Grits

HB43(TS) 98.5/12.8 X1500

" 4 L. Type 2; Highland Border Series

PL4(M13) 97.2/16.6 X1500

" 5 L. Type 2; Highland Border Series

PL4(M3) 106.3/16.8 X2500

" 6 L. Type 2; Highland Border Series

PL4(M1) 106.0/10.0 X1500

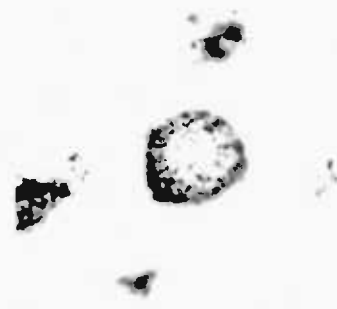
" 7-9 Leiosphaeridia Type 3; Easdale Slates

E36(TS) 97.5/13.7 X1500

Plate 11



1



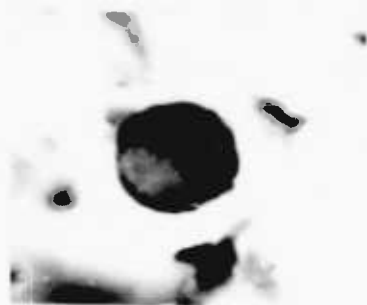
2



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PLATE 11A

Fig. 1 Leiosphaericia Type 3; Easdale Slates

E36(TS) 116.1/11.6 X1500

" 2 " " " X2500

" 3 L. Type 3; Easdale Slates

E36(TS) 98.4/5.6 X1500

" 4 " " " X2500

Plate 11a

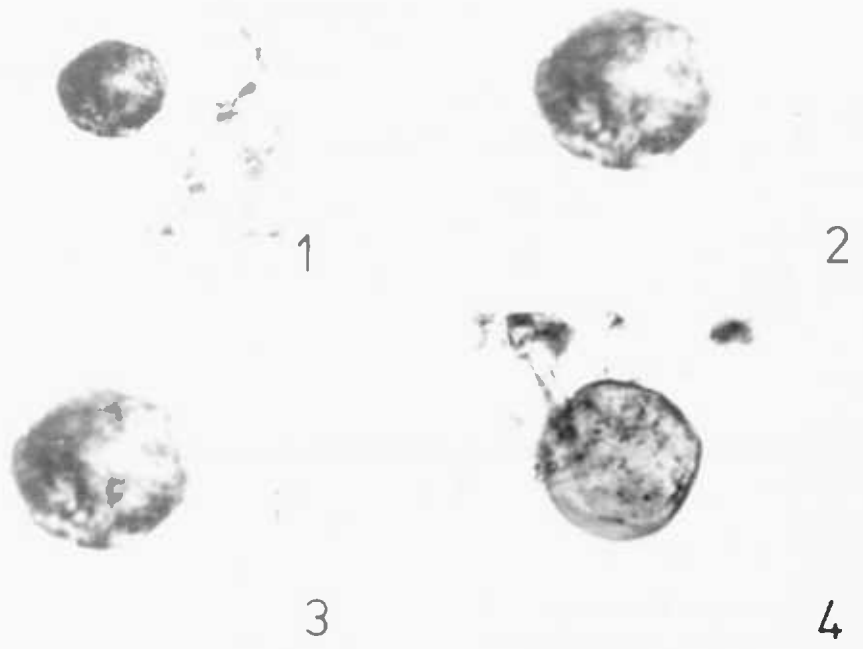


PLATE 12

Fig. 1 Leiosphaeridia Type 4; Easdale Slates

E36(M1) 105.6/5.7 X1500

" 2 L. Type 4; Easdale Slates

E36(M1) 93.4/12.3 X1500

" 3-5 L. Type 5; Mullach Dubh Phyllites

D18(M1) 107.7/9.9 X1500

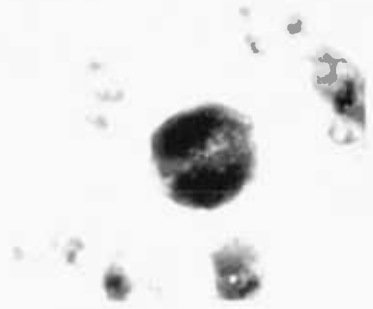
" 6&7 L. Type 5; Mullach Dubh Phyllites

D18(M1) 107.7/9.9 X2500

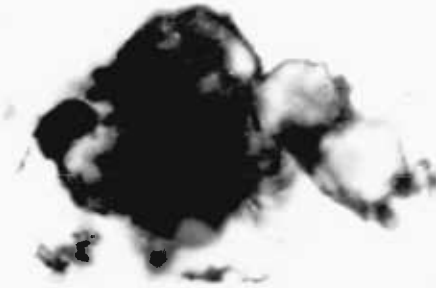
Plate 12



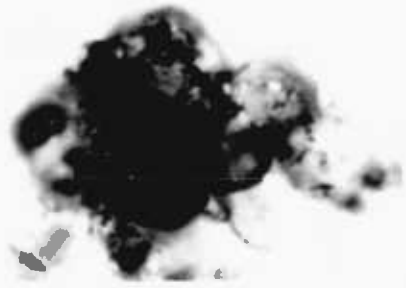
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2



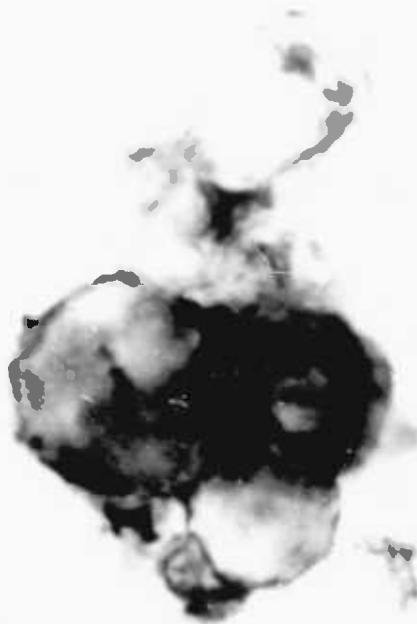
3



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PLATE 13

Fig. 1 Form B(i); Appin Transition Beds

B45(M1) 109.7/17.7 X1500

" 2 Form (ii); Ardvarney Formation

BL5b(TS) 97.3/21.2 X1500

" 3 Form B(i); Cnoc Donn Slates

HB54(TS) 100.4/9.8 X2500

" 4 Form E(i); Easdale Slates

E36(TS) 120.1/3.7 X1500

" 5-8 Form B(ii); Muilach Dubh Phyllites

D18(M1) 110.6/10.8 X2500

Plate 13



1

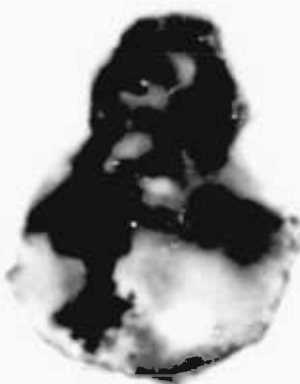
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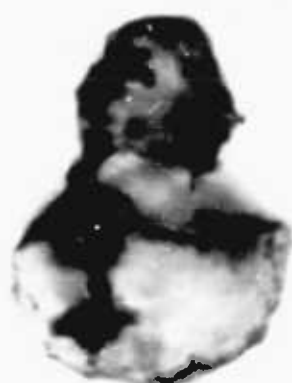
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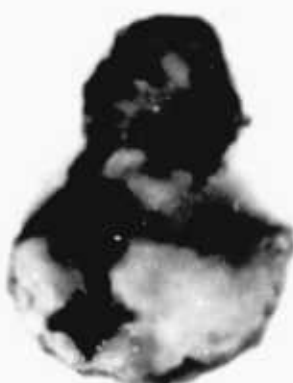
4



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PLATE 14

Fig. 1 Form B(ii); Mullach Dubh Phyllites

D18(TS) 104.8/5.5 X1500

" 2 Form B(ii); Easdale Slates

E36(TS) 117.5/21.6 X1500

" 3 Form B(ii); Mullach Dubh Phyllites

D18(TS) 123.0/10.9 X2500

" 4 Form B(iii); Upper Falcarragh Pelites

I13(TS) 106.0/11.4 X1500

" 5 Form B(iii); Easdale Slates

E36(TS) 117.1/3.1 X1500

" 6 Form B(iii); Easdale Slates

E36(TS) 97.3/21.6 X1500

" 7 Form B(iii); Easdale Slates

E36(TS) 117.0/6.6 X1500

" 8 Form B(iii); Mullach Dubh Phyllites

D18(TS) 108.3/4.6 X2500

" 9 Form B(iii); Crinan Grits

HB43(TS) 110.4/13.1 X1500

" 10 Form B(iii); Ardvarney Formation

BL5b(TS) 96.6/16.5 X1500

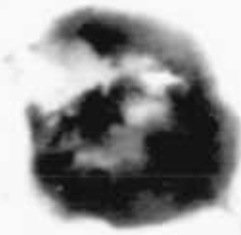
Plate 14



1



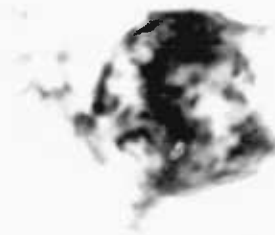
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3



4



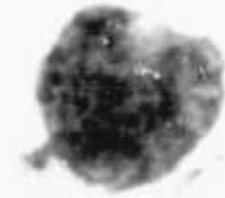
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PLATE 15

Fig. 1 Form B(iii); Upper Falcarragh Pelites

I13(TS) 104.7/8.3 X1500

" 2 Form B(iii); Upper Falcarragh Pelites

I13(TS) 110.6/11.4 X2500

" 3 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1180(TS) 98.3/16.9 X1500

" 4 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1184(TS) 106.9/7.3 X1500 (note stellate pylome).

" 5 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1180(TS) 109.4/14.8 X1500

" 6 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1184(TS) 112.1/9.1 X2500

" 7 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1184(TS) 117.0/7.9 X1500

" 8 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1184(TS) 105.8/10.3 X1500

" 9 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1180(TS) 98.3/16.4 X1500

" 10 Form B(iii); Lough Feagh Group (Ballytooney Formation)

1180(TS) 113.7/9.1 X1500

Plate 15



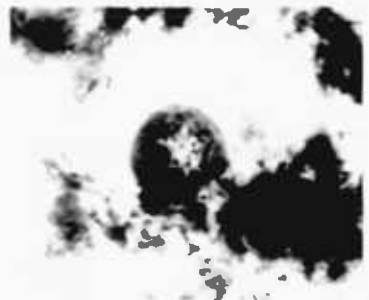
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3



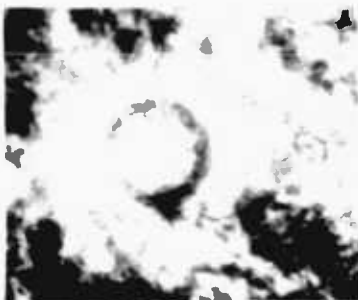
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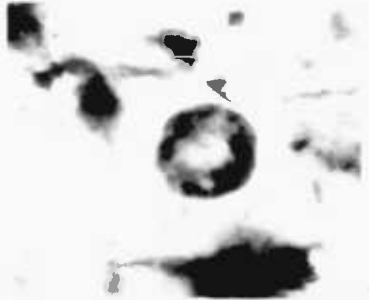
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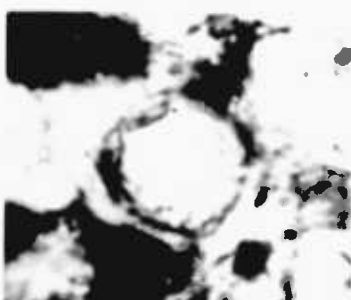
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PLATE 16

Fig. 1 ?Form A; Appin Transition Beds

B49(TS) 115.8/15.2 X1500

" 2 Form A; Appin Transition Beds

B49(TS) 98.6/3.9 X1500

" 3 Form A; Mullach Dubh Phyllites

D18(M1) 106.4/10.2 X2500

" 4 Form A; Mullach Dubh Phyllites

D18(M1) 118.9/11.0 X1500

" 5 Form A; Mullach Dubh Phyllites

D18(TS) 108.6/16.9 X2500

" 6 Form A; Mullach Dubh Phyllites

D18(M1) 121.9/11.0 X2500

" 7 Form A; Bonahaven Dolomite

D18(M1) 95.6/13.1 X1500

" 8 Form A; Bonahaven Dolomite

D19(M1) 121.3/14.7 X1500

" 9 Form A; Bonahaven Dolomite

D19(M1) 100.3/4.7 X1500

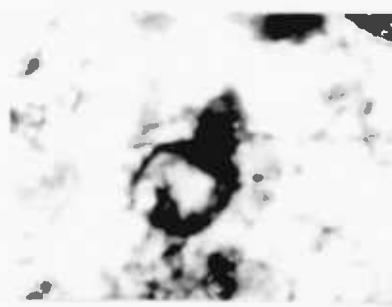
" 10 Form A; Casdale Slates

E36(TS) 117.0/9.2 X1500

Plate 16



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PLATE 17

Fig. 1 Form A; Easdale Slates

E50(TS) 112.0/18.9 X1500

" 2 Form A; Easdale Slates

E36(TS) 116.9/2.9 X1500

" 3 Form A; Highland Border Series

PL4(TS) 123.7/14.7 X2500

" 4 Form A; Highland Border Series

PL4(M3) 115.6/15.2 X1500

" 5 Form A; Highland Border Series

PL4(M3) 115.6/15.0 X1500

" 6 Form A; Leny Limestone

BL27(TS) 104.5/19.5 X2500

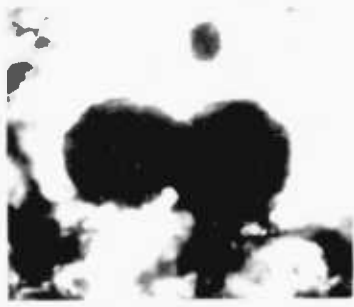
" 7 Form A; Ardvarney Formation

BL55(TS) 95.3/18.5 X1500

" 8 Form A; Lough Feagh Group (Ballytooey Formation)

1180(TS) 103.5/18.0 X1500

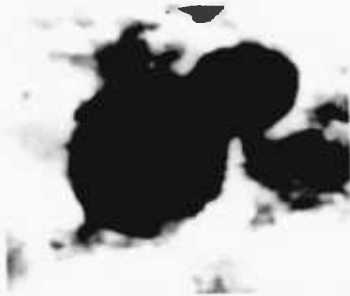
Plate 17



1



2



3



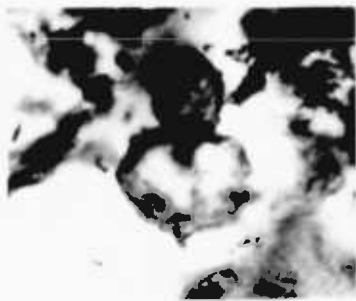
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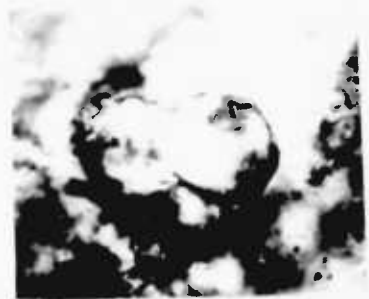
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6



7



8

PLATE 18

Fig. 1 Filaments; Easdale Slates

E31(M1) 122.0/7.4 X500

" 2 Filaments; Easdale Slates

E31(M1) 122.1/2.1 X1000

" 3 Filaments; Easdale Slates

E31(M1) 115.8/6.4 X500



2



1



3

PLATE 19

Fig. 1 Filaments; Easdale Slates

E31(M1) 126.4/5.1 X500

" 2 Filaments; Easdale Slates

E31(M1) 108.1/12.6 X500

" 3 Filaments; Easdale Slates

E31(M1) 98.7/4.9 X500

" 4 Filaments; Easdale Slates

E31(M1) 104.4/10.1 X500

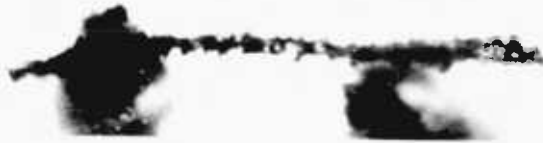
Plate 19



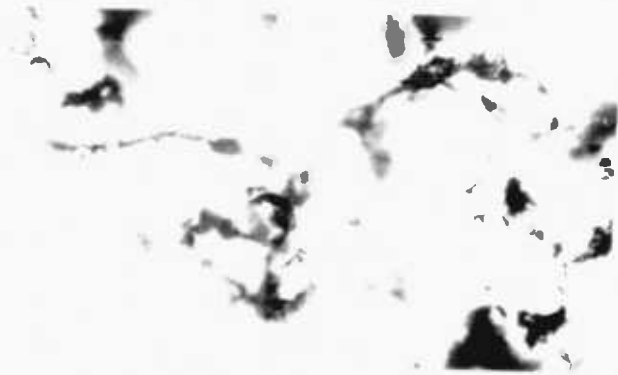
1



2



3



4

APPENDIX

Geographic and Stratigraphic
Localities of Samples.

SERIES 'B'

1	Easdale Slates (basal)	Glen Orchy, S side of river, 50 m. N of stone bank, S of Garbh Eilean.	
2	"	S bank River Orchy at An Grinau	
3	?Corsier Grit	Loch Nant, S side of road, W of spot height 488, in small quarry	NN 024238
4	Tayvallich Slates and Limestones.	250 m. N of track junction S of Loch An Leiod	NN 014240
5	"	"	NN 014240
6	Not Collected		
7	Tayvallich Slates and Limestones	On track in forest near Bealach Mor (L. Nant)	NN 013233
8	"	50 m. S of 2nd right angled bend to W, North of Barr nan Broanan, on R, Berchan.	NN 001215
9	Kilchrenan B.B.	E of Spot Height 619' on R. Berchan	NN 011221
10	"	"	NN 011221
11	Appin Phyllites	E side A 828 opposite Keil	NM 973537
12	"	$\frac{1}{4}$ ml. N of bridge at Dalmatrat (A 828)	NM 969534
13	"	$\frac{1}{2}$ ml. S of bridge at Dalmatrat	NM 962526
14	"	A 828 at large road cutting, $\frac{3}{4}$ ml. S of Bocaldine.	NM 952414
15	"	"	NM 952414
16	"	"	NM 952414
17	"	"	NM 941410
18-21	Not Collected		
22	Easdale Slates	Ardmucknish Bay	NM 902381
23	"	"	NM 902383
24	Appin Limestone	Cuil Bay 400m. from nose of Rudha Mor (S side)	NM 965557
25	Transition Beds	100 m. SW of S end of shingle promintory. WSW of Buck Settlement Cuil Bay.	NM 971565
26	"	600 m. SW of Buck Settlement Cuil Bay	NM 972565
27	Cuil Bay Slates	Cuil Bay. 1st exposure from N end	NM 976554
28	"	40 m. SW of Fisherman's hut	NM 975554
29	"	Cuil Bay W side of Rudha Bage	NM 975554
30-32	Not Collected		
33	Transition Beds	900 m. NE of pile of stones Rudha Mor	NM 966562
34	"	950 m. NE "	NM 976563
35	"	300 m. SW of S end of pebble bed SW of Buck Settlement	NM 969565
36	Ballachulish Slates	Main Ballachulish Quarry, E side, 100 m. from gate.	NN 085 584

37	Ballachulish Slates	Ballachulish Main Quarry E side, opposite track junction	NN 085584
38	"	Ballachulish Main Quarry 50 m. E of track junction	NN 085584
39	"	Main Quarry, 100 m. E of track junction	NN 086584
40	"	Main Quarry, 200m. E of track junction	NN 087584
41	"	SE corner of Easterly of two small quarries W of Ballachulish	NN 074583
42	"	SW corner "	NN 074583
43	"	W face of Westerly of two small quarries.	NN 073583
44	"	$\frac{1}{4}$ ml. E of Glencoe Village on the old road.	NN 106588
45	Transition Beds	River Laroach, 25 m. upstream from bridge at Ardarroch Guest House.	NN 082580
46	Appin Quartzite	R. Laroach, 20 m. " "	NN 082580
47	Transition Beds	" 70 m. " "	NN 082580
48	Binnein Schists	A 82, S side L. Leven, $\frac{1}{2}$ ml. W of Kinlochleven.	NN 175617
49	Transition Beds	R. Laroach, E bank due W of Roman Catholic Chapel.	NN 082579
50	Appin Phyllite	R. Laroach, 40 m. upstream from 1st stream draining Tiger Rock quarry	NN 082572
51	"	R. Laroach, 40 m. downstream from "	NN 082573
52	"	R. Laroach, 100 m. upstream " "	NN 082572
53	Transition Beds	" at 1st small stream, W side of R. Laroach, N of Allt Socaigh	NN 083568
54	Ballachulish Slates	R. Laroach, 100 m. N of N end of small island, just N mouth of Allt Socaigh	NN 083568
55	"	100 m. upstream from mouth of Allt Socaigh	NN 084566
56	"	70 m. " "	NN 083566
57	Not Collected		
58	"	Allt Socaigh, 300 m. upstream from mouth	NN 085565
59	"	350 m. " "	NN 085565
60	"	Allt Socaigh, 100 m. downstream from 1st stream flowing in from E	NN 085565
61	"	Boat house, S side L. Leven	NN 100539
62	Macduff Slates	Macduff harbour	NJ 705649
63	"	" 50 m. E of E end of dry dock	NJ 706649
64	"	" W end of old quarry	NJ 716649
65	"	" 200 m. E of W end of old quarry	NJ 717649
66	"	" 50 m. E of quarry access road	NJ 717649
67	"	" 50 m. E of E end of old quarry	NJ 717649
68	"	" 70 m. E of W end of swimming pool buildings	NJ 719646
69	"	" 40 m. W of swimming pool	NJ 720647
70	"	" Bay of Cullen	NJ 923647
71	"	" W side of harbour	NJ 701646
72	Ballachulish Slates	W of Onich Service Station	NN 047611
73	"	50 m. W of Onich Service Station	NN 047611
74	"	300 m. W of Cuilcheannan House	NN 014616
75	"	E edge Duror Forest 2nd stream E, 100 m. above contact	NN

SERIES 'D'

1	Mull of Oa Phyllites	W of Mull of Oa	NR 268416
2	"	"	NR 268416
3	"	"	NR 268416
4	" (upper)	"	NR 268417
5	Islay Limestone	N of Port nan Gallan	NR 278413
6	Mull of Oa Phyllites		
7	Rubha Gaidnealach Phyllites	N of Kilchiaran Bay	NR
8	Moire Phyllites	$\frac{3}{4}$ km. N of Kilchiaran Bay	
9	Not Collected		
10	Kilchoman Phyllites		
11	Smaull Greywacke		
12	"		
13	Cosprig Grit		
14	"		
15	"		
16	Sanaigmaore Grit		
17	"		
18	Mullach Dubh Phyllites	Esknish Quarry	NR 373648
19	Bonahaven Shale	S side Bonahaven Bay	NR 422733
20	Crinan Grit	Quarry E of Cnoc Reanhor	NR 783915
21	Tayvallich Slates and Limestone	N of Crinan	NR
22	"	Tayvallich Peninsula, W of L. Sween	NR 804976
23	"	" "	NR 804976
24	Tayvallich Green Pelitic Schist	"	NR 715853
25	Shira Limestone	Loch Pearsen	NM 855134
26	Easdale Slates	Railway Cutting, Benderloch	NM 902383
27	"	" "	NM 902383
28	"	Ardmucknish Bay	NM 902379
29	"	Esadale Village	NM 747174
30	"	Clachan Bridge, Seil	NM 385197

SERIES 'E'

1	'Lower Fine-grained Quartzite'	500 m. N of Caol Ila Distillery	NR 429703
2	"	30 m. S of small stream	NR 428704
3	"	First heavily wooded bay N of Caol Ila Distillery	NR 426206
4	"	"	"
5	"	"	"
6	"	"	"
7	"	50 m. N of Na Feamindean	NR 439708
8	"	100 m. N of Na Feamindean	NR 439708
9	"	300 m. S of stranded ship on Bonahaven promintory	NR 424728
10	"	100 m. N of promintory (on track)	NR 424728
11	"	" (on shore)	NR 424728
12	Dolomitic Beds	Bonahaven Bay, 88 m. from gate in distillery wall, bearing 110° from N end of jetty	NR 423733
13	"	"	"
14	"	"	"
15	"	"	"
16	"	"	"
17	"	"	"
18	"	On A 846, 20 m. E of Spot-height 174'.	NR 420687
19	Port Askaig Tillite		NR 431696
20	"Lower Fine-grained Quartzite"	On last bend of road before Bonahaven Distillery	NR 418734
21	"	Above three abandoned huts	NR 419734
22	"		NR 428704
23	"	250 m. S of Na Feamindean	NR 439706
24	Dolomitic Beds	At stranded ship on Bonahaven promintory	NR 423733
25			
26			
30	Easdale Slates	Kerrera. First outcrop S of ferry	NM 829286
31	"	" SE side Pt. a' Bhearnaig, 50 m. from N end of exposure.	NM 841313
32	"	Kerrera. 300 m. S of S end Pt.a' Bhearnaig	NM 841310
33	"	Kerrera. ½ km. E of N end Rudha' Ardan Duire	NM 836306
34	"	"	"
35	"	Kerrera SE side Eilean Dransaig	NM 739265
36	"	Easdale Village, 60 m. E of large dyke	NM 747173
37	"	" " 50 m. "	NM 747173
38	"	" " 100 m. "	NM 747174
39	"	" " " "	"
40	"	" " 100 m. E of most easterly of new houses	NM 747174
41	"	Easdale Village, 100 m. E of road junction to Dunmore House	NM 753169
42	"	70 m. from E end Port a' Mhuillinn	NM 753198
43	"	250 m. S of house at E end Port a' Mhuillin.	NM 753196
44	"	S end of islet group	NM 752196
45	"	Opposite N end of Henderson Island	NM 750160

46	"	S end of Henderson Island	NM 1749159
47	"	At N mouth of Cuar Sound	NM 750149
48	"		
49	"		
50	"		NM 773155
51	"	S end of Balvicar Bay	NM 774167
52	"	NW corner of Balvicar Bay	NM 773177
53a	"	N end of Balvicar Bay	NM 774176
53b	"	30 m. S of Clachan Post Office on E. 8003	NM 780185
54	"	Kerrera. On promintory at S end of Little Horseshoe Bay	NM 818273
55	"	" "	NM 818273
56	"	" "	NM 818273
57	"	Kerrera. Port an t' Strurhain	NM 817270
58	"	Kerrera. Opposite S island of Sgeirean Dubh	NM 814265

SERIES 'HB'

1	Dunoon Phyllites	SW Cowal 100 m. N of school	NS 093732
2	"	" 100 m. S of school	NS 093730
3	"	" 130 m. S of school	NS 093730
4	"	" S of Schoolhouse	NS 084722
5	"	" "	NS 084722
6	"	" "	NS 084722
7	"	" 300 m. N of refuelling station	NS 095717
8	"	" 250 m. N "	NS 095717
9	"	" At northern docking point, N of refuelling station	NS 095715
10	"	" "	NS 095715
11	"	" 40 m. N of refuelling station	NS 095712
12	"	" At northerly of two docking points, S of refuelling station.	NS 095711
13	"	" Immediately N of Craig na Calliche	NS 094707
14	"	" Craig na Calliche	NS 094706
15	"	"	NS 094703
16	"	" Castle gate,	NS 114677
17	"	" 100 m. S of Sailing Club	NS 114677
18	"	" Close to small roadside house	NS 118676
18a	"	"	NS 115677
19	"	" Close to small roadside house	NS 118676
20	"	"	NS 116747
21	Highland Border Series	Jahu's (1926) Conduit Locality	NN 484979
22	" (Shales and Cherts)	Loch Ard Forest	NN 498988
23	"	"	NN 438988
24	Aberfoyle Slates	Aberfoyle Quarry, W side	NN 505032
25}	Leny Limestone and	Leny Limestone Quarry	NN 616099
26}	Shale		
27}	Leny Limestone and	Keltie Water	NN 645126
28}	Shale		
29}	Leny Limestone and	"	NN 645126
30}	Shale		
31	?Leny Grits	Keltie Water, 3rd stream S of ford	NN 646126
32	?Leny Grits	"	NN 646126
33	Birnam Slates	S of Dunkeld	NO 040410
34	Margie Grits and Slates	River N. Esk	NO 592727
35	"	"	NO 592727
36	Gp. 5 Durness Lst.	Durness, W of Loch Caladail	NC 394665
37	Aberfoyle Slates	Aberfoyle Quarry	NN 505032
38	Cnoc Donn Slates	Islay, 300 m. NE of Dun Rosebridge	NR 373606
39	Dunoon Phyllites	SW Cowal 150 m. N of refuelling station	NS 095715
40	Crinan Grit	Tayvallich Peninsula, Port Bealach nan Gall	NR 713853
41	"	" "	NR 713853
42	Not Collected		
43	Crinan Grits	Tayvallich Peninsula, 100 m. S of Port Bealach nan Gall	NR 713853
44	Tayvallich Slates and Limestones	1/2 ml. S of Port Bealach nan Gall	NR 712852

45	Tayvallich Slates and Limestones	South of Port Bealach nan Gall	NR 711850
46	"	"	NR 710849
47	"	"	NR 709848
48	Crinan Grit/ Tayvallich Limestone boundary	Kilmartin 2km. SSE of Loch an Fearphian	NM 836029
49	Crinan Grits	" NW corner Lochan Druim an Rathord	NM 825037
50	Port nan Gallan Phyllites	Islay, NW corner Lochan Dubh	NR 419592
51	"	" Lochan an Beinn Bhan	NR 392564
52	Kintra Phyllites	Islay	NR 387574
53	?Baharradail Phyllite	" NE Loch Baharradail	NR 397638
54	Cnoc Donn Slates	" NE of Dun Rosebridge	NR 373606
55	Jura Slates	" Port Ellen Lighthouse	NR 348445
56	?Scarba Conglomerate	" S of Port Ellen Lighthouse	NR 347443

B: Stratigraphic Locality;

FORMATION	SAMPLE No.		
Highland Border Series	HB 21	Easdale Slates cont.	E 41
	HB 22&23		E 40
	PL 4		E 38&39
			E 36
Upper Leny Grits			E 37
Leny Limestone and Shale	HB 25&26	Islay Quartzite	
	HB 27&28	Bonahaven Dolomite	E 12-16
	HB 29&30		E 26
	HB 31		E 24
	HB 32	Port Askaig Tillite	E 10&11
Lower Leny Grits			E 8
Aberfoyle Slates	HB 24		E 9
	HB 53		E 7
Birnam Grit			E 4-6
Kilchrenan Conglomerate	B 8		E 3
Tayvallich Slates and	B 7		E 23
Limestone	B 5&6		E 2
	B 9&10		E 1
	HB 47		E 22
	HB 46		E 20
	HB 45		E 19
	HB 44	Lismore Limestone	
Crinan Grits	HB 43	Cuil Bay Slates	B 27
	HB 48		B 28
	HB 49		B 29
	HB 41		B 30
	HB 50	Appin Phyllite	B 12
Ardrishaig/Craignish			B 11
Phyllites			B 13
Easdale Slates	B 18-23		B 14
	E 31		B 15
	E 32		B 16
	E 33		B 17
	E 34		B 52
	E 30		B 51
	E 56&60-65	Appin Quartzite	
	E 66	Transition Beds	B 31
	E 59		B 32&50
	E 57		B 49
	E 58		B 47
	E 50		B 46
	E 49		B 45
	E 48		B 26
	E 51		B 33
	E 53a		B 34
	E 53b		B 25
	E 52		B 35&53
	E 47	Ballachulish Slates	B 44&61
	E 46		B 74&76
	E 45		B 36&54
	E 43		B 43
	E 42		B 37&55
			B 38,42&56
			B 39,41&57
			B 40&58
			B 49
			B 60

Appin Group on Islay

FORMATION	SAMPLE No.
Islay Limestone	
Mullach Dubh Phyllites	HB 50
	HB 51
Ballygrant Limestone	
Baharradail Phyllite	HB 53
Cnoc Donn Phyll/Lst.	
Cnoc Donn Quartzite	
Cnoc Donn Slates	HB 54
Kintra Limestone	
Kintra Phyllite	HB 52
Maol an Fhithich Quartzite	

Stratigraphic Localities of Samples from the Highland Border

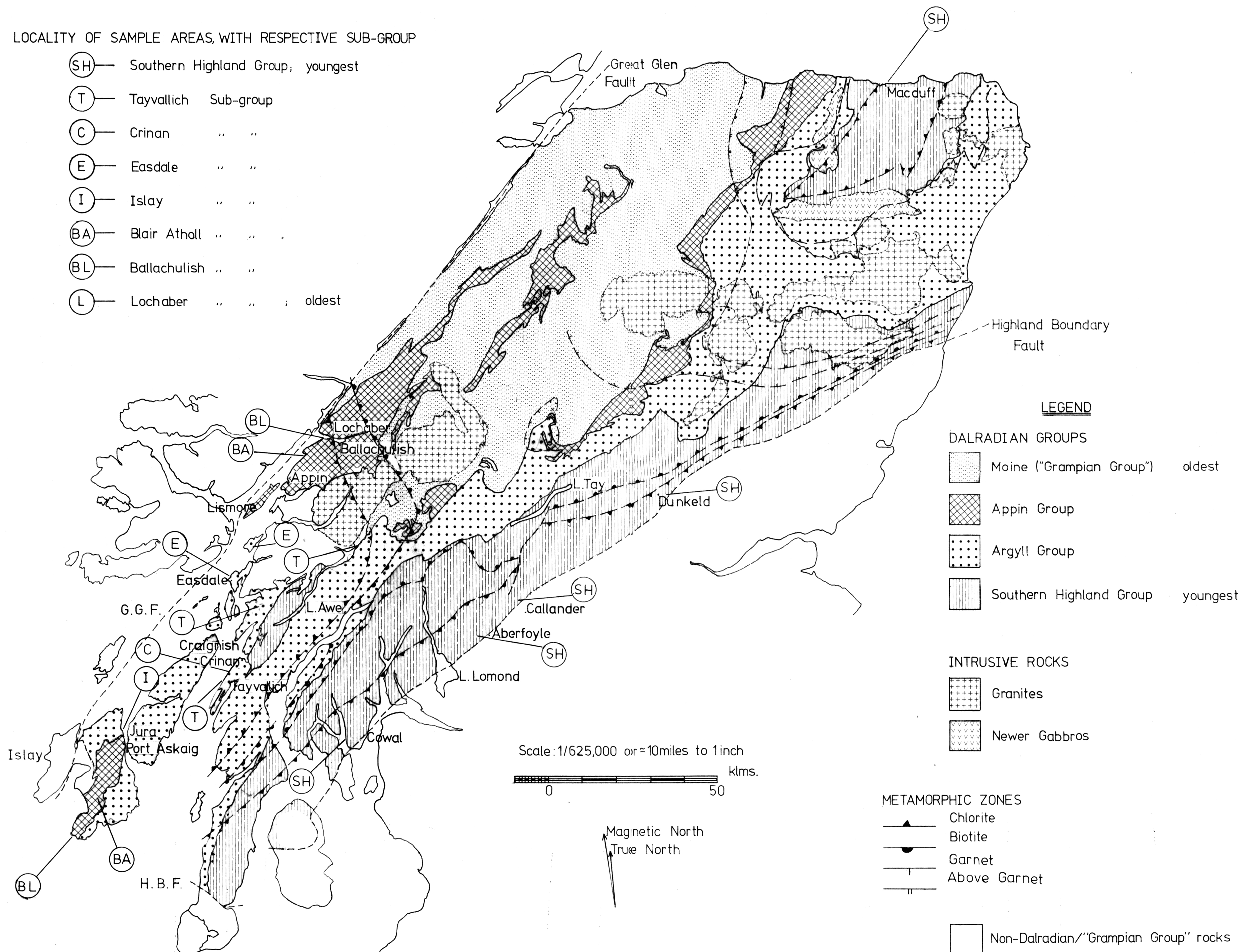
COWAL		ABERFOYLE		CALLANDER		DUNKELD
		Highland Border Series	HB 21			
			HB 22			
			HB 23			
			PL 1-4			
Beinn Bheula Schists		"Psammitic wacke"		Upper Leny Grits		Dunkeld Grits
Dun on Phyllites	HB 1	Aberfoyle Slates	HB 24			Birnam Slates
	HB 2		HB 37	Leny Limestone and Shale	HB 25&26	Birnam Grits
	HB 3				HB 27&28	
	HB 4				HB 29&30	
	HB 5				HB 32	
	HB 6			Leny Grits		
	HB 7			Aberfoyle Slates		
	HB 20					
	HB 8					
	HB 19					
	HB 16					
	HB 9					
	HB 18a					
	HB 10					
	HB 17					
	HB 11					
	HB 16					
	HB 12					
	HB 15					
	HB 13					
	HB 14					
Bullrock Greywacke						

THE DALRADIAN SUPERGROUP IN SCOTLAND, SHOWING THE DISTRIBUTION OF GROUPS, METAMORPHIC ZONES, AND SAMPLE AREAS.

MAP 1

LOCALITY OF SAMPLE AREAS, WITH RESPECTIVE SUB-GROUP

- (SH) — Southern Highland Group; youngest
- (T) — Tayvallich Sub-group
- (C) — Crinan " "
- (E) — Easdale " "
- (I) — Islay " "
- (BA) — Blair Atholl " "
- (BL) — Ballachulish " "
- (L) — Lochaber " " ; oldest



MAP 2

