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Braley , Sharon Mary

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University of Plymouth

The Sedimentology, Palaeoecology and Stratigraphy of Cretaceous Rocks in N.W. Scotland.

by

Sharon Mary Braley.

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Sharon Mary Braley.
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Abstract.

Sediments of Cretaceous age in N.W. Scotland outcrop in small, often isolated exposures throughout the Inner Hebrides and Morvern, and have been dealt with cursorily in most previous work on the Cretaceous rocks of Britain. The aims of this study were (i)to propose a formal integrated stratigraphic scheme for the Cretaceous strata of N.W. Scotland and (ii)to model the development of the Inner Hebrides Basin (where these strata outcrop) during the Cretaceous Period. Detailed field observations, macro- and micro-palaeontology (including palynology), sedimentology and structural data were integrated in an attempt to achieve these aims. Fieldwork was conducted in Morvern (Argyll) and the Inner Hebridean islands of Mull, Eigg and Skye.

In the proposed lithostratigraphy the Morvern Greensand becomes the Morvern Greensand Formation, of which the former "Lochaline Glass Sand" or "Loch Aline White Sandstone" becomes the Lochaline White Sandstone Member. The overlying silicified chalk, outcropping in Morvern and Mull, becomes the Gribun Chalk Formation. Dark grey micritic limestone, previously undifferentiated from the silicified chalk, becomes the Strathaird Limestone Formation of which there are two clastic members: the basal Laig Gorge Sandstone Member and the Clach Alasdair Conglomerate Member. The "Upper Estuarine Series" of Judd (1878), becomes the Beinn Iadain Mudstone Member of which there is a coarser clastic member: the Feorlin Sandstone Member. These Formations comprise the Inner Hebrides Group.

Biostratigraphic evidence (based primarily on dinoflagellate cysts and foraminifera) indicates a latest-Albian to Mid-Cenomanian age for the Morvern Greensand Formation; a Late Cenomanian age for the Gribun Chalk Formation, and an Early - Middle Turonian age for the Strathaird Limestone Formation. The most refined biostratigraphical range for the Beinn Iadain Mudstone Formation was Albian to Palaeocene.

The Mid-Late Cretaceous development of the Inner Hebrides Basin includes two periods of major transgression, the first of which began in the latest Albian and continued through the Early Cenomanian with the deposition of the marginal clastic facies of the Morvern Greensand Formation. A minor period of regression preceded the onset of carbonate deposition in the Late Cenomanian, recorded in the Gribun Chalk Formation. A second major transgressive episode followed the silicification, uplift and erosion of the Gribun Chalk, and reflects rapid deepening of the basin during the Early to Middle Turonian, poorly sorted clastic sediments (the Laig Gorge Sandstone Member) being overlain by biomicritic limestones intercalated with debris flows (the Strathaird Limestone Formation).

These two major transgressive episodes are marked by the deposition of similar lithofacies throughout N.W. Europe (although no in situ deposits of Turonian age are found in Northern Ireland). Some features of the Cretaceous sediments of N.W. Scotland are found elsewhere, for instance the high abundance of calcispheres and organic-rich nature of the Strathaird Limestone are typical features of the Early Turonian transgressive episode in the Anglo-Paris Basin. However, in the Inner Hebrides Basin, these eustatic changes in sea level were imposed upon local tectonic movements as indicated by the weathering and erosion of the silicified Gribun Chalk prior to the deposition of the Strathaird Limestone Formation, and the debris flow events, apparently related to synsedimentary movements along the Camasunary Fault, recorded within that Formation.

Declaration:

This is to certify that the work submitted for the Degree of Doctor of Philosophy under the title "The sedimentology, palaeoecology and stratigraphy of Cretaceous rocks in N.W. Scotland" is the result of original work.

All authors and works consulted are fully acknowledged. No part of this work has been submitted for any other degrees and is not being concurrently submitted in candidature for any other degree.

Candidate

S.M. Braley

Research supervisor

Prof. M.B. Hart

Chalk clasts in basalt overlying Strathaird Limestone, Auchnacraig Cliff, Mull.

"That during all geological periods from the Carboniferous to the Cretaceous inclusive, a very large part of the Highland district was submerged and formed areas of deposition, I think it is impossible to doubt . . .

"It is clear, from the abundance of chalk-flints in certain Miocene inter-volcanic deposits . . . that very extensive masses of Chalk must have been destroyed by denudation in order to supply the quantities of flints accumulated in these deposits. It is probable, indeed, that very considerable masses of strata of Cretaceous age still exist buried under the great lava plateaux of Mull and Morvern."

Judd, 1878, pp.670 & 728.

Acknowledgements:

First to Blob, who supported me emotionally and financially during the course of this research. Also to my other friends who endured (and enjoyed) fieldwork in some of the wilder areas of Morvern and the Inner Hebrides (in some of the wilder weather): Shirley Braley, Kate Lock, Pam Painter and Steve Caswell. Heartfelt thanks go also to the many Highlanders and Islanders that I met during the fieldwork, in particular to Donald and Maggie Kennedy of Doire na Mairst, Morvern; Maggie of Fiunary; the MacFadyens of Balmeanach Farm, Mull, and the people of Cleadale, Eigg. Steve and Pam also provided me with a bed in Plymouth during the final, nomadic, stage of the work, as did Mark Alex-Sanders and Anne.

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Prof. John Hudson of Leicester University kindly provided me with some samples from the Clach Alasdair section, Eigg, and Ken Dorning (PalLab Research) and Geoff Wilkinson (Unocal) lent palynological slides from Claggan, Morvern.

Chevron (U.K.), the British Micropalaeontological Society and Polytechnic South West contributed towards fieldwork expenses, all of which was greatly appreciated.

I am much indebted to Prof. M.B. Hart who provided vital support throughout the three years and identified most of the foraminifera. Also sincere thanks to Ailbhe Duane and Meriel Fitzpatrick who helped with the palynology, and provided continual encouragement and support as did the other geology post-graduates passing through Polytechnic South West during the last three years.

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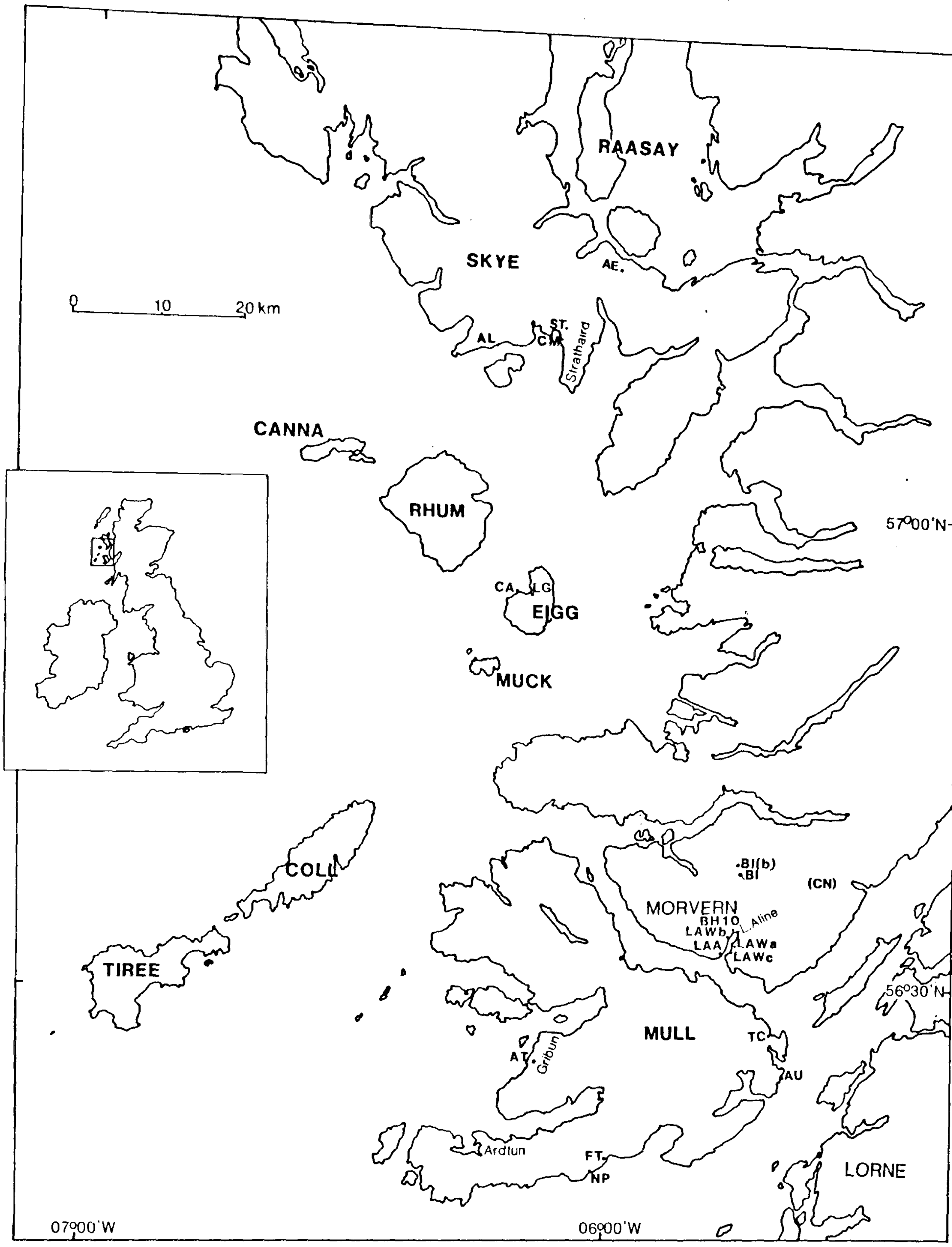
Chapter 1: Previous research and lithostratigraphy.

1.1 Introduction.

Rocks of Cretaceous age occur in widely scattered and generally poorly exposed outcrops within the Inner Hebrides area (see Fig.1.1). Sections in Mull and Morvern were discovered and described by J.W. Judd in the 1870's (Judd, 1872; 1878); later, lithologically similar deposits on Eigg, Skye, Raasay and Scalpay were also assumed to be of Cretaceous age (Lee & Pringle, 1932). However, due to the nature of the outcrop and the rarity of stratigraphically significant macrofossils, correlation of the sections based on a comprehensive stratigraphical study of the succession was never attempted, members of the Geological Survey of Scotland returning to Judd's original work in Morvern as the basis of their lithostratigraphy of Cretaceous rocks in the Hebrides (e.g. Clough *et al.*, 1909; Bailey, 1920; Bailey *et al.*, 1924; Lee & Bailey, 1925). This chapter comprises a review of previous research into the Cretaceous rocks of the Hebrides (Section 1.2), followed by a discussion of the inherent problems and aims of this study (Sections 1.3 & 1.4). The inadequacies of the previous lithostratigraphic schemes for the Cretaceous strata of N.W. Scotland are discussed in Section 1.5 and a new lithostratigraphic scheme is proposed.

1.2 Previous research.

Although the existence in the Hebrides of "more or less isolated patches of limestone, sandstone and shale, frequently



Key to sections:

BI - Beinn Iadain Section A

BI(b) - Beinn Iadain Section (b)

LAW(a-c) - Loch Aline Waterfall (a) (b) (c)

LAA - Loch Aline Adit	CA - Clach Alasdair
TC - Torosay Castle	LG - Laig Gorge
AU - Auchnacraig Cliff	CM - Camasunary
FT - Feorlin Tributary	ST - Strathaird
AT - Allt na Teangaidh	AL - An Leac
NP - Nuns Pass	AE - Allt Eoghainn

Fig.1.1 Locality map.

containing fossils, interposed between the gneissic and volcanic rocks of the region" was known in the eighteenth century (Macculloch, 1819; Judd, 1878), it was the latter who first recognized the glauconitic sandstones and silicified limestone of Morvern and southern Mull as being of Late Cretaceous age (Judd, 1872). Judd also recognized the significance of the relationship between what he had classified as Lower and Upper Chalk (*sensu* Dowker, 1870), and the underlying Jurassic, Permo-Triassic and Moinian rocks, interpreting the unconformity as evidence of considerable uplift and denudation within the Mesozoic itself (Judd, 1878, p.743). The role of the overlying Tertiary basalts in the preservation of the Mesozoic sediments was demonstrated in a generalized cross-section of Morvern (*op cit.*, p.743), and the surviving "Secondary" strata graphically described as being comparable to "the little bits of paper that would escape being washed away if a newspaper with a number of stones on it were laid in a running stream" (Sir Henry James, cited by Judd, 1878, p.667).

Judd's lithostratigraphic division of the exposure at the south-eastern corner of Beinn Iadain, Morvern, is summarized below (for comparison with later stratigraphic schemes see Fig.1.2):

--- --- --- --- --- ---

Table 1.

Miocene basalts.

(1) Upper estuarine series: interbedded carbonaceous sandstones and marl with plant remains.

(2) Upper Chalk (marine): band of weathered chalk flints underlain by highly siliceous white chalk.

(3) Lower estuarine strata: sandstone, including coarse

white sands becoming glauconitic at the base.

(4) Upper Greensand: glauconitic calcareous sands, in places highly fossiliferous.

(From Judd, 1878, p.736).

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Judd noted the petrological similarities between the glauconitic sandstone at the base of this section, the Upper Greensand in southern England and the Hibernean Greensand in Antrim. The Cenomanian age of the Hebridean greensand could be broadly supported by palaeontological evidence, the lack of an ammonite fauna being interpreted as an indication of shallow water conditions (*op cit.*, p.729).

Later work on the greensand in the Hebrides area consists largely of redescriptions of the Mull and Morvern sections, based on Judd's original work with little attempt at correlation between sections (e.g. Clough *et al.*, 1910; Bailey *et al.*, 1920; Bailey *et al.*, 1924; Lee & Bailey, 1925; Scott, 1928; Lee & Pringle, 1932; Richey, 1961; Rawson *et al.*, 1978; Hudson, 1983)(see Fig.1.2). The better exposed sections were identified as being of Cenomanian age on the macrofauna (including an ammonite, *Schloenbachia intermedia* (Mantel), from Loch Don, Mull (Lee & Bailey, 1925)), but smaller, unfossiliferous exposures of glauconitic sandstone were sometimes "assigned to the Cretaceous" on lithology alone (see Lee & Bailey, 1932, p.223; Hudson, 1983, p.59).

The Lochaline White Sandstone overlying the greensand in Morvern and Mull was interpreted by Judd as an estuarine deposit, based upon (i) the apparent presence of "much carbonaceous matter . . . and at one point a seam of coal" and (ii) the "relations to the marine series" i.e. the underlying greensand and overlying chalk (Judd, 1878). This "Lower Estuarine Series" was assigned to the Upper Chalk (*Belemnitella mucronata* zone) (*op cit.*) but is overlain in one locality by a clay horizon which contains a macrofauna diagnostic of a Cenomanian age (Jeans, cited by Rawson *et al.*, 1978)(See Fig.1.2).

Perhaps because of its economic importance to Morvern, (the Lochaline White Sandstone has been mined as a glass sand since 1914 (Anderson, 1941), at present by Tilcon (Scotland) Ltd.), the Lochaline White Sandstone has been subject to more research than any other unit of Cretaceous age rocks in Scotland. Following fieldwork executed for the Geological Survey of Scotland between 1920 and 1924, came the hypothesis that the Lochaline White Sandstone represented a "desert sandstone blown into the sea" (Bailey, 1924, p.107), thus providing "evidence" that the "Chalk seas . . . owed much of their clarity to their situation in a geographical belt where matured desert figured as the typical associated continental form." (*op cit.*, p.102). This idea was quoted as recently as 1961 (Richey, 1961, p.38) and 1989 (Johnstone & Mykura, p.161), but, also in 1961, a detailed petrological study of the Lochaline White Sandstone was published, (Humphries, 1961), which argued convincingly towards a re-interpretation of the unit as a high-energy, shallow water facies of the greensand where constant reworking resulted in "thorough removal of the soluble and less stable constituents" (*op cit.*, p.70)(see Section 6.3.i.). Only one fossil has been described in detail from the Lochaline White Sandstone: this was the impression of a starfish found by some miners working in the Lochaline sand mine (MacLennan, 1949). A

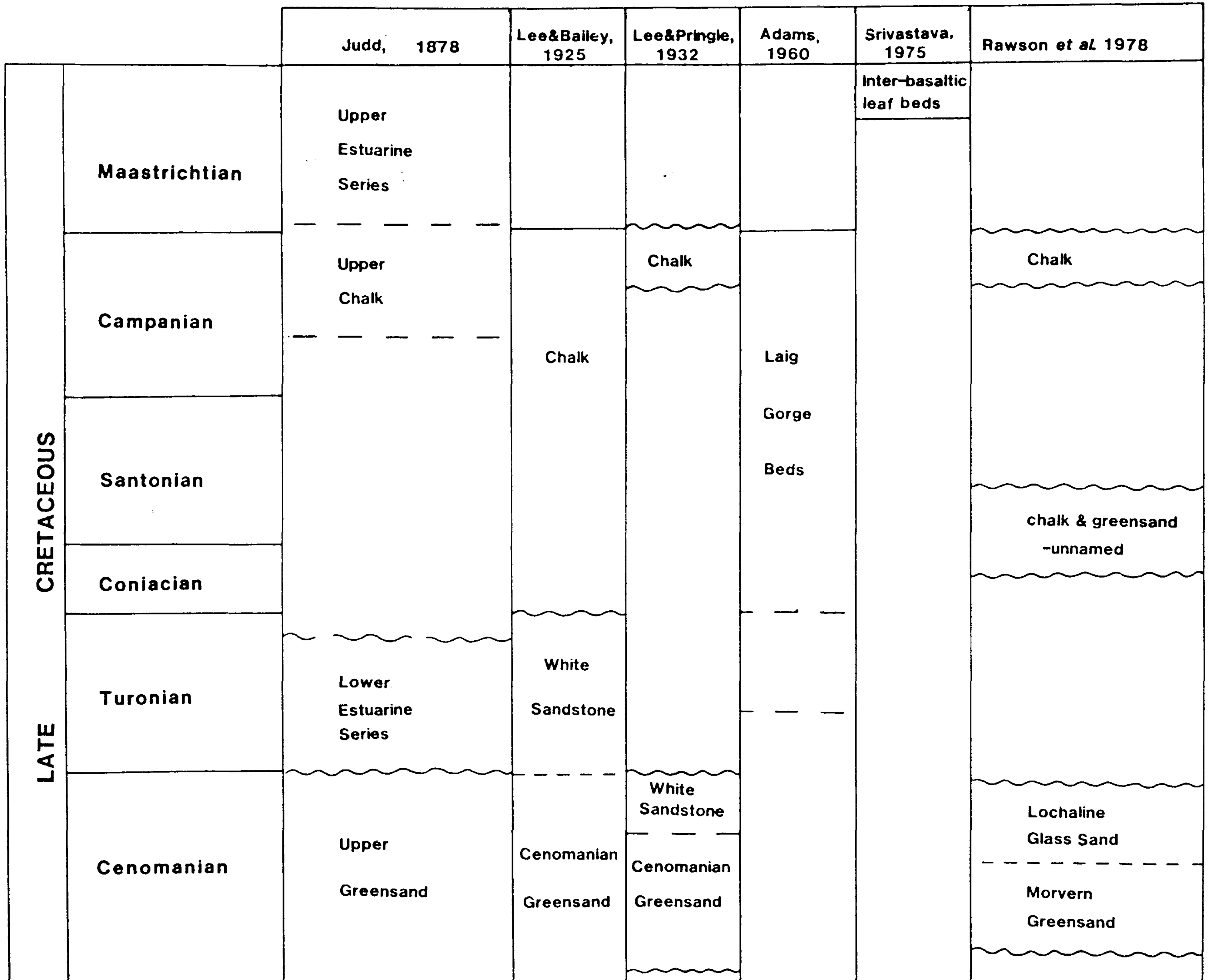


Fig.1.2 Previous lithostratigraphic nomenclature for the Cretaceous strata of N.W.Scotland.

few "indeterminate marine shells" were collected from the less pure Lochaline White Sandstone found on Beinn Iadain, Morvern, (Bailey *et al.*, 1924), but otherwise the unit appears to be essentially unfossiliferous.

Silicified white limestone was described from Gribun and Carsaig, Mull, by Judd in addition to the Beinn Iadain section (Morvern) which was used as the main reference section (Judd, 1878). This silicified limestone has been loosely termed "chalk" since the original description, but the primary structure of the matrix material has been overprinted by the processes of silicification. Foraminifera, inoceramid prisms and sponge spicules remain recognizable however, and were described from thin sections of silicified chalk samples from Carsaig and Gribun, Mull, and Beinn Iadain, Morvern (Rupert-Jones in Judd, 1878). From these, and the occurrence of *?Belemnitella mucronata* (Schlotheim) in the silicified chalk at the east end of Beinn Iadain, the silicified limestone of the Hebrides was correlated with the Upper Chalk of Southern England (Judd, 1878) (See Fig.1.2).

These same thin sections were later re-examined, along with new samples from Clach Alasdair, Eigg; Strollamus, Skye; Ballymichael, Arran and Bealach Ban, Scalpay (Hill, 1915). This study revealed little more micropalaeontological information than Rupert-Jones' original work, other than resulting in the correlation of the limestones of Eigg and Skye with the Upper Chalk of Southern England (*op cit.*). Therefore, from 1915, the dark grey micritic limestones of Skye, Eigg and Mull were considered to be "representative" of the silicified "Senonian Chalk" found in Mull and Morvern (Lee & Bailey, 1925, p.120).

The sediments that unconformably overlie the silicified chalk or greensand within the Inner Hebrides are highly variable in lithology and their true stratigraphic position is often difficult to ascertain. There are two main divisions of these post-chalk to inter-basaltic sediments in the Hebrides: a) micritic limestones and sandstones, sometimes containing silicified chalk clasts and b) inter-basaltic conglomerates, sandstones and lignites including the "Ardtun Leaf Beds" (see Macculloch, 1819; Argyll, Duke of, 1851; Bailey *et al*, 1924; Seward & Holttum, 1924).

The micritic limestones and conglomeratic sandstones of Mull, Eigg and Skye, have largely been overlooked in the literature since the micropalaeontological work by Hill, described above. A brief description of sections on Mull is given in the "Post-Tertiary Memoir for the Mull, Lochaline and Oban area" but these were still correlated with the "Senonian Chalk" (Bailey *et al*., 1924). The Laig Gorge section, Eigg, was, however, described in detail by Hudson (1960), and further investigation of the slides originally described by Hill, from Eigg, plus some new samples, reinforced evidence for the dating of these sediments as Late Cretaceous (Adams, 1960; Hudson, 1960).

Directly overlying the silicified chalk at the Beinn Iadain section, Morvern, Judd noted a "band of weathered chalk flints" (Judd, 1878, p.736). These silicified chalk and flint pebbles actually form clasts in a thin conglomeratic horizon identical in facies to beds at Clach Alasdair, Eigg, and Strollamus and Strathaird, Skye, where silicified chalk and flint clasts are found in a dark grey micritic limestone matrix containing a Late Cretaceous microfauna (Hill, 1915; Adams, 1960), as discussed above.

Included in Group (a) is a small succession of interbedded organic rich "marls" and micaceous sandstones, described by Judd as the "Upper Estuarine Series" (the "Lower Estuarine Series" being the "White Sandstone")(Judd, 1878). These sediments contain no macrofosils apart from some poorly preserved plant material, and consequently their age is uncertain; although Judd regarded them as probably representing "Cretaceous . . . younger than any part of the Chalk of the British Isles", he admitted that: "they may hereafter be proved to belong to the period between the Cretaceous and the Eocene, to the latter formation itself, or even to the Miocene" (Judd, 1878, pp.736-737). Bailey *et al.* (1924), considered similar sandstones, (which overlie silicified chalk at Gribun, Mull, and greensand near Loch Don, Mull,) to be Tertiary in age because of the marked erosion surface between the known "Cretaceous" beds and the unfossiliferous sandstones overlying them (Bailey *et al.*, 1924, p.54).

Directly underlying the basal Tertiary basalt in most of the sections described from Mull and Morvern, is a red-brown mudstone which has been interpreted as a weathered basaltic ash (Judd, 1874; Bailey *et al.* 1924).

Radiometric dating prior to 1986 put the start of volcanism in the British Tertiary Igneous Province (B.T.I.P.) "at or just before 65-66 m.y., in the latest Cretaceous or earliest Palaeocene"(Evans *et al.*, 1973), putting the lowest inter-basaltic sediments of Mull and Ardnamurchan into the Maastrichtian. This was a major factor in the argument of Srivastava for a Cretaceous age for the Ardtun Leaf Beds, Mull, based on the occurrence of the

"Cretaceous" miospore genus *Aquilapollenites* Rouse emend.Funkhouser (Srivastava, 1975, p.16). However, the pre-1986 radiometric dates for the Hebridean basalts were not calculated using the decay constants recommended by Steiger & Jager (1977), and are therefore no longer considered to be reliable (Mussett, 1986). In addition, the miospore genus *Aquilapollenites* is not restricted to the Cretaceous, but ranges into the Early Eocene (Martin, 1961). Recent radiometric dates on Hebridean basalts indicate that lava extrusion began at 60 $\pm$ 0.5 Ma and continued until 57 $\pm$ 1.0 Ma (Mussett, 1986). Consequently, all the inter-basaltic sediments of the Hebrides area must be Palaeocene in age and cannot be either latest Cretaceous, as argued by Srivastava (1975), or Eocene, as proposed by Forbes, (1851), Seward & Holttum, (1924), and Simpson, (1961). Gardner (1887), considered the Ardtun (Mull) palaeoflora to be Early Eocene or older, but pointed out that the taxonomy of many fossil floras was, at the time, based on fragmentary and/or long-ranging forms which could have been placed equally in the Late Cretaceous, Eocene or Miocene (Gardner, 1887, p.298).

As this study is concerned with the Cretaceous rocks of the Hebrides, these inter-basaltic sediments will not be considered further.

1.3 Problems encountered in this study.

From the work described in Section 1.2, some inherent difficulties in the stratigraphical interpretation of many "Cretaceous" age sediments in the Hebrides area become apparent. These can be divided into (i) physical and (ii) historical problems.

1.3.i. Physical problems.

The major difficulty in attempting a detailed study of Cretaceous age rocks in N.W. Scotland is the lack of good exposure. As repeatedly pointed out by Judd (1878, pp.666-667), the mode of preservation of Mesozoic strata in the area has resulted not only in isolation of exposures, which are restricted either to the coast or to stream sections where the basalt cover and scree has been eroded, but also in contact metamorphism of some sections. Where the latter has affected the micritic limestones, the loss of much potentially useful palynological evidence has occurred (see Section 5.10). Silicification of chalk facies rocks and partial decalcification of much of the greensand has resulted in poor and possibly biased preservation of calcareous macro- and micro-fossils (see Sections 4.5 & 5.10). At least one phase of faulting following the basalt extrusion during the Tertiary has caused further complications in the stratigraphy since beds cannot be followed laterally, or extrapolated easily across distances of more than a few tens of metres. The poor exposure and faulting of the silicified chalk in Morvern has, for example, led to controversy over whether this unit is actually *in situ* (Gale, 1988, pers. comm.).

1.3.ii. Historical problems.

The nature of some of the previous work on Cretaceous rocks in N.W. Scotland (described in Section 1.2), has left a legacy of stratigraphical and semantic problems. Many small exposures of glauconitic sandstone in the Inner Hebrides have been correlated with the Cenomanian age greensand of Morvern on lithological grounds alone, yet part of the Jurassic succession in the area also comprises fine-grained, dark green, micaceous sandstone indistinguishable in the field from the Cretaceous greensand (e.g. the Lower Liassic Pabba Beds at Ardtornish Bay, Morvern). There is also confusion in the literature over the stratigraphical position of some of the "flint conglomerates" of the Inner Hebrides, with beds of the same facies being described as both "Tertiary" (e.g.Bailey *et al.*,1924; Lee & Bailey, 1925), and as "Cretaceous" in age (e.g.Judd, 1878; Hill, 1915; Lee & Pringle, 1932).

In his stratigraphical table (Judd,1878,p.737), Judd placed the "White Sandstone", the silicified chalk, and the sands and mudstones of the "Upper Estuarine Series" in the Chalk Formation, with the silicified chalk facies strata being correlated with the Upper Chalk. This precedent was followed by subsequent workers in N.W. Scotland who took the additional step of correlating the dark grey micritic limestones with the Upper Chalk, and then describing them as "chalk" (e.g.Hill,1915; Lee & Bailey,1925; Richey,1961; Rawson *et al.*,1978)(See Fig.1.2). Although demonstrably Late Cretaceous in age (Hill, 1915; Adams, 1960), these dark grey micritic limestones cannot be classified as true chalk facies beds (*sensu* Hancock, 1976), and should not, therefore, be described as "chalk".

1.4. Aims of this study.

The aims of the present work can be summarized as follows:

a) to erect a viable stratigraphic scheme for the

Cretaceous rocks of N.W. Scotland, combining a revised lithostratigraphy with biostratigraphical data based on macrofauna, foraminifera and palynomorphs (primarily dinoflagellate cysts). Such integrated work is necessary because of the variable preservation of the different lithostratigraphical units at different localities.

b) to gain a detailed understanding of the palaeoenvironment and palaeogeography of the Hebrides Basin through the Late Cretaceous, by integrating sedimentological, palaeontological and ichnological data.

c) by combining this sedimentological/palaeoecological model with published structural and geophysical data, to map the evolution of the Hebrides Basin from the Albian to the Palaeocene. Comparison with other similar marginal Cretaceous deposits in N.W. Europe will allow the Cretaceous development of the Hebrides Basin to be viewed in a regional context.

1.5. Lithostratigraphy.

As discussed earlier in this chapter (Sections 1.2 & 1.3), there is confusion over much of the lithostratigraphy of the Cretaceous age sediments of the Hebrides area. This has largely been generated by the physical difficulties of piecing together isolated, poorly exposed, sections comprising highly variable lithofacies, into a viable stratigraphical succession, but is partly due to the historical precedent set by Judd's "Third Paper" (1878) which has, essentially, never been superceded.

The historical lithostratigraphy as summarized in Fig.1.2 is therefore considered inadequate to encompass all the lithologies and complex lithofacies relationships existing in the Cretaceous succession of N.W. Scotland. Former lithostratigraphic schemes do not take into account the silicified chalk conglomerates found within the grey micritic limestone lithofacies, or the poorly sorted sandstones underlying this limestone, but instead tend to over-emphasize the status of the Lochaline White Sandstone lithofacies.

Here, a new lithostratigraphic scheme is proposed for the Cretaceous strata of N.W. Scotland (see Fig.1.3). The term "Inner Hebrides Group" is coined to cover all formations of probable Cretaceous age in N.W. Scotland.

The lower part of the succession, comprising the greensand and chalk lithofacies, is lithostratigraphically uncomplicated. The greensand, where fossiliferous, is easily recognizable as a unit, (although sedimentary facies may vary considerably between sections), and it therefore becomes the "Morvern Greensand Formation". Palaeontological evidence makes the Lochaline White Sandstone lithofacies contemporaneous with the upper part of the Morvern greensand (Jeans, cited by Rawson, 1978), in addition to lithostratigraphic evidence (glauconitic sandstones being found overlying the Lochaline White Sandstone), and this lithofacies accordingly becomes the Lochaline White Sandstone Member of the Morvern Greensand Formation. The type locality for the Morvern Greensand Formation is Beinn Iadain Section (A) and the type locality for the Lochaline White Sandstone Member is the Loch Aline Adit (LAA) section.

The silicified chalk with flints, which is unconformable on the Morvern greensand, is lithologically very distinctive, being

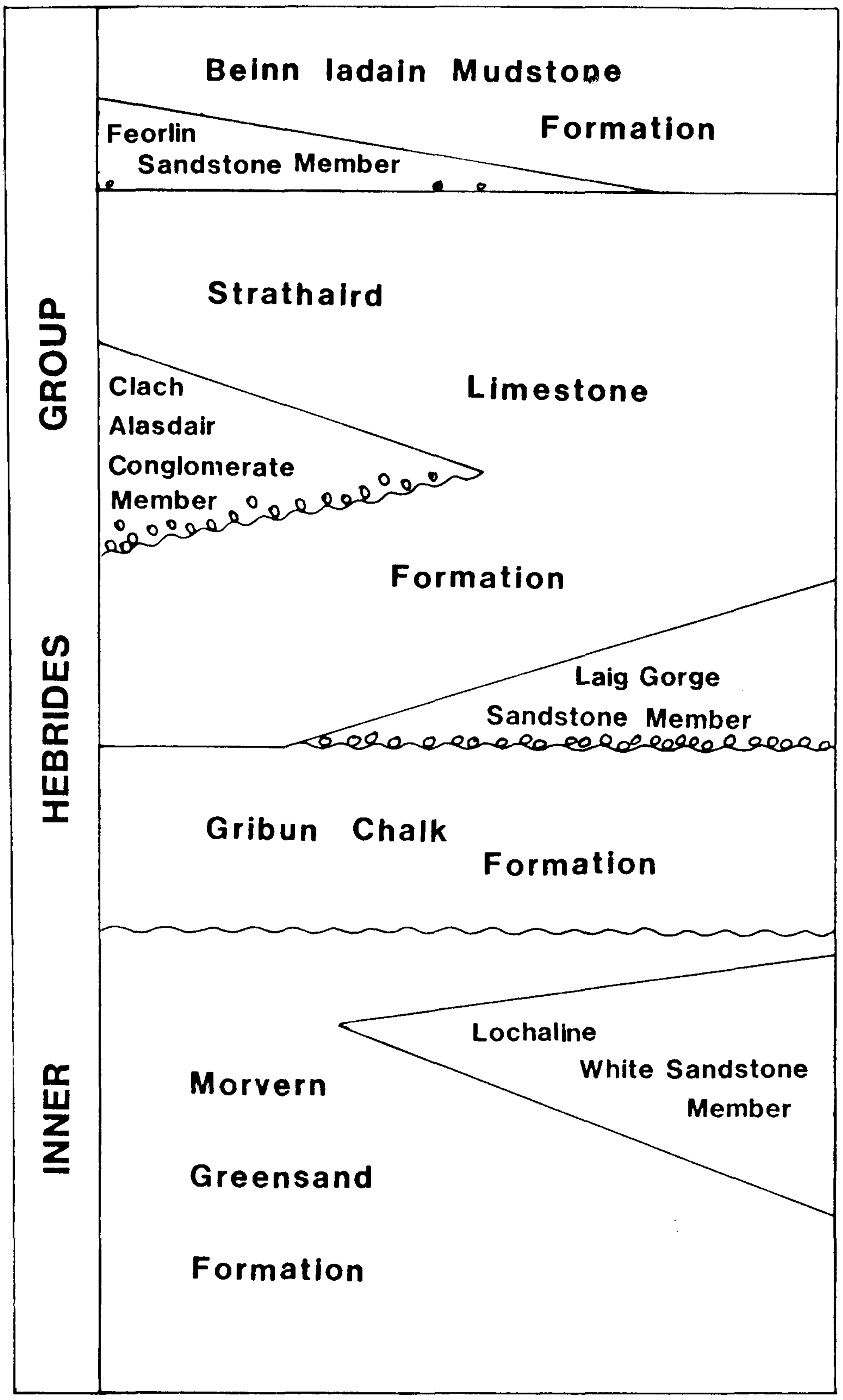


Fig. 1.3

Proposed lithostratigraphy for the Cretaceous rocks of N.W. Scotland.

white in colour, almost totally silicified and very brittle. To distinguish this lithotype from the Ulster White Limestone of Northern Ireland and the Chalk of southern England, it is here termed the "Gribun Chalk Formation". The type locality is Allt na Teangaidh, Gribun, Mull.

The stratigraphic relationships of the sandstones, micritic limestones and silicified chalk conglomerates which fit between the silicified chalk and the mudstone lithofacies which directly overlies the silicified chalk at Beinn Iadain, are complex. These sediments have to post-date the silicification of the Gribun Chalk because clasts of silicified chalk occur within them, and they are here contained within the "Strathaird Limestone Formation" since micritic limestone is the dominant lithotype in this part of the succession. The basal member of the Strathaird Limestone Formation comprises medium to coarse grained, poorly sorted sandstones and conglomerates. This member is here termed the "Laig Gorge Sandstone Member", after the type locality in Laig Gorge, Eigg. The micritic limestone, which is the most widespread and thickest lithofacies in the Strathaird Limestone Formation, outcropping in Mull, Eigg and Skye, is named after the type locality: Strathaird, Skye (ST). The Strathaird limestone contains occasional thin conglomeratic units, the conglomerate comprising silicified chalk and flint clasts.

Another conglomeratic unit, often occurring within the micritic limestone, is lithologically distinctive since it is supported by a coarse sandstone matrix and contains clasts reaching boulder size dimensions. These clasts are dominated by silicified chalk. Because it forms a recognizable unit, this paraconglomerate here becomes the "Clach Alasdair Conglomerate Member" of the

Strathaird Limestone Formation, being named after its type locality, Clach Alasdair (CA), Eigg.

The Members of the Strathaird Limestone Formation are not laterally persistant, as illustrated in Fig.1.3.

The mudstones and organic-rich sandstones which form the top part of the succession at Beinn Iadain are included in the Inner Hebrides Group as the "Beinn Iadain Mudstone Formation", the type locality being Beinn Iadain Section A (BI(A). The basal member of this Formation is a distinctive unit of slightly glauconitic sandstone containing pebbles of silicified chalk. This is termed the "Feorlin Sandstone Member" of the Beinn Iadain Formation, the type locality being the Feorlin Tributary section (FT), Gribun, Mull.

Chapter 2: Structural setting.

2.1 Introduction.

In order to be able to interpret sedimentological and structural data in the context of sedimentary basin dynamics, it is important to have a basic understanding of the structural setting in which a given sedimentary unit is deposited. In this chapter, the deep structural controls on basin development in the Hebrides area will be discussed (Section 2.2). Then the structural limits of the Sea of the Hebrides and Inner Hebrides basins will be reviewed (Section 2.3). A brief history of the Inner Hebrides Basin up to the end of the Jurassic follows. See Enclosure 1 for the general structure and geology of the area.

2.2 Deep structural controls.

The Hebridean basins form part of a compartmentalized half-graben developed in the hanging wall of the Outer Isles Fault (O.I.F.)(Kilyeni & Standley, 1985; Stein, 1988; Stein & Blundell, 1989)(see Fig.2.1). The O.I.F. is a large planar normal fault which has been correlated with the Outer Isles Thrust (O.I.T.) on deep seismic reflection profiles (Brewer & Smythe, 1986; Stein & Blundell, 1989), the O.I.T. being interpreted as an early Proterozoic structure forming part of a major N.E.-S.W. trending shear zone (Lailey *et al.*,1988). (At around 2900 Ma, there was extensive horizontal thrusting and deformation in what now constitutes N.W. Scotland. Following granulite facies metamorphism, there was a change in tectonic style to deformation along discrete shear zones which consequently became the focus for tectonic,

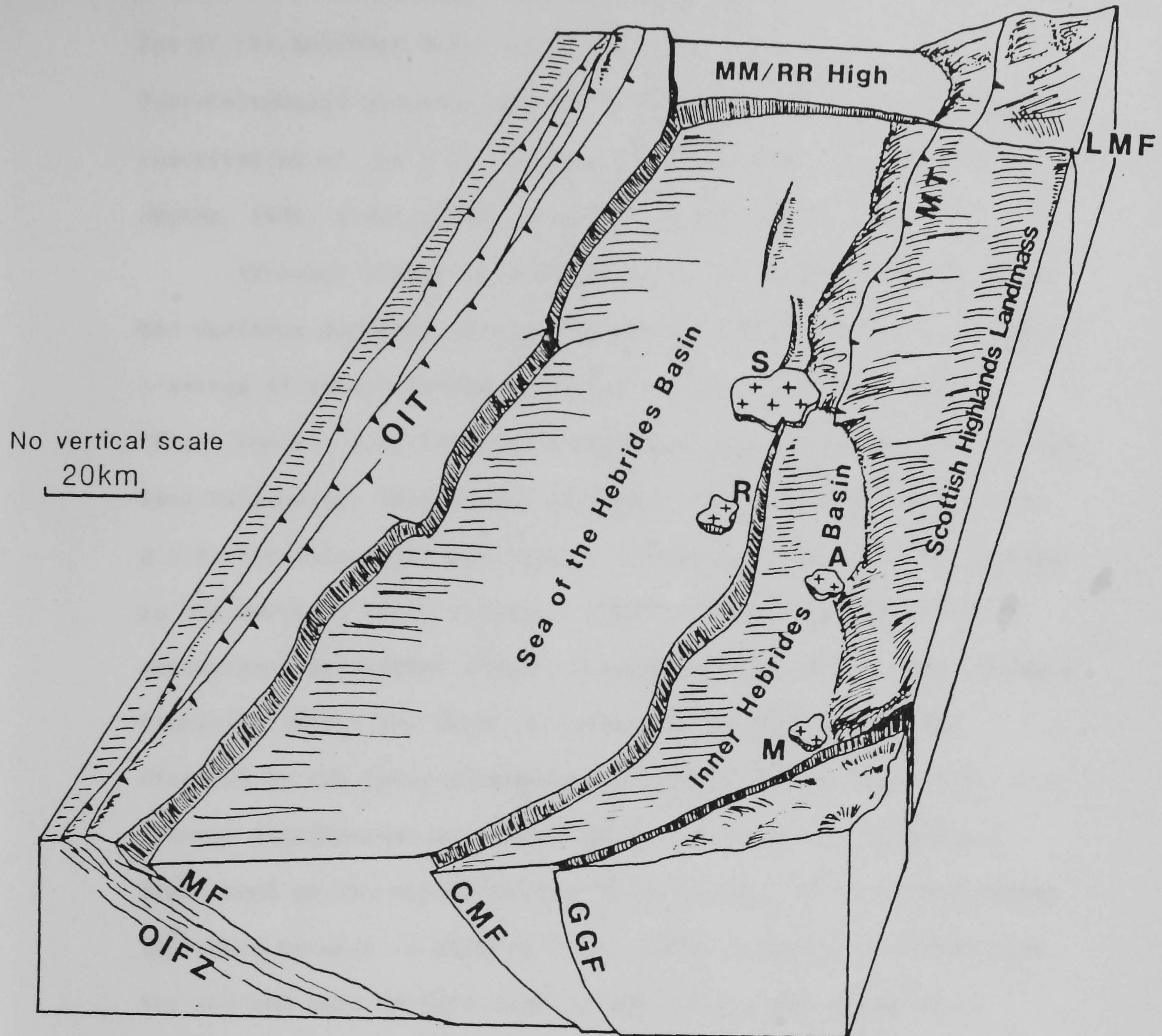


Fig.2.1. Block diagram showing the general structure of the Inner Hebrides and Sea of the Hebrides basins.

MM/RR High - Mid-Minch/Rubha Reidh High

OIT - Outer Isles thrust | MT - Moine Thrust

OIFZ - Outer Isles Fault Zone

MF - Minch Fault | GGF - Great Glen Fault

CMF - Camasunary Fault | LMF - Loch Maree Fault

S - Skye plutonic centre | R -Rhum plutonic centre

A - Ardnamurchan plutonic centre M - Mull plutonic centre metamorphic and magmatic events (Stein, 1988). Up to 8 km of late Proterozoic (Torridonian) sediments may be preserved in the present Sea of the Hebrides Basin (Binns *et al.*, 1974; Stein, 1988). Post-Caledonide movement appears to have been extensional, through reactivation of the O.I.F. during the late Palaeozoic (Brewer & Smythe, 1986; Stein, 1988; Stein & Blundell, 1989).).

Although planar in cross-section, the surface of the O.I.F. has variable geometry (Stein & Blundell, 1989), and it is offset by a series of normal faults which are known collectively as the "Minch Fault" (M.F.)(Kilyeni & Standley, 1985)(see Fig.2.1). In the late Palaeozoic, development of basins in the hanging wall of the O.I.F. was initiated, possibly in response to the start of rifting in the northern North Atlantic, the O.I.F. Zone acting as an extensional detachment (Brewer & Smythe, 1985; Stein, 1988; Stein & Blundell, 1989). The shape of these hanging wall basins was dictated by the three-dimensional configuration of the O.I.F., lateral displacement of which caused the formation of basement highs such as the Mid-Minch High (Fig.2.1)(*op cit.*). Carboniferous sediments outcrop in Morvern (Judd, 1878) and were recovered from the sea-bed west of Skye (Eden *et al.*,1973), and swarms of Permo-Carboniferous dykes found throughout the Hebrides and Scottish mainland indicate the existence of tensional conditions at this time (Baxter & Mitchell, 1984), resulting in reactivation of the O.I.F./M.F. Zone (Stein, 1988). Throughout this, and subsequent extensional episodes, the Highlands Massif remained essentially passive, the active area being the region of extension related to Atlantic rifting to the west with the O.I.F. Zone acting as the boundary between these terranes (Brewer & Smythe, 1986; Stein, 1988; Stein & Blundell, 1989).

The Outer Hebrides Block appears to have acted as a positive feature since the Laxfordian, probably due to a low density granitic basement (Watson,1977). The WINCH deep seismic profile (1983), and earlier deep seismic data, showed that throw on the Minch Fault decreases dramatically beyond the geographical limits of the Outer Hebrides, and that the deepest part of the Sea of the Hebrides Basin is adjacent to the topographically highest part of the Outer Hebrides islands (Brewer & Smythe,1986). The Outer Hebrides Block is therefore interpreted as the isostatically uplifted footwall of the Minch Fault (*op cit.*).

2.3 Structural limits of the Sea of the Hebrides and Inner Hebrides basins.

The "Hebrides Basin", bounded to the west by the M.F./O.I.F. Zone and to the east by the Scottish Highlands Landmass, is divided by the Camasunary-Skerryvore Fault into two westerly-tilting half-graben, the Sea of the Hebrides Basin and the Inner Hebrides Basin (Binns *et al.*, 1975)(See Enclosure 1 & Fig.2.1).This fault follows the same approximate trend as the Minch Fault and dips steeply to the east, the Tiree-Stanton Banks High comprising its uplifted footwall (*op cit.*;Morton *et al.*,1987).

The structural boundaries of the present Sea of the Hebrides and Inner Hebrides basins are as follows:

(i) Sea of the Hebrides Basin. The M.F. Zone forms the western bounding margin of the Sea of the Hebrides Basin, the Tiree-Stanton Banks High acting as the eastern edge (Binns *et al.*,1975; Kilyeni & Standley, 1985). The northern limit is the Mid-Minch/Rubha Reidh

High (Binns *et al.*,1975), a horst-like structure apparently controlled by a N.W. continuation of the Loch Maree Fault (Stein, 1988). To the south, the structure is poorly understood, the M.F. Zone apparently dying out at Stanton Banks, where Mesozoic sediments also wedge out (Binns *et al.*,1974; Binns *et al.*,1975; Kilyeni & Standley, 1985).

(ii) Inner Hebrides Basin. The western margin of the Inner Hebrides Basin is the Camasunary-Skerryvore Fault. North of Raasay, the Camasunary Fault appears to die out before being truncated by the Mid-Minch/Rubha Reidh High (Binns *et al.*,1974; Binns *et al.*, 1975) but may continue N.W., though offset by the Skye plutonic centres (see figs. in Morton, 1987; Kilyeni & Standley, 1985,p.101; Stein & Blundell, 1989, fig.2). The eastern margin of the Inner Hebrides Basin is the passive Scottish Highlands Landmass, and the northern boundary is formed where the Scottish Highlands Landmass, the Mid-Minch/Rubha Reidh High and the Camasunary Fault converge. The Colonsay-Islay High marks the S.E. margin of the basin, which follows the trend of the Great Glen Fault (see Enclosure 1).

2.4 A brief pre-Cretaceous history of the Hebridean basins.

(See Fig.2.2 for Triassic to Cretaceous lithostratigraphy).

Development of the Hebrides Basin half-graben probably started in the late Carboniferous as subsidence started along the Minch Fault Zone (Kilyeni & Standley, 1985). Carboniferous sandstones and shales outcrop at Inninmore Bay on the Sound of Mull; Early Carboniferous shales have been recovered in sea-bed samples from west of Skye (Eden *et al.*, 1973), and reworked Carboniferous miospores have been recovered from boreholes on the

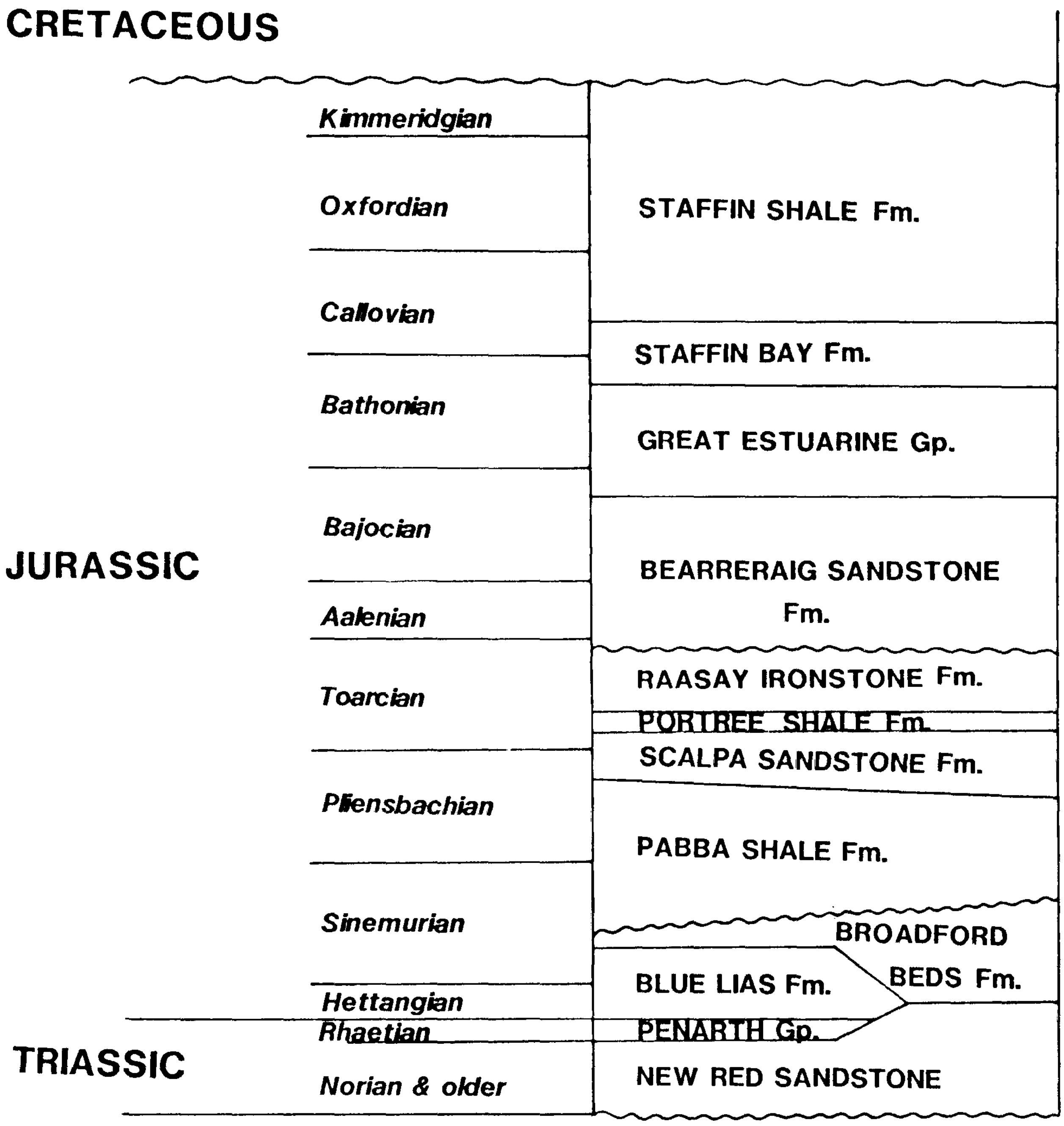


Fig.2.2 Triassic to Cretaceous lithostratigraphy of the Inner Hebrides area (after Morton,1987).

margins of the basin west of the Minch Fault (Binns *et al.*, 1975). Permo-Triassic sediments comprise continental red-beds - fault controlled alluvial fan and flood-plain deposits (Bruck *et al.*, 1967; Steel, 1974, 1977) - possibly indicating that separate Sea of the Hebrides and Inner Hebrides Basins had already developed through synsedimentary movement on the Minch, Great Glen and Camasunary faults (Binns *et al.*,1975; Steel, 1977; Hudson, 1983). Palaeoslopes appear to have been dipping N.N.E. in the Sea of the Hebrides-Minch Basin and S.W. in the "Great Glen"-Inner Hebrides Basin (see Steel, 1977; Hudson, 1983, fig.2), with sediment being shed into the eastern margins of the basins from a westerly-dipping Scottish Highlands Landmass (Hudson,1983). However, Morton *et al.* (1987), point out that the most northerly palaeocurrent measurements (Raasay & Stornoway) were taken from marginal alluvial fan facies, (the only outcrops available), and may therefore be misleading.

The late Triassic-early Jurassic marine transgression that affected most of northern Europe flooded the already existing Hebridean basins (Hudson,1983). Transgression in the Inner Hebrides Basin came from the south, with the deposition of nearshore limestones, sandstones and shales in the north of the basin (Skye), and deeper water shale and limestone facies in the south (Mull & Morvern)(*op cit.*; Morton,1987). During most of the Jurassic, the Inner Hebrides Basin and Sea of the Hebrides Basin appear to have acted as a single depositional basin (the "Hebrides Basin") (Morton, 1987; Morton *et al.*,1987), subsidence curves indicating that the initial rapid subsidence lasted from the latest Triassic to the Toarcian (Morton, 1987). A general coarsening upwards through the Pabba Shale and Scalpa Sandstone may indicate the onset of regression through the Pliensbachian (Hudson, 1983; Morton *et al.*,1987). Toarcian age rocks (Portree Shales and Raasay Ironstone) are thin, and the latter formation is condensed (*op cit.*). This is followed by a hiatus.

Sedimentation resumed with the deposition of the Bearreraig Sandstone Formation in the latest Toarcian. The rapid subsidence indicated by this unit is typical of northern North Atlantic basins during the late Toarcian-late Bathonian interval (Morton, 1987). The Bearreraig Sandstone is thickest in Skye where it reaches ~ 490m, but in Mull it reaches a maximum thickness of 30m (Hudson, 1983). In the late Bajocian, the connections of the basin to open marine conditions became restricted, resulting in the deposition of lagoonal and deltaic sediments, (the Great Estuarine Group), throughout the basin (*op cit.*).

The late Bathonian-early Callovian interval marks the start of a marine transgression which continued through the Oxfordian with the deposition of wholly marine silts and mudstones, the Staffin Shale Formation (*op cit.*; Morton *et al.*, 1987). This phase of subsidence appears to have started earlier in the north of the basin (Skye area) than in the south (Morton *et al.*,1987), but outcrops of the Staffin Shale and Kimmeridgian beds are poorly exposed (Hudson, 1983), and evidence is therefore limited.

As pointed out by Binns *et al.*,(1975), Hudson,(1983), and Morton,(1987), there are insufficient strata preserved onshore in the Hebrides area to accurately locate basin margins through the Mesozoic and the dating of fault movements up to the end of the Jurassic is difficult to determine. However, most authors agree that there was a period of basin inversion in the Hebrides Basin starting in the latest Jurassic-early Cretaceous (Binns *et al.*, 1974; Binns *et al.*,1975; Hudson, 1983; Kilyeni & Standley, 1985; Masson & Miles, 1986; Morton, 1987; Morton *et al.*,1987; Stein, 1988), involving uplift on the Mid-Minch High, the Outer Hebrides Block and the footwall side of the Camasunary Fault. This resulted in a near-present configuration of separate Sea of the Hebrides and Inner Hebrides basins at the start of the Cretaceous (Binns *et al.*,1975; Morton, 1987; Morton *et al.*,1987).

Chapter 3: Locality descriptions.

3.1 Introduction.

As already discussed, (Sections 1.1 & 1.3.i), rocks of Cretaceous age in the Inner Hebridean area occur in widely distributed and poorly exposed outcrops. The most complete exposures exist in Morvern and Mull and these will be described first. For each section, the location will be given (with a sketch-map), followed by a detailed bed by bed description and sedimentological log. The abbreviated section name (usually initials), given in this chapter will be used subsequent to the locality description where appropriate. The sections will be treated in broad lithostratigraphic order. See Fig.1.1 for the regional setting of localities.

3.2 The Morvern sections.

Cretaceous rocks in Morvern outcrop around the margins of Loch Aline and underneath the Tertiary basalts on the Beinn Iadain and Beinn na-h Uamha outliers. The Beinn Iadain sections are the most stratigraphically complete in the Hebrides area and those around Loch Aline are the most laterally extensive.

3.2.i. Beinn Iadain:

Two sections of Cretaceous strata were exposed on Beinn Iadain in May-June 1989. Only one of these is described in the literature; the exposure comprising "B.I. Section (A)" of this study at G.R. NM 6917 5490 (see Judd,1878; Lee & Bailey,1925). A section described as being located at "the south-eastern corner"

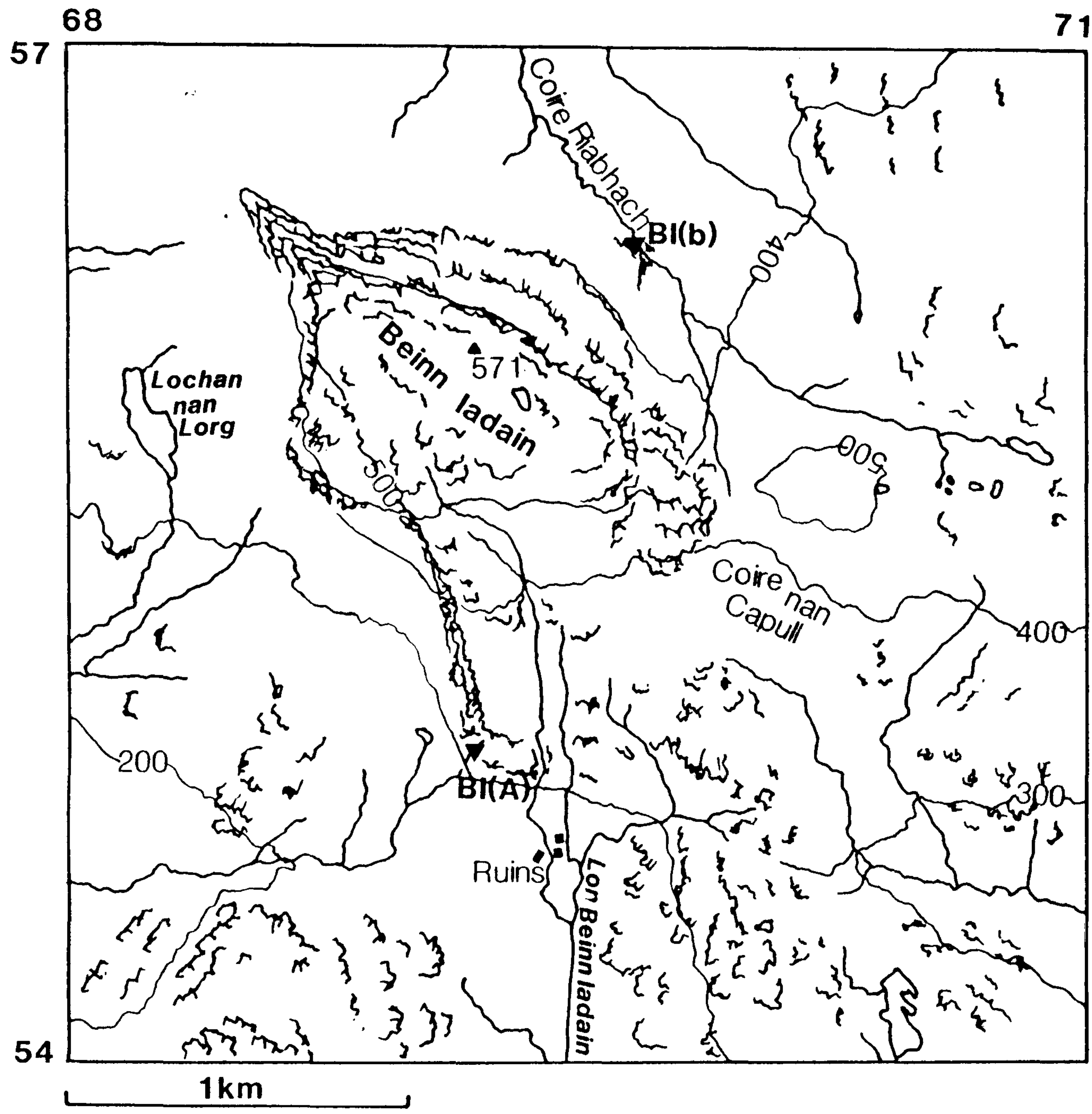


Fig.3.1 Map of Beinn Iadain.

of Beinn Iadain (Judd,1878), and "directly north of the ruined shielings" (Bailey *et al.*,1924), is no longer exposed, though fragments of silicified chalk can be found in the scree at this locality. A second outcrop, (B.I. Section (b) of this study), is exposed in a slope failure at G.R. NM 6965 5645. Beinn Iadain is an SSSI and nature reserve run by the Scottish Naturalists Trust and access is restricted at certain times of the year.

3.2.ii. Beinn Iadain - Section (A). (BI(A)).

Section location: G.R. NM 6917 5490. (See Fig.3.1.)

The exposure is on the S.W. corner of the hill, in and around a small stream (not marked on the 1:25 000 O.S.Map), and is continuous neither laterally nor vertically. The base of the basalt cannot easily be followed as scree is partially covered with vegetation and the section is best found by walking N.W. from the ruined shielings keeping between Allt Beinn Iadain and a parallel tributary, and approximately 15m below the visible base of the basalt. The section is approximately 300m from the ruined shielings. This section forms the type locality for the Morvern Greensand Formation and the Beinn Iadain Mudstone Formation.

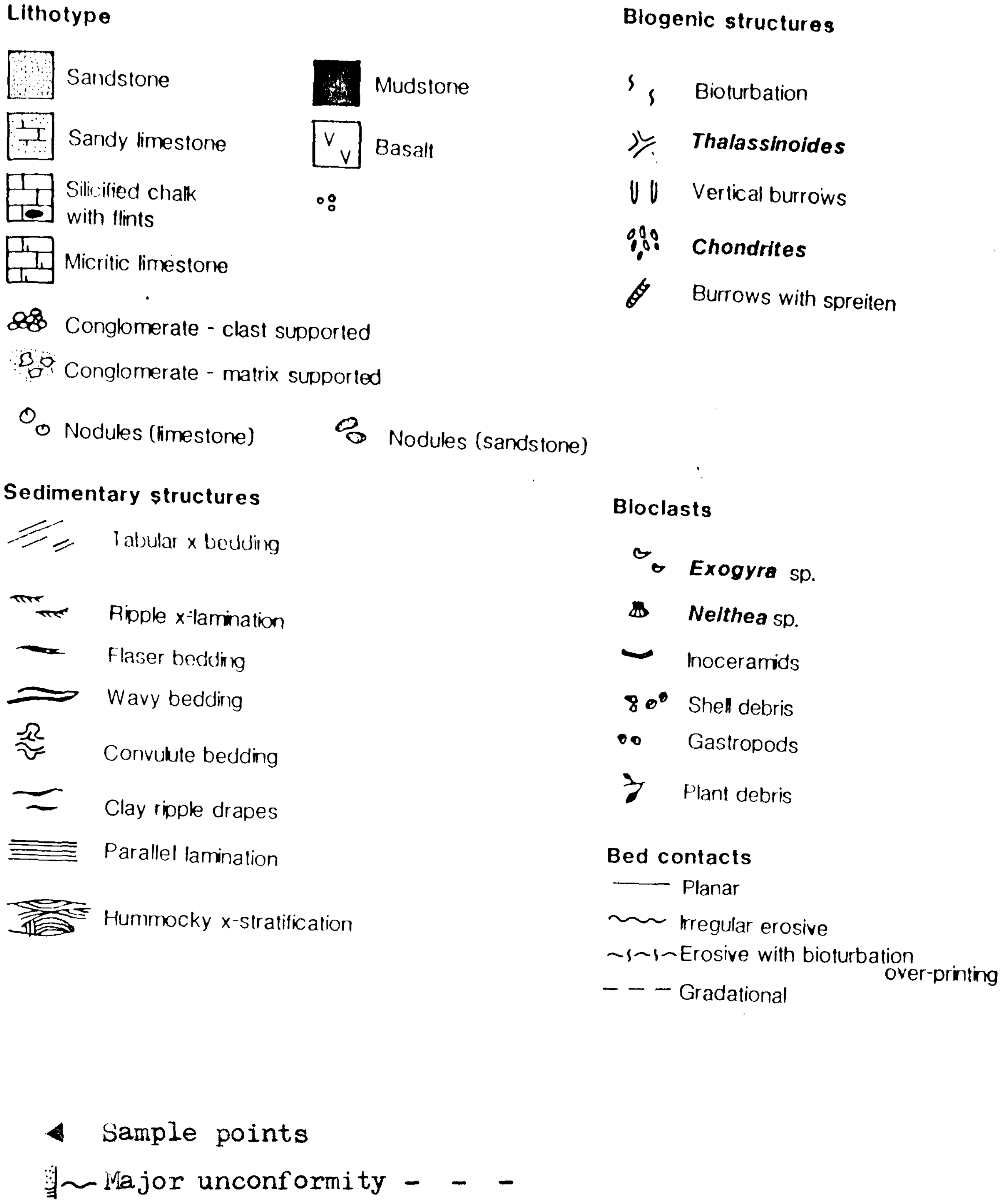
Section description: (See Fig.3.2)

The basal unconformity between the greensand and a thin wedge of Liassic shale apparently outcropping on this corner of Beinn Iadain (see B.G.S. Map NM 52E), is not exposed. The section starts at the base of a small exposure a few metres N.W. of the stream, just above some large blocks of fallen basalt.

At the base of the section is a 66cm thick bed of medium

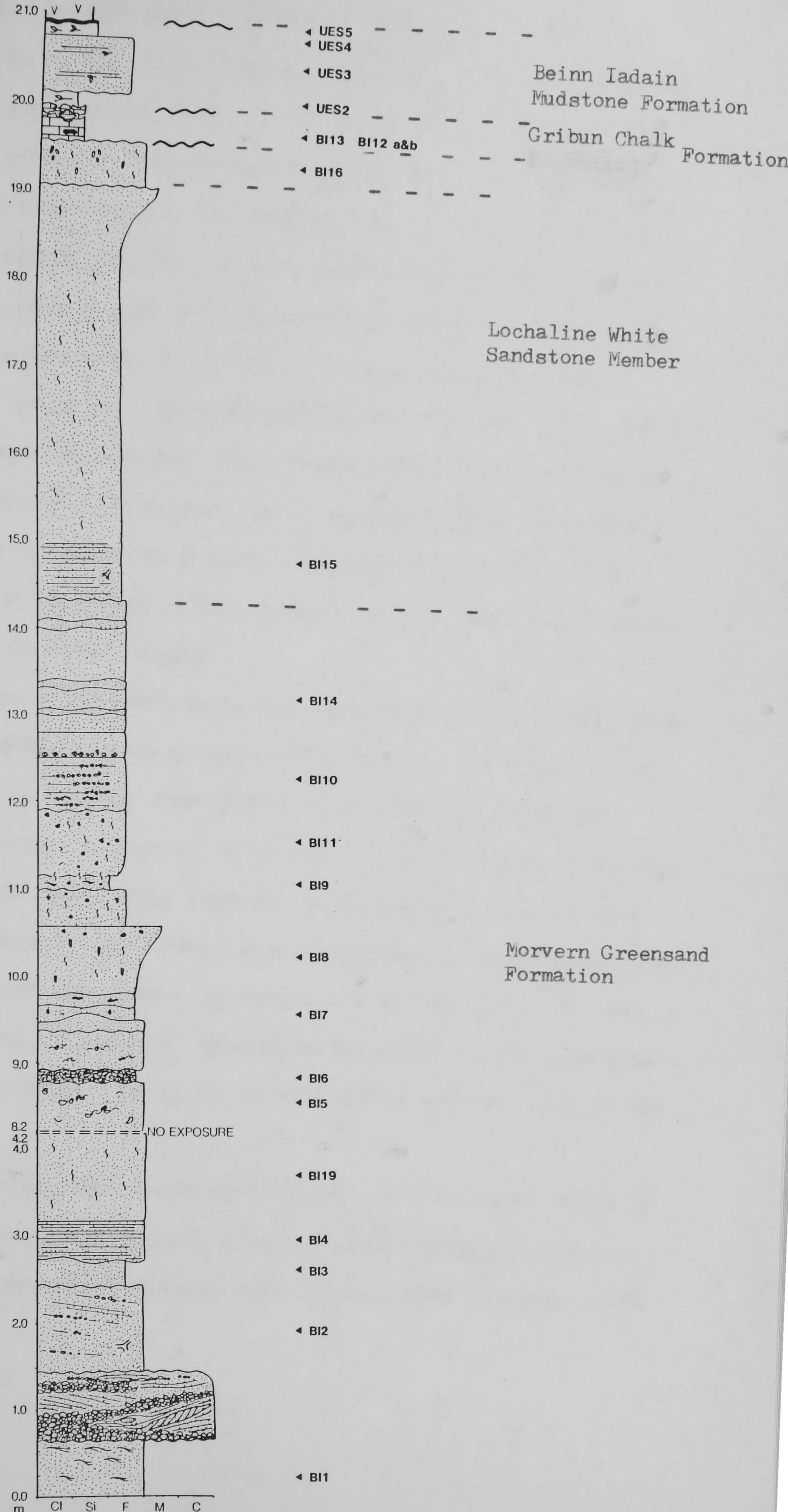
Fig. 3.2a

Key to sedimentological logs.



<u>N.B.</u> Locality maps are based on Ordnance Survey 1:50 000 Sheets 32, 39, 48, 49, and field observations.

Fig. 3.2b LOG 1 Beinn Iadain (a).



(375μm) to fine (187μm) grained organic-rich glauconitic sandstone. Organic content increases upwards with black silt laminae up to 3mm thick picking out ripple cross-lamination. The laminae are wavy and bifurcate. There is an irregular, erosive contact with a 22cm thick conglomeratic unit. The conglomerate is clast-supported and interfingers with, or encloses, lenses of fine to medium grained, laminated fawn-coloured sandstone (see Fig.4.1). Within this laminated sand are occasional unlaminated sandstone clasts which the laminae drape. The conglomeratic material comprises a mixed assemblage of vein quartz, mica schist and red mudstone pebbles, the vein quartz being the most common. The maximum clast size measured was 5.3cm, average clast length being 3cm and clast shape being sub-spherical for all but the mudstone which tended to form elongate clasts. Nearly all pebbles were sub- to well- rounded.

This is followed by an erosive contact with a greyish green fine to medium grained glauconitic sandstone. This bed is 1.6 m thick and is tabular cross-bedded on a relatively large scale, foreset height reaching 40 cm. Foresets are defined by occasional pebble bands and/or fine laminations dipping 4° E. The laminae occur in bundles, with laminae less than 1mm thick being separated by 2 mm thick laminations at regular 1.5 cm intervals. This bed is sporadically bioturbated, *Thalassinoides* burrows being preserved in relief on a cross-bedding set surface on the southern side of the stream.

Disconformably overlying this unit is a very well cemented horizon of grey fine-grained (125 μm) muddy sandstone which has a "pinch and swell" morphology, reaching a maximum thickness of 35 cm. No macrofossils or primary sedimentary structures are visible.

Parallel laminated fine - medium grained greenish grey sandstone follows, concentrations of glauconite, pyrite and fine organic material forming the laminations. This unit is 45cm thick and is succeeded by an apparently massive bed of the same lithology, 1.2m in thickness.

There is then a 3.7m gap in exposure, the section continuing in small exposures adjacent to, and in, the stream bed.

Following the gap, the section continues with 60cm of dark green fine - medium grained sandstone (Bed 8). This bed contains rare whole *Exogyra* sp. and gastropod shells, with shell debris concentrated into thin, non-persistent lenses, sometimes forming laminae parallel to the bedding surfaces. Overlying this is a 13cm thick, more concentrated, shell bed composed of *Exogyra* and broken inoceramid valves in a fine-grained, glauconitic silty sandstone matrix. Glauconite is concentrated in those valves orientated concave downwards but there appears to be no overall preferred orientation of shell material in this bed.

There is an irregular erosional contact with 45cm of fine - medium grained, massive glauconitic sandstone. There are occasional concentrations of shell debris in this unit but these never exceed 7cm in length and are less than 2cm in height.

A shell fragment lag at the base of the next bed indicates an erosive contact. The overlying unit comprises a horizon of pale greyish green well-cemented sandstone of varying thickness (10-22 cm). The bed is distinguished primarily by its high degree of cementation. This horizon is followed by 17cm of dark green, highly glauconitic sandstone with occasional shell fragments throughout. These show no particular orientation. Another well - cemeted unit of varying thickness (10-15 cm) overlies this, comprising fine-grained greenish grey sandstone with occasional small lenses of concentrated shell fragments. There is a non-erosive contact with an 80 cm thick, coarsening upwards (187 - 400 μm), bed of massive glauconitic sandstone with rare shell fragments scattered throughout the top 15cm. Occasional vertical burrows are picked out by the concentration of glauconitic and silty material in the burrow infills. This is overlain by 41cm of fine-grained glauconitic sandstone with shell fragments throughout. These reach a maximum length of 14mm and show no preferred orientation. An erosively based, thin (13cm), horizon of dark green silty sandstone with thin flasers of brownish-black silt follows. Small shell fragments (less than 6mm long) occur in the sandstone. This unit grades into a fine-grained glauconitic sandstone, 40cm thick, containing abundant shell fragments. Bed structure appears massive.

This is overlain by an erosively based, parallel laminated, fine-grained glauconitic sandstone. This bed is 60cm thick and the lamination is defined by thin (<1 cm) layers of shell debris. The long axes of the shell fragments are aligned N-S. Laminae are parallel with the bedding surfaces. The unit grades into 30cm of structureless fine-grained glauconitic sandstone with shell fragments scattered through the sediment in the lower 10cm (these probably being derived from the underlying unit).

The start of the next unit is based on increased cementation rather than any visible lithological or sedimentological change. The whole unit is 1.5m thick and contains three well-cemented horizons: one (5cm thick) forming the base of the unit, one (15cm thick) at 45cm from the base, and one (10cm thick) at 120cm from the base. The thicknesses given for these horizons are maxima, the upper and lower surfaces undulating. The whole unit is unfossiliferous. The well-cemented horizons are not classified as separate beds as they are interpreted as cementation phenomena.

There is a marked iregular erosion surface, then 70cm of very fine-grained (125μm) fawn coloured sandstone. This sediment appears less consolidated than the glauconitic sandstone and contains limonite-rich horizons which are, in places, concentrated into parallel laminae (also marked by heavy mineral accumulations), and horizontal burrows. The laminae dip 3° E. The laminated sand grades into apparently homogenous fine-grained fawn-coloured sandstone which continues for 4.09m.This grades upwards into a reddish-brown medium-grained (375μm) massive sandstone, 60cm thick, which becomes more yellow in colour towards the top. These fawn-coloured beds comprise the Lochaline White Sandstone Member of the Morvern Greensand Formation at this locality.

Disconformably overlying these fawn-coloured beds is a 50cm thick unit of light green, fine-medium grained, glauconitic sandstone. Within this sandstone are numerous small, pale cream to white, silt inclusions with a "chalky" texture. These are elongate, roughly cylindrical, and reach a maximum length of 5cm with a maximum diameter of 9mm. They do not react with dilute HCl, but then nearly the whole section has been decalcified.

A 40cm thick unit of silicified chalk (the Gribun Chalk Formation) is unconformable on this glauconitic sandstone. This part of the succession is extremely poorly exposed and the silicified chalk is highly weathered and extremely brittle, making the true relationship of this unit with the underlying sediment difficult to determine. The chalk contains flints which are distinguishable from the silicified matrix by their dark grey to brownish colour and non-porous texture, the silicified chalk itself being highly porous.

There is a large hiatus between the silicified chalk and the overlying clay. The top 31cm of silicified chalk comprises an unconsolidated rubble with the blue-grey clay acting as an infill between silicified chalk pieces. The clay forms a horizon, 15cm thick, above the chalk rubble, weathers white and is very soft. Plant stems up to 11 cm long are common and relatively well preserved. The base of this blue-grey clay forms the base of the Beinn Iadain Mudstone Formation (formerly the "Upper Estuarine Series" (Judd,1878))for which this is the type locality.

There is an irregular erosive contact with 63cm of fine-grained fawn sandstone. Rare parallel lamination is picked out by the concentration of silt-grade organic material containing occasional lignite fragments up to 3cm long and 7mm wide, but otherwise the bed appears unstructured. Rare well-cemented concretions are present: some of these show concentric banding of iron minerals. Average diameter of the concretions is 12cm. This sandstone is overlain by a 14cm thick horizon of blue-grey, finely laminated, silt containing thin, non-persistant concentrations of organic material, including lignite fragments up to 3mm long and 1mm wide. The top of this bed comprises the top of the Beinn Iadain Mudstone Formation.

A thin, (4cm), bed of pale fawn to reddish-brown clay overlies an irregular erosion surface at the top of the Beinn Iadain Mudstone Formation. This clay contains no visible organic material.

The thickness of the lithostratigraphic units at Beinn Iadain Section A is as follows:

Beinn Iadain Mudstone Formation 92cm

Gribun Chalk Formation 40cm

Lochaline White Sandstone Member 5.39m

Morvern Greensand (not
including the W.Sst.Mem.) 11.87m

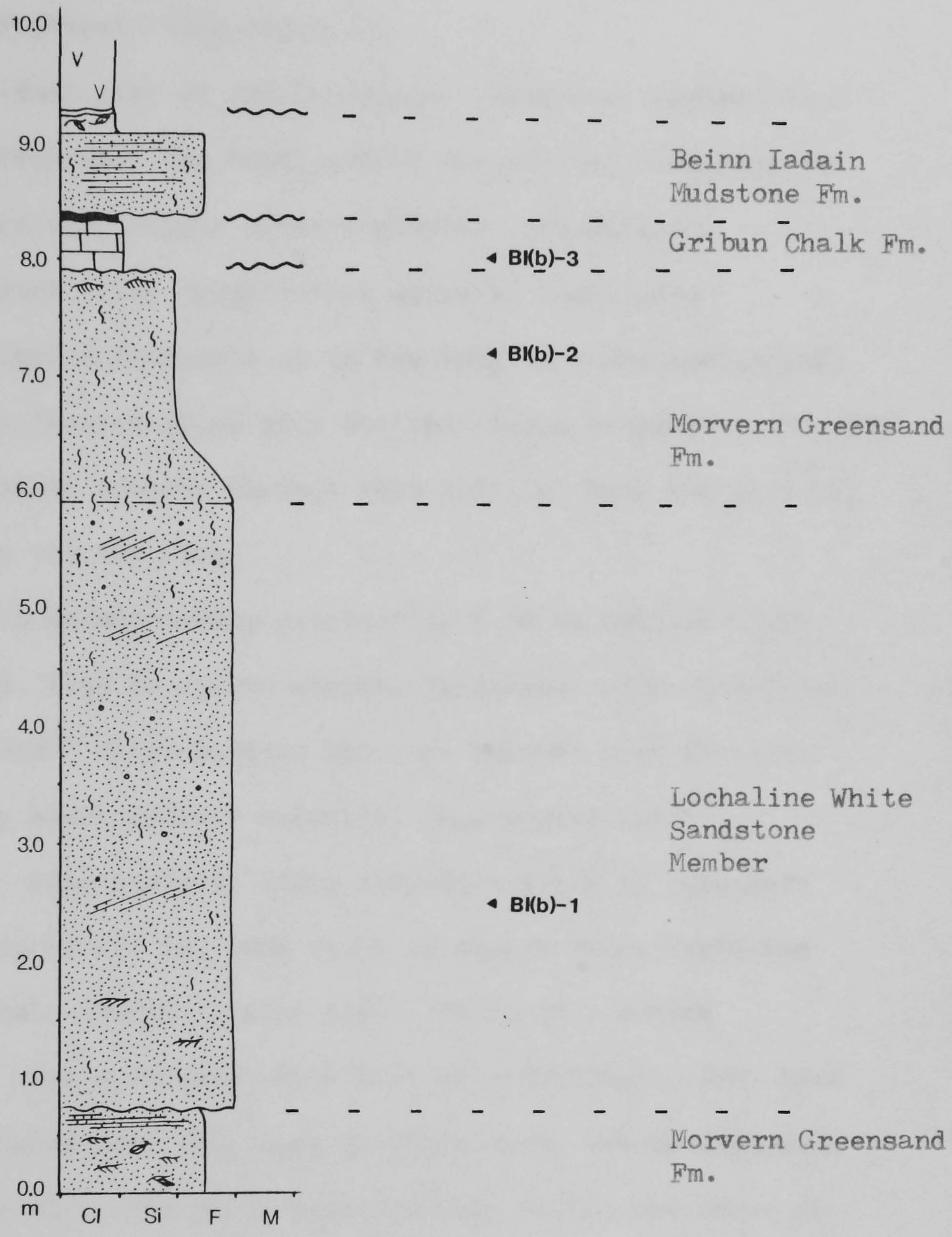
Total thickness of section 18.61m

3.2.iii Beinn Iadain Section (b). (BI(b))

Section location: G.R. NM 6965 5645. (See Fig.3.1.)

The main exposure is in a horseshoe shaped scar where there has been a rotational slope failure in the western bank of Allt Riabhach. The section is most easily found by walking eastwards round Beinn Iadain from Section (A), keeping below the level of the basalt, into Coire nan Capull. From here continue northwards over the watershed marked 486m on the 1:25 000 O.S. map. Once over the watershed, keep down on the flat shelf area adjacent to the stream. Approximately 270m downstream of the

Fig.3.3 LOG 2 Beinn Iadain (b)



confluence of the stream flowing from Lochan nan Lorg with that flowing form the watershed, is another minor confluence and a small waterfall which marks the lowest basalt. Approximately 20m downstream of the waterfall is the main exposure.

Section description: (See Fig.3.3)

The oldest part of the Cretaceous succession exposed here is Morvern Greensand. The basal bed of the section comprises 75 cm of fine-grained, ripple cross-laminated, glauconitic sandstone. Black silty organic-rich material containing occasional lignite fragments up to 6mm long is concentrated into thin (<0.6mm) laminae which pick out the ripple cross-sets. Organic content increases upwards through this unit, picking out parallel lamination in the top 10cm.

This is disconformably overlain by 5.2m of mottled light fawn and grey, fine to medium grained sandstone, with occasional low angle (8-12°) cross-bedding and rare burrows with sprieten picked out by black organic material. This grades into organic-rich, fine-grained, silty sandstone which is intensely bioturbated up to the top 20cm which is ripple cross-laminated on a small scale (foresets <7cm high). There is a marked unconformity with a 40-45cm thick unit of silicified chalk. This is less weathered than that seen at Section (A) and is traceable laterally for 40 m. The chalk contains rare flints but these are only seen in fresh parts of the outcrop.

The top of the silicified chalk is irregular and overlain by the basal unit of the Beinn Tadain Mudstone Formation, a thin (9cm) horizon of blue-grey clay containing disseminated organic material. This is disconformably overlain by 66cm of well-cemented, light fawn, fine-grained sandstone. Grains are sub-rounded to sub-angular. Occasional parallel laminations are picked out by concentrations of detrital glauconite in the basal 25cm of the bed. There is a sharp but apparently non-erosive contact with 15cm of blue-grey organic-rich clay containing well-preserved plant material up to 7cm in length, stems orientated parallel to bedding.

The Beinn Iadain Mudstone Formation is overlain by a thin (5cm) horizon of pale fawn clay underlying the basalt.

The thickness of lithostratigraphic units at Beinn Iadain Section (b) is as follows:

Beinn Iadain Mudstone Formation 90cm

Gribun Chalk Formation 40-45cm

Lochaline White Sandstone Member 5.20m

Morvern Greensand (not
including W.Sst.Mem.) 2.75m

Total thickness of section 9.35m

3.2.iv Lochaline Adit. (LAA.)

Section location: G.R. NM 6800 4535. (See Fig.3.4.)

The section is adjacent to the main adit of the Lochaline Sand Mine. Here, the White Sandstone Member is extracted underground as a glass sand by Tilcon (Scotland) Ltd. and permission should be obtained from the Site Manager before visiting the section. Parts of the section are obscured by vegetation, especially towards the base. Contact with the

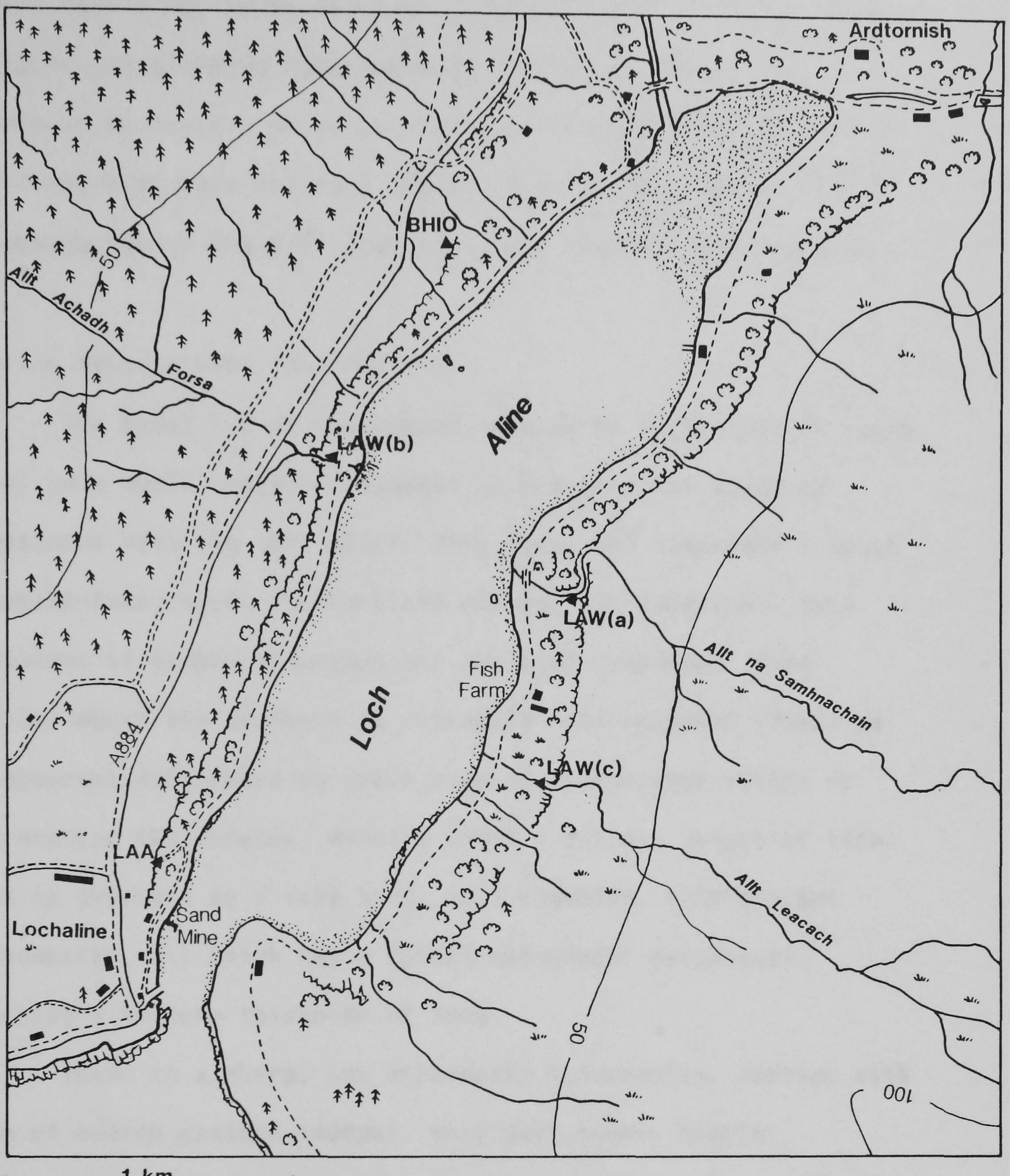


Fig.3.4 Locality map of Loch Aline Sections.

underlying Liassic mudstone is not exposed, but widening of the track in 1988 revealed dark greenish-black laminated mudstone approximately 10m below the base of the exposed Greensand. Minor faulting and slumping have confused the lower part of the Greensand succession which was therefore logged from the base of the least disturbed and best exposed part of the section. This is approximately 30m N.E. down the track from the adit opening.

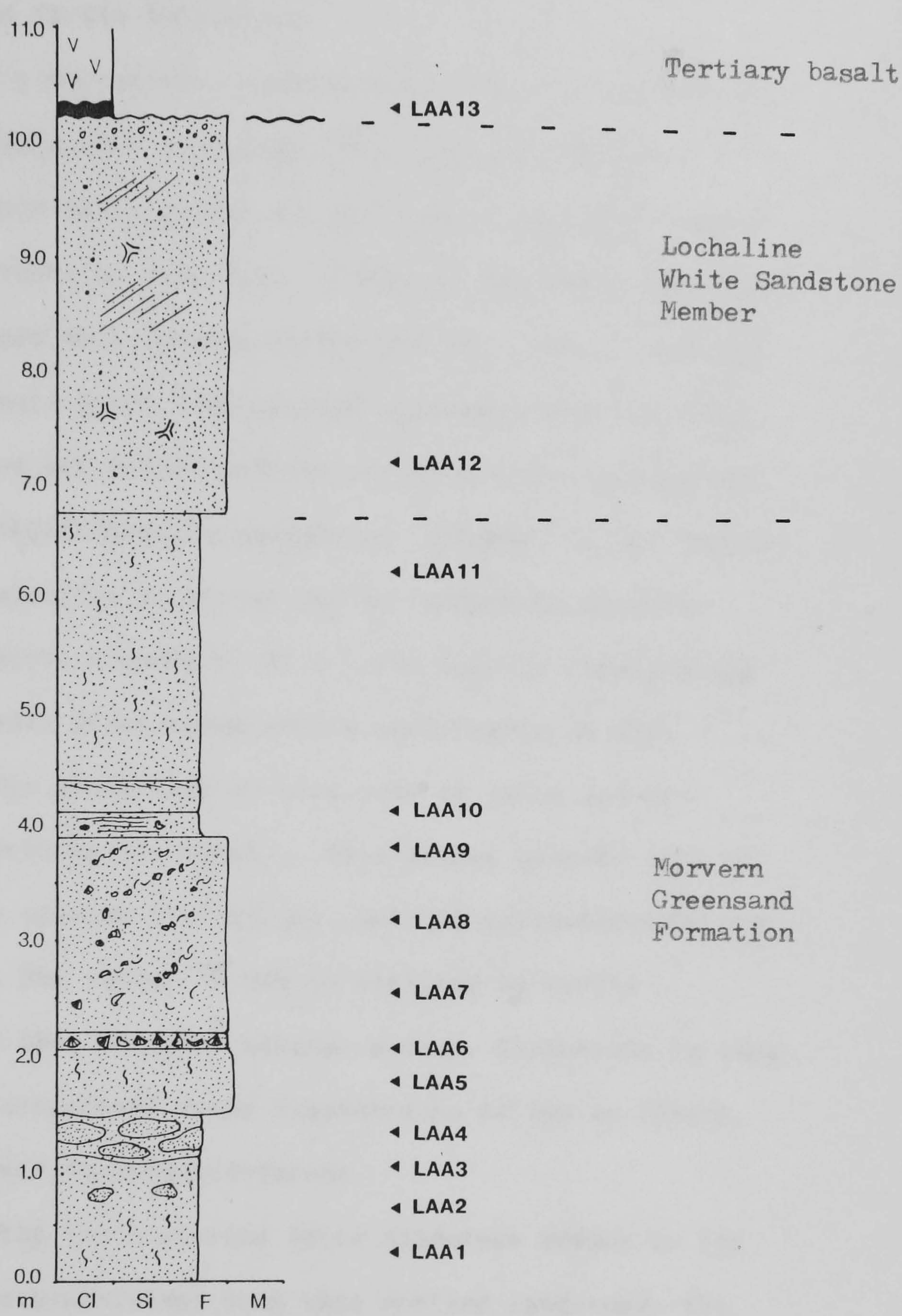
Section description: (See Fig.3.5).

The basal bed of the logged section is first seen at track level in a small exposure adjacent to the main one which is continuous with the adit cliff. This first bed comprises 1.1m of greenish-fawn, hard, fine-grained glauconitic sandstone. This sandstone is highly micaceous and contains occasional hard nodules where the sediment is extremely well-cemented. There is no apparent difference in grain size or composition within or surrounding the nodules. Nodules reach a maximum length of 14cm. This is overlain by a very hard, well-cemented, fine-grained glauconitic unit which has a "pinch-and-swell" morphology, reaching a maximum thickness of 20cm.

There is a sharp, but apparently non-erosive, contact with 55cm of medium grained (400μm), very dark green, highly glauconitic sandstone. No sedimentary structures are visible. An irregular erosion surface is overlain by a 15cm thick shell bed comprising a monogeneric assemblage of *Exogyra* spp. The shells appear largely undamaged and show no preferred orientation. There is a matrix of fine to medium grained glauconitic sandstone.

Overlying the shell bed is 1.58m of soft, reddish-purple

Fig.3.5 LOG 3 Loch Aline Adit



to dark green, fine to medium grained, micaceous sandstone. Shell fragments are abundant throughout the bed, in places concentrated into non-persistant shell lags up to 2cm thick. These sometimes pick out small-scale tabular cross-sets not discernable by grain -size variations in the sand alone.

There is a non-erosive contact with 27cm of fine-grained reddish-purple micaceous sandstone. This unit is finely laminated, laminae being picked out by organic-rich dark purple silt. This bed contains rare shell fragments and fines upwards as lamination becomes more intense in the top 7cm. 25cm of mottled purple-red and pale green fine-grained sandstone overlies this. The mottling does not follow sedimentary structures and appears to be a weathering/diagenetic phenomenon. However, in the top 10 cm, parallel lamination is picked out by reddish-brown silt layers <0.5mm thick, dipping 9° E. A 1.95m unit of fine-grained orange to yellowish green sandstone is conformable on this laminated bed. The grain-size of this sand is 187μm and no sedimentary structures are visible. This grades upwards into 50 cm of coarsening upwards (187-250μm), mottled yellowish-fawn and white sandstone. The colour is due to staining by ferric compounds rather than detrital mineral grains. Glauconite is very rare. There are occasional woody fragments up to 1mm in length, otherwise this unit is unfossiliferous.

Contact with the Lochaline White Sandstone Member in its most pure form is gradational from this mottled sandstone. The Lochaline White Sandstone is 3.5m thick at this locality. The dominant grain-size of this quartz arenite is 250μm but there are occasional sub to well rounded quartz grains 500-1000μm in diameter scattered throughout. There are also extremely rare lignite fragments up to 500μm in size.

Although the structure of this unit appears massive at first sight, there are two laterally extensive well-cemented horizons which can be recognized throughout the sand mine. However, there is no apparant petrological or sedimentological difference between the relatively unconsolidated sandstone and the well-cemented layers except occasional westerly dipping tabular cross-sets and ripple cross-lamination picked out by silty material and grainsize alternations between the hard "ribs" inside the mine (Lowden, 1989, pers.comm.). Thin reddish-brown iron-rich horizons follow joints and cracks in the sandstone and are concentrated in burrow walls. Burrows are also distinguishable by the concentration of coarse (400-750 μm) quartz grains into wall structures. Burrow diameter averages 1.4 cm and most burrows seen are in sub-vrtical and horizontal orientations, probably forming *Thalassinoides* type networks. Occasionally burrows are defined by dark grey silty infills, especially above the level of the second hard "rib". This ichno-assemblage is dominated by *Skolithos* type thin vertical burrows but some contain spreiten. These overprint the larger *Thalassinoides* type systems described above. In the top 40cm of the unit, grain-size increases to an average of 500 μm acting as a matrix to small pebbles up to 1.2cm long.

Unconformably overlying the quartz arenite is an 8cm thick horizon of red-brown silty clay, then the base of the Tertiary basalt.

The thickness of lithostratigraphic units at the Lochaline

Adit section is as follows:

Lochaline White Sandstone Member (taken from the base of Bed 9) 3.50m

Morvern Greensand Formation 6.75m

Total thickness of section: 10.25m

N.B. The base of the White Sandstone Member is difficult to determine at this section because there is a gradation from highly glauconitic silty sandstone to the pure quartz arenite mined as a glass sand. The boundary is therefore taken where the glauconite percentage of the whole sediment is less than 0.5% and where an increase in grain size indicates a change in depositional regime.

3.2.v. Loch Aline Waterfall (a). (LAW(a))

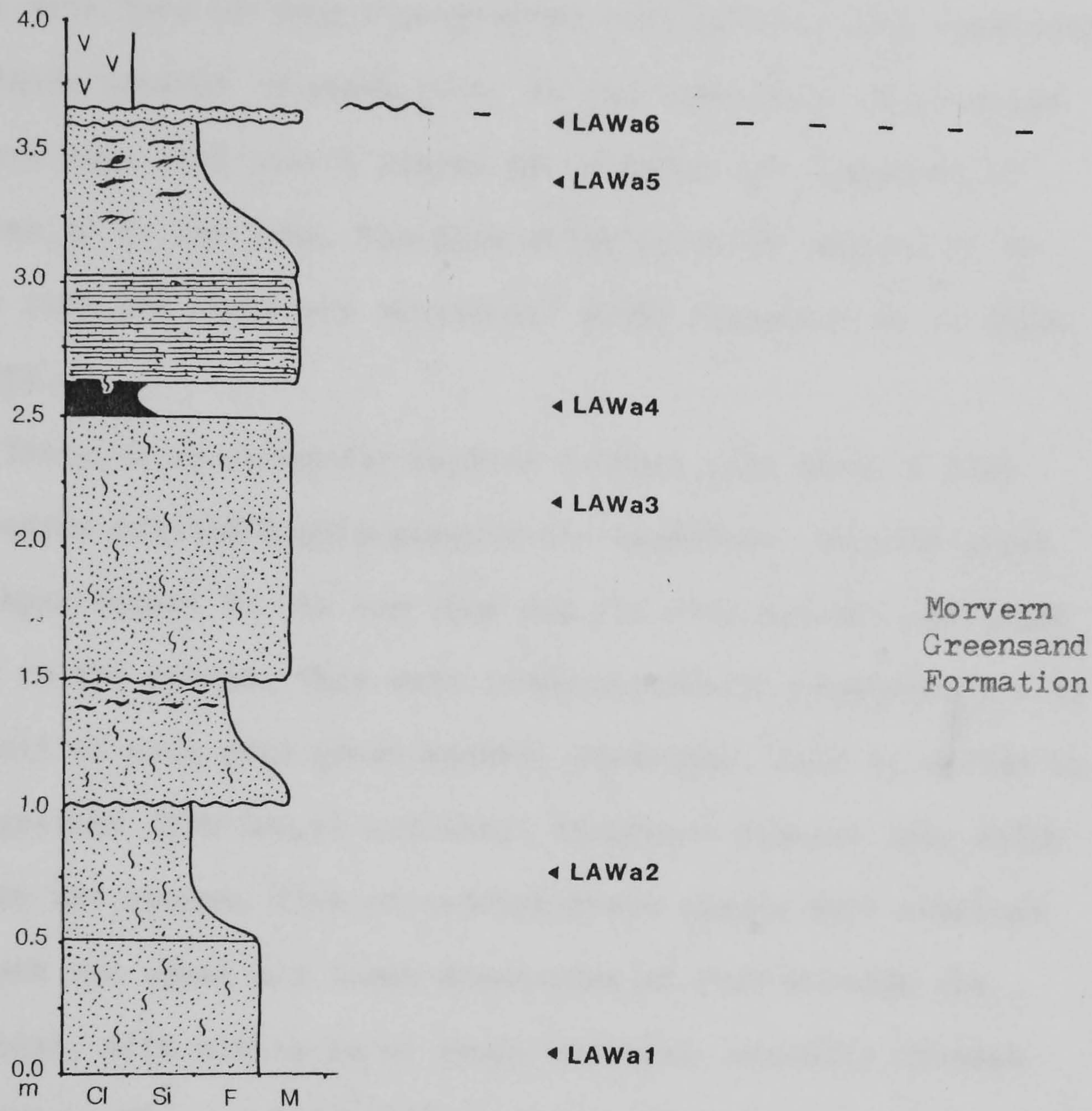
Section location: G.R. NM 6935 4595 (See Fig.3.4).

This section is located on the east side of Loch Aline. Where the Allt na Samhnachain burn crosses the track around the loch, there is a small wooden bridge. Follow the burn upstream past the disused limekiln and climb up the waterfall past rhythmically bedded Jurassic shales and limestones to a small cliff on the south side of the stream which turns sharply northwards. Looking across the burn to the cliff, it is clear that there has been movement on a prominant bedding plane in the shale underlying the Greensand and that the section is therefore located in a slipped block.

Section description: (See Fig.3.6).

The base of the section is an unconformable contact with the

Fig.3.6 LOG 4 Loch Aline Waterfall (a)



laminated silty mudstones of the Liassic Pabba Beds. Exposure of the contact is poor and movement along the plane is indicated by contortion of some of the mudstones.

The start of the Cretaceous succession is a 51cm bed of hard, fine to medium grained (250μm) silty sandstone. This is highly glauconitic and dark green in colour. Shell fragments between 500μm and 3mm in length are common. There is a gradational contact with 50cm of very fine-grained dark purple silty sandstone which fines upwards to sandy silt. In the lower part of this bed there are very rare quartz grains up to 500μm and fragments of limestone up to 1mm long. The fine silty material appears to be organic rich and there are occasional woody fragments up to 600μm in length.

There is an irregular erosive contact with 40cm of dark green medium grained highly glauconitic sandstone. Greyish-brown clay drapes appear in the top 20cm and the clay content increases upwards in the matrix. This unit is disconformably overlain by a 1m thick unit of pale grey-green massive sandstone. This is medium to coarse grained (375-500μm) and shell fragments greater than 500μm in length are common. 11cm of reddish-brown clayey silt overlies this. Both the upper and lower boundaries of this horizon are gradational, with mixing in of sandy material, probably through bioturbation. The overlying bed comprises 85cm of dark green, fine to medium grained (silt-250μm grain size,) laminated silty sandstone. The laminae are formed by fining upwards cycles with increasing organic content upwards. The lamination is parallel to bedding.

Conformably overlying the laminated sandstone is a 62cm thick bed of purple-red mottled greensand which fines upwards to a very fine silty sandstone. There are lignite stringers throughout this bed but in the top 30cm these become thinner, forming flasers rather than lenses, and increase in number. The percentage of silt in the matrix also increases upwards.

There is a gradational boundary with a thin (4cm) horizon of dark green, highly glauconitic fine-grained sanstone. The boundary is probably bioturbated but no individual burrows are preserved. There are occasional limestone grains up to 500μm in diameter; these are sub-rounded.

Unconformable on this greensand is basalt.

The thickness of lithostratigraphic units at Loch Aline Waterfall (a) is as follows:

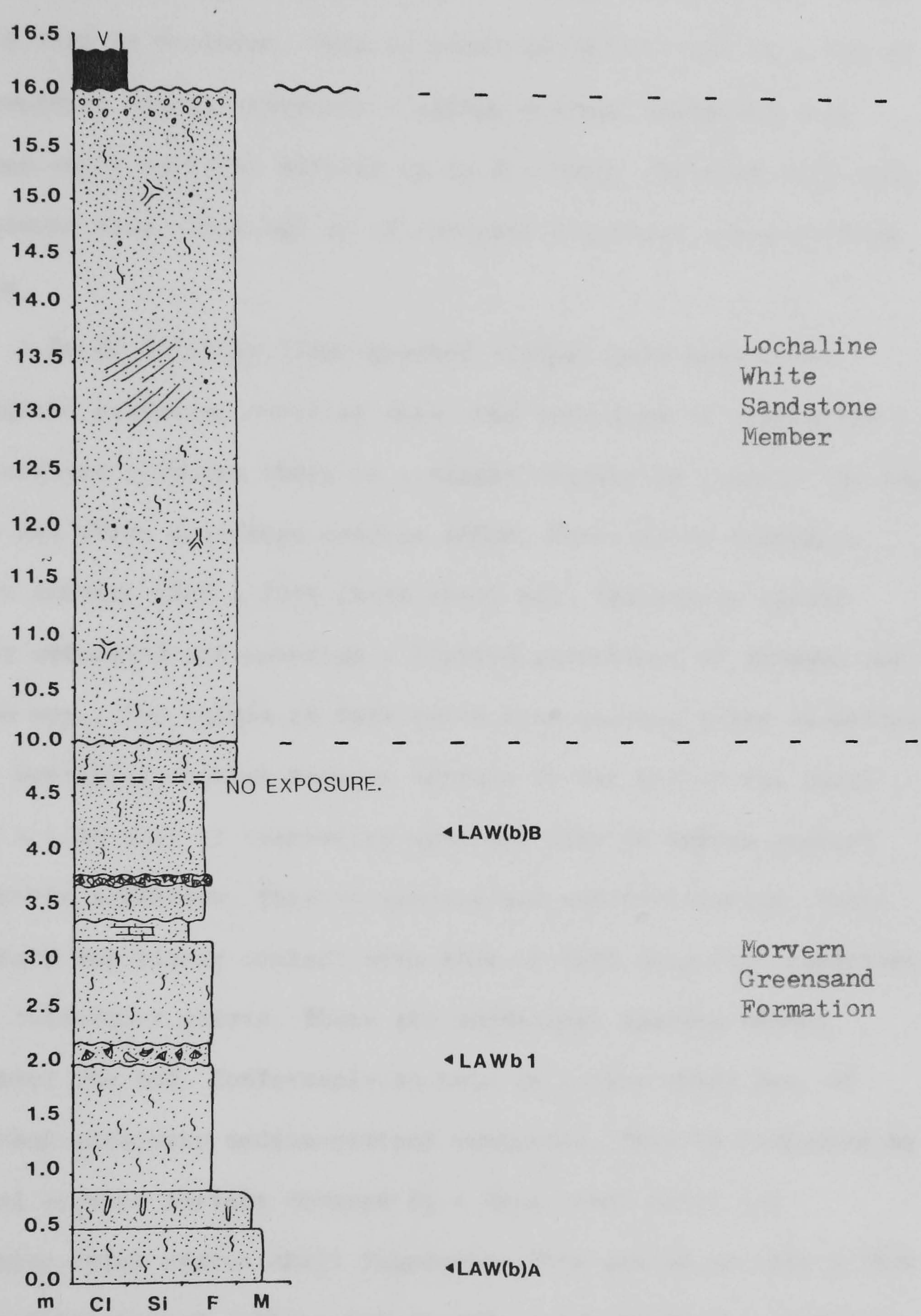
Morvern Greensand 4.03m

3.2.vi. Loch Aline Waterfall (b). (LAW(b)).

Section location: G.R. NM 6869 4665 (See Fig.3.4).

The section is exposed in the Allt Achadh Forsa flowing SE into Loch Aline. Follow the burn NW from the beach to a small waterfall with greensand outcropping on the NE side. About 15m further NE weathered cliffs of white sandstone can be seen. Apart from these exposures, no *in situ* rock can be seen. The burn follows the trend of a fault which has a downthrow of approximately 40m to the west measurable on the basalt. The section is measured from the base to the top of the waterfall and then continues in a small cliff adjacent to the waterfall on the NE bank.

Fig.3.7 LOG 5 Loch Aline Waterfall (b)



Section description: (See Fig.3.7).

The base of the first bed is obscured by boulders at the bottom of the waterfall but the unit comprises 50cm of well-cemented greyish-green massive sandstone. This is medium grained (375μm) yet contains occasional well-rounded quartz grains up to 0.75mm in diameter. This is conformably overlain by a bed of well-cemented highly glauconitic medium-grained sandstone with numerous small vertical burrows up to 4cm long, infilled with fine argilaceous sand. This bed is of variable thickness, ranging from 25-35cm.

1.2m of slightly finer-grained (250μm) pale grey-green glauconitic sandstone overlies this. The sandstone is apparently structureless although there is a slight coarsening towards the top of the bed where grainsize reaches 400μm. There is an irregular erosive contact with a 20cm thick shell bed. The valves appear largely undamaged and comprise a limited assemblage of *Exogyra* and *Neithea* spp.. The matrix is dark green fine-grained silty sandstone.

Overlying another erosion surface at the top of the shell bed is a 1.1m unit of coarsening upwards, fine to medium grained glauconitic sandstone. This is massive and unfossiliferous. There is a sharp but planar contact with 40cm of hard grey fine sandstone with a calcareous matrix. There are occasional *Exogyra* valves throughout the bed. Conformable on this is a 39cm thick bed of grey-green micaceous medium-grained sandstone. This is truncated by a marked erosion surface covered by a thin (5cm) shell lag comprising thick oyster shell fragments. This grades up into a 35cm unit of fine-grained (187μm) bed of pale green micaceous sandstone.

There is then a 6-7m gap in exposure to the nearest cliff comprising the Lochaline White Sandstone Member. This cliff section starts with 48cm of light green fine-grained micaceous sandstone. No sedimentary structures are visible. This is disconformably overlain by 5m of white fine to medium grained quartz arenite with occasional iron rich horizons (maximum thickness 2mm). Very rare burrows are outlined by the concentration of iron minerals in the burrow walls. The iron rich horizons do not follow any other sedimentary features. There are occasional well-rounded quartz grains up to 500μm in diameter.

Overlying this is a 25cm unit of reddish-brown silty clay, then the base of the basalt.

The thickness of lithostratigraphic units at Loch Aline Waterfall (b) is as follows:

Lochaline White Sandstone Member ~5m

Morvern Greensand 4.44m

Total thickness of section exposed: 9.69m

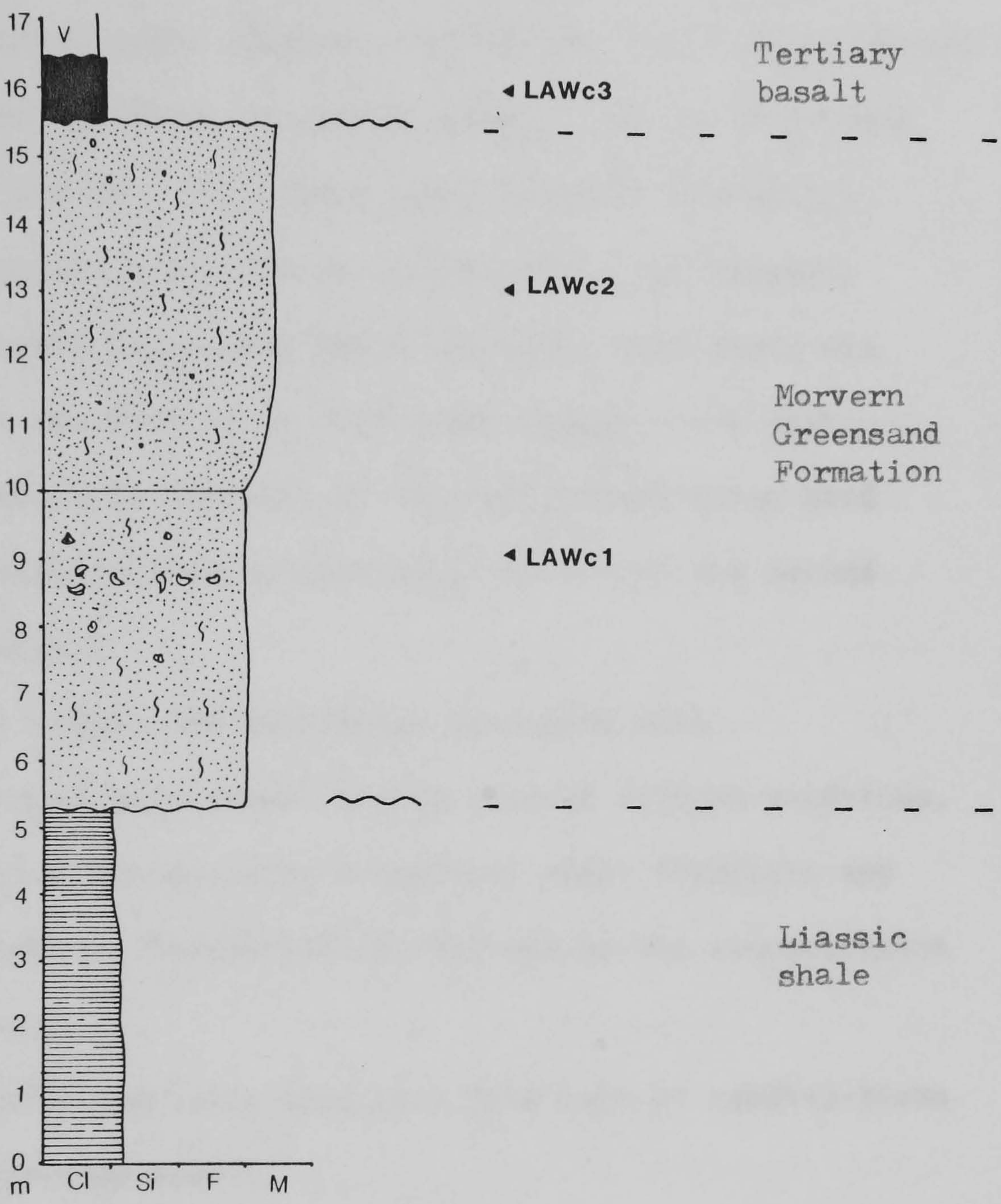
Total thickness of section + gaps: 16.19m

3.2.vii Loch Aline Waterfall (c). (LAW(c)).

Section location: G.R. NM 6935 4535. (See Fig.3.4).

The Allt Leacach burn flows into Loch Aline approximately 100m south of the fish farm buildings. Follow the stream over a boggy hump to a ~17m high waterfall where the burn comes over the basalt cliff. The exposure itself is in the waterfall and is inaccessible. However, large blocks of greensand have broken away and lie at the base of the waterfall. Way up is defined by contact with the Jurassic shale seen in the base of the waterfall and

Fig.3.8 LOG 6 Loch Aline Waterfall(c)



sedimentary structures.

Section description: (See Fig.3.8).

The top of the Jurassic shale forms the first ledge in the waterfall and is unconformably overlain by dark green, highly glauconitic sandstone. This is micaceous, fine to medium grained (250μm), and contains shell fragments throughout. The true thickness of this dark green sandstone is approximately 3.5m. At 40 cm from the base of this bed is a 20cm thick shell horizon. The shells appear mostly complete and comprise an apparently monospecific assemblage of *Exogyra obliquata*. Above the shell band there are occasional lenses and flasers of dark brown organic rich silt.

This sandstone is overlain by 40cm of greyish-green hard sandstone which appears massive and forms the lip of the second ledge in the waterfall.

Above this ledge, the succession continues with approximately 4.5m of pale green, medium grained (375μm) sandstone. This appears massive but contains occasional shell fragments and non-persistant parallel laminations picked out by the concentration of glauconite grains.

Unconformably overlying this is a 70cm unit of reddish-brown silty clay, followed by basalt.

The thickness of the lithostratigraphic units at Loch Aline Waterfall (c) are as follows:

Morvern Greensand 8.40m

Total thickness of section: 9.10m

3.2.viii Loch Aline Borehole No.10. (BH10)

Section location: G.R. NM 6890 4695. (See Fig.3.4).

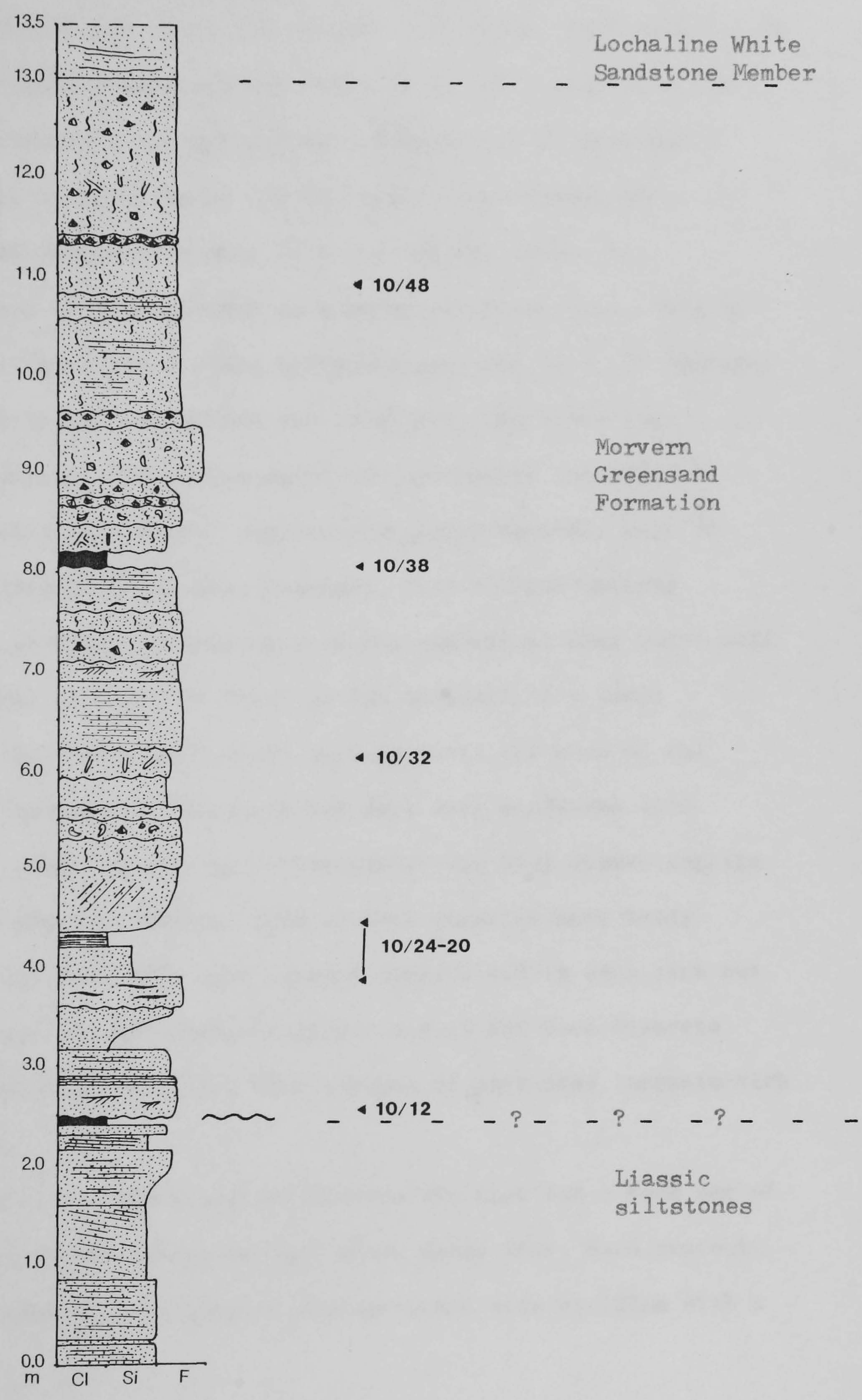
The borehole was drilled in 1987 for Tilcon (Scotland) Ltd. and is located on top of the basalt cliff 1km from Castle Cottage, Kinlochaline, on a bearing of 234°SW. Total depth cored was 70.30m. The core boxes are stored in the main adit entrance of the Lochaline Sand Mine (Summer 1988). Core recovery was reported as 100% below 52.36m. The core was logged from 65.67m in the hope of encountering the Liassic-Cenomanian unconformity in the samples.

Section description: (See Fig.3.9).

The basal bed of the logged section comprises 20cm of finely laminated fine grained (187μm) white sand, and black organic-rich silt. The sand laminae are rarely greater than 1mm thick while the silt layers vary between 2 and 5mm. Sand content increases upwards through the bed. This is overlain by a 5cm horizon of black silty clay with thin layers of white mica. Disconformable on this is a 60cm bed of laminated sandy silt and blue-grey clay. The laminae average 1.5mm thick and undulate, forming wavy bedding structures. This grades into a 55cm thick coarsening upwards unit of laminated dark grey siltstone and very fine-grained (125μm) white sand which increases as a percentage of the sediment upwards. The whole unit is highly bioturbated with small, (maximum length 3cm), *Monocraterion* type vertical burrows with spreiten.

There is a planar contact with 15cm of dark greyish-green homogenous sandstone. This grades into a 10cm thick horizon of very dark greenish-black micaceous silty sandstone. The sandstone is very fine-grained (125μm) and fissile where the micas form layers.

Fig.3.9 LOG 7 Loch Aline Borehole 10/87



This is overlain by a 5cm horizon of greyish-black silty clay.

A marked irregular erosion surface is overlain by 33cm of fine-grained ripple cross-laminated glauconitic sandstone. White sand grains pick out many of the foresets and although the scale of the cross-lamination decreases upwards, the ratio of glauconitic to white sand remains constant and there is no difference in grain size. Some foresets are defined by concentration of glauconite grains. This is overlain by 7cm of ripple cross-laminated fine-grained glauconitic sand with the laminae formed by concentration of organic-rich dark brown silty material. 26cm of pale green fine-grained silty sandstone succeeds this. It contains rare organic-rich laminations and occasional *Skolithos* type vertical burrows. There is a sharp but apparently non-erosive contact with a 45cm thick, rapidly coarsening upwards, unit of micaceous dark greenish-grey mudstone. Silt content becomes noticeable at 10cm and increases at the expense of clay until sand grains appear at 25cm. At the top, the sediment is a sandy siltstone. An irregular erosion surface forms the base of the overlying 35cm unit of fine-grained dark grey sandstone with occasional ripple drapes up to 2mm thick. The clay drapes contain rare black plant fragments. 30cm of dark greenish-grey sandy siltstone follows. This unit appears massive and is mica rich but the micas are disseminated throughout and do not form discrete layers. Overlying this is a 15cm horizon of dark grey, organic-rich silty clay.

There is a sharp contact between the clay and a 65cm bed of coarsening upwards micaceous dark green sandy silt. Sand content increases upwards, reaching an average grain size of 125μm with a maximum of 250μm. Possible cross-bedding is indicated by the concentration of the coarser quartz grains and glauconite into thin, inclined laminae. This is overlain by 30cm of homogenous pale greenish-grey fine-grained sandstone. Both the upper and lower boundaries of this bed appear irregular. A 20cm thick unit of fossiliferous sandstone follows. The sandstone is fine-grained and pale grey-green in colour. The fossils comprise thick-walled bivalves but these could not be identified further. Shell walls were up to 3.5mm thick.

Disconformably overlying the shell bed is a thin (15cm) unit of ripple cross-laminated fine-grained pale green sandstone with clay ripple drapes, some of which bifurcate. The clay is dark grey in colour. This bed is truncated by an irregular erosion surface and is overlain by 31cm of very fine-grained massive silty sandstone which in turn is overlain by a 27cm thick unit of fine-grained very glauconitic sandstone with numerous small sub-vertical burrows infilled with fawnish-grey clay. The maximum diameter of these burrows is 1.2cm. This bed fines upwards as silt content increases with respect to quartz grains.

Overlying an irregular erosion surface is a 70cm thick unit of hard dark green fine-grained sandstone. This is finely laminated throughout, the laminae comprising coarse grained (up to 500μm) layers up to 3mm thick. This lamination is slightly inclined to bedding. This grades into a 20cm horizon of intensely laminated, highly glauconitic and micaceous sandstone. The laminae are formd by concentrations of organic-rich silt up to 2mm thick. Discomformable on this is a 20cm thick shelly bed with *Neithea* type valves forming the most common identifiable fossil. The matrix sandstone is fine-grained, glauconite rich and highly micaceous.

There is an irregular contact with 23cm of highly bioturbated fine-grained greyish-green sandstone. No individual burrows are visible but the general aspect of the bed is disturbed. This is overlain by 44cm of finely laminated fine-grained glauconitic sandstone. The laminae are organic rich. In the lower 15cm of the bed there are clay lenses (possibly ripple drapes); these disappear as the lamination becomes more intense. This is disconformably overlain by a 15cm horizon of very soft dark greyish-green clay.

Brown-grey silty sandstone follows with occasional bright green glauconite lenses. This bed is 27cm thick and has irregular lower and upper boundaries. The glauconite rich lenses may be burrow infills. Overlying this is a 19cm thick dark greyish-green fine-grained sandstone with occasional shell fragments. This is disconformably overlain by a 7cm thick concentrated shell bed. The shelly material is tightly packed in a matrix of fine-grained dark green sandstone. It is not possible to tell if the shells are whole or fragmented.

The shell bed grades into a 17cm thick fining upwards horizon of the matrix sandstone with occasional shells (or fragments). The silt percentage of the sediment increases upwards and thus the grain size decreases to 125μm.

There is a marked irregular erosion surface followed by 53cm of hard greyish-green fine to medium grained sandstone. This contains pieces of shelly material which appear to be fragmented. This is overlain by a 14cm unit of mottled green and fawn fine-grained micaceous sandstone with a shelly layer at the top. A

95cm bed of hard light fawn fine to medium grained sandstone is unconformable on this. Occasional parallel lamination is picked out by layers of coarser grains (up to 300μm) with some heavy minerals. 25cm of intensely laminated light fawn fine-grained sandstone follows. Laminations comprise concentrations of silt-grade brown organic rich material. Disconformable on this is a 54cm bed of mottled purple-brown and greenish-fawn fine-grained sandstone. Burrows appear as light fawn infills with a dark reddish-orange rim. In the top 15cm of the bed fragments of lignitic material up to 1.2mm long are common.

This is disconformably overlain by a thin (7cm) shell bed. The shells are concentrated, thick-walled and probably consist mainly of *Exogyra* spp. The matrix material comprises fine-grained purplish-red sandstone which is highly micaceous. Overlying this is 1.55m of mottled purple-red to pale green fine-grained sandstone. Shelly material is distributed sparsely throughout. Burrows, mainly sub-vertical and not exceeding 1.3cm in diameter are picked out by glauconite concentration in the walls. Conformably overlying this is a 55cm thick bed of unfossiliferous fine-grained very pale fawn sandstone. Very rare low angle foresets are picked out by the concentration of glauconite and heavy minerals. The base of this bed forms the base of the Lochaline White Sandstone Member at this locality. The unit grades into 91cm of greyish-white fine to medium grained (250μm) massive sandstone.

Unconformable on this bed is a 20cm thick unit of reddish-brown clayey silt. This is overlain by red basalt.

The thickness of the "Cretaceous" lithostratigraphic units logged from Loch Aline Borehole 10 is as follows:

Lochaline White Sandstone Member 1.46m

Morvern Greensand 10.44m*

Total thickness of section 11.90m

*The base of the Greensand, on lithology alone, is taken as the base of bed 9 (See Fig.3.9).

3.3 The Mull sections.

Greensand, silicified chalk and micritic limestone of "Cretaceous" age outcrop in the southern half of the Isle of Mull. The sections are widely scattered (See Fig.1.1) but exposure is generally a little better than that of the Morvern sections.

3.3.i. Allt na Teangaidh, Gribun. (AT)

Section location: G.R. NM 4540 3295. (See Fig.3.10).

The exposure is in the Allt na Teangaidh burn itself and in small outcrops adjacent to the stream bed. It can be approached either by walking upstream from Balmeanach Farm or by climbing the crash barrier and fence where the B8035 bends sharply northwards at G.R. 4545 3290. From the barrier walk due west down the steep side of the valley to the stream, then turn upstream to the first greensand outcrop next to the burn. Towards the top of the section there is a tectonic contact between the greensand and the silicified chalk: the true greensand-silicified chalk contact is seen only in the stream bed. This is the type locality for the Gribun Chalk.

Section description: (See Fig.3.11).

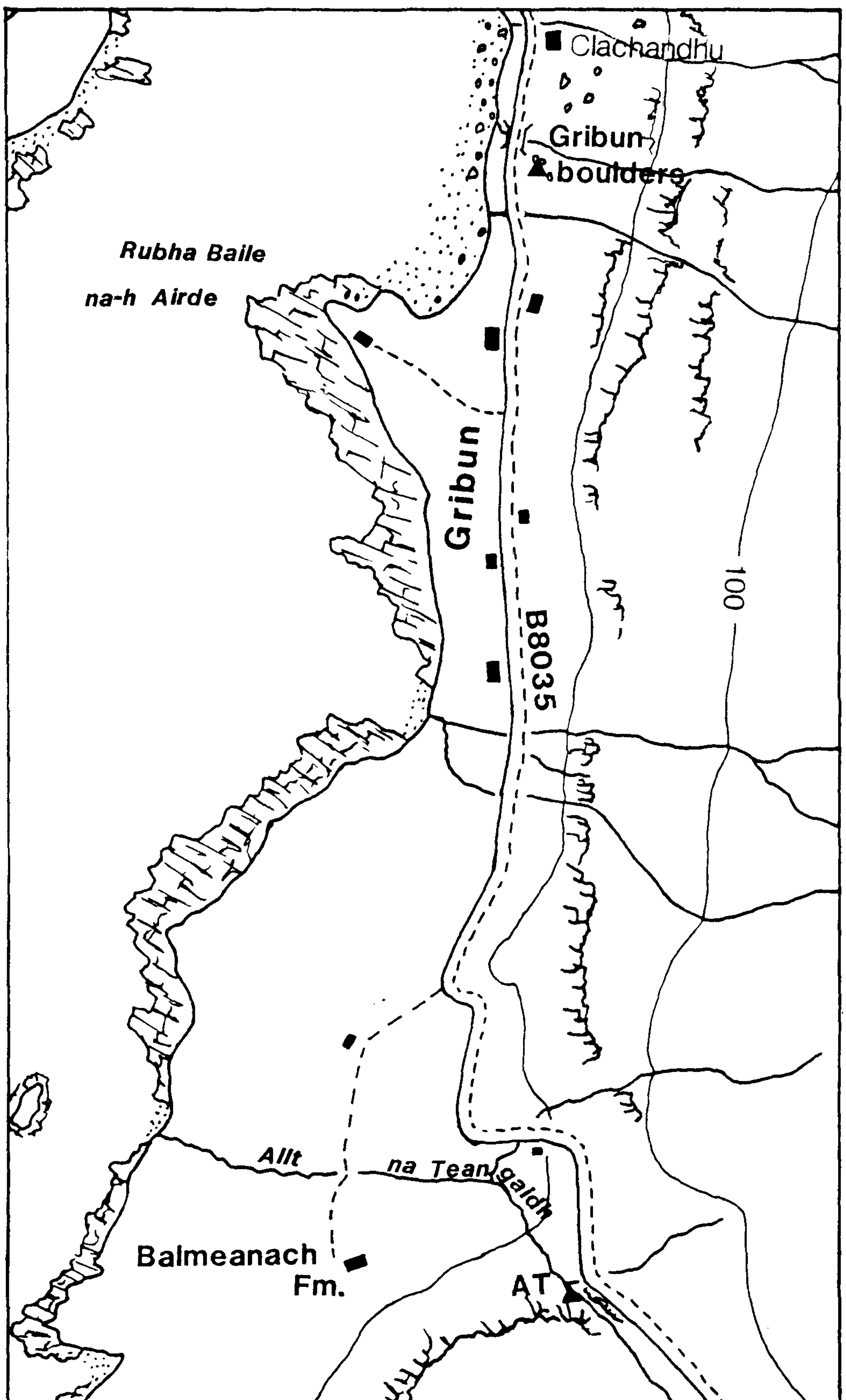


Fig.3.10 Map of Gribun, Mull.

Fig.3.11 LOG 8 Allt na Teangaidh

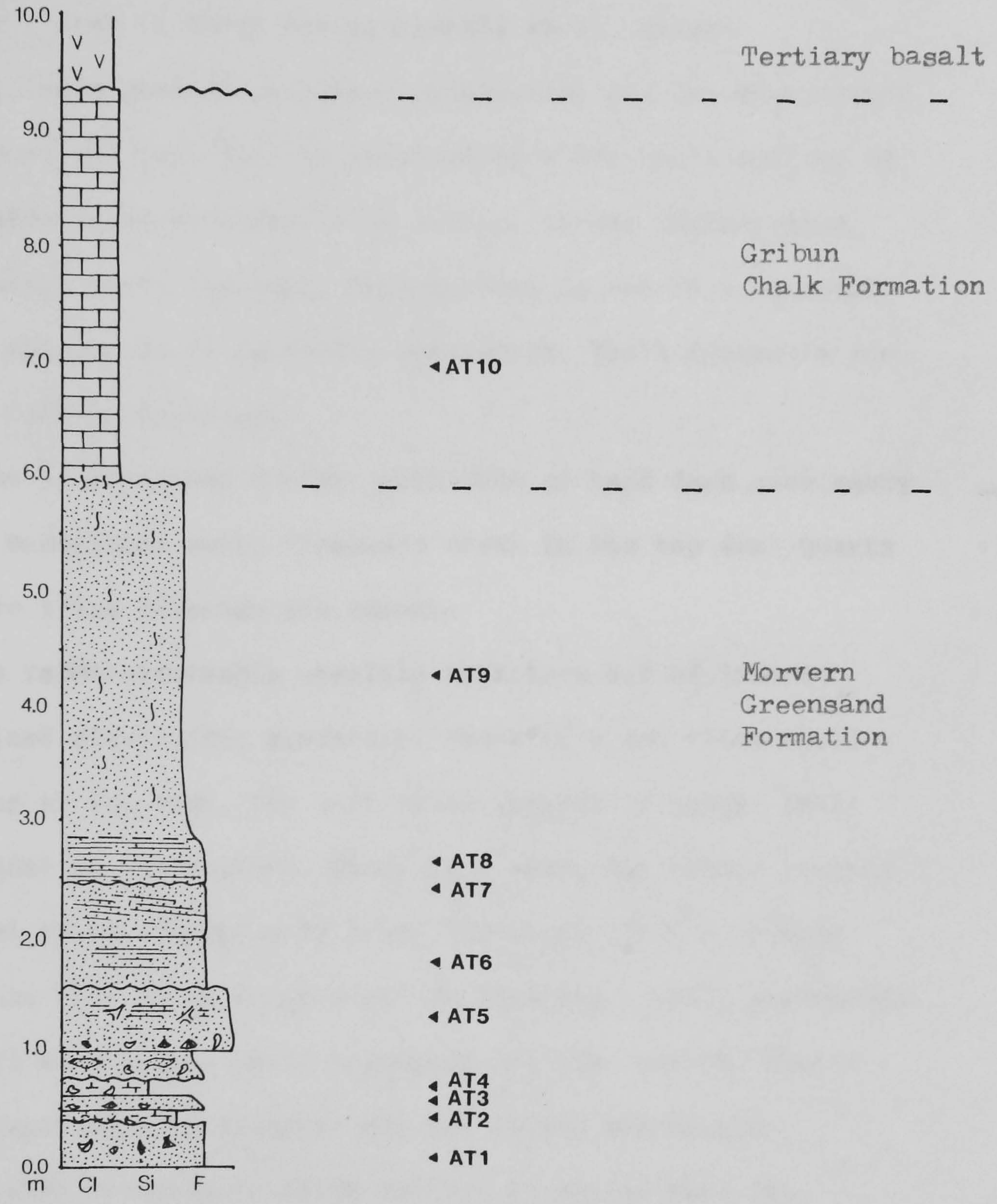


Fig.3.12a. Contact between the Morvern Greensand and Gribun Chalk, Allt na Teangaidh, Gribun.

Fig.3.12b. Limestone "concretions" in glauconitic sandstone, Allt na Teangaidh, Gribun.

being up to 47cms long and 18cm thick (See Fig.3.12b). Laminae in the surrounding sandstone appear to drape the "concretions" but are otherwise parallel to bedding. The lamination is defined by the concentration of coarse quartz grains (up to 375μm in diameter).

Apparently conformable on this "concretionary" bed is a 56cm unit of laminated fine to medium grained glauconitic sandstone. This also contains occasional limestone "concretions" but these measure only 24cm in length and reach a maximum thickness of 11cm. There are some shell fragments in the basal 7cm of the bed but these are not concentrated into a lag and show no particular orientation. Parallel lamination and occasional ripple cross-lamination is picked out by the concentration of glauconite grains, heavy minerals and coarser quartz grains (up to 500μm). The thickness and spacing of the laminae decreases upwards from 2mm to 0.5mm. There is an irregular erosive contact with 34cm of hard unfossiliferous, pale green laminated sandstone. The lamination is parallel to the bedding surfaces.

Conformable on this is a 42cm bed of fine-grained silty purple-red to greyish-green laminated sandstone. The laminae are thin (less then 0.5mm) and comprise concentrations of glauconite grains. Overlying this is a thin (5cm) horizon of bluish-grey sndy siltstone. This unit is laterally persistant across the section. There is an irregular contact with 38cm of dark fawn fine-grained sandstone. The colour varies laterally between purple and greenish-fawn and there are impersistant laminations of organic rich silt. These laminae are less than 1mm thick. This grades into 3.10m of fine to medium grained pale fawn to light grey sandstone. The colour is mottled but does not follow sedimentary structures.

There are occasional hard concretions of well-cemented sandstone up to 15cm in diameter.

There is a marked hiatus between this sandstone and the overlying 3.4m of silicified chalk, the Gribun Chalk Formation, for which this is the type locality. The boundary is bioturbated (See Fig.3.12a) but there is little mixing of the sediment outside the burrows. The silicified chalk is white in colour and extremely brittle which gives a rubbly appearance to the weathered surface.

The thickness of the lithostratigraphic units in the Allt na Teangaidh section are as follows:

Gribun Chalk 3.4m

Lochaline White Sandstone Member 3.10m

Morvern Greensand 2.86m

Total thickness of section 9.36m

3.3.ii Boulders, Clachadhu Bridge, Gribun. (GR boulders)

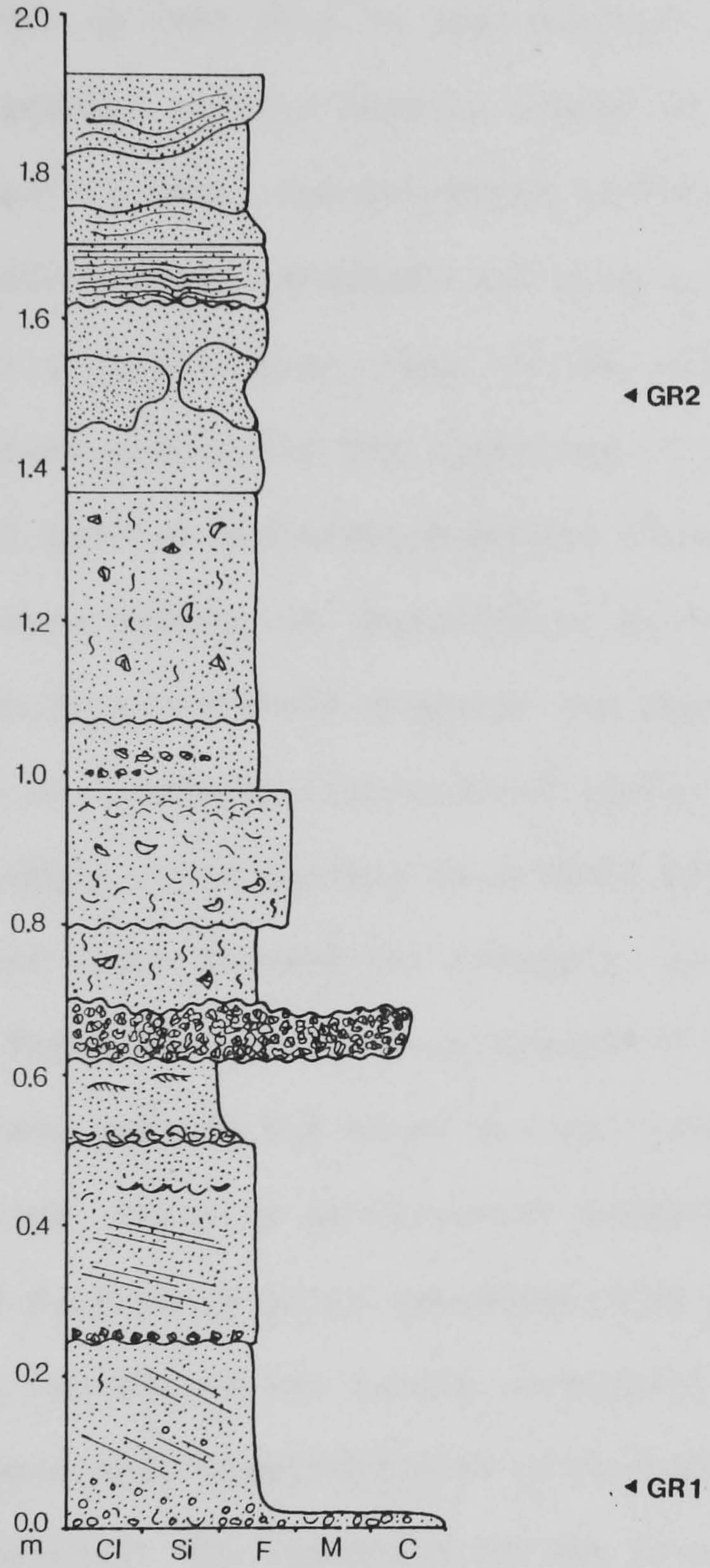
Section location: G.R. NM 4571 3564. (See Fig.3.10).

Approximately 400m north of Clachadhu cottage and 200m south of a bungalow opposite Rubh a'Ghearrain, is a bridge where the B8035 crosses a small un-named stream. About 10m ESE of the bridge are two boulders of greensand (of which the largest is designated Boulder A, the smaller being Boulder B). 11m SE of these boulders is a half-buried block of silicified chalk (Boulder C).

Section description: (See Fig.3.13).

These boulders represent the northward extension of the Allt na Teangaidh section but this is not exposed in the cliffs. Boulder

Fig.3.13 LOG 9 Gribun boulder A



Morvern
Greensand
Formation

A was logged because structures were well preserved and it provided the best example of greensand in the north side of Gribun bay although not *in situ*. Way up was defined on sedimentary structures.

The base of the section is a thin (5cm) pebble conglomerate layer which grades up into 25cm of fine-grained glauconitic sandstone. The pebbles reach a maximum lemgth of 4cm and average 2cm. They are well-rounded, sub-spherical to elongate and are dominated by reddish-brown sandstone and vein quartz clasts. Occasional shell fragments also occur in the conglomerate. Low angle tabular cross-bedding of the sandstone is picked out by occasional small pebbles and heavy minerals concentrated on the foresets. The cross-bedding is truncated by an irregular erosion surface overlain by a 3cm shell fragment lag deposit. This grades into a 23cm bed of micaceous fine-grained highly glauconitic sandstone. Low angle cross bedding is defined by sediment grading with the coarsest layer forming the foresets. Foreset height averages 10cm. There are rare concentrations of *Neithea* valves orientated concave upwards but these are not laterally continuous for more than 25cm. There is an irregular erosive contact with 11cm of fine-grained dark green silty sandstone with a basal lag of *Exogyra* valves. The shells are mainly orientated concave upward. Small-scale ripple cross-lamination is picked out by dark brown organic rich material. The intensity of the ripple cross-lamination increases upwards so there is an overall fining of the sediment through the bed.

There is then a highly irregular erosion contact with a bed composed almost entirely of oyster shell fragments. The top surface of this unit is undulating and the orientation of the fragments picks out the foresets of tabular cross-beds making up symmetrical mega-ripples with a wavelength of 26cm and a foreset height of 8cm. Most of the shell fragments, even though forming the structure, are orientated concave upwards.

Conformable on the shell bed is a 10cm thick horizon of fine-grained grey-green sandstone with occasional *Neithea* valves throughout. These show no particular orientation. This is overlain by 18cm of shelly sandstone. The matrix is fine-grained glauconitic sandstone. The shell material is disseminated throughout the bed and generally orientated concave upwards until the top 4cm of the bed where it becomes more concentrated and orientated concave down. Valves are thin-walled and the size of the fragments decreases upwards from an average length of 4cm at the base to 1.8cm at the top. Apparently conformable on this are 9cm of fine-grained glauconitic sandstone containing linear concentrations of *Neithea* fragments parallel to bedding.

There is an irregular erosion surface, then a 30cm bed of fine-grained micaceous fawn-green sandstone. Rare lenses of shell fragments occur in this bed. This grades into a 25cm unit of fawn-grey fine-grained sandstone containing sub-rounded "concretions" of sandy limestone. The "concretions" are up to 45cm long and reach a maximum thickness of 20cm. The material inside the "concretions" is finer grained than the surrounding sandstone but shows no internal structure.

Disconformable on this is an 8cm horizon of finely laminated fine to medium grained sandstone. This drapes the underlying bed and grades upwards into another 22cm of concretionary sandstone. The matrix sandstone is fine to medium grained, fawn-green in colour and finely laminated. The "concretions" are composed of fine-grained grey silty sandstone, are elongate in shape and reach a maximum length of 30cm.

Total thickness of Morvern Greensand: 1.92m

Boulder B was not logged, being considered too small (1.3m).

Boulder C is composed of silicified chalk. This is extremely brittle as the scree downslope from the boulder testifies. Unlike the silicified chalk seen at the Allt na Teangaidh section, this chalk can be seen to contain flints. However, as there is no textural difference between the silicified chalk matrix and the flint and the material weathers white, these are only seen where the rock surface is fresh.

3.3.iii. Auchnacraig Cliff, Loch Don. (AU)

Section location: G.R. NM 7440 2989 (See Fig.3.14).

At around G.R. NM 7400 3030, on the road to Grass Point, is a gate into a field bordered by deer fences. Follow the eastern fence to the edge of the basalt cliff. To the left of the small hummock with trees climb down a sea-facing gully as far as possible, then continue SW along the platform formed by the lower basalt, following a goat path. Where this is crossed by a basalt dyke walk to the sea. The exposure is between the dyke, a sill cross-cut by the dyke and the sea. Part of the exposure is covered by large pebbles and below the high tide mark it is obscured by algae. This site is an ornithological SSSI and permission should be obtained from the estate before visiting, especially in the spring to early summer.

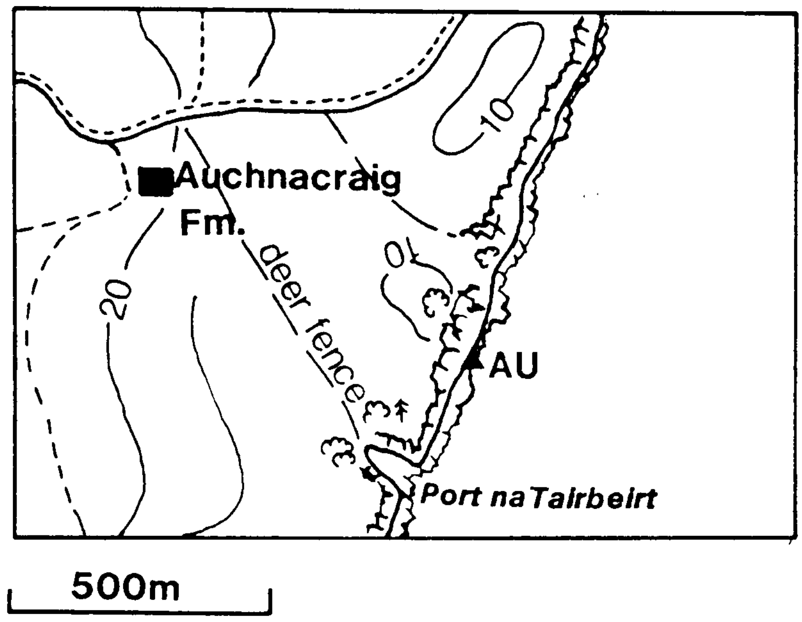


Fig.3.14 Map of Auchnacraig, Mull.

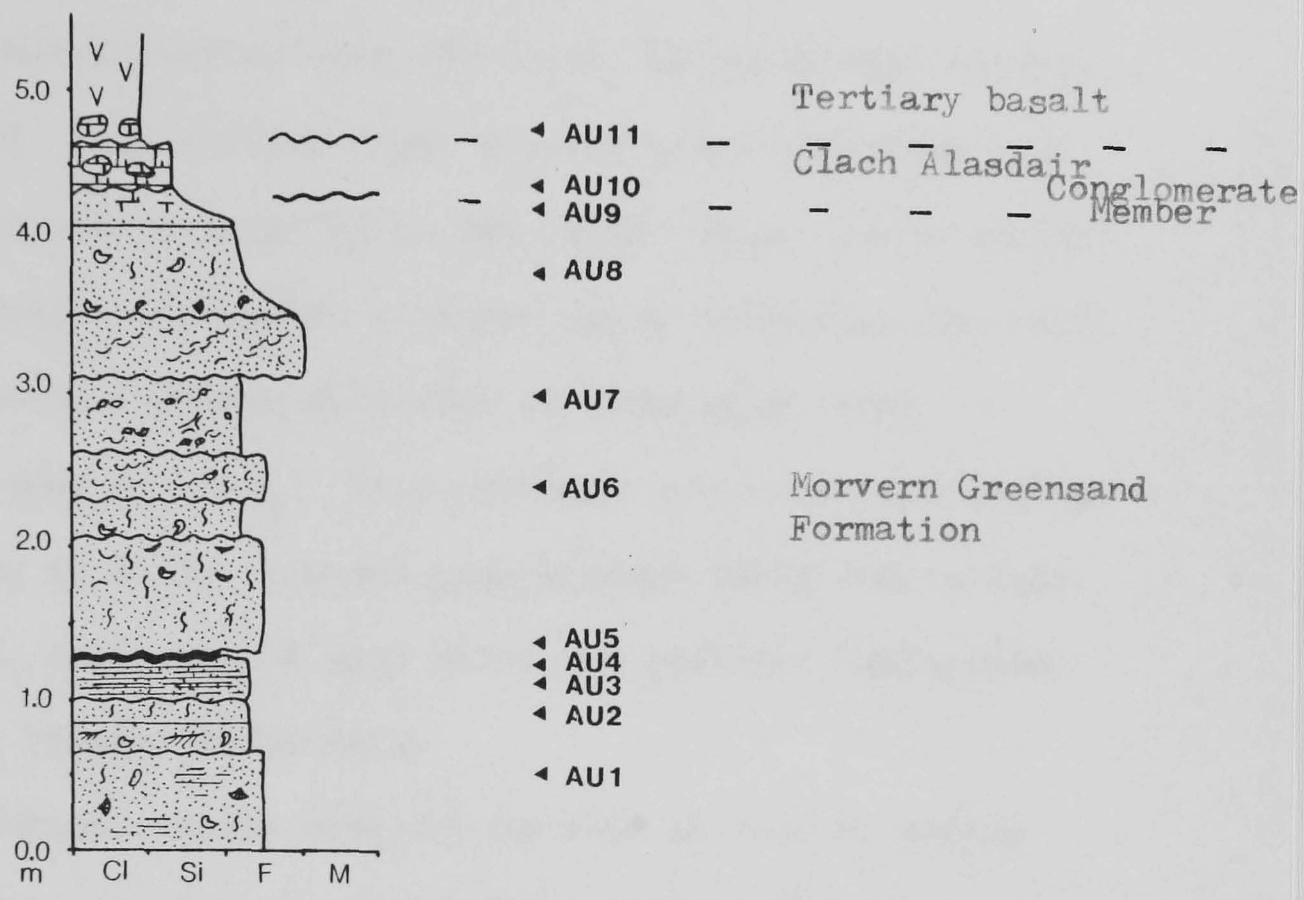
Section description: (See Fig.3.15).

The base of the section is an almost vertical drop into the sea. The lowest bed comprises 65cm of fine-grained well-cemented light fawn sandstone. Weathering has exposed parallel laminations, some dipping at up to 15° from bedding. Some of the laminae are dark in colour due to the accumulation of organic material; others are formed by the concentration of very fine sand layers. Throughout the bed are *Exogyra* valves.

There is an irregular erosive contact with 20cm of fawn-green silty sandstone. Small-scale ripple cross-lamination occurs throughout this unit, picked out by organic-rich material. Apparently whole, *Exogyra* are scattered throughout. Although thin, this bed is laterally continuous.

This is conformably overlain by 25cm of fine-grained hard glauconitic sandstone. Medium scale tabular cross-bedding is picked out by concentrations of shell debris. Average foreset height is 23cm and foreset dip is 18°SSW. There is an irregular contact with a 28cm bed of laminated pale green silty sandstone. The laminae are apparently organic rich and up to 0.8mm thick but they are not laterally persistant. There is an extremely thin (maximum thickness 1.4mm) clay drape over some of the ripple forms. The top of this bed is overlain by a 1.5cm horizon of fawn-green laminated silty sandstone. This is persistant over at least 1.5m laterally but is not exposed further. Apparently conformable on this is 54cm of micaceous pale green fine-grained sandstone. There is a 6cm thick shelly layer at the top of this bed which is otherwise

Fig.3.15 LOG 10 Auchnacraig Cliff



structureless. It is overlain by 21cm of pale green fine-grained sandstone with shell fragments throughout. These fragments become more concentrated towards the top and are orientated concave upwards with their long axes trending NNE-SSW.

There is an irregular contact with 24cm of fine-grained greyish-green micaceous sandstone. Occasional shell fragments occur at the base but no sedimentary structures are visible. The grain size decreases upwards from 250-187μm. Disconformable on this is a 30cm bed of fine-grained light greyish-green sandstone with occasional shell debris bands up to 8mm thick. These are laterally impersistant. Small thin-walled bivalves occur throughout the unit. There is an erosive boundary with 55cm of light grey, very fine-grained, sandy limestone. This contains occasional sub-angular quartz clasts up to 5.4cm long and impersistant shell debris lags up to 5cm thick. Shell debris also picks out parallel lamination and small scale tabular cross-sets.

This is disconformably overlain by 40cm of fine to medium grained glauconitic sandstone. Small thin-walled bivalves are concentrated on the foresets of medium-scale, SSW dipping, tabular cross-beds. Foreset height averages 24cm. There is an erosive contact with 60cm of greenish-grey fine-grained sandstone with an *Exogyra* lag at the base. This fines upwards to hard grey sandy limestone.

This is truncated by an highly irregular erosion surface overlain by 55cm of very poorly sorted chalk clast conglomerate. Clasts range in size from <1mm to 56cm in length, are angular to sub-angular in shape and comprise silicified chalk and flints. The conglomerate appears to be matrix supported, the matrix consisting of dark grey sandy micritic limestone with occasional accumulations of shell debris and quartz grains up to 750μm in diameter. The general structure of this bed is chaotic with no evidence of any size sorting.

Unconformable on this is 1.8m of basalt. At 20cm into the basalt is a horizon of sub- to well-rounded silicified chalk clasts which reach a maximum length of 26cm and are orientated with their long axes parallel to bedding. These clasts show evidence of baking (See Frontispiece Plate).

The thickness of lithostratigraphic units at Auchnacraig Cliff is as follows:

Clach Alasdair Conglomerate Member 55cm

Morvern Greensand 4.25m

Total thickness of section 4.79m

3.3.iv. Torosay Castle Old Quarry. (TC)

Section location: G.R. NM 7245 3521 (See Fig. 3.16).

Take the right-hand track 200m south of the signposted turning to Torosay Castle on the A849. Where the track bends sharply southwards, an outcrop is visible about 12m from the track on a bearing of 270°. This is the main part of the old quarry comprising Jurassic limestone. In the hill directly above the old quarry is a much smaller excavation exposing dark grey limestone belonging to the Inner Hebrides Group.

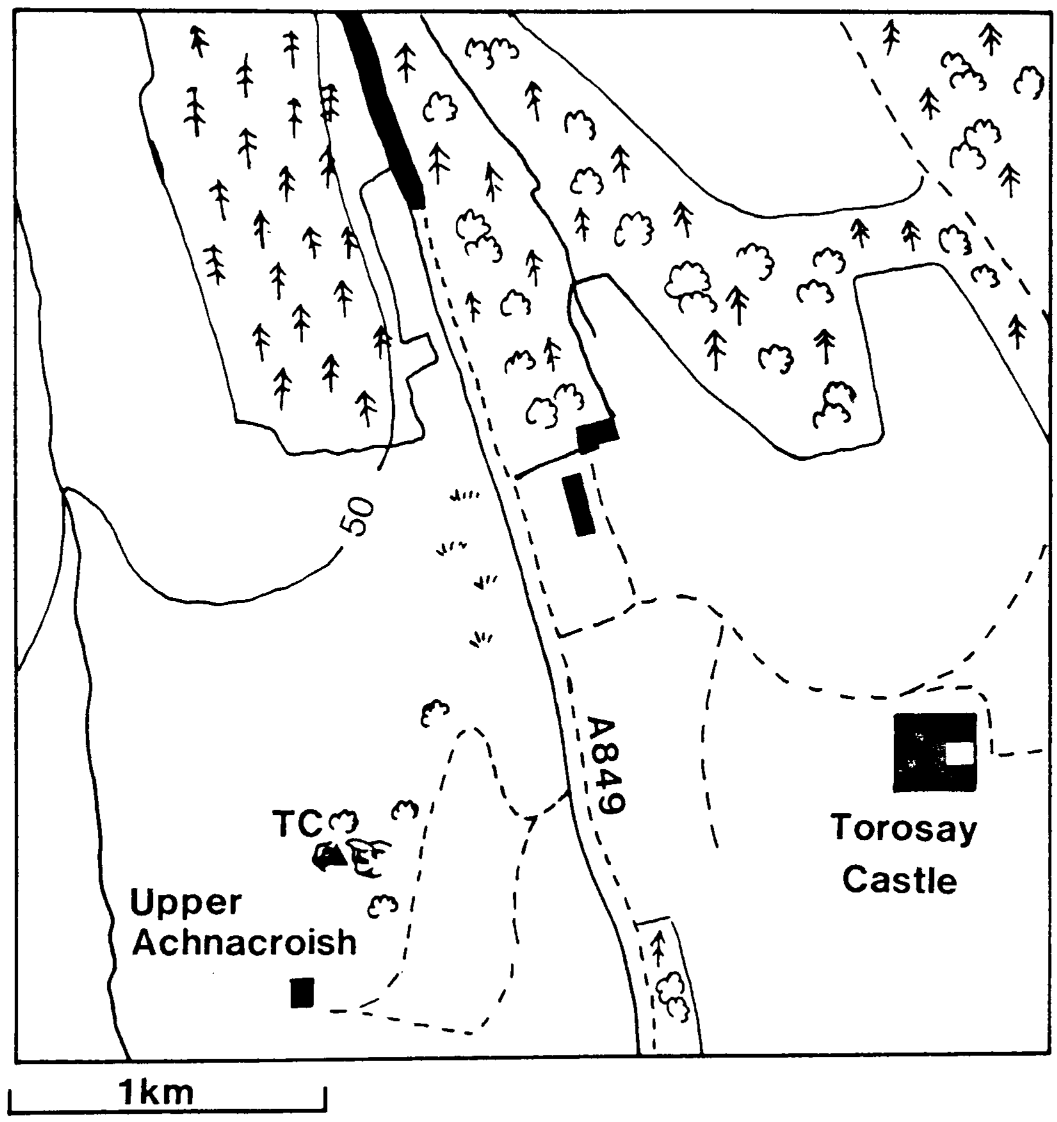
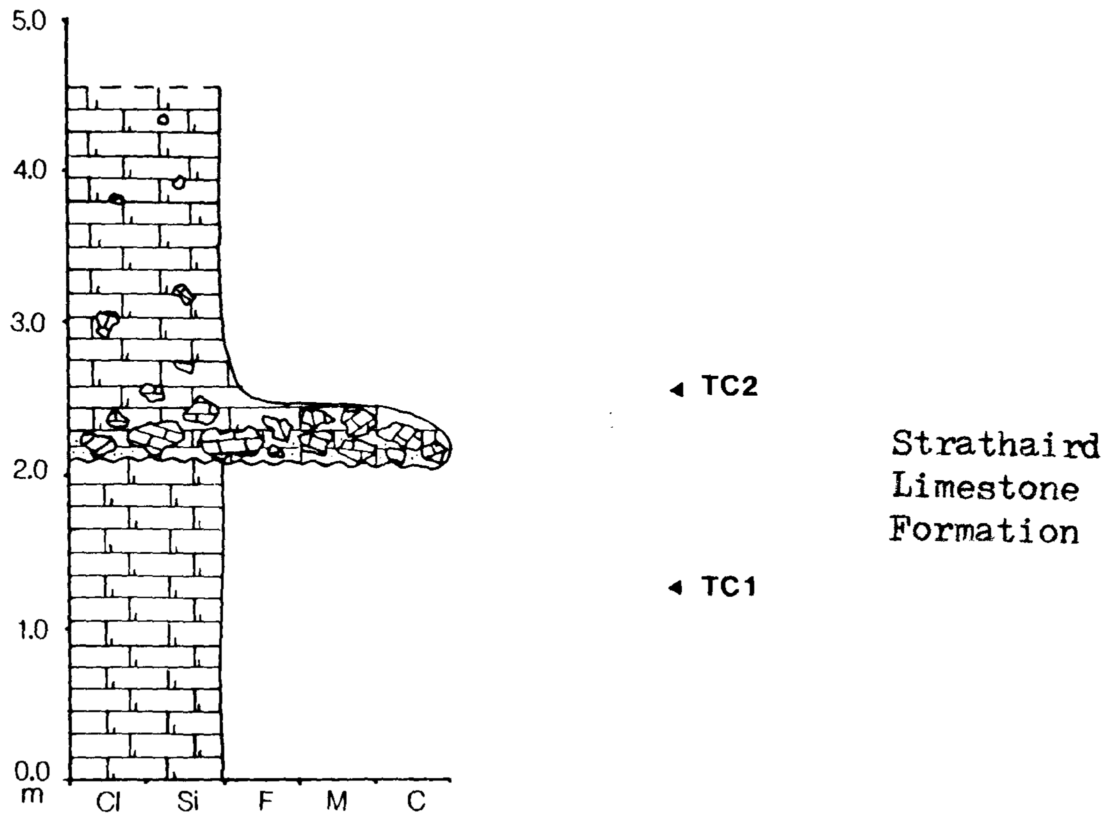


Fig.3.16 Map of Torosay, Mull.

Fig.3.17 LOG 11 Torosay Castle



Section description: (See Fig.3.18)

The basal unconformity with the Oxfordian limestone in the main quarry is not exposed. The section starts with a 2.1m unit of hard, very fine-grained, dark grey micritic limestone. No macrofossils are visible but stylolites are common. An irregular erosion surface of overlain by a 40cm horizon of sparse silicified chalk conglomerate. Clasts are angular to sub-angular and reach a maximum length of 10cm. The conglomerate is matrix supported and extremely poorly sorted. This bed grades into 2.03m of hard, dark grey, micritic limestone with occasional angular silicified chalk clasts up to 4cm long. There is no apparent preferred orientation of clasts but their size decreases upwards as does their frequency.

The total thickness of the Strathaird Limestone in this section is 4.53m.

3.3.v. Feorlin Tributary, Carsaig. (FT)

Section location: G.R. NM 5317 2225 (See Fig.3.18).

From Feorlin Cottage walk up the Abhainn na Feorlin valley for about 150m to an easterly flowing tributary. The section is where "waterfall" is marked on the 1:25 000 map, approximately 100m up the tributary, the top of the sandstone forming the lip of the waterfall. Directly below the waterfall there is no exposure due to boulders in thie stream bed, however above it, sediments can be traced to the first basalt.

Section description: (See Fig.3.19).

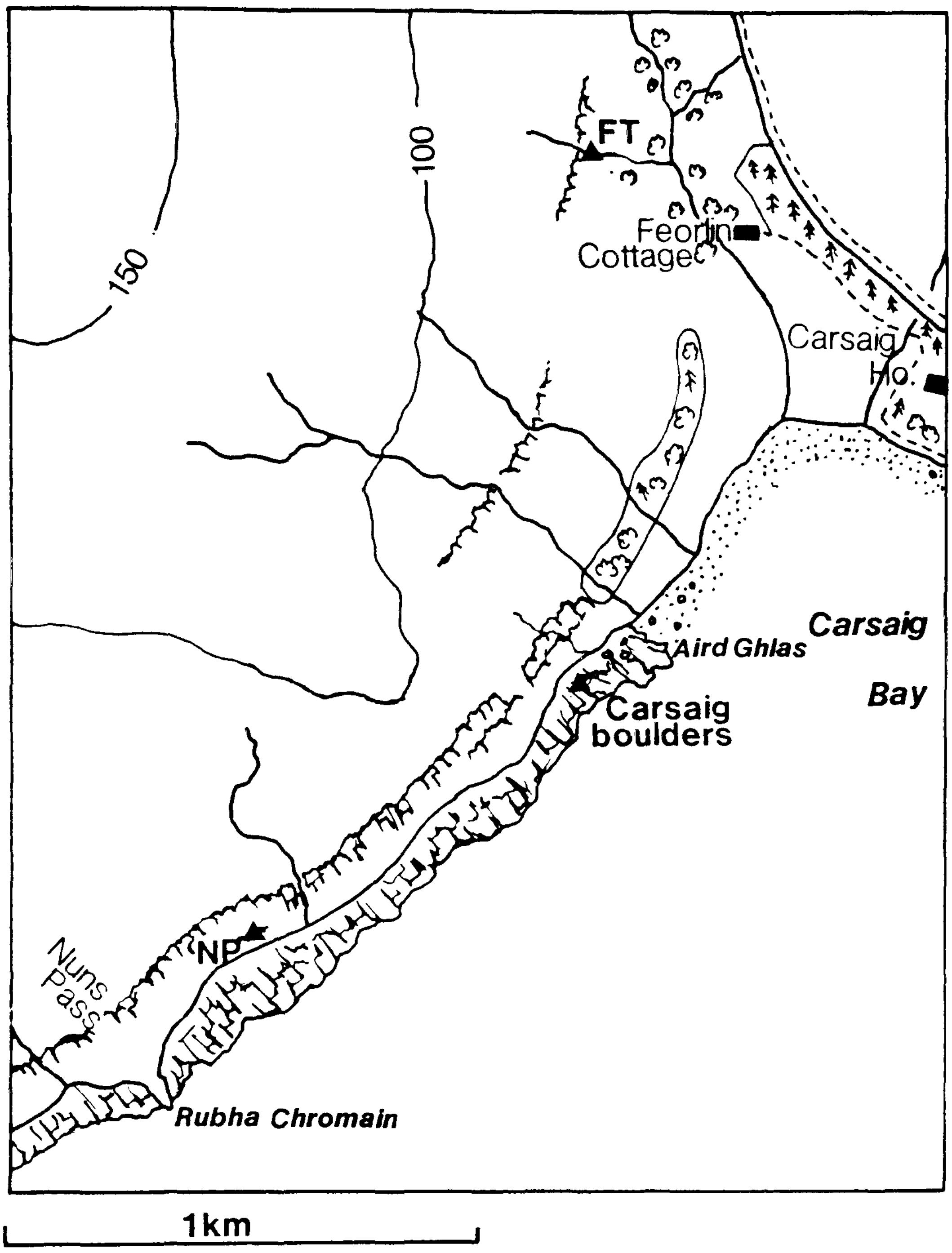
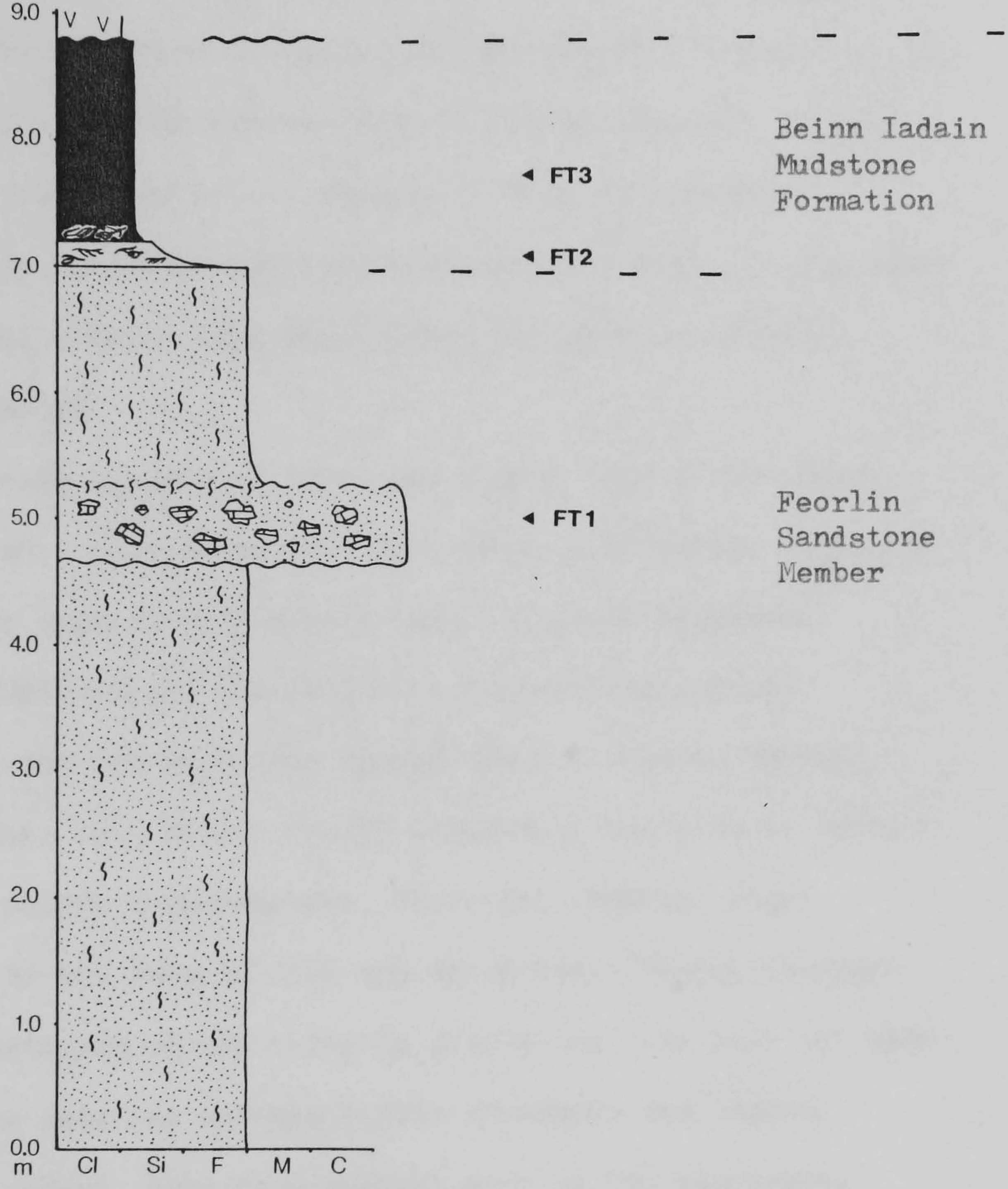


Fig.3.18 Localities near Carsaig, Mull.

Fig.3.19 LOG 12 Feorlin Tributary



The base of the lowest bed is not exposed. This bed comprises 4.60m of fine to medium grained light greenish-grey sandstone. Unconformably overlying this is a 63cm thick pebble conglomerate band. The pebbles consist wholly of silicified chalk and flint clasts. These range in size from 5mm to 6.7cm in length and are angular to sub-angular in shape. The pebbles are matrix supported and decrease in abundance and size upwards. However, throughout the bed the matrix sandstone remains fine to medium grained. At 63cm the conglomorate grades into a further 1.7m of fawn-green sandstone. This sandstone and conglomeratic unit comprise the type locality of the Feorlin Sandstone Member of the Beinn Iadain Mudstone Formation.

This fines upwards to 187μm and grades into a 20cm thick heterolithic unit comprising very fine-grained micaceous sandstone and dark brown organic-rich silt containing plant fragments. Small-scale ripple cross-lamination is common. The overall grain size of the bed decreases upwards as the organic content increases. There is a sharp, though apparently non-erosive contact with 1.6m of purple-grey mudstone. There are numerous plant fragments up to 6cm long in this mud which has a blocky fracture and is not laminated though silty in places. At 1.3m from the base of the bed the mudstone becomes highly micaceous and lighter fawn-grey in colour. This fine-grained part of the succession comprises the Beinn Iadain Mudstone.

Overlying this is basalt.

The total thickness of the Feorlin Tributary section is

F

Fig.3.20 Level of the Morvern Greensand above Carsaig Boulders.

MG - marks the Morvern Greensand strata

S - marks basalt sills.

F - marks the line of the fault which cuts out the greensand facies to the west.

8.80m.

3.4.vi. Carsaig Boulders. (CR boulders)

Location: G.R. 5330 2107. (See Fig.3.18)

Approximately 500m SW of Aird Ghlas (on the coast path to Nuns Pass), are some large blocks of fossiliferous greensand. The sandstone is highly glauconitic and contains thick lags comprising oyster shell debris and occasional conglomeratic horizons. Just to the WNW of these blocks, a minor fault cross-cuts the basalt in the cliff behind and an inaccessible greensand exposure, from which these blocks can be seen to have fallen, is visible (see Fig.3.20).

3.3.vii. Nun's Pass, Carsaig. (NP)

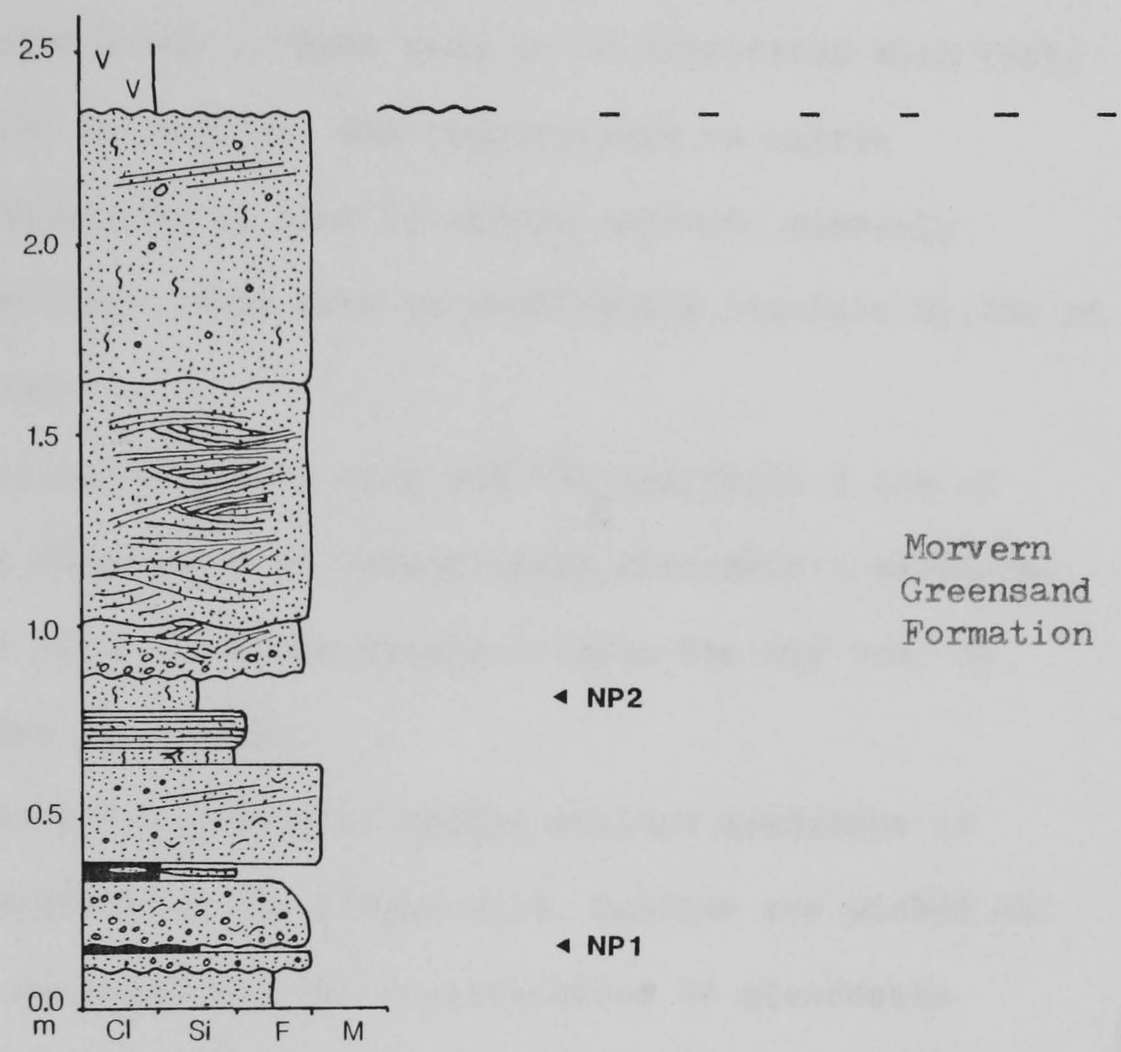
Section location: G.R. NM 5246 2050 (See Fig.3.18).

Follow the coast path S.W. from Aird Ghlas towards Rubh' a'Chromain (past the blocks described above). The "Old Quarries" marked on the 1:25 000 map are barely recognizable, but just past these and approximately 100m west of a large waterfall (also marked on the map), is a small (maximum lateral extent 20m) exposure of greensand sandwiched between two basalt sills.

Section description: (See Fig.3.21).

The section starts with 10cm of non-glauconitic, pale fawn fine-grained sandstone. This is disconformably overlain by a 5cm horizon of pebbly,fine to medium grained, dark green glauconitic sandstone. Pebbles are small (maximum length 6mm), well-rounded and

Fig.3.21 LOG 13 Nun's Pass



composed of quartz. This is overlain by a 3cm thick silty clay horizon.

There is a marked irregular erosion surface overlain by a conglomeratic sandstone bed, 18cm thick. Clasts comprise sub- to well-rounded quartz pebbles up to 5cm long. Occasional thin-walled bivalve shells also occur - these tend to be orientated with their long axes parallel to bedding. The conglomerate is matrix supported, the matrix being fine to medium grained, sparsely glauconitic, sandstone. This unit is conformably overlain by 2cm of greyish-green clay.

Sandwiched between this clay and the overlying 2.4cm of clayey silt is a thin layer of fine-grained glauconitic sandstone. The thickness of this sandstone ranges between 8mm and 2cm. No internal structure is visible.

26cm of parallel laminated medium grained sandstone is apparently conformable on the clayey silt. Laminae are picked out by fine-grained material and the concentration of glauconite grains, small quartz pebbles (up to 5mm long) and thin-shelled bivalves. Overlying this is a 5cm horizon of laminated fine-grained glauconitic sandstone. This grades into 10cm of parallel laminated fine to medium grained sandstone, laminae being defined by grain size differences. This is overlain by 9cm of dark green, highly glauconitic sandstone.

There is a sharp and irregular contact with a 14cm bed of ripple cross-laminated pebbly sandstone. The pebble assemblage is dominated by quartz but well-rounded clasts of pale fawn, fine-grained, well-cemented sandstone are also common. The pebbles reach a maximum length of 1cm and are concentrated on ripple foresets.

A 62cm unit of cross-stratified fine to medium grained sandstone follows. The bounding surfaces of this unit are undulating and the cross-laminae are discordant with foresets and reactivation surfaces. Overlying this is a 70cm bed of massive fine to medium grained, pale green, glauconitic sandstone with occasional lamination picked out by the concentration of fine-grained material. This is unconformably overlain by a basalt sill, above which there is no exposure.

Total thickness of lithostratigraphic units at Nun's Pass is:

Morvern Greensand Formation: 2.34m

3.4. The Eigg sections.

Two sections of "Cretaceous" age rocks outcrop around Laig Bay on the NW coast of the island. The Laig Gorge section was first described by Hudson (1961); the Clach Alasdair section appearing on a map in the same paper.

3.4.i. Clach Alasdair. (CA)

Section location: G.R, NM 4540 8831 (See Fig.3.22).

Walk approximately 1.5km westwards along the beach and coast path from Laig Farm to where the wave cut platform of Oxfordian shale and basalt forms a low headland (Clach Alasdair). The

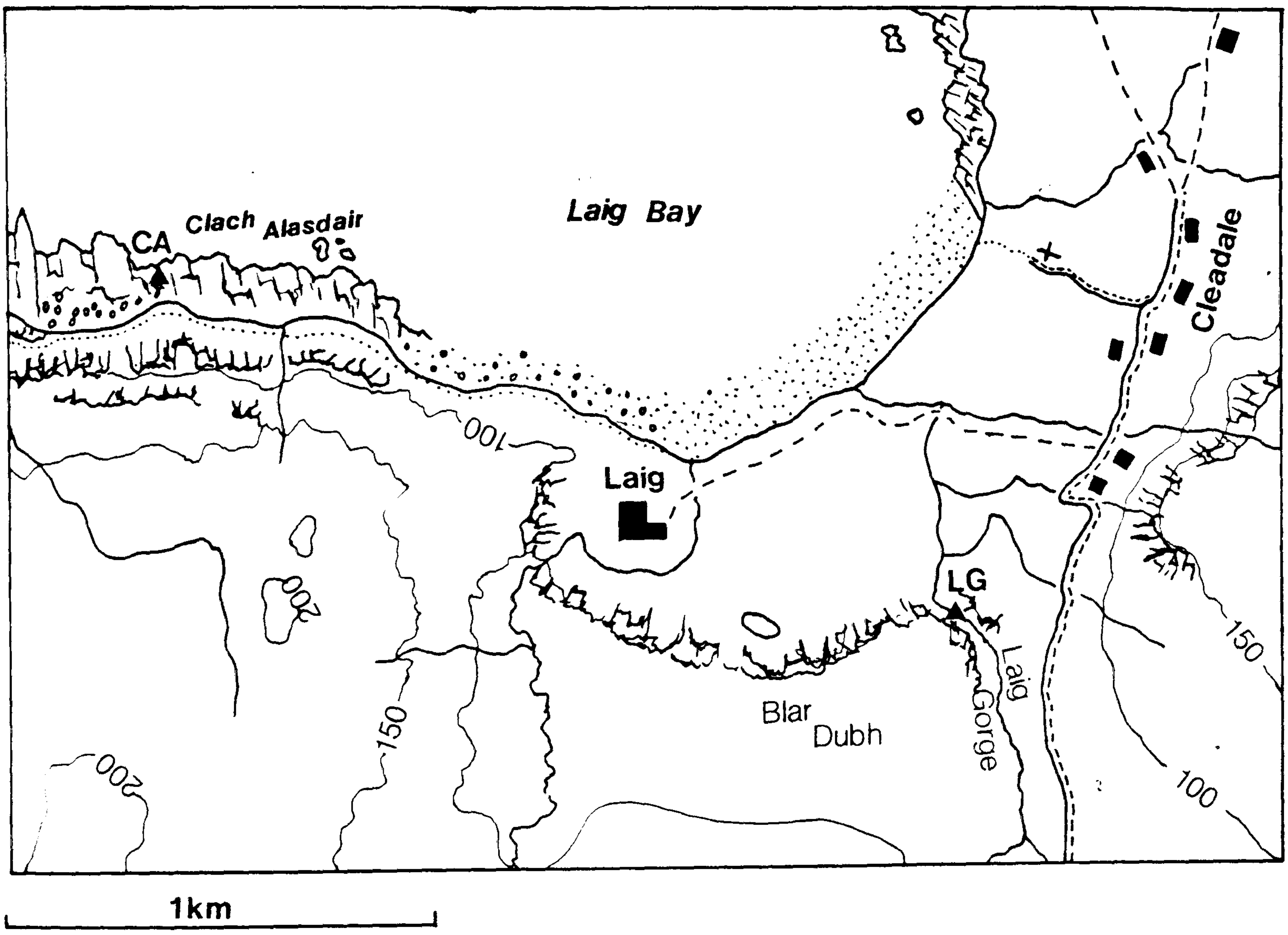
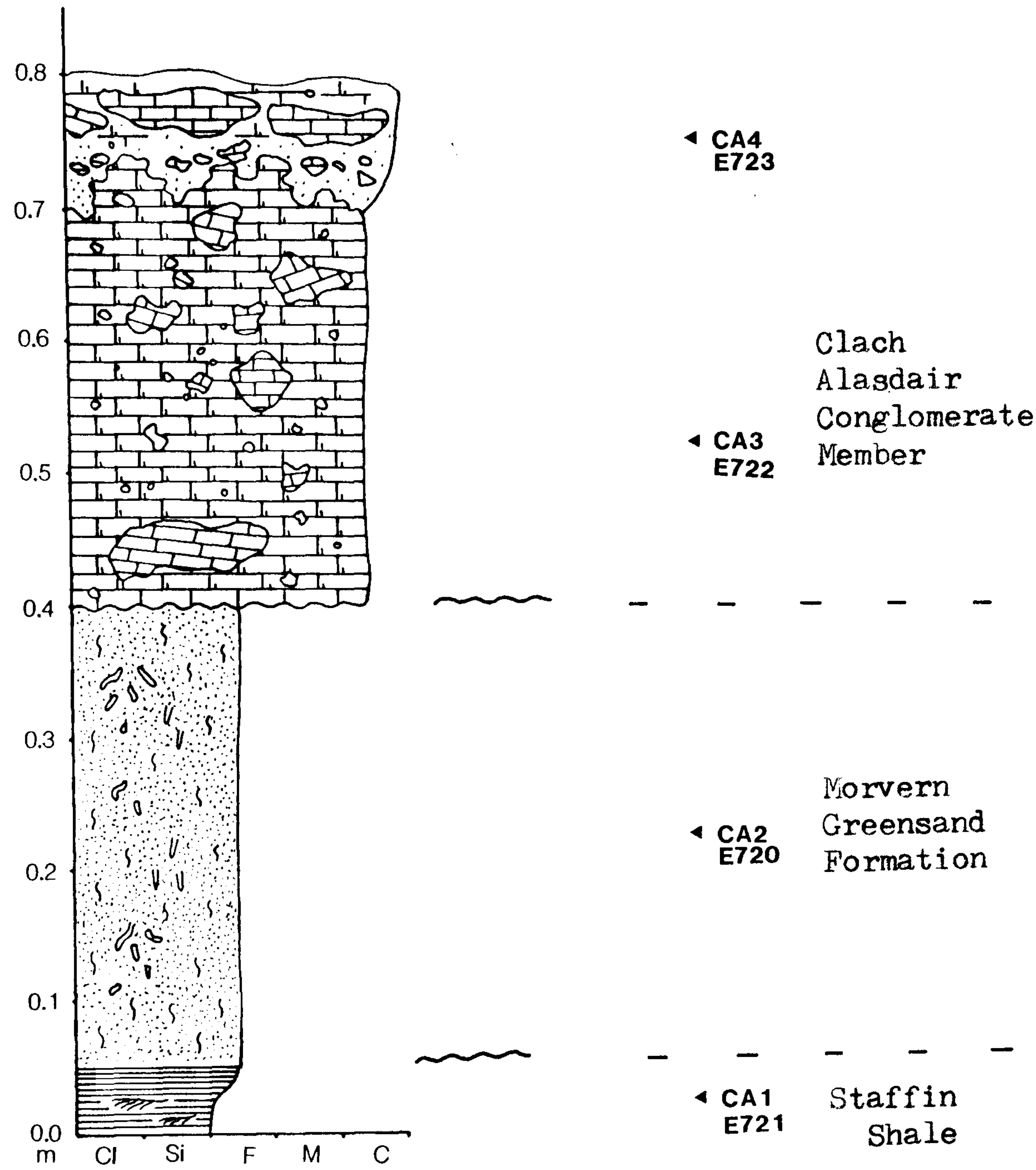


Fig.3.22 Localities near Cleadale, Eigg.

Fig.3.23 LOG 14 Clach Alasdair



section is around 10m seawards from where the sheep track climbs over some weathered basalt pillars (which are a distinctive red colour), and about 5m east of the black basalt of Clach Alasdair. Bearings from the section are 70° on Hulin and 10° on Bla Bheinn, Skye. The exposure cannot be seen from the path.

Section description: (See Fig.3.23).

There is a well-pronounced irregular erosion surface between the Staffin Shale, a dark grey mudstone of Oxfordian age, and the basal bed of the Cretaceous succession. The latter comprises 5cm of finely laminated organic-rich dark brown siltstone and very fine-grained (125μm) sandstone. Laminae are roughly parallel to bedding but there is some small-scale ripple cross-lamination. The sand laminae become thicker upwards, reaching a maximum thickness of 2mm.

There is a sharp but apparently conformable contact with 35cm of fine to medium grained glauconitic sandstone. This is highly bioturbated with *Chondrites* and *Skolithos* burrows infilled with grey silt or highly glauconitic sandstone.

Unconformable on this is a unit of varying thickness (maximum 35cm) comprising a poorly sorted conglomerate, the base of the Clach Alasdair Conglomerate Member of the Strathaird Limestone Formation, for which this is the type locality. The matrix material is quartz sandstone with a grey micritic matrix. Quartz grains up to 3mm long are common but the average grainsize is 250μm. The clast composition is silicified chalk and flint with occasional black phosphatic pebbles up to 3cm long. The silicified chalk clasts tend to be sub-angular to sub-rounded in shape and reach a maximum length of 20cm. There is no apparent preferred orientation of the clasts or size sorting, the general structure of the bed being chaotic (see Fig.4.10).

There is a highly irregular contact with another conglomeratic unit. Because the contact with the underlying bed is so irregular, the thickness of this unit varies between 10 and 32cm. The matrix material is slightly finer than in the former bed, but contains more silt grade material. Silicified chalk and flint clasts occur in size sorted bands. Maximum clast size is 15cm (for rounded to sub-rounded clasts); sub-angular clasts averaging 2cm in diameter. Clasts less than 7cm long tend to be distributed randomly through the bed whereas larger clasts occur in distinct layers. The clasts are orientated with their long axes parallel to general bedding. This horizon is truncated by a gently undulating erosion surface which is overlain by basalt.

N.B. The top 40cm of the section is partially silicified and the matrix appears highly crystalline.

The thickness of lithostratigraphic units logged at Clach Alasdair is as follows:

Clach Alasdair Conglomerate Member 45-50cm

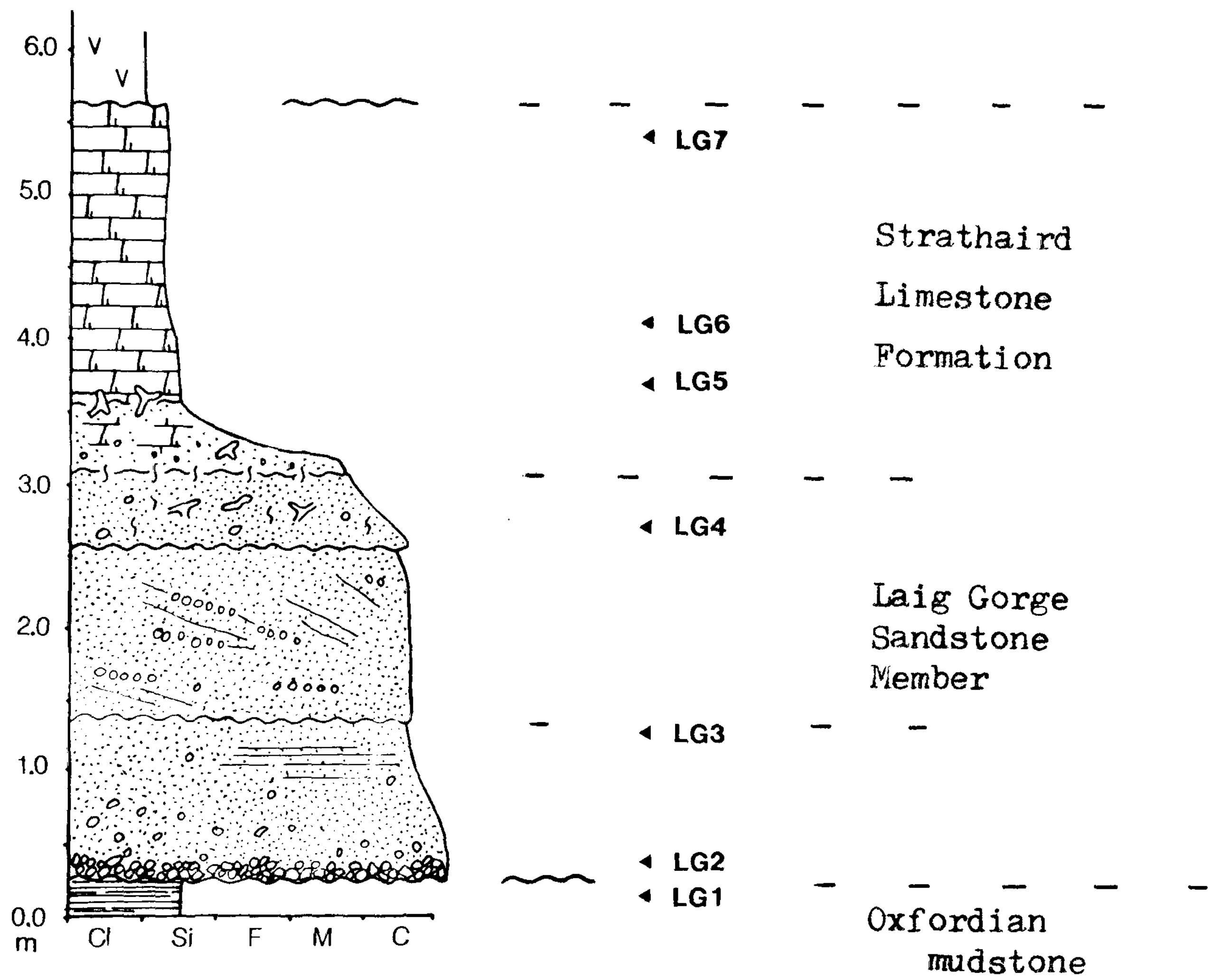
Morvern Greensand 40cm

3.4.ii. Laig Gorge. (LG)

Section location: NM 4735 8750 (See Fig.3.22).

From Cleadale take the road to Galmisdale. After the hill

Fig.3.24 LOG 15 Laig Gorge



out of Cleadale, go through the first gate on the right and walk SW to a small gorse and heather covered hillock formed by a felsite intrusion which acts as the northern side of Laig Gorge. From here the whole section can be seen, the limestone below the basalt being weatered light grey, with the sandstone forming a blocky exposure on the other side of the stream. Extreme care is needed when climbing into the gorge, especially in wet conditions.

Section description: (See Fig.3.24.)

There is a clear unconformity between the Oxfordian black mudstones at the base and the overlying conglomeratic sandstone. The sandstone is 1.1m thick and is extremely poorly sorted, containing clasts up to 5cm in length. These pebbles occur throughout the bed but are concentrated at the base. Mud rip-up clasts from the underlying unit are rare and reach a maximum length of 3.5cm. Black phosphatic and chert pebbles make up around 14% of the clasts composition with the remainder consisting of vein quartz or quartz rich pebbles. The former are mainly sub-angular, the latter predominantly sub- to well-rounded. The matrix sandstone comprises angular to sub-angular quartz grains ranging in size from 250μm to 2mm in diameter.

There is an irregular contact with 1.2m of slightly finer-grained (maximum diameter 500μm), poorly sorted sandstone. This contains rare pebble horizons dipping 18°NE. The pebbles are mainly phosphatic, sub- to well-rounded, and range between 2.5 and 4.2cm in length.

This, in turn, is disconformably overlain by 46cm of fining upwards (~500-375μm) coarse sandstone with small quartz and chert clasts scattered throughout. The pebbles tend to be sub-rounded and reach a maximum length of 5cm. There are elongate limestone nodules concentrated in the top 25cm of the bed which are here identified as *Thalassinoides* burrow infills. These reach a maximum diameter of 6cm. This sandstone part of the succession, from the basal conglomerate to the burrowed horizon forms the type locality for the Laig Gorge Sandstone Member of the Strathaird Limestone Formation.

Overlying this bioturbated surface is an 85cm unit of rapidly fining sandy grey limestone. Occasional sub-rounded quartz clasts occur at the base but the quartz to micrite ratio decreases rapidly upwards. At the top of the bed is a horizon of nodular burrow infills, the limestone inside the burrows being less sandy than the surrounding sediment. This nodular horizon averages 15cm in thickness.

Disconformable on this is 1.6m of hard, dark grey, micritic limestone (the Strathaird Limestone Formation). This appears unfossiliferous and highly crystalline. No primary sedimentary structures are visible but the unit can be subdivided into 20cm "beds" on apparent fissility. However, there appears to be no lithological difference between more or less fissile units. This limestone is directly overlain by basalt but appears unbaked at the contact.

The thickness of logged lithostratigraphic units at Laig Gorge is as follows:

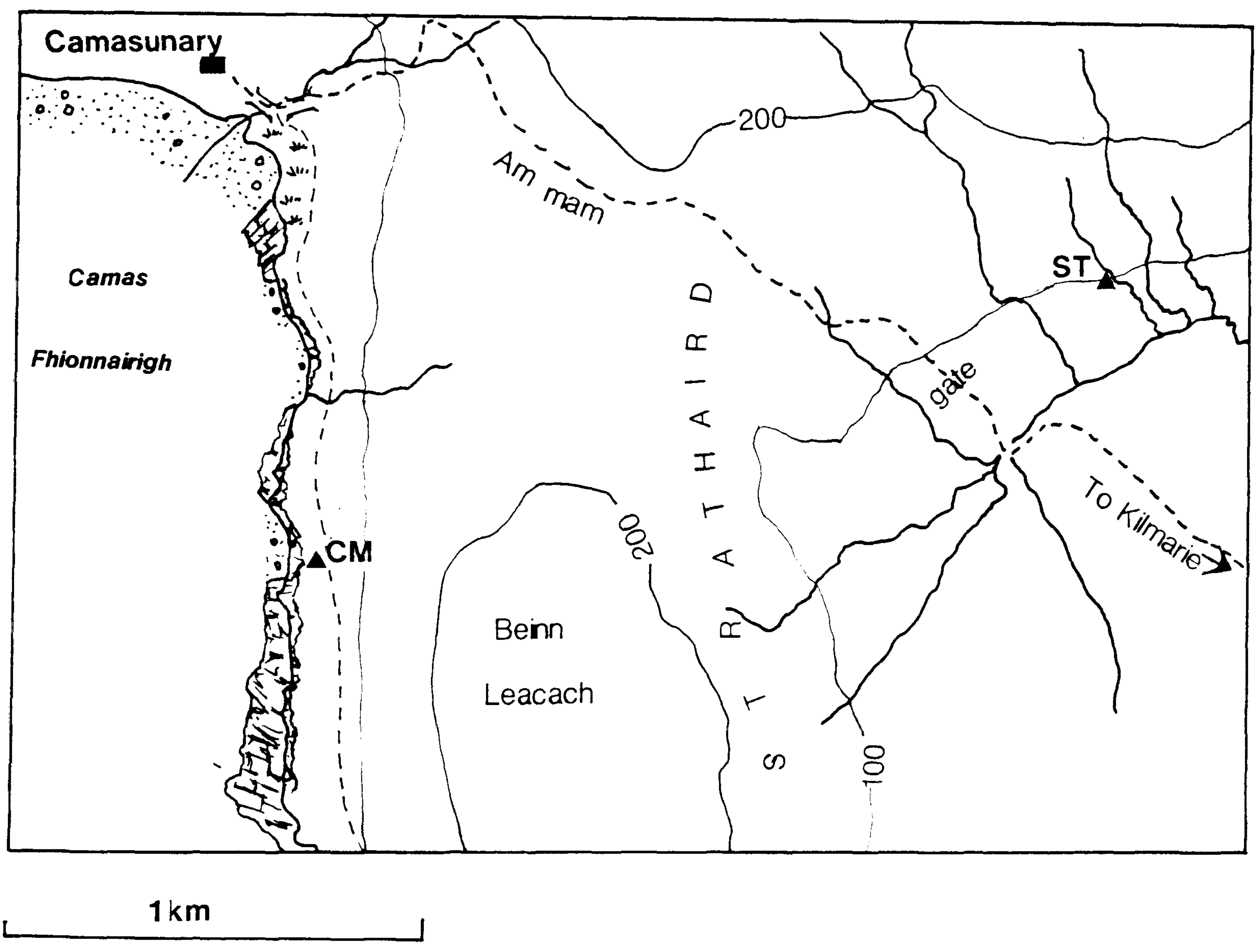


Fig.3.25 Localities in Strathaird.

Strathaird Limestone 1.6m

Laig Gorge Sandstone Member 3.71m

Total thickness of section 5.31m

3.5. The Skye sections.

Four sections were logged from southern Skye. A block of glauconitic sandstone reported from Neist Point in the NW of the island (Hudson,1983) was not located during the course of this study.

3.5.i. Strathaird. (ST)

Section location: G.R. NG 5365 1790 (See Fig.3.25)

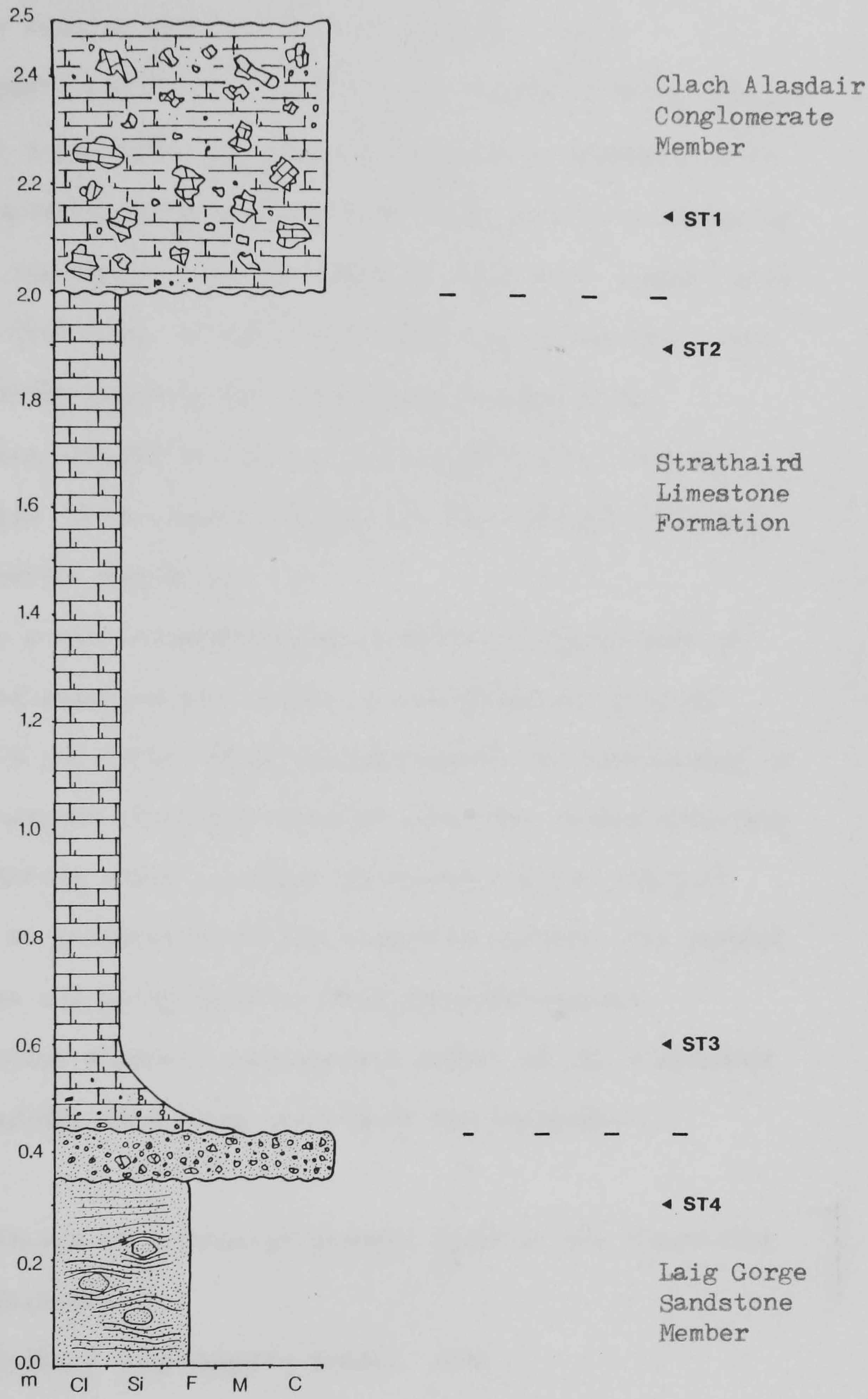
Walk about 1.5km along the Kilmarie to Camasunary track. Approximately 20m past the gate in the deer fence turn NE and follow the ruined enclosure wall to the confluence of two streams. The exposure can be seen ahead as a small hump of light grey rock where the vegetation changes from heather to short grass.

Section description: (See Fig.3.26).

The base of the first bed is not exposed. This unit comprises 35cm of dark grey to black, fine-grained, well-cemented sandstone. Low angle parallel laminations are picked out by the concentration of slightly coarser grains. The laminations enclose white quartzite clasts which are well-rounded and reach a maximum length of 15cm. The grey-black sandstone is identical in lithology to a small stream exposure approximately 1km along strike.

There is a sharp irregular contact with a thin (9cm) horizon

Fig.3.26 LOG 16 Strathaird



of coarse, very poorly sorted, pebble conglomerate. The grain size of the matrix sandstone averages 500μm, maximum grain size being 2mm. The grain shape is angular to sub-angular. Pebble composition is dominated by angular silicified chalk pebbles, though well-rounded quartz pebbles are also common, making up about 37% of the total clast composition. None of these pebbles exceeds 3 cm in length. This sandstone comprises the Laig Gorge Sandstone Member of the Strathaird Limestone Formation.There is an erosive contact with 1.56m of hard, dark grey, micritic limestone (which weathers light grey). This micrite contains rare inoceramid fragments but otherwise appears unfossiliferous. It is highly crystalline and sandy at the base. This limestone forms the type locality for the Strathaird Limestone Formation.

There is a marked disconformity with the overlying 40cm of matrix-supported conglomerate. Clasts are composed entirely of silicified chalk and flint. These are sub-angular to sub-rounded in shape and the maximum clast size seen is 10cm. The matrix comprises calcareous sandstone which is medium to coarse grained and dark grey in color. No orientation of the clasts is visible, the general structure of the bed being chaotic. This paraconglomerate comprises the Clach Alasdair Conglomerate Member of the Strathaird Limestone Formation. This forms the top of the exposure.

The thickness of lithostratigraphic units at the Strathaird section is as follows:

Clach Alasdair Conglomerate Member 40cm

Strathaird Limestone 1.56m

Laig Gorge Sandstone Member 44cm

Total thickness of section 2.40m

3.5.ii. Camasunary, Strathaird. (CM)

Section location: G.R. NG 5181 1775 (See Fig.3.25)

The section is located approximately 1km south of the bridge at Camasunary and is reached by walking due south along the path to Elgol. A marked vegetation change to short grass around the limestone makes the section easily recognizable from the beach.

Section description: (See Fig.3.27).

There is no definite *in situ* exposure of Cretaceous rocks at this locality, the area being cross-cut by dykes and sills. However, the little that can be seen shows the same lithofacies sequence as that seen at the Strathaird section, with blue-grey micritic limestone being overlain by a matrix-supported conglomerate. The clasts in the conglomerate in this section comprise very angular silicified chalk pebbles up to 8cm long. The matrix comprises poorly sorted sandy limestone with quartz grains up to 2mm long.

The underlying limestone contains numerous inoceramid fragments and appears bioturbated.

The maximum thicknesses seen at this section are:

Clach Alasdair Conglomerate Member 16cm

Strathaird Limestone 47cm

Fig.3.27 Strathaird Limestone exposure at Camasunary, Skye. Note the bright green of the vegetation on the limestone contrasting with the brown grass and heather on the basalt in the background.

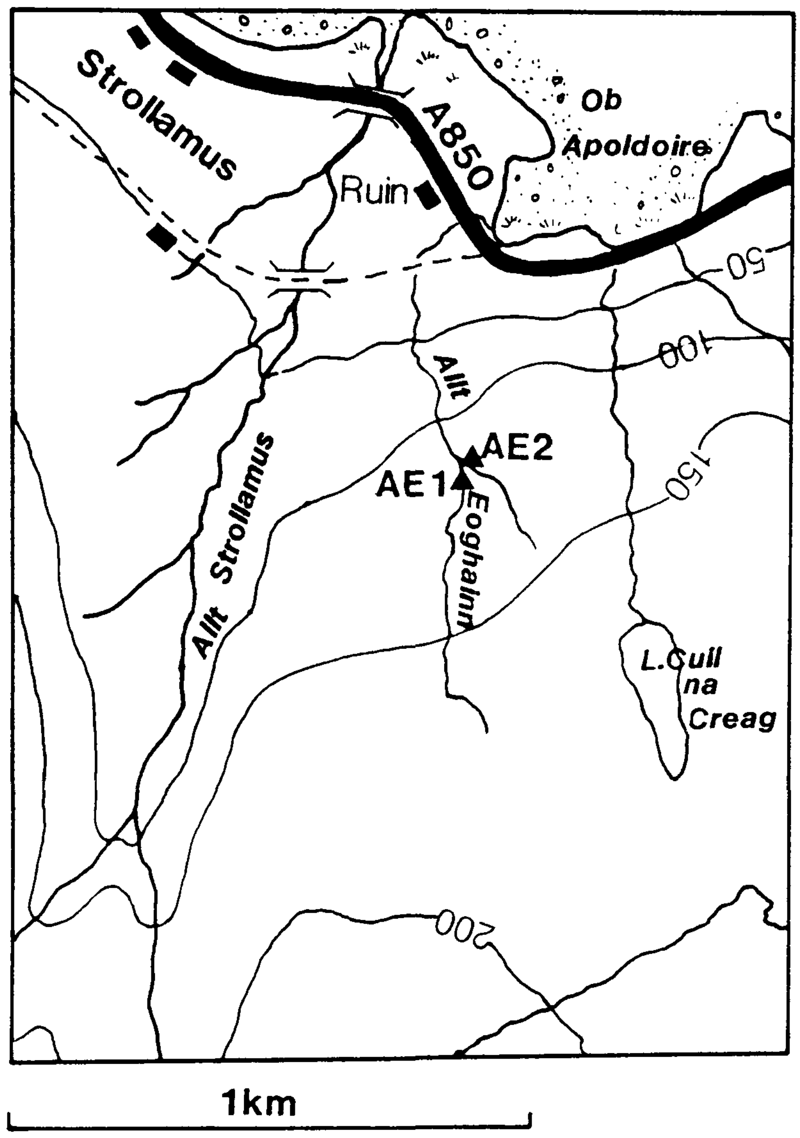


Fig.3.28 Map of Strollamus, Skye.

3.5.iii. Allt Eoghainn, Strollamus. (AE1 & AE2)

Section location: G.R. NG 5965 2645 (See Fig.3.28).

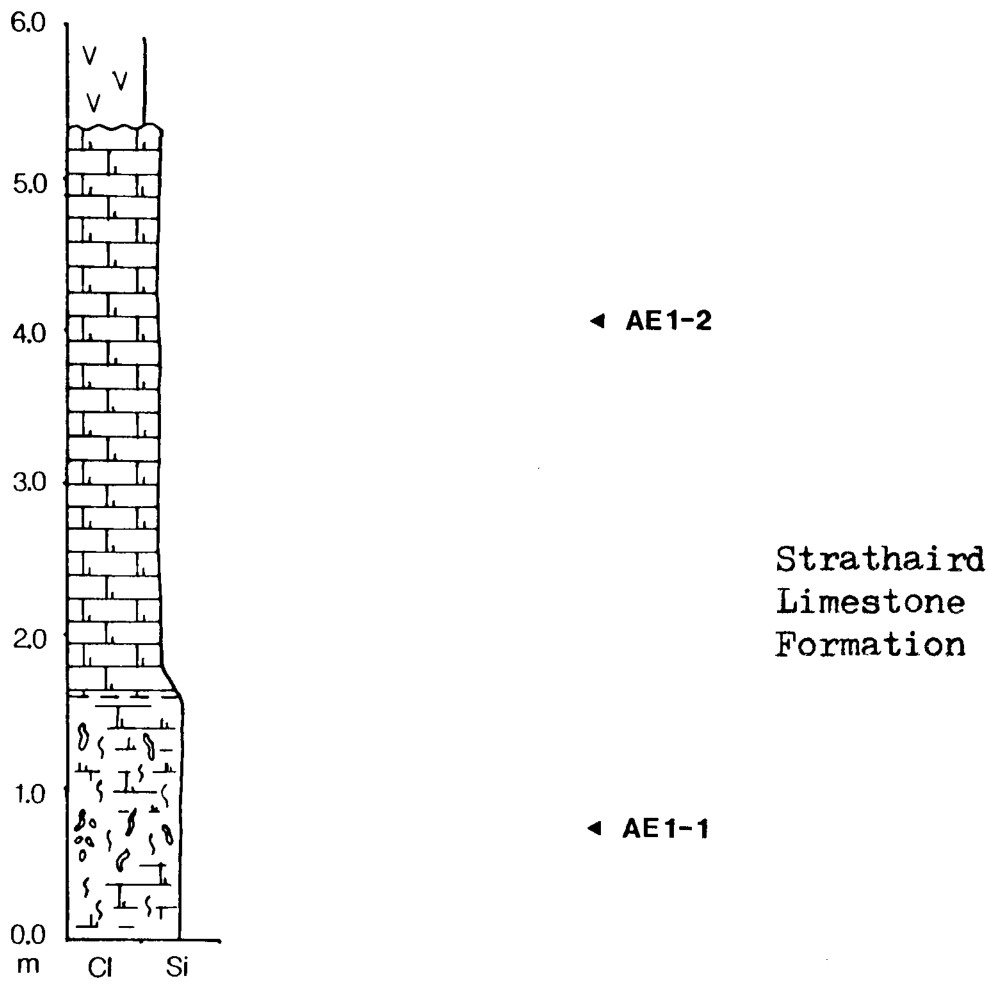
Walk about 0.25km westwards along the track from Strollamus to Luib (from the Ob Apoldoire end). There is a bridge over the Allt Eoghainn adjacent to the ruined bungalow beside the A850. Walk upstream on a bearing of 158° on the bungalow for approximately 300m. The exposures are easily located due to the marked vegetation change on the limestone which is noticeable from 12m north of the confluence of Allt Eoghainn and a small tributary. The exposures are in and immediately adjacent to the streams. AE1 is the section in the main stream which is cross-cut by a sill and a dyke, the latter forming the roof of a cave where the limestone has weathered out underneath; AE2 is a stream section in the small tributary to the east.

Section descriptions:

AE1. (See Fig.3.29).

A basalt sill is intruded between the dark brownish-grey Staffin Shale and the Cretaceous limestone, so no direct contact is seen. The basal 1.6m of dark grey, fine-grained micritic limestone is highly bioturbated with *Rhizocorallium* and *Monocraterion* burrows and convolute structures prominant. Light fawn-grey silt infills several generations of *Chondrites* burrows which overprint the other trace fossils (see Fig.4.8). This limestone is conformably overlain by (or grades into as bioturbation contrast decreases) 3.65m of hard, highly crystalline dark grey micrite with

Fig.3.29 LOG 17 Allt Eoghainn 1.

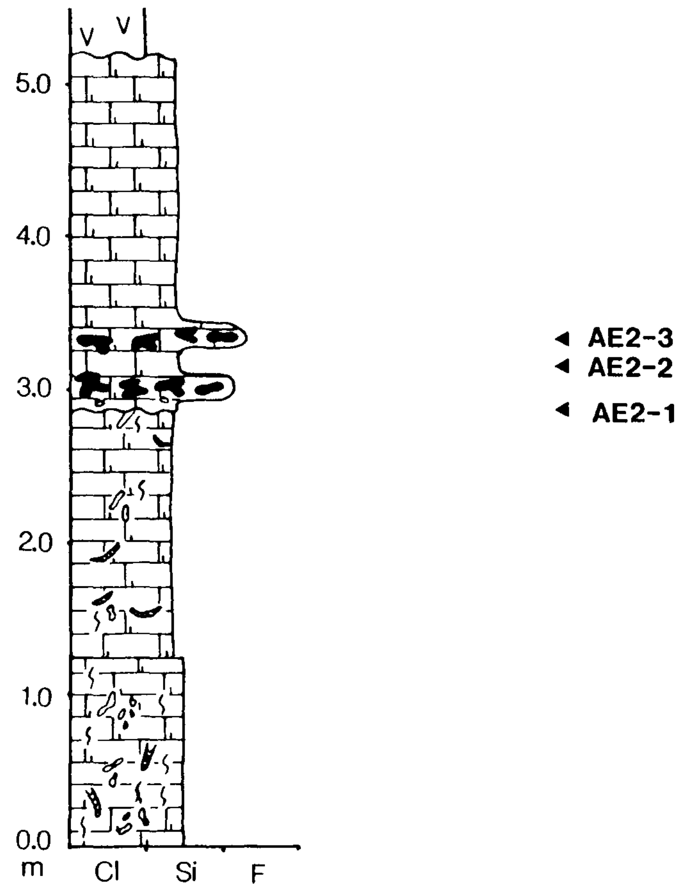


very well pronounced jointing and intense stylolitization. This bed is unconformably overlain by basalt.

AE2: (See Fig.3.30).

The base of this section is obscured by boulders. The first 1.25m seen comprises medium to dark grey, highly bioturbated micritic limestone. *Chondrites* and *Rhizocorallium* burrows are infilled with light fawn silty material. This is conformably overlain by, (or may grade into), 1.65m of dark grey micrite with rare inoceramid fragments and *Chondrites* burrows. Stylolites are common. An irregular erosion surface is overlain by 55cm of matrix-supported conglomerate. Clasts consist of intraformational limestone pebbles and silicified chalk and flint material. The latter is concentrated in two bands, 35 and 15cm from the basal erosion surface of the bed. The flints are sub to well- rounded and many appear to be *Thalassinoides* burrow infills up to 19cm in length. The long axes of all the clasts are orientated N-S and although they are concentrated horizontally into bands, these are only one clasts thick and the clasts tend to be widely spaced (at least 7cm space between each). These bands mark omission surfaces and are easily identifiable by the concentration of angular silicified chalk grains ranging from 250μm to 6mm in diameter between clasts. At 10cm above the top flint band, the grain size decreases and the conglomeratic sediment grades into 1.65m of hard grey micritic limestion. This is highly crystalline and contains numerous stylolites.

Fig.3.30 LOG 18 Allt Eoghainn 2.



Strathaird
Limestone
Formation

The total thickness of this section is 5.20m.

3.5.iv. An Leac, Soay Sound. (AL)

Section location: G.R. NG 4400 1695 (See Fig.3.31).

Follow the Allt na Meachnaish SSW from Loch Meachdannach, keeping on the eastern side of the stream. Do not follow the stream down the gorge to the beach but walk approximately 150m eastwards along the cliff and climb down onto the small rocky headlend called An Leac. This headland comprises the exposure.

Section description: (See Fig.3.32a&b).

The whole headland is composed of limestone and conglomerate which is cross-cut by basalt sills and dykes. The total thickness of the whole exposure is approximately 15m, but the succession is repeated at least once, and movement along the discontinuities where the basalt has been intruded has further complicated the section. The true order of the beds appears to be as follows:

~1.5m of hard, metamorphosed limestone with occasional quartz grains up to 2mm long. No sedimentary structures remain. This is overlain by a unit of variable thickness comprising relatively well-sorted micritic limestone conglomerate. The thickness of this unit ranges between 30cm and 3m. The matrix comprises dark purple-red poorly sorted sandstone, grain-size ranging between 125μm and 2mm but averaging 175μm. The clast composition appears to be wholly blue-grey micrite forming sub-angular to sub-rounded clasts (average length 12cm). The limestone is recrystallized but not silicified. The matrix never

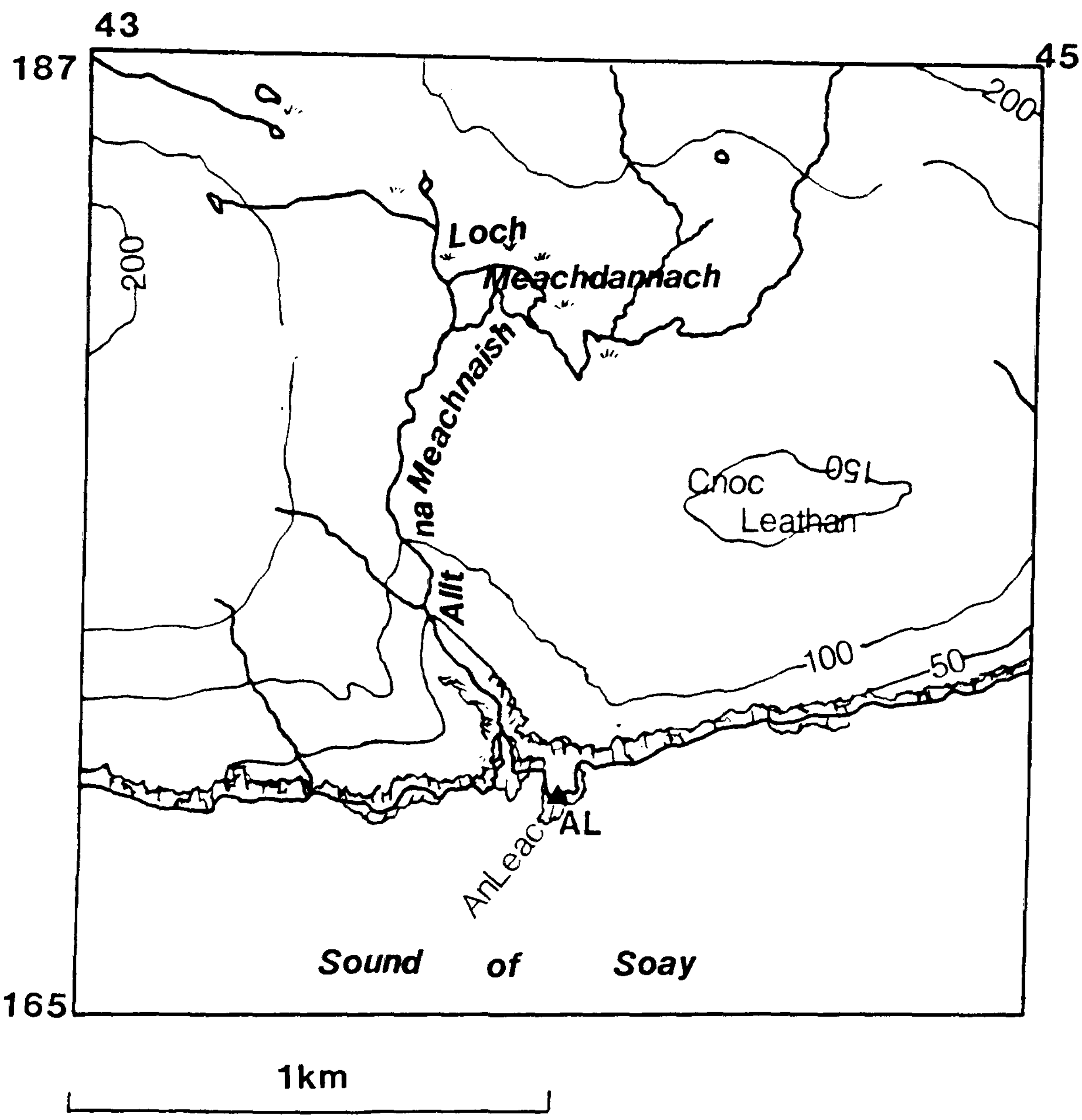


Fig.3.31 Map of An Leac, Skye

Fig.3.32a View of An Leac, Soay Sound, Skye, from the east. The whole area is composed of basalt sills, Strathaird Limestone and conglomerates.

Fig.3.32b Part of the An Leac section. Basalt sill containing Strathaird Limestone clasts sandwiched between Strathaird Limestone containing Gribun Chalk clasts.

exceeds 2cm thickness between clasts on a visible surface and the sediment therefore appears clast supported.

There is a clear irregular disconformity with the overlying chaotic conglomerate. The dominant clast type in this deposit is the blue-grey micrite, followed by vein quartz, pinkish limestone and reddish-brown siltstone. Clasts are sub-angular to sub-rounded, maximum clast length being 37cm, average clast length being 8cm. This conglomerate is matrix-supported, the matrix comprising impure sandy limestone. The thickness of this unit is difficult to ascertain due to the faulted nature of the outcrop, but appears to range between 40cm and 2.6m.

Chapter 4: Sedimentology - facies descriptions and diagenesis.

4.1 Introduction.

The Cretaceous rocks of the Inner Hebrides Basin display a wide variety of sedimentary facies, often over relatively short lateral distances (<5m). Detailed analysis of these facies is essential for the modelling of the environment in which the sediments were deposited. The effects of diagenesis and/or contact metamorphism also have to be taken into account (see Section 4.5).

In this chapter each individual sedimentary facies will be described and interpreted in terms of the process(es) responsible for its evolution. The significance of repeated facies associations will then be discussed and assessed in terms of a broad environmental interpretation for all the groups of facies identified. Detailed environmental interpretation of these facies groups is discussed in Chapter 6 and their palaeogeographical significance in Chapter 7.

A sedimentary facies is here defined as a distinctive unit of sedimentary rock whose characteristic features are the product of the action of specific environmental processes combined with sediment supply. The same unit of sediment can be described, for example, as a "matrix-supported conglomerate facies" in an attempt to define it as a sedimentary product, or as a "high energy debris-flow facies" in an attempt to define the probable process(es) responsible for its deposition. Energy levels cited are purely relative, where the extremes are: (a)very low energy where little or no movement of the transporting medium allows sedimentation of only very small particles through gravity settling, and (b)very high energy where there is sufficient velocity of the transporting medium to allow deposition of block or boulder sized particles only.

Separate sedimentary facies will be described and discussed in broad lithostratigraphic order so as to elucidate the significance of facies relationships (in Section 4.3) and facies groups (in Section 4.4).

4.2 Facies descriptions and primary interpretation.

For the purposes of this study, the term "primary interpretation" is used to define a broadly process-related rather than very detailed environmental interpretation. Integrated sedimentological, ichnological and palaeontological evidence which allows relative O_2 levels, water salinity, proximity to land etc to be inferred will be discussed in Chapter 6. However, animal/plant:sediment interactions resulting in bioturbation, ichnofossils and the formation of rootlet/plant beds are here considered to be sedimentary processes.

Each facies described is here assigned a letter which will be used instead of the full facies name where appropriate. The lithological sections in which the facies occurs are listed following the facies description, the abbreviations introduced in Chapter 3 being used instead of the full locality names.

4.2.A. Cobble conglomerate facies.

Description: This facies is characterized by having a flat or slightly irregular erosive base and comprises sub- to well-rounded pebbles. At the base the pebbles show some imbrication but this does not continue upwards through the unit. There is little matrix material, the conglomerate being clast supported and showing crude grading, clast size decreasing upwards through the bed. No other structure is visible, pebbles not displaying any preferred orientation above the basal cobbles. The smaller clasts (those less than 3cm long) tend to be relatively irregular in shape (except those composed of vein quartz, which are usually sub-spherical), whereas those larger than 4cm tend towards an elongate oval or wedge shape.

Distribution: BI(A), LG, AL.

Interpretation: Clast supported conglomerates are common in the sedimentary record of braided rivers and high energy littoral environments (Tucker, 1982; Massari & Parea, 1988). The sorting and size of the clasts in this facies (averaging 3.9 cm long at BI and 3.1 cm at LG) indicate high energy conditions with turbulent rather than catastrophic flow; current flow direction being indicated by the dip of the imbricated clasts. The coarse to medium grained sandstone filling the interstices between clasts may not have been deposited with the clasts themselves but filled the gaps after deposition on top of the conglomerate. Waning and possibly less turbulent flow is indicated by the decrease in clast size through the facies following the initial high energy conditions resulting in the deposition of imbricated cobbles at the base.

4.2.B. Hummocky cross-stratified conglomeratic facies.

Description: This facies comprises fine to medium grained sandstone which is characterized by undulating sets of cross-lamination, sets cutting across one another with curving erosion surfaces. The convex-upwards laminae forming the top layer comprise the "hummocks" on the horizontal surface of the structure.

Fig.4.1. Conglomerate wedges in hummocky cross-stratified sand, Beinn Iadain Section (A). Note the normal grading and possible cross-bedding in the conglomerate and the well-rounded nature of the pebbles.

Hummocks are spaced around 6m apart and the laminae (and reactivation surfaces) dip at <17°. Laminae are approximately 1-2mm thick and represent small-scale fining upwards cycles, maximum grain-size being 500μm.

The most distinctive feature of this facies is that conglomeratic material is enclosed within the hummocky cross-stratified sand. The conglomerate is clast supported and is composed of granule to medium pebble size clasts. These are mainly sub- to well- rounded and sub-spherical to elongate in shape, depending on composition. Clasts decrease in size upwards.

The view of this facies is limited and therefore the true shape of the conglomeratic horizons is not known. Because of the poor exposure, most of the conglomeratic layers appear as wedges (see Fig.4.1), but when followed laterally they are seen to be more of a flattened lens shape.

Distribution: BI(A).

Interpretation: Hummocky cross-stratification is most often found in sediments of shallow marine shelf origin but interpretation is problematical because no modern analogue has been described (Collinson & Thompson, 1982). The structure appears to be a high to medium energy deposit and the most credible explanation for its formation is that is the product of storm events. The conglomeratic horizons, representing the highest energy depositional phase of a storm event, following the initial erosional scour, are preserved in the "troughs" of the hummocky cross stratification and are draped by the next set of laminae deposited during the waning storm phase.

4.2.C. Pebble lag facies.

Description: This facies comprises a coarse grained overlay of (usually planar) erosion surfaces. The coarse grained material is usually granule to medium pebble size but pebbles may be relatively sparse in their distribution (see Fig.4.2). The matrix material may be as fine as 375μm but is usually poorly sorted. Pebbles are mainly sub to well-rounded. Where more than a few cms thick, the sediment is graded to medium or coarse grained sand with occasional pebbles. There is not sufficient thickness (or layers) for this facies to be classed as a conglomerate since the pebble horizon is only one or two clasts thick.

Distribution: BI(A), CR (blocks), GR (boulders), AT, ST, AL.

Interpretation: The coarse grain size, including pebble size clasts indicates that this facies was deposited under fairly high energy conditions. Such lags are common in transgressive shallow marine or storm event sequences where a thin winnowed lag is preserved over the newly cut erosion surface as normal weather deposition resumes or storm wave base move landwards as transgression continues (Massari & Parea, 1988).

4.2.D. Shell/shell debris lag.

Description: Like Facies C, this facies comprises a concentrated horizon of relatively coarse sediment overlying an erosion surface. However, this facies is distinctive in that the coarse grained element is composed entirely of shelly material (sometimes whole or partially damaged valves, sometimes crushed shell debris) in a sparse, fine to medium grained sandstone matrix (see Fig.4.3). The erosion surfaces overlain by these shelly horizons are usually irregular and gently undulating in shape and often cut across

Fig.4.2. Bedding plane view of pebble lag, Gribun Boulder A. Note the apparently random orientation and grouping of the pebbles and the poor size sorting.

Fig.4.3. Shell lags and shell debris lags, Auchnacraig Cliff, Mull. Above the hammer is a horizon comprising shell fragments up to 2.5cm long; all the pale cream coloured horizons below the hammer head comprise lags of very fine <3mm long shell debris.

cross-bedded units. The thickness of these shelly horizons ranges between 0.5 - 12 cm.

Distribution: BI(A), LAA, LAW(b), BH10, AU, CR.

Interpretation: The relatively large particle size, compared to the matrix sand, and concentration of material in this facies indicates that deposition occurred under relatively high energy conditions. Particle size ranges from fragments of less than 1mm in length to oyster shells up to 4.2cm long. This facies is interpreted as an high - medium energy storm deposit, erosion surfaces scoured by storm events being directly overlain by a winnowed shell lag, material being reworked and deposited by waning storm generated currents (Fürsich, 1982).

4.2.E. Medium scale tabular cross-bedded sandstone facies.

Description: This facies is most easily recognized when seen in an exposure trending parallel to flow direction where the foresets are seen in longitudinal section. The facies most commonly comprises medium grained sand which fines upwards to 275μm within each foreset. Foreset height averages 35cm and foreset dip ranges between $18^{0}$and 35^{0}. Concentration of heavy minerals in the coarse grained element of the foresets is common. Occasional well-rounded near-spherical quartz grains up to 1.6mm in diameter are sparsely distributed within the facies, being commonly associated with reactivation surfaces. Poorly preserved walled burrows (*Ophiomorpha?*) are also associated with the reactivation surfaces but are rare otherwise within the facies. The reactivation surfaces themselves are low-angle, dip reaching a maximum of 7^{0}, and are gently curved, tending towards a concave upwards shape.

Distribution: BI(A), BI(b), BH10, LAA, AT, LG.

Interpretation: The scale and type of the cross-bedding in this facies is characteristic of small-scale sandwaves (Harms *et al.*,1975; Collinson & Thompson, 1982). This structure is usually formed under moderate energy flow conditions (though higher energy than the flow required to form ripples (*op cit.*)).Reactivation surfaces mark erosion due to changes in flow direction and/or water depth, and the bioturbation associated with these surfaces indicates a period of non-deposition before sandwave migration over the erosion surface.

<u>Variations:</u>

<u>Facies Ei</u> - Here, some of the foresets and reactivation surfaces are characterized by pebble "stringers". This feature usually occurs where the sediment is medium to coarse grained (up to 750μm). Pebble size ranges between 4-17mm and they are usually well-rounded though the shape is variable. Pebbles were only found on foresets dipping less than 22^{0}.

Distribution: BI(A), LG.

Interpretation: Pebbles on foresets are rare and probably represent the reworking of pebble lags as the sandwaves migrate. Reactivation surfaces represent erosional events and those overlain by scattered pebbles may record high energy storms (see 4.2.C).

<u>Facies Eii:</u> Sometimes foresets are not defined by the marked grading of sand grains but by the concentration of shelly material. This usually occurs where the sand is fine to medium grained and the shelly material is usually less than 13mm in length with the long axes of particles orientated parallel to dip.

Distribution: BI, LAA, AU, CR, GR.

Interpretation: This concentration of shelly material in the base of foresets probably represents the reworking of winnowed shell lags (see 4.2.D), the shelly material being deposited during the highest energy phase of sandwave formation.

4.2.F. Parallel laminated sandstone facies.

Description: This facies most commonly comprises fine to medium grained sandstone which is characterized by horizontal or sub-horizontal parallel lamination (see Fig.4.4). Laminae are a maximum of 3mm thick and coarsen upwards. The coarser grained material tends to be better cemented and therefore stands out on weathered surfaces but sometimes there is little visible grain size or mineralogical contrast and the lamination is consequently difficult to see. Fine-grained material at the base of laminae may include fine silt-grade organic material or heavy minerals or detrital glauconite. Occasional bundles of laminae occur with several 1-2mm thick laminae sandwiched between thicker (2-4mm thick) laminations. Parallel laminated units may dip, but the angle of inclination never exceeds 7^{0} and the lamination remains parallel to the bounding surface of the bedding.

Distribution: BI(A), BI(b), LAA, BH10, AU, AT, ST.

Interpretation: Planar, parallel laminated sandstones are typical of high energy, shallow water conditions and are therefore characteristic of beach foreshore deposits (Thompson, 1937; Clifton, 1969). The origin of coarsening upward laminae appears to be deposition through bedflow processes during the backwah of breaking waves (Clifton, 1969). Coarser laminae would then be the product of higher energy events than normal eg.storms, spring tides.

Fig.4.4. Ripple cross-laminated sandstone grading into parallel laminated sandstone just below the level of the hammer head. Morvern Greensand, Beinn Iadain Section A.

4.2.G. Ripple cross-laminated sandstone facies.

Description: This facies comprises fine to medium grained sandstone. Cross-lamination is defined by thin (maximum thickness 1.2mm) layers of silt grade organic material or very fine (125μm) glauconitic sandy silt. The ripple forms, where seen in true cross-section, are symmetrical or near symmetrical and the internal structure often comprises asymptotic tabular cross-sets. Ripple height averages 3cm and wavelength approximately 12cm. Sometimes there is the development of climbing ripple cross-lamination within this facies but this dies out into parallel laminated or bioturbated sediment.

Distribution: BH10, LAW(a), BI(A), BI(b), AU, AT, FT, CA.

Interpretation: Symmetrical ripples are usually associated with wave action (Clifton, 1976). The concentration of heavy minerals in ripple laminated sets has been interpreted as the product of continuous reworking of the sediment with little new sediment input (Howard & Reineck, 1981), and the relative rarity of climbing ripples indicates that there is little rapid vertical accretion. The tabular shape of the internal foresets suggests that the ripples are dominantly straight crested, also a trend in wave-formed ripples. Studies on modern high-energy nearshore profiles (eg. Clifton *et al.*,1971; Howard & Reineck, 1981) show that this type of small-scale wave ripple lamination is most common in the shoreface zone below the mean low water level.

4.2.H. Sandstone with clay ripple drapes.

Description: This facies comprises fine to medium grained sandstone with thin undulating clay horizons representing ripple drapes. With little contrast in sediment colour or grain size, the internal structure of the ripples cannot easily be discerned in this facies although the morphology of the ripple drapes suggests that the ripples are slightly asymmetrical. The wavelength of these ripples averages 40cm and the distance between clay drape horizons (i.e. ripple set thickness) averages 18cm. Clay ripple drapes are not laterally extensive over more than 1.2m and reach a maximum thickness of 4mm in the ripple troughs. Where thickest, silt grade partings are visible within the clay. These partings are generally lighter in colour than the clay itself and demonstrate normal grading in the fine sediment depositional phase.

Distribution: BH10, LAW(b), BI(b).

Interpretation: Asymmetrical sand waves with ripple drapes have been described in detail from modern and fossil environments (see review by Allen, 1982). The asymmetry of the ripples indicates the domination of one current flow direction. This facies is typical of a tidal environment where sand deposition is prevalent during one tidal stage followed by mud deposition during slack water resulting in drapes over ripples or sandwaves (Allen, 1982).

4.2.I. Massive sandstone facies.

Description: This facies comprises fine to coarse grained sandstone, often a pure quartz arenite, which appears homogenous and relatively poorly sorted. Occasionally small areas of tabular cross-bedding are visible but these are rare and non-persistent. Walled burrows (similar to small *Thalassinoides*) are picked out by the concentration of iron minerals in the walls. The burrows are mainly vertical, up to 1.2cm in diameter and range from 3 to 17cm in length. Where apparently unstructured, the grain size ranges from 187 to 700μm and the largest grains tend to be near spherical and well-rounded.

Distribution: BI(A), BI(b), LAW(a), AT, LG.

Interpretation: The primary sedimentary structure was tabular cross-bedding (see 4.2.E) but post-depositional bioturbation has largely destroyed this primary fabric and homogenized the sediment. The lack of clay and glauconite characteristic of this facies has been interpreted as the result of constant high energy reworking of the sediment (Humphries, 1961). No shell material was recorded from this facies: this could be a primary or a diagenetic factor. If the former, then the lack of a shelly fauna might support a high energy, shallow water interpretation for this facies, as does the presence of walled burrows (see Section 6.2.ii).

4.2.J. Shelly sandstone facies.

Description: This facies comprises fine to medium grained sand containing abundant, randomly orientated, shells and shell fragments (see Fig.4.5). The bioclasts are distributed fairly evenly within the sand. Both thick and thin shelled genera are present and fragments tend to be large (>1.3cm). Some shell material in this facies shows signs of abrasion and boring yet much appears little damaged.

Distribution: BI(A), BH10, LAA, LAW(b), AT, GR, CR.

Interpretation: Shell beds in which there is no sign of size sorting or concentration of bioclasts are most likely to result from *in situ* storm reworking of material (Fursich, 1982). Significant lateral transport of the shell material is unlikely since signs of abrasion are rare and many shells are well preserved. The sand shows no sedimentary structures and thus

Fig.4.5. Shelly bed, Beinn Iadain Section A. The shell material appears to be randomly distributed in the bed above the basal lag in the middle of the picture.

appears to have been thoroughly homogenized by bioturbation, resulting in the apparently random distribution of the shelly material.

4.2.K. Shelly "limestone" facies.

Description: This facies comprises a highly fossiliferous sandy biomicrite. The fauna is relatively diverse and includes abundant serpulid worm tubes. Most bivalve valves appear whole but shell fragments are common throughout. The matrix material consists of a sandy lime mud. Bioclasts appear evenly distributed within the facies but they tend to be orientated with their long axes parallel to bedding at the top.

Distribution: BI(A), AT, GR, AU.

Interpretation: This facies probably represents more than one period of deposition and reworking since carbonate mud deposition normally occurs under a lower energy regime than that required for the deposition of medium to fine sand (Selley, 1982; Leeder, 1982). The fauna is mainly epifaunal or shallow infaunal, indicating that the substrate surface was relatively solid. Mixing of the sediment may have occurred largely through bioturbation but high energy storm events may also have had an effect, accounting for the abundance of shell fragments (Fursich, 1982). The orientation of bioclasts at the top of the facies indicates increasing energy conditions, resulting in a winnowing effect.

4.2.L. Organic rich mud facies.

Description: This facies comprises silty mud containing organic-rich silt horizons and/or plant debris. The mudstone occasionally appears finely laminated and the organic rich horizons (which never exceed 8mm in thickness) have a non-persistent flaser type morphology. Plant debris appears to be randomly orientated on bedding surfaces and consists mainly of stem material. Any lamination within the mudstone is on a <1mm scale.

Distribution: BH10, LAW(b), BI(A), BI(b), FT.

Interpretation: The lamination in this facies is the result of grading from silty mud to fine mud and reflects regular alternation in either sediment input or current flow. The apparently random orientation of the plant debris suggests that current flow was not significant during deposition and that the plant material simply settled down through the water column when waterlogged. Organic rich silt flasers are interpreted as drapes over irregularities in the mud surface. This facies can be interpreted as the product of a low energy environment near to a terrestrial source for the plant material.

4.2.M. Heterolithic parallel laminated facies.

Description: This facies comprises finely laminated silt and clean, fine grained sand. The sand laminae average 1mm thick and are sharp-based and grade into clayey silt at the top. The clayey silt laminae tend to be slightly thicker (up to 1.4mm). Lamination is parallel but may be slightly inclined with respect to the bedding surfaces.

Distribution: BH10.

Interpretation: The marked difference in grain size of the sediments in this facies suggests a higher degree of energy fluctuation or variation in sediment input than that descibed in 4.2.L.. The lack of bioturbation and macrofauna is indicative either of a high rate of sedimentation (unlikely, given the generally fine grain size), or of unfavourable ecological conditions e.g. fluctuating salinity in a tidally influenced estuarine or lagoonal environment.

4.2.N. White chalk facies (silicified).

Description: The sediments which are here described as "chalk" have been almost totally silicified by diagenetic processes and the original composition of the sediment is not preserved (see Fig.4.6). Some calcite remains within the silicified rock but it is rare and may not be primary. The main physical properties of chalk facies limestone (*sensu* Hancock, 1976), remain however: (i) high porosity (which has resulted in the extremely brittle nature of the silicified chalk) (ii) low permeability (iii) whiteness (this varies from locality to locality but at worst is a pale greyish cream hue). Whether the rock is *in situ* or hand specimen, no convincing macrofossils are visible and the rare flints are identifiable only on colour (medium to dark brownish grey), and their non-porous texture. In thin section, foraminifera, dinoflagellate cysts, calcispheres, echinoid plates, echinoid spines and bivalve shells can be discerned, either by the concentration of iron minerals in and around them, or by the coarsely crystalline replacement of the original calcite, both of which serve to provide a contrast with the cryptocrystalline silica of much of the matrix.

Distribution: BI(A), BI(b), AT.

Interpretation: The diagenesis affecting this facies will be discussed in Section 4.5. Chalk facies limestone is an extremely pure biomicrite composed largely of coccolith and other microfossil debris (Hancock, 1976), and its deposition is therefore controlled

Fig.4.6. Silicified chalk, Gribun Boulder C. Note its very weathered and brittle appearance.

by productivity, the level of the CCD and water movement. Such fine material could only be deposited under extremely low energy conditions but there is evidence for the winnowing of some bioclasts which show a marked preferred orientation in thin section probably caused by current or storm activity (see Section 6.3.ii. and Fig.6.5). Flints are thought to form within the chalk sediment under specific geochemical conditions where there is a permeability contrast given sufficient silica supply (Clayton, 1986). The fauna will be discussed in Chapter 5 but is indicative of open marine conditions.

4.2.0. Biomicritic limestone facies.

Description: This facies comprises dark grey to pale bluish grey limestone (See Fig.4.7a). The limestone is a fine-grained biomicrite, bioclasts being dominated by foraminifera, calcispheres, echinoid plates and inoceramid valves and prisms (see Fig.4.7b). Rare sub-rounded quartz grains occur throughout this facies, reaching a maximum diameter of 187μm. The bioclasts pick out a definite lineation which persists throughout this facies, bioclasts being orientated with long axes aligned parallel to bedding. The matrix comprises a brownish grey-green lime mud with very fine-grained pyrite disseminated throughout. Stylolites are common, concentrating iron and clay minerals along their length. The stylolites are roughly parallel (in the majority of cases) to the lamination defined by the orientation of bioclastic material.

Distribution: TC, LG, ST, AE, CM, AL.

Interpretation: There is a higher clastic component to this limestone than to the chalk facies limestone (Facies N), suggesting that this is a more marginal deposit. The linear orientation of

Fig.4.7a. Grey biomicritic limestone, Strathaird.

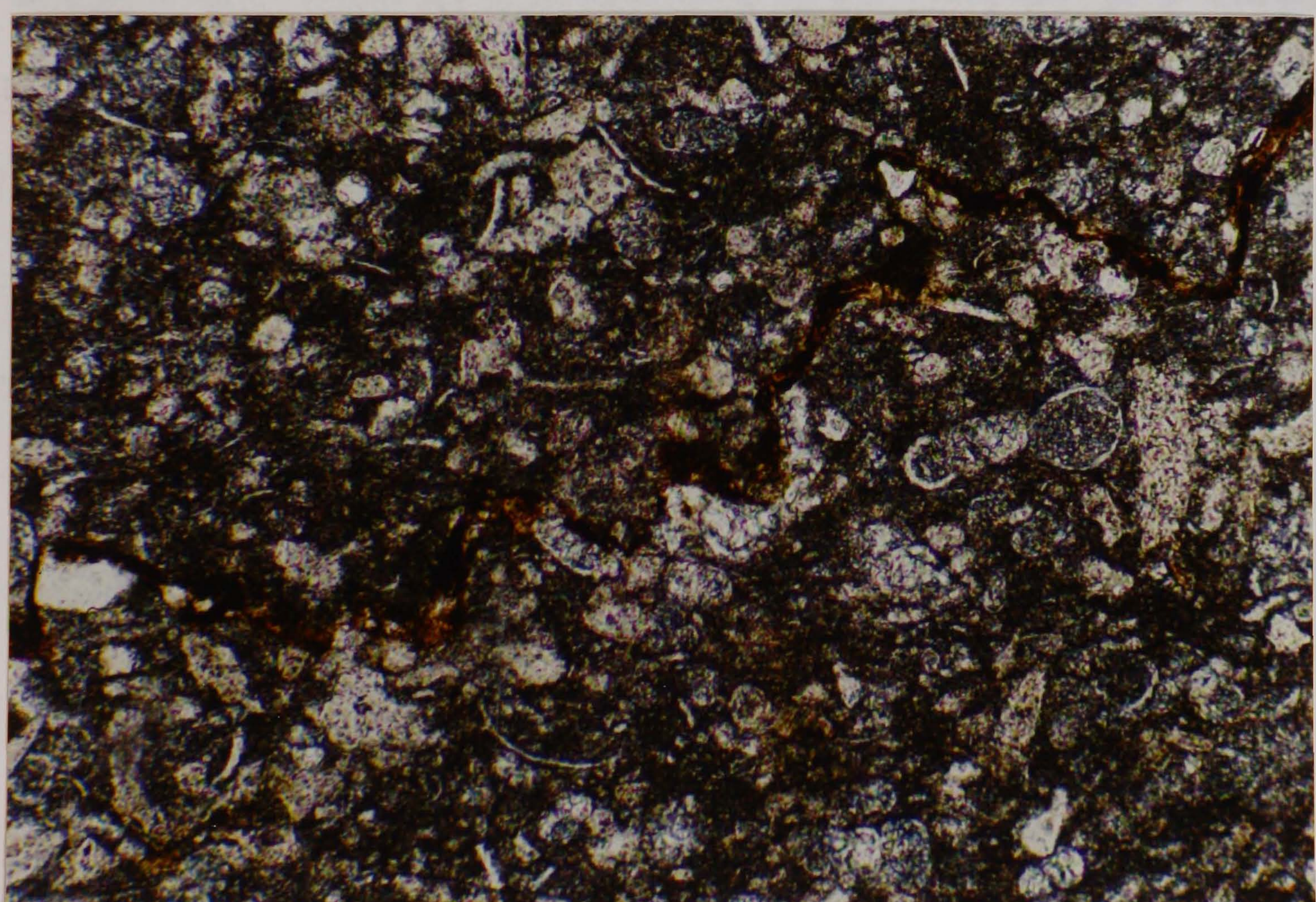


Fig.4.7b. Thin section of the same limestone. Note the abundance of calcispheres and concentration of minerals in the stylolite crossing the picture. Field of view 3mm.

Fig.4.8. Bioturbated micrite, Allt Eoghainn, Skye. Note the light colour of the *Thalassinoides* infills and the dark *Chondrites* overprinting (arrowed).

most of the bioclastic material indicates periodic higher energy events than the background low energy depositional regime represented by the micrite matrix. The fauna is indicative of marine conditions (see Section 6.2.iii). The occurrence of disseminated pyrite may indicate reducing conditions just below the sediment/water interface (e.g. Love, 1967), or could reflect a later diagenetic phase (e.g. Curtis, 1977). The lack of bioturbation may support the former.

Variations:

Facies Oi: This facies differs from Facies O in being intensively bioturbated. Small *Chondrites* and *Rhizocorallium* type burrows are fairly common and are infilled with light fawn silt(see Fig.4.8). In thin section, the bioclasts, dominated by foraminifera and calcispheres, show apparently random orientation.

Distribution: AE.

Interpretation: The thorough bioturbation of this facies indicates a slow rate of deposition. The material forming the burrow fills suggests sediment input from a different source than the background lime mud, and the fact that this is not preserved as a separate layer indicates either erosion of the overlying silt or thorough mixing and homogenization of the sediment by a later phase of bioturbation than the burrows with the silty fill.

4.2.P. Nodular hardground facies.

Description: This facies is characterized by the concentration of cemented burrow fills (predominantly *Thalassinoides*) below an irregular erosion surface (see Fig.4.9). The matrix between the burrows is a calcareous medium-grained sandstone; the burrow fills comprise hard micritic limestone.

Fig.4.9. Hardgrounds, Laig Gorge, Eigg. The *Thalassinoides* burrows are infilled with finer, more micritic material than the surrounding coarse sandstone.

Distribution: LG.

Interpretation: This facies is interpreted as a nodular omission surface (*sensu* Kennedy & Garrison, 1975), representing a period of non-deposition with some erosion.Discolouration around the burrows and on the erosion plane surface may indicate the start of sea-floor diagenesis i.e. limonitization or phosphatization, but could equally be due to preferential concentration of minerals on the sea floor (*op cit.*).

4.2.R. Matrix-supported boulder bed facies.

Description: This facies can be subdivided according to the matrix material into: Ri - sandstone supported boulder bed and Rii - mud supported boulder bed. However, the primary interpretation applies to both sub-facies. Regardless of matrix type, this facies is characterized by angular to sub-angular clasts of silicified chalk and flint which are supported by the matrix material (see Fig.4.10). The general structure of the facies is chaotic although there may be a crude grading in the size of clasts (decreasing upwards). The base of this facies is always an irregular scoured erosion surface with reworked material from the underlying unit often comprising a basal lag. Clast size ranges from grains to boulders up to 1.5m in length.

Facies Ri: The sandstone forming the matrix to this facies is coarse (average grain size 750μm) and poorly sorted. The grains are generally sub-angular but granules tend to be angular and often comprise silicified chalk fragments. Occasionally shelly material is included. The matrix material is mainly poorly sorted but sometimes laminae can be found partially enclosing clasts or picking out scour fills.

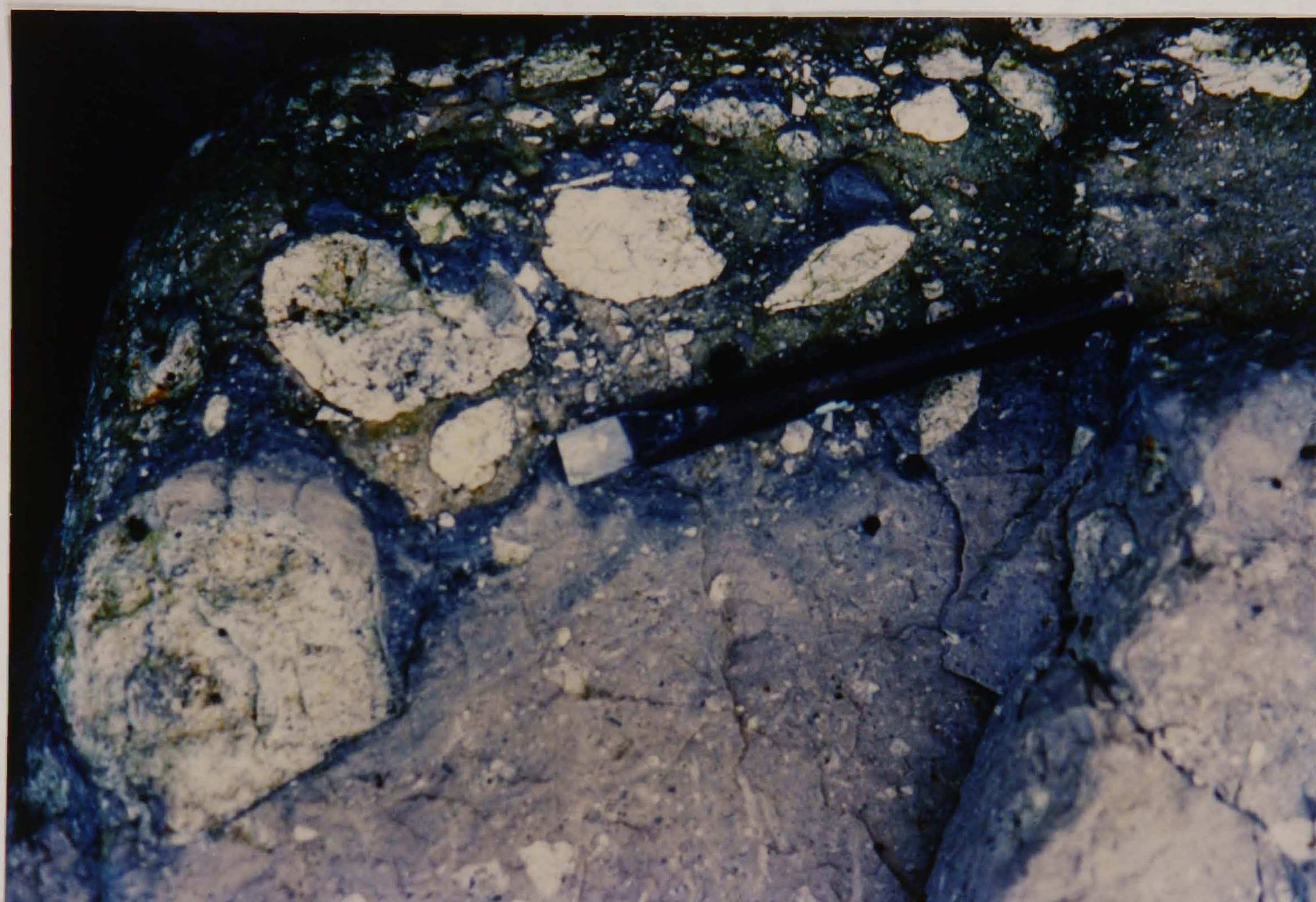


Fig.4.10. Matrix-supported conglomerate, Clach Alasdair, Eigg. The chisel is at the erosive boundary between a limestone-supported conglomerate and one with a sandy matrix. The clasts comprise silicified chalk.

Distribution: CA, ST, FT, CM.

Facies Rii: The limestone matrix comprises a sandy biomicrite. Bioclasts are identical in type to those in Facies O but quartz grains comprise a higher proportion of the sediment (approximately 16%). These grains are mainly sub-angular and reach a maximum size of 500μm. Granules of silicified chalk up to 1.2mm long are common and are usually highly angular. Silicified chalk clasts over 5cm long in this matrix tend to show a rough preferred orientation with their long axes parallel or sub-parallel to bedding.

Distribution: AE, AU, TC, AL.

Interpretation: Chaotic paraconglomerate deposits indicate extremely high energy events e.g. debris flows where downslope forces exceed the shear strength of the sediment (Hilbrecht, 1989). When the downslope forces equal the shear strength of the debris mass, the flow "freezes", leaving a matrix-supported "debrite" deposit (Reading, 1986).

The differences in matrix composition may reflect the provenence of the material forming the whole flow rather than distance from the origin of the flow, since boulder sized clasts are found in deposits of both matrix types, and the internal structure appears equally chaotic. However, some of the micrite-supported examples of this facies are extremely thin and clasts show a clear preferred orientation (i.e. AE, TC), possibly indicating deposition during waning energy conditions at a more distal position on the flow. On a small scale though (particles less than 2cm long), bed structure is still chaotic.

The angular nature of the clasts indicates an extremely immature sediment but is also a product of the brittle texture of the silicified chalk. Many of the clasts show evidence of sub-aerial weathering (discoloured rinds with enhanced permeability), yet are still sub-angular in form. Differences in clast composition (i.e. clast type is dominated by micritic limestone in the AL deposit), can be interpreted as reflecting variations in source area (and/or relative timing of the flow).

4.3. Facies associations.

The main criteria for the identification of facies associations in this study are (i) that a sequence of two or more individual facies is repeated (preferably in more than one section), and (ii) that the facies are realated by the processes responsible for their development. It is essential that the facies are conformable upon one another although there may be periods of non-deposition within an individual facies (e.g. between ripple sets).

4.3.i. Cobble conglomerate : hummocky cross-stratified conglomerate (Facies A:B).

Both these facies are rare but they occur in clear association, the cobble conglomerate facies grading into the hummocky cross-stratified sand with conglomeratic lenses. Both facies record alternations of high energy conditions with reworking of pebble or cobble size clasts and slightly lower flow regime conditions allowing the deposition of laminated sand. Overall, there is a reduction in flow energy and/or coarse sediment supply reflected in this facies association, possibly related to the waning of individual storm events or the movement of storm wave base related to transgression.

4.3.ii. Pebble lag : tabular cross-bedded sand with pebble stringers (Facies C:Ei).

As already described, the pebble lag deposit is typical of high energy conditions, pebble deposition following an erosive stage. For the pebble lag to be preserved, energy levels would have to decrease, a moderate flow regime combined with sufficient sediment supply resulting in the formation of sandwaves. The occurrence of pebbles on the foresets and reactivation surfaces within the cross-bedded facies suggests the reworking of pebble beds during periods of sandwave migration or erosive storm events. Landward migration of storm wave base would account for the preservation of this association.

4.3.iii. Shell lag : tabular cross-bedded sand with shell debris stringers (Facies D:Eii).

The interpretation of this facies association is essentially the same as that for Facies C:Ei, the main difference being that shell debris forms the lag sediment and is concentrated on cross-bedding foresets. This suggests the occasional reworking of a shelly accumulation or lag during sandwave migration, and a lower velocity energy regime than that required for pebble transport.

4.3.iv. Parallel laminated sand : ripple cross-laminated sand (Facies F:G).

Parallel laminated sand has already been described as being typical of a high energy flow regime coupled with shallow water conditions (Section 4.2.F.). This facies often grades into small-scale ripple cross-laminated organic-rich fine sand. This indicates a decrease in overall energy conditions and/or an increase in water depth, allowing ripple formation, and the deposition of very fine-grained sediment from suspension.

4.3.v. Shelly limestone : shelly sandstone (Facies K:J).

These facies often occur together and are apparently conformable on each other although the boundaries between the calcareous and non-calcareous units are sharp. This association is problematical because although many of the features such as bioclast orientation are primary, the calcareous cement is probably diagenetic. The poorer fauna (both in diversity and abundance) in the sandstone facies may be the result of selective dissolution. An analogous situation was discussed in some detail by Fursich (1982), who argued that diagenetic processes commonly enhanced the distribution of the shelly fauna by cementation rather than drastically altered it. The percentage of quartz grains decreases in the calcareous facies which might support a non-diagenetic origin for the faunal distribution since primary differences between the facies do exist. The variation in matrix material can be interpreted as the result of fluctuating energy conditions, carbonate mud being deposited during quiet periods.

4.3.vi. Ripple cross laminated silty sand : organic-rich mud (Facies G:L).

These facies commonly occur together, the ripple cross-laminated silty sand grading into the mud. The ripple cross-laminations are usually picked out by fine organic-rich silt, the organic content increasing towards the mud only facies. The association indicates a decrease in clastic input and/or energy conditions: small-scale ripple development giving way to low energy sedimentation of fines from suspension.

4.4. Facies groups.

Facies can be broadly grouped on sediment type, which is a product of sediment supply, depositional regime and palaeoenvironment. The value of facies grouping is that related, rather than associated, facies can be recognized. The palaeoenvironmental significance of these facies groups is evaluated further in Chapter 6. Thus far, facies have been described using criteria of sedimentary structures and broad sediment type but many of these can be further subdivided according to the maturity of the sediment without invalidating the original facies description or primary interpretation. Thus the same facies may appear in more than one facies group.

4.4.i. Mature clastic facies.

Facies belonging to this group are characterized by well-sorted sediment with a stable heavy mineral assemblage and sub-rounded to well-rounded grains. The group includes facies resulting from high energy events and extremely low energy conditions. Pebble and shell lag facies satisfy the criteria of being well-sorted, and even in the latter case of being relatively mature where the shelly material shows evidence of transport and reworking. Allogenic glauconite is a common component of the sediment in this facies group (see Section 6.2. for further discussion).

The facies classified under this group and the sections in which they occur are:

A - Cobble conglomerate facies: BI(A).

B - Hummocky cross-stratified facies: BI(A).

C - Pebble lag facies: BI(A), CR, GR, ST.

D - Shell lag facies: BI(A), LAA, LAW(b), BH10, AT, GR, CR, AU.

E,Ei,Eii - Tabular cross-bedded facies: BI(A), LAA, CR, GR, AT, AU.

F - Parallel laminated sandstone facies: BI(A), LAW(a), BH10, LAA, AT, AU.

G - Ripple cross-laminated facies - BI(b), BH10, LAW(a), AU, FT, CA.

H - Sandstone with clay ripple drapes: BI(b), BH10, LAW(b).

I - Massive sandstone facies: BI(A), BI(b), LAW(a), LAA, AT.

J - Shelly sandstone facies: BI(A), BH10, LAA, AU, AT, GR, CR.

L - Organic-rich mud facies: BI(A), BI(b), BH10, LAW(b), FT.

M - Heterolithic parallel laminated facies: BH10.

4.4.ii. Immature clastic facies.

This group comprises those facies characterized by poorly sorted to extremely poorly sorted clastic sediments. Grains and clasts are generally sub-angular to angular. These facies are mainly the product of moderate to high energy conditions.

Facies classified under this group and the sections in which they occur are:

A - Cobble conglomerate facies: LG, AL.

Ei - Tabular cross-bedded sandtone with pebble stringers: LG.

F - Parallel laminated facies: ST.

I - Massive sandstone facies: LG.

Ri - Matrix (sand) supported boulder bed: AU, FT, CA, AL.

(Rii - Matrix (micrite) supported boulder bed: ST, AE, TC, AL.

4.4.iii. Carbonate facies.

This group comprises those carbonate facies which reflect generally low energy depositional conditions and is typified by biomicrites.

Facies classified under this group and the sections in which they occur are:

K - Calcareous shelly facies: BI(A), AU, GR, AT.

N - White chalk facies: BI(A), BI(b), AT.

O - Biomicritic limestone facies: TS, LG, ST, AE, AL.

Oi - Bioturbated biomicritic facies: AE.

Facies which do not comfortably fit into this classification are Facies Rii which is included in the immature clastic facies group as it satisfies the main criteria of the group despite being characterized by a carbonate matrix, and Facies P (nodular hardground). The latter is the product of a period of non-deposition and cementation rather than being the product of sedimentation and thus does not strictly fit the definition of a sedimentary facies outlined in Section 4.1. However, it is a recognizable unit whose characteristic features are the product of specific environmental processes and sediment supply, and is therefore included as a separate facies.

4.5. The effects of diagenesis.

The recrystallization and/or replacement of calcium carbonate material in the sediments described is extremely common and ranges from silicification of bioclasts in the glauconitic sandstone facies to total silicification of the chalk facies biomicrite. All the sections in Morvern have been at least partially decalcified (regardless of sedimentary facies), but there is little evidence (such as moulds in the matrix sediment) that any macropalaeontological material has been lost. Valve wall material in silicified bivalves appears to have been replaced on a very fine scale in most cases, since the wall detail is preserved, but the inside is usually filled with sparry silica crystals. Such silicification of bioclasts in sediment is very common (e.g. see Carson, 1987).

The silicification of the chalk facies sediment has been briefly discussed in Section 4.4.N. where it was pointed out that the silicified infill of bioclasts in this facies is much coarser than the silicified matrix. In fact, the matrix material in its unweathered state, appears glassy in thin section (see Fig.4.11). The sparry and drusy infill of some of the bioclasts may therefore indicate the formation of calcite infills prior to silicification although virtually none of this calcite remains. Details of other bioclasts such as bryozoans and echinoderm ossicles are well preserved through the concentration of iron minerals in textural features of the fossil material. Organic material e.g. foraminiferal test linings is sometimes preserved as moulds in near perfect three-dimensional detail (see Fig.4.11).

The preservation of "ghosts" of such micron-scale features as stereom pores in echinoderm ossicles can be interpreted as resulting from simultaneous silica precipitation and carbonate dissolution along thin solution films (Maliva & Siever, 1988), and the silicification of coarse calcite crystals may have occurred by the same mechanism. Evidence from silicified bioclasts and nodules in chalk facies rocks from Northern Ireland and southern England suggests that silicification occurred at a relatively shallow

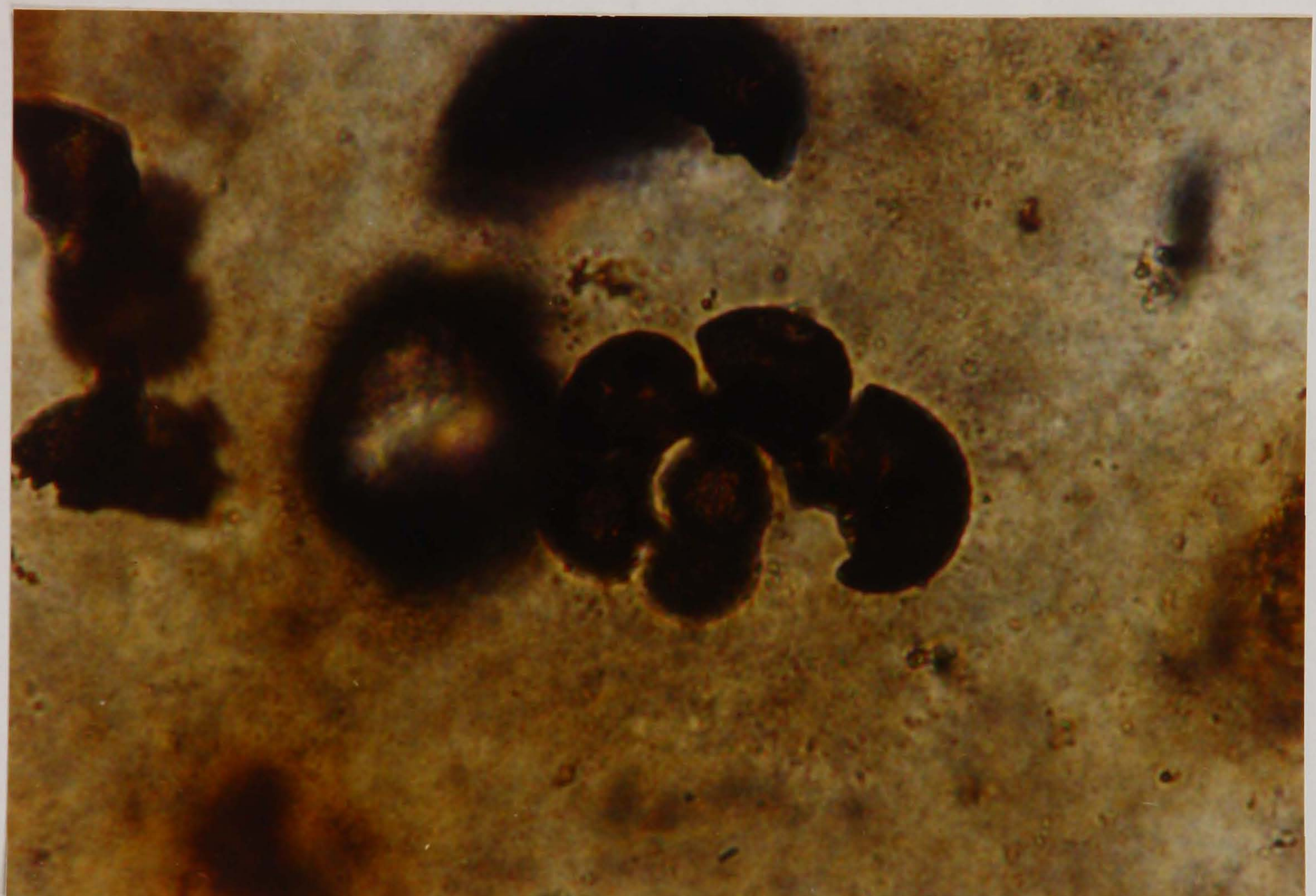


Fig.4.11. Mould of foraminiferid lining preserved in three-dimensional detail in silicified chalk, Beinn Iadain. Note the glassy nature of the silicified matrix. Field of view 1mm.

burial depth in a meteoric phreatic environment (Carson, 1987; Maliva & Siever, 1988).

The effects of diagenesis on flints within the chalk is difficult to evaluate but appears to have been insignificant. The non-porous texture of the flint has been retained, and the contact between flint and the matrix material is sharp.

All the micritic limestones (Facies O & Oi) encountered have been recrystallized to some degree. Least affected are the limestones of the LG and ST sections where the formation of microspar infills of foraminiferid tests and other bioclasts is the most marked indication of recrystallization. Limestones from the TC, AE and AL sections are far more severely affected, with extremely coarse recrystallization of the matrix material overprinting or replacing all except the thickest walled bioclasts e.g. inoceramid valves.

Pressure solution has led to the formation of stylolites in all examples of Facies O & Oi described. It is most marked in section AE where remobilization of fine ?clay and iron minerals has also led to the formation of wavy and flaser type structures (see Fig.4.12). These are similar in form (though more diffuse) than flaser marls described by Hancock (1976). Stylolites are extremely common at this locality, occasionally cutting across "flasers" which indicates that stylolitization post-dated the initial pressure solution phase.

Fig.4.12. Wispy flaser structures formed by pressure solution in biomicritic limestone, Allt Eoghainn (1), Skye.

Chapter 5: Biostratigraphy.

5.1. Introduction.

As already discussed (Section 1.2), the only part of the Cretaceous succession that has previously been dated with any certainty is the Morvern Greensand. A major aim of this project was therefore to refine and expand the biostratigraphy to cover the whole of the Cretaceous succession in the area using microfossils, concentrating on foraminifera and dinoflagellate cysts.

In this chapter, the macro-biostratigraphy is reviewed first in order to identify the gaps in the biostratigraphical record. The remainder of the chapter is concerned with micropalaeontology and palynology, with a brief discussion of processing methods used and then a section by section description of the microfossil assemblages (calcareous and organic-walled forms) from the samples studied. This is followed by a discussion of the implications of the results for both groups.

5.2. Sampling methods.

Initially, joint samples of at least 750gms were taken, to be split in the laboratory for micropalaeontological and palynological processing. Great care was taken to avoid contamination by geological or organic material; some contamination by the latter was, however, inevitable when sampling from algae-rich stream sections. In the laboratory, such organically-contaminated samples, after splitting for micropalaeontology, were cleaned by chipping off the contaminated surface and/or vigorous scrubbing and washing with distilled water before processing (see Section 5.8).

When it was realized that the Morvern Greensand is effectively almost barren of calcareous microfossils, smaller field samples of this unit were taken (approximately 100gms), for palynology only. The other lithostratigraphic units were sampled jointly, large cobble sized specimens being needed where thin sectioning was thought necessary for micropalaeontology.

5.3. Stratigraphic macropalaeontology.

Sections will be discussed in broad lithostratigraphic order, starting with the Morvern Greensand.

The Morvern Greensand Formation is characterized by shell lags, shelly sandstones and shelly limestones (Facies D, J & K), but the fauna of most of the former horizons is extremely limited in diversity, often comprising almost monogeneric assemblages of *Exogyra* spp. accompanied by shell debris.

The total fauna recorded from the Morvern Greensand is as follows; those forms also found during this study are marked with an asterisk, and the original reference for the occurrence of the form in N.W. Scotland is given:

* *Exogyra obliquata* (Pulteney) - Judd, (1878)

* *Aequipecten aspera* (Lamarck) - Judd, (1878).

* *Neithea quinquecostata* (Sowerby) - Judd, (1878).

* *Entolium orbiculare* (Sowerby) - Judd, (1878).

* *Serpula* sp. - Judd, (1878).

Nautilus sp. - Judd, (1878).

Schloenbachia intermedia (Mantel) - Lee & Bailey, (1925).

Turritella granulata Sowerby - Lee & Bailey, (1925).

Grammatodon carinatus (Sowerby) - Lee & Bailey, (1925).

? Calliderma sp. - MacLennan, (1949).

Gervillella sublanceolata (d'Orbigny) - Richey, (1961).

* *Neithea sexcostata* (Woodward) - Richey, (1961).

This list represents the best preserved forms. Rhynconellid and terebratulid brachiopods have also been reported from the Beinn Iadain section but not identified further (Richey, 1961), and small, broken gastropods similar to *Natica* sp. were found at the Allt na Teangaidh section during this study. The fauna listed constrains the Morvern Greensand to a Late Albian - Middle Cenomanian age (on ranges given in Castell *et al.*, 1975).

As already noted (Section 1.2), the silicified Gribun Chalk was placed in the *Belemnitella mucronata* zone of the Upper Chalk by J.W. Judd, who reported finding the zonal belemnite at Beinn Iadain (Judd, 1878). The only macrofossils encountered during this study were those seen in thin section, including echinoid plates, sections of inoceramid valves, and other bivalves. Macrofossils previously recorded from the Gribun Chalk are as follows:

Belemnitella mucronata (Schlotheim) - Judd, (1878).

Salenia? sp. *cf. S.geometrica* Agassiz - Kitchin, (1934).

Inoceramus sp. - Judd, (1878).

The single specimen of *Belemnitella mucronata* recorded by Judd (*op cit.*) has apparently been lost (Rawson, 1978), and no further examples of belemnites from the Gribun Chalk have been recorded. In addition, the original identification of *Salenia? cf. S.geometrica* was doubtful (Kitchin, 1934). Given the highly weathered, totally silicified and extremely brittle nature of the Gribun Chalk (especially at the Beinn Iadain section, from which both fossils were reported), it seems highly unlikely that either could have been preserved in a form recognizable to sub-generic level. The macrofaunal evidence on which the Gribun Chalk has previously been dated therefore appears doubtful.

The members of the Strathaird Limestone Formation are generally poor in macrofossils although, as with the Gribun Chalk, macrofossil fragments are broadly recognizable in thin section. Macrofossils reported from the Laig Gorge Sandstone Member and the Strathaird Limestone are as follows:

Ostrea sp. - Barrow, (1908).

Cucullea sp. - Barrow, (1908).

Astarte sp. - Barrow, (1908).

Terebratula sp. - Lee & Bailey, (1925).

* *Inoceramus* sp. - Lee & Pringle, (1932).

Barrow also reported finding other pieces of fossil material, not recognizable to generic level, from the base of the Laig Gorge Sandstone on Eigg, including a bone fragment, reptile tooth, gastropod and lamellibranch (Barrow, 1908). Abraded fish teeth and small bone fragments were also found from the same unit during this study. However, none of the macrofaunal assemblage from the Strathaird Limestone Formation is stratigraphically diagnostic.

Hudson (1960) reported the finding of a reworked and phosphatized ammonite from the basal conglomerate of the Laig Gorge Sandstone Member. The ammonite was identified as belonging to the sub-genus *Cardioceras (Scarburgiceras)* which makes its age Early

Oxfordian (Howarth, cited by Hudson, 1960).

No macrofossils, apart from indeterminate plant material, have ever been reported from the Beinn Iadain Formation.

To summarize, macropalaeontological evidence constrains the age range of the Morvern Greensand relatively tightly, but is of limited use in the younger parts of the Cretaceous succession in the Inner Hebrides area. The occurrence of inoceramids throughout the Strathaird Limestone Formation at least constrains this unit to the Cretaceous.

5.4. Micropalaeontology: Introduction.

This section is mainly concerned with foraminifera since these are the most stratigraphically useful calcareous microfossils found in the Cretaceous rocks of the Inner Hebrides area. The processing methods will be described first, then the results will be reviewed in Section 5.6.

5.5. Processing methods (for micropalaeontology).

Clay and sandstone samples were relatively easily processed using the solvent method (Brasier, 1980) to disaggregate the clay matrixes. Samples were first weighed to a standard size of 300gms and broken up with a hammer before being dried at 60°C for 24hrs. The dried samples were then soaked for approximately 40 minutes in white spirit (turpentine substitute) inside a fume cupboard. Once the samples were judged to be saturated, the solvent was filtered off, and the sample residue covered with distilled water. After

30-40 minutes most samples were disaggregated and could be wet-sieved, using a 63µm mesh, the remaining residue being dried in the oven as before. For samples which had only partially disaggregated, the process was repeated.

Samples were then sieved through a standard 500µm: 250µm: 125µm mesh sieve nest and picked, using a binocular microscope. All sieve fractions, including the <125µm fraction were picked.

The silicified chalks and recrystallized limestones were too hard to process and therefore had to be thin sectioned. To maximize the chances of obtaining true longitudinal and cross-sections through foraminiferids, thus facilitating identification, six sections were taken through each sample, each section being at a differnt orientation. This method is of especial value where the microfacies of the sediment shows a preferred orientation of grains/bioclasts not visible in hand specimen, as in the case of some samples of the Strathaird Limestone. In such a case, thin sections made at one orientation with respect to the sample might be at such an angle to the preferred orientation of the bioclasts as to make the sections through foraminiferids useless for identification purposes. Thin sections were made to a standard thickness of 30µm.

5.6. Micropalaeontological results.

The results of all picked samples are summarized in Fig.5.1.

It is important to note that the identification of foraminiferids from thin section is, at best, speculative, since in most cases no details of the aperture or accessory structures can be seen, a true cross-section of a formaniferid being obtained purely by chance. In the samples studied there is the additional problem of recrystallization of the test wall, causing the loss of such important diagnostic features as the wall structure and the presence/absence of keels. Consequently, identification to specific level is rather often tentative, and this has to be considered when attempting to erect a biostratigraphy using "species" identified from thin sections only.

Because of the poor preservation of picked foraminifera and the necessity of using thin sections, no formal taxonomy is attempted. However, Appendix I comprises notes on those taxa identified with some certainty.

5.6.i. Microfossils from the Morvern Greensand.

Samples of the Morvern Greensand were processed using the solvent method. Total residues were picked, including the <125μm fraction. In addition to foraminifera, representative assemblages of other bioclasts were picked, including calcispheres, siliceous spherules, sponge spicules, fish teeth and shell fragments.

Because of the rarity of foraminifera in the Greensand samples, the results are discussed for the whole lithostratigraphic unit and not locality by locality. Sample location and spacing within individual sections can be seen on the logs in Chapter 3, samples processed for micropalaeontology being as follows: Loch Aline Adit - samples LAA1-12; Loch Aline Waterfall (a) - samples LAWa1-6; Loch Aline Waterfall (b) - samples LAW(b)1&2; Loch Aline Waterfall (c) - LAW(c)1-3; Beinn Iadain (A) - samples BI1-5 & BI7-11.

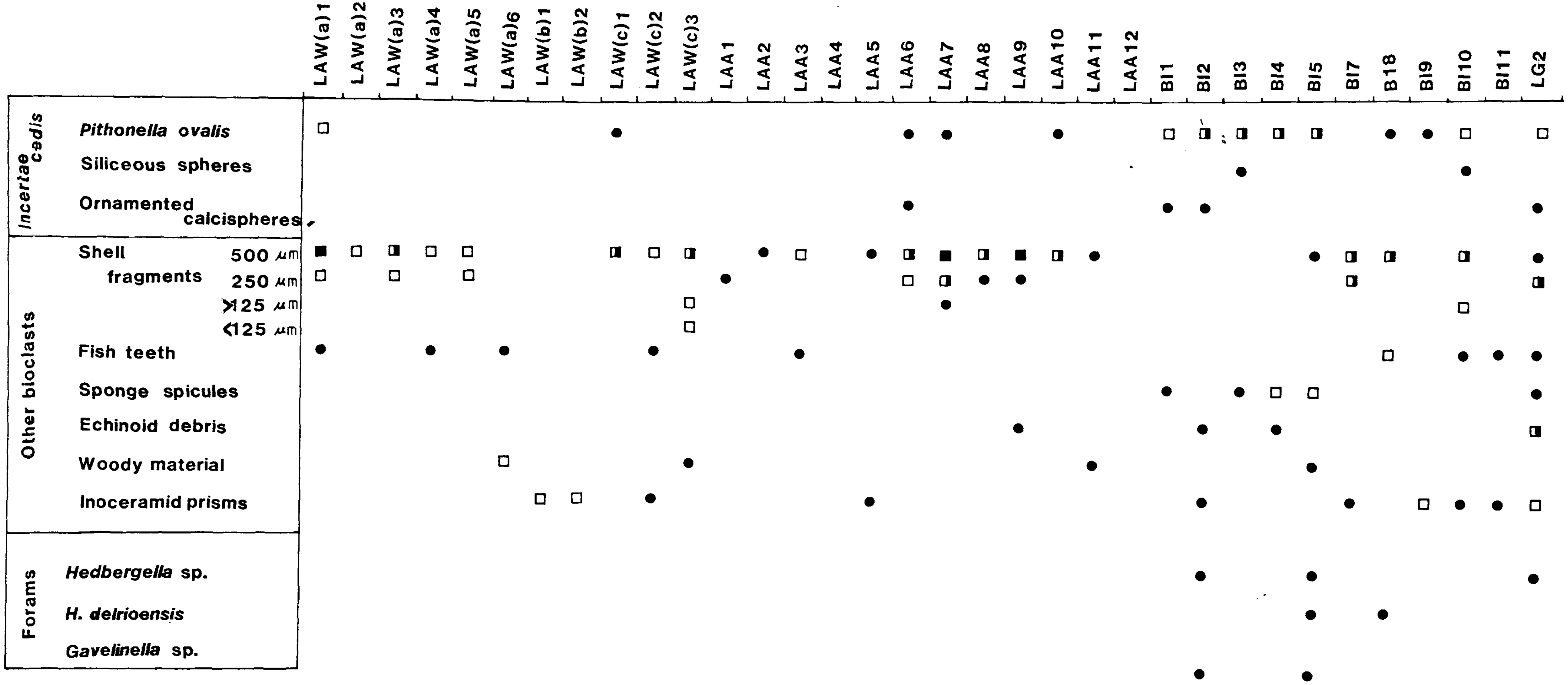


Fig.5.1 Bioclast assemblage from picked samples

● Present 0-1% ◨ 5-20% As % of picked residue.

□ Rare 1-5% ■ > 20%

The only foraminiferid species found in these samples were:

Gavelinella sp.

? *Hedbergella* sp.

Hedbergella sp. *cf. H.delrioensis* (Carsey)

All the foraminifera found came from the <125μm fraction: those identified only to generic level were extremely poorly preserved, and in nearly all cases broken. The best specimen of *Hedbergella* sp. *cf.H.delrioensis* was preserved as a glauconitic cast.

The stratigraphical range of *H. delrioensis* is mid-Albian to late Turonian (Robaszynski & Caron, 1979)(see Appendix I).

5.6.ii. Microfossils from the Gribun Chalk.

Foraminifera were first described from the Gribun Chalk by T. Rupert Jones (in Judd, 1878), from thin sections of silicified chalk from Gribun, Carsaig and Beinn Iadain, but the only form identified to sub-generic level was *Globigerina cretacea* d'Orbigny. However, during the late 1870's, *G.cretacea* covered any hedbergellid/whiteinellid of Cretaceous age.

Rawson *et al.*,(1978), report *Gavelinella thalmanni* (Brotzen) and *Stensioeina gracilis* Brotzen from the silicified chalk at Gribun, but cite no original reference. *G.thalmanni*, in thin section, would be almost impossible to separate from *G.baltica* Brotzen and *G.intermedia* (Berthelin) which are indicative of a Cenomanian age; *G.ammonoides* (Reuss), which is indicative of a Turonian age, and *G.lorneiana* (d'Orbigny) which is indicative of the Santonian. Some *Lingulogavelinella* spp. also appear similar to

G.thalmanni in thin section. *S.gracilis* has a distinctive outline which would be readily identifiable in a good section but no similar form was seen in thin sections of the Gribun Chalk, the nearest being *G.tourainensis* (Butt), a gavelinellid with a moderately-sized boss.

Six randomly orientated thin sections were made from each of the following samples: Beinn Iadain - BI12; Gribun - GR3. The combined assemblage from both samples was as follows:

Textularia sp. *cf. T.chapmani* Lalicker
Hedbergella delrioensis
Gavelinella sp.
Heterohelix sp. *cf. H.reussi* (Cushman)
Heterohelix globulosa (Ehrenberg)
Hedbergella sp.
Lingulogavelinella sp.
Globulina sp.
Gyroidinoides sp. *cf. G. nitida* (Reuss)
Whiteinella sp. *cf. W.aprica* (Loeblich & Tappan)
Globigerinelloides sp.
?Rotalipora sp.

On ranges given in Robaszynski & Caron, (1979) and Jenkins & Murray (1989) this assemblage indicates a maximum range of Late Cenomanian to Late Turonian, *Textularia chapmani* Lalicker and *Hedbergella globulosa* ranging from the Albian to Late Turonian, with *Whiteinella aprica* Loeblich & Tappan being resticted to the Turonian. The genus *Rotalipora* would be indicative of a Cenomanian age. However, it must be stressed that these diagnoses are tentative, given the problems of identifying foraminifera in thin section.

5.6.viii. Microfossils from the Strathaird Limestone Formation.

In previous work (Hill, 1915; Adams, 1960), foraminifera have been described from the matrix of the Laig Gorge Sandstone and from the Strathaird limestone. The only stratigraphically significant forms identified in these studies were: *Heterohelix cf.globulosa* (Ehrenberg), ?*Praeglobotruncana (Hedbergella)* sp., and *Globotruncana* sp. (Adams, 1960). This assemblage was interpreted by Adams to indicate a Senonian age (on the occurrence of *Globotruncana* sp.)(*op cit.*). His ?*Praeglobotruncana* (*Hedbergella*) sp. would probably now be classified as *Hedbergella* or *Whiteinella,* and in 1960 *Globotruncana* would have included any twin keeled planktonic morphotype. *Globotruncana* now ranges from the Santonian to the Maastrichtian but twin-keeled marginotruncanids range down into the earliest Turonian (Robaszynski & Caron, 1979; Robaszynski *et al.*, 1984).

Samples studied were as follows:

Laig Gorge Sandstone: Laig Gorge - LG2, LG4; Strathaird - ST4; Kirkibost (Strathaird) - KR1.

Strathaird Limestone: Laig Gorge - LG6; Strathaird - ST2,ST3; Allt Eoghainn - AE1; Torosay Castle - TC1.

Results for LG2 which was a picked sample, are summarized in Fig.6.1. Samples LG4 and KR1, both sandstones which were thin sectioned, were barren. Results for those samples of Strathaird Limestone which were thin sectioned (LG6 & ST2) were as follows:

Hedbergella sp. *cf. H.praehelvetica* (Trujillo)

Whiteinella archaeocretacea Pessagno

Whiteinella sp. *cf. W.baltica* Douglas & Rankin

Whiteinella aprica

Eouvigerina sp.

Hedbergella sp.*cf. delrioensis*

Hedbergella praehelvetica (Trujillo)

Globigerinelloides sp.

Heterohelix globulosa (Ehrenberg)

Gavelinella tourainensis (Butt)

Calcispheres

The samples of Strathaird Limestone were dominated by calcispheres and almost devoid of a benthonic fauna. The foraminifera are indicative of a Turonian age with *Hedbergella praehelvetica* being diagnostic of the Lower to Middle Turonian. Thin section LG6c yielded good cross-sectional views of *H.praehelvetica*. Samples from Strathaird contained a poorer fauna than those from Laig Gorge, Eigg but assemblages from both localities were dominated by planktonic forms.

5.7. Stratigraphic palynology - Introduction.

Palynomorphs through the Inner Hebrides Group are dominated by dinoflagellate cysts. In this section, the palynological assemblage will be considered for its biostratigraphical significance, palynofacies being discussed in Chapter 6. Processing methods are described, then the results discussed section by section and presented on range charts (Figs.5.2-5.7). Systematic palynology is described in Appendix II.

Initially, three widely spaced samples were selected and processed from each section, in order to identify those lithologies and localities which would yield the best results. Where palynomorphs were so badly preserved that they were no longer recognizable to generic level, or all three samples were barren of palynological material, no further samples were processed from that section.

5.8. Processing methods (for palynology).

To extract acid-resistant organic material from sediments, it is necessary to remove all mineralogical matter from the sample. Samples were first weighed to a standard size of 60gms and then broken up into granules between 2 and 6mm long, using a pestle and mortar. All equipment was kept scrupulously clean between samples, to minimize cross-sample contamination. The crushed material was then immersed in concentrated hydrochloric acid (35% HCl) in order to remove any carbonate material. Where there was a strong reaction, HCl was added until no trace of a reaction could be seen, even after stirring. Samples were then neutralized by decanting off some of the acid and adding distilled water. (Sieving was not practicable at this stage due to the danger of the HCl attacking the sieve mesh material). The decanting and addition of distilled water was repeated until the sample was neutral. Technical grade hydroflouric acid (60% HF) was then added (with extreme caution). Very fine-grained samples such as mudstones tended to react vigorously, but other, highly siliceous samples, such as the silicified chalk, often showed no visible reaction with HF. As it was essential that all siliceous material was removed, after 5 days in HF (during which the sample was stirred), the spent acid was decanted off and fresh HF added. This process was repeated until all the samples had broken down to a very fine organic residue. Following thorough removal of the siliceous fraction of the sediment in this way, the remaining liquid was decanted off and distilled water added until the sample was neutral.

The neutral liquid and residue was then sieved. Initially, samples were wet-sieved using distilled water through a 10μm mesh but it was found that too much amorphous organic material was retained with this mesh size, and a 20μm mesh was used instead. To check that no valuble palynological material was being lost with this mesh size, the material going through the mesh was caught, and some of the residue kept and made into slides.

In some samples, flouride crystals had formed through a reaction between remaining carbonate material and HF. This was removed by adding 20% HCl to the residue and boiling for 5 - 10 minutes in a fume cupboard.

Where a large amount of amorphous organic material remained in the >20μm fraction, an ultrasonic water bath was used to disaggregate the unwanted material which could then be removed by further sieving. The sample was always split and only half subjected to the ultrasonic treatment in case of damage to structured organic material. Slides were made of both treated and untreated material where ultrasonic exposure had been thought necessary. The length of treatment was dependent on the amount of unwanted material present and ranged from 10 seconds where the method was used simply to disaggregate clumped palynological material, to 120 seconds where structured organic material was almost totally obscured by amorphous organic matter. Oxidation using fuming nitric acid (HNO_3) was not used since this method is known to preferentially destroy some dinoflagellate cysts, thus producing bias in the assemblage (Duane, 1989, pers.comm.).

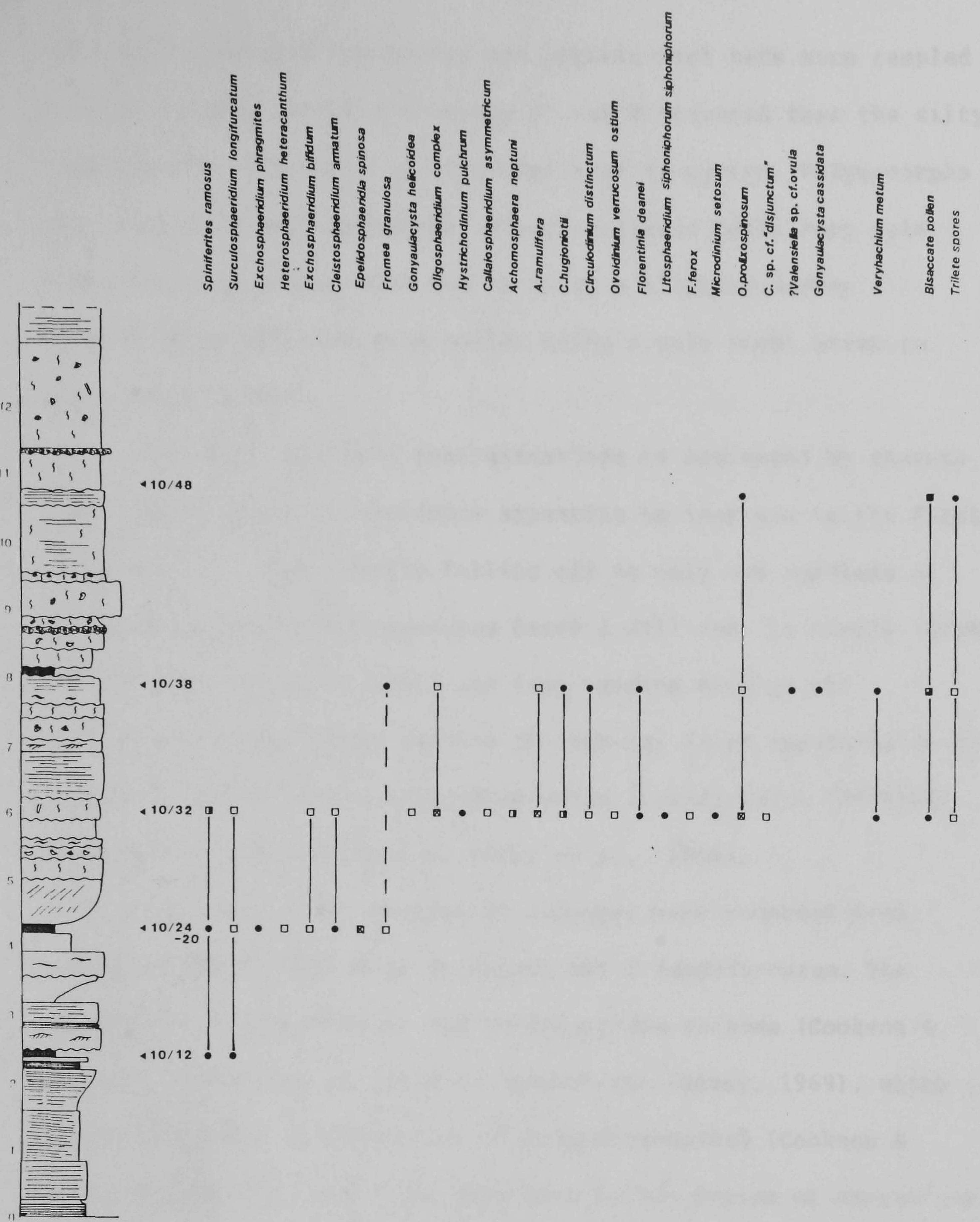
Following treatment (where thought necessary), the residue in the sieve was pipetted off and stored in plastic bottles, a drop of phenol being added to prevent algal growth during storage. Part of the residue was then concentrated by centrifuging and mounted on slides, using a glycerine-glycerol gel as the mounting medium.

5.9. Palynological results.

Sampled sections will be discussed in broad lithostratigraphic order. From a total of 79 samples investigated, 49 yielded dinoflagellate cysts; 9 yielded pollen and/or spores and/or acritarchs only; 6 yielded structured woody and/or cuticle material only, and 15 were barren of structured organic material.

5.9.i. Palynomorphs from Loch Aline Borehole 10/87. (See Fig.5.2).

Sampling from this core was restricted and therefore only



KEY:

● Single occurrence	○ 26-30 specimens
□ 2-5 specimens	◑ 31-35 specimens
⊠ 6-20 specimens	x 36-40 specimens
◧ 11-15 specimens	△ 41-45 specimens
◪ 16-10 specimens	▲ 46-50 specimens
■ 21-25 specimens	▲^{x} >50 specimens
	x=total no.

Fig.5.2 Palynomorphs from Loch Aline borehole 10/87.

the most relatively low-energy and organic-rich beds were sampled for palynology. During processing it was discovered that the silty clay material from this locality was rich in pyrite. Palynomorphs were generally well-preserved, dinoflagellates being very pale light brown in colour with spores being a slightly darker reddish-brown and bisaccate pollen being a pale light brown to light straw yellow.

The dinoflagellate cyst assemblage is dominated by chorate cysts, their relative abundance appearing to increase in the first three samples, then rapidly falling off to only one specimen of *Oligosphaeridium prolixospinosum* Davey & Williams, in sample 10/48. The forms occurring in 10/12 are long-ranging through the Cretaceous; *Spiniferites ramosus* (Ehrenberg) first appearing in the middle Barremian, and *Surculosphaeridium longifurcatum* (Firtion) appearing in the late Aptian (Davey *et al.*, 1966).

A total of eight species of dinocyst were recorded from sample 10/24-20, including *S.ramosus* and *S.longifurcatum*. The assemblage is dominated by *Epelidosphaeridia spinosa* (Cookson & Hughes), indicating an early Cenomanian age (Davey, 1969), which is supported by the co-occurrence of *Fromea granulosa* (Cookson & Eisenack) (Tocher, 1984). No bisaccate pollen grains or spores were recorded from this sample.

Sample 10/32 yielded a relatively diverse assemblage including *Cleistosphaeridium huguoniotii* (Cookson & Eisenack), *Ovoidinium verrucosum ostium* (Davey), *Litosphaeridium siphoniphorum siphoniphorum* (Cookson & Eisenack) and *Microdinium setosum* Sarjeant emend.Below, probably indicative of a late Albian to middle Cenomanian age (Davey *et al.*, 1966, 1969; Lucas-Clark, 1984; Jarvis *et al.*,1988). Spores and pollen were rare in this sample.

A pronounced drop in both diversity and abundance of dinoflagellate cysts occurs in sample 10/38, the number of species falling from nineteen in 10/32 to ten, seven of which are based on single specimens. *Gonyaulacysta cassidata* (Eisenack & Cookson) appears in this sample, which with the occurrence of *C. huguoniotii* and *O.prolixospinosum*, indicates a Cenomanian age (Davey *et al.*,1966). This sample is dominated by bisaccate pollen.

O.prolixospinosum is the only dinocyst species seen in sample 10/48. Bisaccate pollen is, however, relatively abundant.

5.9.ii. Palynomorphs from Loch Aline Adit.

The initial three samples from this section (LAA5, LAA10, LAA13)(see Fig.3.5 for sample location), were barren of dinoflagellate cysts. Sample LAA5, comprising fine to medium grained glauconitic sandstone, yielded bisaccate pollen grains: these were medium to dark red-brown in colour. Dark brown to black structured cuticle material was also common in this sample. LAA10, comprising fine grained, glauconitic silty sandstone, contained rare black cuticle and ?woody material up to 125μm in length. LAA13, comprising the red-brown mudstone between the Lochaline White Sandstone and the basalt, contained abundant dark brown to black degraded cuticle material.

No further samples were processed for palynology from this section.

5.9.iii. Palynomorphs from Loch Aline Waterfall (a).

Three samples were processed from this section, LAW(a)1, LAW(a)4 and LAW(a)5. Sample LAW(a)1, comprising fine to medium grained glauconitic silty sandstone, yielded very rare but well-preserved plant cuticle but no other structured organic material. Finely disseminated, amorphous organic matter was common, however. See Fig.3.6 for sample location.

Sample LAW(a)4, comprising dark reddish-brown clayey silt, yielded no structured organic material, although pale brown amorphous organic matter was relatively common. LAW(a)5, (organic rich medium grained glauconitic sandstone), yielded a few red-brown pollen grains and rare dark brown cuticle material. Amorphous light brown organic material was common in this sample.

No further samples were processed for palynology from this section.

5.9.iv. Palynomorphs from Loch Aline Waterfall (b).

Palynomorphs from this section are dominated by dinoflagellate cysts. Both relative abundance and diversity of palynomorphs decrease moving up the section (see Fig.5.3), yet this does not appear to be related to sedimentary facies.

The dinocyst assemblage is dominated by *Oligosphaeridium complex* (White), *S.longifurcatum, Cleistosphaeridium armatum* (Deflandre), and *O.prolixospinosum,* all of which occur in all the three samples logged, though in decreasing relative abundance from LAW(b)A to LAW(b)B.

Sample LAW(b)A yielded a total of 16 species of dinoflagellate cyst, including the stratigraphically useful *Cleistosphaeridium huguoniotii, Florentinia deanei* (Davey & Williams), and *Microdinium setosum* which indicate a Cenomanian age

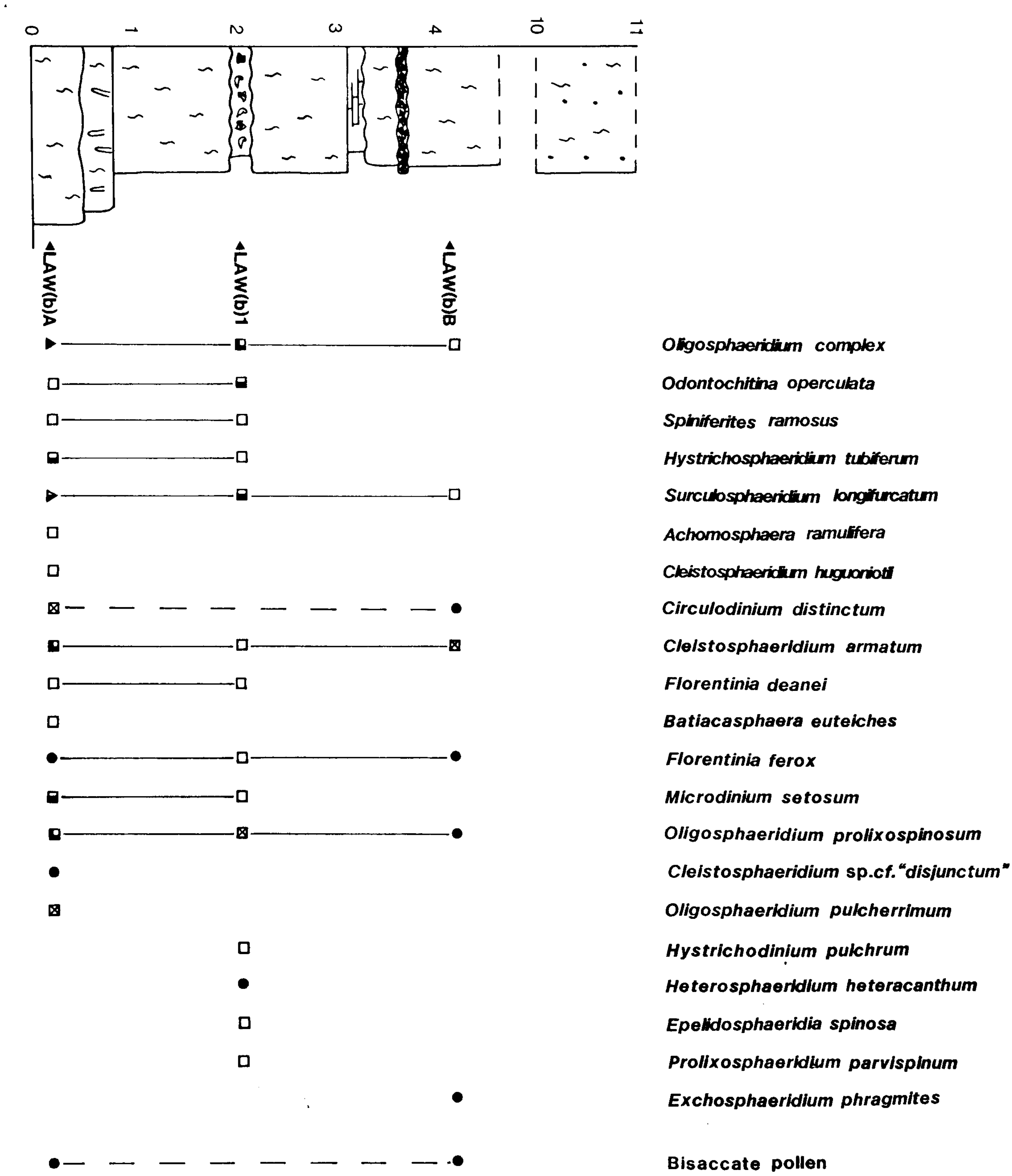


Fig.5.3 Palynomorphs from Loch Aline Waterfall (b).

(Davey *et al.*,1966; 1969). This supported by the occurrence of *Epelidosphaeridia spinosa* in sample LAW(b)1.

Bisaccate pollen was found to be rare, but when found was a pale brown hue and, like the dinoflagellate cysts, was relatively well-preserved.

5.9.v. Palynomorphs from Loch Aline Waterfall (c).

Only one sample was processed from this section (LAW(c)1), this being the most likely to contain palynomorphs since it comprises fine grained glauconitic sandstone (see Fig.3.8).

LAW(c)1 yielded a few very poorly preserved dinoflagellate cysts which were dark brown in colour and badly corroded. *?O.complex* and *Circulodinium ?distinctum* (Deflandre & Cookson) were recorded; these make the sample younger than late Aptian (Deflandre & Cookson, 1955). A few dark brown, badly corroded pollen grains were also seen.

5.9.vi. Palynomorphs from Beinn Iadain Section A.

Palynomorphs from this section are dominated by dinoflagellate cysts. In samples BI1-BI14 (see Fig.5.4), palynomorphs were relatively well-preserved and very pale light brown in colour. In samples BI16 and UES2-5 palynomorphs were a darker hue and rather poorly preserved. Samples BI15 and UES5 were barren of structured organic material.

Overall, the dinocyst assemblage is dominated by long-ranging forms such as *O.complex*, *S.longifurcatum* and *C.armatum*. 36 species of dinocyst were found but the maximum nuber for one sample was 19 (in BI5 and BI14).

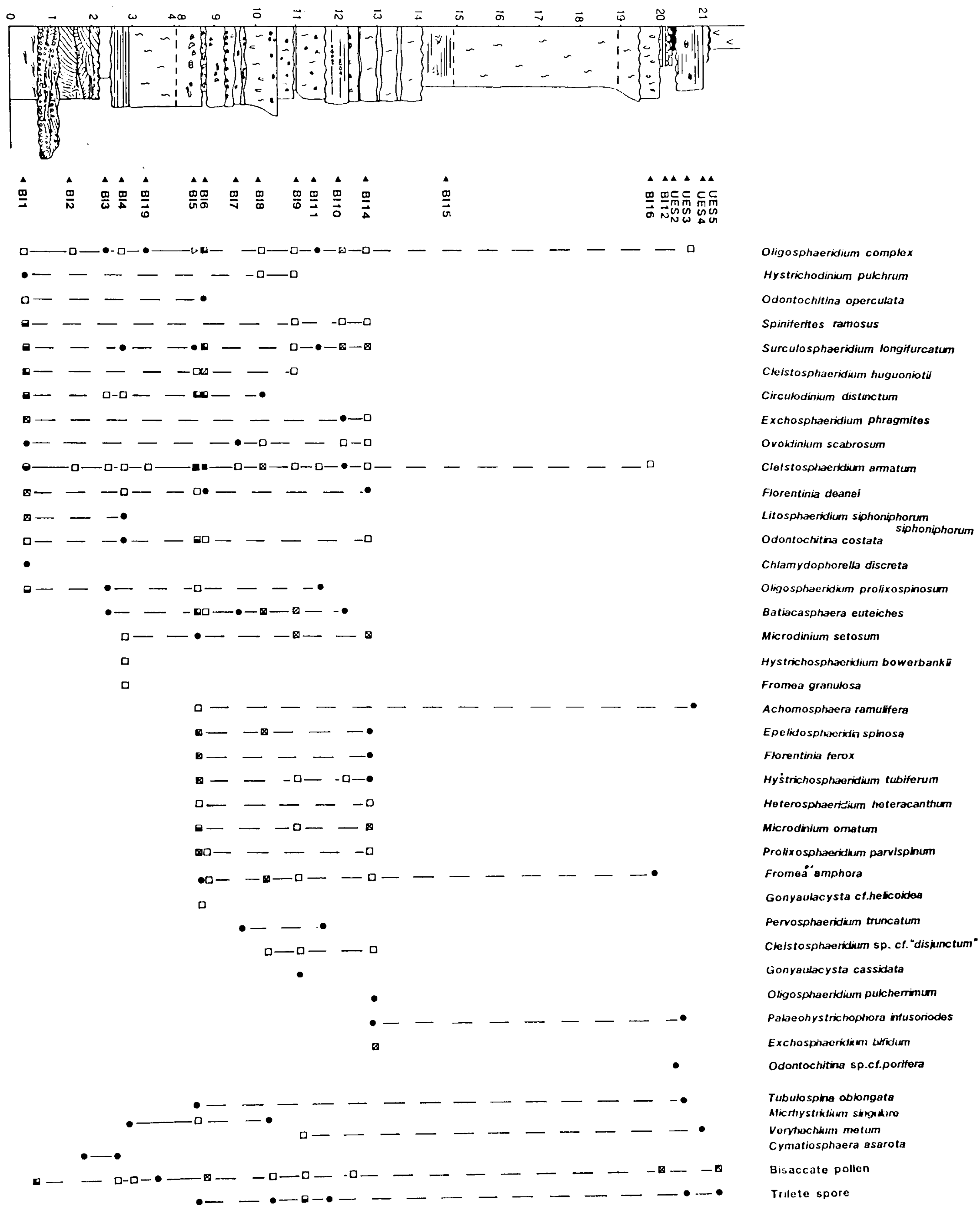


Fig.5.4 Palynomorphs from Beinn Iadain Section A

Sample BI1 yielded *C.hugnoniotii, Ovoidinium scabrosum* Cookson & Hughes, *L. siphoniphorum siphoniphorum* and *C.armatum*, which with the occurrence of *Chlamydophrella discreta* Clarke & Verdier and *O.prolixospinosum*, are indicative of an earliest Cenomanian age (Foucher, 1979). *Batiacasphaera euteiches* (Davey), which appears in sample BI3; *E.spinosa, Florentinia ferox* (Deflandre) and *Microdinium setosum* Sarjeant emend.Below, which appear in sample BI5, are all typical Cenomanian species (Jarvis *et al.*, 1988), most of which persist up to sample BI14. The continuation of *Ovoidinium scabrosum* to this level however, suggests a mid-Cenomanian age at the youngest for this part of the section (Davey, 1970).

The dinocyst assemblage yielded in BI16 was restricted to *C.armatum* and *Fromea amphora* Cookson & Eisenack, both of which are relatively long-ranging.

Sample BI12, comprising silicified chalk, was totally barren of structured organic material although amorphous organics were common. However, a possible dinoflagellate cyst, tentatively identified as *Odontochitina* sp. was seen in a thin section of the same sample (see Fig.5.5).

Samples UES2-4 were dominated by cuticle and woody material, yielded a few dinoflagellate cyst, none of which were stratigraphically significant, *O.complex,* and *Achomosphaera ramulifera* (Deflandre) all ranging well into the Palaeocene (Foucher, 1979).

The acritarch *Cymatiosphaera asarota* Davey occurred in samples BI2 and BI3, and *Micrhystridium singulare* Firtion was found in BI5. Both these support a Cenomanian age (Davey, 1969).

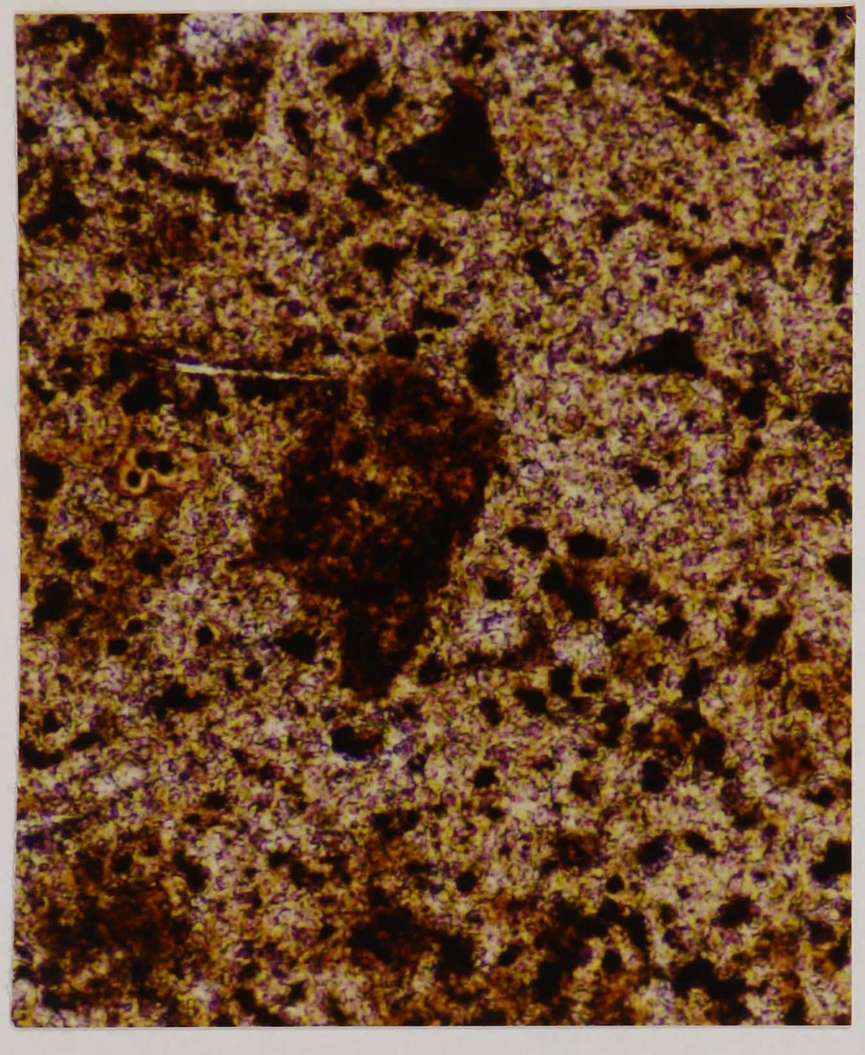


Fig.5.5. Thin section of Gribun Chalk from Beinn Iadain with possible *Odontochitina* sp. Overall length of cyst 184μm.

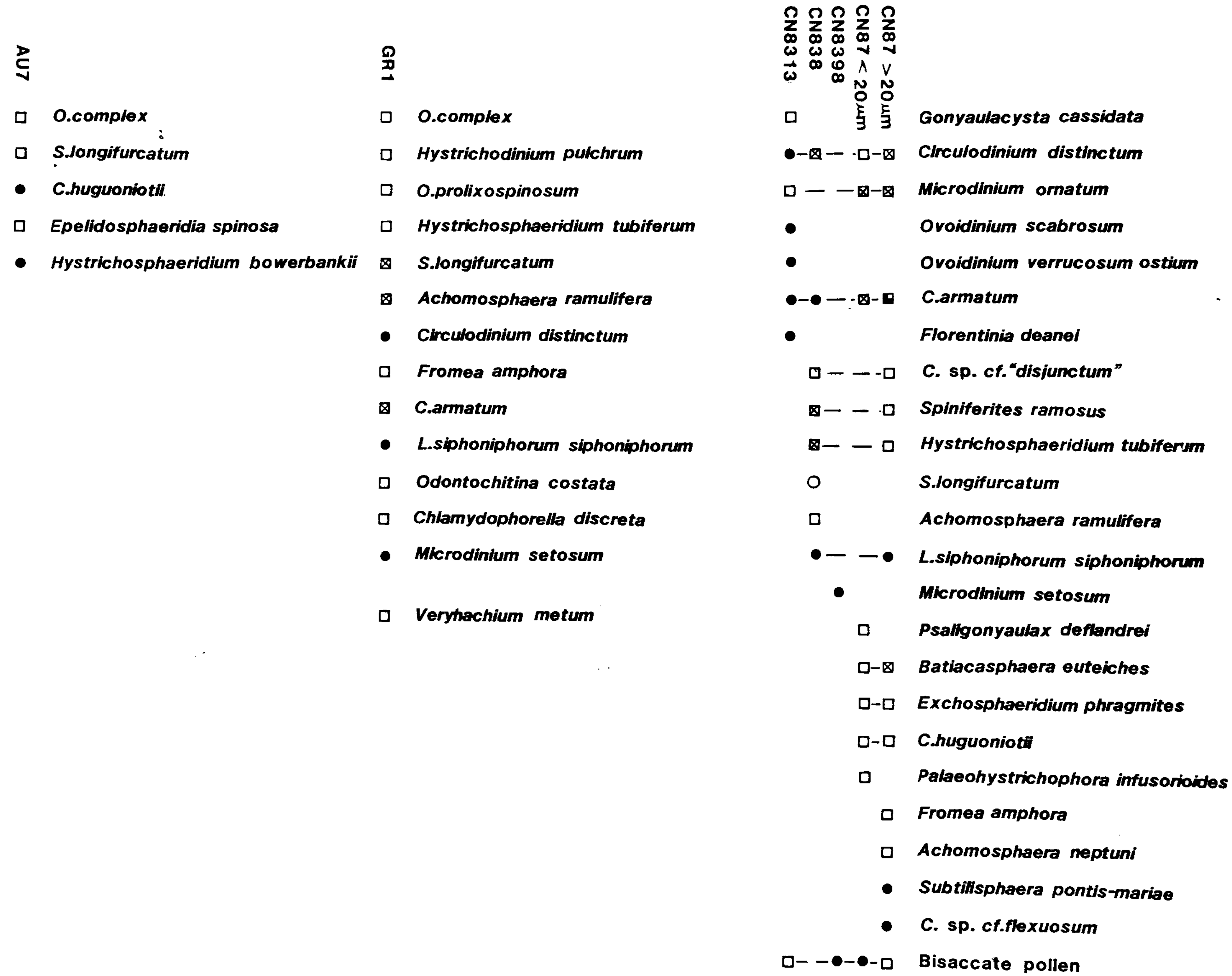


Fig.5.6 Palynomorphs from Claggan, Morvern and Gribun & Auchnacraig Cliff, Mull.

Bisaccate pollen is relatively common through the section and occasional trilete spores appear in BI5 and range sporadically up to UES4. The pollen grains are a reddish-brown colour in the greensand samples but become darker in BI16 and UES4.

5.9.vii. Palynomorphs from Claggan, Morvern. (See Fig.5.6).

In addition to those samples collected during this study, five samples from a greensand exposure in a road cutting at Claggan, Morvern, were kindly lent to the author (see acknowlegements). Unfortunately no log was available. The samples yielded an assemblage typical of the Morvern Greensand, with the occurrence of *Ovoidinium scabrosum, Ovoidinium verrucosum ostium* (Davey) and *L.siphoniphorum siphoniphorum* indicating a late Albian to early Cenomanian age (Foucher, 1979; Lucas-Clark, 1984; Wilkinson, 1988, pers. comm.). Organic material was well-preserved, being light brownish-yellow in colour, or almost colourless.

5.9.viii. Palynomorphs from Allt na Teangaidh, Gribun.

Palynomorphs from this section are dominated by dinoflagellate cysts (see Fig.5.7). These were generally well-preserved, being a very pale light brown hue.

The assemblage is dominated by *S. longifurcatum* and *O. complex* through the section. The additional occurrence of *E.spinosa* in samples AT1 and AT2, and the presence of *C.huguoniotii* in AT1 to AT7, suggests a Cenomanian age. The absence of *Spiniferites* and Achomosphaera spp. from this section is noteable. AT10, a sample of silicified chalk, yielded one bisaccate pollen grain and amorphous organic material.

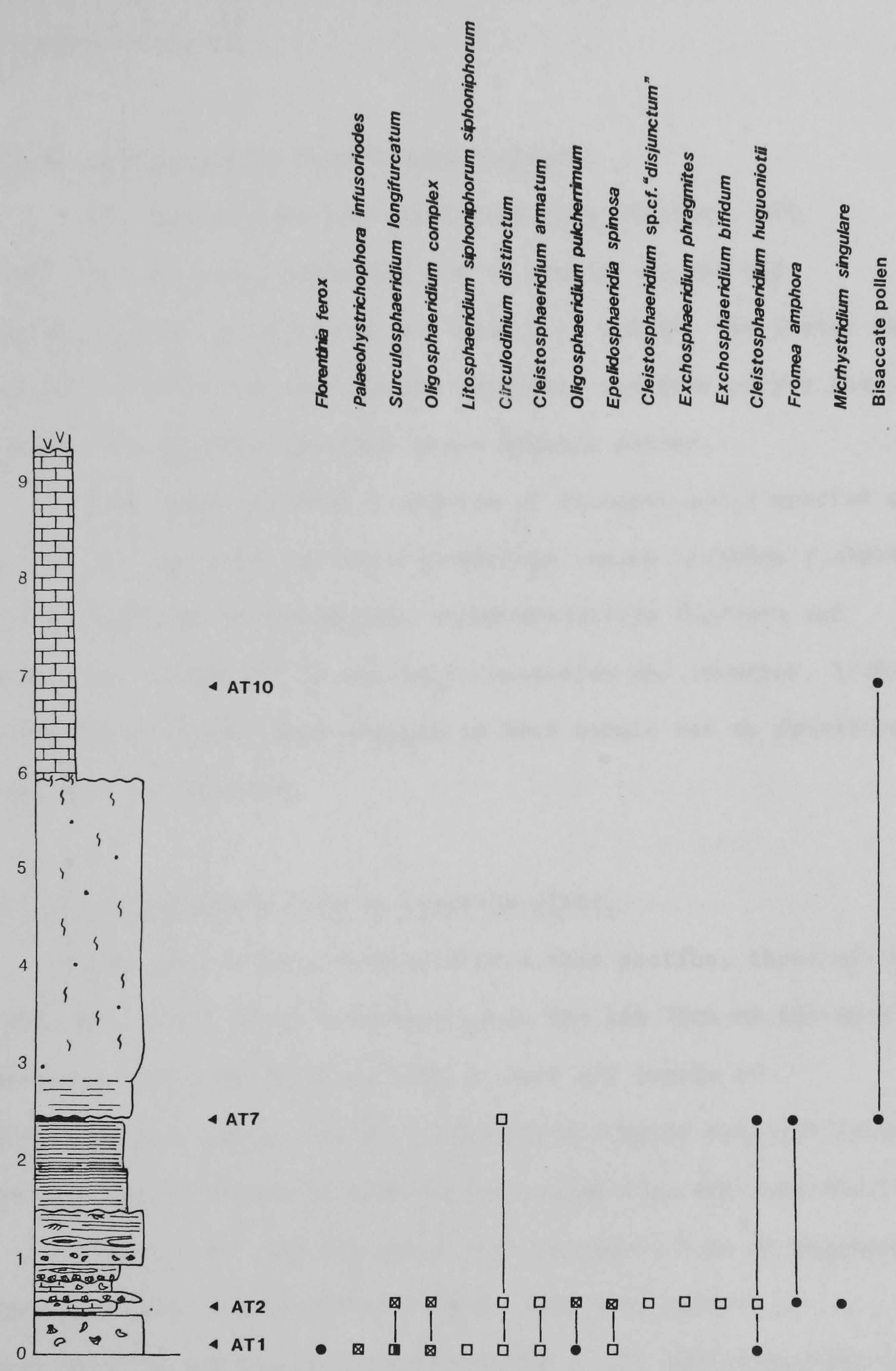


Fig.5.7 Palynomorphs from Allt na Teangaidh,Gribun.

Overall, 14 species of dinocyst were logged from this section. Both AT2 and AT7 also contained a relatively high proportion of dinocyst fragments, including operculae with processes attached.

5.9.ix. Palynomorphs from Gribun Boulders.

Two samples were processed from this locality, GR1, comprising the basal greensand bed of Boulder A, and GR3, comprising silicified chalk (see Figs.3.13 & 5.6). The latter sample was barren of structured organic material, yielding only a few patches of amorphous brownish green organic matter.

Sample GR1 yielded 15 species of dinocyst and 2 species of acritarch. The dinoflagellate assemblage, which includes *C.armatum, L.siphoniphorum siphoniphorum, Chlamydophorella discreta* and *M.setosum,* is typical of an early Cenomanian age (Foucher, 1979). *Achomosphaera ramulifera* appears in this sample but no *Spiniferites* spp. were encountered.

5.9.x. Palynomorphs from Auchnacraig Cliff.

Six samples were processed from this section, three of these (AU8, AU9, AU11) being concentrated in the top 75cm of the section (see Fig.3.15). These three samples were all barren of dinoflagellate cysts, the only structured organic material found being some corroded bisaccate pollen grains from AU8 (see Fig.5.6).

Samples AU1 and AU3 (both from the basal 1,5m of greensand) were barren of dinoflagellate cysts. Both were rich in greyish-brown amorphous organic material, only AU3 containing any structured matter, this comprising occassional black woody fragments and pieces of plant cuticle.

Sample AU7, comprising fine grained silty sandstone, contained four identifiable species of dinoflagellate cyst: *C.huguoniotii, O.complex, S.longifurcatum* and *E.spinosa.* There was also one broken specimen of ?*Hystrichosphaeridium bowerbankii* Davey & Williams. This assemblage confines the age of the sample to the Cenomanian.

5.9.xi. Palynomorphs from Torosay Castle.

Two samples were processed from this locality, TC1 and TC2 (see Fig.3.17). Both were rich in leiospores and ?algal filaments but yielded only one dinoflagellate cyst, a badly corroded ?*Oligosphaeridium* sp. (from TC2). The organic material in both samples was dark reddish-brown in colour.

5.9.xii. Palynomorphs from Feorlin Tributary.

Three samples (FT1-3) were processed from this section (see Fig.3.19), but all were barren of dinoflagellate cysts. FT2 and FT3, comprising organic rich mudstone and silty sandstone respectively, were dominated by dark brown to black amorphous organic material but structured cuticle and woody fragments were also common.

5.9.xiii. Palynomorphs from Clach Alasdair, Eigg.

Five samples from this section were processed (E720-723 and CA4) (see Fig.3.23). Of these, only the lowest sample, E721, comprising glauconitic sandy siltstone yielded structured organic material in the form of a few bisaccate pollen grains and some dark brown cuticle. Samples E720, E722, E723 and CA4 contained rare pieces of amorphous organic material and fine grained pyrite.

5.9.xiv. Palynomorphs from Laig Gorge, Eigg.

Five samples were processed from this section (LG2, LG3, LG5-7)(see Fig.3.24), only one of which yielded dinoflagellate cysts. LG7 yielded *O.complex* and *Membranilarnacia* sp.*cf.reticulata,* both of which are long-ranging (Lentin & Williams, 1989). The organic material from this sample was very dark brown to black in colour. Very little organic material was found in any of the other samples, but finely disseminated pyrite was common in all the samples of the biomicritic limestone (LG5-7). Samples LG2 and LG3 contained some dark brown amorphous organic material.

5.9.xv. Palynomorphs from Strathaird, Skye.

Three samples were processed from this locality (ST1-3), all of which yielded dinoflagellate cysts (see Fig.5.8). In sample ST2 especially, the assemblage appeared to be diverse but the state of preservation of the material in all samples from this section was so poor that no details of archaeopyle, paratabulation or wall morphology could be discerned, the cysts appearing black in colour and at least partially corroded. Overall, chorate cysts appear to dominate the assemblage. Identification, even to generic level is tentative, due to the lack of detail preserved.

The species which have been identified tend to be long-ranging, with a maximum age of Albian (on *Achomosphaera ramulifera* and *Circulodinium distinctum*), ranging to Coniacian (on *Florentinia deanei*) or early Campanian (on *S.longifurcatum* and *C. armatum*)(Foucher, 1979). One rather corroded specimen tentatively

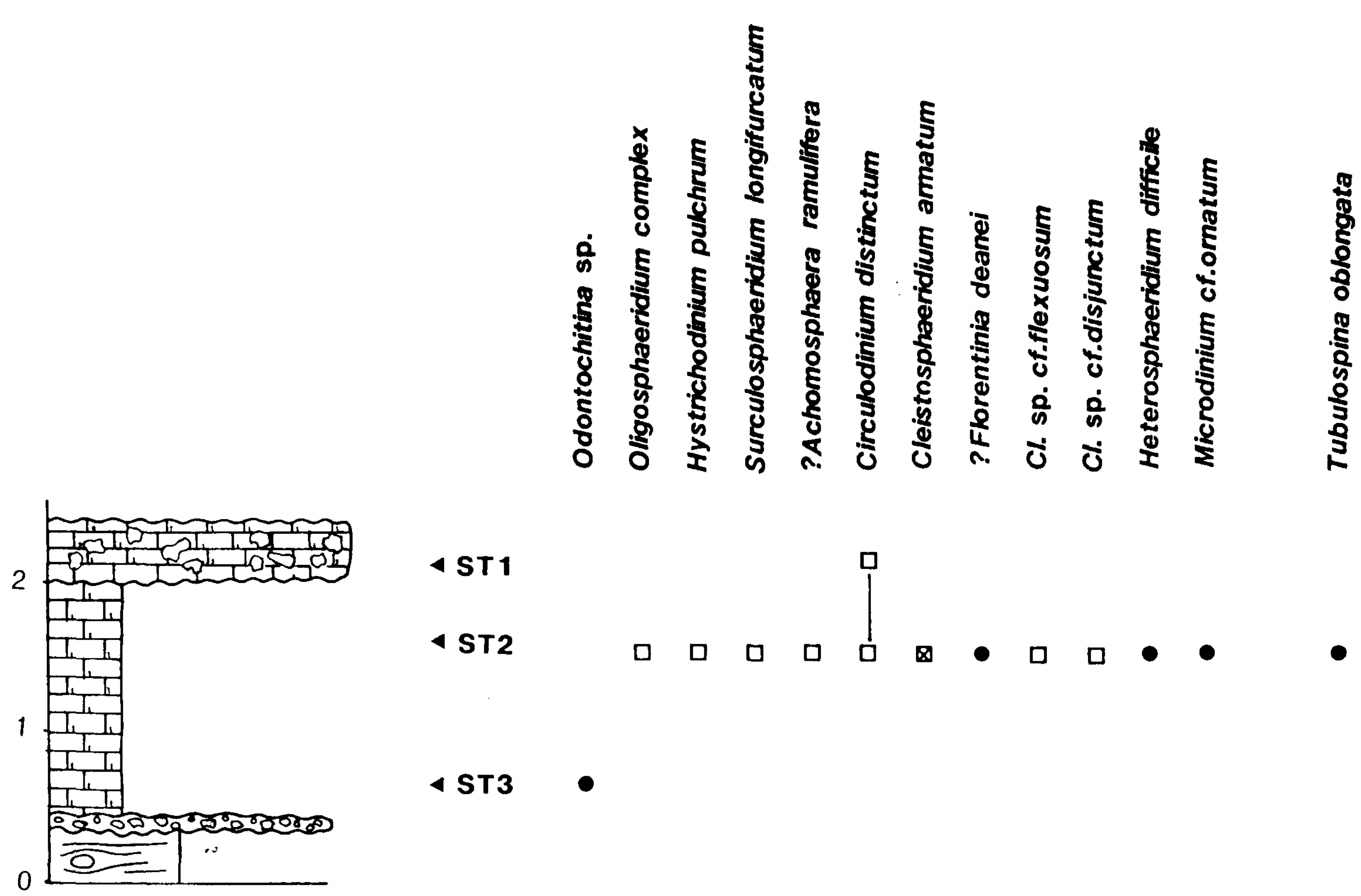


Fig.5.8 Palynomorphs from Strathaird

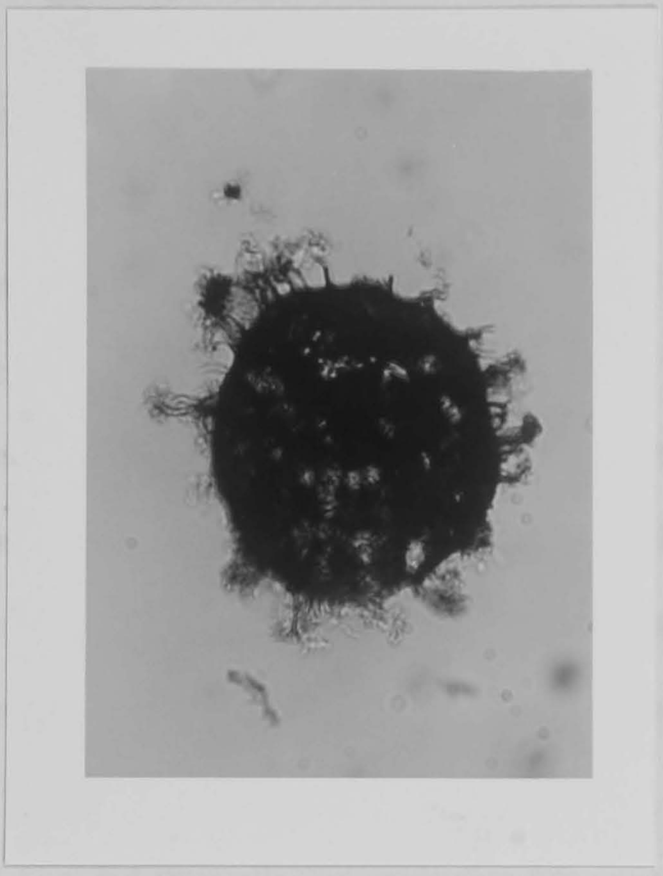


Fig.5.9. *Heterosphaeridium* sp. *cf.difficile* (x400) from sample ST2. Note the very dark colour and rather poor preservation.

identified as *Heterosphaeridium difficile* (Manum & Cookson) was also found (see Fig.5.9): this species is indicative of a Turonian age.

In all three samples, no pollen grains or spores were recognized, though black corroded cuticle material was relatively common.

5.9.xvi. Palynomorphs from Allt Eoghainn, Skye.

Four samples were processed from this locality (AE1, AE2, AE2-1 and AE2-2) (see Figs.3.29, 3.30), two of which, AE2 and AE2-1, were barren of structured organic material. Sample AE2-2 yielded one bisaccate pollen grain and a chorate cyst so corroded as to be unidentifiable to generic level. Sample AE1 yielded rare bisaccate pollen, also corroded. All organic material in these samples was black and at least partially corroded, and fine grained pyrite was common.

5.10. Summary of palynological results.

Samples of the Morvern Greensand from Mull and Morvern, yielded a consistant, though never particularly diverse dinoflagellate cyst assemblage, generally indicative of a late Albian to mid-Cenomanian age. Little difference in the relative diversity and abundance of dinocysts from sections in Morvern and Mull was noticed, except for the absence of *Spiniferites* spp. from the latter.

The lack of structured organic material in silicified chalk samples BI12, AT10 and GR3 may suggest that the ?*Odontochitina* sp. and foraminiferid linings seen in thin section (see Fig.4.11) are preserved as moulds, with none of the original organic material surviving.

Samples of the Strathaird Limestone and Laig Gorge Sandstone yielded little of stratigraphic significance, the colour and corrosion of those dinoflagellate cysts seen indicating that they had been subjected to very high temperatures. A maximum range of Albian to Campanian can be tentatively construed for sample ST2 on dinoflagellate cysts with the occurrence of *Heterosphaeridium* sp. *cf.difficile* indicating a possible Turonian age.

Few stratigraphically significant palynomorphs were encountered in samples of the Beinn Iadain Formation (samples UES from the Beinn Iadain section, and FT). However, the long-ranging species of dinoflagellate cysts found in sample UES3 confine the age of this unit to a range of Albian to Palaeocene.

5.11. Summary of the biostratigraphical results.

The stratigraphic position of the Morvern Greensand Formation, previously put at a Late Albian to Middle Cenomanian age, is confirmed by the palynological evidence on the relatively diverse dinoflagellate cyst assemblage. The foraminiferal assemblage was almost negligable from this lithofacies.

Conversely, the Gribun Chalk was effectively barren of palynomorphs but yielded a relative diverse assemblage of foraminifera in thin section. These are broadly indicative of a Late Cenomanian to Turonian age but this biostratigraphical evidence is not conclusive, given the difficulties of positively identifying foraminiferids in thin section.

The Strathaird Limestone Formation is constrained to the

Cretaceous on the occurrence of inoceramids in this lithofacies. It yielded a few dinoflagellate cysts but these tended to be poorly preserved although possibly indicative of a Turonian age. Calcareous microfossils in the Strathaird Limestone were dominated by calcispheres and the foraminiferal assemblage was dominated by planktonic forms. The foraminiferal assemblage is broadly indicative of a Turonian age on the occurrence of *Whiteinella aprica* and *Heterohelix globulosa* but the occurrence of *Hedbergella praehelvetica* refines this to an Early to Middle Turonian age.

The Beinn Iadain Mudstone Formation was barren of any macrofauna and yielded few dinoflagellate cysts. These indicate an Albian to Palaeocene biostratigraphic range for this part of the succession.

Chapter 6: Palaeoenvironmental interpretation.

6.1. Introduction.

By integrating sedimentological, palaeontological and ichnological evidence it is possible to make detailed environmental interpretations for each of the lithotypes encountered during this study. The integrated evidence is also invaluable in reconstructing palaeogeographies on a local scale (see Section 6.3). In Chapter 7 the relationship between the palaeoenvironments and structural features of the area is discussed.

Here, factors used as palaeoenvironmental indicators, in addition to sedimentary facies, will be described. These will then be applied to the major lithostratigraphical units of Cretaceous age in the Inner Hebrides Basin.

6.2. Palaeoenvironmental indicators.

Sedimentary palaeoenvironments can be reconstructed using sedimentary facies alone, especially where exposure is good (e.g. Swift *et al.*, 1987; Massari & Parea, 1988), but where there is poor exposure and considerable lateral variation in facies, all available evidence is required. Therefore, in addition to the primary sedimentary facies described in Chapter 4, the following factors will be taken into consideration:

6.2.i. Glauconite.

A large volume of literature has evolved on the mineralogy, formation and environmental significance of glauconite (see Burst, 1958, for a review of pre-1958 papers; Hower, 1961; Porrenga, 1967), however little is known on the details of the environmental conditions necessary for its genesis (Wildberg, 1980; Williams, 1989. pers. comm.). The term "glauconite" is here used loosely to describe dark green to dark greyish green argillaceous pellets which give the greensand lithofacies its characteristic colour. The true mineralogy of these pellets was not investigated in this study but most were found to be allogenic (using the criteria stated by Wildberg, (1980)).

In addition to the allogenic pellets which have sharp, smooth, surfaces with shrinkage cracks, there is also authigenic "matrix" glauconite which occurs in more amorphous pellets with "fuzzy" edges in the more argillaceous units of the Morvern Greensand. This may have a diagenetic origin or may have developed during sedimentation and can be used as an indicator of fully marine though low energy conditions since most authors agree that glauconite forms in marine conditions at depths between 30 and 2000m (Cloud, 1955; Burst, 1958; Porrenga, 1967).

6.2.ii. Trace fossils.

Trace fossils are the direct product of animal:sediment interactions and are therefore related to the specific environmental conditions in which the trace-making organism had a niche. Trace fossils are particularly useful in the interpretation of the dynamics of the sedimentary environment in which the animal lived. Where there is continuous slow deposition in a favourable environment, biogenic reworking will completely overprint any primary sedimentary structures, resulting eventually in a completely homogenized unit with rare identifiable ichnofossils.

Continuous rapid deposition is usually indicated by sediments in which primary sedimentary structures are preserved. Trace fossils are rare in such an environment, and those found often have agglutinated walls such as *Ophiomorpha* and *Thalassinoides* which may have formed during the primary depositional phase, or are escape structures, the organism moving upwards to keep pace with the accumulating sediment. Where there is discontinuous, relatively rapid sedimentation with no erosion, the same degree of bioturbation is possible as that occurring when there is continuous slow deposition. However, this depends on the thickness of the beds deposited rapidly. If these are very thick, the top only will be within range of burrowing organisms.

One of the most common depositional regimes in marginal marine environments is where discontinuous periods of sediment accumulation are preceded and followed by erosion (Howard, in Frey, 1975). The resulting bedding is charaterized by erosional upper and lower boundaries and a gradation from primary sedimentary structures in the lower third of the bed to a bioturbated top third, trace fossils becoming more abundant as the sedimentation rate decreases. Burrows at the top of the unit are then often truncated by the erosive base of the next sedimentary sequence.

Specific trace fossil assemblages can be related to particular benthonic environments (following Seilacher, 1967), but have to be used with care since similar burrows can be made by more than one type of organism adapted to possibly different environmental conditions.

6.2.iii. Palynofacies.

The potential of assemblages of organic-walled microfossil assemblages as depth and shoreline indicators was recognized early in the history of palynology (see review by Williams & Sarjeant, 1967). Spores and pollen, being derived from terrestrial sources, are generally unreliable as indicators of depth or distance from shoreline alone since windborne pollen can remain airborne for over 24 hours and its distribution is highly variable (Stanley, 1965; Williams & Sarjeant, 1967). The concentration of water-borne spores and pollen has been found in studies of modern environments to increase seawards to a maximum distance of 185 miles from the shoreline, decreasing after this distance (*op cit.*). However, when combined with other palynomorphs, especially dinoflagellate cysts and acritarchs, which increase in abundance and diversity with distance from shoreline, spore and pollen data becomes more significant. Living dinoflagellates are found occasionally in brackish water and freshwater environments and therefore the presence of dinoflagellate cysts alone cannot be used as an indicator of marine conditions (Williams & Sarjeant, 1967; Evitt, 1985).

A possible relationship between dinoflagellate cyst morphology and sedimentary environment was first suggested by Vozzhenikova (1965) in a model where thin-walled cysts with elaborate processes to assist buoyancy would indicate open marine conditions, while cysts with a thick endophragm and periphragm would be pre-adapted to higher energy, more marginal environments. The theory is supported in some studies of Cenomanian deposits (e.g. Davey, 1966; Tocher, 1984). Chorate cysts have also been related to warm water masses (Davey & Rogers, 1975).

Amorphous organic material can also be an important environmental indicator, fibrous, membraneous and "spongy" material tending to indicate non-marine sources, while granular or "flakey" material tends to originate from a marine environment (Batten, 1983). The presence of woody and cuticle material, when considered with other groups of palynomorphs, can be used as a broad indicator of proximity of a shoreline as such relatively heavy palynomorphs tend to dominate total assemblages only within the innermost shelf area (Farr, 1988).

6.2.iv. Macrofauna and flora

As already discussed (Section 5.3), the macrofaunal diversity in the Cretaceous sediments of N.W. Scotland is extremely poor, and this is unlikely to be due to diagenesis (Section 4.5). However, where the mode of life of a fossil organism can be inferred from analogous extant forms, important palaeoenvironmental inferences are possible such as rate of sedimentation, suitability of the substrate for colonization etc.

6.2.v. Calcareous microfauna.

Because planktonic foramanifera appear to occupy different levels in the water column during their ontogeny, they can be used as indicators of water depth (Leary & Hart, 1989). Assemblages representative of all stages in the ontogeny of a given species are indicative of relatively deep water in which the life cycle is undisturbed, while assemblages dominated by juveniles only represent shallow water conditions in which depth is not sufficient to allow completion of the ontogenic cycle (*op cit.*). The only other calcareous microfossils encountered during this study were calcispheres. These are extremely common in some beds of the Hebrides Greensand and Inner Hebrides Limestone, but are of unknown affinities, though some may be calcareous-walled dinoflagellate cysts (Keupp, cited in Jarvis *et al.*,1988), and under some conditions show an inverse relationship to organic-walled dinoflagellate cysts (Jarvis *et al.*,1988).

All the above factors are closely inter-related, even glauconite genesis usually requiring the presence of faecal pellets (Wildberg, 1980). Trace fossils, palynofacies, macrofauna and flora, and calcareous microfossils can be classified together into specific biofacies indicative of specific ecological conditions.

6.3. Palaeoenvironmental analysis.

By integrating the evidence from sedimentary facies, biofacies and broad lithofacies, the depositional palaeoenvironment of sediments can be reconstructed in detail. In this section each lithostratigraphic unit will be discussed in stratigraphic order and the broad environmental changes which affected the Inner Hebrides Basin during the Late Cretaceous will be described in Section 6.4. See Enclosure 2 for logs.

6.3.i. Palaeoenvironments of the Morvern Greensand.

Sections will be analysed moving across the Inner Hebrides Basin from East to West.

Apart from the Lochaline White Sandstone Member, all the sediments of the Hebrides Greensand Formation can be interpreted as being of marine origin on the presence of authigenic glauconite in the silt fraction and a macrofaunal assemblage which is dominated by *Exogyra* spp. and *Neithea* spp.. Although there is considerable variation in sedimentary facies between geographically close sections (e.g. compare logs for BH10 & BI), this is largely a factor of exposure and preservation. Certain marker horizons can be correlated however, such as the whole shell bed which can be located in LAA, LAWb and BH10 (see Enclosure 2). This particular bed contains the same fauna and matrix material in the same state of preservation in all three sections and is thus considered a valid "event horizon" (Seilacher, 1982) for correlation.

The maximum transgressive phase occurring during the deposition of the greensand lithofacies in Morvern is represented by the organic-rich ripple cross-laminated silty sandstone underlying the conglomerate at the BI section, and by the cross-laminated sandy silts and clays of BH10 below sample 10/24-20 (see Fig.6.1).

The sedimentary facies comprising this part of the succession (Facies F, G, H, I & L) are typical of the lower shoreface to offshore - transition zone of the shelf (Hamblin & Walker, 1979), below mean low water level but with limited clastic input and within the influence of storm activity. These facies contain a relatively high proportion of terrestrially-derived plant cuticle and woody material in comparision to facies higher in the succession, indicating the close proximity of land. Disemminated pyrite is common and may indicate locally reducing conditions within the sediment (Love, 1967).

On palynological evidence, these sediments can be dated as latest Albian - earliest Cenomanian in age (see Sections 5.9.i & 5.9.vi). The ripple cross-laminated glauconitic silty sandstone at CA, Eigg, may also correlate with this period of transgression but

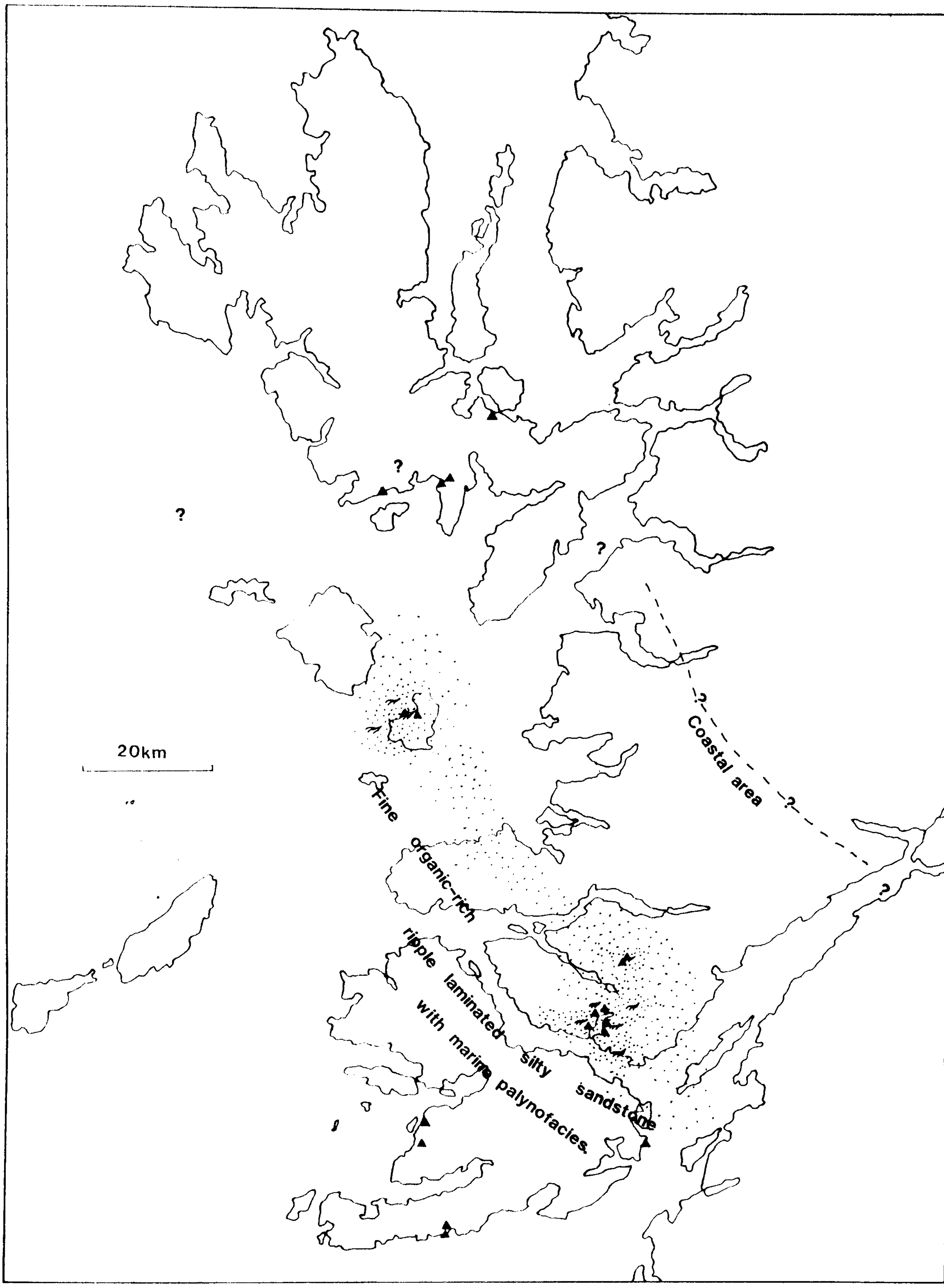


Fig.6.1 Morvern Greensand (latest Albian–early Cenomanian).

there is no biostratigraphical data to support this.

At the BI section, the basal ripple cross-laminated sandstone is unconformably overlain by the start of the next transgressive sequence, represented by an orthoconglomerate of Facies A. This phase of transgression makes up the bulk of the greensand sections in Morvern and Mull (based on similarities in the dinoflagellate assemblage, which indicates an early to middle Cenomanian range). The sedimentary facies sequence at BI is transgressive up to 14.4m, with a general trend towards medium to low energy intensively bioturbated argillaceous sandstones. The thorough bioturbation of many of these beds, resulting in a homogenous mixed sediment, reflects a low background sedimentation rate in predominantly medium to low energy conditions, as does the abundance of the free-lying bivalve *Exogyra*. This relatively quiet marine environment was interrupted by high energy storm events, resulting in the formation of shell lag and reworked shell bed deposits. These facies indicate deposition in a shallow water shelf environment between normal and storm wave base, but with the landwards movement of storm wave base being suggested by the decreasing frequency of storm deposits between 12.5 and 14.4m in the section.

This transgressive facies sequence is not so clear in the Mull sections where massive, highly bioturbated beds are less common (see Fig.6.2). Here, the sediment appears to have a higher argillaceous component and shelly, impure "limestones" (Facies K) are relatively common. The macrofauna is also slightly more diverse than in Morvern, gastropods and serpulid worm tubes being very abundant in some beds. This implies that the sedimentation rate was

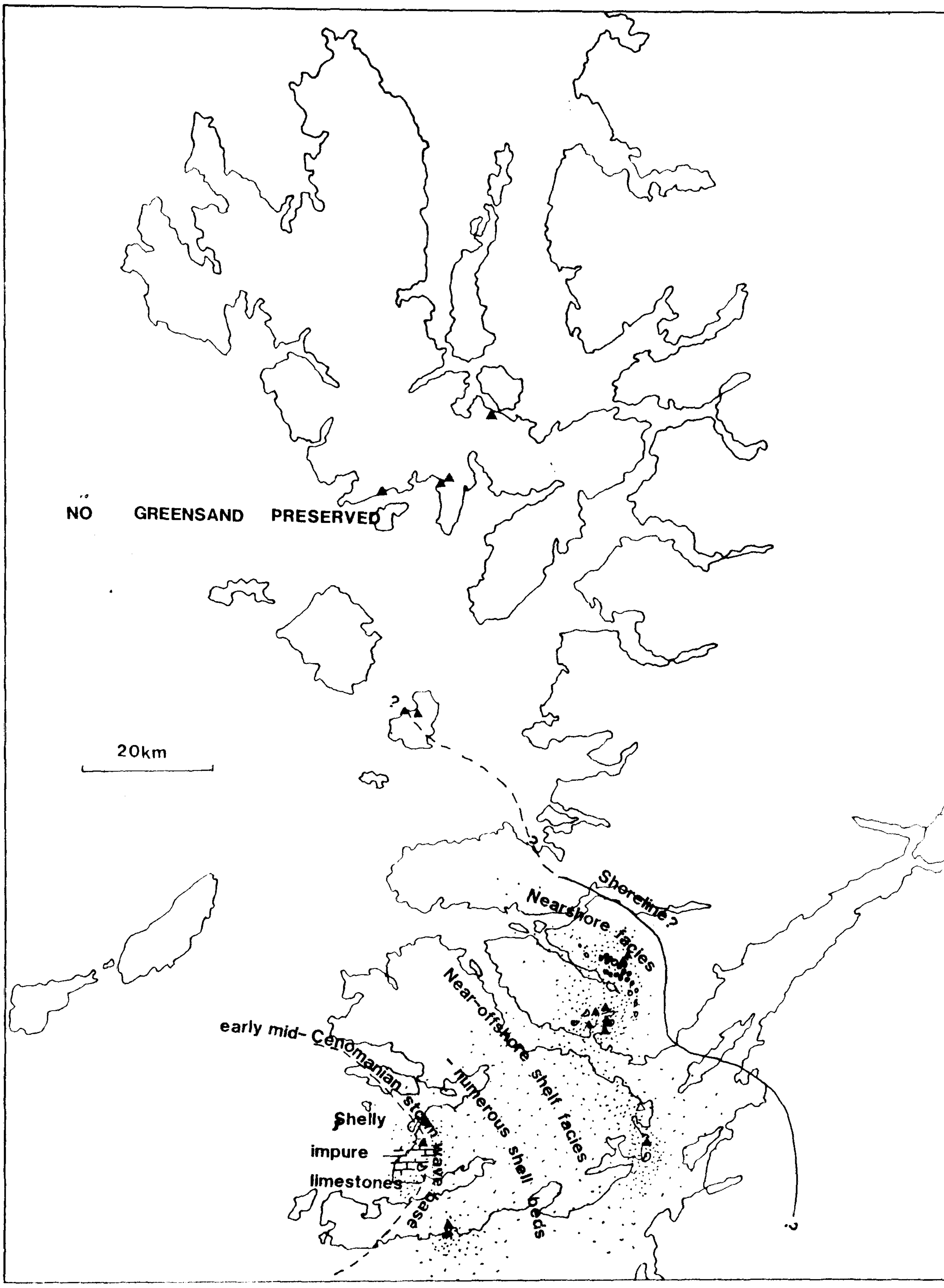


Fig.6.2 Morvern Greensand Formation (early-mid Cenomanian)

generally slow. Woody and cuticle material was rare in palynological preparations from these sections, indicating a position outside the inner shelf area (see 6.2.iii), yet the frequency of storm-derived shell beds suggests that deposition occurred between normal and storm wave base.

Above 14.4m in the BI section, shallowing water is indicated by the re-appearence of gently inclined parallel lamination (Facies F). Suggestive of an increase in sedimentation rate or rapid reworking of sediment under moderately high energy conditions is the scarcity of trace fossils, only a few *Thalassinoides* burrows being seen. In this section the contact between this unit and the overlying quartz arenite of the Lochaline White Sandstone Member is not exposed, but at LAA and AT the contact appears to be gradational. At both these localities there appears to be little sedimentological difference between the two units, the main distinguishing feature of the Lochaline White Sandstone being its lack of glauconite. The heavy mineral assemblage of the two is almost identical, the non-opaque mineral composition being dominated by tourmaline and zircon while the opaque mineral assemblage is dominated by leucoxene, magnetite, limonite and pyrite. The absence of glauconite in the Lochaline White Sandstone was thought by Humphries (1961) to be the result of constant reworking of greensand in a localized high energy shallow water environment, although he did not cite any sedimentological evidence. Sedimentary structures are difficult to discern in this quartz arenite due to the lack of contrast in the sediment, but tabular cross-bedding and *Thalassinoides* burrows are common. The preservation of a starfish in the Lochaline White Sandstone Member

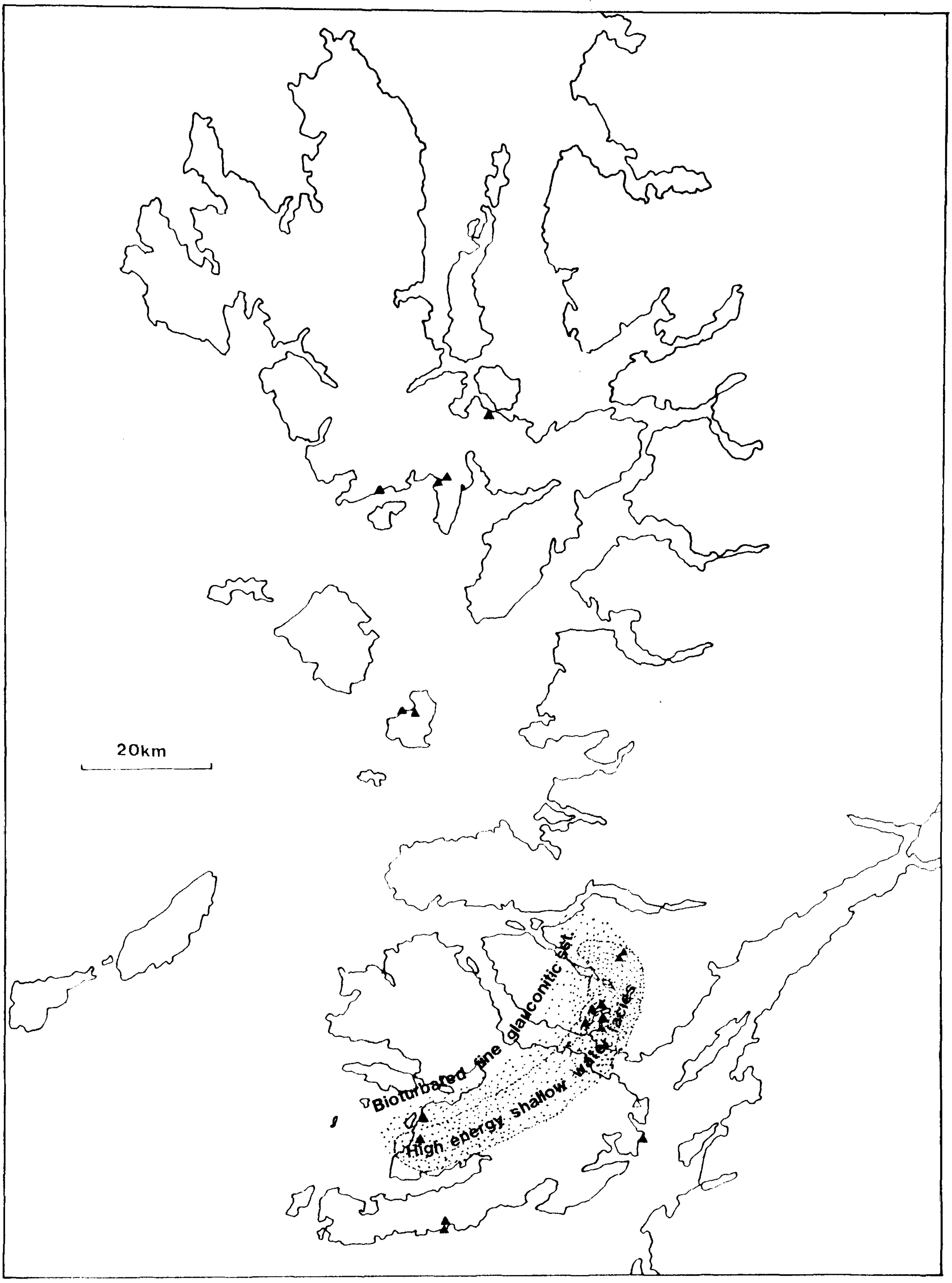


Fig.6.3 **Morvern Greensand Formation** (mid-Cenomanian).

at the Lochaline Sand mine (MacLennan, 1949) suggests that deposition was very rapid (Gale, pers. comm.).

The distribution of the Lochaline White Sandstone lithofacies is suggestive of a bar or shoal (see Fig.6.3), particularly if a river is inferred down the lineament of the Great Glen Fault (see Section 7.2 & Fig.7.1), but this may be a product of the limited outcrop.

Resumption of glauconitic sandstone deposition is seen only in the BI section. There is a bioturbated boundary with the Lochaline White Sandstone lithofacies and a hiatus can thus be inferred. The glauconitic facies is fine-grained and highly bioturbated, thus indicating a return to relatively quiet water conditions with a slow rate of deposition or lack of sediment input.

Palynofacies from the Morvern Greensand are difficult to interpret because of possible biases in the preservation potential of different sedimentary facies. Such biases often turned out to be opposite to the expected trend, with fine-grained clay and silty facies (e.g. BI3 & BH10/24-20) often yielding less diverse and abundant assemblages than relatively high-energy deposits (e.g. BI5 & BI6). Sandy limestones and sandstones with a fine-grained matrix usually yielded the best assemblages.

All the dinoflagellate cyst assemblages from sections in Morvern and Mull were dominated by *Oligosphaeridium complex*, *Circulodinium distinctum*, *Surculosphaeridium longifurcatum* and *Spiniferites ramosus*, all of which (except *S. longifurcatum*) are considered to be relatively tolerant cosmopolitan forms (Tocher & Jarvis, 1987).

Palynofacies analysis of all samples logged from the BI section shows a general increase in the number of genera with ornate morphologies and/or elaborate processes e.g. *Microdinium, Florentinia* and *Achomosphaera* spp., up to 13.0m. These are regarded as relatively deep-water associated cysts (Davey & Rogers, 1975; Tocher & Jarvis, 1987), also being indicative of warm water conditions (Williams, 1977).

The numbers of spore and bisaccate pollen grains show two apparent cycles in the BI section: a rapid decrease in numbers from BI1 to BI19, followed by a similar event from 14 individuals in a single slide to zero within 4.5m of sediment. The acritarch genus *Micrhystridium*, which appears to indicate shallow water inshore conditions, especially when associated with *Spiniferites* spp. (Davey 1970; Williams, 1977), also ocurs in BI5 but is not found elsewhere in the section. Woody and cuticle material was also common in this sample. However, this evidence must be interpreted with caution since sample BI5 also yielded the most abundant and one of the most diverse assemblages of dinoflagellate cysts in the section, including the species listed above as being indicative of open marine, relatively deep water environments.

Palynofacies from other greensand sections in Morvern and Mull are dominated by chorate dinoflagellate cysts. Sample BH10/48 contained abundant bisaccate pollen grains and extremely rare dinoflagellate cysts yet comprised a highly bioturbated glauconitic sandstone. Sample BH10/38 was also dominated by bisaccate pollen, though it also contained dinocysts. However, in both these samples, woody and cuticle material, which would be expected in abundance if the relatively high numbers of bisaccate pollen grains were taken as an indicator of the close proximity of land, was rare. Spores, pollen, woody and cuticle material were rare in samples from Mull while chorate cysts were relatively common, supporting the interpretation of these sediments as being of deeper water origin than the equivalent greensand facies in Morvern.

The Lochaline White Sandstone lithofacies was barren of palynomorphs in all the sections sampled; this supports the interpretation of this unit as a high energy deposit in which the sedimentation of very fine-grained (<125μm) material could not take place. At BI, the glauconitic sandstone overlying the Lochaline White Sandstone Member yielded *Cleistosphaeridium armatum*, *Fromea amphora* and some bisaccate pollen grains, supporting the model of a return to relatively quiet marine conditions in which such fine-grained material could be deposited.

6.3.ii. Palaeoenvironments of the Gribun Chalk.

Because of its limited exposure (see Fig.6.4) and the severe degree of alteration of the Gribun Chalk, detailed analysis of the conditions under which it was deposited is not possible. As already discussed however (Sections 4.2.N. & 4.5), the coarse fraction of the bioclastic content of the sediment is recognizable in thin section. The assemblage comprises inoceramids, thin-walled bivalves, echinoid plates and spines, bryozoans, calcispheres, planktonic and benthonic foraminifera and very rare dinoflagellate cysts. The diversity of this assemblage indicates a relatively favourable environment for the establishment of a stable ecosystem with respect to nutrients, oxygen, salinity and temperature, since the same groups of organisms occur in thin sections of the

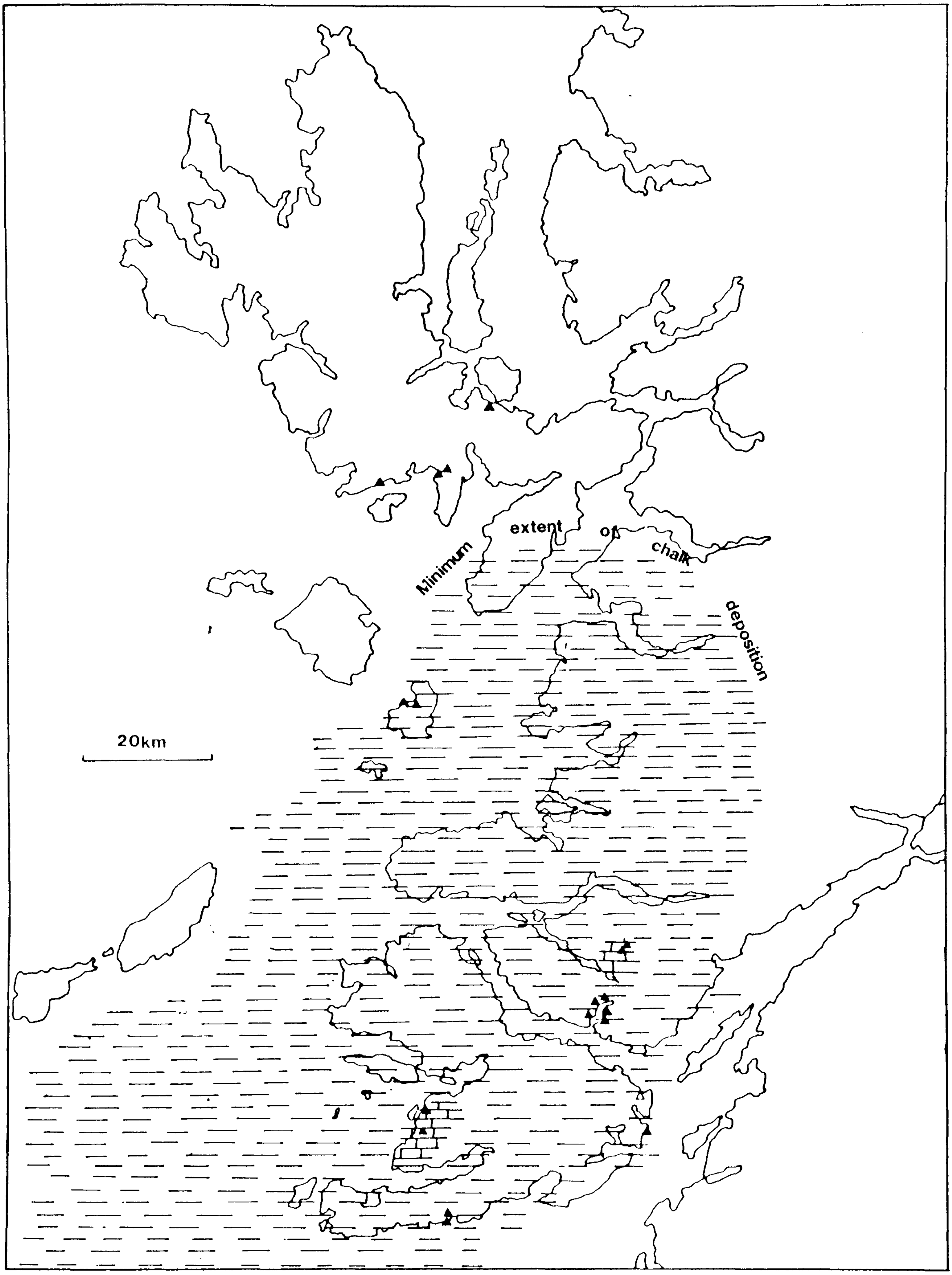


Fig.6.4 Gribun Chalk.

silicified chalk from BI, AT, GR, and in clasts of silicified chalk from conglomerates on Mull (TC), Eigg (CA) and Skye (AE). Disaggregated inoceramid valves are fairly common and may indicate soft substrate conditions, the large surface area of these bivalves being a possible adaptation to semi-fluid substrates (Kennedy & Garrison, 1976).

The chalk lithofacies presumably represents sedimentation over much, if not all, of the Inner Hebrides basin, and the rate of deposition must have been slow, given the fine grain size of the presumed matrix material of nannofossil debris. There are occasional horizons where bioclasts appear to be concentrated (see Fig. 6.5), probably representing current winnowing, but most of the bioclastic material in the Gribun Chalk appears to be randomly scattered through the matrix, possibly due to bioturbation.

Chalks from southern England and N.W. Europe have been generally described as pelagic sediments deposited in an outer shelf environment, well below storm wave base but influenced by possibly storm related bottom currents (Håkansson *et al.*,1974; Hancock, 1976; Kennedy & Garrison, 1976). However, the low diversity and small size of planktonic foraminifera from the Gribun Chalk may indicate relatively shallow water conditions using the model of Leary & Hart, (1989).

The silicified chalk from the BI section contains occasional flint nodules. These also make up a significant proportion of the clasts in some of the debris flow deposits (Facies Ri & Rii). Flint formation is thought to occur at depths within the sediment of 5-10m (Clayton, 1986), thus for flints to form, the Gribun Chalk must have been at least 5m thick in Morvern.

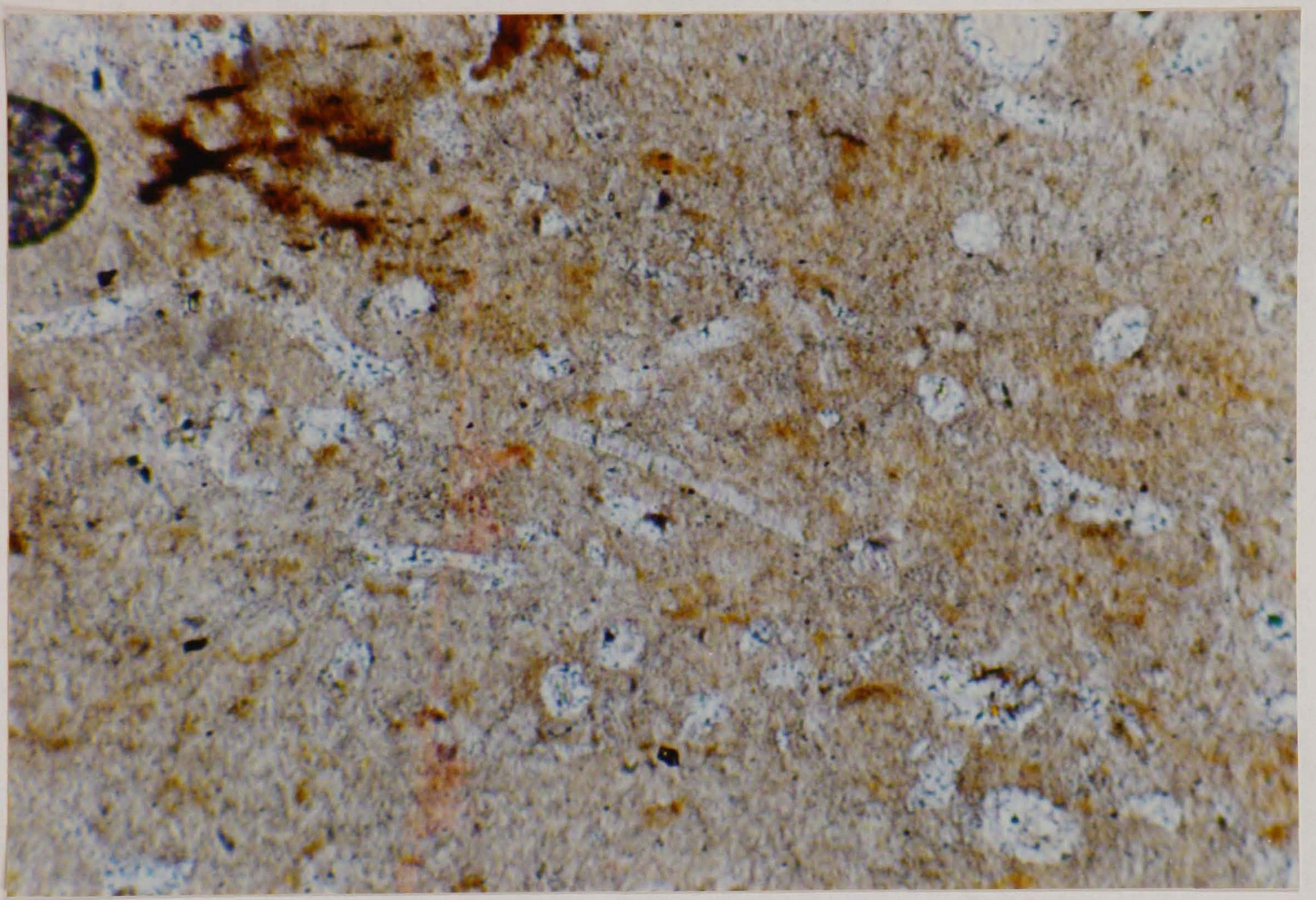


Fig.6.5 Winnowed bioclast horizon in a thin section of Gribun Chalk from Beinn Iadain. The bioclasts are mostly infilled with coarsely crystalline silica but in the small bivalve in the centre of the picture silicification has pseudomorphed the original calcite prisms of the shell wall. Field of view 3mm.

6.3.iii. The palaeoenvironments of the Strathaird Limestone Formation.

The members of the Strathaird Limestone Formation are here considered together because the lithofacies of the Laig Gorge Sandstone appears to grade into the Strathaird Limestone. (See Fig.6.6 for lithofacies distribution).

The Laig Gorge Sandstone on Eigg is dominated by poorly sorted, coarse-grained deposits, and on Skye by finer-grained but still poorly sorted sediments. Sedimentary facies are dominated by conglomerates and cross-bedded sandstones, both of which are indicative of high energy conditions, and consequently biogenic evidence is sparse. Reworked bone fragments and fish teeth are found in the basal conglomerate of the LG section which also contains calcispheres and small, poorly preserved planktonic foraminifera. These bioclasts identify the deposit as being of shallow marine origin, and when integrated with the sedimentological evidence, as being typical of the foreshore to shallow shoreface zone of a wave-dominated beach system (Clifton *et al.*, 1971).

The sedimentary facies sequence at Laig Gorge is transgressive, with an apparently rapid grading from the coarse grained sandstones to fine-grained micritic limestone over two bioturbated hardground surfaces. These hardgrounds record periods of non-deposition following erosional events, and may represent considerable hiatuses in the sedimentary sequence. High energy conditions are indicated by the monospecific trace fossil assemblage which consists of large (up to 5cm diameter)

Thalassinoides burrows. These are infilled by micritic material, marking the start of carbonate deposition in this part of the basin.

The Laig Gorge Sandstone on Skye comprises similar poorly sorted (though finer-grained) sandstone facies, also typical of relatively high energy environments, but there is no biogenic evidence to indicate whether these were deposited in a fluvial or marine environment. At the ST section a paraconglomeratic horizon representing a high energy event is unconformably overlain by sandy micritic limestone which, as in the LG section, rapidly fines upwards to a relatively pure biomicrite. This sequence represents a considerable decrease in depositional energy and clastic input. In other exposures of the Strathaird Limestone Formation on Skye, these basal conglomeratic and sandy limestone units do not appear.

The blue-grey micrite (Facies O, Oi, P) which comprises the Strathaird Limestone itself, is widespread in the Inner Hebrides Basin, being almost identical in biofacies and sedimentology in Mull, Eigg and Skye. The biofacies is less diverse than in the chalk facies, being dominated by inoceramids, with rare thin-walled brachiopods and occasional echinoid plates being seen in thin section. The inoceramids are large and flat, indicating soft substrate conditions, and are nearly always found orientated with their long axes parallel to bedding. The microfauna appears more abundant but less diverse than the chalk facies material with benthonic foraminifera being rare. Calcispheres dominate the planktonic microfaunal assemblage, but planktonic foraminifera are also common. Palynomorphs from the Strathaird Limestone at LG and ST comprise dinoflagellate cysts, dominated by chorate forms,

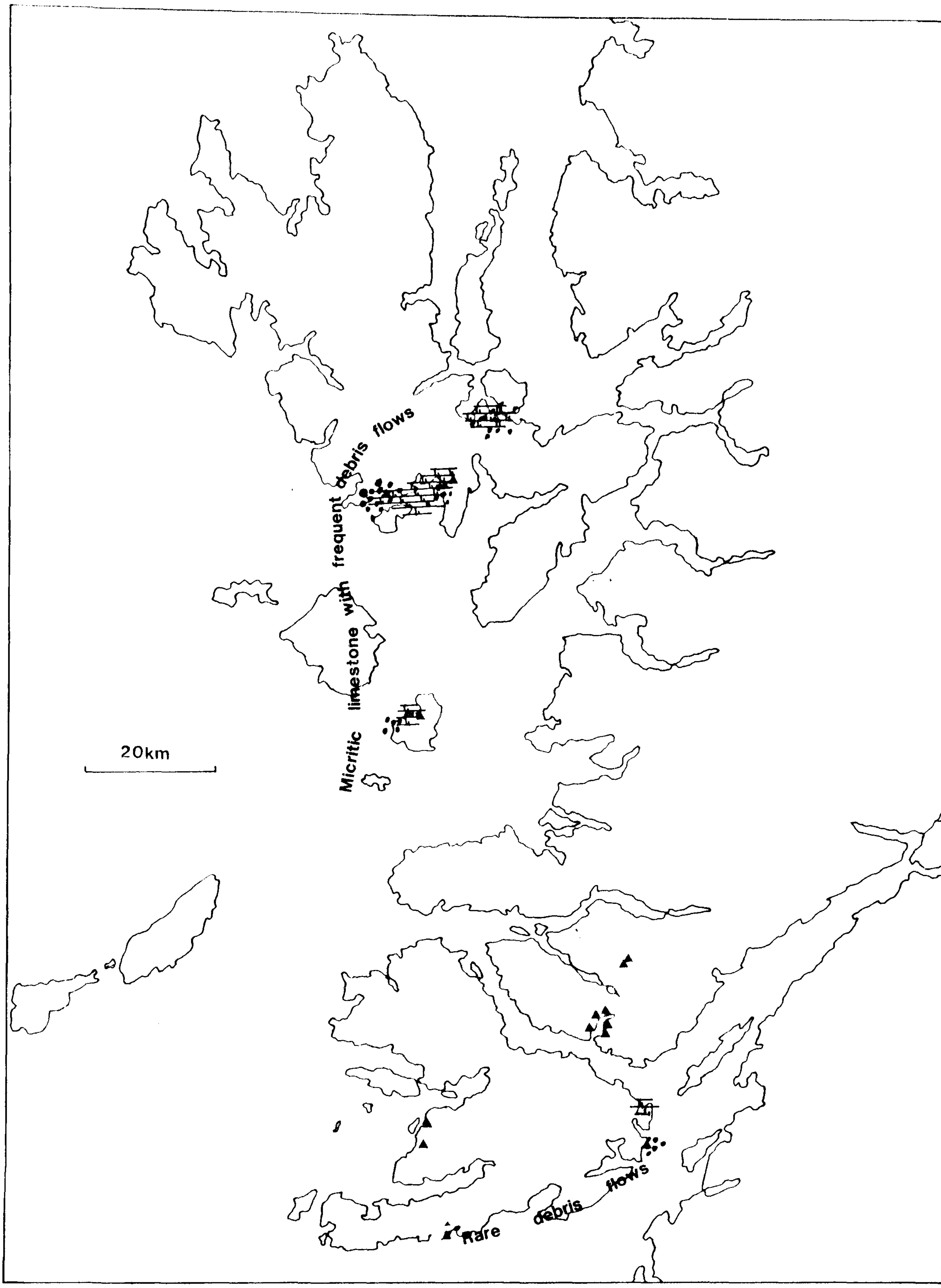


Fig.6.6 Strathaird Limestone Formation

including those with elaborate processes believed to be indicative of deep water offshore shelf conditions e.g. *Florentinia* and *Achomosphaera* spp.

Calcispheres are considered to be an opportunistic group (Jarvis *et al.*, 1988), often proliferating in neritic conditions or where surface water conditions are unfavourable to the normal plankton (Arthur *et al.*, 1987). The relatively low diversity in planktonic foraminifera and dinoflagellate cysts in this facies may therefore be a primary feature due to hostile surface water conditions in which calcispheres took advantage of the available nutrients.

In thin section, a clear linear orientation of bioclasts is visible with more bioclast-rich layers alternating with more mud-rich layers. This crude lamination is very fine, laminae being less than 1mm in thickness. The preservation of such laminae indicates a low degree of bioturbation and periodic higher energy events than the quiet conditions necessary for the deposition of fine mud, which effectively concentrated the bioclastic material by suspending mud sedimentation. At the AE section, this finely laminated biomicrite grades into highly bioturbated biomicrite in which the bioclastic and matrix material is thoroughly mixed. Some of the burrows are infilled with pale silty material, testifying to the deposition of units now only preserved as burrow fills. *Rhizocorallium* and *Monocraterion* type burrows are overprinted by *Chondrites* burrow systems. *Chondrites* is often found, as here, to be the last phase in a bioturbated sequence, and may represent dysaerobic conditions within the sediment (Bromley & Ekdale, 1984). Disemminated pyrite is common in the matrix and may indicate organic-rich reducing environments within the sediment (Love, 1967).

The low energy conditions in which these biomicritic facies were deposited were interrupted by occasional high energy events resulting in the formation of scoured erosion surfaces and the deposition of matrix-supported conglomerates (Facies R). These "event horizons" are widespread within the Strathaird Limestone, being missing only at the LG section. Clasts in these paraconglomerates are generally angular to sub-angular, suggesting a very immature sediment, and comprise, almost exclusively, silicified chalk and flint clasts. The matrix material, where micritic, tends to be rather sandy and does not contain any recognizable fauna. This facies is very similar to pebbly debris flow deposits from the mid-Turonian of the Lower Saxony Basin related to synsedimentary tectonic movements (Hilbrecht, 1988; Dahmer, pers. comm., 1989).

At AU and CA, this high energy facies is unconformable on the Morvern Greensand and at both these localities the clasts tend to be larger than those in the flows intercalated with the biomicrite facies. This may indicate relatively higher energy in the former, or a more proximal position on the flow. However, no evidence is available on which individual debis flow events could be correlated between sections.

6.3.iv. Palaeoenvironments of the Beinn Iadain Mudstone Formation.

Sedimentary facies within the Beinn Iadain Mudstone Formation are dominated by low energy, organic rich clastic facies. Plant stems and rootlets are common throughout, but no other

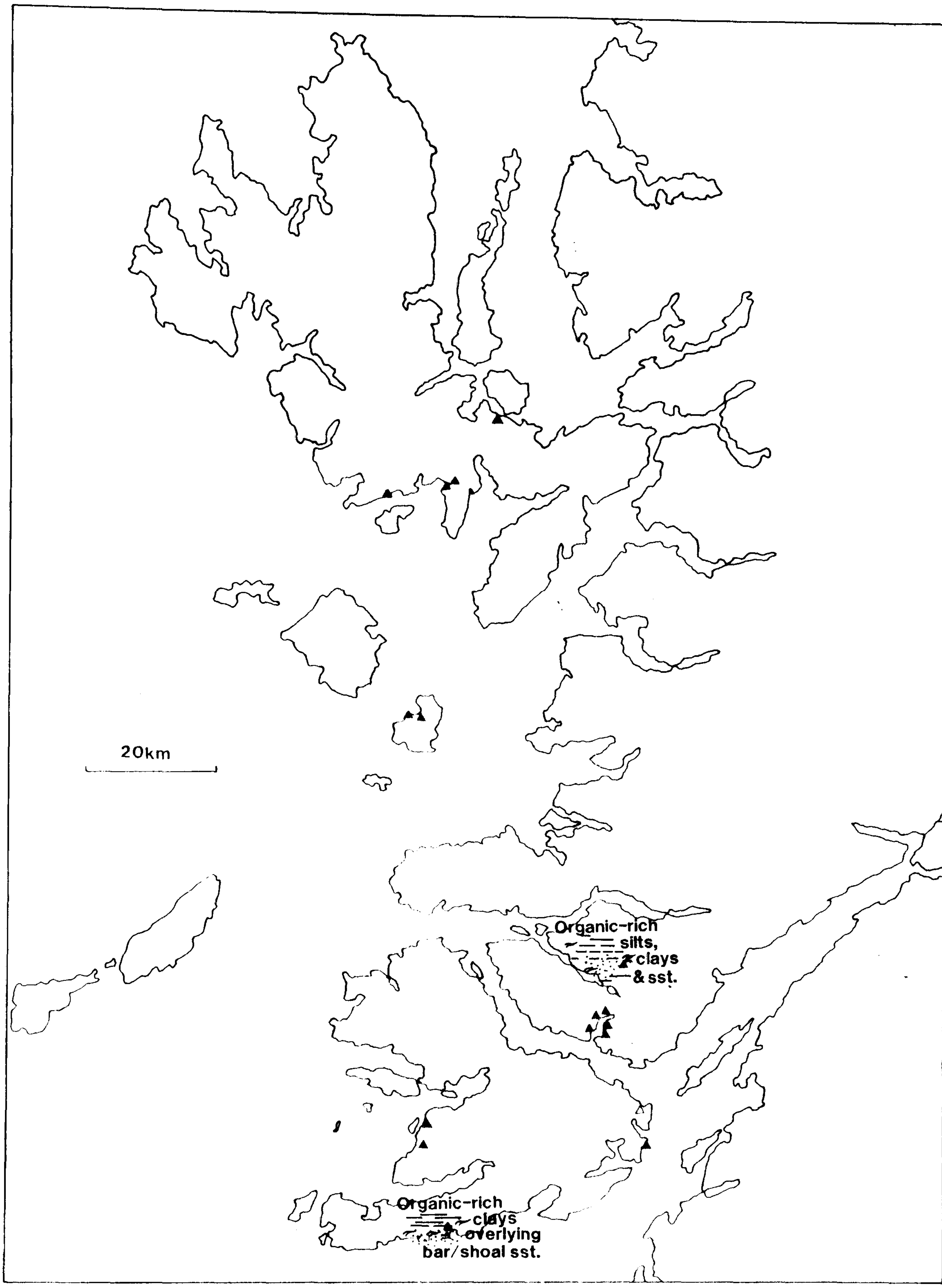


Fig.6.7 Beinn Iadain Mudstone Formation.

macrofossils were found. Palynofacies were dominated by structured cuticle and woody material.

In the BI sections, this sequence starts with organic rich clay containing large plant fragments. This is interpreted as a low energy water-lain deposit, there being no biogenic evidence for the salinity of the environment. Unconformably overlying this is a laminated sandstone facies. This is also organic rich and contains rare dinoflagellate cysts although the palynofacies is dominated by woody material and plant cuticles, indicating close proximity to land. This is overlain by organic-rich silt. This facies sequence is interpreted as probably representing a backshore swamp to estuarine environment, dinoflagellate cysts and terrestrial plant material being found in association up to the upper tidal reaches of modern estuarine environments (Farr, 1989).

Sedimentary facies belonging to this Formation at FT are dominated by an apparently massive (probably highly bioturbated and therefore relatively slowly deposited) sandstone (the Feorlin Sandstone Member) which contains a thin conglomeratic horizon representing a high energy event. There is no biogenic evidence for the depositional environment of this sandstone, but at the top it grades into heterolithic, ripple cross-laminated silty sandstone. The ripples appear to be symmetrical, suggesting wave action,the clay indicating very low energy conditions and/or high rates of flocculation. There is no bioturbation at this boundary and the facies sequence is therfore interpreted as being continuous. The silty ripple cross-laminated facies grades into silty mudstone with numerous plant fragments reflecting extremly low energy conditions. The muddy part of this sequence, like that at BI, is interpreted as a backshore lagoon/estuarine type environment while the sandy facies could represent a marine shoal or fluvial bar in which a single high energy (storm?) event is recorded.

6.4. Broad palaeoenvironmental changes in the Inner Hebrides Basin during the Late Cretaceous.

From the evidence described above, two major, and at least one minor, transgressive changes can be recognized within the Cretaceous sediments of the Inner Hebrides Basin. The first of the major transgressive sequences resulted in the deposition of the glauconitic shoreface to offshore facies of the Morvern Greensand and was widespread within the southern half of the basin, but there is no evidence that water depth ever exceeded severe-storm wave base during greensand deposition. A minor regressive event during the initial transgressive phase is represented by the erosion surface at the base of the conglomerate unit at the BI section but the resumption of transgression is recorded in the continuation of marine clastic deposition to the east (Morvern), with carbonate deposition starting in Mull.

There is evidence (from the AT section) that the greensand was only partially lithified at the start of chalk facies deposition, the boundary between the two lithotypes being bioturbated. It is therefore possible that the hiatus between the chalk and greensand sedimentary facies marks a period of non-deposition rather than actual regression and that the chalk records a later phase of the same transgressive event whose onset is marked by the start of greensand deposition. The chalk facies limestone, being deposited in relatively deep water conditions, represents the maximum extent of this first major transgression in the Inner Hebrides Basin during the Cretaceous.

Regression following the deposition of the chalk facies limestone is marked by the silicification and erosion of the Gribun Chalk. However, this was followed by another major transgression, represented by the Strathaird Limestone Formation. This sequence may record a considerable increase in water depth, given the wide sedimentary facies range, from the coarse shallow marine sediments of the Laig Gorge Sandstone Member to biomicrites, but this may simply be a product of a waning supply of clastic sediment since the biomicrites appear to have been deposited under neritic conditions.

The contact between the Strathaird Limestone Formation and the shallow water, organic rich facies of the Beinn Iadain Formation is not exposed in any of the sections logged, but it represents a considerable change in sedimentary environments from relatively deep water, low energy marine limestones to backshore low energy facies. Thus a hiatus between the two lithotypes is inferred, during which regression occurred.

The relationship between palaeoenvironments, biostratigraphy and tectonics will be discussed in Chapter 7.

Chapter 7: The geological history of the Inner Hebrides Basin during the Cretaceous.

7.1. Introduction.

The palaeoenvironmental evidence discussed in Chapter 6 becomes especially valuable when integrated with structural and biostratigraphic data to elucidate the effect and timing of tectonic activity. In this concluding chapter, the relationships between the sediments and major structural features of the basin will be described (Section 7.2), followed by the biostratigraphic evidence for the timing of the various depositional phases in the basin during the Cretaceous (Section 7.3). The Cretaceous history of the basin will then be briefly compared with that of Northern Ireland and other areas of Europe (Section 7.4).

7.2. Tectonic controls on sedimentation.

From Fig.6.1 it is evident that the initial phase of transgression in the Inner Hebrides Basin during the Cretaceous was widespread, the resulting organic-rich glauconitic sandstones being preserved as far north as Eigg and indicating a coastline well east of Beinn Iadain. During the second transgressive pulse recorded in the Morvern Greensand (Fig.6.2), the coastline appears to be nearer Beinn Iadain, with clastic-rich sediments also being deposited in the south of Mull (AU). The distribution of the Lochaline White Sandstone appears to parallel the trend of the Great Glen Fault (see Fig.6.3). This may be a product of limited exposure, but the Great Glen Fault provides an obvious structural lineament down which run-off from the Scottish Highlands Landmass could be

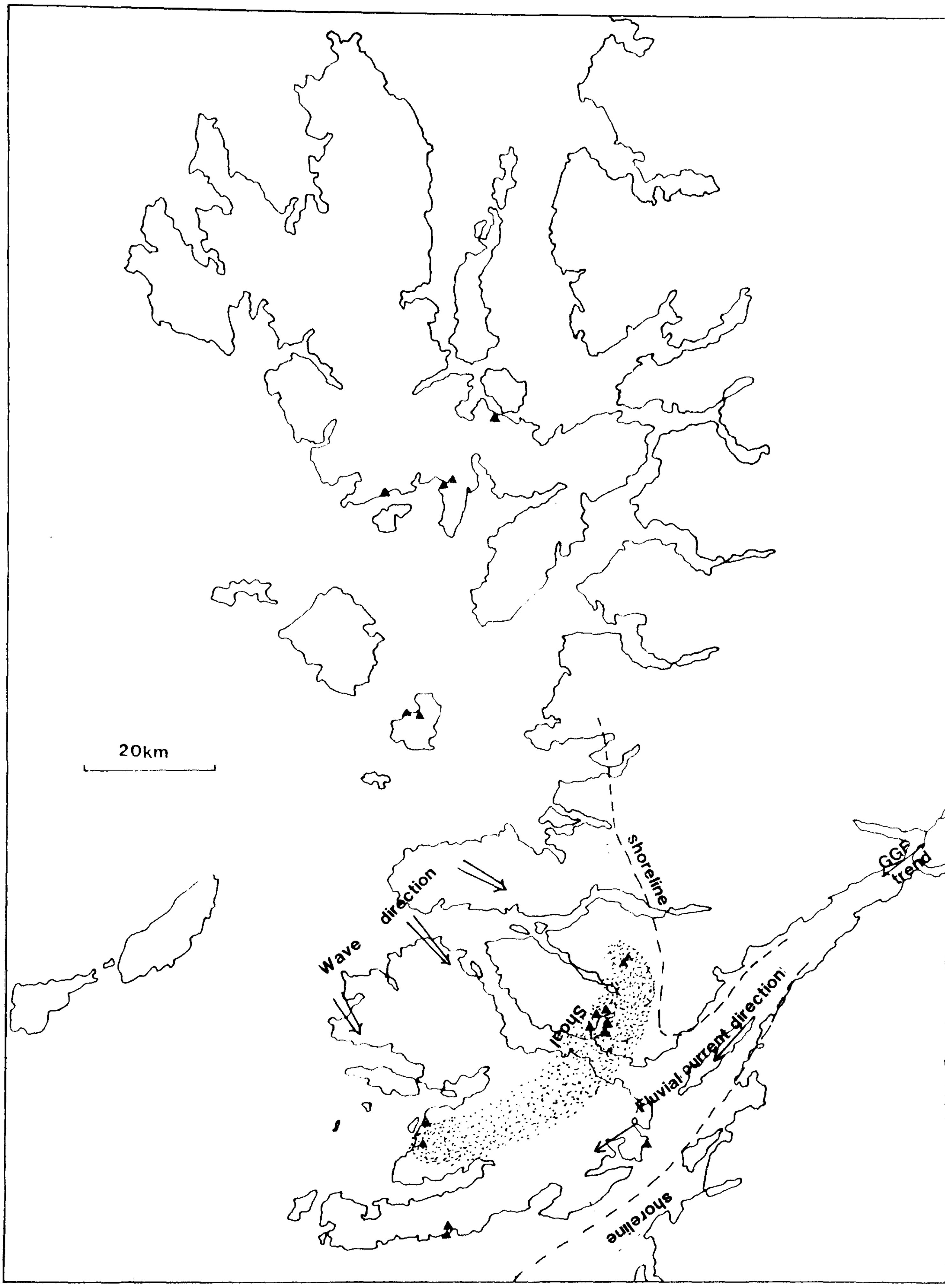


Fig.7.1 Possible conditions for the formation of the Lochaline White Sandstone bar.

channelled. A wave direction across the basin from the north west meeting fluvial currents from the Great Glen area would result in the formation of a spit or bar trending parallel to the fluvial current direction (see Fig.7.1). This bar would migrate in a north-westerly direction as relative sea level dropped. The occurrence of low energy glauconitic sandstones overlying the Lochaline White Sandstone may refect the continuation of trangression and the consequent south-easterly migration, or destruction, of the bar.

The main structural control on the deposition of the Morvern Greensand Formation therefore appears to have been the Scottish Highlands Landmass and the transgression probably reflects a eustatic rise in sea level and/or general subsidence in the Hebrides area rather than movement on the faults bounding the Inner Hebrides basin.

Further downwarping/eustatic rise in sea level resulted in the widespread deposition of chalk facies limestones in the Inner Hebrides area. No chalk is preserved *in situ* north or east of Beinn Iadain but the palaeogeographical extent of chalk deposition (reflected by the abundance of silicified chalk clasts in the Strathaird Limestone), probably extended well onto the Scottish Highlands Landmass, westwards over the Sea of the Hebrides Basin and northwards over Skye and into the Minch Basin.

A period of effective regression resulted in the sub-aerial weathering, silicification and erosion of most of the chalk in the Inner Hebrides area (and probably the whole of N.W. Scotland).

Rapid transgression in the Inner Hebrides Basin is indicated by the deposition of the Laig Gorge sandstone which is shallow marine in origin yet poorly sorted, indicating a lack of reworking.

Two stillstands or periods of non-deposition are recorded by the formation of hardgrounds in the Laig Gorge section following which carbonate deposition appears to have dominated throughout the basin (see Fig.6.5), indicating either a lack of clastic input or further relatively rapid deepening of the basin. Synsedimentary tectonic movement in the region is indicated by the widespread debris flow deposits which sometimes intercalate with the Strathaird limestone.

The Strathaird Limestone Formation is thickest in the deepest part of the Inner Hebrides half-graben which suggests that the tectonic movement responsible for the debris flows was related to the Camasunary Fault, sediment being shed eastwards off the Tiree-Stanton Banks High. It is also probable that the cause of this phase of relatively rapid transgression was at least partly due to the deepening of the basin through downthrow on the Camasunary fault rather than a slow regional downwarping. (The position of the An Leac section at the time of deposition with respect to the Camasunary Fault is unclear, since the line of the fault in Skye has since been distorted by the extrusion of the Skye Plutonic Centre (Bell, & Harris, 1986)). Similar debris flow facies preserved on the downthrow side of the Great Glen Fault in the south of Mull may suggest that this area was also active at the time.

The preservation of the Beinn Iadain Formation reflects a subsequent period of subsidence in the southern part of the Inner Hebrides Basin (Mull & Morvern).

7.3. The timing of depositional phases in the Inner Hebrides Basin during the Cretaceous.

The initial phase of transgression in the Inner Hebrides Basin can be dated with some certainty on dinoflagellate cysts to the latest Albian to earliest Cenomanian, trangression continuing with the deposition of glauconitic sandstones and limestones until the Middle Cenomanian. This age range agrees with that indicated by the macrofauna previously reported, and found during this study, from the Morvern Greensand (see Sections 5.3 & 5.10).

The paucity of stratigraphically diagnostic palynomorphs from the Gribun Chalk and the problems of positively identifying foraminifera from thin sections have already been discussed, (Sections 5.10 & 5.11), but the available biostratigraphic data suggests that the chalk facies limestone was deposited in the Late Cenomanian. This lithofacies thus represents the continuation of the major transgressive episode which started in the late Albian with the deposition of the Morvern Greensand.

Lithostratigraphically, deposition of the Strathaird Limestone must post-date the deposition and uplift of the Gribun Chalk because of the occurrence of silicified chalk clasts in the debris flows interbedded with the limestone. However, the available microbiostratigraphic data suggests an Early to Middle Turonian age. Therefore, the post-chalk regression must have been very rapid to allow for the silicification, weathering and erosion of the Gribun Chalk prior to the deposition of the Strathaird Limestone and was very possibly fault controlled.

No biostratigraphically useful data was obtained from the Beinn Iadain Formation other than a maximum range of Albian to Palaeocene on dinoflagellate cysts and there is thus no evidence that this unit is Cretaceous in age.

7.4. Comparison of Cretaceous sediments in the Inner Hebrides area with other Cretaceous deposits in N.W. Europe.

Geographically, the closest onshore outcrop of Cretaceous rocks to the Hebrides area is in Antrim, Northern Ireland. Deposition of fossiliferous glauconitic sandstones (the Hibernian Greensands) started in Antrim in the Early to Middle Cenomanian, with an erosive phase in the Late Cenomanian (Hancock, 1961). No deposits of Turonian age are preserved in Antrim but a remanie Turonian fauna is found at the base of the Upper Glauconitic Sandstone (Rawson, *et al.*,1978).

Clastic sedimentation resumed in Northern Ireland in the late Turonian and continued until the Santonian when carbonate sedimentation began to dominate with the deposition of the Ulster White Limestone which continued until the early Maastrichtian (Hancock, 1961; Fletcher, 1977; Rawson *et al.*,1978). Thus, although the Albian-early Cenomanian transgression is recorded in Northern Ireland with the deposition of similar marginal clastic deposits to those in N.W. Scotland, on the ages indicated by microfossils during this study, neither the Gribun Chalk or the Strathaird Limestone can be correlated with the Ulster White Limestone.

Worldwide transgressive peaks collated by Hancock & Kauffman (1979) and Haq *et al.* (1987) include a major transgression starting in the early Late Albian (this is described as "the transgression that carried Cretaceous seas onto many ancient massifs" (Hancock & Kauffman, 1979)), followed by another in the Early Turonian (see Fig.7.2). Jarvis *et al.* (1988), describe rapid transgression during the mid-late Cenomanian in the Anglo-Paris Basin, with continuing sea level rise in the early Turonian. The initial phase of

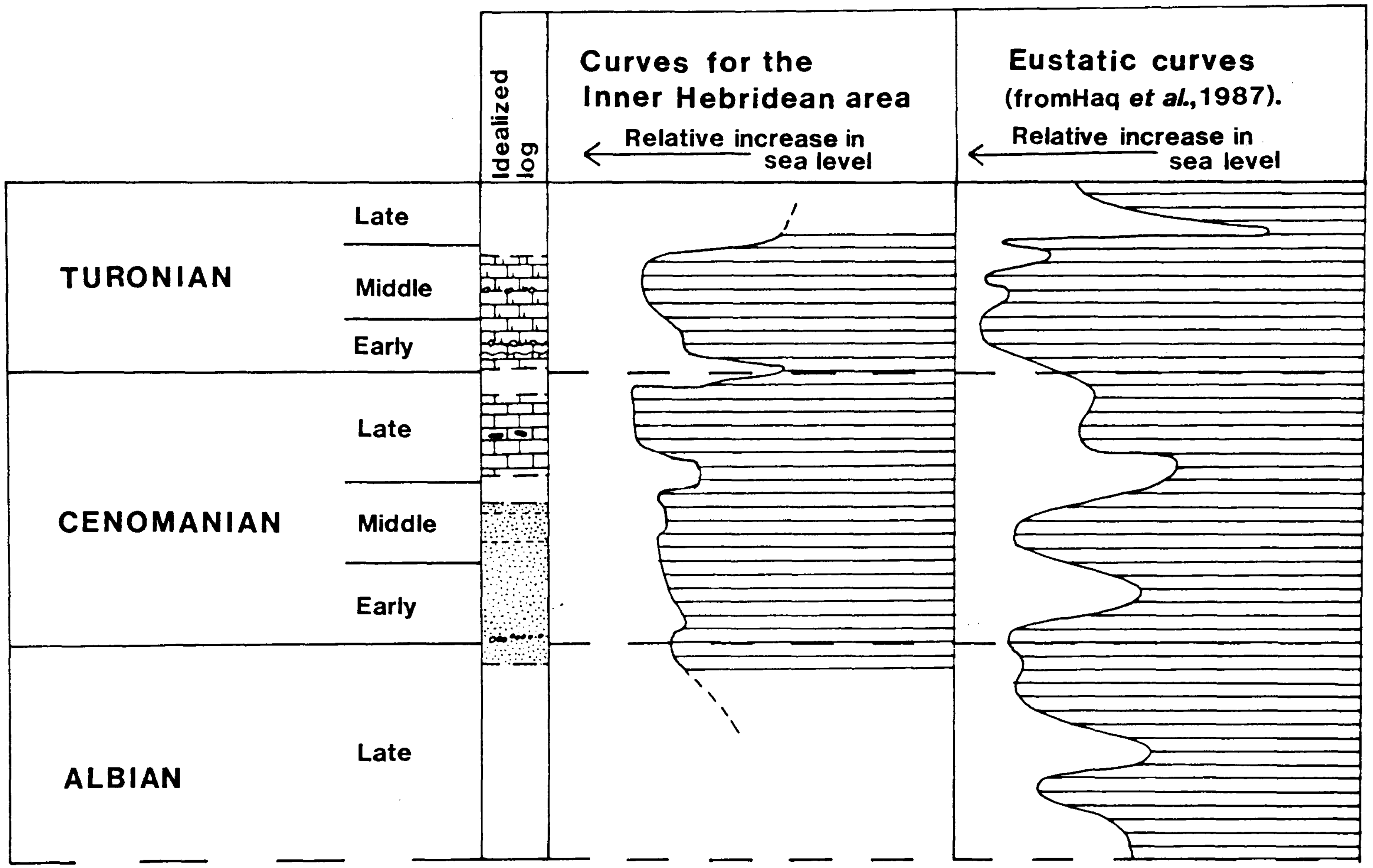


Fig.7.2 Sequence stratigraphy for the Inner Hebrides Basin during the Cretaceous.

transgression during the late Albian to Cenomanian is marked by greensand deposition in many marginal areas in N.W. Europe, including N.W. Scotland and Antrim but as widespread as Bornholm, Denmark; Poland and S.W. England. In the North Sea and Southern England chalk deposition continued through the Cenomanian and Turonian and into the Campanian with minor regressive episodes and stillstands being marked by erosion surfaces and hardgrounds (Hancock, 1976; Rawson, 1978).

Depositional episodes in the Inner Hebrides Basin during the Cretaceous therefore appear to correlate with major eustatic sea level changes, the late Albian-early Cenomanian transgression resulting in the deposition of the Morvern Greensand with the continuation of sea level rise through the late Cenomanian resulting in the deposition of the Gribun Chalk (see Fig.7.2).

The deposition of the Strathaird Limestone in the Early Turonian correlates with the worldwide transgressive peak at this time (Hancock & Kauffman, 1979; Haq *et al.*, 1987) and also exhibits features typical of this particular period of trangression, organic-rich micritic limestones with a diverse plankton dominated by calcispheres occurring throughout N.W. Europe during the Early Turonian e.g. in the Haute Savoie at the base of the Sewen Limestone in the Alps (Hart, 1990, pers.comm.) and in the south Pyreenees (Caus, 1990, pers.comm.). Widespread debris flow deposits, almost identical to those seen within the Strathaird Limestone Formation from the Mid-Turonian of N.W. Germany (Hilbrecht, 1988), and Poland (Peryt, 1989, pers. comm.), may suggest that tectonic activity during this period was widespread.

Chapter 8: Conclusions and implications of this study.

8.1. Stratigraphical implications of the study.

The revised lithostratigraphy, combined with the new biostratigraphical data discussed in Chapter 5, disagrees with most previous stratigraphic schemes for the Cretaceous strata of N.W. Scotland (see Section 1.2). The evidence cited in this study puts the start of deposition of the Morvern Greensand in the latest Albian, sedimentation continuing into the Mid-Cenomanian, a slightly older age than that previously described (see Fig.1.2). The probable Cenomanian age of the Gribun Chalk indicated by micropalaeontological evidence in this study is supported lithostratigraphically by the occurrence of silicified clasts of Gribun Chalk in the Strathaird Limestone which appears to be of an Early - Mid-Turonian age. The biomicritic limestones, sandstones and conglomerates of the Strathaird Limestone Formation have not formerly been recognized as representing a later phase of deposition than that represented by the Gribun Chalk, both being assigned a Senonian age by previous authors (e.g. Adams, 1960; Rawson *et al.*, 1978). No evidence that the Beinn Iadain Mudstone Formation is of Cretaceous age was forthcoming during this study.

The strata of known Cretaceous age preserved in the Inner Hebrides and Morvern thus represent depositional phases ranging over a relatively limited time period (Late Albian to late Middle Turonian) in comparison to the Early Cenomanian to Maastrichtian range cited by previous authors (e.g. Judd, 1878; Lee & Bailey, 1925; Lee & Pringle, 1932; Rawson *et al.*, 1978).

8.2. Palaeoenvironmental conclusions of the study.

Detailed environmental interpretation of the Cretaceous sediments of the Inner Hebrides Basin has allowed the recognition of relative sea level changes affecting the basin. These are summarized as follows (see Fig.7.2):

(i) latest Albian to Early Cenomanian - the start of deposition of the Morvern Greensand marks the initiation of a major trangresson in the Inner Hebrides Basin.

(ii) Early to Mid-Cenomanian - further greensand deposition indicates continuing sea level rise with more carbonate-rich facies being deposited. In the Mid-Cenomanian a minor regressive episode may be indicated by the deposition of the Lochaline White Sandstone Member.

(iii) late Mid to Late Cenomanian - following a hiatus, which may indicate a stillstand and/or lack of clastic input, carbonate sedimentation became dominant in the Inner Hebrides Basin, resulting in the deposition of the Gribun Chalk Formation and indicating a continued rise in relative sea level.

(iv) latest Cenomanian to earliest Turonian - a relatively short-lived but pronounced drop in relative sea level, probably due to local tectonic movement, resulted in the weathering and erosion of the now-silicified chalk lithofacies. The conditions under which silicification of the Gribun Chalk occurred are, at present, unknown.

(v) Early to Middle Turonian - rapid marine transgression is marked by the deposition of the poorly sorted Laig Gorge Sandstone Member followed by carbonate mud deposition (the Strathaird Limestone). Carbonate deposition was periodically interrupted by high energy debris flows initiated by synsedimentary tectonic movements along the Camasunary Fault.

The Strathaird Limestone Formation represents the youngest deposit of known Cretaceous age in the Inner Hebrides Basin.

8.3. Regional implications of the study.

From the biostratigraphic evidence described in this study, although greensand facies sediments in Antrim (the geographically closest onshore Cretaceous strata to the Inner Hebrides), can be correlated broadly with the Morvern Greensand Formation, later deposits of Cretaceous age in Northern Ireland do not reflect the same periods of deposition as those indicated by the sediments in the Inner Hebrides Basin. However, major periods of relative sea level change in the Inner Hebrides Basin correlate with major eustatic sea level fluctuations documented by Hancock & Kauffman (1979) and Haq *et al.*, (1987), although the magnitude of the sea level changes differ (see Fig.7.2). These differences in relative scale are interpreted as being the product of the local tectonic movements on which the eustatic changes were imposed. Many lithological features of the Cretaceous sediments of the Inner Hebrides Basin are similar to those exhibited by other Mid to Late Cretaceous sediments in N.W. Europe, the initial Mid Cretaceous transgression being marked by the deposition of glauconitic clastic sediments followed by chalk sedimentation in the early Late Cretaceous in southern England, Denmark, Poland and Germany. The Strathaird Limestone Formation exhibits features typical of the Early Turonian transgressive episode (see Section 7.4). That global events and widespread environmental changes can be recognized in the Cretaceous strata of the Inner Hebrides is of some potential significance, given the apparent isolation, relatively small size and high palaeolatitude of the Inner Hebrides Basin.

Appendix I: Notes on Foraminifera seen in Thin Section.

This appendix comprises brief descriptions of the main diagnostic features of selected foraminiferid taxa identified from thin sections. No attempts at formal diagnoses are made and complete synonomies are not listed although key references are given.

a) Planktonic foraminifera.

Genus *Hedbergella* Bronniman & Brown, 1958.

Hedbergella is characterized by having a trochospiral, biconvex, non-keeled test. The chambers are rounded and the umbilicus ranges from narrow to relatively wide (up to 25% of the maximum diameter of the test) (Robaszynski & Caron, 1979). Hedbergellids are difficult to distinguish from whiteinellids in thin section, the latter also having a biconvex, non-keeled test with globular to ovoid chambers but generally having a larger umbilicus than *Hedbergella* (*op cit.*).

Occurrence: BI12, GR3, LG6, ST1, ST2.

Hedbergella delrioensis (Carsey)

1926 *Globigerina cretacea* d'Orbigny var. *delrioensis* Carsey, p.43.

1977 *Hedbergella delrioensis* (Carsey); Carter & Hart, p.35, pl.4, figs 1-3.

Remarks: *H. delrioensis* is distinguished in thin section by having a narrow umbilicus (16-20% of the maximum diameter of the test) (Robaszynski & Caron, 1979) with a moderate to low spire (Carter & Hart, 1977). In lateral view the test appears asymmetrical.

Occurrence: BI12, GR3, LG6, ST2.

Genus *Heterohelix* Ehrenberg, 1843.

The test comprises biserially arranged subglobular to globular chambers, overall test morphology tapering to the early planispirally arranged chambers.

Heterohelix globulosa (Ehrenberg)

1840 *Textularia globulosa* Ehrenberg,p.135,pl.4,figs 2b,4b,5b,7-8b.

1967 *Heterohelix globulosa* (Ehrenberg);Pessagno,p.260,pl.187.

Remarks: This species is characterized in thin section by the highly inflated later chambers, giving a broad triangulate outline.

Occurrence: BI12, ST1, ST2, LG6.

Genus *Praeglobotruncana* Burmudez, 1952.

Praeglobotruncana praehelvetica (Trujillo)

1960 *Rugoglobigerina praehelvetica* Trujillo p.340-341,pl.49, figs 6a-c.

1979 *Praeglobotruncana praehelvetica* (Trujillo);Robaszynski & Caron,p.46-47,pl.47,figs 1d,2c.

Remarks: *P. praehelvetica* is characterized in thin section by having an asymmetrical, plano-convex test with a pseudo-keel formed by a line of pustules sometimes seen in lateral view. Because of the lack of a true keel, the species could equally be placed in *Whiteinella* (Robaszynski & Caron, 1979) or *Hedbergella* (Hart, 1990, pers. comm.).

Occurrence: LG6, ST2.

Genus *Whiteinella* Pessagno, 1967.

As already noted, whiteinellids are similar to hedbergellids but have a larger umbilicus (up to 33% of the maximum diameter of the test)(Robaszynski & Caron, 1979). The two genera cannot be easily separated since transitional forms are common *(op cit.)*.

Whiteinella aprica (Loeblich & Tappan)

1961 *Ticinella aprica* Loeblich & Tappan,p.292,pl.4,figs 14-16.

1979 *Whiteinella aprica* (Loeblich & Tappan);Robaszynski & Caron, pp.157-160,pl.32,figs 1a-c,2a-c.

Remarks: In thin section, *W. aprica* is characterized by a very low trochspiral, slightly asymmetrical test with circular chambers. The umbilicus is shallow but wide (reaching approximately 25% of the maximum diameter of the test (*op cit.*).

Occurrence: BT12, GR3, ST1.

Whiteinella archaeocretacea Pessagno

1967 *Whiteinella archaeocretacea* Pessagno,p.298,pl.51,figs 2-4; pl.54,figs 19-25;pl.100,fig.8.

Remarks: *W. archaeocretacea* differs from *W. aprica* in having a slightly higher trochospire, more elongate chambers and a wider umbilicus.

Occurrence: LG6, ST2.

Whiteinella baltica Douglas & Rankin

1969 *Whiteinella baltica* Douglas & Rankin,p.197.

Remarks: *W. baltica* has a low trochospire and chambers which are circular in section. The test is characteristically almost

bilaterally symmetrical and the umbilicus is narrow (less than 25% of the maximum diameter of the test)(Robaszynski & Caron, 1979).
Occurrence: LG6, ST2.

Genus *Rotalipora* Brotzen

The genus *Rotalipora* comprises single keeled foraminifera with a trochospiral test and angular to rhomboid chambers. Examples of this genus seen in a thin section of Gribun Chalk clasts in a conglomerate from Strathaird (slide ST1-2) showed the characteristic high angularity of the chambers and well-developed single keel characteristic of the species.
Occurrence: ST1-2.

b) Benthonic foraminifera.

Genus *Textularia* Defrance in de Blainville, 1824.

Textularia chapmani Lalicker

1935 *Textularia chapmani* Lalicker
Remarks: The test is biserial, triangulate in outline and has a distinctively widening growth form (Jenkins & Murray, 1989). The chambers are globular but rather elongate. The wall of this species is composed of finely agglutinated material.
Occurrence: BI12, GR3.

Appendix II: Systematic Palynology.

Systematic palynology.

Dinoflagellate cysts are here classified according to archaeopyle type, following the argument of Singh (1983) that a "natural" supergeneric classification of dinoflagellate cysts is impracticable, cysts representing one part of the dinoflagellate lifecycle of which the motile stage is not preserved, and extant dinoflagellates representing a "relict" survival from the late Mesozoic to which many extinct Mesozoic forms could not be related.

Genera and species listed conform to the 1989 Index (Lentin & Williams, 1989) and are grouped according to archaeopyle type following Wilson & Clowes (1980) and Singh, (1983). Detailed descriptions are given only where a morphotype differed from the original or previously emended diagnosis. Genera within a given archaeopyle group are treated alphabetically. Unless otherwise stated, the range of measurements given under "Dimensions" for each species were taken from six specimens.

Phylum Algae

Division PYRROPHYTA Pascher 1914

Class DINOPHYCEAE Fritsch 1929

I. Dinoflagellate cysts having an apical archaeopyle.

Genus *Batiacasphaera* Drugg, 1970b.

Genotype *Batiacasphaera compta* Drugg, 1970b.

Batiacasphaera euteiches (Davey)

Plate 1, Fig.1.

1969 *Chytroeisphaeridia euteiches* Davey,p.14,pl.4,figs 3,4,6.

1979 *Batiacasphaera euteiches* (Davey);Davey,p.217.

Remarks: The outer shell wall was densely granular. *B.euteiches* was noticeably darker in colour than most other species of dinocyst in a given sample.

Dimensions: Diameter of shell 38-47µm.

Occurrence: LAW(b)A, BI3, BI5, BI6, BI7, BI8, BI9, BI10.

Genus *Chlamydophorella* Cookson & Eisenack, 1958; emend.Duxbury, 1983.

Genotype *Chlamydophorella nyei* Cookson & Eisenack, 1958.

Chlamydophorella discreta Clarke & Verdier, 1967.

Plate 1, Fig.2.

1967 *Chlamydophorella discreta* Clarke & Verdier,p.24,pl.2,figs 9,10, text-fig.9.

Remarks: The rod-like pillars separating the inner body and outer membrane are flat topped and of apparent uniform length.

Dimensions: Overall diameter 28µm.

Length of pillars 3µm. 1 specimen measured.

Occurrence: BI1.

Genus *Circulodinium* Alberti,1961.

Genotype *Circulodinium hirtellum* Alberti,1961.

Circulodinium distinctum (Deflandre & Cookson)

Plate 1, Fig.3.

1955 *Cyclonephelium distinctum* Deflandre & Cookson,pp.285-286,pl.2, fig.14;text-figs 47-48.

1989 *Circulodinium distinctum* (Deflandre & Cookson);Jansonius,p.204.

Remarks: *C.distinctum* showed a high degree of variation: in process detail, spines terminating in a blunt end or branching; also in the size of the central body. The unornamented mid-dorsal and mid-ventral areas also varied in size.

Dimensions: Length of central body 31-78µm.

Width of central body 28-72µm.

Length of processes 3-17µm. (10 specimens measured).

Occurrence: LAW(b)A, LAW(b)B, LAW(c)1, BH10/32, BH10/38, CN8313, CN838, CN87, BI1, BI3, BI4, BI5, BI6, BI8, AT1, AT2, AT7, GR1, ST1, ST2.

Genus *Cleistosphaeridium* Davey *et al.*,1966.

Genotype *Cleistosphaeridium diversispinosum* Davey *et al.*

Cleistosphaeridium armatum (Deflandre)

Plate 1, Fig.4.

1937 *Hystrichosphaeridium armatum* Deflandre,p.76,pl.16,figs 6,7.

1963 *Baltisphaeridium armatum* (Deflandre);Downie & Sarjeant,p.91.

1969 *Cleistosphaeridium armatum* (Deflandre);Davey,p.153,pl.8, figs 1,2,12.

Remarks: This species has a distinctive "hairy" appearance. Process length varied by up to 5μm on a single specimen, with striations occasionally being visible on the proximal processes.

Dimensions: Diameter of central body 18-37μm.

Length of processes 7-17μm.

Occurrence: LAW(b)A, LAW(b)1, LAW(b)B, BH10/24-20, BH10/32, BI1-14, BI16, BI19, AT1, AT2, CN8313, CN838, CN87, GR1, ST2.

Cleistosphaeridium sp. *cf."disjunctum"* Davey *et al.*

Plate 1, Fig.5.

1966 *Cleistosphaeridium "disjunctum"* Davey *et al.*,p.169,pl.11,fig.9.

Remarks: In view of the regular arrangement of processes seen in the holotype, the original allocation of this species to *Cleistosphaeridium* was provisional (Davey *et al.*, 1966). Reid (1974, p.591), considered the species to be a junior synonym of *Lingulodinium machaerophorum* (Deflandre & Cookson), but the processes of specimens seen in the Scottish samples did not reflect a consistant paratabulation pattern and therefore they are tentatively referred to *Cleistosphaeridium*.

Dimension: Diameter of central body 37-49μm.

Length of processes 11-17μm.

Occurrence: LAW(b)A, BH10/32, CN838, CN87, BI8, BI9, BI14, AT2, ST2.

Cleistosphaeridium ?flexuosum Davey *et al.*;

emend.Sarkar & Singh

Plate 1, Fig.7.

1966 *Cleistosphaeridium ?flexuosum* Davey *et al.*,p.169,pl.2,fig.5.

1988 *Cleistosphaeridium ?flexuosum* Davey *et al.*;Sarkar & Singh,p.39.

Remarks: *C.flexuosum* is distinguished by the flexuous nature of its rather fibrous processes. Specimens assigned to this species conform to the original diagnosis but due to the corroded nature of the cysts in sample ST2 it was impossible to tell whether the flexous processes were a primary morphological feature.

Dimensions: Length of central body 32µm.

Length of processes ?14µm.

Occurrence: ST2, CN87.

Cleistosphaeridium huguoniotii (Valensi)

Plate 1, Fig.6.

1955 *Hystrichosphaeridium huguoniotii* Valensi,p.38,test-fig.2a.

1960 *Hystrichosphaeridium anchoriferum* Cookson & Eisenack,p.8,pl.2, fig.11.

1966 *Cleistosphaeridium anchoriferum* (Cookson & Eisenack);Davey *et al.*,p.167,pl.9,fig.1.

1969 *Cleistosphaeridium huguoniotii* (Valensi);Davey,p.135.

1978 *Chlamydophorella huguoniotii* (Valensi);Davey,p.893.

1981 *Cleistosphaeridium huguoniotii* (Valensi)Davey;Lentin & Williams, p.49.

Remarks: *C.huguoniotii* and *C.anchoriferum* are here considered to be the same species, the former name taking precedent. The processes are distinctively anchor-shaped.

Dimensions: Diameter of central body 26-43μm.

Length of processes 5-10μm.

Occurrence: LAW(b)A, BH10/32, BH10/38, CN87, BI1, BI5, BI6, BI9, AU7, AT1, AT2, AT7.

Genus *Epelidosphaeridia* Davey,1969.

Genotype *Epelidosphaeridia spinosa* (Cookson & Hughes,1964)

Epelidosphaeridia spinosa (Cookson & Hughes)

Plate 1, Fig.8.

1962 *Palaeoperidinium spinosa* Cookson & Hughes,p.49,pl.8,figs 6-8.

1969 *Epelidosphaeridia spinosa* (Cookson & Hughes);Davey,p.143.

Remarks: Examples of this species conformed to the original diagnosis, all individuals logged having a smooth periphragm. *E.spinosa* tended to be slightly darker in colour than most other dinocysts in a given sample but generally appeared well-preserved.

Dimensions: Length of body 52-66μm.

Width of body 46-58μm.

Length of spines 2-7μm.

Occurrence: LAW(b)1, BH10/24-20, BI5, BI8, BI14, AU7, AT1, AT2.

Genus *Fromea* Cookson & Eisenack emend.Yun, 1981.

Genotype *Fromea amphora* Cookson & Eisenack, 1958.

Fromea amphora Cookson & Eisenack

Plate 1, Fig.9.

1958 *Fromea amphora* Cookson & Eisenack,p.56,pl.5,figs 10,11.

Remarks: Specimens assigned to this species were often folded or damaged but could be identified by the finely granular wall, apical archaeopyle and absence of paratabulation.

Dimensions: Length of body 72-88μm.

Width of body 38-54μm.

Occurrence: CN87, BI5, BI6, BI8, BI9, BI14, BI16, AT2, AT7, GR1.

Fromea granulosa (Cookson & Eisenack)

Plate 1, Fig.10.

1974 *Palaeostomocystis granulosa* Cookson & Eisenack,p.79,pl.28,fig.10.

1978 *Fromea granulosa* (Cookson & Eisenack);Stover & Evitt,p.48.

Remarks: *F.granolosa* is distinguished from *F.amphora* by the rough granular texture of the cyst wall.

Dimensions: Length of body 65-79μm.

Width of body 48-62μm.

Occurrence: BH10/24-20, BH10/38, BI4.

Genus *Heterosphaeridium heteracanthum* Cookson & Eisenack, 1968.

Genotype *Heterosphaeridium conjunctum* Cookson & Eisenack, 1968.

Heterosphaeridium difficile (Manum & Cookson)

Fig.5.9, Plate 2, Fig.2.

1964 *Hystrichosphaeridium difficile* Manum & Cookson,pp.12-14,pl.3, figs 1-3,7.

1986 *Heterosphaeridium difficile* (Manum & Cookson);Ioannides,p.24, pl.13,figs 11,13-16;pl.14,fig.1.

Remarks: Only one specimen of this species was found and it was rather poorly preserved. Thus its assignation to *H.difficile* is tentative. However, the characteristic processes which are highly variable in width and have distally serrated margins were visible.

Dimensions: Diameter of body 57μm

Length of processes 5-15μm

1 specimen measured.

Occurrence: ST2.

Heterosphaeridium heteracanthum (Deflandre & Cookson)

Plate 2, Fig.1.

1955 *Hystrichosphaeridium heteracanthum* Deflandre & Cookson,p.276, pl.2,figs 5,6;text-figs 40-41.

1963 *Baltisphaeridium heteracanthum* (Deflandre & Cookson);Downie &

Sarjeant,p.91.

1966 *Cleistosphaeridium heteracanthum* (Deflandre & Cookson);Davey *et al.*,pp.168-169,pl.2,figs 6,7.

1971a *Heterosphaeridium heteracanthum* (Deflandre & Cookson);Eisenack & Kjellström,p.451.

Remarks: The large ?apical process described by Davey *et al.*(1969), was not seen. *H.heteracanthum* was often darker in colour than most other cysts in a given sample.

Dimensions: Diameter of central body 51-70μm.
Length of processes 16-25μm.

Occurrence: LAW(b)1, BH10/24-20, BI5, BI14.

Genus *Hystrichosphaeridium* Deflandre, 1937b;
emend.Davey & Willams,1966b.

Genotype *Hystrichosphaeridium tubiferum* (Ehrenberg, 1838).

Hystrichosphaeridium bowerbankii Davey & Williams
Plate 2, Fig.3.

1966b *Hystrichosphaeridium bowerbankii* Davey & Williams,pp.69-70,pl.8, figs.1,4.

Remarks: Cysts assigned to this species conform to the original diagnosis but are slightly smaller than those described by Davey & Williams (1966b).

Dimensions: Diameter of central body 26-35μm.
Length of processes 19-24μm.

Occurrence: BI4, AU7.

Hystrichosphaeridium tubiferum (Ehrenberg)

Plate 2, Fig.4.

1838 *Xanthidium tubiferum* Ehrenberg,pl.1,fig.16.

1904 *Ovum hispidum (Xanthidium tubiferum)* Ehrenberg;Lohmann,p.21.

1933 *Hystrichosphaera tubifera* (Ehrenberg);O.Wetzel,p.40,pl.4,fig.16.

1937 *Hystrichosphaeridium tubiferum* (Ehrenberg);Deflandre,p.68.

1966b *Hystrichosphaeridium tubiferum* (Ehrenberg);Davey & Williams, pp.56-58,pl.6,figs 1,2,;pl.8,fig.5;pl.10,fig.2;text-fig.13.

Remarks: Cysts assigned to this species conformed with the description of Cenomanian samples from Fetcham Mill (Surrey) in Davey & Williams, 1966b, except that no sacae were visible within the cyst wall.

Dimensions: Diameter of central body 27-44µm.

Length of processes 13-29µm.

Occurrence: LAW(b)A, LAW(b)1, CN838, CN87, BI5, BI9, BI10, BI14.

Genus *Litosphaeridium* Davey & Williams, 1966b; emend.Davey & Verdier,1973;emend.Lucas-Clark,1984.

Genotype *Litosphaeridium siphoniphorum* (Cookson & Eisenack, 1958).

Litosphaeridium siphoniphorum siphoniphorum (Cookson & Eisenack);emend.Lucas-Clark.

Plate 2, Figs 5,6.

1958 *Hystrichosphaeridium siphoniphorum* Cookson & Eisenack,p.44,pl.11, figs 8-10.

1963 *Hystrichokolpoma* sp.B. Baltes,p.587,pl.6,figs 6-8.

1963 *Hystrichokolpoma* sp.A. Baltes,p.587,pl.6,figs 1-5.

1964 *Hystrichosphaeridium siphonophorum* Cookson & Eisenack;Cookson & Hughes,p.48,pl.9,fig.15.

1966b *Litosphaeridium siphoniphorum* (Cookson & Eisenack);Davey & Williams,pp.80-82,pl.7,figs 7,8;text-figs.16,17.

1984 *Litosphaeridium siphoniphorum siphoniphorum* (Cookson & Eisenack); Lucas-Clark,p.186,pl.2,figs 1,3,4.

Remarks: The specimens from the Morvern Greensand differed from the emended diagnosis for *L.siphoniphorum siphoniphorum* in that the periphragm ornament did not appear to extend onto the processes. This agrees with Davey & Williams (1966b), where specimens from the Cenomanian were figured with smooth processes but a granulate or reticulate body.

Dimensions: Diameter of central body 27-39μm.

Length of processes 15-23μm.

Occurrence: BH10/32, CN8313, CN87, BI1, BI4, ST2.

Genus *Membranilarnacia* Eisenack, 1963a; emend.Williams & Downie,1966.

Genotype *Membranilarnacia leptoderma* (Cookson & Eisenack, 1958)

Membranilarnacia sp. *cf.*"*reticulata*" Williams & Downie

Plate 4, Figs 7,8.

1966 *Membranilarnacia reticulata* Williams & Downie,pp.220-222,pl.24, figs 4-6;text-fig.59.

Remarks: Only one specimen was found that resembled *M."reticulata"* and the "netted" appearence of the outer membrane which is diagnostic of this species may have been due to corrosion of the organic material.

Dimensions: Diameter of central body 37µm.

Length of processes 19µm.

1 specimen measured.

Occurrence: LG6.

Genus *Microdinium* Cookson & Eisenack, 1960a;

emend.Sarjeant,1966b;emend.Stover & Evitt,1978.

Genotype *Microdinium ornatum* Cookson & Eisenack.

Microdinium ornatum Cookson & Eisenack.

Plate 2, Fig.8 .

1960a *Microdinium ornatum* Cookson & Eisenack,p.6,pl.2,figs 3-8;text-figs 2-4.

Remarks: The surface of the plates was sometimes ornamented with small tubercles. This species is distinguished from *M.distinctum* by the presence of cingular plates.

Dimensions: Length of body 28-42µm.

Width of body 19-33μm.

Occurrence: CN8313, CN87, BI5, BI9, BI14.

Microdinium setosum Sarjeant.

Plate 2, Fig.7.

1966b *Microdinium setosum* Sarjeant,p.151,pl.16,figs 9,10;text-fig.39.

1978b *Phanerodinium setosum* (Sarjeant);Below,p.38.

1989 *Microdinium setosum* Sarjeant;Lentin & Williams,p.243.

Remarks: Most specimens of *M.setosum* from the Morvern Greensand had lost their apex in archaeopyle formation. Unlike the text-fig. in Sarjeant (1966b), the boundary of the archaeopyle appears to be a suture bearing low crests and spines.

Dimensions: Length of body 30-38μm.

Width of body 23-36μm.

Occurrence: BH10/32, LAW(b)A, LAW(b)1, CN8398, BI4, BI5, BI9, BI14.

Genus *Odontochitina* Deflandre, 1935; emend.Davey,1970; emend.Bint,1986.

Genotype *Odontochitina operculata* (Wetzel)Deflandre & Cookson,1955.

Odontochitina costata Alberti; emend.Clarke & Verdier.

Plate 2, Fig.9.

1961 *Odontochitina costata* Alberti,p.31,pl.6,figs 10-13.

1967 *Odontochitina costata* Alberti;Clarke & Verdier,pp.58-59.

Remarks: A complete specimen with all three (two antapical and one apical) horns intact was not seen from the Morvern Greensand. However, *O.costata* could be distinguished from *O.operculata* (Wetzel) by fine ribs on the horns of the former. All specimens of *O.costata* seen were folded and/or badly damaged.

Dimensions: Total length (apical horn missing) 216μm.

Length of inner body 77μm.

Width of inner body 63μm.

Length of antapical horns 113μm; 108μm.

1 specimen measured.

Occurrence: BI1, BI4, BI5, BI6, BI14, GR1.

Odontochitina operculata (Wetzel)

Plate 3, Fig.1 .

1933a *Ceratium operculatum* Wetzel,p.170,pl.II,figs 21-22;text-fig.3.

1935 *Odontochitina silicorum* Deflandre,p.274,pl.9,figs 8-10.

1935 *Odontochitina operculata* (Wetzel);Deflandre & Cookson,pp.291-292, pl.3,figs 5,6.

Remarks: No complete specimens of *O.operculata* were found, and as with *O.costata*, the horns were often folded.

Dimensions: Length of central body 46μm.

Width of central body 41μm.

Length of antapical horns 77μm; 83μm.

Occurrence: LAW(b)A, LAW(b)1, BI1, BI6.

Odontochitina sp.*cf.porifera*

Plate 3, Fig. 2.

1956 *Odontochitina porifera* Cookson,p.188,pl.1,fig.17.

Remarks: The body is wide with two stout appendages, the walls of which are perforated. Small perforations can be seen in the specimen in Fig.6, but no detail of the cyst wall is preserved in the similarly shaped "cyst" in thin section.

Dimensions: Width of body 77μm

Length of appendages 63 and 68μm

Occurrence: ?BT12, ST2.

Dimensions: Width of central body 71μm.

Length of antapical processes 59 μm; 62μm.

1 specimen measured.

Occurrence: BT12.

Genus *Oligosphaeridium* Davey & Williams, 1966b;

emend.Davey,1982b.

Genotype *Oligosphaeridium complex* (White,1842).

Oligosphaeridium complex (White)

Plate 3, Figs.4,5.

1842 *Xanthidium tubiferum complex* White,p.39,pl.4.div.3,fig.11.

1848 *Xanthidium complexum* (White);Bronn,p.1375.

1940 *Hystrichosphaeridium elegentulum* Lejeune-Carpentier,p.22;

text-figs 11,12.

1946 *Hystrichosphaeridium complex* (White);Deflandre,p.11.

1962 *Hystrichosphaeridium tubiferum* (Ehrenberg);Pocock,p.83,pl.15, fig.230.

1964 *Hystrichosphaeridium complex* (White);Cookson & Hughes,p.46,pl.9, fig.6.

1966b *Oligosphaeridium complex* (White);Davey & Williams,pp.71-74,pl.7, figs 1,2;pl.10,fig.3;text-fig.14.

Remarks: *O.complex* was common in samples of the Morvern Greensand. The morphology of the distal branches of the processes was highly variable but conformed to that illustrated in Davey & Williams (1966b,p.72). The periphragm of the central body was granular.

Dimensions: Diameter of central body 32-45μm.

Length of processes 17-32μm.

Occrrence: LAW(b)A, LAW(b)1, LAW(b)B, BH10/32, BH10/38, (LAW(c)1), BI1-6, BI8-11, BI14, BI19, UES3, GR1, AU7, AT1, AT2, LG7, ST2.

Oligosphaeridium prolixospinosum Davey & Williams

Plate 3 , Fig. 6..

1966b *Oligosphaeridium prolixospinosum* Davey & Williams,pp.76-77,pl.8, figs 2,3.

1980 *Tanyosphaeridium prolixospinosum* (Davey & Williams);Duxbury, p.132.

1981 *Oligosphaeridium prolixospinosum* Davey & Williams;Lentin & Williams,p.201.

Remarks: *O.prolixospinosum* is distinguished from *O.complex* its more elongate central body and by having tubular processes which terminate in long, thread-like spines. As most of the specimens seen in samples of the Morvern Greensand were damaged, often with broken processes, identification was sometimes tentative.

Dimensions: Length of central body 30-41μm.

Width of central body 19-27μm.

Length of processes 16-22μm.

4 specimens measured.

Occurrence: LAW(b)A, LAW(b)1, LAW(b)B, BH10/32, BH10/38, BH10/48, BI1, BI3, BI5, BI11.

Oligosphaeridium pulcherrimum Deflandre & Cookson

Plate 3, Fig.7.

1955 *Hystrichosphaeridium pulcherrimum* Deflandre & Cookson,p.270, pl.1,fig.8;text-figs 21,22.

1966b *Oligosphaeridium pulcherrimum* (Deflandre & Cookson):Davey & Williams,pp.75-76,pl.10,fig.9;pl.11,fig.5.

Remarks: The fenestrate appearance of the distal terminations of the processes is the most distinctive diagnostic feature of *O.pulcherrimum*. The specimens from the Morvern Greensand were damaged but the number of processes (less than 18) and their appearance were typical of this species. The true shape of the body and reflected tabulation could not be clearly seen.

Dimensions: Approximate diameter of central body 27-35μm.

Length of processes 21-32μm.

3 specimens measured.

Occurrence: LAW(b)A, BT14, AT1, AT2.

Genus *Ovoidinium* Davey, 1970;emend.Lentin & Williams, 1976;emend.Duxbury,1983.

Genotype *Ovoidinium verrucosum* (Cookson & Hughes).

Ovoidinium scabrosum (Cookson & Hughes)

Plate 4 , Fig. 1.

1964 *Ascodinium scabrosum* Cookson & Hughes,p.40,pl.5,figs 1-3.

1970 *Ovoidinium scabrosum* (Cookson & Hughes);Davey,p.352.

1983 *Ascodinium (Ovoidinium) scabrosum* Cookson & Hughes;Helenes,p.158.

1983 *Ovoidinium scabrosum* (Cookson & Hughes);Bujak & Davies,pp.62-63.

1985 *Ascodinium scabrosum* Cookson & Hughes;Lentin & Williams,pp.27, 263.

1989 *Ovoidinium scabrosum* (Cookson & Hughes);Lentin & Williams,pp.269 -270.

Remarks: Cysts assigned to this species from the Morvern Greensand differed from the original diagnosis in that no equatorial girdles were observed. The inner body was finely granular.

Dimensions: Length of body 49-63μm.

Width of body 40-51μm.

Occurrence: CN8313, BT1, BI7, BI8, BT14.

Ovoidinium verrucosum subsp.*ostium* (Davey)

Plate 4, Fig. 2 .

1970 *Ovoidinium ostium* Davey,p.353,pl.4,figs 5,6;text-fig.18.

1973 *Ovoidinium verrucosum* var.*ostium* (Davey);Davey & Verdier,p.198.

1975 *Ovoidinium verrucosum* subsp.*ostium* (Davey);Lentin & Williams, p.2153.

1983 *Ascodinium verrucosum* subsp.*ostium* (Davey);Helenes,p.158.

1989 *Ovoidinium verrucosum* subsp.*ostium* (Davey);Lentin & Williams, p.270.

Remarks: The specimens seen from the Morvern Greensand conform to the original diagnosis but tended to be rather poorly preserved. The inner body wall and outer membrane were visibly in contact only in the cingular region.

Dimensions: Length of inner body 33µm.
Width of inner body 39µm.
Overall length 48µm.
1 specimen measured.

Occurrence: CN8313, BH10/32.

Genus *Prolixosphaeridium* Davey *et al.*,1966;
emend.Davey,1969a.

Genotype *Prolixosphaeridium parvispinum* (Deflandre, 1937b)

Prolixosphaeridium parvispinum (Deflandre)

Plate 4, Fig. 3.

1937b *Hystrichosphaeridium xanthiopyxides* var.*parvispinum* Deflandre, p.77,pl.13,fig.5.

1958 *Hystrichosphaeridium parvispinum* (Deflandre);Cookson & Eisenack, p.45.

1960 *Baltisphaeridium parvispinum* (Deflandre);Klement,p.59.

1969b *Prolixosphaerisium parvispinum* (Deflandre);Davey *et al.*,p.17.

Remarks: This species was rare in the Morvern Greensand but conformed to the original diagnosis. The processes taper distally to a point.

Dimensions: Length of body 38μm.

Width of body 19μm.

Length of processes 12-15μm.

1 specimen measured.

Occurrence: BI5, BI6, BI14, (?ST2).

Genus *Surculosphaeridium* Davey *et al.*, 1966b;

emend.Davey,1982b.

Genotype *Surculosphaeridium cribrotubiferum* (Sarjeant).

Surculosphaeridium longifurcatum (Firtion)

Plate 4, Figs. 4,5.

1952 *Hystrichosphaeridium longifurcatum* Firtion,p.157,pl.9,fig.1; text-figs I,H,K,L,M.

1963 *Baltisphaeridium longifuracatum* (Firtion);Downie & Sarjeant,p.91.

1966b *Surculosphaeridium longifurcatum* (Firtion);Davey *et al.*,pp.163-164,pl.8,figs 7,11;text-figs 43,44.

Remarks: *S. longifurcatum* was common in samples from the Morvern Greensand, and specimens conformed to the description in Davey *et* *al.*(1966b), the processes closing distally but being rather variable in form. Occasionally the periphragm appeared to be pitted but this feature was random and was therefore interpreted as a secondary feature.

Dimensions: Diameter of central body 27-43μm.

Length of processes 12-31μm.

Occurrence: LAW(b)A, LAW(b)1, LAW(b)B, BH10/12, BH10/24-20, BH10/32, CN838, BI1, BI4, BI5, BI6, BI9, BI10, BI11, BI14, GR1, AU7, AT1, AT2, ST2.

Genus *Valensiella* Eisenack, 1963.

Genotype *Valensiella ovulum* (Deflandre, 1947).

Valensiella ovulum (Deflandre)

Plate 4, Fig.6 .

1947c *Membranilarnax ovulum* Deflandre,p.9,text-figs22,23.

1963a *Favilarnax ovulum* (Deflandre);Sarjeant,p.720.

1963a *Valensiella ovulum* (Deflandre);Eisenack,p.101.

Remarks: This species was extremely rare in the samples investigated.

Dimensions: Diameter of inner body 32μm.

Length of processes 4-8μm.

1 specimen measured.

Occurrence: BH10/38.

II. Dinoflagellate cysts having a precingular archaeopyle.

Genus *Achomosphaera* Evitt, 1963.

Genotype *Achomosphaera ramulifera* (Deflandre,1937b)

Achomosphaera neptuni (Eisenack)

Plate 4, Fig. 9.

1958 *Baltisphaeridium neptuni* Eisenack,p.399.pl.26,figs 7,8; text-fig.8.

1966a *Achomosphaera neptuni* (Eisenack);Davey & Williams,pp.51-52,pl.3, fig.7;pl.9,fig.11.

1983 *Spiniferites neptuni* (Eisenack);Duxbury,p.55.

1985 *Achomosphaera neptuni* (Eisenack);Lentin & Williams,p.5.

1985a *?Florentinia neptuni* (Eisenack);Sarjeant,pp.89-90;92-93.

1988b *Achomosphaera neptuni* (Eisenack);Lister & Batten,pp.31-32.

Remarks: Faint parasutural markings were common and the cingular processes were branched, often trifurcating. The cell wall could be seen to be reticulate in most specimens. The archaeopyle was rarely seen.

Dimensions: Diameter of central body 32-56μm.

Length of processes 10-19μm.

Occurrence: BH10/32, CN87.

Achomosphaera ramulifera (Deflandre)

Plate 4, Fig.10.

1935 *Hystrichosphaera cf.ramosa* (Ehrenberg);Deflandre,pl.5,fig.11.

1937 *Hystrichosphaeridium ramuliferum* Deflandre,p.74,pl.14,figs 5,6; pl.17,fig.10.

1963 *Baltisphaeridium ramuliferum* (Deflandre);Downie & Sarjeant,p.92.

1963 *Achomosphaera ramulifera* (Deflandre);Evitt,p.163.

1974 *Spiniferites ramulifera* (Deflandre);Reid,pp.608-609.

1977b *Achomosphaera ramulifera* (Deflandre);Lentin& Williams,p.2.

1980 *Spiniferites ramulifera* (Deflandre);May,p.63.

1981 *Achomosphaera ramulifera* (Deflandre);Lentin & Williams,p.3.

Remarks: The periphragm appeared smooth in all specimens seen but there was considerable variation in the degree of expression of the parasutural markings. These were always faint but rarely absent.

Dimensions: Diameter of central body 36-58µm.

Length of processes 14-30µm.

Occurrence: LAW(b)A, BH10/32, BH10/38, CN838, BI5, UES3, GR1, ST2.

Genus *Cribroperidinium* Neale & Sarjeant, 1962;
emend.Davey,1969a;emend.Sarjeant,1982b;
emend.Helenes,1984.

Genotype *Cribroperidinium septimentum* Neale & Sarjeant, 1962.

Cribroperidinium cooksoniae Norvick

Plate 5, Fig.1 .

1976 *Cribroperidinium cooksoniae* Norvick,pp.36-37,pl.1,figs 1-3;

text-fig.13.

Remarks: The cyst body is oval in shape but tapers to a prominant apical horn. The paratabulation is defined by narrow ridges: these bear no spines or other ornamentation. All specimens encountered were light to medium reddish-brown in colour.

Dimensions: Length of body (including apical horn) 48-89μm.

Width of body 30-67μm.

2 specimens measured.

Occurrence: LAW(a)6.

Genus *Exchosphaeridium* Davey *et al.*,1966.

Genotype *Exchosphaeridium phragmites* (Davey *et al.*, 1966).

Exchosphaeridium bifidum (Clarke & Verdier)

Plate 5, Fig.2 .

1967 *Baltisphaeridium bifidum* Clarke & Verdier,pp.72-73,pl.17, figs 5,6;text-fig.30.

1968 *Exchosphaeridium bifidum* (Clarke & Verdier);Clarke *et al.*,p.182.

Remarks: *E.bifidum* was usually well-preserved. The processes are distinctive, being numerous, thin and distally bifid. The apical process only appeared to be branched.

Dimensions: Diameter of central body 46-54μm.

Length of processes 9-27μm.

Occurrence: BH10,24-20, BH10/32, BI14, AT2.

Exchosphaeridium phragmites Davey *et al.*

Plate 5, Fig. 3.

1966 ***Exchosphaeridium phragmites*** Davey *et al.*,pp.165-166,pl.2,
figs 8-10.

Remarks: As described in the original diagnosis, an alignment of the processes adjacent to the cingulum could be seen, although the arrangement of the other processes appeared to be unrelated to the paratabulation of the cyst. The apical process was broad-based and branched, other processes tending to be blunted distally or rarely bifurcating.

Dimensions: Diameter of central body 27-39μm.
Length of processes 8-17μm.

Occurrence: LAW(b)B, BH10/24-20, CN87, BI1, BI10, BI14, AT2.

Genus *Gonyaulacysta* Deflandre, 1964;emend.Sarjeant, emend.Stover & Evitt,1978;emend.Sarjeant,1982b.

Genotype *Gonyaulacysta jurassica* (Deflandre)Norris & Sarjeant.

Gonyaulacysta cassidata (Eisenack & Cookson)

Plate 5, Fig.4.

1960 *Gonyaulax helicoidea* subsp.*cassidata* Eisenack & Cookson,p.3,pl.1,
figs 5,6.

1962 *Gonyaulax cassidata* Eisenack & Cookson;Cookson & Eisenack,p.486, pl.2,figs.1,2.

1966b *Gonyaulacysta cassidata* (Eisenack & Cookson);Sarjeant,pp.125-126, pl.14,figs.3,4;text-fig.31.

Remarks: *G.cassidata* was rare and poorly preserved, the thin shell wall being easily folded. Identification of this species was therefore rather tentative but the visible paratabulation and the denticulate crests marking the plate boundaries conformed to the emended diagnosis (Sarjeant,1966b).

Dimensions: Overall length 67μm.

Overall width 49μm.

1 specimen measured.

Occurrence: BH10/38, CN8313, BT9.

Gonyaulacysta helicoidea (Eisenack & Cookson)

Plate 5, Fig. 5.

1960 *Gonyaulax helicoidea* Eisenack & Cookson,p.2,pl.1,figs.4-9.

1966b *Gonyaulacysta helicoidea* (Eisenack & Cookson);Sarjeant,pp.116-117,pl.13,figs.7,8;pl.15,figs.8,9;text-fig.26.

Remarks: *G.helicoidea* was extremely rare in the samples studied. The crests were not as markedly denticulate as illustrated in Sarjeant (1966b,p.117).

Dimensions: Overall length of body 48μm.

Overall width of body 45μm.

1 specimen measured.

Occurrence: BH10/32, ?BT5.

Genus *Hystrichodinium* Deflandre, 1935;

emend.Sarjeant,1966b;emend Clarke & Verdier,1967.

Genotype *Hystrichodinium pulchrum* Deflandre, 1935.

Hystrichodinium pulchrum Deflandre

Plate 5, Fig. 6.

1935 *Hystrichodinium pulchrum* Deflandre,p.225,pl.5,fig.1;text-figs. 9-11.

Remarks: Specimens from the Morvern Greensand conformed with the original diagnosis, the cingulum being well-defined but other parasutural markings being faint.

Dimensions: Diameter of body 32-47μm.

Length of processes 19-32μm.

Occurrence: LAW(b)1, BH10/32, BT1, BT8, BI9, CR1, ?ST2.

Genus *Pervosphaeridium* Yun, 1981.

Genotype *Pervosphaeridium pseudohystrichodinium* (Deflandre,1937b), Yun,1981.

Pervosphaeridium truncatum (Davey)

Plate 5, Fig.8 .

1969a *Exchosphaeridium striolatum* var.*truncatum* Davey,p.165,pl7, figs.1-3.

1973 *Exchosphaeridium striolatum* subsp.*truncatum* (Davey);Lentin &

Williams,p.56.

1978 *Exchosphaeridium ?truncatum* (Davey);Stover & Evitt,p.154.

1982c *Pervosphaeridium truncatum* (Davey);Below,p.27,pl.5,figs 10,12.

Remarks: The archaeopyle was only visible in one specimen. The processes were characteristically widely spaced and thorn-shaped.

Dimensions: Diameter of body 37μm.

Length of processes 6-13μm.

1 specimen measured.

Occurrence: BI7, BI11.

Genus *Spiniferites* Mantell, 1850;emend.Sarjeant,1970.

Genotype *Spiniferites ramosus* (Ehrenberg,1838);Loeblich & Loeblich,1966.

Spiniferites ramosus (Ehrenberg)

Plate 6., Fig. 1.

1838 *Xanthidium ramosum* Ehrenberg,pl.1,figs 1,2,5.

1838 *Xanthidium furcatum* Ehrenberg,pl.1,figs 12,14.

1854 *Xanthidium ramosum* Ehrenberg,pl.7,figs 9,10.

1854 *Xanthidium furcatum* Ehrenberg,pl.7,figs 9,10.

1932 *Hystrichosphaera furcata* (Ehrenberg);O.Wetzel,p.136.

1932 *Hystrichosphaera ramosa* (Ehrenberg);O.Wetzel,p.144.

1935 *Hystrichosphaera furcata* (Ehrenberg);Deflandre,p.14,pl.5,fig.9; pl.8,fig.3.

1937 *Hystrichosphaera ramosa* (Ehrenberg);Deflandre,p.64,pl.11, figs.5,7.

1941 *Hystrichosphaera furcata* (Ehrenberg);Conrad,text-fig.2,no.1.

1947 *Hystrichosphaera furcata* (Ehrenberg)Deflandre,p.22,text-fig.1, no.11.

1947 *Hystrichosphaera ramosa* (Ehrenberg);Deflandre,p.22,text-fig.1, no.13.

1952 *Hystrichosphaera furcata* (Ehrenberg);Deflandre,text-fig.15.

1952 *Hystrichosphaera ramosa* (Ehrenberg);Deflandre,text-fig.17.

1966 *Spiniferites ramosus* (Ehrenberg);Loeblich & Loeblich,p.56.

Remarks: Some variation in the thickness of processes and process type (bifurcate or trifurcate) was common. The periphragm and endophragm were both smooth. Details of the archaeopyle were rarely seen and *S.ramosus* was therefore not divided into subspecies, the variation in process type not being thought sufficient justification for splitting. The form of the processes and general morphology conform to the text-fig. in Davey (1966a,p.33).

Dimensions: Diameter of central body 27-46µm.

Length of processes 11-25µm.

Occurrence: LAW(b)A, LAW(b)1, BH10/12, BH10/24-20, BH10/38, CN838, CN87, BI1, BI9, BI10, BI14.

III Dinoflagellate cysts having a combination archaeopyle.

Genus *Florentinia* Davey & Verdier, 1973;

emend.Duxbury, 1980.

Genotype *Florentinia laciniata* Davey & Verdier, 1973.

Florentinia deanei (Davey & Williams)

Plate 6, Fig. 2.

1966 *Hystrichosphaeridium deanei* Davey & Williams, pp.58-59, pl.6, figs 4,8.

1973 *Florentinia deanei* (Davey & Williams); Davey & Verdier, p.187.

Remarks: The extremely wide apical process described in the original diagnosis for this species was not observed, but as stated by Davey & Williams (1966b), this is a variable feature.

Dimensions: Diameter of central body 36-47μm.

Length of processes 15-35μm.

Occurrence: LAW(b)a, LAW(b)1, BH10/32, BH10/38, CN8313, BI1, BI4, BI5, BI6, BI14, ?ST2.

Florentinia ferox (Deflandre)

Plate 6, Fig. 3.

1937b *Hystrichosphaeridium ferox* Deflandre, p.72, pl.11, figs 3-4.

1963 *Baltisphaeridium ferox* (Deflandre); Downie & Sarjeant, p.91.

1969 *Hystrichokolpoma ferox* (Deflandre); Davey, p.181.

1976 *Silicisphaera ferox* (Deflandre);Davey & Verdier,pp.322-325,pl3, figs 1,2;text-fig.4.

1980 *Florentinia ferox* (Deflandre);Duxbury,p.121.

Remarks: Process morphology was variable, some bifurcating and some trifurcating distally. In some specimens the processes were markedly striate.

Dimensions: Diameter of central body 34-41μm.

Length of processes 14-17μm.

Occurrence: LAW(b)A, LAW(b)1, LAW(b)B, BH10/32, BI5, BI14, AT1.

Genus *Palaeohystrichophora* Deflandre, 1935;

emend.Deflandre & Cookson, 1955.

Genotype *Palaeohystrichophora infusoriodes* Delandre, 1935.

Palaeohystrichophora infusoriodes Deflandre

Plate 6, Fig.4 .

1935 *Palaeohystrichophora infusoriodes* Deflandre,pp.230-231,pl.8, fig.4.

Remarks: *P.infusoriodes* was rare in samples of the Morvern Greensand but distinctive because of the well-defined cingulum and tubular, distally closed processes which decrease in size towards the apex and antapex of the cyst.

Dimensions: Length of body 34-56μm.

Width of body 26-45μm.

Length of processes 5-22μm.

3 specimens measured.

Occurrence: CN87, BT14.

IV Dinoflagellate cysts having an epicystal archaeopyle.

Genus *Callaiosphaeridium* Davey & Williams, 1966b; emend.Duxbury,1980;emend.Below,1981a.

Genotype *Callaiosphaeridium asymmetricum* (Deflandre & Courtville, 1939);Davey & Williams, 1966b.

Callaiosphaeridium asymmetricum (Deflandre & Courtville)

Plate 6, Fig.5 .

1939 *Hystrichosphaeridium asymmetricum* Deflandre & Courtville,p.100, pl.4,figs 1,2.

1966b *Callaiosphaeridium asymmentricum* (Deflandre & Courtville);Clarke & Verdier,p.104,pl.8,figs 9,10;pl.9,fig.2.

1967 *Hexasphaera asymmetrica* (Deflandre & Courtville);Clarke & Verdier,p.43.

1968 *Callaiosphaeridium asymmetricum* (Deflandre & Cookson);Clarke *et al.*,p.181.

Remarks: *C.asymmetricum* was rare in samples of the Morvern Greensand. The most distinctive feature of this species is the pentagon formed by the ribs joining the five post-cingular processes and the large tubular paracingular processes.

Dimensions: Diameter of central body 36-47μm.

Length of paracingular processes 22-35μm.

Length of post-cingular processes 14-23μm.

2 specimens measured.

Occurrence: BH10/32.

Genus *Subtilisphaera* Jain & Millepied, 1973; emend. Lentin & Williams, 1976.

Genotype *Subtilisphaera senegalensis* Jain & Millepied, 1973.

Subtilisphaera sp. *cf. pontis-mariae* (Deflandre)

Plate 6, Fig. 6.

1936 *Gymnodinium pontis-mariae* Deflandre, p.167, pl.2, figs.7-9.

1966 *Ascodinium pontis-mariae* (Deflandre); Deflandre, p.3.

1970 *Deflandrea pontis-mariae* (Deflandre); Davey, 1970, p.341.

1976 *Subtilisphaera pontis-mariae* (Deflandre); Lentin & Williams, p.119.

Remarks: This species was extremely rare in samples of the Morvern Greensand and was folded so that the original shape was difficult to determine. Thus the identification is tentative.

Dimensions: Overall length 49μm.

Overall width 22μm.

Occurrence: CN87.

V. Group Acritarcha Evitt,1963.

Genus *Cymatiosphaera* O.Wetzel;emend.Deflandre,1954.

Cymatiosphaera asarota Davey

Plate 7, Fig. 6.

1970 *Cymatiosphaera asarota* Davey,p.380,pl.9,figs 6,7.

Remarks: The shell is divided into 26-40 crudely polygonal areas by ridges. This acritarch was rare in samples of the Morvern Greensand.

Dimensions: Shell diameter 38-49μm.

2 specimens measured.

Occurrence: BI2, BI3.

Genus *Micrhystridium* Deflandre;emend.Sarjeant,1966.

Micrhystridium singulare Firtion.

Plate 7, Figs. 1,2.

1952 *Micrhystridium singulare* Firtion,p.160,pl.8,figs 1,2.

Remarks: *M.singulare* was common in samples of the Morvern Greesand but often appeared distorted, the wall being thin and easily folded. The spines were longer than the body and slightly curved. An opening in the form of an elongate oval was seen in one specimen (see Plate 7,Fig.1).

Dimensions: Diameter of central body 12-17μm.

Length of processes 8-23µm.

Occurrence: BI4, BI5, BI8, AT2.

Genus *Tubulospina* Davey, 1970.

Tubolospina oblongata Davey

Plate 7, Figs. 3,4.

1970 *Tubulospina oblongata* Davey,pp.375-376,pl.8,figs 7-9; text-fig.4A-F.

Remarks: The central body is roughly rectangular, each corner giving rise to one process. Up to three subsidiary processes were also counted.

Dimensions: Length of body 23-26µm.

Width of body 17-21µm.

Length of processes 13-25µm.

2 specimens measured.

Occurrence: BI5, ST2.

Genus *Veryhachium* Deunff;emend.Downie & Sarjeant,1963.

Veryhachium metum Davey, 1970.

Plate 7, Fig. 5.

1970 *Veryhachium metum* Davey,p.374,pl.8,figs 5,6;text-figs 3H,I.

Remarks: The central body is tetrahedral with four simple processes tapering from the corners of the body. The colour was often lighter than that of dinoflagellate cysts in the same sample.

Dimensions: Diameter of central body 13-19μm.

Length of processes 10-21μm.

Occurrence: BH10/32, BH10/38, BI9, UES3, GR1.

PLATES

Scale bar 25um unless otherwise stated.

Plate 1.

1. Batiacasphaera euteiches Drugg

2. Chlamydophorella discreta Cookson & Eisenack

3. Circulodinium distinctum Deflandre & Cookson

4. Cleistosphaeridium armatum (Deflandre)

5. Cleistosphaeridium sp. cf. "disjunctum" Davey et al.

6. Cleistosphaeridium huguoniotii (Valensi)

7. Cleistosphaeridium ?flexuosum Davey et al.

8. Epelidosphaeridia spinosa (Cookson & Hughes)

9. Fromea amphora Cookson & Eisenack

10. Fromea amphora (Cookson & Eisenack)

PLATE I

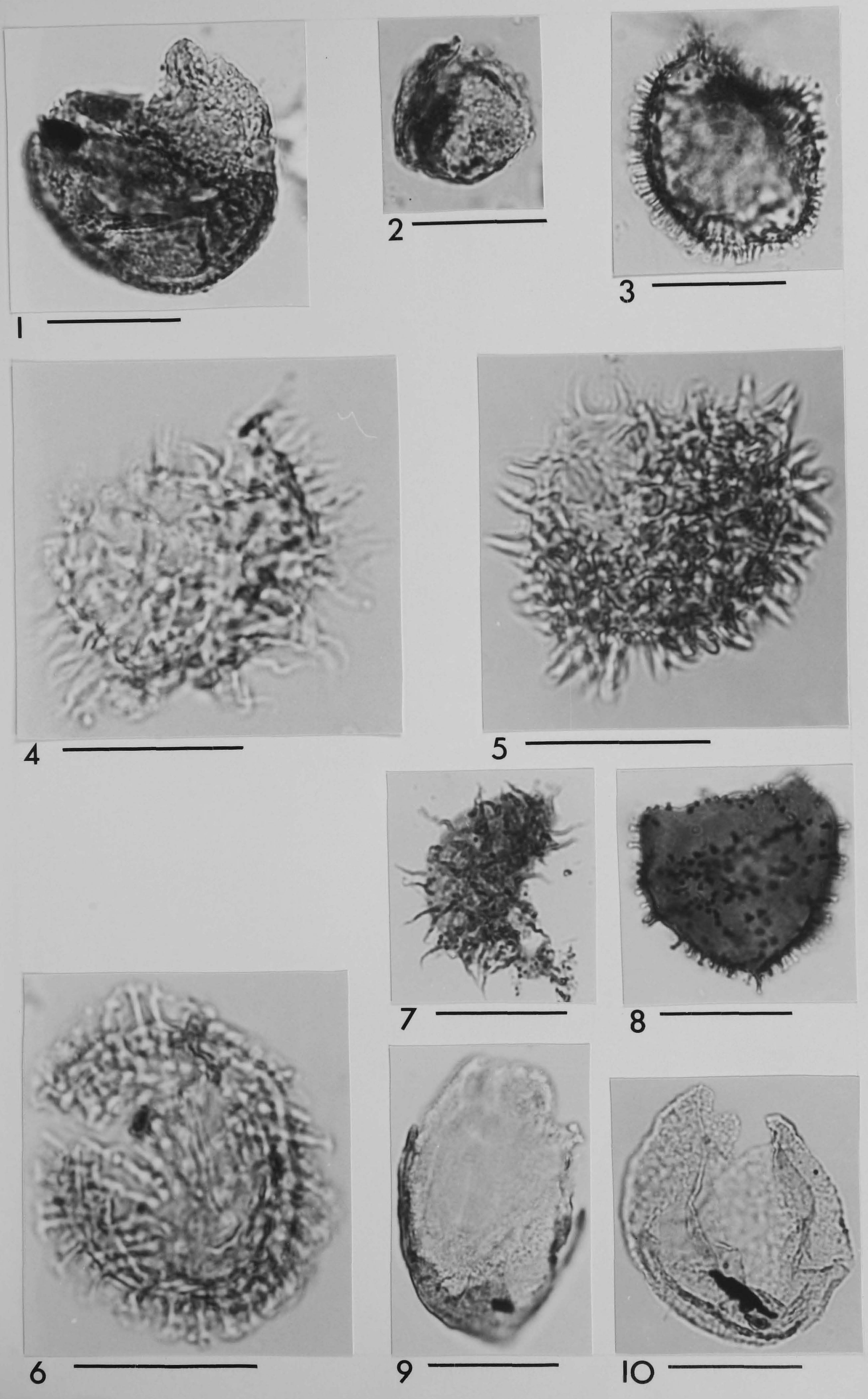


Plate 2.

1. *Heterosphaeridium heteracanthum* (Deflandre & Cookson)

2. *Heterosphaeridium difficile* (Manum & Cookson)

3. *Hystrichosphaeridium bowerbankii* Davey & Williams

4. *Hystrichosphaeridium tubiferum* (Ehrenberg)

5,6. *Litosphaeridium siphoniphorum siphoniphorum* (Cookson & Eisenack)

7. *Microdinium setosum* Sarjeant

8. *Microdinium ornatum* Cookson & Eisenack

9. *Odontochitina costata* Alberti

PLATE 2

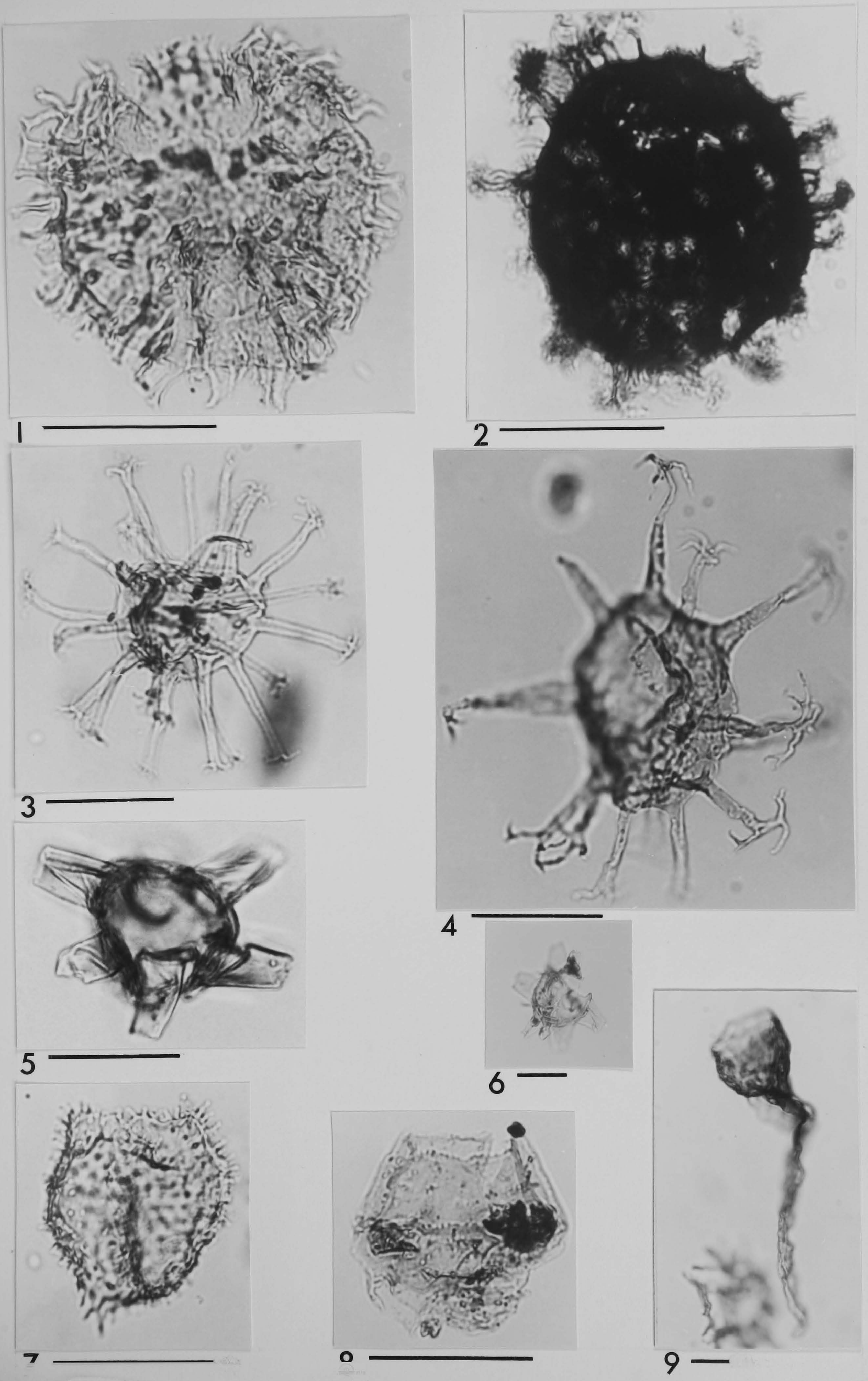


Plate 3.

1. *Odontochitina operculata* (Wetzel)

2. *Odontochitina* sp. *cf. porifera* Cookson

3. ? *Odontochitina* sp.

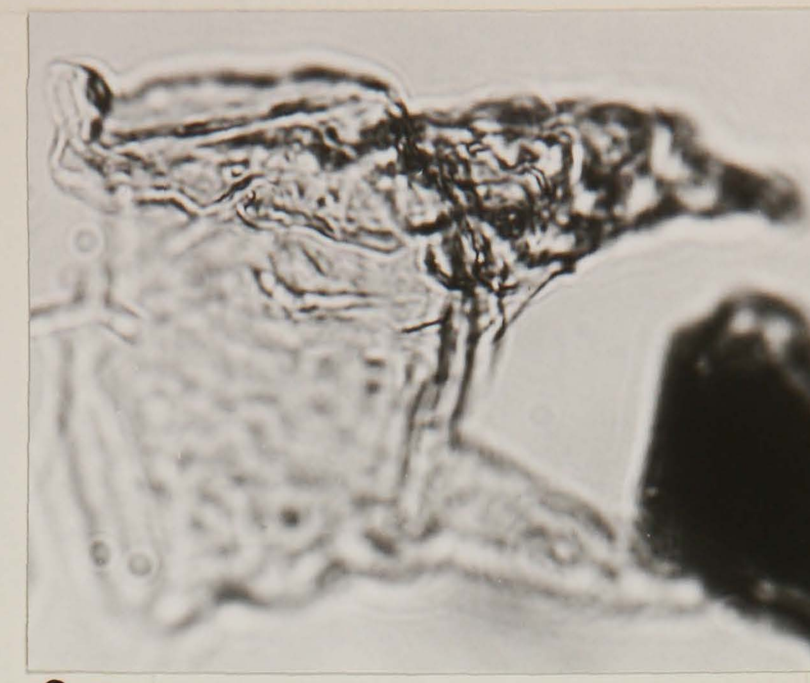
4,5. *Oligosphaeridium complex* (White)

6. *Oligosphaeridium prolixospinosum* Davey & Williams

7. *Oligosphaeridium* sp. *cf. pulcherrimum* Deflandre & Cookson

PLATE 3

1



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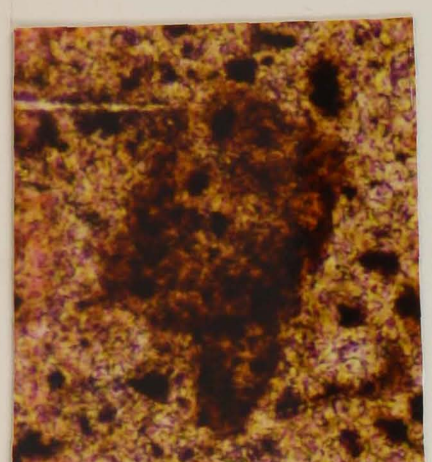

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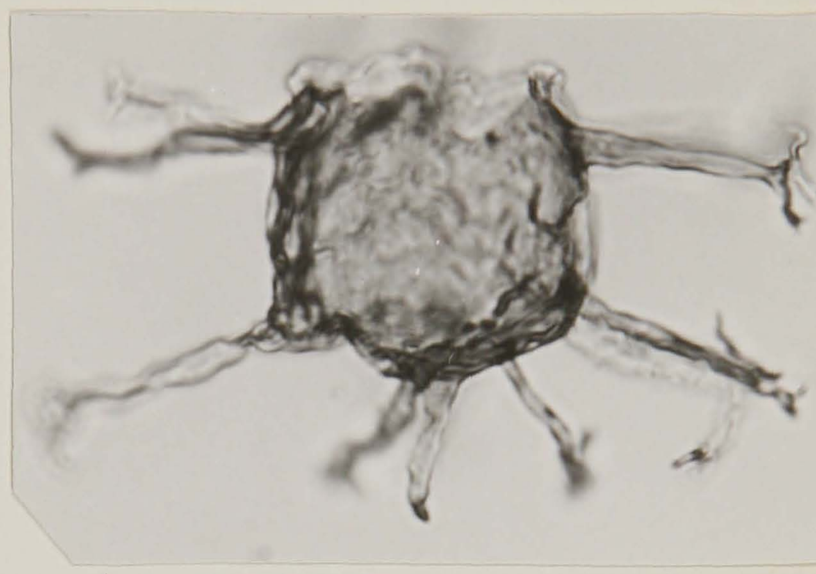

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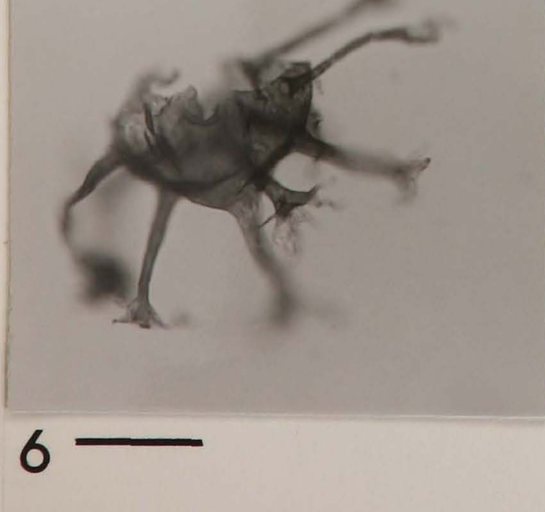

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Plate 4.

1. *Ovoidinium scabrosum* (Cookson & Hughes)

2. *Ovoidinium verrucosum ostium* (Davey)

3. *Prolixosphaeridium parvispinum* (Deflandre)

4,5. *Surculosphaeridium longifurcatum* (Firtion)

6. *Valensiella ovulum* (Deflandre)

7,8. *Membranilarnacia* sp. *cf.* "*reticulata*" Davey et al.

9. *Achomosphaera neptuni* Evitt

10. *Achomosphaera ramulifera* (Deflandre)

PLATE 4

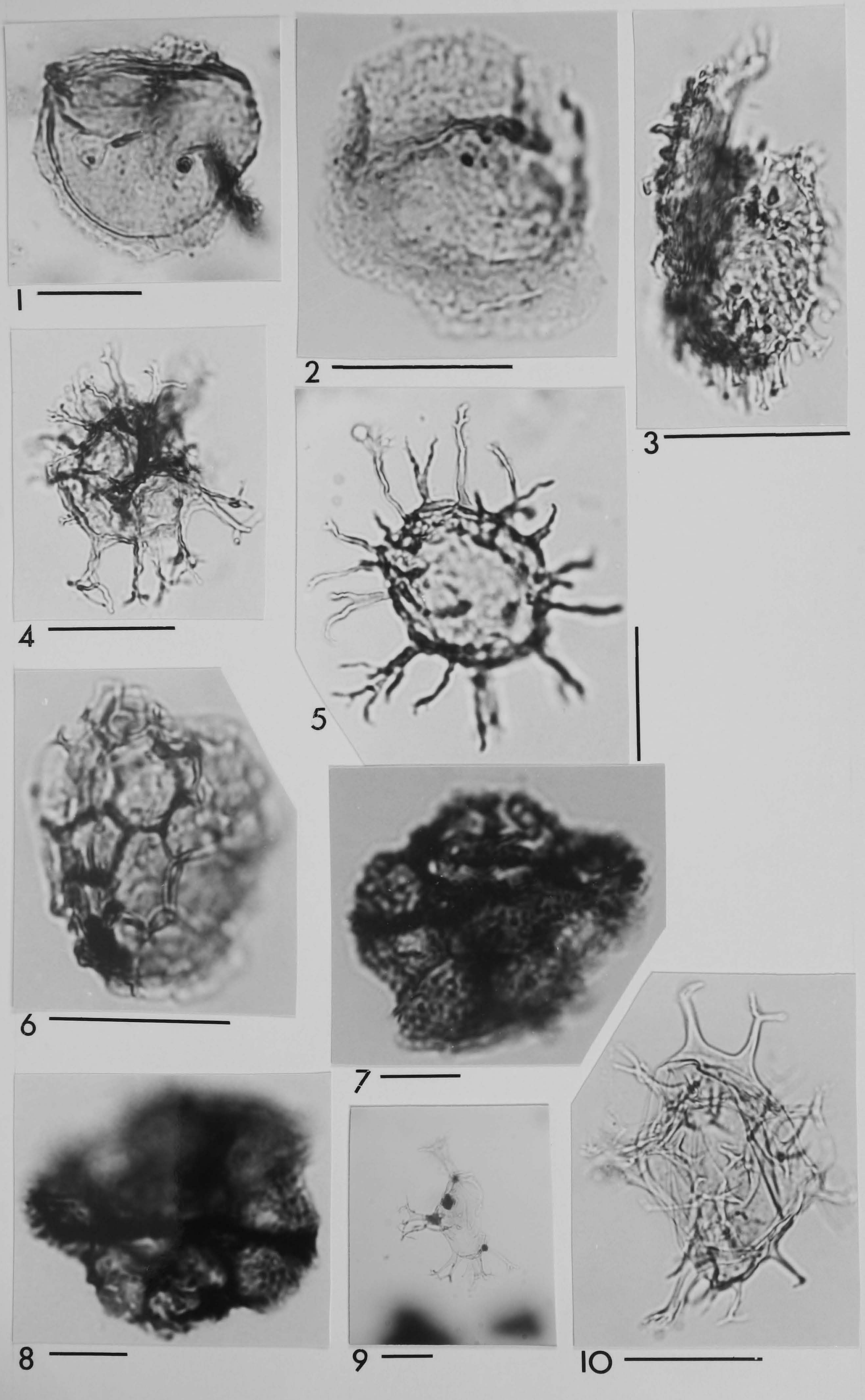


Plate 5.

1. *Cribroperidinium cooksoniae* Norvick

2. *Exchosphaeridium bifidum* (Clarke & Verdier)

3. *Exchosphaeridium phragmites* Davey et al.

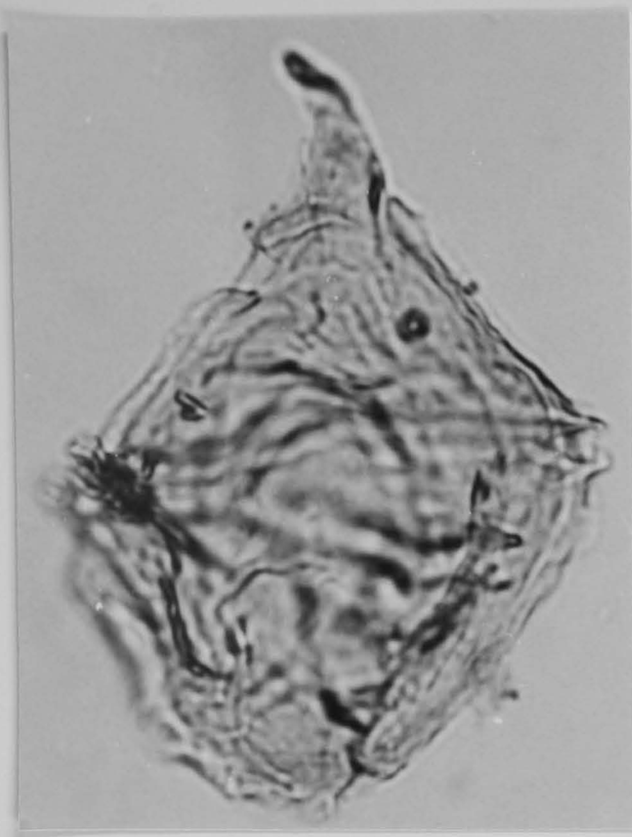
4. ?*Gonyaulacysta cassidata* (Eisenack & Cookson)

5. *Gonyaulacysta helicoidea* (Eisenack & Cookson)

6. *Hystrichodinium pulchrum* Deflandre

7. *Pervosphaeridium truncatum* (Davey)

PLATE 5



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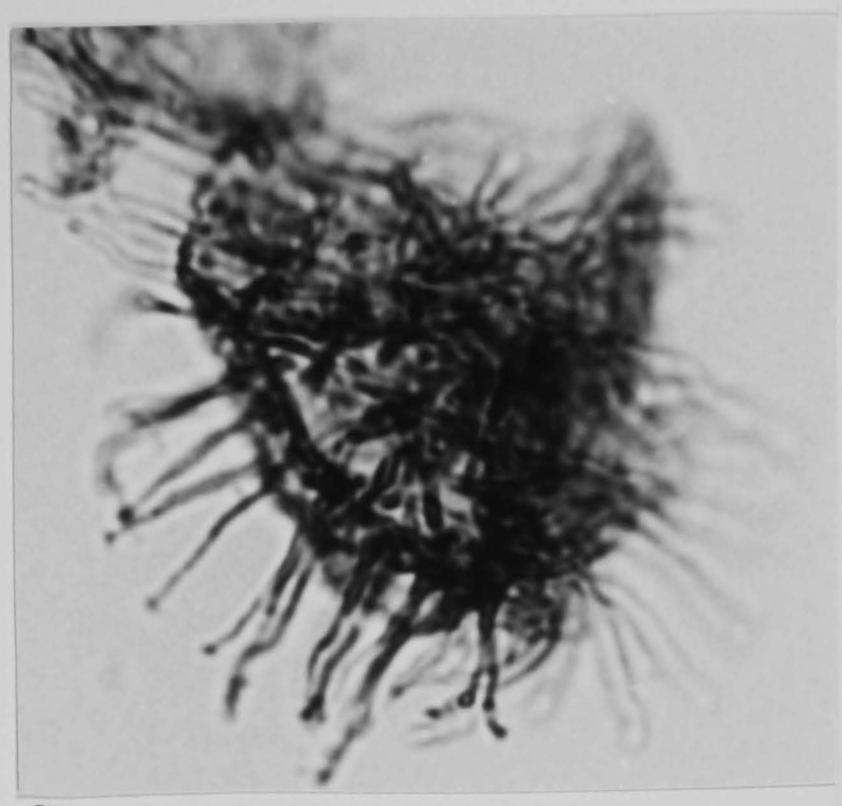

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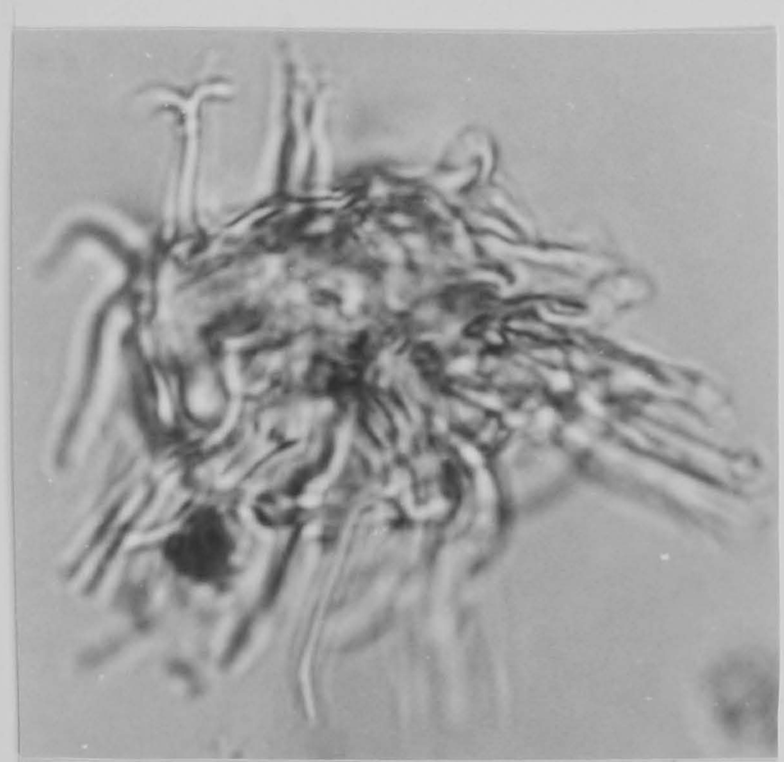

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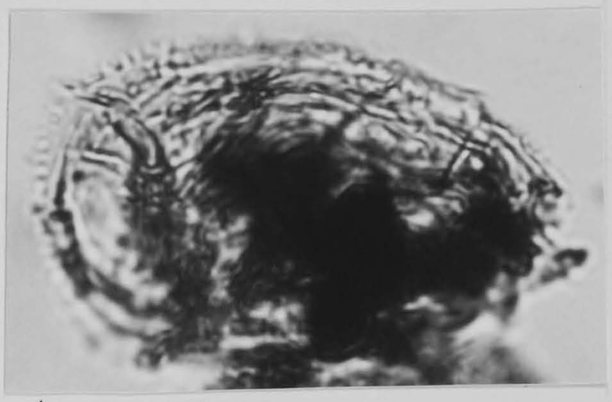

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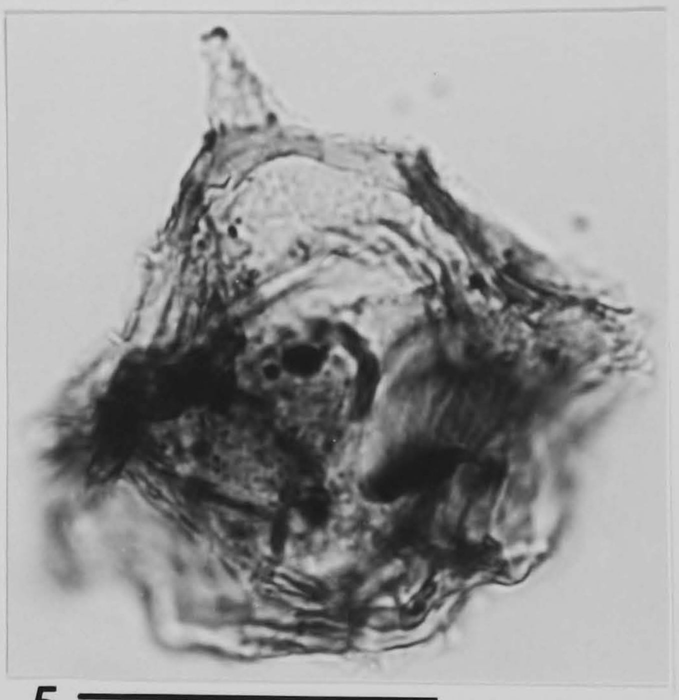

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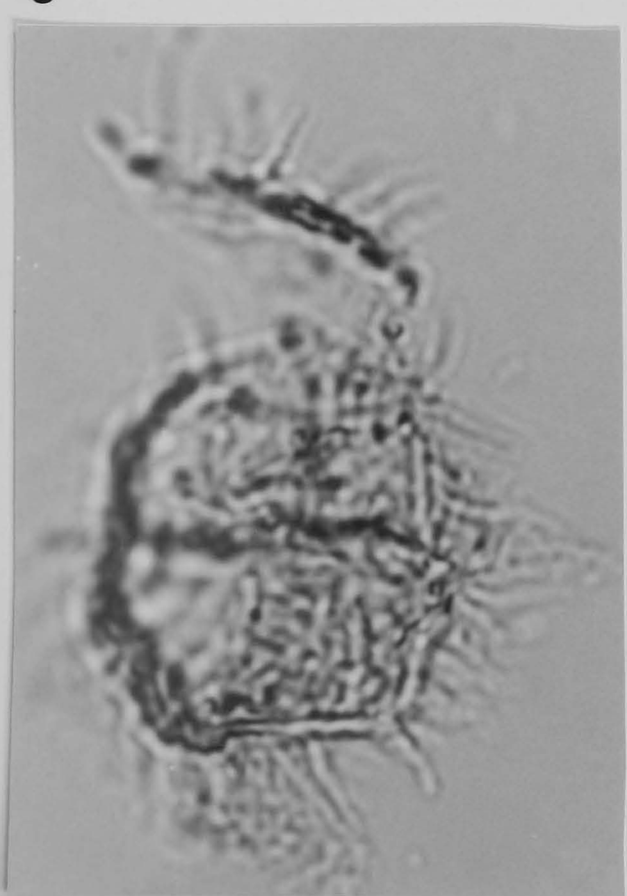

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Plate 6.

1. *Spiniferites ramosus* (Ehrenberg)

2. *Florentinia deanei* (Davey & Williams)

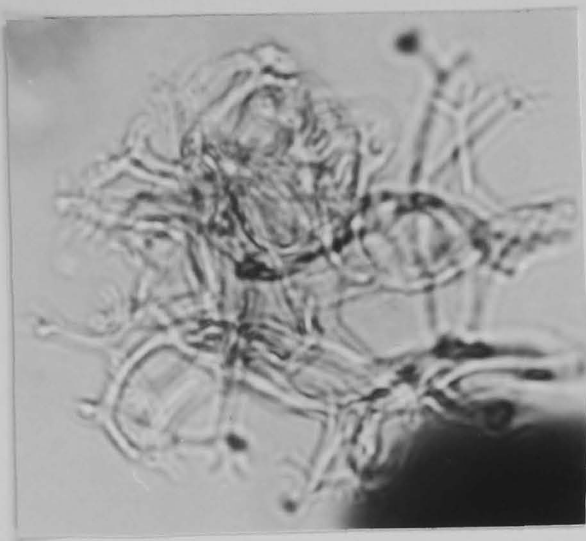
3. *Florentinia ferox* (Deflandre)

4. *Palaeonystrichophora infusoriodes* Deflandre

5. *Callaiosphaeridium asymmetricum* Davey & Williams

6. *Subtilisphaera pontis-mariae* (Deflandre)

PLATE 6



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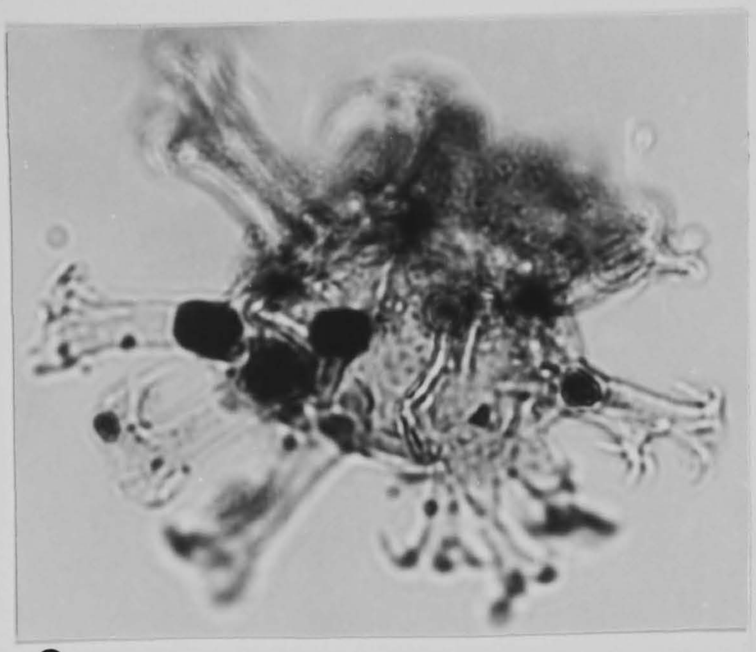

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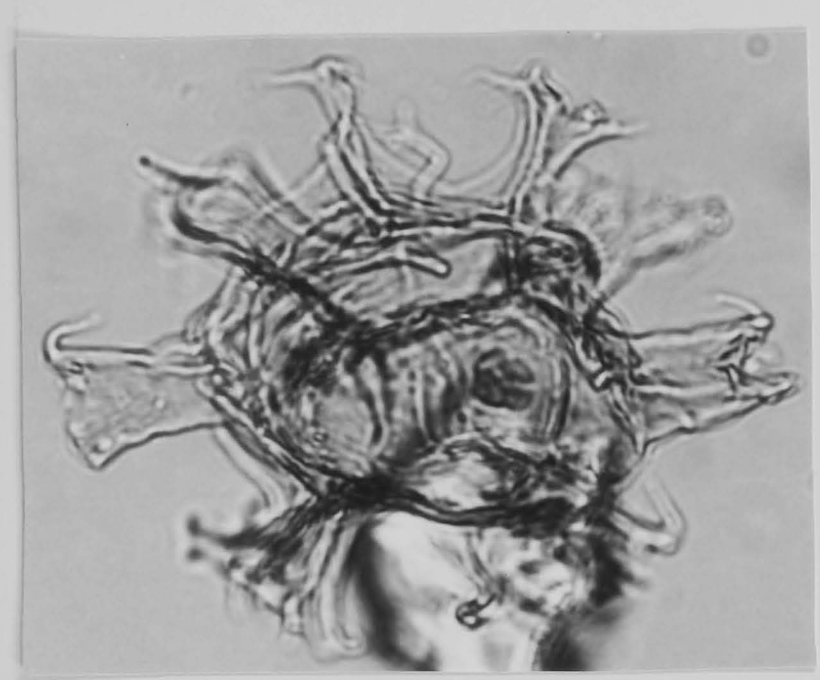

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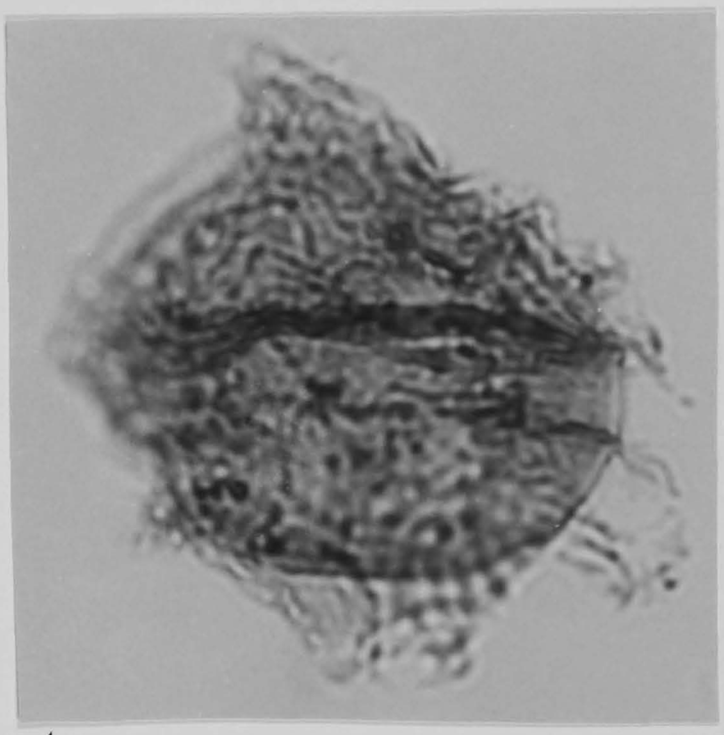

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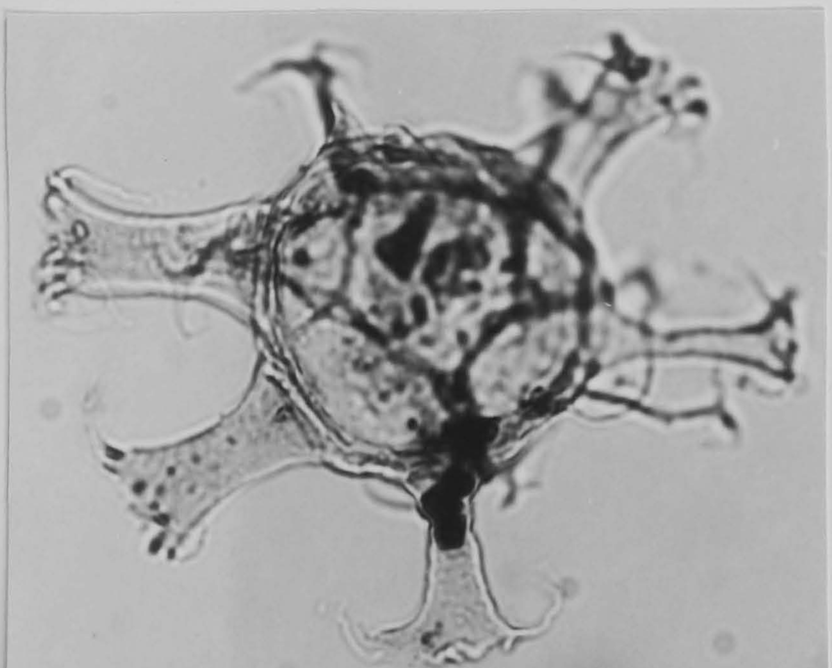

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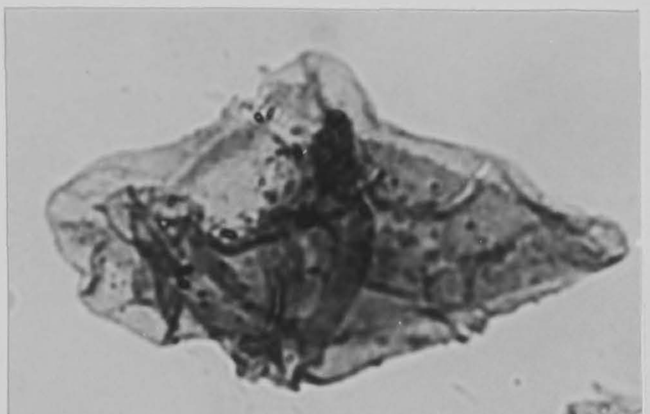

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Plate 7.

1,2. *Micrhystridium singulare* Deflandre (Scale bar 10um for (2))

3,4. *Tubulospina oblongata* Davey

5. *Veryhachium metum* Deunff

6. *Cymatiosphaera asarota* o.Wetzel

PLATE 7

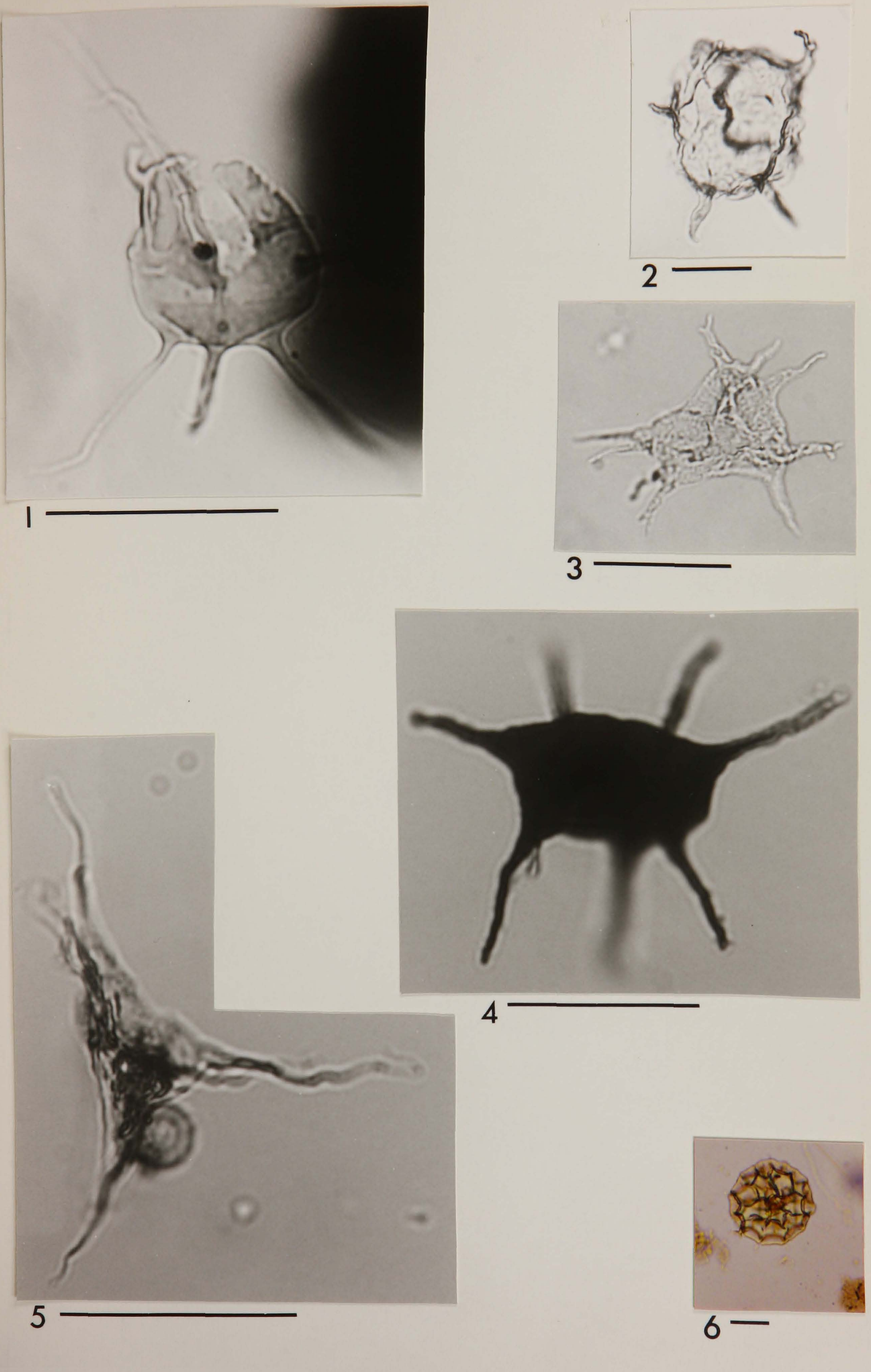


Plate 8. Palynodebris.

i. Sample BI6-a. Field of view 3mm.

a - amorphous organic material

b - leaf cuticle

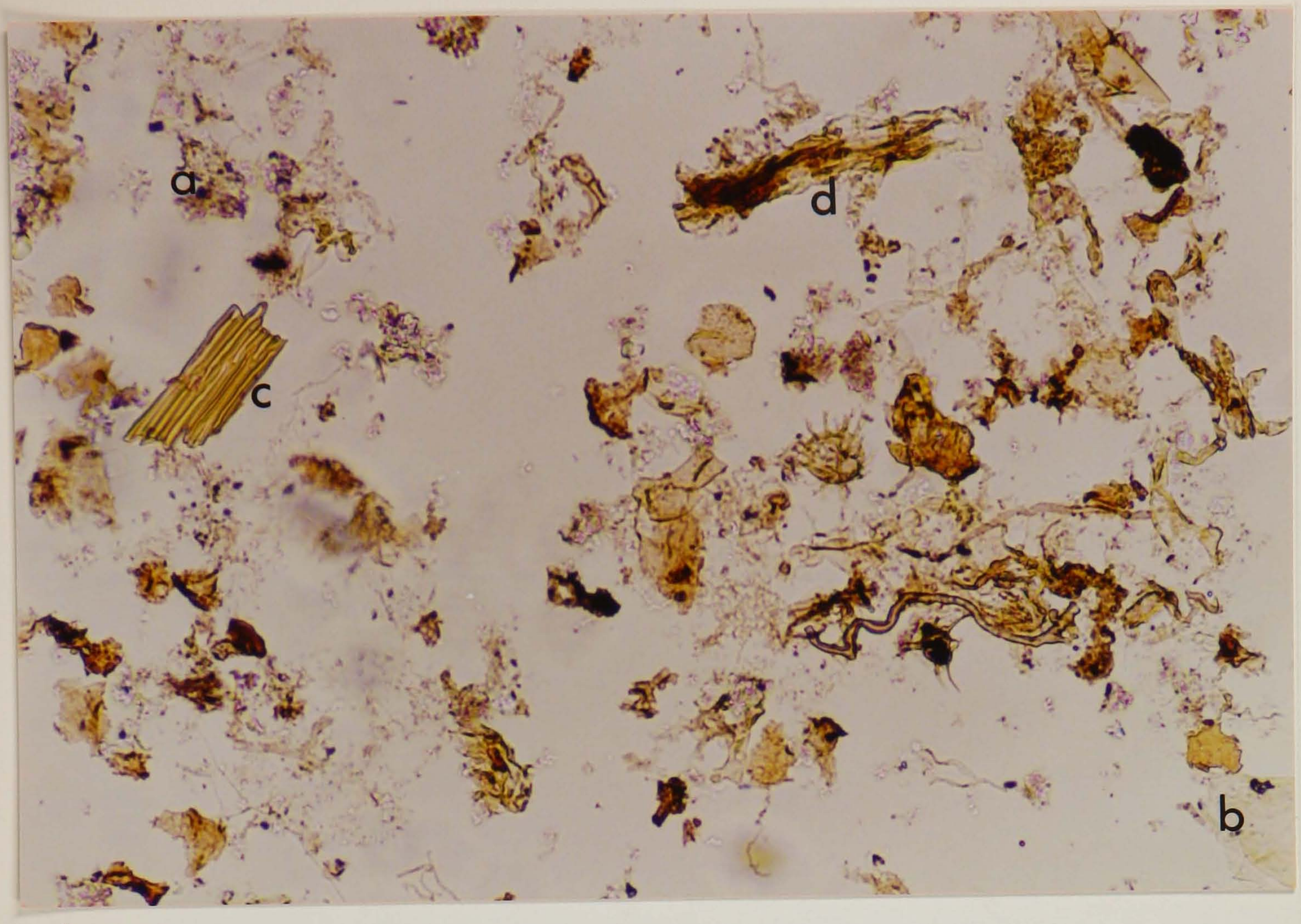
c - striped woody material

d - degraded woody material

ii. Sample BI1. Field of view 3mm.

a - bisaccate pollen grain

b - degraded organic debris



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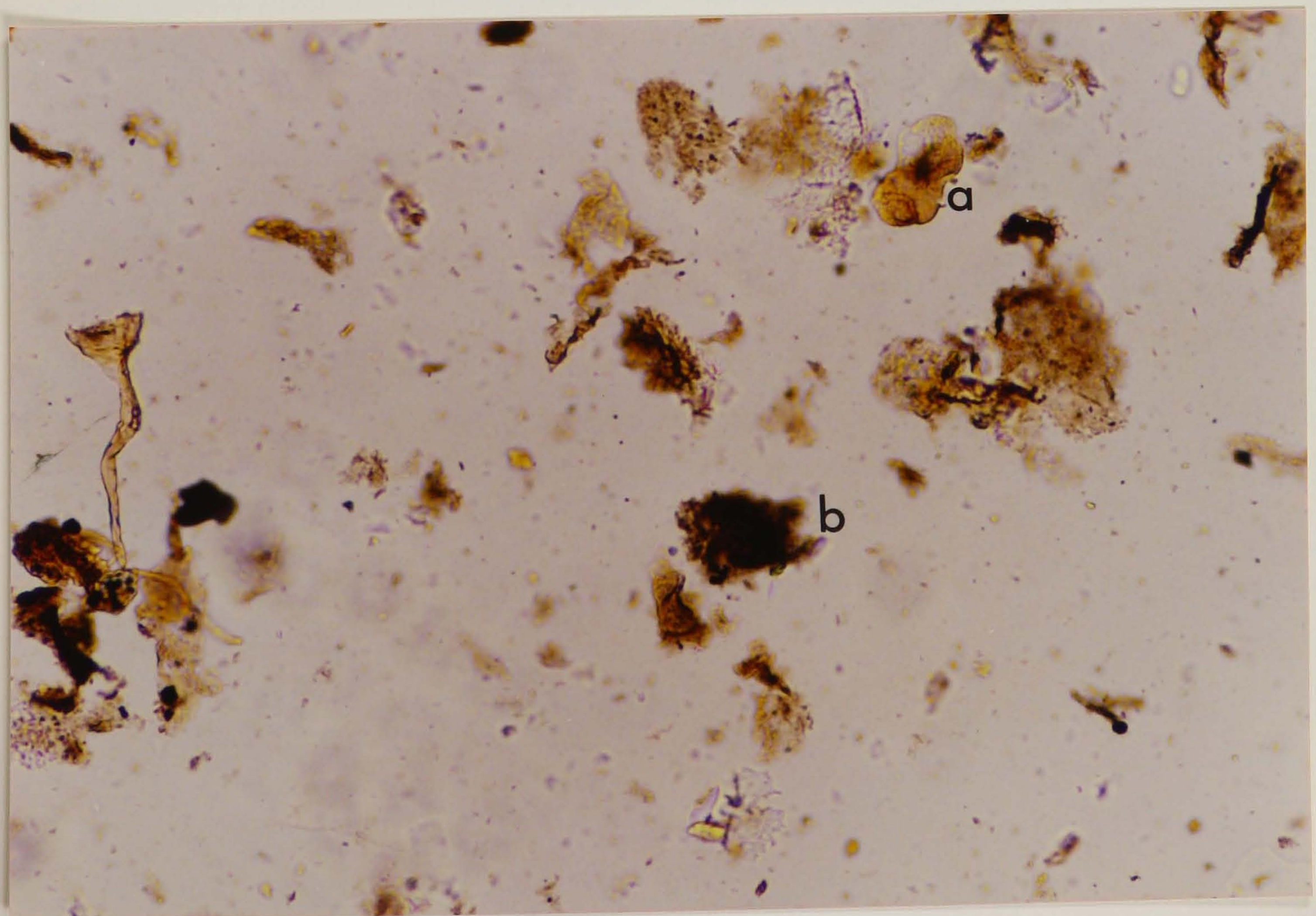

ii

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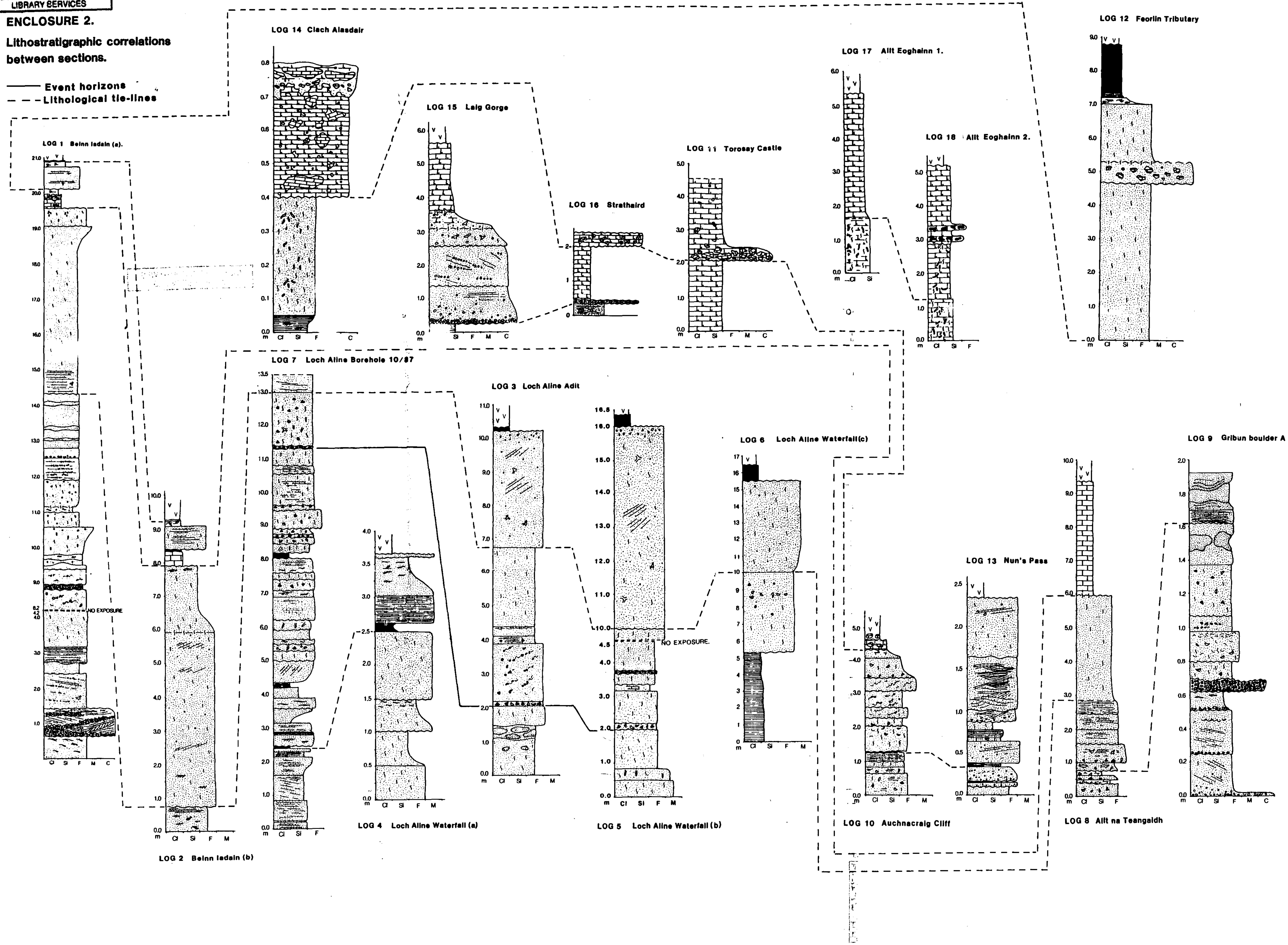
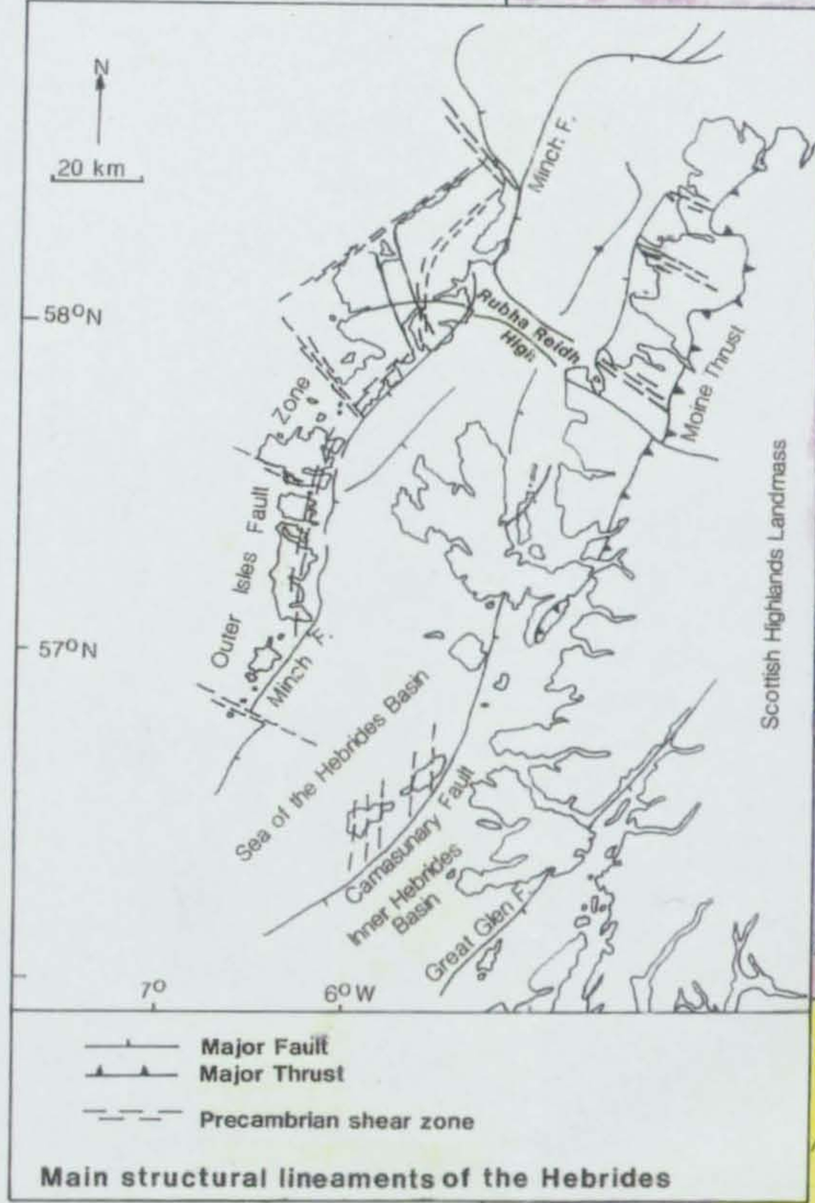
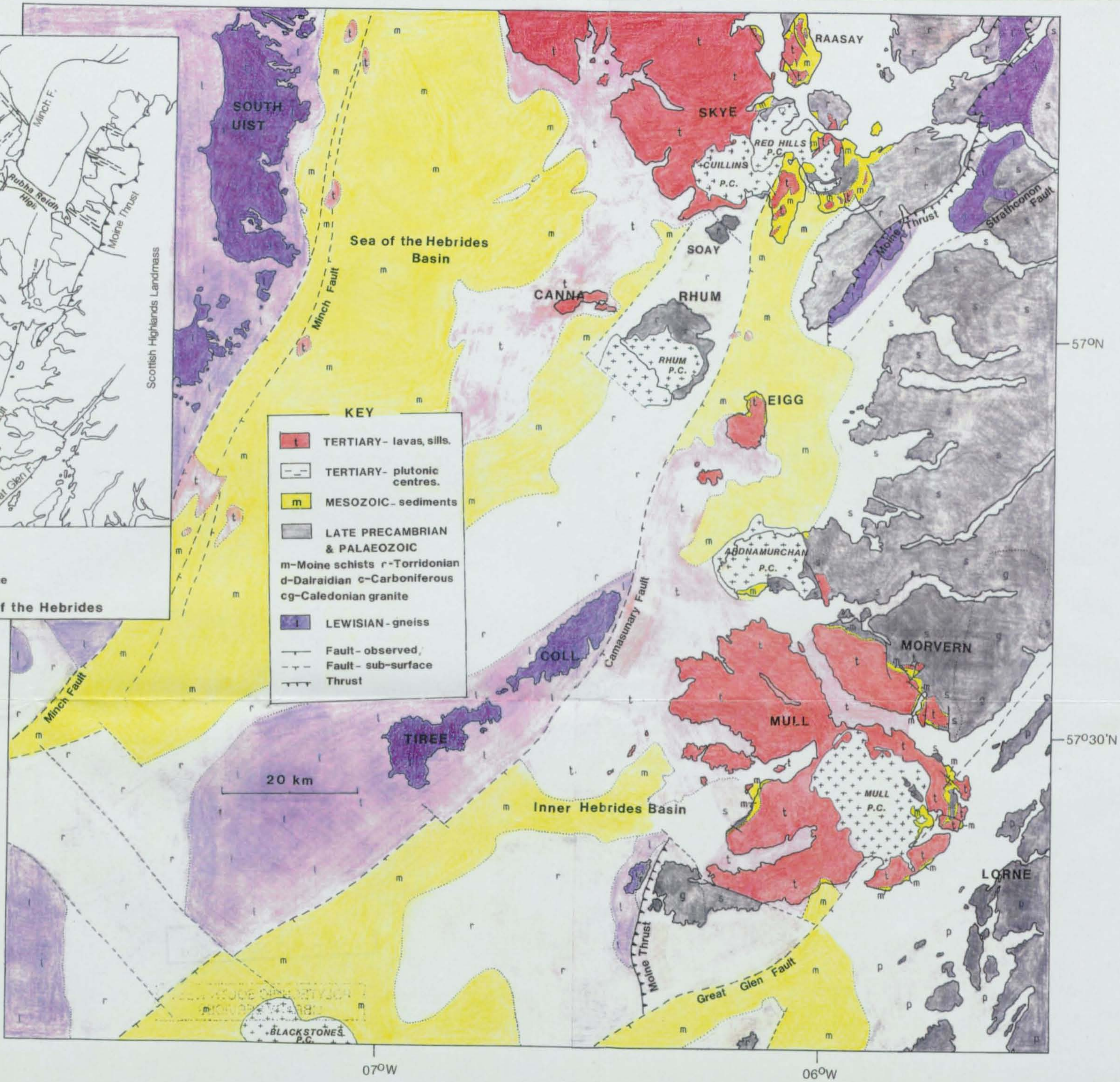
ENCLOSURE 2.

Lithostratigraphic correlations between sections.

—— Event horizons
– – – Lithological tie-lines







ENCLOSURE 1:

General structure and geology of the Inner Hebrides.