Palaeoenvironments, stratigraphy and tectonics of parts of the Asbian and Brigantian succession in Fife and the Lothians (eastern part of the Midland Valley of Scotland).

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DECLARATION

The research presented in this thesis has been undertaken by myself. The work of others, where used, has been stated specifically as a reference, or as an acknowledgement.

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ABSTRACT

Asbian and Brigantian (Dinantian) rocks have been studied in parts of Fife and the Lothians (eastern part of the Scottish Midland Valley). Asbian Oil-Shale Group sequences were examined in parts of central Fife and West Lothian, where intercalations of fluvio-deltaic facies and non-marine bay-lagoon facies are present. The bay-lagoon environments record water body fluctuations in the lagoons and lakes, and contain distinctive horizons characterized by desiccation cracks, stromatolites and other features indicative of carbonate mudflat facies. Lower Oil-Shale Group localities at Colinswell, South Queensferry and Hopetoun provide evidence of a basin-wide 'regressive event', whilst Upper Oil-Shale Group rocks at Kingswood record local water body fluctuations around the margins of a lagoon. The Oil-Shale Group facies are succeeded by the Pathhead Beds and Lower Limestone Group where Yoredale-type cycles record the interaction between fluvio-deltaic and marine conditions. The marine horizons appear to be of two types; those which are widespread and record major marine transgressions, and those which are localised and may record tectonic and/or deltaic control. Tectonism is suggested by; i) geographically restricted emergent surfaces on the tops of limestones, ii) variable clastic:carbonate ratios detected within sequences when traced from highs to lows, iii) the presence of a wide variety of paleosols, and iv) regional disruptions of successions of faunal phases within individual marine bands. The late Dinantian rises in sea level appear to have modified the deltaic complex from a constructive elongate-type, to a lobate-type, where point-concentrated delta-front mouth bars were replaced by wave/storm-reworked, laterally continuous, lobate-shaped sand sheets.

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CHAPTER 1 INTRODUCTION

1.1. Aims, location, reasons for the study and layout of thesis

The original aim of this project was to study the late Asbian and Brigantian succession in central Fife, and to identify lateral equivalents of the various sequences elsewhere in Fife and the Lothians. This was undertaken so that the changes in depositional environments concomitant with the late Asbian/early Brigantian marine transgressions could be elucidated, and the possible effects of 'background' sedimentary processes (e.g. deltaic deposition) and intra-basinal tectonics assessed. The well-exposed coastal section between Burntisland and Kirkcaldy, central Fife was chosen as the main area on which the study was to be focussed. In the centre of the Burntisland Anticline, Lower and Upper Oil-Shale group rocks are exposed, younging towards Kirkcaldy into the Fife-Midlothian Basin, where strata of Pathhead Beds and Lower Limestone Group age crop out. Seven sequences were studied from this coastal succession, with Lower and Upper Oil-Shale group outcrops forming the basis for chapters 4 and 5, Pathhead Beds outcrops forming the basis for chapter 9, and Lower Limestone Group outcrops forming the basis for chapters 10, 11, 12, and 13. The sequences studied in these chapters were invariably identified from surface outcrops and subsurface sections elsewhere in central Fife, and usually in other parts of Fife and the Lothians. Although chapters 7 and 8 do not draw directly upon sequences within this broad coastal section, chapter 7 involves the Pathhead Beds section in the Glenrothes Borehole, which is inland of the coastal section. These beds are then compared with the equivalent succession in East Fife. The strata studied in the borehole are equivalent in age to the rocks studied from the coastal outcrops in chapter 9. Chapter 8 is not concerned directly with the central Fife area, but the sequence is equivalent in age to some of the rocks studied from central Fife in chapters 9 and 7.

Each of the main chapters (chapters 4,5,7,8,9,10,11,12 and 13) involves a 'case study' of a sedimentary sequence and its lateral correlatives. Chapters 3 and 6, however, are introductory review chapters to the Oil-Shale groups and the Pathhead Beds/Lower Limestone Group. The remaining chapters (1, 2 and 14) are concerned with an introduction to the study, the general relevant stratigraphy, and the overall conclusions.

The chapters are in stratigraphic order, with chapters 3, 4 and 5 dealing with the oldest rocks of the Oil-Shale Group, and chapters 6 to 13 concerned with the youngest Pathhead Beds and Lower Limestone Group. By organising the layout in this manner, it was hoped that this study would provide a time transect, dealing with the sedimentary and tectonic evolution of part of the Midland Valley Basin, at the eastern end of the Scottish Midland Valley from the late Asbian to the end of the Brigantian. This period in time is critical, because the area was subjected to profound changes in environment due to a series of major marine transgressions which markedly altered the patterns of sedimentation and led to an improvement in intra-basinal 'communication'. In order to understand these changes, depositional settings which prevailed before the marine incursions were studied (Lower and Upper Oil-Shale groups, chapters 4 and 5), together with rocks deposited during the earliest major transgressions (Pathhead Beds, chapters 7, 8 and 9), and environments developed after the initial rises in sea level, when marine conditions reached their acme (Lower Limestone Group, chapters 10, 11, 12 and 13).

Each of the main 'case study' chapters together with the two introductory review chapters and the stratigraphy are written so that they could be read independently of the other chapters, and are therefore to some degree self-contained and written as a series of papers. Chapter 4 has already been published as a paper (see Appendix B), and it is hoped that some of the other case studies may also be eventually condensed and published.

1.2. Methods and rationale of the study

This study was primarily field based, and the most important procedure invariably centred around the logging of surface exposures and borehole cores. This 'first-hand' data was supplemented by details of successions encountered in boreholes, the cores of which had been discarded, but the measured sections lodged with the B.G.S. (British

Geological Survey). First-hand sedimentary logging was accompanied by sampling, and the samples formed the basis of a variety of analyses, techniques and laboratory based investigations summarised in Fig. 1.1. Although laboratory based study provided a great deal of 'back-up' information concerning the logged sequences, facies analysis of the rocks was the most important 'technique' that was utilised. This involved the logging and interpretation of a sequence and the recognition of marker horizons which could be identified elsewhere at other localities. The most useful marker horizons used were marine bands, and the correlation of these allowed facies reconstructions of the intervening clastic rocks. The correlation of marine horizons and the comparison of the intercalated fluvio-deltaic facies was the basic approach used in this study, providing a great deal of information concerning sedimentary environments, tectonics, stratigraphy and marine transgressions. In the Pathhead Beds and Lower Limestone Group, where marine limestones and shales are common, this provided no problem, but in the underlying Oil-Shale Group, where marine facies are rare, lithologically distinctive markers such as stromatolitic-mudflat dolostones had to be used.

1.3. Implications of previous research

Although there is a great deal of literature relating to particular aspects of the sedimentary sequences in the late Dinantian succession of Fife and the Lothians, very little work has been published on facies analysis and environmental reconstructions. As a consequence, the tectonic and sedimentary controls upon late Dinantian sedimentation are poorly understood, as compared with facies of similar age in the Northumberland Basin (see Leeder 1973, 1974a, 1974b, 1976). Recent work on the late Dinantian rocks of Fife and the Lothians (e.g. Cater 1987; Maddox and Andrews 1987), however, has underlined the potential of the area as a location for facies-based work.

CHAPTER 2

STRATIGRAPHY

2.1. Introduction

A lack of diagnostic marine fossils in the pre-Asbian part of the Dinantian succession in the Midland Valley of Scotland has resulted in difficulties in relating parts of the succession to the regional stages of the Dinantian recognised in England (George *et al.* 1976). Therefore, the boundary between the Upper Old Red Sandstone and the Dinantian cannot be satisfactorily delineated, and some of the Upper Old Red Sandstone may belong in the Dinantian. The term 'Devono-Carboniferous' is therefore used for rocks such as those of the Kinnesswood Formation (Browne *et al.* 1986), which straddles the Devonian-Carboniferous boundary, and is therefore of uncertain age.

Another major problem has been the continued resilience of the older informal lithostratigraphic terminology used on geological survey maps (Macgregor 1960), which conflicts with attempts to define formal lithostratigraphical units such as formations (Jameson 1980, 1987; Loftus 1985; Monro 1982a) within informal groups. Recently, however, the lithostratigraphy has been revised and improved, arising from a radical reappraisal by the British Geological Survey (B.G.S.) (Paterson and Hall 1986). The stratigraphy of the Dinantian within the Midland Valley of Scotland is summarised in Fig. 2.1., whilst the general stratigraphy of the Dinantian in relation to absolute dates, major cycles (Ramsbottom 1973) and foraminiferan and coral-brachiopod zones (not generally applicable in the Midland Valley) is summarised in Fig. 2.3.

2.2. Dinantian Subsystem

The term 'Dinantian' has long been used as a series name for rocks of Lower Carboniferous age in Europe, and the term 'Silesian' was proposed as a series name for the Upper Carboniferous in Europe (van Leckwijk 1960). More recently, however, both the Dinantian and Silesian were given the status of subsystems for the lower and upper divisions of the Carboniferous System respectively (George and Wagner 1972, p. 142). Subsequently, the Tournaisian and the Visean, which had hitherto been regarded as stages, became series of the Dinantian Subsystem, but were not subdivided into stages (George *et al.* 1976) (Fig.2.1).

Traditionally, the Dinantian has been zoned using macrofossils, and the fauna and flora have been investigated for over 100 years (Anderton *et al.* 1979). Various biostratigraphical schemes have been erected, using fossil groups such as corals, brachiopods and goniatites. Unlike lithostratigraphical schemes, biozones are generally independent of local facies controls and are therefore geographically widespread, and are generally the only means of correlation between different sedimentary basins. Major problems exist in the Dinantian, however, where facies influences, provincialism and homeomorphy among the shelly macrofaunas (mainly brachiopods and corals) have hindered the potential usefulness of biostratigraphical schemes. These problems are particularly acute in the Midland Valley of Scotland where most of the succession is regarded as non-marine, and fossils such as corals, brachiopods and goniatites are particularly scarce.

2.3. Chronostratigraphical divisions

Recently, George *et al.* (1976) have erected six stage names for chronostratigraphical divisions of the British Dinantian (Figs. 2.1 and 2.3). Only the base of each stage was defined, the top delineated by the base of the overlying stage (Harland *et al.* 1972; Hedberg 1976). The chronostratigraphical divisions have replaced the original system of Vaughan, and other zonal schemes, for use within the British Isles (George *et al.* 1976). The new classification is based upon precisely defined stratotype stages, and has provided a framework for reorganisation of British Dinantian rocks, as a standard for correlation by any convenient means.

The chronostratigraphical stages of the Dinantian are generally recognised by the presence of diagnostic fossils, which are usually marine forms. In the Midland Valley of Scotland, however, there are few if any diagnostic marine fossils below the strata which are equated with the base of the Asbian Stage (George *et al.* 1976).

2.4. Courceyan to Holkerian

The lowest four chronostratigraphical stages cannot be satisfactorily delineated in the Dinantian of the Scottish Midland

Valley, due to an absence of marine fossils. The recently erected miospore zones based on work in the eastern part of the Midland Valley (Neves *et al.* 1973) have, however, been correlated with the new stages (George *et al.* 1976) (Fig. 2.1). Neves *et al.* (1973) placed the CM miospore zone and part of the overlying PU Zone in the Tournaisian, therefore by inference at least some of the Courceyan is present at the base of the Spilmersford Borehole, East Lothian (Davies 1974). The PU Zone is assumed to include rocks of late Courceyan to Holkerian age, but until this zone is subdivided, the completeness of the succession cannot be fully ascertained (George *et al.* 1976). There are two miospore zones below the CM Zone which have not been recognised in the Scottish Midland Valley, and it is likely that they are present in the Upper Old Red Sandstone facies, which the Dinantian conformably overlies. It is probable therefore, that at least part of the traditionally assigned Upper Old Red Sandstone succession belongs to the Dinantian, suggesting the lack of any major facies break across the Devonian-Carboniferous boundary in the Midland Valley.

2.5. Asbian

The Asbian Stage is more readily recognised in the Midland Valley, due to the presence of diagnostic Asbian goniatites in the Cove Lower Marine Band near Dunbar, East Lothian (Wilson 1952) and the Pumpherston Shell-Bed (Lower Oil-Shale Group) of West Lothian (Currie 1954). These and other marine bands at approximately the same stratigraphic level have been collectively termed 'the Macgregor Marine Bands' (Wilson 1974), and are considered to lie at the boundary between the TC and NM miospore zones (Fig. 2.1).

The lower part of the Asbian (TC Zone) includes all the strata down to the lavas in the East Lothian Spilmersford Borehole (Davies 1974), all the strata below the Macgregor Marine Bands in East Fife, and almost all the strata below the Pumpherston Shell-Bed down to the Arthur's Seat Volcanic Rocks (Paterson and Hall 1986) in West Lothian (Fig. 2.1). Farther west, in the borehole at Rashiehill, Stirlingshire (Anderson 1963), the upper part of the lavas is of Asbian age, but the precise age of the lower part is uncertain. In the western part of the Midland

Valley, the base of the Asbian has yet to be delineated (George *et al.* 1976).

2.6. Brigantian

The Brigantian Stage includes all of the Lower Limestone Group, which is the uppermost lithostratigraphical division in the Midland Valley (Fig. 2.1). The group contains reasonably thick marine limestones and associated calcareous mudrocks, which are intercalated with fluvio-deltaic deposits to form Yoredale-type cycles. The group is known to be of a Brigantian (P_2) age (Currie 1954), due to the presence of occasional diagnostic goniatites (Wilson 1980). The limestones often contain an abundant microfauna and microflora of foraminifera and algae, which are similar to Brigantian assemblages documented by Hallet (1970) from the Yoredale limestones of the north of England. Foraminifera from some of the limestones are characteristic of the V_{3c} biozone in Belgium (Jameson 1980), which lies wholly within the Brigantian (Conil *et al.* 1971). The base of the Brigantian has yet to be delineated in the west of the Midland Valley, but P_1 goniatites are known to occur as low as the Raeburn Shell-Bed (Upper Oil-Shale Group) in West Lothian (Currie 1954). Neves *et al.* (1973) suggested that the base of the VF miospore zone probably corresponds with the base of the Brigantian, which is equated with the horizon of the Lower Longcraig Limestone in East Lothian (George *et al.* 1976).

2.7. Lithostratigraphical divisions

Within the Midland Valley of Scotland, the Dinantian Subsystem (and indeed the whole of the Carboniferous) has been subdivided lithostratigraphically for many years (Macgregor 1930). Each lithostratigraphical division is composed of cycles with generally similar lithological characteristics (see Fig. 2.1).

The lithostratigraphical division of the Dinantian of the Scottish Midland Valley, after modification by Macgregor (1960), corresponds broadly with major North-West European stratigraphical classification (Francis 1983a, p. 254). The chronostratigraphical divisions, however, as proposed by George *et al.* (1976) and amended by Ramsbottom and

Mitchell (1980) have yet to be fully recognised within the Midland Valley (see above), and only the uppermost Brigantian Stage has been satisfactorily delineated (Francis 1983a, p. 279).

The lithostratigraphical division of the Dinantian of the Scottish Midland Valley allows a means of correlation within defined lithostratigraphical units, in a succession of rocks noted for a lack of biostratigraphically useful zone fossils.

The Dinantian succession within the Midland Valley is traditionally subdivided into two major lithostratigraphical units; the Calciferous Sandstone Measures (or Series) below, and the Lower Limestone Group above (Fig. 2.1).

2.8. Calciferous Sandstone Measures

The term 'Calciferous Sandstone Measures' was probably first used by Maclaren (1839). In the original definition, however, it included part of the Upper Old Red Sandstone and the Lower Limestone Group. The Calciferous Sandstone Measures or Series forms the major part of the Dinantian succession within the Scottish Midland Valley. It encompasses all the chronostratigraphical stages of the Dinantian (George *et al.* 1976), the overlying Lower Limestone Group occupying only the uppermost part of the youngest Brigantian Stage (Fig. 2.1). Whereas the top of the Calciferous Sandstone Measures is traditionally drawn at the base of the Hurlet Limestone (and its correlatives), the base is poorly defined. In some places it rests conformably upon red beds, which on facies grounds are assigned to the Upper Old Red Sandstone (Forsyth and Chisholm 1977, p. 9). In many areas, however, the exact position of the boundary is uncertain, due to the similarity of the facies at the top of the Upper Old Red Sandstone and the base of the Calciferous Sandstone Measures.

The Calciferous Sandstone Measures are not uniformly developed throughout the Midland Valley of Scotland and each depositional 'basin' or low (Grayson and Oldham 1987) is characterised by a different style of sedimentation (e.g. the localised Lothian Oil-Shale Group present in the Edinburgh Low (Browne 1986; Loftus 1985)) (Figs. 2.1 and 2.2). Therefore, each basinal succession is characterised by a different internal stratigraphy, as there is no evidence to suggest that each individual lithostratigraphic scheme can be accurately correlated with the others with any degree of confidence.

2.9. Calciferous Sandstone Measures-Lothians

Traditionally, in the Lothians area, and particularly within the so-called Edinburgh Low, the Calciferous Sandstone Measures have been subdivided into a lower Cementstone Group and an upper Oil-Shale Group (Figs. 2.1 and 2.2). This scheme was modified by Wilson (1974), who subdivided the whole succession into a Lower Lothian Group and an Upper Lothian Group (Fig. 2.2). The Lower Lothian Group is equivalent to the Cementstone Group, and most of the overlying Oil-Shale Group, up to the level of the Macgregor Marine Bands (e.g. Pumpherston Shell-Bed) and their stratigraphic equivalents (Wilson 1974). The Upper Lothian Group can be equated with the uppermost part of the Lower Oil-Shale Group, and the whole of the Upper Oil-Shale Group (from the base of the Macgregor Marine Bands to the base of the Lower Limestone Group).

2.10. Calciferous Sandstone Measures-Fife

In parts of central and west Fife, the Calciferous Sandstone Measures is not particularly well known, and is either not subdivided into lithostratigraphic units, or the terminology from the Lothians and East Fife is adopted. In East Fife, however, the measures are divided into informal lithostratigraphical divisions. The Calciferous Sandstone Measures reach a maximum thickness in the south-eastern part of East Fife (over 2000 m), which is comparable to that attained in the West Lothian part of the Edinburgh Low (Forsyth and Chisholm 1977, p.9). The Cementstone Group is not recognised in East Fife, together with marker horizons which are internally useful in the Edinburgh Low (such as the Burdiehouse Limestone Formation (Loftus 1985)). This underlines the non-correlation between lows and therefore reinforces the need for local internal stratigraphies (within individual lows) united within a general stratigraphic framework. Because of the non-correlation with the Edinburgh Low, the traditional tripartite stratigraphical terminology applied there (Cementstone Group, Lower Oil-Shale Group and Upper Oil-Shale Group) (Fig. 2.2) cannot be used in East Fife (Forsyth and Chisholm 1977, p. 10), and the Calciferous Sandstone Measures are mapped as one unit. Four lithostratigraphical divisions, however, which are unique to East Fife have been recognized in the Anstruther-Pathead coast section and the Anstruther Borehole (Fig.2.2). A fifth East Fife division, thought to lie below the other four has been pieced together from coastal sections around Fife Ness, where it is regarded as passing down into the Upper Old Red Sandstone. These lithostratigraphical divisions (Fife Ness Beds, Anstruther Beds, Pittenweem Beds, Sandy Craig Beds and the youngest Pathhead Beds) have recently been given the status of formations (Browne 1986) within a formal Strathclyde Group (Paterson and Hall 1986). Approximately 2000 m of sedimentary rocks of Calciferous Sandstone Measure age are present in East Fife, and this is contrasted with the situation approximately 40 km to the west in the tectonically positive Lomond Hills (Glenrothes area of central Fife), where the succession is only 30 m thick (see chapter 7) (Browne 1980, p.326; Browne *et al.* 1986).

2.11. Calciferous Sandstone Measures-central and western Midland Valley

In the central and western parts of the Midland Valley of Scotland, the Calciferous Sandstone Measures are traditionally divided into three lithostratigraphical units, comprising a Lower Sedimentary Group, the volcanic rocks of the Clyde Plateau, and a younger Upper Sedimentary Group (Macgregor 1930, p. 490; Francis 1965, p. 312) (Fig. 2.2). The Lower Sedimentary Group consists of rocks known as the Cementstone Group (Belt *et al.* 1967). Recently, the volcanic rocks of the Clyde Plateau have been assigned to the Clyde Plateau Volcanic Formation, and the rocks of the Upper Sedimentary Group to the Kirkwood Formation (Monro 1982a, 1984). The rocks of the Upper Sedimentary Group probably belong to the Strathclyde Group, and the Lower Sedimentary Group must belong to the Inverclyde Group of the Paterson and Hall (1986) classification. Therefore, the volcanic rocks of the Clyde Plateau Volcanic Formation probably belong in part to the top of the lower group and the bottom of the upper group.

It is, unfortunately, very difficult to even begin to correlate the much thinner succession of the west of Scotland with that in the east. The west of Scotland was subjected to a massive amount of volcanism, and for much of the Dinantian experienced erosion as opposed to deposition.

2.12. Biostratigraphical divisions

The only way in which the lithostratigraphical scheme in the Dinantian succession of the Midland Valley can be reconciled with the chronostratigraphy is by the recognition of diagnostic fossils or fossil assemblages which are known to be indicative of particular chronostratigraphical stages (George *et al.* 1976) (Fig. 2.1). Because the Dinantian succession prior to the Brigantian Stage is largely non-marine, it has been very difficult to relate the lower lithostratigraphic divisions to the regional chronostratigraphical stages. Internally, within the Midland Valley, the bulk of the Dinantian is zoned using non-marine bivalves (Browne 1986) and miospores. It is only in the Asbian that thin marine bands yielding goniatites allow a goniatite biozonation to be established. In the biostratigraphic study of the Scottish Dinantian succession, fossils have two purposes. One is to relate the lithostratigraphy of the area to the regional stages, therefore aiding correlation with successions outside the Midland Valley. The other is to provide an internal biozonation to aid broad correlation within the basin as a whole.

2.13. Miospore biozonation

The bulk of the pre-Lower Limestone Group strata within the Midland Valley of Scotland is believed to be of a non-marine origin (Neves *et al.* 1973, p. 4). These rocks are difficult to correlate lithostratigraphically throughout the Midland Valley because they exhibit wide variations in thickness and facies. Therefore, within the lower and middle parts of the Dinantian succession the most useful method of correlation is the biozonal scheme based on miospores (Neves *et al.* 1972; Neves *et al.* 1973). Miospores are considered to be stratigraphically significant within the Dinantian of the Midland Valley (Neves *et al.* 1973, p. 4) and five concurrent range zones have been recognized (Fig. 2.1).

Although the miospore zonation is most useful within the Midland Valley Dinantian succession, where many recognised Dinantian fossils do not occur, there are problems in correlating the miospore zones with the established faunal biozones recognised elsewhere. The miospore biozonation, however, provides a method of correlation within a succession of rocks which are notable for a lack of stratigraphically useful macrofossils. The miospore zones have also been established in the adjacent Northumberland Trough, thereby providing a means of correlation between the two areas. The great value of miospore zonation lies in its applicability in areas where stratigraphically useful marine fossils do not occur in any abundance (George *et al.* 1976, p. 3).

2.14. Bivalve biozonation

Non-marine bivalves are quite common throughout the Dinantian succession in the Midland Valley, but are particularly abundant in parts of the Calciferous Sandstone Measures (Bennison 1960, 1961). It is interesting to note that some of the genera (e.g. *Naiadites* and *Carbonicola*) which became dominant elsewhere much later in the Carboniferous, are first recorded within these rocks. The potential for bivalve biozonation of the Dinantian appears to have first been realised by Wilson (1961) in the Lothians area. Wilson (1961) recognised a significant change in the non-marine bivalve faunas above the Pumpherston Shell-Bed (marine band), where *Naiadites* is replaced by *Curvirimula*. There are many instances in the field, however, where *Naiadites* is present above the Pumpherston Shell-Bed. This has led to a revision by Browne (1986, p. 424) where the changeover from *Naiadites* to *Curvirimula* is drawn at the Burdiehouse Limestone Formation (cf. Loftus 1985), which is the traditional boundary between the Lower and Upper Oil-Shale groups (Fig. 2.1). Four non-marine bivalve zones are recognised (Browne 1986, Fig. 2., p.423). These are; the oldest *Modiolus* Zone, the *Paracarbonicola* Zone, the *Naiadites* Zone, and the youngest *Curvirimula* Zone (Fig. 2.1). The vertical distribution of non-marine bivalves was first deduced from the study of borehole specimens. These bivalve zones are only useful for correlation within the Midland Valley, and are not of value for correlating the Midland Valley succession with that elsewhere. They provide a crude guide, however, to the age of the rocks in which they occur, but their ranges are of much too broad a nature to be useful in 'bed by bed' correlations. In this respect they are similar to all of the other biozones.

2.15. Goniatite biozonation

Goniatites, which offer the potential of a reasonably precise biozonation, are rare within the Dinantian succession of the Midland Valley of Scotland (Currie 1954). They are confined largely to the Lower Limestone Group at the top of the succession (cf. Wilson 1980), although occasional specimens have been recovered from thin Asbian Stage marine bands within the lower, largely non-marine part of the Calciferous Sandstone Measures. The uppermost two goniatite zones of the Dinantian (P_1 and P_2) have been approximately demarcated, and the underlying B_1 and B_2 zones are hesitatingly recognized, but the zonational scheme breaks down below the middle Asbian Stage Pumpherston Shell-Bed, which lies within the B_1 Zone (Fig. 2.1).

2.16. Foraminiferan biozonation

A comprehensive foraminiferal biozonation has yet to be established within the Dinantian of the Midland Valley of Scotland (Jameson 1980, p. 15). Despite the fact, however, that work on foraminiferal biozonation within the British Dinantian is in its infancy (George *et al.* 1976; Haynes 1981), enough has already been done to show that the biozonation developed in Belgium (Conil *et al.* 1971) (Fig. 2.3) is applicable to the British succession with only minor amendments (George *et al.* 1976). In Britain, the stratigraphical potential of foraminifera was first realised by Cummings (1955, 1956), 1957 and further work resulted in the recognition of a sequence of foraminiferan assemblages (F.A. 1-10), ranging from the Tournaisian Series to the lower part of the Silesian Subsystem (Namurian) (Cummings 1961, p. 108).

Unfortunately, foraminiferal biozonation of the Midland Valley Dinantian is likely to be severely limited, as most of the pre-Lower Limestone Group rocks are of a non-marine origin. Jameson (1980, p. 16) has established a V_{3c} foraminiferan date for the Lower Limestone Group Petershill Formation near Bathgate, West Lothian. Jameson (1980, p. 16) states "the foraminiferan date provides the basis on which to correlate the Scottish Dinantian succession with the internationally recognized biozones." It is likely, however, that only the topmost V_{3c} Zone will be present, as foraminifera are largely restricted to the topmost Dinantian Lower Limestone Group, the base of which lies within the V_{3c} Zone.

2.17. Conodont biozonation

Conodonts, like other marine fossils such as goniatites and foraminifera, are largely restricted to the uppermost Dinantian Pathhead Beds and Lower Limestone Group (Clarke 1960). Studies on conodonts have neglected the bulk of the Calciferous Sandstone Measures, largely because this part of the succession is mostly non-marine, with only occasional horizons yielding marine fossils. Some of these marine bands, however, yield conodonts, and recently, one thin marine horizon yielded the first conodont animal to be discovered (Briggs *et al.* 1983; Aldridge *et al.* 1986), something of an irony considering the general non-marine setting of the locality (Cater 1987).

No biostratigraphic scheme, based on conodonts, however, has yet been applied to the Dinantian in the Scottish Midland Valley, although work in progress (Dean pers. comm.) suggests that there may be some potential for biozonation using these fossils.

2.18. Dinantian radiometric chronology

Lambert (1971) has claimed that the absolute chronology of the Carboniferous (and in particular the Dinantian) is better established than that of any other pre-Tertiary system. The base of the Dinantian has been dated at approximately 360 Ma (Fig. 2.3), whilst the top of the Dinantian has been dated at 325 Ma, the latter date being obtained from the Hillhouse Sill, Linlithgow, Midlothian, which was intruded into the topmost Dinantian Lower Limestone Group (Francis and Woodland 1964, p. 229; Fitch, Miller and Williams 1970, p. 781). Radiometric dates within the Dinantian can be related to Dinantian stages, and the majority of dates are from Dinantian igneous rocks (especially volcanics) within the Midland Valley of Scotland.

2.19. Revised lithostratigraphy

Recently, Paterson and Hall (1986) have provided a revised lithostratigraphy of the Dinantian in the Midland Valley, and the term 'Calciferous Sandstone Measures' has now been made redundant. The previous informal lithostratigraphy has now been replaced by the formal scheme, where the Calciferous Sandstone Measures are subdivided into a lower Inverclyde Group (including the Devono-Carboniferous Kinnesswood Formation) and an upper Strathclyde Group (Fig. 2.1).

2.20. Inverclyde Group

This group is equivalent to the Cementstone Group and the top of the Upper Old Red Sandstone succession (Fig. 2.1), thereby overcoming the problem of where to draw the Dinantian-Upper Old Red Sandstone boundary. The top of the group is drawn at the traditional boundary between the Cementstone Group and the overlying Oil-Shale Group (and its lateral equivalents). The Inverclyde Group consists of three formations (Kinnesswood, Ballagan and the youngest Balcomie) (Paterson and Hall 1986).

2.21. Strathclyde Group

The rocks within the Strathclyde Group are laterally variable and although formations have been defined in the type area (Paterson and Hall 1986), local informal lithostratigraphical schemes exist elsewhere. Correlation between local successions is severely hampered, however, due to the lack of common, regionally persistent marker horizons.

In parts of the Lothians (West Lothian and Edinburgh area) and the southern part of central Fife, the base of the Strathclyde Group is drawn at the base of the Arthur's Seat Volcanic Rocks, which is the traditional lower boundary of the Oil-Shale Group (Mitchell and Mykura 1962, p. 43) (Fig. 2.1). The Oil-Shale Group has been formally called the Lothian Oil-Shale Group (Browne 1986, p. 16) as a recent amendment to the scheme used by Paterson and Hall (1986). In East Fife, the Strathclyde Group consists of five formations (Fife Ness, Anstruther, Pittenweem, Sandy Craig and the youngest Pathhead) (Browne 1986) (Fig. 2.2).

2.22. Methods of correlation between localities studied

Because the major chrono-, litho- and biostratigraphic divisions are generally very broad, covering great thicknesses of rock and large amounts of time, the resolution is generally too coarse to be of any value in correlating logged sequences in boreholes and at outcrop. Therefore, the only method of 'bed by bed' correlation is to use lithostratigraphically and/or palaeontologically distinctive marker horizons which transgress local facies variations in, for example, deltaic sandstones (cf. Maddox and Andrews 1987).

In the pre-Brigantian succession, however, good marker horizons are scarce, although rare marine bands are useful (Wilson 1974), as are occasionally widespread (basin-wide) non-marine limestones (Loftus 1984, 1985, 1986). In the Brigantian Yoredale-type cycles the situation is vastly improved and major marine horizons and coals are often well developed. These are used to correlate geographically separated sequences (Wilson 1966), but many of the markers are not in themselves particularly distinctive, depending on recognition largely by virtue of their respective positions within the various successions.

CHAPTER 3

Introduction to chapters on the Oil-Shale Group; a review of Asbian sedimentation in the eastern part of the Midland Valley of Scotland

3.1. Introduction

This chapter aims to provide background information for chapters 4 and 5 which centre on Lower and Upper Oil-Shale group case studies.

The Oil-Shale Group is an informal lithostratigraphic term applied to a 2000-metre thick Dinantian succession which crops out at the eastern end of the Midland Valley of Scotland (Figs.3.1. and 3.2.) (Francis 1983a). The group is thought to fall largely within the Asbian Stage of the Dinantian Subsytem (George *et al.* 1976), although confirmatory palaeontological evidence to support this is lacking. The Oil-Shale Group is mainly exposed on the southern shore of the Firth of Forth in West Lothian and Midlothian, and on the northern shore of the Firth of Forth, in the southern part of central Fife (Fig.3.1.). The geographical restriction of the Oil-Shale Group does not appear to be an artefact of the restricted outcrop, as a similar geographic distribution pattern has been obtained from a large amount of subsurface data. The term 'Oil-Shale Group' has been in use for many years (George *et al.* 1976), and is derived from the distinctive beds of oil-shale which are particularly common in the upper part of the group (Upper Oil-Shale Group), yet constitute a mere 2-3% of the total succession (Greensmith 1962; Loftus 1984).

The Oil-Shale Group is largely known from subsurface data gathered during geological investigations serving the now defunct Scottish oil-shale industry which thrived towards the end of the nineteenth and the early part of the twentieth century (Conacher in Carruthers *et al.* 1927; Hallet *et al.* 1985). Surface exposures are largely limited to the southern and northern shores of the Firth of Forth, although a few overgrown inland exposures are present. Oil-Shale Group outcrops have been studied as a whole in the late 1950's and the early 1960's (Greensmith 1959, 1960, 1961a, 1961b, 1962, 1966), but more recent studies have tended to concentrate on individual horizons (e.g. the Burdiehouse Limestone Formation (Loftus 1984, 1985, 1986)). The Oil-Shale Group is still poorly understood from a modern sedimentological viewpoint, however, and facies-based studies are hampered by a lack of stratigraphic marker horizons. Therefore, the correlation of disjointed and scattered sedimentary rock sequences, especially across the Forth from the poorly understood succession in Fife to the more complete succession in the Lothians, has always been a problem. For example, the freshwater Burdiehouse Limestone has always been used as a marker horizon, but it is neither lithologically nor palaeontologically distinctive (George *et al.* 1976) and some of the correlations made using this horizon as a marker have been questioned (Browne 1986). In the overlying Lower Limestone Group, marine horizons are common, and these can provide good marker bands (Burgess 1965; Wilson 1966), on account of their palaeontological distinctiveness. Unfortunately, marine horizons are rare in the Oil-Shale Group, constituting less than 2% of the total thickness of the succession, and the fauna and flora are predominantly non-marine (Wilson in Mitchell and Mykura 1962). Occasional thin, but areally widespread marine bands do occur, however (Fig.3.3), and these become more numerous towards the top of the group. No single marine band, however, can be traced over an appreciable distance with any degree of confidence. Moreover, the marine horizons are often inconspicuous, lithologically indistinctive and poorly exposed, lying within thick mudrock units which are largely non-marine. The recurring search for suitable marker horizons in the Oil-Shale Group finds a parallel in the largely non-marine Middle Jurassic Great Estuarine Group, where, for example, specific horizons of winnowed lags of worm tubes (Andrews 1986a), and stromatolitic algal limestones (Harris and Hudson 1980) have been traced over significant distances.

Facies analysis and the resulting palaeoenvironmental interpretations are relatively meaningless unless the various scattered outcrops can be correlated, so that environments of deposition can be sensibly reconstructed. In the Oil-Shale Group, where rapid lateral facies and thickness changes are common, especially within fluvio-deltaic sandstones (Kennedy 1943, pp.14-15) these problems are compounded. It is therefore important to be able to identify relative time markers so that the magnitude, extent and importance of facies changes can be properly assessed.

3.2. Oil-Shale Group lithologies

Sandstones constitute between 30-50% (Greensmith 1961) of the total thickness of the Oil-Shale Group succession and are probably the dominant lithology in the group. Despite this, their importance and even their dominating presence is often overlooked by many workers (e.g. Rayner 1981), who invariably stress the importance of the fine-grained rocks such as oil-shales. This oversight has resulted in some gross misinterpretations of the succession, especially by authors reviewing the biased literature.

Sandstones in the Oil-Shale Group often form very thick units exceeding 100 m in thickness (e.g. the Binny Sandstone of the Upper Oil-Shale Group at Philipstoun), which can thin dramatically over relatively short distances (Kennedy 1943, pp.14-15). Petrographically, the dominant types of sandstones are mature quartz-arenites, containing well-rounded quartz grains, which are invariably carbonate, quartz, or kaolinite cemented (Greensmith 1961). Minor amounts of feldspars, micas, heavy minerals (Bosworth 1913; Mackie 1923), and fine-grained structureless detritus are also present, and mudstone, shale and carbonate clasts occur in some sandstones.

The sandstones display a wide range of sedimentary structures. They are sometimes well-bedded, and are often trough and tabular/planar cross-bedded, the cross-beds invariably grouped into cosets which may be separated by reactivation surfaces (cf. Collinson 1970). The bases of the cross-bedded sandstone units are often sharp and erosive, and may be lined with thin conglomeratic layers. Channellised, erosive scour structures ('cut and fills') are also present, and sets of cross-bedding are most commonly developed within medium to very coarse-grained sandstones. Smaller bedforms such as cross-laminae and wave-ripples most commonly occur in medium to fine-grained sandstones, and cross-laminae (e.g. climbing ripples, trough cross-laminae etc.) are often observed alternating with, and passing gradationally upwards into, larger bedforms such as trough and tabular/planar cross-bedding. The foresets of the cross-bedded sandstones predominantly dip towards the SSW or SW (Greensmith 1961), suggesting a NE to SW palaeocurrent direction. Other features of the sandstones include soft sediment deformation structures, and load casts, the latter often developed where sandstones overlie shales.

Although the sandstones are generally unfossiliferous, certain horizons are characterised by abundant drifted plant remains, stigmarian rootlets, and *in situ* rootlets. Despite the obvious lack of body fossils, trace fossils sometimes occur (e.g. McAdam 1986) and bioturbate textures are also occasionally developed. Compared with the overlying Lower Limestone Group, however, trace fossils and bioturbation are rare.

Together with the sandstones, shales and siltstones form almost 90% of the total thickness of the Oil-Shale Group succession. The differences between shales and oil-shales (*sensu-stricto*) are difficult to define and gradational relationships exist in the field between beds of shale and oil-shale. Generally, however, less kerogenous shales are richer in siliciclastic grains or diagenetic carbonates, but the yellow algal bodies so characteristic of the oil-shales may be present, albeit in reduced numbers, and some shales have high total organic carbon (TOC) contents (up to 15%) and are potential source rocks (Parnell 1984). Like the oil-shales, shales and siltstones contain variable amounts of components such as detrital siliciclastics, plant remains, yellow algal bodies, non-specific organic matter, phosphatic fish remains, valves of invertebrate fossils, carbonate minerals and diagenetic replacement minerals. The relative proportions of the components, however, may markedly vary within any one horizon (Parnell 1984).

Oil-shales are defined in economic terms as organic-rich mudrocks (ORM) which on pyrolysis yield petroleum in commercially viable quantities (Fleet 1986). As the commercial viability of oil-shales has varied greatly, however, and will continue to do so, oil-shales are perhaps most satisfactorily defined by the TOC content, which varies between 10-75% in most recognised oil-shale deposits (Fleet 1986). Oil-shales comprise a mere 2-3% of the total thickness of the Oil-Shale Group, and are commonest within the Upper Oil-Shale Group and the upper part of the Lower Oil-Shale Group (Cameron and McAdam 1978). The oil-shales are typically minutely laminated, fine-grained, tough and sometimes flexible. They are dark brown to black in colour, and a characteristic feature of an oil-shale with a high TOC content is a rich brown coloured streak (MacGregor 1973; Cameron and McAdam 1978). Individual oil-shale horizons vary in thickness from several centimetres to several metres and commonly pass upward into decreasingly kerogenous shales, and are known to grade laterally into other lithologies. A good example of this is the Two Foot Coal horizon (Upper Oil-Shale Group), which varies through coal, shaly coal, bituminous shale and oil-shale (Parnell 1984). Fossil trees have also been reported in life position within the Fraser Oil-Shale (Upper Oil-Shale Group) (Cadell 1925). The oil-shales (*sensu-stricto*) have TOC contents of up to 30% and atomic H/C ratios ranging from 1.5 to 2.0 (Parnell 1984). Several oil-shales, however, are represented at some localities by shales with a very low TOC content (a few per cent). As the TOC content of most recognised oil-shales varies between 10-75% these shales are not oil-shales (*sensu-stricto*).

The oil-shales in the Oil-Shale Group have a bituminous groundmass, which is believed to be a decomposition product of algae (Parnell 1984). Other components of the oil-shales include detrital siliciclastics, plant remains, yellow algal bodies, phosphatic fish remains and coprolites, carbonate minerals, pyrite and framboidal pyrite (Love 1958), and diagenetic replacement minerals. Ultraviolet fluorescence microscopy has allowed the recognition of a wide range of liptinite macerals in the oil-shales, the dominant type of which is alginite. This is derived from algal precursors and is divisible into telalginite (derived from large colonial or thick-walled unicellular algae), and lamalginite (possessing a lamellar form normal to bedding). The oil-shales contain abundant lamalginite, and sparse to common telalginite, vitrinite and inertinite.

Limestones (including dolostones) form approximately 3% of the total thickness of the Oil-Shale Group (Loftus 1984) and are predominantly non-marine. A variety of different types of limestone are present, and individual beds are occasionally several metres thick, although in general the thickness is very variable. The grain sizes and textures of the limestones in the Oil-Shale Group are also very variable, ranging from dark coloured micritic mudstones (cf. Dunham 1962) to lighter coloured oolitic and pisolitic (coated grain-rich) grainstones and packstones, which may contain terrigenous siliciclastic quartz grains. Some of the limestones are dolomitised (often due to early diagenetic dolomitisation), and many contain abundant ostracodes, spirorbids, fish remains, worm tubes, bivalves (*Naiadites* and *Curvirimula*) and cyanobacterial filament moulds. Thin kerogenous layers are also common within the finer-grained micritic limestones, and desiccation cracks are present in some beds (Parnell 1984; Loftus 1984; Maddox 1986; Maddox and Andrews 1987). Stromatolites have also been identified at several horizons in the Oil-Shale Group (Greensmith 1959; Parnell 1983; Loftus 1984; Rex and Scott 1987; Maddox and Andrews 1987), associated with features indicative of carbonate mudflat facies. Within the Oil-Shale Group it is apparent that non-marine limestones and shales are closely related stratigraphically, and some limestones contain thin kergenous layers indistinguishable from laminae in the oil-shales. Oil-Shale Group limestones often grade from beds of almost pure carbonate into beds of calcareous siltstone (e.g. Barracks Limestone of the Upper Oil-Shale Group), and limestones also commonly thicken towards the margins of the postulated Oil-Shale Group depositional basin (Parnell 1984; Loftus 1985).

Subordinate lithologies developed in the Oil-Shale Group include a variety of paleosols (e.g. coals, seat-earths and ganisters), volcaniclastics and ironstones. Coal seams are relatively rare, however, comprising an insignificantly small percentage of the total thickness of the succession (Greensmith 1962), and are generally not associated with oil-shales, the seams that do occur being of poor quality and varying between 0.3-1.5 m in thickness. The thicker coal seams, however, are invariably split into separate smaller seams by thin seat-earths (paleosols) and cannel coals. Coals and seat-earths overlying siltstones or silty shales are often impersistent, and are replaced laterally by sandstones (Greensmith 1962, p.359). Very thin (approximately 5 cm thick) coal lenses do occur, however, within limestones (particularly the Burdiehouse Limestone) at several localities (Parnell 1984).

3.3. Oil-Shale Group rhythmic or cyclic sedimentation (see Fig.3.4)

The concept of cyclic or rhythmic sedimentation involves the detection of a series of lithological elements (for example, shale, siltstone, sandstone, coal) repeated through a succession (Duff *et al.* 1967). Once such cyclic sedimentation is thought to have been recognised, it is common practice to define an 'ideal' cycle, which is supposed to represent the ordered group of lithologies which most commonly recur through a succession. In reality, the relative proportions of each lithology vary geographically, so that, as demonstrated by Duff and Walton (1962), there is no such thing as an ideal cycle. Despite this, the concept forms the basis for lithostratigraphical division and correlation throughout much of the Dinantian (and indeed the whole of the Carboniferous) of the Midland Valley of Scotland, and is thus of continuing practical value (Francis 1983a). Although there have been arguments as to the exact definition of the terms 'rhythmic' and 'cyclic', it is generally agreed that these terms are synonymous, and generally refer to the asymmetrical (ABCABC) rhythm or cycle (Duff *et al.* 1967).

Due to the inherent subjectivity involved in the definition of cycles (and particularly ideal cycles), the validity and usefulness of the concept has been questioned. It does, however, enable generalisations to be made about sedimentary sequences, which may form part of the basis for genetic interpretation. Statistical techniques which allow an objective analysis of the arrangement of lithologies in sequences composed of alternating rock types (Selley 1970) can be used, and these determine the number of lithological transitions which occur more often than expected if the beds were randomly arranged. This enables facies relationship diagrams to be constructed, which are essentially similar to objectively defined 'ideal' cycles.

Whatever the merits of the concept of cyclic sedimentation, the idea appears to have been (and still is) a resilient one, especially with respect to the Oil-Shale Group. Richey (1937) appears to have been the first geologist to define a complete Oil-Shale Group cycle of sedimentation, although he stressed that "the majority of the rhythmic sequences contain only a portion of the full cycle." Subsequently, at least 5 other 'ideal' cycles, and some partial (incomplete) cycles (Greensmith 1962) have been published in the geological literature. There are, however, even arguments as to whether the published cycles are essentially similar, or dissimilar, the latter case suggesting that the cyclicity is not well developed (Duff *et al.* 1967). Another point of contention has arisen as to what point in a cycle the base should be drawn. In Yoredale-type cycles, which have been well documented (Leeder and Strudwick 1987 and references therein), the beginning of a cycle is usually drawn at the base of a marine limestone or shale (Moore 1959), which is usually geographically more widespread than the intercalating fluvio-deltaics. The scarcity of marine horizons in the Oil-Shale Group, however, has meant that the bases of cycles cannot be drawn at such a position. Previous workers have tended therefore to draw the base of an ideal Oil-Shale Group cycle at a coal (Tulloch and Walton 1958; Francis 1965, 1983a), oil-shale (MacGregor 1938), or shale (Richey 1937; Loftus 1985). The paucity, however, of coals and marine limestone/shale horizons in the group has led Greensmith (1962) to define the beginning of a cycle at the base of an erosively-based fluvio-deltaic sandstone. Many of the previously defined Oil-Shale Group cycles, however, are clearly unsatisfactory. Workers drawing the base of the cycle at a coal, have apparently overlooked the scarcity of such horizons in the succession, whilst Greensmith's (1962) cycle, drawn at the erosive base of a sandstone is unsatisfactory, as the coarse siliciclastics invariably display very rapid thickness and facies changes over short distances.

3.4. Oil-Shale Group facies

The rocks of the Oil-Shale Group were deposited as a result of the south-westerly progradation of a large fluvio-deltaic complex, into a largely non-marine basin which was the site of oil-shale deposition (Fig.3.2). The basin or gulf was hemmed in to the west by the extrusion of the Clyde Plateau Lavas, and was only occasionally inundated by marine incursions from the east arising from rises in sea level. The facies resulting from these processes can be clearly outlined and interpreted, and three distinct major facies associations can be documented.

3.4.i. Delta-top facies

The delta-top (delta plain) facies is largely represented by thick sandstone units. These are predominantly trough and/or planar-tabular cross-bedded, representing subaqueous dune/sandwave bedforms which migrated in large distributary channels on the delta-top at high flow stage. Reactivation surfaces punctuating the cosets of cross-bedding, in contrast, appear to have resulted from dune/sandwave modification at low flow stage. Pebble stringers and mudclasts represent lags which accumulated in the channel thalweg. Soft sediment deformation structures are also extremely common within the sandstones, suggesting sedimentary dewatering accentuated in an unstable tectonic setting (cf. Ord *et al.* 1988). Although sandstones predominate in this facies, coals and other types of paleosols are sporadically developed. Mudrocks and siltstones are uncommon, although facies similar to the bay-lagoon type are developed within delta-top interdistributary bay tracts.

One of the principal difficulties in the Oil-Shale Group, revolves around the discrimination of the delta-top interdistributary bays and the bay-lagoon complexes into which the delta was actively prograding. This is accentuated because of the connection via the the delta-front of the delta-top bays with the 'offshore' bay-lagoons in elongate deltas, rendering a positive distinction difficult. Major delta abandonment heralded the return of the bay-lagoon facies and the repeated progradation and abandonment of the deltas resulted in recurrent groups of facies constituting cycles of sedimentation (Duff *et al.* 1967).

3.4.ii. Prodelta/delta-front facies

The Prodelta/delta-front facies marks the transition from the bay-lagoon facies to the delta-top facies, and represents the various stages of progradation of deltas into the basin. The facies is characterised by a coarsening-upward sequence from mudrocks containing siderite nodules to interbedded mudrocks, siltstones and sandstones which are overlain by the thick sandstone units of the delta-top facies. The sandstones in the interbedded units are often sharply-based and load-casted, containing abundant plant debris and representing rapid, river-generated sand incursions at the delta-front, possibly within mouth-bar complexes. This type of facies is occasionally poorly developed, apparently due to deltas prograding onto exposed supralittoral carbonate mudflats. In such cases, the gradational coarsening-upward sequence is absent, replaced by an upward transition from wave-rippled sandstones, some of which contain reworked carbonate mudclasts and mud flasers, to thick sandstones which are often trough cross-bedded. These two variations are interpreted as representing deltas prograding into deeper and shallower water 'basins' respectively. From independent fossil evidence, the salinity of the water into which the sands prograded appears to have been fresh to brackish (cf. Stanley and Surdam 1978; Eager *et al.* 1985), with periodically higher salinities only established during rare marine incursions.

3.4. iii. Bay-lagoon facies

The bay-lagoon facies was developed in a basin or gulf which was predominantly non-marine, and starved of coarse siliciclastic sediment for long periods of time. Mudrocks predominate, and oil-shales are developed as a subordinate lithology. The oil-shales (*sensu-stricto*) are essentially organic rich mudrocks (ORM) containing alginite and bituminous anastomosing streaks derived from the decomposition of algal precursors. Alginite is divisible into telalginite (derived from large colonial or thick-walled unicellular algae such as the Recent *Botryococcus*), and lamalginite (possessing a lamellar form normal to bedding). The Lothian oil-shales predominantly contain lamalginite with sparse to abundant telalginite. The presence of large, delicately preserved floral fronds and early diagenetic framboidal pyrite suggests that conditions necessary for the preservation of large amounts of organic matter, such as low-energy anoxic/reducing environments were periodically attained within the muddy substrates. This is further supported by the finely laminated nature of the oil-shales, the preservation of which indicates an environment lacking water circulation and thus oxygen, therefore inhibiting the activities of burrowing organisms. Incipient desiccation cracks within mudrocks and the presence of early diagenetic dolomites suggests periodic desiccation events in a shallow water tract (Maddox and Andrews 1987), and these events are often associated with oolitic and pisolitic grainstones (indicating increases in energy), desiccation breccias, and the colonisation of mudflats by stromatolitic algal mats. The fossil fauna within the rocks of this facies consists of paleoniscoid fish, ostracodes, non-marine bivalves (e.g. *Naiadites* and *Curvirimula*), gastropods, problematical worm tubes, sponges, spirorbid worms, algae, conchostracans (*Euestheria* sp.), and assemblages of these fossils are often monotypic, a feature characteristic of low salinities (cf. Hudson 1980).

The bay-lagoon facies contains rare marine bands, suggesting that salinities were periodically raised during brief but widespread marine incursions. In the east, brachiopod-coral faunal assemblages are present, degenerating into more restricted assemblages of cephalopods and bivalves when traced west into the Oil-Shale Group basin, suggesting a decrease in salinity to the west, and open marine conditions towards the east (Fig.3.3) (Wilson 1974).

3.5. Salinity controlled fossil assemblages; Oil-Shale Group

With the exception of rare, but areally widespread marine bands, the Oil-Shale Group is dominated by a non-marine fauna of ostracodes, fish remains, bivalves, gastropods, sponges, conchostracans, spirorbid worm tubes and occasional rarer faunal elements such as scorpions, arachnids and other terrestrial fossils (Wood *et al.* 1985), together with a flora of algae and the remains of higher plants (Wilson in Mitchell and Mykura 1962). As in other well documented non-marine successions, the Oil-Shale Group faunas are typically facies dependent, and occur in high absolute numbers but with low faunal diversity (Maddox and Andrews 1987). A good example of this is the presence of monotypic shell beds composed solely of the bivalves *Naiadites* and *Curvirimula*. Collectively, the Oil-Shale Group fossils are considered to be indicative of brackish to freshwater salinities (abnormal salinities)

(Belt 1975), and generally comply with 4 criteria applied to brackish water fossil assemblages (Hiltermann 1949; Schmidt 1951; Hudson 1963). These criteria include the absence of stenohaline marine fossil organisms, the presence of euryhaline fossils (e.g. bivalves, gastropods, and ostracodes which dominate the hard shelled microfauna), and conditions favourable for the development of brackish water tracts.

The Middle Jurassic Great Estuarine Group (Hudson 1980) is arguably the best documented non-marine/lagoonal succession containing fossil assemblages interpreted as being salinity controlled (Hudson 1963; 1980). Although marine and restricted marine facies and faunas are known within the group, it is dominated by a largely brackish to freshwater fauna of bivalves, ostracodes, conchostracans (branchiopods) and fish remains. Algae are also common, and sometimes form spectacular stromatolites traceable over significant distances (Hudson 1970). In recent work on the Oil-Shale Group (Maddox and Andrews 1987), references have been made to the similarity of facies and faunas in the Great Estuarine and Oil-Shale groups, and this comparison is preferred to those made between the Oil-Shale Group and ancient lake successions (e.g. Green River Formation, U.S.A. (Bradley 1970; Surdam and Stanley 1979)) by previous workers (Parnell 1984; Loftus 1985). Although some of the lacustrine-type facies developed in the Oil-Shale Group bear a close resemblance to Green River Formation facies (e.g. oil-shales), it is clear that there was marine influence during the deposition of the former, supported by the presence of thin marine bands, suggesting a coastal setting as opposed to an inland, land-locked lacustrine basin (as is the case with the Green River Formation).

The non-marine fauna of the Oil-Shale Group can also be compared to the non-marine fauna of the Coal Measure interdistributary bays where bivalve genera such as *Naiadites* and *Carbonicola* occur with ostracodes, spirorbids, conchostracans, drifted plant remains and occasional cyanobacterial filament moulds (Pollard and Wiseman 1971). Carbonates of any kind, however, are quite rare in such coal-bearing settings, which are usually clastic dominated, although non-marine limestones have been described from the English Upper Coal Measures (Pollard and Wiseman

1971), coal-bearing sequences in Novia Scotia (Duff and Walton 1971), and the Pennsylvanian of the Central Appalachians (Donaldson 1974). Coal Measure bay sequences do not usually contain oil-shales, and are often characterised instead by well-developed coarsening-upwards sequences culminating in a paleosol (seat-earth, ganister, coal) facies (Elliot 1974b).

Ostracodes, which are perhaps the single most abundant faunal element in the Oil-Shale Group are taxonomically restricted in diversity (Loftus 1985), despite occuring in numerical abundance. Characteristic genera include *Paraparchites*, *Cavellina*, *Carbonita* and *Glyptopleura*, which are often collectively interpreted as indicators of brackish water (Robinson 1978). This assemblage of ostracode genera, however, is also commonly found in carbonaceous and ferruginous mudrocks, where species diversity is low, but the number of individuals high.

3.6. Conclusions

The Oil-shale Group represents a distinctive phase of largely non-marine sedimentation in the Asbian and early Brigantian of parts of central Fife and the Lothians. The Midland Valley of Scotland (Midland Valley Basin) was the last known major area of Dinantian sedimentation to be affected by the widespread marine conditions characteristic of much of the Lower Carboniferous elsewhere in Britain. During the Brigantian, however, major marine transgressions began to penetrate the area, and Yoredale-type cycles were developed as a consequence of the interaction between the fluvio-deltaic complex already established in the eastern part of the basin, and the newly created, widespread shallow marine conditions. The acme of marine influence was reached in the Brigantian Lower Limestone Group (see Chapters 10-13), but initially the interactions between deltas and marine incursions resulted in the deposition of a series of rocks known in East Fife as the Pathhead Beds (see Chapters 7-9) (Forsyth and Chisholm 1977). These beds succeed the largely non-marine facies of the Oil-Shale Group and its lateral equivalents.

CHAPTER 4

Lithofacies and stratigraphy of a Dinantian non-marine dolostone from the Lower Oil-Shale Group of Fife and West Lothian

4.1. Introduction

Oscillations between shallow-marine conditions and fluvially-derived deltaic facies (see Leeder 1982 for discussion on the definition of facies), or brackish-freshwater lagoons leave behind a series of identifiable sediments, sedimentary structures and faunas. In the ancient record each distinctive depositional facies can potentially be assigned to a lithofacies which may be areally extensive, allowing a regional lithostratigraphic correlation, for example the Middle Jurassic Great Estuarine Group (Harris and Hudson 1980) and the Upper Jurassic Purbeck Formation of southern England. The correlation, however, of disjointed and scattered sedimentary rock sequences within mappable formations is a perennial problem which hinders precise correlation. The principal difficulty is that non-marine, or restricted-marine faunas are typically facies dependent, occuring in high absolute numbers but with low faunal diversity. Even potentially useful fossils, for example ostracodes in the Jurassic-Cretaceous Purbeck Formation (Anderson 1971) or spores in the Scottish Dinantian of the Midland Valley (Neves *et al.* 1973) only provide a coarse biostratigraphy with a resolution too poor to allow metre by metre correlations of outcrops. When studying the deposits of delta-dominated clastic shorelines, where rapid lateral facies changes occur in unfossiliferous sandstones these problems are compounded.

It is therefore important to identify other types of relative time markers in rocks where biostratigraphical schemes are untenable. Within the Great Estuarine Group, for example, specific beds such as winnowed lags of worm tubes (Andrews 1986a) or stromatolitic algal limestones (Harris and Hudson 1980) can be traced basin wide providing unique stratigraphic marker horizons for correlation.

In this study a remarkable dolostone horizon is described from deltaic, non-marine, interdistributary bay-lagoon lithofacies of the Dinantian Lower Oil-Shale Group (Strathclyde Group) (Francis 1983a, p.258; Paterson and Hall 1986) of the Burntisland area in Fife, Scotland. On the basis of facies analysis and petrography this dolostone horizon is related to other dolostones exposed in the stratigraphically well constrained outcrops of the Lower Oil-Shale Group in the South Queensferry area of West Lothian.

4.2. Stratigraphy

The Strathclyde Group is laterally variable, and although formations have been defined in the type area (Paterson and Hall 1986), local informal lithostratigraphical schemes exist elsewhere (e.g. Oil-Shale Group). Correlation between the local successions, therefore, is severely limited due to the lack of common, regionally persistent marker horizons.

The Lower Oil-Shale Group is subdivided into six informal lithostratigraphical units, the uppermost of which is the Queensferry Beds (Mitchell and Mykura 1962, p.43). Within the Queensferry Beds the laterally persistent marker horizon of the marine Pumpherston Shell-Bed is used to correlate geographically separated rock sequences. The sequence of rocks between the top of the Pumpherston Shell-Bed and the base of the Burdiehouse Limestone is the subject of this chapter, and it is within this sequence that the dolostone unit is located. The stratigraphy is summarised in Fig.2.1.

4.3. Localities

Three Lower Oil-Shale Group outcrops were examined in this study, one in Fife and two in West Lothian. In the Burntisland district of Fife, rocks of the Oil-Shale Group are brought to the surface in the centre of the Burntisland Anticline (Francis 1961a). The rocks examined crop out on the northern shore of the Firth of Forth, at Colinswell [NT 221 860]; north-west of Ross Point, Burntisland. The West Lothian localities crop out in the vicinity of South Queensferry, where part of the Oil-Shale Group succession is repeated within a series of broad folds. The first locality is exposed on the foreshore east of the Forth Railway Bridge in a small rocky bluff, west of Long Craig Pier [NT 140 785]. The second locality is exposed on the foreshore west of the Forth Road Bridge, approximately 500 m west of Society to the NE of Hopetoun House [NS 093 793].

4.4. Description of the Colinswell sequence, Burntisland; field description

The lowest rocks in the Colinswell sequence are thinly-bedded silty sandstones. These rapidly coarsen-upward into approximately 7 m of medium to coarse-grained quartz-arenitic sandstones which are locally pebbly, and dominantly cross-bedded (Fig. 4.1). Sets of tabular cross-bedding with foreset dips up to 11 degrees orientated in a SW direction are commonly grouped into cosets. The sets are bounded by low-angle, non-erosive, planar surfaces. The sandstones are locally ripple cross-laminated, micaceous, and are punctuated by thin silty-mudstone beds and carbonaceous layers. The sandstones are unfossiliferous except for coalified plant remains, and evidence of bioturbation is sparse except within the uppermost beds.

The sandstones pass upward into a 1 m thick fissile shale (Fig.4.1). The shale contains articulated and disarticulated fish remains, paraparchitid ostracodes (Latham 1932), the bivalve *Naiadites obesus* (R. Etheridge jun.), carbonaceous and pyritised plant remains including *Lepidostrobus* sp., yellow algal bodies of the *Pila*-type and coprolites.

The shale is succeeded by a 2.2 m thick dolostone unit (Fig.4.1). The basal dolostone contains desiccation cracks and millimetre scale intraclasts and is intercalated with shaly layers. The main dolostone unit is divisible into two sub-units. The basal 1.2 m is a yellow-weathering massive carbonate. The lower half of this sub-unit is strongly laminated on a 2-3 mm scale. The lamination is generally planar to gently undulose but is in places cut by 'pockets' of intraclastic breccia up to 14 cm deep and 26 cm wide (Fig.4.2A). Where these pockets occur, upper laminated layers drape over the irregular topography of the intraclasts. In one horizon the laminated carbonate contains small folds and overturned layers.

The upper half of the sub-unit is partly laminated and oolitically coated grains are common in some laminae. One prominent horizon is a creamy coloured calcilutite with strongly contorted laminae. This layer is overlain by a prominent intraclastic conglomerate. The clasts are mainly irregular chips less than 5 cm long with internal laminae well preserved. The upper bed of the sub-unit is again laminated, with laminae draped over and re-cementing intraclastic chips (a feature noted by Geikie (1900)) producing an irregular bedding surface.

A 10 cm thick sandstone bed separates the lower sub-unit from the upper sub-unit, which is a 60 cm thick sandy dolostone containing oolitically coated grains and rounded dolostone pebbles up to 4 cm in diameter. Some pebbles have oncolite-like coatings and one bedding surface is covered by a flat-pebble conglomerate with clasts up to 9 cm long. The topmost bedding surface contains prominent polygonal desiccation cracks. No macrofossils were found in the dolostone unit.

Two metres of mudstones, shales, ripple laminated sandstones and limestones overlie the dolostone (Fig.4.1). These beds contain fish remains, ostracodes, plant remains and coprolites. The sedimentary sequence is terminated by a massive picrite sill with a transgressive base which has metamorphosed and fractured those beds which abut it. The fractures are filled by a coarsely crystalline carbonate cement.

4.5. Petrography of the dolostone unit

The dolostone was investigated in detail using polished slabs and thin sections stained after the method of Dickson (1965). Polished slabs revealed that the millimetre scale lamination is in places both folded and fractured (Fig.4.2B). Moreover, some groups of laminae form millimetre to centimetre sized domes. Individual laminae within the domes pinch out toward the dome margins over a distance of approximately 2 cm. A few micritic laminae are distinctive in containing wispy-shaped micro-cracks, now filled by a sparry carbonate cement.

Cavities up to 5 cm long and 2 cm high are present between brecciated clasts of laminated dolostone or in troughs between domes. The cavities are commonly filled by two generations of matrix (Fig.4.2B). The first is a mid-grey coloured micrite with abundant oolitically coated grains. The upper surface of this matrix is planar-horizontal and overlain by a second generation of matrix, which is a buff-cream coloured micrite containing no allochems. Any remaining pore-space in the rock (less than 5%) was filled by fracture-fed kaolinite and sparry carbonate cements respectively

Stained thin sections and microprobe analysis of polished thin sections confirm that the rock is composed of ferroan dolomite. The micritic fabrics have average molar Mg/Ca ratios of approximately 0.73 and average molar Fe/Mg ratios of approximately 0.17. The micrites also contain 2000 ppm Mn and 1000 ppm Si. Fracture filling spar cements have Fe/Mg ratios of approximately 0.37 and 4000 ppm Mn which indicate ankeritic composition. Patches of micrite, laminated carbonate and allochem margins usually possess a dull orange-brown coating of goethite.

In thin section the millimetre scale lamination is composed of 100μm thick sub-laminae. The sub-laminae fabrics range from massive textured dolomicrites, through clotted textured peloidal dolomicrites to dolomicrosparites. Some micritic layers contain vertical tubular structures up to 100μm long and 20μm wide (Fig.4.3A) filled with ankerite spar cements. Other layers contain distinctive micro column-dome structures up to 300μm high and 10μm wide (Fig.4.3B). Where the laminated fabrics have been folded and fractured the cavities are infilled by coated grain-rich wackestone-packstone material. In thin section the strongly contorted calcilutite horizon is composed of a massive textured dolomicrite containing tear fractures associated with the folding. Some intercalated laminae within this horizon are almost entirely composed of smooth margined rod-ovoid shaped faecal pellets, typically 0.5-1.0 mm long.

In brecciated dolostone specimens some of the micritic dolostone intraclasts preserve the laminated texture described above (Fig.4.3C). Clast shapes range from rounded to angular and some display a crinkly textured micritic-microsparitic laminated coating up to 500μm thick (Fig.4.3D). Microsparite laminae are commonly seen draped over and cementing micritic intraclasts (Fig.4.3E). In the upper sandy dolostone beds packstone fabrics are common with allochems including rounded intraclasts, micritic oncolites (*Ortonella* sp. and other cyanobacterial moulds are well preserved) and oolitically coated grains.

Oolitically coated grains are common throughout the dolostone ranging from 0.01-1.0 mm in diameter. Ooid cortices are generally dolomicritic but in some cases a radial texture is preserved (Fig.4.3F). The ooids have not been studied in detail, but their cortical structure appears to be complicated and variable (see also Strasser 1986). Ooid nuclei are generally quartz silt-sand grains or lumps of dolomicrite. Some micritic laminae are composed of compacted ooids and ooid aggregates (grapestones) are quite common. Other allochems include faecal pellets and phosphatic fragments some of which contain endolith borings.

In general the dolostone is dominated by laminated mudstone-wackestone and sandy intraoo-wackestone-packstone fabrics.

4.6. Interpretation of the Colinswell sequence

The overall coarsening-upward trend of the sandstones is interpreted as representing the progradation of proximal mouth-bar sediments. The dominant sedimentary structure in the upper sand-dominated member of the mouth-bar facies is tabular cross-bedding, interpreted as representing straight-crested sandwaves. These migrated at high flow stage in channels confined to the bar-back, and were probably deposited on the bar-crest. These structures and the presence of minor pebbly veneers are indicative of the bar-crest channel environment (Coleman and Wright 1975). Ripple cross-laminated sandstones passing upward into tabular cross-bedded cosets are the result of increasing flow velocities generated during high flow stages. The intercalated siltstones and muddy sandstones probably represent partial deposition from suspension during low flow stages, which alternated with the river-generated sand incursions. The foreset dip direction of many of the cross-beds suggest a south-westerly flowing distributary channel. This is in accordance with many palaeocurrent measurements recorded by Greensmith (1961) from East Fife, central Fife and West Lothian. The distributary mouth-bar is the focus of sand deposition within fluvially-dominated deltaic complexes (Coleman *et al.* 1964) and the high rates of deposition usually preclude bioturbation by burrowing infaunas. Here, the bioturbated bed at the top of the sandstone sequence probably indicates reduced sediment input during mouth-bar abandonment (cf. De Raaf *et al.* 1965; Elliot 1974a, 1976a).

The shale which overlies the sandstones is interpreted as an interdistributary bay mud, deposited from suspended organic matter (Moore 1968a), and fine clastic sediment introduced during distributary overbank flooding (cf. Elliot 1974b). The fossils within the shale are indicative of low salinities and the bivalve *Naiadites obesus* (R. Etheridge jun.) has been interpreted as a brackish water form (Bennison 1962) populating the inner margins of interdistributary bays (Greensmith 1966). The yellow algal bodies of *Pila*-type are similar to the Recent alga *Botryococcus braunii*, which is the principal constituent of resilient sapropelic deposits forming at the surface of ephemeral lakes (Parnell 1984).

The millimetre scale lamination of the lower dolostone sub-unit coupled with macro and micro columnar-dome features, vertical tubular moulds and crinkly textured coatings on intraclasts suggest lamination formed by the trapping, binding and carbonate precipitation activity of cyanobacteria. It is proposed therefore that the dolostone represents a fossil algal stromatolite (see Bathurst 1975, pp.217-30) following Greensmith (1959). Generally the sub-laminae do not contain filament moulds after cyanobacteria and the clotted micritic and microspar fabric is usually referred to as a cryptalgal laminite (Monty 1976).

The brecciation of the dolostone and the preservation of the laminated cryptalgal fabrics within the breccia-derived intraclasts implies that the carbonate sediment was at least coherent prior to brecciation. It is suggested that at least two phases of deformation occured; folding whilst the sediment was coherent and brecciation after some degree of early diagenetic cementation. In general the intraclasts are angular sided flat-pebbles which imply a minimal degree of transportation after dislocation.

In keeping with the interdistributary bay-lagoon environment (above) it is suggested that the brecciation was caused by subaerial exposure and desiccation, an interpretation supported by the local presence of desiccation cracks. The discrete beds of intensely brecciated material intercalated with less disturbed, well-laminated beds suggest that exposure was periodic and at times prolonged. The origin of the breccia pockets which locally cut cryptalgally laminated fabrics is not understood although they appear to be 'pockets' rather than small channel fills or tepees. That the cryptalgal laminites formed domes, draped over, and rebound intraclasts is clear evidence that the brecciation was syndepositional. Micritic laminae with wispy micro-cracks are interpreted as shrinkage pores or birdseyes (Shinn 1983) and are good evidence of periodic supralittoral deposition.

The origin of the folds in the cryptalgal laminites is uncertain. Folded cyanobacterial mats have been reported from Recent tidal flats, e.g. Shark Bay, Western Australia (Davies 1970) where the folding is relatively localised and probably caused by flood tidal surges. Ancient examples of this type of folding exist (Andrews 1986b), however, the folding in the cryptalgal laminites of the Colinswell sequence is on a much larger scale, possibly in response to syndepositional seismic shocks associated with volcanicity or fault movement in the Midland Valley (see also Mayall 1983 and Bartsch-Winkler and Schmoll 1984, fig.11). The contorted calcilutite horizon could represent a cryptalgal structure, but it is more likely the product of soft sediment deformation. The massive dolomicritic fabric of this layer and the association with faecal pellets suggest that the carbonate mud was deposited as a supralittoral storm layer, similar to those described from Recent carbonate muds in South Florida and the Bahamas (Ball *et al.* 1967, pl.9; Shinn *et al.* 1969, fig.21).

The presence of abundant dolomicritic and radial fabric oolitically coated grains in the dolostone probably indicate formation in shallow, gently agitated water, although the dolomitization of the ooids complicates the interpretation of their formation and significance. Micritic and radial fabrics in ooids have been interpreted as both diagenetic and primary features (see Flugel (1982, pp. 145-158) for a review). Where present in these Carboniferous ooids, however, the radial fabric is well preserved which suggests that it may be the remnant of a primary fabric, possibly a former Mg-calcite mineralogy. Oolitically coated grains occur in a variety of marine and non-marine environments and their fabric cannot be used to distinguish between them (Richter 1983). Given the non-marine setting envisaged for the deposition of these rocks it is suggested that these ooids formed in a shallow sub-littoral environment closely associated with the stromatolite (ooids were not found associated with any other beds in the studied sequence).

On the basis of the evidence discussed above it cannot be unequivocally concluded that the cryptalgal laminites were deposited upon supralittoral mudflats, they could have formed in a shallow sublittoral environment, but it is clear that the sediments were subaerially exposed for significant periods of time. It is proposed therefore that a supralittoral setting was the most likely depositional environment.

Above the lower sub-unit of the dolostone the thin sandstone bed probably records a short lived pulse of delta-derived sand which prograded across the cryptalgal laminites. In the upper dolostone, sand grains and carbonate allochems (ooids, rounded intraclasts and oncoids) are mixed and probably represent the reworking of carbonate mudflat material in a shallow sublittoral environment. The upper rippled sandstones, mudstones and limestones in the sequence herald a return to shallow interdistributary bay facies with restricted faunas indicative of low salinity.

4.7. Diagenesis

Staining (cf. Dickson (1965)), microprobe, and cathodoluminescence (C.L.) analysis of dolostone thin sections was undertaken so that the diagenetic history of the sequence (and particularly the dolostone) could be elucidated. The uncovered thin sections stained a turquoise colour, indicative of ferroan dolomite, a diagnosis further supported by x-ray diffraction (X.R.D.) analysis and C.L. The fine preservation of cyanobacterial filament moulds and radial ooid fabrics suggests that the dolomitization may have been early diagenetic, as late-stage, burial dolomitization is often fabric-destructive. Moreover, the dolostone occurs only 1 m below undolomitized limestones. The mechanism of the early diagenetic dolomitization was therefore probably a micro-scale dissolution-reprecipitation process, which took place soon after the deposition of the precursor carbonate (cf. Tucker 1983).

4.8. Early diagenesis

Early diagenetic dolomitization can take place soon after deposition (almost penecontemporaneously) within sediment deposited in perilittoral and supralittoral settings. This type of dolomitization is usually associated with a suite of sedimentary structures indicative of supralittoral environments, such as fenestrae (birdseyes), desiccation cracks, stromatolites, intraclastic desiccation breccias and restricted assemblages of fossils (cf. Matter 1967; Schenk 1969; Muir *et al*. 1980; and papers in Ginsburg (1975)). Recent work on Oil-Shale Group carbonate mudflat facies (Greensmith 1978; Parnell 1984) indicates that early diagenetic dolomitization was a characteristic of mudflats, tens of kilometres wide, and is considered to have been initiated by periodic flooding and subsequent desiccation. The facies-type represented by the Colinswell dolostone in this sequence (i.e. non-marine exposed carbonate mudflats) probably controlled the extent and distribution of dolomitization.

Most penecontemporaneous (including early diagenetic) dolomites can be interpreted by the sabkha model for coastal supratidal dolomite genesis (see Curtis *et al*. 1963; Illing *et al*. 1965), where dolomite is associated with evaporites. This, however, does not explain the occurrences of penecontemporaneous dolomites from non-marine environments in the geological record where evaporites are absent. Dolomite, however, is known to form in alkaline ephemeral lakes of the Coorong region in southern Australia in a relatively humid climate (von der Borch and Lock 1979), associated with a characteristic suite of sedimentary structures and the absence of saline evaporite solids or their pseudomorphs. The Coorong dolomites provide a modern analogue for early diagenetic dolomitisation in the Oil-Shale Group mudflat carbonates, where the conditions appear to have been at least partially humid during a period of transitional climate (Belt 1975). The absence of evaporites in the Oil-Shale Group and the presence of low salinity fossil assemblages suggests that modern analogues for dolomitization should be sought from low salinity settings (e.g. Coorong), which are more applicable than the 'classic' arid sabkha model for dolomite formation.

4.9. The Colinswell sequence; facies summary and significance

In the preceding section, the Colinswell sequence has been interpreted as representing the transition from a fluvially-dominated distributary mouth-bar of a deltaic complex into a low salinity interdistributary bay-lagoon facies. The dolostone, intercalated within the interdistributary bay facies appears to represent a significant period of time during which bay-marginal stromatolitic mudflats prograded into the depositional basin, probably in response to a significant 'regressive event'. It is plausible, given the thickness and distinctive lithology of the Colinswell dolostone that this 'event' was recorded by similar rocks elsewhere within the basin. With this reasoning the well exposed Lower Oil-Shale Group sequences in the Queensferry area of West Lothian were examined in an attempt to locate similar dolostone lithologies.

4.10. The Queensferry Beds of West Lothian; Description

In the Burntisland district of Fife the only unequivocal Lower Oil-Shale stratigraphic marker is the Burntisland Marine Band (Francis 1961a) correlative of the Pumpherston Shell-Bed in West Lothian. The marine band was located in the Burntisland Water Borehole and was taken to be approximately 55 m below the dolostone unit at Colinswell (Francis 1961a, p.13). Hence, any correlative of the Colinswell dolostone in West Lothian should lie some way above the Pumpherston Shell-Bed and below the Burdiehouse Limestone, within the Queensferry Beds of Mitchell and Mykura (1962). These beds crop out at two localities, South Queensferry and Hopetoun (see below).

In general the sequences at South Queensferry and Hopetoun are similar being only 4.5 km apart (see Fig. 4.4). Above the Pumpherston Shell-Bed lie 30-50 m of fissile papery shales (Pumpherston Shales) including two oil-shale seams (Cameron and McAdam 1978). The shales contain fish remains, ostracodes, the bivalve ***Naiadites obesus*** (R. Etheridge jun.), the conchostracan ***Euestheria*** sp., plant remains and coprolites. Centimetre thick concretionary dolostone and siderite beds are intercalated within the shale.

At South Queensferry the shale passes upward into a 1 m thick buff-yellow coloured dolostone which in its upper part is well laminated on a millimetre scale forming irregular shaped hemispherical domes up to 15 cm high and 55 cm in diameter. Other features include desiccation cracks, brecciated laminae with clasts up to 2 cm long, oolitically coated grains, pisoids and synsedimentary folds. At Hopetoun this bed is represented by 10-50 cm thick dolostone layers interbedded with shale. The dolostones contain millimetre scale undulose lamination, breccia pockets (as at Colinswell, see above), flat-pebble conglomerates, oolitically coated grains and pisoids.

At South Queensferry the dolostone is overlain by 24 m of sandstone (here informally named for the first time the Port Neuk Sandstone). The lowest beds are fine-medium grained with an erosive base above the dolostone. Ooids, pisoids, ostracodes and spirorbid worm tubes are present within the sandstones and straight to slightly sinuous crested ripple marks are common with an average ripple index of 6. The lower beds coarsen-upward into very coarse-grained sandstones with metre scale trough cross-bedding orientated NE-SW. Cross-bed cosets are separated by scoured reactivation surfaces and the uppermost beds contain convoluted and folded foresets. The equivalent of the Port Neuk Sandstone at Hopetoun comprises 18 m of coarse to medium-grained sandstones. At the base, trough and tabular cross-bedding occurs with foreset dips toward the SW. Several reactivation surfaces were observed bounding cross-bed cosets and separating different cross-bed types. One bed contains foresets which are folded, the resultant antiforms displaying ruptured crests. The upper 5 m of sandstones are dominated by tabular cross-bedding with non-erosive cross-bed set contacts. Straight to slightly sinuous symmetrical ripple marks are common with an average ripple index of 6 and ripple crests orientated NW-SE. At the base of the uppermost bed a mud-clast lag was observed containing rounded clasts of yellow weathering dolomicrite.

The interval between the Port Neuk Sandstone and Burdiehouse Limestone is represented by mudrocks, and dolostones which contain ooliths, worm tubes and desiccation cracks. At Hopetoun this interval is 26 m thick whilst at South Queensferry only 7 m of rock are exposed. It is not clear whether the attenuated sequence at South Queensferry is a sedimentary thickness or whether some strata have been cut out by faulting.

4.11. Interpretation and discussion

The Pumpherston Shales of the Queensferry Beds contain a low salinity fauna (cf. Belt 1975) and probably represent interdistributary bay-lagoonal facies. The oil-shales within these beds suggest that at times clastic sedimentation effectively ceased and only organic matter accumulated (Moore 1968a; Parnell 1984). The upper beds between the Port Neuk Sandstone and the Burdiehouse Limestone also represent interdistributary bay-lagoonal facies, with the oolitic dolostones interpreted as carbonate packstone sand sheets which were periodically subaerially exposed allowing desiccation cracks to form. These compare well with oolitic packstone 'sheets' in the non-marine, lagoonal, Lonfern Member of the Middle Jurassic Great Estuarine Group (Harris and Hudson 1980).

At South Queensferry the coarse-grained trough cross-bedded Port Neuk Sandstone is interpreted as a delta plain distributary channel facies, the rippled sandstones and upward-coarsening sequence at the base marking a transition from interdistributary bay sand sheets to distributary channel, delta plain deposits. At Hopetoun the trough cross-bedded horizons at the base of the sandstones are again channel deposits, although smaller and with evidence of reworking. The upper sandstones which are planar cross-bedded and wave-rippled probably represent channel abandonment complexes which underwent partial wave reworking (cf. Fisk *et al.* 1954). The average ripple index (6) and gross morphological characteristics of the ripple bedforms at both South Queensferry and Hopetoun are indicative of wave-formed ripples (cf. Harms 1969). The dolostone unit at South Queensferry and Hopetoun is strikingly similar to that described from Colinswell (both in the field and petrographically), the principal difference being that it is thinner, and at Hopetoun intercalated with shaly beds. The domes on the upper surface of the dolostone at South Queensferry are laterally linked hemispheres (LLH domes), characteristic of Recent stromatolites forming in shallow sublittoral to intertidal settings (Logan *et al.* 1964). The unit is interpreted as a shallow-sublittoral to supralittoral stromatolitic mudflat which was periodically brecciated during exposure.

4.12. Correlation of the dolostone units

From the foregoing discussion it is obvious that if the Colinswell dolostone is located between the Burntisland Marine Band and the Burdiehouse Limestone, then it is very probably the lateral equivalent of the dolostone unit at the top of the Pumpherston Shales in West Lothian. If this correlation is correct, then comparison of the measured sections from Fife and West Lothian (Fig.4.5) show that the sandstones which crop out below the dolostone at Colinswell are missing in West Lothian. Given the nature of rapid facies changes in deltaic sandstones (cf. Fisk 1955; Elliot 1975) this would be expected. Clearly the mouth-bar sandstones below the Colinswell dolostone have pinched out and are replaced by interdistributary bay-lagoonal shales in West Lothian. Similarly, above the dolostone at Colinswell, limestones and shales are present whereas in West Lothian the Port Neuk Sandstone crops out. The 'Port Neuk delta lobe', therefore, must have bypassed the Colinswell area at this time.

The thickness variation in the dolostone and slight facies changes are probably a function of position within the depositional basin. The Hopetoun locality is in the basin depocentre (based on the isopach map of Browne *et al.* (1985)) suggesting that stromatolitic mudflats only formed during the most intense 'regressive events'; at other times mud deposition continued un-interrupted. Conversely, the Colinswell sequence is more toward the margin of the basin, where regressive events resulted in prolonged exposure of mudflats and intense brecciation. The South Queensferry locality is in an intermediate position between these end members. Here, a relatively thick mudflat sequence accumulated, similar to that at Colinswell. The LLH-type stromatolitic domes at this locality were probably well preserved and unbrecciated because they were rapidly buried by mud and sandsheets of the advancing 'Port Neuk Delta lobe'.

4.13. Conclusion

The important point of this chapter is that in the absence of biostratigraphical marker horizons certain distinctive lithologies within non-marine sequences may be useful for correlation purposes. In this case a cryptalgally laminated dolostone unit with distinctive breccia horizons was identified at isolated outcrops up to 15 km apart. These lithological sequences were individually interpreted, but palaeogeographical reconstructions were only possible after the importance of an individual isochronous time marker (dolostone horizon) was recognised. The unique lithologies of the dolostone were probably generated basin-wide even toward the basin depocentre, by a geological event, in this case a 'regression' which transgressed local facies changes and established a relative time marker.

CHAPTER 5

Shoreline facies equivalents of oil-shales and the association between volcanism and stromatolites; Upper Oil-Shale Group, central Fife and West Lothian

5.1. Introduction

The Oil-Shale Group has been described as a distinctive 'facies' developed within the Dinantian succession at the eastern end of the Scottish Midland Valley (Greensmith 1962). The only major lithological difference, however, between the Oil-Shale Group and equivalent-aged successions elsewhere in the Midland Valley is the presence of thick mudrock units containing oil-shales (Cameron and McAdam 1978; Fleet 1986), and consequently the geographic boundaries of the group are difficult to define. The lithostratigraphic uniqueness of the group has also been overemphasised, and the importance of mudrocks, and particularly oil-shales has been overestimated at the expense of fluvio-deltaic sandstones which constitute approximately 50% of the total succession (Greensmith 1962). It must be emphasised, however, that the oil-shales were probably deposited over a long period of time as opposed to the sandstones which may have been deposited relatively quickly. Furthermore, despite the insignificant percentage of the total Oil-Shale Group succession occupied by oil-shales, their abundance and thickness when compared with other areas of the Midland Valley of Scotland is a unique and distinguishing feature. The geographic extent of oil-shale horizons also appear to define the former positions of lakes and lagoons developed during high water stands, the shoreline positions of which may be consequently demarcated.

Oil-shales are most common immediately to the west of Edinburgh, where the local Dinantian succession is the thickest in the Midland Valley. Away from this area, the Oil-Shale Group thins rapidly to the north, south and west, concomitant with a decrease in the number and thickness of oil-shale beds. To the west, the group is ultimately replaced by the thick lava flows of the Clyde Plateau Volcanic Formation (Paterson and Hall 1986). To the north-east, the Oil-Shale Group is replaced by an equivalent-aged succession in East Fife (Forsyth and Chisholm 1977), composed largely of fluvio-deltaic deposits which are similar to the rocks of the Oil-Shale Group, except that they only occasionally contain oil-shale horizons (MacGregor 1973, pp.152-53). East of Edinburgh, in East Lothian, oil-shales are only infrequently encountered (Clarkson 1986b, p.145), leading Wilson (1974) to conclude that the term 'Oil-Shale Group' cannot be satisfactorily applied to the equivalent-aged rocks of this area. Little is known of the possible extension of the group to the east under the North Sea, although the Dinantian succession is known to thicken in this direction.

5.2. Rationale

The most northerly outcrop of the Oil-Shale Group occurs in the Burntisland district of central Fife, where rocks of both the Lower and Upper Oil-Shale groups are brought to the surface in the centre of the Burntisland Anticline (Francis 1961a). The Oil-Shale Group in this area is considerably thinner than the succession in the Lothians to the south-west, and the only noteworthy representative of the oil-shales is the 1.83 m thick Dunnet Oil-Shale (Upper Oil-Shale Group) which was formerly worked in the vicinity of Burntisland (MacGregor 1973). When traced through the Burntisland district in a north-easterly direction, however, the Dunnet Shale appears to die out and is apparently only represented by two thin bituminous mudrock beds (Browne pers. comm.) in a 12 m thick volcano-sedimentary sequence in the cliffs adjacent to the Kingswood Hotel [NT 253 8655] (Fig.5.1), at the base of a thick sequence approximately 100 m thick which consists of intercalated sills and lavas forming Kingswood End (Rex and Scott 1987). The sequence at Kingswood, therefore, appears to be the lateral equivalent of the Dunnet Shale which is present throughout the Burntisland district of central Fife, and to the south, in the Queensferry area of West Lothian, towards the presumed depocentre of the Oil-Shale Group basin (based upon the isopach maps of Browne *et al.* (1985)). Previous studies in the Oil-Shale Group (Maddox 1986; Maddox and Andrews 1987) have shown that the Burntisland area lay on the margins of the depositional basin (MacGregor 1973), and was characterised by prograding deltaics which pinched out toward the basin depocentre. These were replaced by 'offshore' facies such as shales and oil-shales which accumulated towards the centres of the bay-lagoons, free from coarse terrigenous clastic input. Carbonate mudflat facies with associated stromatolites were also preferentially developed in the marginal shoreline areas, which were predictably first to be subjected to subaerial exposure during 'regressive events' (Maddox and Andrews 1987) causing contractions of the water body.

In this study, the Kingswood sequence is taken to be the shoreline equivalent of the 'offshore' Dunnet Shale, and was studied so that the characteristics of the bay-lagoon margins could be ascertained. The sequences exposing the Dunnet Shale around Burntisland are also discussed and related to the sections in the South Queensferry area, so that comparisons could be made between the offshore facies and the lateral equivalents which formed along the bay margins.

5.3. Kingswood Hotel sequence, central Fife; field description (see Figs.5.1 and 5.2)

The Kingswood sequence consists of interbedded limestones, mudrocks, volcaniclastics and sandstones (Fig.5.2). Three of the limestones are spectacularly stromatolitic and are associated with coated grain-rich packstones and grainstones. Two desiccation cracked horizons are present, and one caps a volcaniclastic unit and is overlain by one of the stromatolitic limestones. The mudrocks are very fossiliferous, and are dominated by the non-marine bivalve *Curvirimula scotica* (R. Etheridge jun.), which forms prominent monotypic shell beds (cf. Hudson 1980). The volcaniclastics are normally graded and are characterised by coarse tuffs horizons, one of which contains a volcanic bomb lying in an impact created 'sag-pit'.

The lowest bed in the sequence is a 0.55 m thick micritic limestone, the base of which is not exposed. It is characterised by a prominent shaly layer containing phosphatic fish remains and is conspiciouly banded. The overlying 0.50 m thick dark, fissile, calcareous mudrock (Fig.5.3B) contains very abundant specimens of the bivalve *Curvirimula scotica* (R. Etheridge jun.), some of which are encrusted by *Spirorbis* sp. (Figs.5.10 and 5.11). Other fossils include abundant ?paraparchitid ostracodes (Figs.5.12), rare specimens of the gastropod *Naticopsis scotoburdigalensis* (Fig.5.12A), phosphatic fish remains, coprolites and highly fragmented plant compressions. The shale passes upward into a 0.33 m thick micritic limestone which is capped by a 0.09 m thick prominent desiccation cracked horizon (Figs.5.2A and 5.3). The cracks are crudely subpolygonal, averaging 6 mm in width and are infilled by coated grains forming coarse grainstone textures. The desiccation cracked horizon is succeeded by a thin 0.025 m thick limestone, the lower part of which is a coarsely oolitic rippled 'sand' which blankets the top of the mud-cracked layer. The upper part is a brown coloured micritic limestone which contains fish remains and is overlain by a fine-grained, soft, unconsolidated claystone which passes upward into a 0.15 m thick limestone weathering sandy yellow-orange and coarsening-upwards. The overlying 0.06 m thick light grey coloured, soapy textured clay is unconsolidated and passes upward via an undulatory, erosive contact into a 0.47 m thick 'sandstone' which fines-upwards and has a coarse basal lag characterised by reworked clasts, carbonate grains and bioclasts. The sandstone is overlain by a cryptic, 0.74 m thick banded volcaniclastic tuffaceous siltstone which is an earthy green-brown colour and characterised by low-angle cross laminae. It grades upwards into a major 3 m thick volcaniclastic tuff deposit (Figs.5.5 and 5.6) consisting of thick, coarse-grained lithic tuffs (Fig.5.6B) with associated breccias and conglomerates, interbedded with finer-grained tuffs, 2-5 cm thick concretionary beds (Fig.5.6A) and fissile shales (Fig.5.6). The coarser beds are characterised by very low-angle, large-scale tabular/planar cross-bedding, with mud-draped foresets (Fig.5.5A), normal grading and volcanic bombs (Fig.5.5B). One particular bomb lies within a sag-pit 40 cm wide and 30 cm deep which is associated with a very coarse-grained tuff unit (Fig.5.5B).

The tuff unit is capped by a 0.16 m thick oncolite horizon (Fig.5.8C), characterised by rounded, concentrically laminated oncoids averaging 1.5 cm in diameter, which have volcanic/tuffaceous nuclei. This oncolite bed passes into the overlying (and lowest) stromatolitic limestone which is 0.39 m thick and is composed of an undulose laminated fabric characterised by laterally linked hemispheroids which contain horizontally continuous layers, and vertically stacked hemispheroids in which laminae between domes are not connected (Fig.5.8B). The overlying 0.56 m thick calcareous mudrock is dark and fissile, and contains very abundant specimens of *Curvirimula scotica* (R. Etheridge jun.) (some of which are encrusted by *Spirorbis* sp.), fish remains, megaspores, cone compressions and highly fragmented plant compressions. This mudrock passes upward into a 0.20 m thick micritic, banded limestone which contains fish remains and is overlain by a 2.10 m thick volcaniclastic deposit composed of calcareous tuffs, concretionary bands and finer-grained mudrocks. Like the previous tuff horizon, this unit is capped by a stromatolitic limestone (middle stromatolitic unit) which is 0.09 cm thick and has a desiccation cracked base. Diminutive, 0.8 cm high LLH-type stromatolitic domes occur directly above the mud-cracked layer, but the limestone is predominantly composed of carbonate grains and clasts (including reworked stromatolitic domes) which form a coarse grainstone fabric overlying the *in situ* algal stromatolitic horizon at the base.

The middle stromatolitic unit is succeeded by a 0.50 m thick tuffaceous mudrock containing coarser-grained tuff bands towards the top, which is capped by the uppermost stromatolitic limestone unit (Figs. 5.7, 5.8 and 5.9). This limestone is characterised by laterally linked hemispheroids containing horizontally continuous layers which are capped by a coated grain-rich top, where grains averaging 0.25-1.00 mm in diameter form coarse grainstone fabrics. The remaining part of the sequence consists of largely unfossiliferous interbedded sandstones and shales, and the Kingswood sequence is capped along the entire length of outcrop by the basal lava flow of Kingswood End (Rex and Scott 1987).

5.4. Petrography

The mudrocks in the Kingswood sequence have a structureless yellow-brown coloured bituminous groundmass and contain abundant framboidal pyrite (cf. Love 1958). Occasional yellow algal bodies occur with bituminous wisps anastomosing around them, but the dominant bioclasts are phosphatic fish remains, bivalves, ostracodes, and spirorbid worm tubes, which are often concentrated along certain laminae. Framboidal pyrite is often associated with fossils and is commonly observed inside articulated ostracodes. The fine-grained micritic limestones with which the mudrocks are intimately associated are usually distinctly banded, with darker, coarser-grained bands containing greater amounts of pyrite and red-brown coloured resinous material than the lighter, finer-grained bands. Bioclasts are generally rare, although coarser bioclastic beds composed almost exclusively of *Curvirimula* valves and *Spirorbis* worm tubes occur (Fig.5.13). Occasional burrows and problematical soft sediment deformation features are present within the finer-grained beds, which are invariably neomorphosed homogeneous micrites.

The stromatolitic limestones and associated desiccation cracked horizons are characterised by coarser-grained textures, with grainstones and packstones commonly developed (Figs.5.14 and 5.15). A variety of coated grains, including ooids, pisoids, oncoids and coated quartz grains and bioclasts predominate, and these fill the desiccation cracks and are intimately associated with the three stromatolitic horizons. Peloids, intraclasts, quartz grains and bioclasts also occur, together with aggregate grains (grapestones). In the stromatolitic horizons, the grains are often bound and trapped by cryptalgal laminae (Fig.5.15) which are associated with a variety of cyanobacterial filament moulds which are often present within the cores of small micro dome-like structures. Many of the ooids display a strong and well preserved radial fabric, and crude radial fabrics are also developed in coated grains with quartz grain or bioclast nuclei. The grainstones and packstones appear to have had quite a significant primary porosity, and the pore spaces have subsequently been filled by two cement stages. The first is a pink staining (non-ferroan calcite) isopachous palisade cement possibly replacing a precursor Mg calcite/aragonite, whilst the second stage which filled the remaining pore space is a dark blue staining, vein-fed late diagenetic equant ferroan calcite.

5.5. Interpretation of the Kingswood sequence

Stromatolites, which were presumably intimately associated with the peri- to supralittoral bay margin sediments are recognised at three discrete levels within the sequence, capping volcaniclastic units. The lowest stromatolitic unit consists of laterally linked hemispheroids overlying a lag type deposit of spheroidally structured oncolites. Each oncolite has formed around a tuffaceous nucleus and it is upon this oncolite horizon that the successive layers of LLH-type domes have accreted. The intermediate stromatolitic horizon caps a desiccation cracked tuffaceous unit and consists of diminutive LLH-type domes which are overlain by a thin grainstone 'sand' sheet. The intimate association of stromatolites and tuffaceous deposits points to a blanketing of shallow water bay marginal tracts by ashes, resulting in the destruction and stabilisation of productive and formerly inhabited high energy settings. The stromatolites represent pioneer cyanobacterial communities which colonised the area after ash-fall tuff events. The resumption of normal background bay sedimentation resulted in the deterioration of such communities, probably due to the migrating grainstone 'sand' sheets and an increase in competing faunal activity (e.g. stromatolite-destructive browsers and grazers). Although the stromatolites show some evidence of an ability to trap and stabilise carbonate grains, it is considered that the migration of larger 'sand' sheets was not conducive to stromatolite formation.

The association between stromatolites and volcanic activity evident from the Kingswood sequence has been noted elsewhere by Anderson (1950), who suggested that periods of volcanism appear to produce environments favourable to algal growth. Other associations of stromatolites and volcanics in the Oil-Shale Group are found on the island of Inchkeith in the Firth of Forth (Davies 1936), where stromatolites can be seen encrusting blocks of lava on the broken-up top of a lava flow (Davies 1936; Anderson 1950; Loftus 1985).

The mud-cracked horizons are clearly the result of desiccation, initiated by subaerial exposure of sediment substrates in shallow water tracts. The bay lagoons appear to have been periodically subjected to contractions in the water body and these 'regressions' often resulted in the generation of basin-wide distinctive mudflat facies (Parnell 1984; Maddox 1986; Maddox and Andrews 1987). The desiccation cracked horizons in the Kingswood sequence, however, do not appear to record major desiccation events and may only represent minor fluctuations in the position of the bay-margin shorelines. The desiccation cracked horizon at the base of the stromatolitic limestone, however, may have resulted from the infilling of a shallow water bay by ash-fall tuffs, resulting in shoaling and the temporary emergence of the sediment substrate. The coarse-grained infills of the desiccation cracks suggest that the emergent surfaces were associated with higher energy shallow water settings where grainstone and packstone textures predominated, forming in response to wave and current activity in shallow sublittoral conditions soon after the substrates were once again re-submerged. The presence of two distinct and prominent desiccation cracked horizons within the sequence suggests shallow water conditions and a palaeogeographical location close to the margins of the bay-lagoon. The grainstones and packstones infilling desiccation cracks are interpreted as very shallow water sediments forming in highly agitated conditions, as strand-line carbonate 'sand' sheets along the fringes of the bay margin. The shallower peri- to supralittoral areas of the bay margins appear to have been characterised by higher energy conditions, and the carbonate grainstones and packstones which often infill desiccation cracks (and are associated with stromatolites) contain few fossils, with the exception of fragmentary bioclasts (e.g. ostracodes, spirorbids, fish remains and bivalves) which are often coated with dark cryptocrystalline micrite. Non-skeletal carbonate grains such as peloids and coated grains such as ooids predominate, and the harsh environmental conditions (e.g. subaerial exposure) coupled with high energy (e.g. ripple marks in oolite sand shoals) appear to have precluded faunal colonisation.

The volcaniclastic rocks were evidently deposited from ash-fall tuffs which fell into shallow water bay-lagoons where 'background' Oil-Shale Group sediments were being deposited. The volcaniclastics are calcareous, and the carbonate may have been derived from the leaching and breakdown of volcanic ashes. The green colour of the rocks is a result of the presence of chlorite, derived from the breakdown of volcanic glass. The graded bedding and laminae generally suggests deposition rapidly from suspension with a minimum of sedimentary reworking. The presence of cross-bedding, however, suggests that at times high energy conditions characterised the depositional setting and the volcaniclastics were reworked by currents and waves to form subaqueous sandwave and dune bedforms. The sedimentary material present in the volcaniclastics also supports some degree of sedimentary reworking, although the high rates of deposition seem to have precluded any degree of faunal colonisation. The presence of a large volcanic bomb (also recorded from this general area by Geikie (1864; 1900)) in the main volcaniclastic unit records the impact of a volcanic projectile presumably originating from a nearby active volcano (?the Binn Vent, Burntisland), as it is unlikely that such a large object could have been projected any great distance. That the tuffs modified the patterns of sedimentation in the Oil-Shale Group bay-lagoons is supported by the presence of a stromatolitic horizon capping each volcaniclastic unit. This phenomenon suggests that the tuffs infilled the shallow bays, resulting in the destruction of 'background' environments and faunas, paving the way for colonisation by environmentally tolerant cyanobacterial communities (stromatolites) which appear to have thrived in niches free from competing grazing and browsing organisms.

The fauna in the two mudrock units suggest non-marine conditions with possibly brackish to freshwater palaeosalinities (see Belt 1975). The lack of sedimentary structures and the fine-grained nature of the rocks are interpreted as indications of a low energy setting where mud was deposited from suspension possibly as a result of overbank flooding into large interdistributary bay-lagoons. The high organic content of the mudrocks further suggests that at times clastic deposition effectively ceased and only organic matter effectively accumulated (Moore 1968a). The structureless bituminous groundmass possibly resulted from the decomposition of algae (Parnell 1984), and rare algal bodies indicate that phytoplanktonic oozes may have contributed to the organic input. The fauna of paleoniscoid fish, ostracodes, gastropods, and monotypic shell beds of non-marine bivalves (with associated spirorbids) is typical of the Oil-Shale Group (Wilson in Mitchell and Mykura 1962), and the absence of stenohaline marine fossils suggests abnormally low salinities. The presence of early diagenetic framboidal pyrite (cf. Love 1958) records anoxic reducing conditions within the sediment substrate, ideal for the preservation of abundant organic matter (Love 1958; Moore 1968a) which may result in the formation of oil-shales.

Non-stromatolitic limestones which are intimately associated with the mudrocks are interpreted as low energy, sublittoral sediments which were deposited in the marginal tracts (sub-wave base) of the large interdistributary bay-lagoons. The lack of wave and current disturbance is recorded by the development of banding and lamination, and the presence of laminae rich in framboidal pyrite suggests that substrates were periodically characterised by anoxic reducing conditions. Evidence of an active infauna is not abundant although burrows and evidence of bioturbation is present in some beds. Occasional higher energy conditions appear to have been attained, resulting in limestones rich in transported shelly lag horizons. Low energy non-stromatolitic limestones often grade into higher energy deposits, and this is interpreted as a possible transition from deeper water to shallower water agitated conditions. The fossils in the limestones suggest low salinity conditions, although it is apparent that only the mudrocks probably represented the settings in which organisms most proliferated.

Occasional erosive-based, thin sandstone beds containing reworked carbonate grains, clasts and bioclasts are interpreted as representing erosive sandy influxes (?possibly a distal tongue of a crevasse splay sand sheet) which resulted in erosion, dislocation and reworking of carbonate clasts, grains and bioclasts. The fining-upward trends exhibited suggest a decrease in ?current energy which waned throughout the 'event'. The mineralogical immaturity indicates limited transport and sorting, representing only the local derivation of bay-margin carbonate material. The presence of reworked carbonate clasts both in these deposits and the grainstone sheets associated with stromatolitic mudflat facies suggests some degree of coherency prior to dislocation, possibly the result of early diagenetic cementation/lithification.

5.6. Discussion of stromatolites

Cryptalgal structures often arise from a biochemically induced carbonate precipitation around blue green algae which can result in the building of mats and the binding of sediments. The interaction between algal activity and physical and biological processes results in the production of laminated fabrics. Such biosedimentary structures, or stromatolites, are commonly found in intertidal, supratidal and shallow subtidal settings (Flugel 1982). Stromatolites consist of domed and flat structures comprising alternating algal-rich and sediment-rich layers, and are considered to be important indicators of depth and energy of the water and the proximity to the coast (see papers in Walter (1976)), although some of the accepted views concerning stromatolite ecology have recently been questioned (Awramik *et al.* 1978).

The stromatolites at Kingswood display several growth forms (cf. Logan *et al.* 1964). These are predominantly LLH (laterally linked hemispheroids) and SH (stacked hemispheroid) type structures, although oncolitic 'lag' horizons are characterised by predominantly SS (spheroidal structure) type growth forms. Although growth structures have been interpreted as possible environmental indicators (Logan *et al.* 1964; Walter 1976; Purser 1980) of conditions such as water energy intensity, biological factors (e.g. varied interactions of different species of algae with carbonate precipitation and sediment deposition) are also important (see papers in Walter (1976)). Moreover, although factors such as water turbulence may influence growth morphology (especially of the larger macrostructures), small scale structures such as domes and columns may be the result of the biological growth habits of algae. The inferred low salinity setting of the Kingswood sequence is consistent with the present day distribution of stromatolites, which are forming in freshwater marshes (Andros Island, Bahamas) and meromictic lakes (Green Lake, New York) (Flugel 1982). Fossil stromatolites have also been described from inferred fresh to brackish water environments, and the most important factor in the preservation of cryptalgal fabrics is an early and rapid cementation and lithification, which in Recent settings occurs in hypersaline, brackish, and freshwater environments as well as in intertidal zones with normal marine conditions (Pratt 1979). The dearth of stromatolites in subtidal marine settings at the present day and throughout the Phanerozoic is largely due to grazing organisms such as gastropods, and the absence of metazoans in the Precambrian (Brasier 1979) was one of the main factors in the widespread and diverse development of stromatolites at that time, including many in subtidal and deeper water settings (Hoffman 1974). The repeated development of well-preserved stromatolites at Kingswood, and thoughout the Oil-Shale Group in general (Davies 1936; Kennedy and

Pringle 1946; Anderson 1950; Greensmith 1959; Parnell 1983; Rex and Scott 1987; Maddox 1986; Maddox and Andrews 1987) suggests that conditions which were environmentally stressful to metazoans (e.g. low salinity, desiccation, volcanism etc.), resulted in the creation of niches where cyanobacterial communities became established, and Oil-Shale Group environments (especially those where volcanics and stromatolites are associated) may provide a 'window' through which Carboniferous environments similar to some Precambrian settings may be viewed. The tectonic and volcanic instability of the extensional Midland Valley Basin during Oil-Shale Group times, coupled with an absence of a marked marine influence appears to have been conducive to stromatolite development, and no major stromatolitic horizons have yet been described from the overlying Pathhead Beds and Lower Limestone Group.

The spectacular and intricate cryptalgal structures at Kingswood are very well preserved. The preservation potential of cryptalgal structures such as algal stromatolites in the rock record may be considerably lessened by eroding tides, waves, bioturbation, or grazing metazoans. Bioturbation and a destruction of the algal structures by grazers may be supressed, however, by overly vigorous environmental conditions (Flugel 1982), which at Kingswood appear to have included periodic desiccation, fluctuating (and largely low) salinities, ?periodically high energy conditions and destructive ash-fall tuff showers.

5.7. Summary of the Kingswood sequence

The Kingswood sequence is characterised by rapid vertical facies changes resulting from shoreline fluctuations and ash-fall tuff 'events' at the margins of an Oil-Shale Group bay-lagoon, where the Dunnet Shale was contemporaneously forming towards the basin depocentre. The mudflat facies in the sequence, however, are clearly localised bay-shoreline features and do not prograde into the basin depocentre as do horizons recording the more major regressive events (Maddox and Andrew 1987). The two bituminous mudrock beds are interpreted as representatives of the 'Dunnet Shale facies' which along with some of the finer-grained limestones were deposited during periods of water body expansion, when the bay margins were covered by deeper water and characterised by low energy conditions. The Kingswood sequence is clearly localised and is replaced by the Dunnet Shale to the south-west throughout the Burntisland District, and south of the Forth in the Queensferry area of West Lothian. The shale overlies the Dunnet Sandstone which is approximately 91 m thick in the Queensferry area (MacGregor 1973) and 40-50 m thick in the Burntisland district of central Fife. The Dunnet Sandstone is underlain by the Burdiehouse Limestone in the Burntisland area, but to the south in West Lothian the intervening Camps Shale is present. This implies that whilst major sand bodies were being deposited above the Burdiehouse Limestone in central Fife, oil-shales were accumulating in West Lothian. Major geological events such as the south-westerly progradation of thick deltaic sand bodies appear to transgress local facies changes, however, and the Dunnet Sandstone is present in both Fife and the Lothians.

5.8. Burdiehouse Limestone and the Dunnet sandstone and shale

The Burdiehouse Limestone which crops out on the southern shore of the Firth of Forth in the South Queensferry area, and in the Burntisland district of central Fife (Fig.16A and B), has been interpreted as a major lacustrine/lagoonal phase (Loftus 1984, 1985, 1986) which represented a major expansion of the Oil-Shale Group basin water body. In Fife, the limestone is directly overlain by deltaic sandstones (Fig.16A) recording the gradual south-westerly progradation over the lacustrine/lagoonal tract of a major delta sand body (Dunnet Sandstone). In West Lothian, the Camps Shale intervenes between the Burdiehouse Limestone and the Dunnet Sandstone suggesting that in the early stages of delta progradation, offshore mudshale facies were contemporary with prograding deltaic facies which were advancing into the Oil-Shale Group basin. The Dunnet Sandstone is well exposed at both South Queensferry and Hopetoun, displaying large-scale soft sediment deformation structures, abundant plant scraps, large-scale cross-bedding (Fig.5.16D), sandstone casts of stigmarian rootlets and channellised 'cut and fill' structures (Fig.16C). Palaeocurrent data suggests a south-westerly palaeoflow.

In the Burntisland district, the Dunnet Sandstone is exposed in the Dalachy and Newbigging quarries. The Dalachy Quarry is disused and overgrown, but the overlying Dunnet Shale is exposed and the underlying sandstones display occasional abandoned 'cut-and-fill' type structures, the channelloid scours blanketed by mudrock drapes (Fig.5.16C). In the Newbigging Quarry, where the rocks are still periodically worked, the sandstones are grey-white coloured and massively bedded. In the lower part of the quarry face they are regularly bedded and intercalated with finer-grained beds, whilst towards the top of the quarry face the regular bedding is disturbed by erosive contacts within the sandstone, and axes of channelloid-type scours and cross-bedding foreset dip directions suggest palaeocurrents to the SSE and SE.

5.9. Dunnet sandstone and shale; interpretation

The Dunnet Sandstone clearly represents the establishment of deltaic conditions over a wide area, with delta-top facies represented by major distributary channel deposits. The abandonment of the deltaic facies is represented by rootlets, plant-rich horizons, stigmarian rootlets, bioturbation and U-shaped *Diplocraterion* or *Arenicolites* type burrows which have been interpreted as representing a local marine inundation (McAdam 1986, p.189). The Dunnet Shale records the re-establishment of bay-lagoon conditions over a relatively wide area after the abandonment of the Dunnet Sandstone, and is largely represented by offshore mudrock oil-shale facies representing sediment-starved areas where phytoplanktonic algal oozes accumulated in anoxic substrates resulting in the preservation of abundant organic matter. Whilst these basin-centre facies are relatively well understood (Parnell 1984), the marginal shoreline equivalents are not. The importance of the Kingswood sequence as the lateral equivalent of the Dunnet shale, which developed along the lagoon margins cannot, therefore, be underestimated.

5.10. Conclusions

The sequence at Kingswood which is considered to have accumulated along the margins of the 'Dunnet Oil-Shale bay-lagoon' records a series of water body fluctuations reflected in the changing position of the shoreline. Superimposed upon these patterns of sedimentation are localised ash-fall tuffs representing volcanic activity confined to the Burntisland area. The tuffs modified the local patterns of bay-margin sedimentation blanketing the shallow water tracts and destroying formerly inhabited environments allowing stromatolites to invade the vacated and environmentally 'difficult' supralittoral-shallow sublittoral mudflat niches. Although volcaniclastics clearly modified the style of sedimentation, the rapid facies changes reflected in the sedimentary rocks appear to have been controlled by water depth which was ultimately linked to water energy. The offshore mudshale facies which is characteristic of the basin depocentre contrasts with the bay margin sequence in its lithological homogeneity, absence of an abundant fauna and very fine-grained nature. This indicates that mud and organic matter were largely deposited from suspension in offshore sub-wave base conditions where anoxic substrates resulted in the preservation of abundant organic matter.

This study indicates the restricted geographical nature of some (if not all) of the Lothian Oil-Shales, and provides a facies transect from the bay margins into the basin depocentre of an Oil-Shale Group bay-lagoon. As a bay marginal 'facies', the Kingswood sequence is valuable because it throws light on the environments which flanked the large lakes and lagoons where oil-shales were developing towards the basin depocentre.

CHAPTER 6

Introduction to chapters on the Pathhead Beds and Lower Limestone Group; a review of Brigantian sedimentation in the Midland Valley of Scotland

6.1. Introduction

The Lower Limestone Group and underlying Pathhead Beds (for information on type area see chapter 7) are composed of Yoredale-type cyclic or rhythmic sequences (Fig.6.1) (Peach 1888, p.16; Francis 1965, p.321). Yoredale-type cyclothems are geographically distributed from the Midland Valley of Scotland to the southern edge of the Pennine Block (Moore 1959; Selley 1970, p.78) and were the first cycles to be described in the geological literature by Phillips (1836) from the 'type' area of Wensleydale (Uredale), Yorkshire. These cyclothems generally consist of clastic and carbonate rocks, and the lower boundary of the cycle is traditionally drawn at the base of a laterally persistent marine limestone (Wilson 1975, p.203). The limestone is succeeded by mudrocks which coarsen-upward into siltstones and sandstones overlain by cross-bedded, erosively-based laterally impersistent sandstones which usually pass upward into seat-earths, ganisters and thin coal seams, above which is another cycle (Fig.6.1). These cycles were the result of the interaction of the deltaic complex which had existed at the eastern end of the Midland Valley prior to the Brigantian (Greensmith 1966; Belt 1975), and the newly created marine conditions resulting from a Brigantian rise in sea level (Ramsbottom 1981). These processes further interacted with a complex tectonic and volcanically active background setting (Goodlet 1957, 1959) to give rise to a complicated situation where rapid vertical and lateral facies and thickness variations are common (Francis 1983a).

The Pathhead Beds and especially the Lower Limestone Group represent the acme of marine conditions in the Midland Valley during the Dinantian, and indeed throughout the whole Carboniferous, and generally succeed non-marine conditions where Oil-Shale Group facies were locally developed (cf. Parnell 1984). The major marine phases in the Brigantian can be traced throughout the Midland Valley (Burgess 1965; Wilson 1966), largely on account of distinctive fossil assemblages or microfossils, vastly improving the lithostratigraphic correlation of geographically separated sequences which had previously been a problem (cf. Maddox and Andrews 1987).

6.2. Marine phases

Marine phases in the Pathhead Beds and Lower Limestone Group are usually represented by mudrocks and limestones, and although clastic delta-front (and even delta-top) facies show some evidence for marine influence and reworking, marine body fossils are generally only found in mudrocks and limestones. Fossils include brachiopods, bivalves, corals, crinoids, echinoderms, sponges, bryozoans, ostracodes, foraminifera, algae, fish remains, conodonts (Clarke 1960) gastropods and rarer elements such as trilobites, conularids, cephalopods and even graptolites. Microfossils are also common in some of the shales and particularly the limestones, and are dominated by foraminifera, algae (cf. Hallet 1970) and ostracodes. Algae include the codiacean *Calcifolium*, represented by two species, *C. punctatum* and *C. okense*. (Burgess 1965), but various species of *Girvanella* are also common. Foraminifera include *Eotuberitinia*, *Pachysphaera* (and other simple spherical forms), *Endothyranopsis*, *Saccaminopsis*, *Janiskewskina*, *Howchinia*, *Bradyina*, *Valvulinella*, *Eostafella*, *Earlandia*, *Pseudoammodiscus*, *Palaeotextularia*, *Cribostomum* and *Loeblichia*. These and other foraminifera from particularly the Lower Limestone Group indicate a Belgian V_{3c} date, a zone which is wholly within the Brigantian (Jameson 1980, 1987).

Marine limestones and shales display few primary sedimentary structures, although coarser-grained crinoidal packstones and grainstones which often cap limestone beds are sometimes cross-bedded and even crudely hummocky cross-stratified. Bedding is common, but is often either accentuated or overprinted by pressure dissolution initiated nodular hummocky surfaces which are commonly characterised by shaly stylocumulate deposits (cf. Simpson 1985). These appear to be a deep burial diagenetic effect and diagenetic overprinting has often resulted in a loss or modification of primary fabrics and microfabrics. Aggrading neomorphic textures (cf. Folk 1965) are common, as is late stage diagenetic dolomitisation, and many of the limestones in the Pathhead Beds and Lower Limestone Group can be described as biomicrosparites or biosparites due to the transformation of primary micrite into micro- or pseudospar.

Late diagenetic (burial) replacement dolomitisation often results in the complete replacement of the primary fabrics by coarse-grained dolomite rhombs which are zoned and average 0.5 mm in length. These limestones are composed of ferroan dolomites which are fabric destructive (Tucker 1981, pp.142-3; Scoffin 1987, pp.136-7), and show a black and a red phase in cathodoluminescence (C.L.). The black phase is considered to correspond to a very iron-rich ferroan dolomite, whilst the red phase probably relates to a less ferroan dolomite. These phases are probably linked to a chemical or inclusion defined zonation (Tucker 1981) and the dull violet orange C.L. colours for Lower Limestone Group dolomites are not consistent with the normal 'blood-red' colour for dolomites, suggesting heavy quenching by iron (Fe) (Amieux 1982). Dolomitisation of limestones in the Pathhead Beds and Lower Limestone Group is common and many beds are partially or completely dolomitised (Robertson *et al.* 1949; Selim and Duff 1974; Forsyth and Chisholm 1977). Partial dolomitisation usually involves the selective or partial replacement of bioclasts by dolomite rhombs, or merely the presence of scattered rhombs throughout thin sections. The more extreme fabric destructive dolomitisation which replaces the whole rock is clearly a late diagenetic burial phase which has resulted in the virtual replacement of the rock, with hardly any of the original textures, fabrics or constituents preserved. Staining suggests that most of the dolomites are predominantly ferroan and many characteristically weather in the field to a buff-yellow or orange colour due to the oxidisation of iron. Dolomitisation of this kind is common in sequences of shallow water limestones interbedded with mudrocks, the latter possibly providing a source of Mg during compaction (e.g. Mg^{+2} released during montmorillonite to illite transformation), and dolomites are very uncommon in carbonates that are basinal in origin (Scoffin 1987).

Although dolomites commonly preserve original fabrics, textures and constituents (Murray 1964), both late diagenetic dolomitisation and aggrading neomorphism modify the originally deposited sediment, obscuring primary fabrics which may have been useful in the interpretation of depositional environments. For example, a biomicrite could be transformed into a biosparite or biomicrosparite via aggrading neomorphism, with most of the original micrite gone, and clays surrounding the microspar/pseudospar crystals as expelled insoluble residues. The limestones of the Pathhead Beds and Lower Limestone group also show several phases of cementation, some of which are clearly late and vein-fed. Bioclasts with micrite envelopes (Bathurst 1966, 1975) are commonly filled with a clear blocky spar suggesting the creation of a former moldic porosity via an earlier dissolution phase. Stylolites are also common (cf. Wanless 1979), suggesting pressure dissolution and modification of limestones via dissolution of carbonate, which can sometimes result in the thickness of sequences being reduced by up to 41%. Such pressure dissolution could also have provided a source of $CaCO_3$ for limestone cementation, and is known to act as a source for late diagenetic ferroan sparitic calcite cements (Oldershaw and Scoffin 1967; Hudson 1975). Silica cements are also present in some limestones (cf. Orme 1974; Meyers 1977), and sponge spicules which are not uncommon in some beds may have been the source of the SiO_2.

It is clear from the foregoing discussion that the diagenesis of the limestones of the Pathhead Beds and Lower Limestone Group is complex and involved, and whilst it is beyond the scope of this investigation to study this in detail, it is clear that diagenetic overprinting and modification has severely affected the original textures and fabrics and has often resulted in the removal and/or obliteration of bioclasts. Although the diagenetic histories of the limestones are quite poorly understood, however, the diagenesis of the inter-marine clastic rocks are even less well known.

Textures most commonly developed in the limestones are wackestones and packstones, although much finer-grained mudstones and coarser grainstones are sometimes developed. Most of the limestones were originally biomicrites, but due to diagenetic modification are now biosparites and biomicrosparites. Skeletal grains predominate and non-skeletal grains are quite rare. Occasional coated grains are present, although many of these have merely resulted from micritization via the process of the formation of micrite envelopes, and coated grains such as ooids are absent. Intraclasts are also very rare, but some of the limestones contain abundant terrigenous siliciclastic quartz grains, and have sandy bases, which are a common feature of 'Yoredale' limestones (cf. Selley 1970; Elliot 1975). These sandier limestones are characterised by abundant trace fossils such as *Zoophycos*, *Teichichnus*, *Diplocraterion* and *Rhizocorallium*. These trace fossils also occur in finer-grained limestones and their spreiten-filled burrows are sometimes lined with pyritized faecal pellets. Many of the finer-grained limestones are very 'muddy' and are intercalated with shaly layers and flaggy-shaly limestones. These beds often contain early diagenetic framboidal pyrite and bioclasts are sometimes selectively pyritized. Fossils also commonly contain pyrite framboids and this suggests that anaerobic reducing conditions were established in the muddy carbonate substrates and within fossils, locally associated with decomposing organic matter.

Skeletal grains (bioclasts) are often fragmentary and comminuted, and are only occasionally well sorted into coarse grainstones. In most cases, they form poorly sorted, muddy wackestones and packstones, suggesting low to moderate energy conditions. Bioclasts are predominantly crinoid ossicles (Cain 1968) which are sometimes articulated, but more commonly disarticulated. These are sometimes encrusted by fenestrate bryozoans, and most commonly form the coarser and more well sorted grainstones and packstones, where other bioclasts are uncommon (Selim and Duff 1974; Cain 1968). Other skeletal grains include foraminifera, brachiopod valves and spines, ostracodes, bryozoans, bivalves, corals and algae. Adherent foraminifera such as *Tetrataxis* are often observed attached to valve fragments, and the codiacean alga *Calcifolium* often encrusts *Lithostrotion* corallites (Burgess 1965). Many fossils are articulated (e.g. ostracodes) and productid brachiopods, solitary corals and *Lithostrotion* colonies are often observed in life position. Coarse grainstone and packstone textures are most commonly developed in beds capping major limestones and in thin lensoidal-lenticular bedded limestones intercalated with associated calcareous mudrocks. Most of the limestones in the Pathhead Beds and Lower Limestone Group are thin, yet laterally extensive, suggesting marine conditions which were not particularly prolonged but geographically widespread. The 'Charlestown Main Limestone marine transgression', however, is characterised at various localities by carbonate buildups (Wright 1912; MacGregor 1973, pp.246-7; Jameson 1980, 1987) suggesting prolonged marine conditions over a wide area with deeper water conditions established, compared with many of of the other marine transgressions.

Calcareous mudrocks associated with limestones also contain a very abundant marine fauna, with many of the same fossils present that are also found in the adjacent limestones (e.g. Ferguson 1962; Wilson 1966; 1974). These mudrocks, however, show more variation than the limestones, and may be characterised by a more diverse and abundant fauna (Whyte 1973, 1984), or a less diverse and restricted fauna (Ferguson 1962). Mudrocks supporting a more diverse marine fauna than associated limestones may indicate a substrate preference exercised by certain organisms, with well aerated muddy substrates characterised by a more abundant and diverse fauna than carbonate substrates. The mudrocks contain abundant framboidal pyrite, and pyrite-filled burrows, but although bioturbation and trace fossils are common, they are not as readily preserved, or as easily recognisable as biogenic structures in other lithologies. The mudrocks associated with limestones, which contain abundant pyrite framboids and are almost always faunally barren, suggest anoxic, anaerobic reducing conditions deterring organisms. Mudrocks which are intimately associated with limestones grade upwards and downwards into less calcareous mudrocks. Shales underlying limestones usually pass down into paleosols such as coals and/or seat-earths, fireclays and ganisters, and often show a downward trend into lower diversity fossil associations (Ferguson 1962) with lingulids, non-marine bivalves, fish remains, spirorbids, ostracodes and gastropods dominating the fossil assemblages. Similar trends are present above the limestones, where mudrocks grade upwards into siltstones which eventually become interbedded with fine-grained sandstones deposited at the distal delta-front/prodelta. Another characteristic feature of mudrocks under- and overlying the marine limestones is the presence of oval-oblate spheroid shaped carbonate and siderite nodules, some of which contain fossils, burrows (Chisholm 1970a), and septarian structures. These concretions are often uncompacted relative to the surrounding shales, indicating pre-compaction formation. The septarian nodules are believed to have had an originally gel-like consistency, forming in highly porous water-laden sediments. It appears that the exterior hardened during concretion formation, and this was accompanied by dehydration and shrinkage of the interior where calcite crystals were later precipitated in cracks (Scoffin 1987, p.141).

The marine limestones and associated calcareous mudrocks have geographically extensive sheet-like geometries and are usually independent of local facies changes in the underlying and overlying fluvio-deltaic clastics. This suggests that the marine phases were deposited during rises in sea level (Ramsbottom 1981), although occasional geographically restricted marine bands containing some body fossils (Wilson 1980; Forsyth and Chisholm 1981) may record localised transgressions induced by delta lobe abandonment, compaction and subsidence, allowing reworking by marine conditions (cf. Elliot 1974a, 1975). Such marine bands are often characterised by bioturbated, cross-bedded calcareous sandstones suggesting reworking of deltaic sands by marine incursions. The marine transgressions resulting from rises in sea level led to the establishment of extensive, shallow water carbonate marine shelves with little terrigenous siliciclastic input. Normal marine salinities, tropical-equatorial latitudes and shallow clear-water warm seas are indicated by the fossils, and the textures and fabrics suggest generally low energy conditions with only intermittent higher energy phases represented by grainstones and packstones which are occasionally cross-bedded (Selley 1970) and hummocky cross-stratified, the latter suggesting storm sedimentation. Shallowing-upwards trends are indicated by crinoidal grainstone caps and the local development of beds containing oncolites, and ostracodes, together with rare stromatolitic structures (Monro 1982a). Such facies and faunal associations and the presence of lingulids and fish-dominated assemblages towards the top of some limestones may indicate abnormal salinities associated with shallowing, and rooted, kaolinitised emergent surfaces (Whyte 1973, 1980; Monro 1982a; Craig 1975; Clarkson 1986a) also suggest shallowing with eventual subaerial exposure. Such shallowing-upwards trends may be associated with regressions if recognised over a wide area, or be due to tectonic uplift if relatively localised. It is suggested that transgression and regression largely determined whether deltas constructively prograded or not. Rises in sea level appear to have caused deltas to deposit sediment on their own delta-tops and to stop prograding. Due to waterlogging of the delta plain concomitant with a rise in the water table (transgression-induced), the delta lobe was abandoned, and paleosols developed, represented by hydromorphic organic peaty paleosols (coals) and gley soils (fireclays and seat-earths) which accumulated in water saturated environments. This explains the close association of paleosols with marine phases, and paleosols often directly underlie the marine shales and limestones and overlie the inter-marine fluvio-deltaics (cf. Elliot 1974a, 1975; Percival 1986). The non-calcareous mudrocks which overlie the paleosols and grade upwards into calcareous mudrocks and limestones were clearly deposited during the early stages of the marine incursions (Ferguson 1962; cf. Calver 1968a, 1968b) and are characterised by non-marine bivalves such as *Curvirimula scotica* (Forsyth 1970) and *Naiadites crassus* (Ferguson 1962), associated with lingulids and fish remains (e.g. bone beds) which often accumulated during erosive phases at the start of a transgression. Reworked paleosol clasts are often also included in the basal shales. Faunal phases or 'topozones' (Calver 1968a, 1968b, Ferguson 1962) are often recognised in the mudrocks, reflecting increasing salinities developed during the transgression, with the calcareous shales and limestones representing the acme of the incursion (cf. Wignall 1987).

The shales overlying limestones grade upwards into non-calcareous shales which also contain an impoverished marine fauna, presumably developing in response to marine regression rather than transgression. It is not clear, however, if the deltas prograded onto a shallow marine shelf established during the transgresion, or whether they started to prograde in direct response to regression. Certainly, some of the marine-influenced delta-front sequences observed in the Pathhead Beds and Lower Limestone Group would suggest progradation into a marine environment (although admittedly regression could have been taking place), whereas other more constructive delta-front sequences indicate progradation into non-marine conditions (after regression). It is considered most likely that sea level rises and falls controlled deltaic abandonment and progradation, rather than vice-versa (except in rare cases) and that regression therefore was underway when progradation began.

The correlation of faunally distinctive marine phases (Burgess 1965; Wilson 1966) across the Midland Valley suggests that remarkably uniform conditions were established during the acme of marine transgressions. The sandy bases of some marine limestones imply that delta sands were often reworked by marine phases during the early stages of marine incursions, and that strand line sand bars were often physically and biogenically reworked in shallow marine conditions (Chisholm 1970a, 1970b). Although the marine phases are remarkably uniform, some local facies changes are discernible. For example, the variable tectonic regime dictated the carbonate:clastic ratio so that it was greater on the tectonic highs than within the adjacent lows (Goodlet 1957, 1959; Grayson and Oldham 1987). The local tectonic setting also resulted in the development of localised emergent surfaces on the tops of some of the limestones (Monro 1982a), and in this way, marine phases were locally influenced. Local facies differences have also been invoked to explain the absence of the Neilson Shell Bed fauna in some areas (Wilson 1966, 1974), and the codiacean alga *Calcifolium* is invariably absent at localities where crinoidal limestones are developed (Burgess 1965). Local tectonic influences and the presence of penecontemporaneous lava piles may have also resulted in the preferential development of 'mid-basin' highs where carbonate buildups developed (Jameson 1987).

6.3. Non-marine phases

The marine phases are much thinner than the intercalated non-marine fluvio-deltaic phases, but were probably deposited at a much slower rate. In general, the non-marine phases consist of sequences which broadly coarsen-upward and are capped by paleosols. This involves a classic 'Yoredale' transition from the marine limestones and shales to delta-top sandstones and overlying coals (paleosols), via shales, siltstones and sandstones. This broadly represents active delta progradation, with deltas building out onto shallow marine shelves. The deltas are believed to have been of a lobate type, developed due to the interaction of marine and deltaic conditions resulting in reworking of delta-front sands to form lobe-shaped sand sheets flanking the delta-front (Galloway 1975; Galloway and Hobday 1983). This contrasts strongly with the elongate deltas of the underlying Oil-Shale Group (Greensmith 1966; Cater 1987; Maddox and Andrews 1987), where point-concentrated mouth-bars developed which were unconnected along the delta-front, with muds being deposited in between (Elliot 1976b). Most Yoredale inter-marine clastic intervals are now believed to have been deposited by lobate deltas (Elliot 1975; Leeder and Strudwick 1987), and the delta-front sequences show evidence of wave-reworking.

Delta progradation appears to have followed regression, or developed in response to it, but there is no clear evidence to show that this was always the case, and delta lobes could have prograded into shallow marine conditions. Rapid falls in sea level probably resulted in the influx of coarse clastics into a very shallow water marine environment, resulting in sandstones lying directly on top of limestones. Most limestones, however, are overlain by a gradual coarsening-upward sequence of mudrocks, siltstones and sandstones reflecting gradual progradation developed during a slow regression. Alternatively, deltas could have prograded into a static marine environment, with no regression, the influx of deltas merely resulting from avulsion (switching of the position) of active distributary channels and the deltaic complex in general.

6.3.1. Prodelta facies

The prodelta facies is generally developed on top of the marine facies and consists largely of dark coloured, laminated claystones, fine-grained siltstones and mudrocks with occasional thin sandstone laminae (ribs). These rocks contain siderite nodules and bands, carbonate concretions, abundant plant remains, and occasionally an impoverished marine fauna. Pyrite is common and the rocks have often been subjected to a great deal of post-depositional compaction and sedimentary dewatering, the precompaction nodules preserving original (primary) uncompacted fossils and fabrics. Burrows and bioturbation are common, and are often filled or associated with pyrite. Some of the precompaction siderite nodules may also be burrowed by trace fossils such as *Chondrites, Phycodes, Keckia, Saportia* and *Taenidium* (Chisholm 1970a). The prodelta facies may sometimes be associated with a marine fauna, which is usually impoverished and sometimes of low diversity, indicating abnormally low salinities which may be due to regression, and/or freshwater runoff from deltaic complexes.

The prodelta facies represents the first phase of deltaic sedimentation following the marine conditions of the underlying limestones and shales. This records the accumulation of fine-grained muds and silts deposited largely out of suspension from prodeltaic mud plumes transported offshore, distal to the delta-front. The clastic mud and silt plumes terminated shallow marine sedimentation and represent some of the finest material transported by the delta, and therefore deposited furthest offshore. The fossils indicate the continuation of marine conditions for some time until regression and/or freshwater runoff coupled with an increase in depositional rates largely acted as a deterrent to faunal colonisation. Trace fossils and bioturbation, however, become common in the prodeltaic facies indicating substrate preferences and a greater preservation potential. The occasional thin sandstone laminae and beds (sandstone ribs) are interpreted as the earliest river-generated sand incursions at the delta-front/prodelta. These are sharp based, sometimes loaded, and occasionally cross-laminated. Generally, however, the prodelta facies was deposited below wave-base in quiet water conditions where anaerobic reducing conditions were periodically developed in the sediment substrates. Salinities appear to have ranged from fully marine to brackish and the trace fossils are indicative of marine to quasi-marine conditions. The plant material present is largely drifted and the preservation of delicate floral fronds also suggests low energy conditions where waterlogged plants sank to the bottom and were buried in muddy substrates.

6.3.ii. Delta-front facies

Delta-front facies in the Pathhead Beds and Lower Limestone Group consist of coarsening-upward sequences comprising mudrocks and siltstones passing upwards through interbedded mudrocks, siltstones and sandstones ('striped beds') into coarser-grained sandstones which are invariably wave-rippled and cross-bedded. The delta-front facies are of two types; those which are clearly wave-reworked and appear to have formed as shallow water sand sheets rather than point-concentrated mouth-bars, and those which do appear to have formed as mouth-bars, or parts of mouth-bar complexes. The latter, however, are most commonly developed on the delta-top, where 'deltas' prograded into non-marine or largely non-marine interdistributary bays. The former, on the other hand, appear to have prograded into at least partially marine conditions (possibly undergoing regression). In such sequences as these, thin wave-rippled sand sheets are developed, which are characterised by wavy, flaser and lenticular bedding (cf. Reineck and Wunderlich 1968). Trace fossils and bioturbation are common, as are muddy and silty laminae rich in mica and plant remains. Trace fossils include *Asterosoma*, *Teichichnus*, *Monocraterion*, *Palaeophycos*, *Scolicia*, *Zoophycos*, *Rhizocorallium*, *Chondrites*, *Planolites*, *Gyrochorte*, *Arenicolites*, and *Skolithos*. The sandstones also contain ripple cross-laminae, cross-laminae, climbing ripples, and are usually sharp-based, with load-casts, and sole structures such as tool marks, flute casts, prod marks and gutter casts.

At the delta-front, the alternation of background mudrocks and the river-generated sand incursions (sandstones) gives rise to 'striped beds' (Kelling and George 1971). Deltas prograding into deeper water (e.g. above the 'Charlestown Main Limestone marine phase') are characterised by thin, sharp-based sandstones intercalated with thick mudrocks rather than sand sheets resting directly on top of marine limestones which reflect delta progradation into shallower water. Delta-front sands, as well as being extensively wave-rippled are also commonly hummocky cross-stratified, and these structures are often associated with ?storm-induced soft sediment deformation structures (e.g. pseudo-nodules, slumped blocks etc.).

Delta-front sequences are sometimes capped by mouth-bars which are characterised by cross-bedded sandstones representing sandwave/dune bedforms deposited on the bar crest and associated with high flow stage activity in the associated distributary channels, which often cut into the delta-front sediments and their own mouth-bars. Mouth-bars, however, although being the focus of sand deposition at the delta-front show evidence of wave-reworking (wave-ripples), and abandonment facies overlying mouth-bars often provide indications of marine reworking in the form of marine/quasi-marine trace fossils such as *Rhizocorallium* and *Teichichnus*. The delta-front 'striped beds' often display features suggestive of contrasts in competency such as loop bedding, pull-apart structures and microfaults (cf. Cole and Picard 1975), and the contact between the delta-front facies and the prodeltaic facies is commonly loaded and erosive, with pseudo-nodules and associated erosion surfaces. The delta-front sands are initially subordinate to muds and silts, and display lenticular bedding and starved-ripples which are often loaded and convoluted (soft sediment deformation structures). Indistinct vertical burrows and horizontal trails are also characteristic of this facies. The lenticular bedded heterolithic units with starved ripples are overlain by wave-rippled, wavy and flaser bedded sandstones which are usually mud-draped. Siderite nodules are common in the mud- and silt-rock dominated part of the delta-front sequence, and the mouth-bars and delta-front sand sheets are sometimes capped by paleosol facies (e.g. coals, fireclays, ganisters, seat-earths, rooted horizons etc.) and/or bioturbated abandonment facies (De Raaf *et al.* 1965; Elliot 1976a). The uppermost sand dominated members of the mouth-bar sequences are also occasionally channellised indicating that the distributary channels cut into their own mouth-bars. It is interesting to note that the delta-front sand sheets may relate to delta-front equivalents of the delta-top interdistributary bays, whilst the mouth-bars are the delta-front equivalents of the distributary channels.

The delta-front facies clearly represents the earliest influxes of delta-derived sands which prograded into shallow water, wave-agitated conditions, where they were invariably reworked and redeposited above effective wave-base. Thin sandstones at the base of the coarsening-upward units, however, are often not wave-rippled, implying that initial deposition was below effective wave-base, and that the sequences essentially represent shallowing-upwards trends. Sometimes two or three coarsening-upward sequences are superimposed upon one another above the marine phases of the cycles. The lowest of such a group of sequences is usually characterised by extensive wave-reworking, abundant marine/quasi-marine trace fossils and a sheet-like morphology indicating marine wave influence. The higher sequences, in contrast, are capped by mouth-bars and are more constructive, and these are less wave-rippled and devoid of many of the formerly abundant trace fossils.

6.3.iii. Delta-top facies

The delta-top facies succeeds the delta-front facies and generally consists of three broad subdivisions; the distributary channels, interdistributary bay facies, and delta-top abandonment facies (largely paleosols).

The delta-plain distributary channels are generally composed of basal coarse members consisting of trough and/or tabular-planar cross-bed sets which are grouped into cosets and are often separated by large-scale reactivation surfaces. The bases of the channel sandstones are often erosive and undulatory and the channels sometimes cut down into the delta-front/prodelta facies and even into the underlying marine phase. The bases of the sandstones are often characterised by scour pits filled with lithoclasts, drifted logs and other plant remains. These intraformational conglomeratic lags line the erosive bases and fill the scour pits, and consist of mudclasts, crinoidal mudclasts, siderite nodules and coaly 'rafts'. Such lag deposits result from the erosion and undermining of the river cliff wall, which often culminates in channel collapse structures. Once the material falls into the channel it is reworked in the channel thalweg to form a lag at the base of the channel. Channel collapse structures and associated soft sediment deformation features are often observed in channel sandstones along with lateral accretion surfaces (the epsilon cross-stratification of Allen (1963)) which represent deposition on a point bar accreting outwards into the channel in the direction of the erosion of the river cliff. Lateral accretion structures are common in the Pathhead Beds and Lower Limestone Group, and may occupy the whole of the sand body or be confined to small channels within larger ?braided stream channel complexes (cf. Allen 1983). Most of the channels, however, are considered to be of the meandering type, but the Seafield Tower Sandstone and its equivalent in Midlothian, the North Greens Sandstone, may have been deposited within a braided river system. The laterally accreted sandstones are often punctuated by finer-grained siltstones and mudrocks, and the sandstones are sometimes rooted suggesting periodic abandonment of the point bar surface and colonization by vegetation. These features, along with the reactivation surfaces, indicate flow stage fluctuations in the distributary channel.

Palaeocurrent directions from the small 'cut-and-fill' channels, and trough and tabular cross-bedding indicates distributaries flowing to the S and SW, with some minor deviations suggestive of meandering. The coarse members of the channel sandstones are also characterised by soft sediment deformation features such as water escape structures and convoluted bedding. Individual foresets within cross-beds often show grading and fining-upward trends. The coarse members of the channels often display cut-and-fill structures, which are represented by small channels with widths of 4-6 m. These and other erosional structures in the coarse members are usually draped by mudrocks and other fines. Fossils in the coarse members are rare, but drifted plant remains are common. The coarse members are commonly overlain by fine members consisting of thin cross-laminated sandstones which are often rooted, and are interbedded with finer-grained mudrocks, coals and siltstones. These are overlain by paleosol facies which if localised appear to record channel abandonment, but if widespread represent abandonment of the whole delta-top. Trace fossils are generally restricted to delta-front, prodelta and marine facies, but in some rare cases channel sandstones are associated with marine trace fossils suggesting marine influence on the lowest part of the delta plain (Chisholm 1970b).

The channels appear to have been characterised by fluctuating river stage levels. At high stage, large dune and sandwave bedforms were deposited, and at even higher velocities plane-laminated and primary current lineated beds were developed. At low flow stages, however, the bedforms were often eroded and modified, forming reactivation surfaces and becoming mud-draped. Channel abandonment was either the result of local avulsion, or was part of a widespread delta-top abandonment due to a rise in the water table before the onset of a marine transgression. The channels were the major conduits by which sediment was transported to the delta-front, but in some marine-influenced parts of the succession they are not very well developed. The assertion by Belt (1975), however, that channels and major constructive delta progradational phases are not well represented in the Lower Limestone Group cannot be supported.

Contemporary with the delta-top distributary channels on the ancient delta-top were the interdistributary bays (cf. Elliot 1974b). Investigation of major inter-marine clastic intervals in the Pathhead Beds and Lower Limestone Group clearly shows that channel sands were contemporaneous with areas of finer-grained sedimentation (bays), as the sands pinch out laterally over relatively short distances. The bays are not considered to have been commonly connected to open marine conditions via the delta-front, as in lobate-type deltas the front of the delta is barred by delta-front sheet sands. Delta-top interdistributary bay lakes in the Lower Limestone Group and Pathhead Beds are characterised by coarsening-upward sequences similar to delta-front sequences, marking the progradation of 'crevasse splay deltas' into the shallow restricted non-marine lakes. These sequences are often underlain and overlain by paleosols (e.g. organic soils, gley soils, podzols) reflecting either waterlogged or freely drained conditions. Some trace fossils are present in the bay-lake sequences (e.g. vertical burrows and horizontal trails such as *Gyrochorte*), although they are uncommon and fossils are very rare, and are only occasionally represented by the non-marine bivalve *Curvirimula*, although plant remains are very abundant. In general, the 'background' sediments of the bay lakes appear to have been predominantly silts and muds. The progradation of crevasse channels, however, resulting from breaching of the levees of a major distributary channel caused a rapid influx of crevasse splay sand sheets. These are represented by sharp, erosive-based sandstones with load-casted bases. They are often cross-laminated, wave-rippled and even cross-bedded, and are frequently rooted. Small crevasse channels are also sometimes observed cutting through the progradational 'crevasse delta'-front striped bed sequences on the delta-top, and the erosive cut-and-fill channel bases are often lined with reworked intraclasts. A large number of variations upon a general theme are observed, however, and most of the variations outlined by Elliot (1974b) for interdistributary bay sequences are observed. These include overbank flooding sequences where fine sediments are overlain by paleosols, or where thin sandstones alternating with muds are capped by paleosols. Crevasse splay sequences and minor mouth-bar-crevasse channel sequences are also present and interdistributary bay sequences are often represented by 'fine members' overlying the coarse members of abandoned channels. Bay mouth/sand spit sequences are sometimes present at the delta-front, barring the bays from open marine conditions.

Bay-lake sequences are capped by a variety of different types of paleosols, including podzols represented by quartz-arenitic sandstones (ganisters) with stigmarian roots and well-developed albic horizons (cf. Percival 1986). These represent well-drained soils, and contrast with gley soils and coals (organic soils) which indicate more hydromorphic conditions. As with the channels, these paleosols can indicate either localised (bay) abandonment (i.e. abandonment of part of the delta-top), or more widespread abandonment of the delta-top. Siderite nodules which are characteristic of delta-top bay muds are generally suggestive of non-marine conditions, similar to those developed at the present day in Mississippi Delta bays (Ho and Coleman 1969).

The delta-top facies are invariably capped by paleosols which are represented by gley soils, organic soils and podzols. The gley soils are called fireclays, seat-earths and seatclays etc. (Moore 1968b) in the older literature and are often nodular, with iron (Fe) carbonate nodules in a siltstone host rock, and rootlets and pyrite. Such paleosols are often overlain by a coal and may contain coaly fragments, and are considered to have formed in persistently waterlogged conditions. The associated coals are organic paleosols which formed as peat blankets in water saturated conditions where the bacterial destruction of organic matter (humus) was suppressed. These types of paleosols formed in areas where the water table was high and are often developed prior to marine transgressions when the water table was rising. The quartz-arenitic paleosols (formerly called ganisters (Percival 1983)) contain stigmarian roots, *Lepidodendron* trunks and are often underlain by clay-rich horizons formed by leaching and illuviation. These and associated ferruginous podzols with B horizon accumulations of iron oxides are thought to have formed in settings characterised by free water drainage. Coalified rootlets and rootlets encased in ferruginous concretions are common, as are albic horizons characterised by very irregular, slaggy contacts with underlying horizons. All these types of paleosol are equally abundant and compound paleosols are present. The presence, however, of paleosols recording free drainage on what was otherwise a waterlogged lower delta plain may indicate periods of tectonic uplift.

CHAPTER 7

A comparison of the upper part of the Dinantian Pathhead Beds in the Glenrothes Borehole, central Fife, with the East Fife coastal exposures at Elie-St Monans; an example of conflicting depositional styles on highs and lows.

7.1. Introduction

During the Dinantian, over 2000 m of Strathclyde Group sediments were deposited in the rapidly subsiding (tectonically negative) East Fife Low (Forsyth and Chisholm 1977). To the west in the Lomond Hills-Glenrothes district of central Fife, however, the succession is severely attenuated, and the Strathclyde Group is represented by a mere 41 m of Pathhead Beds strata which overlie a major intra-Dinantian unconformity (Browne 1980, 1986; Browne *et al.* 1986). This suggests that whilst the Lomond Hills area of central Fife represented a tectonically positive high, the adjacent East Fife area was a rapidly subsiding low which acted as a sediment trap, encouraging the progradation of active delta lobes (cf. Leeder and Strudwick 1987). Towards the end of the Dinantian, however, sediments were deposited on the high (e.g. uppermost Pathhead Beds and Lower Limestone Group) suggesting that tectonic activity was beginning to wane, and/or rises in sea level (cf. Ramsbottom 1981) resulted in the submergence of tectonically positive areas. Highs in the Midland Valley Dinantian appear to have been characterised by condensed sequences sometimes containing unconformities. The clastic:carbonate ratio was also considerably lower than within the adjacent lows (Goodlet 1957, 1959), and highs are often characterised by volcanic plugs and vents (Francis 1961a), suggesting that they were prone to volcanism (Francis 1983a, 1983b). Although these NE-SW to N-S trending highs and lows are poorly understood, it has been suggested that similar structures in the north of England represent tilt blocks/half-grabens, the highs developing upon the footwall of the tilt block (Grayson and Oldham 1987; Leeder and Strudwick 1987).

7.2. Rationale

The Pathhead Beds are the uppermost of the five informal lithostratigraphical divisions of the Calciferous Sandstone Measures in East Fife (Forsyth and Chisholm 1977), which have recently been given the status of a formation (Browne 1986; Browne *et al.* 1986) in the formal Strathclyde Group (Paterson and Hall 1986). The upper part of the Pathhead Beds largely consists of Yoredale-type cycles comprising intercalations of marine limestones and mudrocks with fluvio-deltaic clastics. These facies are generally unlike those developed throughout much of the Strathclyde Group (e.g. Oil-Shale Group facies), and bear more similarity to those developed in the overlying Lower Limestone Group. Outside East Fife, however, these beds have usually been placed in the Calciferous Sandstone Measures, and no differentiation has been made between them and the underlying non-marine facies. A case can be made for extending the use of the division of the Pathhead Beds outside East Fife, to cover the Yoredale-type cycles developed directly below the Lower Limestone Group (cf. Browne *et al.* 1986) throughout the Midland Valley. Until recently, for example, marine limestones and intercalated facies now assigned to the Pathhead Beds in central Fife (Browne *et al.* 1986), were included within the Upper Oil-Shale Group. Such an inclusion is clearly a mistake, as Oil-Shale Group facies (*sensu-stricto*) are dissimilar to Yoredale-type sequences, and should not on facies grounds be included within the same lithostratigraphic unit.

Unlike the underlying Oil-Shale Group (and stratigraphic equivalents), the Pathhead Beds are widely developed over much of the Midland Valley, and some of the major marine phases are areally widespread. This suggests a gradual unification of the 'Midland Valley Basin', possibly due to a waning of tectonic controls and volcanicity which had previously helped to demarcate the basin. One of the most important factors, however, was the advent of widespread marine transgressions which started to penetrate the area during the deposition of the Pathhead Beds. These incursions transgressed local facies controls and established widespread marine marker horizons, presumably as a result of rises in sea level during the late Asbian and early Brigantian (Ramsbottom 1981). The Pathhead Beds are therefore an important link between the non-marine deposits of the Oil-Shale Group (and equivalent strata) and the Lower Limestone Group, which represents the acme of marine conditions in the Midland Valley during the Dinantian.

In this study, the 41 m thick Pathhead Beds sequence in the Glenrothes Borehole [NO 25615 03142], central Fife, is compared with the equivalent section which crops out on the East Fife coast around Elie and St Monans. Correlations using the major marine marker horizons of the Charlestown Station (St Monans Brecciated), St Monans White, and Upper and Lower Ardross limestones has enabled a comparison of the intervening clastic-dominated sequences represented in the borehole, with the equivalent-aged inter-marine intervals developed to the east along the coast.

7.3. Pathhead Beds

The Pathhead Beds have been penetrated in a number of boreholes in East Fife (Forsyth and Chisholm 1968), but are perhaps best known from the coastal sections where they are 311 m thick and exposed in a complete unbroken sequence (Forsyth and Chisholm 1977). These rocks have largely been assigned to a so-called 'grey facies' (Forsyth and Chisholm 1977) consisting of coarsening-upward and fining-upward sequences and indeterminate sequences containing silty and argillaceous beds which are grey in colour. Paleosols (coals and rooted horizons) are widespread, as are bedded dolomites and nodular ironstones. A so-called 'thick sandstone facies' was also recognised (although only partially represented in the Pathhead Beds), consisting of sandstones between 9-36 m in thickness. Along the coast, only one marine horizon (marine band) has been identified in the lower part of the formation, but the upper part is characterised by the presence of a *Lingula* band and five marine bands with rich and varied marine faunas, resembling those of the overlying Lower Limestone Group (Forsyth and Chisholm 1977). In the Glenrothes Borehole, the Upper and Lower Ardross, the Duloch Under and the St Monans White limestones were identified, although correlation with the marine bands present in the coastal sequence is problematical and only very generalised comparisons can be made. It is suggested, however, that the Duloch Under Limestone recognised in the borehole may be an equivalent of the Pathhead Marine Bands which are present between two major sand bodies on the coast. Therefore, by generally correlating these major marine phases (Fig.7.1), broad comparisons between inter-marine clastic intervals in the borehole and the coastal sections can be made.

7.4. Pathhead Beds, Glenrothes Borehole, central Fife and coastal sections at Elie and St Monans, East Fife; Ardross limestones and associated beds

In the Glenrothes Borehole, the uppermost 41 m of Pathhead Beds strata is separated from the underlying Ballagan Formation (cf. Belt *et al.* 1967) by a major intra-Dinantian unconformity which appears to cut out almost 2000 m of Strathclyde Group strata. This unconformity is marked by a 0.23 m thick basal conglomerate which rapidly fines-upward through 5.5 m of medium to fine-grained grey-white coloured sandstones into a 3 m thick sequence of interbedded marine limestones and mudrocks containing a rich and varied marine fauna including productid brachiopods, crinoid ossicles, *Crurithyris* sp., lingulids, and bivalves such as *Promytilus*, *Edmondia* and *Sanguinolites*. (Fig.7.7). These marine beds have been correlated with the Upper and Lower Ardross limestones (Brand in Browne *et al.* 1986).

To the east, in the Elie-Ardross coastal section, East Fife, the major intra-Dinantian unconformity is absent, and the sequence is conformable. Here, the two Ardross limestones are separated by a major progradational coarsening-upward sequence represented by a distributary channel mouth-bar sequence, which is subdivided into three major coarsening-upward units, termed A, B, and C (Fig.7.2).

7.4.i. Elie-Ardross mouth-bar sequence; coarsening-upward unit A

The clastic sequence between the Lower and Upper Ardross limestones at Elie-Ardross is approximately 11-12 m thick and consists of several coarsening-upwards sequences which are superimposed upon one another (Fig.7.2). The Lower Ardross Limestone which contains crinoid ossicles and articulate brachiopods is overlain by a 2 m gap succeeded by 0.55 m of mudrocks and sandy mudrocks which are characteristically load-casted, lenticular bedded, and contain ball and pillow structures and a prominent erosion surface. Palaeocurrents indicated by starved ripples suggest a predominantly south-westerly palaeoflow and these beds are characterised by the quasi-marine trace fossil *Teichichnus*. The sandy mudrocks coarsen-upward into a massive 3.25 m thick sand body which is sharp-based and predominantly composed of climbing-rippled sandstones.

These contain bivalve escape burrow shafts (cf. Broadhurst *et al.* 1980), pyritised fragmentary plant remains, cross-laminae (current ripples), planar-laminated horizons, and are medium to coarse-grained. Erosion surfaces characterised by pyritised intraclasts are present and palaeoflow indicators suggest paleocurrents to the S and SW. The uppermost 0.55 m of the sand body has an erosive base, contains soft sediment deformation features and is trough cross-bedded. It is characterised by massive, exhumed dune-like structures with wavelengths of 5 m and amplitudes of 0.50 m. The top of this uppermost unit contains an erosion surface, overlain by cross-laminated sandstones with a wave-rippled, rooted, bioturbated top and N-S palaeocurrent trends (from wave-ripples). The wave-rippled top displays giant examples of the trace fossil *Rhizocorallium*, accompanied by ?*Beaconites* and *Teichichnus*.

7.4.ii. Interpretation of A (Fig.7.2)

The major upward-coarsening unit (A) is interpreted as a delta-front mouth-bar prograding onto a shallow marine shelf environment (as represented by the Lower Ardross Limestone), and the presence of *Teichichnus* towards the base indicates at least quasi-marine prodeltaic conditions. The soft sediment deformation features such as load casting and ball and pillow structures at the base of the unit clearly record the progradation of deltaic sands onto thixotropic prodelta muds, and the presence of lenticular bedding and starved ripples suggests that the environment was initially starved of coarse clastic sediment. The major erosion surface at the base of the unit and the relative scarcity of wave-ripples in the major sand body suggest only minimal wave-reworking, and the river-generated climbing-rippled sands indicate that the delta was highly constructive with mouth-bars forming as the foci of distributary channel sand deposition at the delta-front. Periodically higher rates of deposition are signified by bivalve escape burrows (cf. Broadhurst *et al.* 1980) and increases in the current velocity apparently resulted in plane-laminated beds. The horizons rich in drifted plant debris are characteristic of mouth-bar sedimentation (e.g. 'coffee-grounds' observed in modern mouth-bars (Galloway and Hobday 1983)), and the major trough cross-bedded sand body with an erosional base and large exhumed dune bedforms is interpreted as the deposit of a fluvial distributary channel, which due to rapid progradation cut into its own mouth-bar. The thin wave-rippled and cross-laminated sand veneer on the top of the channel records localised channel abandonment, when the area became a shallow wave-agitated bay with an *in situ* vegetation (cf. Elliot 1974b; Fielding 1984). The presence of the marine/quasi-marine trace fossils *Rhizocorallium* and *Teichichnus* suggests brackish-marine conditions in the bay-lagoons, which were possibly connected to more open marine conditions at the delta-front (a feature of many elongate deltas (Elliot 1976a)). This bioturbated horizon is an abandonment facies, probably restricted to the mouth-bar (cf. De Raaf *et al.* 1965; Elliot 1976a; Maddox and Andrews 1987), and representing ?marine/quasi-marine biogenic and wave/current reworking during compaction, subsidence and low rates of sedimentation.

7.4.iii. Coarsening-upward unit B (Fig. 7.2)

This unit consists of three minor coarsening-upward sequences superimposed upon one another. The lowest sequence is only 0.60 m thick and consists of a transition from silty mudrocks and muddy sandstones at the base, to medium-grained sandstones at the top. The silty muds are characterised by starved ripples and lenticular bedding, with palaeocurrents to the SW. The muddy sandstones are cross-laminated and climbing-ripple cross-laminated, and a prominent erosion surface separates these beds from the uppermost trough cross-bedded sandstones with palaeocurrents to the SSW and NE.

The middle sequence which is 0.88 m thick consists of mudrocks, silty mudrocks and fine-grained sandstones which contain starved ripples at the base, passing upwards into medium to coarse-grained sandstones containing climbing-ripples at the top. The upper surface of the uppermost bed is characterised by abundant horizontal burrows and trails.

The upper sequence is approximately 1.60 m thick and consists of mudrocks, siltstones and fine-grained sandstones at the base, which are lenticular bedded, and contain starved ripples and vertical burrows.

These coarsen-upward into sandstones and sandy mudrocks which are cross-laminated (current-rippled) and contain transported plant remains and abundant vertical burrows towards the base. The top of the sequence consists of sandy mudrocks and coaly mudrocks containing *in situ* rootlets, transported plant remains and micaceous partings which pass upward into a 0.24 m thick coal with *in situ*, erect *Lepidodendron* tree stump casts (tree trunks).

7.4.iv. Interpretation of B (Fig.7.2)

Coarsening-upward unit B consists of three minor coarsening-upward sequences which represent the repeated infilling of delta-top bays, lakes and interdistributary bay-lagoons (cf. Elliot 1974b; Broadhurst *et al.* 1980; Fielding 1984; Haszeldine 1984). The lowest sequence mimics the major coarsening-upward unit A, in that it represents a small mouth-bar which was cut into by its own feeder channel and then abandoned. This mouth-bar, however, was probably associated with a minor crevasse splay channel which prograded into a very shallow (ca. 2 m deep) delta-top lake (cf. Haszeldine 1984) which may originally have been open to some marine influence (e.g. presence of quasi-marine/marine trace fossils in the previous abandonment facies). The middle sequence also represents a crevasse splay sand complex spilling into a shallow bay-lake, and originating from a major delta-top distributary channel. The abandonment of these sands is recorded by the bioturbated and trace fossil hosted sandy veneer which caps the sequence and is a destructive, reworked abandonment facies. The upper sequence is a coarsening-upward interdistributary bay fill, capped by a coal recording the development of an organic paleosol peat blanket which developed across the bay as a result of the preservation of humic organic matter in water-saturated conditions. The underlying rooted sandy paleosols suggest that an *in situ* vegetation colonised the infilled bay, establishing itself on the top of abandoned crevasse splay sands which had infilled the shallow non-marine lake. Larger *in situ Lepidodendron* club mosses also developed suggesting that this abandonment 'event' was a significant and major one which covered a large time period. It must be stressed, however, that these abandonment facies (both paleosols and bioturbated beds) do not represent major delta-top abandonment (cf. Elliot 1975), but only a localised abandonment of individual delta-top interdistributary bays (cf. Elliot 1974b).

7.4.v. Coarsening-upward unit C (Fig.7.2)

As in coarsening-upward unit B, C consists of three minor coarsening-upward sequences superimposed on top of each other. The lowest sequence is 1.20 m thick and consists of basal blue-grey siltstones with starved ripples and sand stringers coarsening-upward into a medium-grained sandstone with cross-laminae (current ripples) at the base and climbing ripples towards the top. It has a sharp ?erosional base and contains transported plant fragments. The top surface of the climbing-rippled sandstone has a thin rippled veneer, with N-S palaeocurrent trends. The middle and upper sequences are largely sandstone dominated although the base of the middle sequence is characterised by a thin, diminutive siltstone bed, which coarsens-upwards through cross-laminated silty sandstones into a major trough cross-bedded sand body with erosional, coaly-draped reactivation surfaces. The upper sequence consists of a 1 m thick sandstone with fine to medium-grained, coaly draped cross-laminated sandstones at the base, coarsening-upward into coarse-grained, massively trough cross-bedded sandstones at the top, with palaeocurrents to the S. This sequence is capped by a 0.11 m thick rooted sandstone which underlies the marine Upper Ardross Limestone.

7.4. vi. Interpretation of C

The lower sequence records the progradation of a mouth-bar, and associated crevasse channel into a shallow interdistributary bay, which was later abandoned and wave-reworked in shallow water, agitated conditions. The middle sequence is interpreted as representing the progradation of a more major distributary channel which cut into the 'prodelta' sediments and was characterised by large dune-like bedforms migrating at high flow stage, and reworked at low flow stage. The upper sequence records an increase in current velocity and consequently in the bedform size within a distributary channel, with small sandwaves being succeeded by large curve-crested dune bedforms perhaps deposited during a major flood event. The abandonment facies which caps the channel sands records channel abandonment and probably also represents a major delta-top abandonment when the whole of the delta was abandoned and marine conditions prevailed. The rooted sandy paleosol below the Upper Ardross Limestone represents the development of an *in situ* vegetation on the delta-top during a ?rise in the water table associated with the ensuing 'Upper Ardross Limestone marine transgression' which probably signifies a major rise in sea level.

7.5. Upper Ardross Limestone (Figs.7.1, 7.2, 7.3, 7.7)

The Upper Ardross Limestone, together with the Lower Ardross Limestone contains an abundant marine fauna including crinoids and colonial corals. These mark the first definite appearance of corals in the Scottish Carboniferous of the Midland Valley (Forsyth and Chisholm 1977), and the marine bands are the first of a series of marine transgressions which were to reach their acme in the overlying Lower Limestone Group. At Ardross-Elie, the 0.46 m thick Upper Ardross Limestone overlies a thin dark shale and is totally dolomitised (cf. Forsyth and Chisholm 1977; Selim and Duff 1974). It is overlain by at least 5 m of mudrocks which contain a marine fauna which is often associated with large septarian nodules measuring up to 33 cm long and 8 cm high. In the Glenrothes Borehole the sequence between the presumed equivalents of the Ardross limestones is composed of a 2.30 m thick marine mudrock, and the marine-influenced sequence of limestone and shale interbeds is totally different to that developed at Ardross.

7.6. Ardross limestones and associated beds; interpretation (Glenrothes borehole and East Fife)

The sequence which includes the supposed Ardross limestones in the Glenrothes borehole is quite dissimilar to that developed along the Elie-Ardross coast in East Fife, and is characterised by fine-grained marine limestones and shales, although the mudrocks between the Ardross limestones contain a thin coal and a quasi-marine/brackish water fauna. In the borehole, the fining-upward trend from the basal conglomerate to the marine sequence, via sandstones suggests a waning positive tectonism with subsidence promoting deposition. The Ardross limestones clearly represent major marine phases as do the intervening shales, although the presence of a thin (0.05 m) coal seam and quasi-marine/brackish water faunas (e.g. fish, ostracodes, lingulids and bivalves) in some of the beds suggests that the incursion consisted of a complex series of minor transgressions and regressions, during which organic paleosols occasionally accumulated in brackish water swamps marginal to the more open marine conditions. The sequence in East Fife between the Ardross limestones is much thicker and sand-dominated, representing a major progradational deltaic phase which established delta-top conditions. Throughout the sequence, however, marine influence is characterised by the presence of trace fossils known to be characteristic of marine/quasi-marine conditions. These are usually found in facies which developed when the delta was periodically abandoned, and subjected, therefore, to marine reworking.

In conclusion, it is proposed that some marine influence was maintained between the deposition of the Ardross limestones. In the Glenrothes area of central Fife, mudrocks containing one thin coal and representing marginal/quasi-marine conditions were deposited on a tectonic high, whereas in the more rapidly subsiding East Fife Basin, a major progradational deltaic mouth-bar phase is recorded with associated delta-top facies. Despite the highly constructive nature of this sequence, some marine influence is still noted, although the presence of actively prograding delta lobes does not appear to have been conducive to the establishment and preservation of body fossils. The absence of sandstones between the limestones in the Glenrothes Borehole, and the condensed nature of the interval suggests that whilst some subsidence was taking place, the area was still a tectonically active high, where subsidence rates were still considerably less than in the adjacent East Fife Low. In East Fife, rapid tectonic subsidence encouraged the progradation of active delta lobes, even during times of marine influence (e.g. between the two Ardross limestones). The marine phases themselves appear to have been largely independent of the local tectonic controls, but prolonged marine phases containing regressional pulses resulted in the deposition of contrasting sequences in areas characterised by different subsidence rates. In East Fife, because of major tectonic subsidence, the inter-marine phase between the Lower and

Upper Ardross limestones contains a major intercalated progradational (though marine-influenced) deltaic sequence, whilst in the tectonically stable/positive Glenrothes area of central Fife, the Lower-Upper Ardross limestones are merely separated by a thin condensed sequence of quasi-marine muds containing a thin coal which may be a correlative of the coal at Ardross. This marine-influenced sequence, free from prograding deltaics, records the subtle 'waxings' and 'wanings' of the transgression, which unlike the fluvio-deltaic clastics was not greatly influenced by the local tectonics.

7.7. Ardross limestones-St Monans Brecciated (Hurlet) Limestone interval

In East Fife, along the Ardross-Elie coastal section, the interval between the Upper Ardross and St Monans Brecciated limestones contains two very major sandstone bodies which occupy much of the sequence. Between the two sandstones, however, the Pathhead Marine Bands (Forsyth and Chisholm 1977) are developed, which may be equivalent to the Duloch Under Limestone in the borehole (Fig. 7.1). In the Glenrothes Borehole, the interval is occupied by six coarsening-upward sequences, three of which are capped by marine phases (Duloch Under (?Pathhead Marine Bands), St Monans White and St Monans Brecciated limestones) (Figs.7.1, 7.7, 7.8 and 7.9). No major sandstones are present and the interval is only 33 m thick, compared with the 130 m thick, equivalent-aged sequence in East Fife.

7.7.i. East Fife (Figs.7.3 and 7.4)

The marine mudrocks above the Upper Ardross Limestone coarsen-upward through silty mudrocks, siltstones and silty sandstones into wave-rippled sandstones which are rooted towards the top and overlain by coals, coaly shales and siltstones. This sequence is approximately 11 m thick and the mudrocks contain nodules towards the base, a ?non-marine fauna, and thin sandstone beds, some of which are cross-laminated and characterised by pull-apart structures (cf. Cole and Picard 1975). The wave-rippled sandstones are heterolithic, and the ripple crests are orientated NE-SW with ripple indices averaging 4. The coaly beds are overlain by 2 m of clays and claystones which coarsen-upward into a 3 m trough cross-bedded sandstone containing diagenetic 'snuff-box' nodules and soft sediment deformation structures. This sandstone fines-upwards into coaly laminated siltstones which are part of the lower major sandstone body in the 'Ardross-Hurlet limestones marine phase' interval. At Ardross-Elie, only the lower 24.5 m of the sandstone is exposed, recording delta-top sedimentation, with major channel sandstones, bay-fill heterolithic deposits and associated crevasse channels. The major channel sand bodies consist of medium to coarse-grained sandstones which are predominantly trough cross-bedded with palaeocurrents to the SW, and are characterised by soft-sediment deformation structures (convolute laminae), coaly/bay fill reworked intraclasts, plant-rich horizons and large diagenetic 'snuff-box' nodules. The associated interdistributary bay sediments are represented by 'striped beds' consisting of intercalated thin sandstones, mudrocks and organic-rich horizons composed of plant debris. These are invariably wave-rippled, the troughs of the ripples filled with coaly material, with N-S and NE-SW palaeocurrent trends. These 'striped beds' (bay-fill deposits) are up to 0.70 m thick, often laterally discontinuous, and small crevasse channels with reliefs of approximately 0.5 m are observed cutting into them. The bases of such channels are invariably load casted and characterised by basal lags consisting of coaly chunks, 3-7 cm in length.

The upper part of the lower major sandstone body, the intervening Pathhead Beds, and the lower part of the upper major sandstone body (Fig. 7.1) were not studied, but the sequence containing the upper part of the sandstone body to the base of the St Monans Brecciated Limestone was investigated at outcrop on the west and east sides of the St Monans Syncline (Figs.7.4, 7.5 and 7.6). The upper major sandstone body is characterised by large-scale trough cross-bedding recording palaeocurrents to the SW, but the whole unit is highly disturbed by large-scale soft sediment deformation (liquefaction) structures. The 15.5 m of intervening strata between the sandstone and the St Monans White Limestone are characterised by nodular sandy-silty paleosols, mudrocks containing siderite nodules and bands, coals and coaly shales, and distinctive bioturbated ?marine/quasi-marine sandstones (often overlying coals) containing the trace fossils *Teichichnus* and

Pelecypodichnus (Fig.7.10). The St Monans White Limestone is 4 m thick and consists of interbedded limestones and shales. It passes upwards through marine mudrocks containing prominent siderite nodules into lenticular and flaser beds which are succeeded by interference wave-rippled sandstones with NE-SW crest orientations and ripple indices of 5. The coarsening-upward sequence is capped by a distinctive sandy paleosol containing large stigmarian roots, and smaller coalified roolets, which underlies the St Monans Brecciated (Hurlet) Limestone.

7.7. ii. East Fife; interpretation

The transition from the Upper Ardross Limestone into the lower major sandstone body at Elie-Ardross is marked by a progradational deltaic coarsening-upwards sequence with evidence of wave-reworking of the delta-front sands. The overlying coaly beds record abandonment of the delta-top and the development of organic paleosol peat deposits on the delta plain. The lower sandstone body is a complex delta-top sequence recording the migration of large distributary channels and the development of wave-rippled, heterolithic bay-fill deposits. These lake sediments appear to have been periodically cut into and eroded away by minor crevasse channels which originated via breaching of distributary channel levees during flood events. Once breached, minor crevasse channels formed, ripping up the bay sediments and incorporating the reworked material into a basal channel lag where it accumulated in the channel thalweg.

The lower sandstone body clearly represents a major deltaic phase with widespread delta-top sedimentation. The overlying Pathhead Marine Bands and associated strata, however, suggest that a major marine transgression took place after the abandonment of the deltaic phase, but the upper sandstone body indicates that deltaic conditions were quickly re-established. The upper sandstone body records major delta-top sedimentation with large trough cross-bedded cosets representing stacked curve-crested dune bedforms. The prominent soft sediment deformation features are interpreted as the result of sedimentary dewatering, possibly in response to contemporaneous tectonic activity (cf. Ord *et al.* 1988). The upper sandstone body is capped by a major paleosol indicating delta-top abandonment, and the intervening beds between the paleosol and the St Monans White Limestone are marine/quasi-marine influenced abandonment facies, with organic paleosols (peats), and bioturbated marine sandstones containing *Teichichnus* suggesting a marine-influenced subsiding/compacting deltaic complex. The St Monans White Limestone records a major marine incursion which was probably the result of a rise in sea level affecting much of the Midland Valley. The overlying sequence passing upward into the St Monans Brecciated Limestone represents the progradation of a delta lobe into marine waters, where the delta-front was wave reworked and attenuated. The paleosols which cap the coarsening-upward sequence and underlie the St Monans Brecciated Limestone represent delta-top abandonment facies with *in situ Lepidodendron* club mosses recording reduced rates of sedimentation and vegetation of the delta-top prior to the Hurlet transgression.

7.7.iii. Glenrothes Borehole, central Fife (Figs.7.7, 7.8 and 7.9)

The interval between the Upper Ardross Limestone and the equivalent of the St Monans Brecciated Limestone in the Glenrothes Borehole contains as many major marine phases as the coast sections in East Fife, but is considerably thinner. It consists of six small-scale coarsening-upward sequences representing delta progradation, five of which are capped by post-abandonment marine facies. Each sequence is fairly similar and generally consists of marine and non-marine mudrocks and siltstones which coarsen-upwards into siltstones and silty sandstones. The non-marine mudrocks contain abundant plant remains, occasional estheriids, and bivalves, whilst the marine/quasi-marine beds contain specimens of *Naiadites crassus*, *Orbiculoidea* sp., productids, *Sanguinolites* sp. and crinoids. These muddy and silty beds at the base of progradational sequences are also characterised by sandstone ribs, abundant pyrite, lenticular bedding, siderite beds and nodules, and starved ripples. They invariably coarsen-upward into interlaminated sandstones and siltstones which are wavy and flaser bedded, wave-rippled, bioturbated, load casted, and characterised by trace fossils and burrows. A distinctive feature of the six upward-coarsening sequences in this part of the borehole is the lack of any major sandstone bodies, and most delta-front deposits pass-upward into diminutive, rooted, fine-grained sandstones which are often silty and heterolithic, and only occasionally cross-laminated towards the base. The upper, rooted parts of the sandstones contain occasional stigmarian roots, and three of the coarsening-upward sequences contain coals, which overlie the rooted sandy paleosols. These abandonment facies are usually succeeded by marine mudrocks and limestones, although the abandonment facies capping coarsening-upward sequence 2 is overlain by plant-rich, but otherwise unfossiliferous non-marine mudrocks. The marine facies, however, are sometimes underlain or overlain by mudrocks yielding low salinity faunas of lingulids and bivalves such as *Naiadites*, which are interpreted as faunal phases developed prior to, or after the acme of the incursion.

7.7.iv. Glenrothes Borehole, interpretation

The Upper Ardross-St Monans Brecciated (Hurlet) limestones interval in the Glenrothes Borehole contains all the main marine phases which are present in East Fife, but the succession is less than 1/5 of the thickness of that developed in East Fife. This suggests that although the tectonically positive area of Glenrothes had started to subside and relatively normal patterns of sedimentation had been established, subsidence rates were much lower than those to the east, and the area still represented a Dinantian high (cf. Grayson and Oldham 1987). This is supported by the absence of any major sand bodies at Glenrothes, and the comparative thinness of the inter-marine clastic sequences. The coarsening-upward sequences clearly represent the repeated progradation and abandonment of delta lobes, with the delta-front sequences showing clear evidence of marine reworking.

7.8. Conclusions

The comparisons made between the Pathhead Beds in the Glenrothes Borehole and the equivalent sequence in East Fife highlight the facies and thickness changes which characterise a transect from a tectonically positive Dinantian high to a contemporary negative low. Due to more rapid subsidence, the lows are characterised by thicker successions with a higher clastic:carbonate ratio than the adjacent highs (cf. Goodlet

1957, 1959), and the presence of a greater number of major distributary channel sand bodies. This suggests that the lows were areas of more competent drainage characterised by major active deltaic complexes containing large distributary channel networks. The marine transgressions which are believed to have been the result of rises in sea level are more uniform, over low and high alike, suggesting that they were largely independent of local tectonic controls. As this is the case, they represent the only truly reliable stratigraphic marker horizons from which correlations between two areas with totally different clastic sequences can be correlated and compared. This study shows how such comparison can be achieved, and how it highlights the significant palaeogeographic and associated facies and thickness variations which characterised the tectonically active depositional setting in which the Yoredale-type cycles of the Dinantian Pathhead Beds and Lower Limestone Group were deposited. There is no evidence, however, to such that there was any major relief (e.g. fault scarps) (Francis 1983a).

Throughout the two sections studied it was also noted that as marine influence becomes increasingly significant towards the top of the Pathhead Beds, the nature of the delta-front sequences dramatically alters, with a great deal more wave-reworking and bioturbation in the stratigraphically higher beds. A decrease in the number of major channel sand bodies upsection also points to a deltaic complex which was becoming increasingly marine-influenced (Belt 1975), and less highly constructive through time. These features coincide with the increase in the number of marine limestones and shales which reach a peak of importance in the Lower Limestone Group. The lowest beds studied in East Fife (e.g. the Ardross-Elie mouth-bar section) record the first major marine transgressions to affect the Midland Valley, and it is from this point onward that the nature of the intervening clastic sequences also change, with a greater abundance of marine trace fossils and marine reworking suggesting an increase in marine conditions and a decrease in the fluvio-deltaic influence. This appears to have resulted in a modification of the deltaic complex from elongate to lobate (Belt 1975).

CHAPTER 8

Tectonic controls upon limestone emergent surfaces and the position of active prograding delta lobes; the uppermost Strathclyde Group (Brigantian Stage; Dinantian), East Lothian.

8.1. Introduction

Emergent surfaces upon the tops of limestone beds are a phenomenon which in recent years have been studied in many Dinantian sequences throughout England (Walkden 1974, 1987; Burgess and Mitchell 1976). Although such karstic surfaces are present within the Scottish Dinantian succession of the Midland Valley of Scotland, only a few studies have been made of them (Whyte 1973, 1981; Monro 1982a), and many await detailed investigation. One such surface has been recognized upon the top of the Middle Longcraig Limestone which crops out in the Catcraig and Longcraig coastal sections in East Lothian (Whyte 1973; Craig 1975; Clarkson 1986a; Davies *et al.* 1986). This karst is also present in the BGS Skateraw Borehole [NT 7373 7546], and all the localities where it is recognised are within the Upper Palaeozoic Oldhamstocks Basin (Lagios 1983). Although a recent BGS memoir (McAdam *et al.* 1986) has claimed that the karstic surface may be locally present in the Haddington area of East Lothian (outside the Oldhamstocks Basin), coastal sections at Aberlady Bay, and the section in the BGS Spilmersford Borehole (Fig.8.6) (Davies 1974) indicate that it is absent.

The Middle Longcraig Limestone occurs at the top of the recently erected Strathclyde Group (Paterson and Hall 1986), only a few metres below the overlying Lower Limestone Group. The carbonate and intervening clastic rocks are predominantly arranged in Yoredale-type cycles (Hemingway 1968; Wilson 1975), and the carbonate rocks are generally considered to have been deposited in open marine shelf settings (Wilson 1975), as a result of rises in sea level (Ramsbottom 1981). Emergent surfaces upon the tops of limestones are therefore often interpreted as the result of regressive phases. Localised karsts, however, confined to restricted areas are more difficult to explain in terms of falls in sea level, and tectonism has to be invoked (Whyte 1981). One of the major problems in determining the mechanisms by which emergent surfaces are initiated relates to the correlation of the limestones over large distances. It is, however, only by examining the limestones at a variety of localities that the geographic extent of the emergence can be estimated. In this study, the refined lithostratigraphy in the upper part of the Strathclyde Group and the overlying Lower Limestone Group enables the Middle Longcraig Limestone to be recognised not only throughout East Lothian and Midlothian, but also across the Firth of Forth to the north in Fife. Although Whyte (1973) claims to have recognised emergent features on the tops of limestones at this level throughout the Midland Valley, no evidence exists to support this, and certain localities in the Haddington district investigated during this study provide evidence which firmly refutes such a suggestion.

8.2. Catcraig/Longcraig, East Lothian; clastic interval between the Upper and Middle Longcraig limestones (Fig. 8.2)

The emergent surface is perhaps best exposed at Catcraig and Longcraig (Fig. 8.1) where it forms a spectacular wave-cut platform which is very well exposed at low tide (Fig. 8.2). Here, the clastic interval between the Middle and Upper Longcraig limestones is approximately 1.75-2.10 m thick and is largely composed of fine-grained rocks, and coarser clastic rocks such as sandstones are absent (Fig. 8.2). This interval thickness is abnormally small, and the usual upward-coarsening sequence capped by a sandstone which characterises the inter-marine part of most Yoredale-type cycles is absent. The anomalous nature of this interval has been noted by Clarkson (1986a), who remarked that the deltaic part of the cycle was absent. The Middle Longcraig Limestone has a very uneven upper surface, which is pitted by regularly spaced basin-shaped hollows (Fig.8.3A). This surface is overlain by a fireclay (claystone) which is of a variable thickness (0.35-0.75 m) and infills the hollows of the irregular top of the limestone. The fireclay is a dark, blue-grey coloured mudrock containing rootlets, specimens of *Stigmaria ficoides* and browny-red coloured nodules and pipes of sphaerosiderite which appear to have formed around rootlets as rhizocretions. Streaks of coalified material are also present and some roots pass down from this unit into the underlying limestone (Fig. 8.3B and C). The fact that the concretionary fireclay infills the potholes or hollows on the top surface of the limestone suggests that the hollows are penecontemporaneous in origin, and this assumption is supported by observations which indicate that the rubbly upper part of the Middle Longcraig Limestone is mixed with the fireclay (seatclay) (Davies *et al.*

1986). Some specimens of *Stigmaria ficoides* in the fireclay actually pass down into the underlying limestone (Whyte 1973) (Fig. 8.3B), and Hemingway (1968) reports that root systems from the thin coal (which overlies the fireclay) penetrate the top of the limestone, and that each rootlet is encased in a ferruginous concretion (Fig. 8.3C).

The fireclay passes upward into a very thin (0.05 m) clay which is overlain by a thin coal seam, 0.06 m in thickness. This thin foul-coal layer (Davies *et al.* 1986) is best observed in the low cliff at Catcraig (Clarkson 1986a), and is fissile to blocky, pyritous, and contains vertical cracks and joints. It has been reported to reach 0.1 m in thickness (Davies *et al.* 1986) and roots pass down from this horizon into the underlying rocks (Hemingway 1968). The overlying mudrock is 0.90 m thick, thinning to approximately 0.71 m along strike, and containing abundant lingulids and pyritic laminae in the lower part. In the upper part there are abundant marine fossils, including 'shell pavements' of the brachiopod *Eomarginifera*. Whyte (1973) has included this unit along with the overlying Upper Longcraig Limestone and termed it the 'basal shale' which was considered a useful horizon for purposes of correlation.

8.3. Middle-Upper Longcraig limestones interval; interpretation

The hollows on the top of the Middle Longcraig Limestone are clearly penecontemporaneous in origin as they are infilled by the overlying seatclay. The hollows themselves are probably features initiated by the solution of the limestone and these pits may have been produced around root systems and later enlarged by ?vadose diagenesis. This would explain the regularity of the spacing, and support the suggestion that they mark the position of large Carboniferous trees (Clarkson 1986a). The fact that the top of the limestone was vegetated is indicated by the presence of *in situ* rootlets and rhizocretions in the top of the limestone (Fig. 8.3C). These suggest that plants grew on the upper surface of the limestone and that the carbonate may have been soft enough to allow penetration by roots/rootlets. The overlying seatearth/seatclay and thin coal seam indicate the presence of a soil profile overlying the limestone, and the seatclay may be a type of gley soil which was at times partially emergent, but became progressively more waterlogged due to a rise in the water table. The coal is interpreted as an organic soil or peat, suggesting a relatively waterlogged area which began to develop in response to an ensuing marine incursion. The overlying mudrock is interpreted as a transgressive deposit resulting from a marine incursion, the acme of which is represented by the overlying Upper Longcraig Limestone. As this marine phase is recognised throughout the Midland Valley (Hurlet transgression), it was probably the result of a major rise in sea level, independent of local facies controls.

8.4. Comparison of the paleosol profile to modern soil profiles

The upper surface of the Middle Longcraig Limestone and the overlying interval compare well with modern and ancient soil-profiles. This paleosol profile consists of the palaeokarstic surface of the limestone, the overlying seatclay and the thin foul coal. These are comparable with the C, B, and A soil horizons recognised in modern soil profiles. The palaeokarstic surface of the Middle Longcraig Limestone represents the C horizon where partly altered bedrock or sediment passes down into fresh parent material. Here, carbonate goes into solution and kaolinite is produced in the acid tropical soil where leaching is intensive. Characteristics of the C horizon are the kaolinite-filled cavities and evidence of an *in situ* vegetation which may have been established. Sphaerosiderite is also present (Fig. 8.5A, B and C) (Tucker 1983) suggesting that the soil profile may have been partially emergent (Collinson 1986). The overlying seatclay or B horizon represents the zone of illuviation, where clays accumulate and sesquioxides of iron are precipitated. Excessive leaching in the humid tropical climate results in the generation of kaolinite in the acid soil, where an *in situ* vegetation is established. The coal, or A horizon represents the zone of eluviation where material is transferred to the B horizon below (e.g. clay minerals, colloidal organic matter and ions into solution). It is within this organic paleosol (peat blanket) that abundant organic matter was decomposing into humus to produce a peat deposit. Peat swamps require a more-or-less water saturated environment in which to form, otherwise oxidation and bacterial destruction of organic material will predominate, suggesting a humid climate and poor drainage (Anderton *et al.* 1979). Coals and other paleosols are often developed below marine horizons (Percival 1986), and it is suggested that the transition from emergent or partially emergent conditions signified by the C and B horizons to hydromorphic conditions indicated by the A horizon may have been initiated by a rise in sea level ultimately responsible for the deposition of the Upper Longcraig Limestone.

8.5. The Middle Longcraig Limestone

The upper surface of the Middle Longcraig Limestone is characterised by numerous regularly-spaced basin-shaped hollows or depressions (Fig. 8.3A) constituting an extremely irregular upper surface. These potholes average approximately 1.4 m in diameter and up to 0.50 m in depth and have been exhumed by present day erosion. The upper surface of the limestone is creamy, nodular and 'pseudo-brecciated', the pseudo-brecciation arising from the preferential weathering of the kaolinite-filled cavities which are numerous and interconnected within the uppermost part of the limestone (Fig. 8.4A, B and C). The slaggy top of the limestone is penetrated by abundant orange-pinky red weathering rhizocretions which are so numerous in some areas as to render the whole of the limestone surface an orangey colour. These rhizocretions are cylinder-shaped and circular in cross-section with diameters of 1.7-2.3 cm. The tubes consist of red-brown coloured outer rims with a grey core averaging 1-1.2 cm in diameter, and are sometimes enclosed around a coalified root (Fig. 8.3B and C). Coaly wisps and rootlets together with small (12 cm in length, and 2 cm in width) and very large (several metres in length) stigmarian rootlets also characterise the top of the limestone, and the Middle Longcraig Limestone contains immense coral colonies and 'carpets' of *Lithostrotion* which have led to this limestone being known as the 'spaghetti or macaroni rock' (Craig 1975).

8.6. Middle Longcraig Limestone; petrography

Study of polished blocks reveal that the top of the Middle Longcraig Limestone contains irregular-shaped cavities (with red-brown iron-stained edges) which are filled with a creamy-grey white coloured deposit of kaolinite (Fig 8.4). These clay deposits are pervasively developed throughout the top of the limestone and are not merely confined to the larger-sized cavities and vugs, and kaolinitic areas are invariably fringed by iron-stained rims. The clay deposits also contain scattered carbonate fragments of darker-grey coloured limestone with iron-stained rims which 'float' in the kaolinite. The development of these clay-filled vugs and cavities has affected much of the upper part of the limestone and very little of the original rock has remained unaffected. The clay deposits are penetrated by carbonised/coalified streaky rootlets which are very thin (less than 0.5 mm in width) and are largely restricted to the vugs and cavities.

In thin section the rock can be seen clearly to consist of two components; a) original limestone which is relatively unaltered, and b) altered limestone which is permeated by clay-filled cavities and vugs (Fig. 8.4). The contact between unaltered and altered areas is characterised by a diffuse boundary zone where there is an intimate intermingling of the clay fill and pieces of degraded carbonate which have been incorporated into the cavity. The red-brown coloured areas which commonly characterise the margins of cavities often contain abundant dolomite rhombs which are restricted to such areas and are not present throughout the rock. Where coalified rootlets occasionally penetrate the relatively unaltered limestone, there is an accompanying zone of iron-staining, suggesting that roots may have acted as conduits for ?oxidisation.

Uncovered (double-polished) thin sections subjected to cathodoluminescence (C.L.), illustrate that there is a great contrast in the C.L. characteristics of the cavity fill and the surrounding limestone. The areas of internal sediment have a very strong purple blue to turquoise luminescence (transient blue luminescence) suggestive of kaolinite. This is in strong contrast to the pale orange to orange-red luminescence of the surrounding carbonate. The use of C.L. enables the relationship of the clay fill to the relatively unaltered limestone to be determined in the areas adjacent to the cavity walls, where the amount of the kaolinite in the carbonate increases towards the cavity.

In the clay deposits, small carbonate fragments luminesce orange, and occasional yellow to green luminescing heavy minerals such as apatite also occur.

8.7. Middle Longcraig Limestone; interpretation and statement of problem

The Middle Longcraig Limestone contains immense coral colonies and coral 'carpets' of *Lithostrotion* which indicate 'normal' marine salinities, and it is suggested that the limestone was originally deposited in an open, shallow marine shelf environment, prior to exposure to the zone of meteoric water. The mechanisms whereby the top of the limestone became exposed to meteoric waters (emergence) could involve either; a) regression (eustatic fall in sea level) or, b) tectonic uplift. The palaeokarstic surface of the Middle Longcraig Limestone may have been produced when the limestone was directly exposed to the atmosphere, but it is more likely that it developed beneath a soil profile. Once exposed to the zone of meteoric water, it is likely that a large amount of $CaCO_3$ was leached by acidic/humic waters and pits formed around root systems of *Lepidodendron* club mosses, the roots perhaps acting as a focus for the concentration of intense solution of the limestone. This suggestion also helps to explain the very regular spacing of the hollows.

Karstification of carbonate rocks and sediments involves their exposure to the environment of meteoric water where $CaCO_3$ is dissolved and eroded, promoting geomorphological features which are referred to as karst topographies (Scoffin 1987). A zone of weathering will develop and although $CaCO_3$ is dissolved, some will locally precipitate. This, however, involves remobilization and reprecipitation of $CaCO_3$, rather than a new input, and deposition is therefore essentially diagenetic. The morphologies of karstic (emergent) surfaces in the Dinantian are relatively well known (Walkden 1974; Walls *et al.* 1975; Gray 1981). These range from smooth rolling and pit-bearing surfaces to those which are scalloped and fretted (terminology after Walkden 1987).

Karstic surfaces have been reported from Brigantian limestones in the Scottish Midland Valley (Whyte 1973, 1981; Monro 1982a), although attempts to correlate individual karstic surfaces over long distances (Whyte 1981) are fraught with many difficulties and do not appear to be viable (Monro 1982b; Wilson 1982). The karsts appear to have been developed at many different stratigraphic levels, examples being the Middle Longcraig Limestone at the top of the Strathclyde Group, and the Dockra Limestone ('white post') towards the middle of the overlying Lower Limestone Group (Whyte 1973, 1981; Monro 1982a). Some of the major problems relating to these emergent surfaces which still have to be fully resolved are the factors involved in initiating their development. With respect to the Scottish examples, tectonic activity has been invoked as a mechanism by which uplift could have taken place (Whyte 1981), possibly via the process of fault-controlled footwall uplift causing periodic uplift episodes close to basin axes (Leeder and Strudwick 1987). Alternatively, a fall in relative sea level would also result in possible emergence via a shoaling-upwards through peri- and supra-littoral facies (e.g. Maddox and Andrews 1987). The resultant emergent features are markedly diachronous, progressively younging towards the basin centre (Maddox and Andrews 1987; Leeder and Strudwick 1987). In parts of England where karstic surfaces are relatively well documented (Walkden 1987), two types can be clearly distinguished; a) those that are persistent and can be correlated over relatively wide areas, and b) those that are only locally developed. Bearing this in mind, the Middle Longcraig Limestone was investigated in the Skateraw Borehole (also in the Oldhamstocks Basin), and at two localities (Spilmersford Borehole and Aberlady Bay) in the Haddington district outside the basin (Figs. 8.1 and 8.6). It should be possible, therefore, to determine whether the emergent surface is a localised or widespread feature, so that its origin can be more fully determined.

8.8. Tracing the emergent surface away from Catcraig/Longcraig

The BGS Skateraw Borehole [NT 7373 7546] (Figs. 8.1 and 8.2), like Catcraig/Longcraig is located within the Upper Palaeozoic Oldhamstocks Basin, and the Middle Longcraig Limestone is also characterised by a very irregular 'potholed' surface associated with paleosol facies. The limestone is 1.22 m thick, nodular, creamy, hard and compact, and the very irregular top has a seatclay matrix (?clay-filled vugs and cavities). It is overlain by a 0.22 m thick pale grey coloured seatclay which contains small pale-brown sideritic nodules, and is crushed, broken and structureless. The seatclay passes upward into a 0.13 m thick coal with dull and bright laminae and ankerite veins. This is succeeded by a 0.56 m thick calcareous siltstone containing marine fossils which passes up into the 7.24 m thick Upper Longcraig Limestone.

In the Haddington district of East Lothian (outside the Oldhamstocks Basin), to the west of the previous localities, the Middle Longcraig Limestone and the overlying inter-marine clastic interval are present in the BGS Spilmersford Borehole (Davies 1974) and on the coast at Kilspindie, Aberlady Bay (Figs. 8.1 and 8.6). In the Spilmersford Borehole [NT 4570 6902], the 4.51 m thick Middle Longcraig Limestone is a grey-coloured shelly horizon containing pale grey nodules, abundant corals, and an impure lower part. It is succeeded by a 4.57 m thick coarsening-upward sequence with siltstones at the base passing upward into sandstones at the top. This progradational deltaic sequence is overlain by a 0.10 m thick coal which is succeeded by a 4.72 m thick silty mudrock which is dark grey, shelly (marine fossils), calcareous and contains bands of impure limestone up to 0.10 m thick in the upper part before passing upwards into the overlying 2.89 m thick Upper Longcraig Limestone.

On the coast at Kilspindie, Aberlady Bay, the Middle Longcraig Limestone is approximately 3.30 m thick, ?dolomitised, and weathers to an orangey-yellow brown colour. Approximately 0.50 down from the top of the limestone there are huge 'carpets' of colonial *Lithostrotion* corals, and as at Catcraig this limestone is sometimes known as the 'spaghetti-rock or macaroni-rock' (Duff 1986). The limestone contains abundant marine fossils including *L. junceum* and *L. pauciradiale*, and the brachiopods *Eomarginifera*, *Spirifer*, *Avonia*, *Pustula*, *Composita* and *Pugnoides* (fossil list after Duff 1986, p.85). It is overlain by at least 1.8 m of silty shales which coarsen-upwards and contain nodules at the base and sandstone ribs towards the top. This is capped by a 0.80 m thick sandstone-siltstone which also coarsens-upwards. It consists of brown coloured, fine-grained sandstone beds which are intercalated with siltstones, and is still quite fissile towards the top. The sandstones pass upward into a 1.1 m thick sandy siltstone which is dark grey and contains rootlets. This paleosol has no discernible bedding (presumably as a consequence of rhizoturbation), and contains sandy-brown coloured nodules in the lower 0.30 m which average 8 cm in diameter. The overlying coal is 0.20 m thick and contains bright bands, and is succeeded by a 0.20 m thick mudrock which is grey coloured, fossiliferous (marine fossils) and contains carbonate nodules characterised by abundant fossil material.

8.9. Interpretation of the sequences at Skateraw, Spilmersford and Kilspindie

The Middle Longcraig Limestone and overlying sequence in the Skateraw Borehole is virtually identical to that developed on the coast at Catcraig/Longcraig, suggesting that the emergent surface is not a very localised feature, and was at least developed over a reasonable distance. Outside the Oldhamstocks Basin (Lagios 1983), however, in the Spilmersford Borehole and at Kilspindie (Aberlady Bay), the emergent surface is clearly absent, despite recent claims in BGS memoirs that it is locally developed in the Haddington district (McAdam *et al.* 1986). What is perhaps more interesting is the presence of 'normal' progradational deltaic coarsening-upwards sequences between the Middle and Upper Longcraig limestones in the Haddington district. This suggests that the delta lobes prograded into these areas contemporary with the emergence and the development of the overlying paleosol facies of the Middle Longcraig Limestone in the fault-bounded Oldhamstocks Basin (Fig. 8.7). This implies that the Haddington district was undergoing greater tectonic subsidence than the Catcraig/Longcraig-Skateraw area, and that the active delta lobes bypassed the latter district. These facies patterns fit the tilt block/half-graben model (Leeder and Strudwick 1987; Grayson and Oldham 1987) and provide a good example of facies variations which can develop in Yoredale-type cycles as a result of differential subsidence and uplift.

8.10. Summary

The emergent surface on the top of the Middle Longcraig Limestone was studied at three localities within the fault-bounded Oldhamstocks Basin, but when the limestone was traced outside the basin to the west, in the Haddington district of East Lothian (Fig. 8.1), the surface was absent. Furthermore, a relatively thick coarsening-upwards sequence was present between the Middle and Upper Longcraig limestones (representing delta lobe progradation) which was absent at the localities in the Oldhamstocks Basin. This suggests that the Oldhamstocks area experienced uplift and lesser subsidence contemporary with greater subsidence to the west in Haddington. These tectonic variations appear to have controlled the geographical extent of the karst and the position of active delta lobes and it is suggested that these facies patterns may fit a half-graben/tilt block model (Fig. 8.7).

8.11. Correlations outside East Lothian

The Middle Longcraig Limestone is probably a correlative of the Bone Bed Limestone (Midlothian), the First Abden Limestone (central Fife) and the St Monans White Limestone (East Fife). None of these limestones show evidence of emergent surfaces and it is concluded that the karst on the top of the Middle Longcraig Limestone was limited geographically to the Oldhamstocks Basin. The interval between the First and Second Abden limestones (correlatives of the Middle and Upper Longcraig limestones) is occupied by a thick volcanic sequence (Francis 1961a), and this exemplifies the complex variety of localised facies patterns which existed at this time. Most of the geographically widespread marine limestones (and associated calcareous mudrocks) are clearly independent of such local facies controls and are therefore probably the result of rises in sea level. The local tectonic regimes, however, played a very important role in controlling sedimentation, and both the marine and intervening deltaic phases (not to mention local volcanism) appear to have been profoundly influenced by intermittent tectonism. In this study, it has been shown that such tectonism affected not only the distribution and patterns of clastic influxes, but also influenced the carbonates, where emergent surfaces developed as a result of local uplift.

8.12. Conclusions

Although the geographically widespread Brigantian marine phases appear to have resulted from rises in sea level which were presumably accompanied by regressions, the emergent surface identified in parts of East Lothian is too restricted geographically to be the result of a sea level fall. It appears most unlikely that a regression would merely affect such a small area, and it is probable that the restriction of the localities characterised by the surface to the fault-bounded Oldhamstocks Basin is more significant in explaining the origin of the karst. As a regression would tend to affect a wide area (as does a transgression), it is proposed that the karst originated via tectonic uplift. This is supported by examining the Middle-Upper Longcraig limestones interval in the Haddington district, where the presence of progradational deltaic coarsening-upwards sequences suggest more rapid tectonic subsidence. As variable subsidence is characteristic of documented extensional regimes (Leeder 1987), it is proposed that the facies variations outlined are a good example of the response of Yoredale-type cycles to such tectonism, in an area where the interplay between sea level fluctuations and a south-westerly trending deltaic complex were also important.

CHAPTER 9

The application of optimized similarity matrices to palaeoecology; an example from fossiliferous mudrocks in a volcanically-influenced sedimentary sequence, Kinghorn, central Fife, and the validity of the 'Abden fauna' as a stratigraphic marker.

9.1. Introduction and rationale

In this study, a Brigantian volcanically-influenced sedimentary sequence is described which contains volcanics (lavas, tuffs and boles), paleosols, mudrocks and limestones. The rocks are interpreted as representing volcanic extrusions into shallow water environments temporarily establishing a land surface, which was vegetated, before the volcanic pile was transgressed. Within the fossiliferous mudrocks deposited during the incursions, relays are detected, involving the systematic shifting of the relative importance of fossil components throughout the sampled profiles. The relays were detected using optimized similarity matrices (Hennebert and Lees 1985), a technique which may be potentially useful in palaeoecological study, where fossil assemblages change both vertically and laterally in stratigraphic sections (see Ferguson 1962; Johnson 1972; Miller 1986). This type of relay within transgressive and regressive sequences has long been recognized (Ferguson 1962; Calver 1968a, 1968b; Rollins *et al.* 1978; Miller 1986), but little attempt has been made to objectively quantify the fossil changes (relay) using a simple technique, requiring only a relatively modest database.

9.2. Localities and stratigraphical position of the sequence

The sequence to be described (Fig. 9.2) crops out on the northern shore of the Firth of Forth between the coastal towns of Kinghorn [NT 275 872] and Kirkcaldy [NT 278 881], central Fife (Fig. 9.1), and occurs at the top of the recently erected Strathclyde Group (Paterson and Hall 1986), although the exact position of the boundary between the latter group and the overlying Lower Limestone Group is in dispute away from the type section at Hurlet near Paisley (Wilson 1974, 1979).

There has always been some uncertainty as to which of the Abden limestones marks the base of the Lower Limestone Group in the Kinghorn-Kirkcaldy area of central Fife (MacGregor 1973). The base of the First Abden Limestone has traditionally been regarded as the base of the Lower Limestone Group (Macnair 1917), although more recent work has tended to discredit this assumption, and the abundance of the alga *Calcifolium* *punctatum* Maslov in the Second Abden Limestone (Oldroyd in MacGregor 1973) suggests that the base of this limestone marks the base of the Lower Limestone Group (Fig.9.1) (cf. Burgess 1965).

9.3. Description of the sequence (Fig. 9.2)

The sequence consists of two units, a lower unit capped by the First Abden Limestone and an upper unit capped by the Second Abden Limestone, the base of which marks the base of the Lower Limestone Group. Each unit consists of volcanics capped by seat-earths which pass upwards into transgressive deposits comprising mudrocks overlain by limestones.

The base of the First Abden Limestone unit (A) is occupied by a 9.18 m thick amygdaloidal basalt lava flow of Hillhouse type (Allan 1924), which displays a pillow-like structure (Geikie 1900). The basalt has an irregular, weathered top (MacGregor 1973), and passes upward into a soft, friable, green coloured siltstone paleosol (seat-earth) containing abundant coalified rootlets. The seat-earth contains many ooid-like structures which constitute approximately 50-70% of the total rock.

The paleosol passes upward into a 1.4 m thick fossiliferous mudrock containing marine fossils, a *Naiadites crassus* Fleming band and the Abden Bone Bed (Anderson 1886; Traquair 1897) towards the base. This is punctuated by an erosively-based, 1.92 m thick unit of grey-green coloured, calcareous tuffaceous sandstone-siltstone (terminology of Francis (1961b)). The tuffaceous sandstones which contain crude multiple graded-bedded units fine-upward into tuffaceous siltstones containing coarser-grained and finer-grained units arranged in couplets. Some of the coarser-grained units contain sand-starved lenticles, which are internally cross-laminated and hummocky cross-stratified. The tuffaceous siltstones contain occasional poorly preserved articulated bivalves and plant remains, and the top of the tuffaceous unit is thoroughly bioturbated and characterised by the presence of abundant small pyritic tubes.

The volcaniclastics are succeeded by the remainder of the mudrocks with which they are intercalated, and these pass upward into the First

Abden Limestone which consists of several thick beds (1-2 m thick) intercalated with dark grey mudrocks. The limestone and associated mudrocks contain a diverse assemblage of marine fossils but the uppermost limestone bed which is an extremely fine-grained calcilutite contains low-diversity fossil assemblages, including phosphatic fish remains and *Lingula*. This bed is capped by a thin (2.2 cm thick) bone bed, containing abundant disarticulated fish remains, quartz and chlorite grains, injected mudrock wisps, and a patchy calcite cement.

The First Abden Limestone is overlain by a 0.63 m thick, micaceous mudrock containing plant remains, which passes upward into a basalt lava flow of Dalmeny type (Allen 1924). The contact between these rocks is undulatory and flame-like structures and load-casts are developed within the deformed mudrock and overlying basalt.

The basalt of Dalmeny-type, which overlies the deformed mudrock at the top of the previous sequence is approximately 4.3 m thick and passes upward into a 1.1 m thick green tuff, which has largely been altered to a brick-red bole (MacGregor 1973). The bole is overlain by a 4.3 m thick intrusive teschenite (Allan 1924) which closely resembles the extrusive basalt lava flows, but is coarser-grained. The teschenite is overlain by approximately 6.4 m of fine-grained tuffs which are lateritised and altered to a dark-red bole. The lateritised tuffs pass upward into a 0.31 m thick unit of grey-green coloured tuffaceous sandstone-siltstone, which is overlain by a 0.47 m thick, white-grey coloured mudrock containing coalified rootlets (seat-earth).

The contact between the seat-earth and the overlying fossiliferous mudrock unit is erosional and clasts of the pale-coloured seat-earth are present within the basal 0.07 m of the mudrock. The mudrock varies in thickness (1.1-3.5 m) along strike (as do the underlying and overlying rocks (see MacGregor 1973)), and contains a thin band characterised by numerous specimens of the bivalve *Naiadites crassus* Fleming at the base. It is a dark fissile shale containing marine fossils, passing upward into the Second Abden Limestone. The limestone is pale grey-white in colour and is prominently weathered into pseudo-beds possessing irregular, nodular bounding surfaces. The limestone contains diverse assemblages of marine fossils, including large colonies of the colonial coral *Lithostrotion* sp. and is abruptly overlain by approximately 1.42 m of wavy and flaser bedded, fine-grained micaceous sandstones.

9.4. First and Second Abden limestone units; interpretation

The basalt of Hillhouse-type at the base of the sequence is interpreted as a volcanic lava flow which was extruded into a shallow water palaeoenvironment. The basalt was originally interpreted as a subaqueously extruded pillow-lava (Geikie 1900) due to the presence of pillow-like structures, although Allan (1924) has provided evidence which suggests that these basalts are not true pillow lavas. The extrusion of a substantial thickness of volcanics into shallow water resulted in the formation of a temporary land surface which was subaerially weathered during a period of volcanic quiescence (cf. Ziegler *et al.* 1969; MacGregor 1973; Francis 1983b), and vegetated, resulting in the development of the seat-earth. The ooid-like structures within the seat-earth are interpreted as accretionary lapilli (see Moore and Peck 1962) formed during volcanic eruptions. The overlying mudrock containing marine fossils was probably deposited during a marine incursion over the lava pile (cf. Ferguson 1962), the transgression resulting as a consequence of a rise in sea level. The tuffaceous sandstone-siltstone unit which punctuates the mudrock is interpreted as an ash-fall tuff (Francis 1961b) extruded during a volcanic eruption (cf. Allen and Williams 1981). Initial rates of sedimentation precluded faunal colonisation, and crude multiple graded units developed, suggesting rapid sedimentation from suspension. Towards the top of the unit, the cross-laminated lenticles (hummocky cross-stratification) suggest that the tuffaceous sediment was partially storm reworked by currents and waves (cf. Dott and Bourgeois 1982; Jeferry and Aigner 1982, p.241; Retallack 1985). The presence of bioturbation and a fossil fauna towards the top of the unit indicates that the sediment was colonised and biogenically reworked during a period of relative quiescence. This is considered to have ensued during the resumption of 'background' shelf sedimentation, after the initial major depositional event (cf. Craig 1956; Fischer and Schminke 1984).

The mudrock containing the tuff passes upward into the First Abden Limestone which contains a diverse assemblage of marine fossils indicative of a shallow marine (shelf) environment. The degeneration of diverse marine fossil assemblages to restricted low diversity associations of lingulids and fish towards the top of the limestone, suggests, however, that regression may have been taking place. This probably led to the development of marginal marine environments where carbonate muds were deposited, and inhabited by burrowing lingulids (cf. Craig 1952). It is interesting to note, that the occurence of *in situ* lingulids in carbonate rocks is quite rare (see Pickerill *et al.* 1984), and they are most commonly found in fine-grained mudrocks (Ferguson 1963 ; Graham 1970). The mudrock which overlies the limestone is interpreted as representing a muddy sediment which was deformed prior to lithification by the subaqueous influx of the overlying basalt lava flow (MacGregor 1973; cf. Needham 1978). The mud wisp injections in the thin bone bed which caps the limestone are also probably the result of the interaction between wet sediment and lava, whereby sediment was hydroplastically deformed, mobilised and intruded into brittle fractures in the subjacent strata.

The basalt of Dalmeny-type at the base of the sequence is interpreted as a lava flow which was extruded into a shallow water, subaqueous palaeoenvironment. The presence of the bole (duricrust) which overlies the lava flow suggests that a temporary land surface was established by the lavas extruded into the shallow water setting, resulting in the subaerial tropical weathering of the volcanic and volcaniclastic rocks (cf. Goudie 1973). The overlying teschenite is clearly an intrusive igneous rock, possibly intruded during the early-mid Carboniferous (Francis 1983b). The overlying tuffs are lateritised, indicating subaerial exposure and tropical weathering, prior to the development of the seat-earth which represents the subsequent vegetation of the volcanic pile. The overlying mudrock containing marine fossils is interpreted as a transgressive deposit, resulting from a rise in sea level which appears to have affected much of the Midland Valley of Scotland ('Hurlet transgression'). The erosive nature of the base of the mudrock, and the presence of seat-earth clasts indicate that the initial stages of the transgression were erosive (cf. Swift 1968; Belt 1975). The marine fossils in the Second Abden Limestone represent a shallow marine shelf palaeoenvironment and the pseudo-bedding is interpreted as a diagenetic effect, resulting from pressure dissolution during burial (Simpson 1985).

The overlying wavy-flaser bedded sandstones which terminated shallow marine sedimentation are interpreted as delta-front sands resulting from the advance of a prograding delta lobe.

9.5. Summary of sedimentology and statement of problem

The two fossiliferous mudrocks within this sequence are regarded as representing transitions between two end-members; a terrestrial seat-earth and a shallow, sublittoral marine limestone. Ferguson (1962), who studied the mudrock below the Second Abden Limestone in great detail recognised four successive fossil 'topozones' reflecting gradual changes in the composition of the fossil assemblages (relay) from the base to the top of the unit. The changes were interpreted as representing salinity and depth gradients inherent within a marine transgression. Although there has been a great deal of subsequent interest in Ferguson's work (see Schafer 1965; Beerbower and Jordan 1969; West 1976), and similar types of examples identified elsewhere (e.g. Calver 1968a, 1968b), no attempt has been made to detect relays objectively, using a simple technique requiring a relatively small database. In this study, optimized similarity matrices were used to detect relays, using a restricted database, consisting of selective fossil identifications made at different taxonomic levels. This technique may be useful to sedimentologists possessing a relatively limited knowledge of fossils, but requiring an accurate interpretation of potentially informative mudrocks which lack easily interpreted sedimentary structures (cf. Potter *et al.* 1980).

The two mudrocks were randomly spot sampled and approximately 180 samples were collected from each one. Each individual sample consisted of a fossiliferous parting plane surface which was studied using a binocular microscope. The fossils which were present were identified (at a variety of taxonomic levels) and noted (presence-absence data), and the fossils most commonly identified within the mudrocks were designated as parameters, selected in order to reflect any changes in the fossil content throughout the sampled profiles. Thirteen different fossil parameters were defined for the mudrock in the First Abden Limestone unit, and fifteen different fossil parameters were defined for the mudrock in the Second Abden Limestone unit. The parameters used in the Microsoft BASIC program of Hennebert and Lees (1985) were components of carbonate rocks which had to be changed to the fossil parameters herein defined, before the matrix of the Jaccard coefficients could be calculated and optimized (for explanation see Hennebert and Lees 1985).

9.6. Jaccard coefficients and optimization

Jaccard coefficients are similarity coefficients based on presence-absence data which ignore double zeros (both components absent from the sample (Hennebert and Lees 1985)). Similarity coefficients enable the degree of association between two fossil components to be calculated, and this will be larger the more specimens there are which contain both components. The method of calculating the degree of association between two fossil components is outlined by Hennebert and Lees (1985), and is therefore not repeated here.

Optimization involves the perfect ordering of the matrix of the Jaccard coefficients so that it is symmetrical, and the degree of association between fossil components decreases as the distance between them along the relay increases. Optimization and the calculation of Jaccard coefficients was completed by the BASIC program using a microcomputer and the resulting matrices for both data sets are presented (Figs. 9.3, 9.4, 9.5 and 9.6).

9.7. Interpretation of the optimized matrices.

The optimized matrix of the fossil data from the mudrock in the First Abden Limestone unit reveals the presence of a relay (Figs.9.3 and 9.5). The respective degree of association and dissociation of the fossil components in the optimized matrix is very similar to the stratigraphic positions which the fossils occupy in the mudrock.

Therefore, the articulate brachiopods (e.g. productids) and certain bivalves such as *Actinopteria* occur at the top of the mudrock and are closely associated at one end of the relay, whereas the bivalve *Promytilus* and the inarticulate brachiopod *Lingula* are associated at the other end of the relay. This degree of dissociation between certain faunal components is interpreted as representing different environmental preferances displayed by the organisms. The fossils which occur near the base of the mudrock are considered to have inhabited a restricted marine environment which developed during the early stages of the incursion and was subjected to fluctuations in salinity and other controlling variables. In contrast, the fossils which occur towards the top of the mudrock are considered to have inhabited a more stable marine environment established towards the 'acme' of the marine incursion.

The optimized matrix of the data from the mudrock in the Second Abden Limestone unit also reveals the presence of a relay (Figs. 9.4 and 9.6). As in the First Abden Limestone unit, the respective degree of association and dissociation of the fossil components in the matrix is 'mirrored' by the relative stratigraphic positions which the fossils occupy in the mudrock. For example, corals and crinoids which occur near the top of the mudrock are closely associated at one end of the relay, whereas plant remains and certain gastropods and bivalves which occur close to the base of the mudrock are associated at the other end of the relay. The relay is interpreted as reflecting original changes in faunal community structure, which is indicated in the distribution of the fossil components. The fossils which occur near the base of the mudrock probably inhabited a marginal marine environment established during the early stages of a marine incursion, whereas the fossils which occur towards the top of the mudrock inhabited a fully marine environment established towards the 'acme' of the incursion.

9.8. Taphonomy

The majority of the fossils in the mudrocks appear to have experienced very little *post-mortem* disturbance. This is supported by high articulation:disarticulation ratios for the bivalved fossils and the preservation of many fossils in hydrodynamically unstable attitudes and assumed life positions. Size-frequency data shows that individual fossil species are represented by specimens of a wide size-range, suggesting that *post-mortem* size-sorting was negligible. There are, however, certain accumulations of fossil elements which are clearly the result of *post-mortem* disturbance. These include thin shell beds composed of the valves of the bivalve *Naiadites crassus* Fleming, and a bone bed (Abden Bone Bed) containing the disarticulated and broken remains of fish and lingulids. These fossil accumulations are considered to be the result of *post-mortem* disturbance and concentration during erosive phases at the beginning, and during the early stages of the marine incursions (cf. Swift 1968; Belt 1975; Reif 1982).

9.9. Palaeoecology

Towards the base of each mudrock, the parting plane surfaces are often dominated by large numbers of one individual fossil species. These low diversity fossil assemblages are succeeded by higher diversity assemblages towards the top of the mudrocks. The changes in diversity are accompanied by changes in the faunal composition of the assemblages. For example, the fossils which occur near the base of the mudrocks are dominantly bivalves, gastropods, ostracodes and lingulid brachiopods (Fig. 9.7). Towards the top of the mudrocks, however, articulate brachiopods such as *Eomarginifera*, *Crurithyris*, and *Rhipidomella* are common, along with crinoids, bryozoans, foraminifera and corals. These changes in fossil composition and diversity from base to top of the mudrocks are interpreted as reflecting original changes in community structure, which developed in response to environmental gradients inherent within a marine incursion. The fossil assemblages characterising the early stages of the transgression are considered to represent the colonization by 'pioneer' species, of a newly created marginal marine environment. These species were probably able to tolerate the fluctuating and unstable conditions characterising the initial part of the incursion. The difficulties of inhabiting such an environment are reflected in the low diversity fossil assemblages. The higher diversity assemblages near the top of the mudrocks probably reflect a more stable, fully marine environment which was inhabited by a wider number of species. It is suggested that environmental gradients such as salinity and depth, inherent within the marine incursions may have been the primary controls upon the composition and diversity of the fossil assemblages (cf. Ferguson 1962; Calver 1968a, 1968b).

Relays involving faunal changes in transgressive sequences would appear to be relatively common throughout the geological record (cf. Wilson 1958, p.21; Ziegler *et al.* 1968), yet few quantitative techniques exist to detect them which only require presence-absence data and a relatively modest database. It is concluded that such relays, though relatively common, are often overlooked due to the lack of readily available statistical techniques using easily acquired data. With easier recognition, it is hoped that the significance of such relays and their bearing on problems such as the dynamics of fossil community structure will be better understood.

9.10. The recognition of the marine bands throughout Fife and the Lothians

The relays detected within these mudrocks, involving the shifting of the relative importance of the fossil components throughout the sampled profiles are similar to the 'faunal phases' recognised in Westphalian marine bands (cf. Calver 1968b). These phases have been interpreted as reflecting environmental changes associated with the advance of a marine incursion (Calver ibid.). Westphalian marine bands are often laterally continuous, and lithologically and faunally uniform over large geographic distances, and it has been possible to recognise successions of faunal phases within one marine band over great distances (Wignall 1987). Work on marine bands in the Scottish Dinantian succession has largely concentrated on single localities (Craig 1954; Ferguson 1962), or several localities separated by relatively insignificant distances (Whyte 1973), and little has been done to investigate whether successions of faunal phases or 'topozones' within any one marine band can, as in the Westphalian examples, be correlated over long distances. With this question in mind, the supposed lateral equivalents of the First and Second Abden mudrock horizons were examined in various parts of Fife and the Lothians.

9.11. The 'Abden fauna'

The fossils in the mudrock underlying the First Abden Limestone at Abden near Kinghorn, Fife have been regarded as stratigraphically diagnostic (Macnair 1917), although it was originally thought that the limestone which they lay beneath was the Hurlet Limestone, the base of which marks the base of the Lower Limestone Group (Francis 1983a). It is now known that the First Abden Limestone lies at the top of the underlying Strathclyde Group (Paterson and Hall 1986) and the base of the Second Abden Limestone marks the base of the Lower Limestone Group. This oversight, along with the presence of some of the supposedly diagnostic fossils occuring at other stratigraphic levels has led to the usefulness of the 'Abden fauna' being discredited, but the occurence of fossils such as *Sanguinolites abdenensis* is still regarded as a useful index to the base of the Lower Limestone Group (Manson 1927). Although some of the localities of the 'Abden fauna' originally listed by Macnair (1917) are clearly at different stratigraphic levels than the First Abden Shale, one particular outcrop in Bilston Burn, Midlothian is almost certainly at this horizon.

The Bone Bed Limestone which crops out in the Bilston Burn is generally regarded as the correlative of the First Abden Limestone (Macnair 1917; Macconochie 1927; Francis 1983a) and the underlying mudrock is therefore the equivalent of the First Abden Shale. The mudrock beneath the Bone Bed Limestone is a 0.55-0.90 m thick, dark grey-blue weathering shale containing parting planes dominated by the orthid brachiopod *Rhipidomella michelini* Leveille in the upper part. Productid brachiopods and orthocones are also present, but the lower part of the shale is characterised by bivalves including *Actinopteria persulcata* and *Streblopteria ornata*. At the base of the mudrock, there is a thin band of lingulid fragments and fish remains (bone bed) which contains virtually all the same species of fish identified from the Abden Bone Bed (Macnair 1917, Macconochie 1927). The succession of faunal phases or 'topozones' from the bone bed at the base, through mudrocks rich in bivalves to a fauna containing articulate brachiopods such as productids and orthids at the top is almost identical to that developed at Kinghorn, despite the fact that the underlying and overlying sequence is totally dissimilar.

In the Glenrothes Borehole [NO 25615 03142], central Fife, the local correlative of the First Abden Limestone is underlain by mudrocks containing *Lingula*, *Promytilus* and *Sanguinolites* sp. (Brand in Browne *et al.* 1986). Although these fossils are similar to those occuring in the First Abden Shale, the fossils in the mudrock below the local equivalent of the Second Abden Limestone in the borehole bear a greater resemblance, throwing doubt upon the validity of the 'Abden fauna' as a stratigraphic index. The faunas in the First and Second Abden shales are very similar, however, and together may provide some guide as to the approximate base of the Lower Limestone Group.

In general, it is considered that successions of faunal phases cannot be correlated within individual marine bands in the Scottish Dinantian, except in rare cases such as at Abden and Bilston Burn. In this case, both localities are within the same part of the Fife-Midlothian Low, and 'faunal communication' between the two areas during the marine transgression may have been good. It has been noted that the intra-basinal highs and lows within the Midland Valley may have controlled faunal distribution (Wilson 1967), and it is suggested that the complex tectonic setting of the area may have affected patterns of faunal colonization, preventing well-defined faunal phases from being developed within transgressions.

9.12. Second Abden Shale

A clearly defined and easily recognised succession of faunal phases is not readily detected in the Second Abden Shale, although there is a definite change from lingulid-bivalve assemblages at the base to assemblages dominated by articulate brachiopods such as *Crurithyris* and *Eomarginifera* towards the top. As the shale underlies the basal Hurlet Limestone (known locally by a variety of different names such as the Second Abden Limestone) it is easily recognised throughout the Midland Valley. South of the Firth of Forth, at Catcraig in East Lothian, the shale underlies the Upper Longcraig Limestone which is the local Hurlet

Limestone correlative. Here, the mudrock is underlain by a thin coal and is dominated by lingulid brachiopods and bivalves towards the base. In its upper part, the brachiopod *Eomarginifera* is very abundant (Clarkson 1986a) forming 'shell pavements' along certain parting planes. These changes in faunal composition from the base to the top of the shale clearly represent a relay, but it is not possible to detect distinct faunal phases and relate them to those developed in the Second Abden Shale. Certain differences, however, are immediately apparent, such as the absence of a basal *Naiadites crassus* Fleming bed at Catcraig, and it is obvious that during major marine transgressions, each area would have been characterised by certain local faunas which were not widespread. Likewise, certain other faunal elements appear to have been more widespread, and may have been characteristic of a certain point within any one particular marine transgression. Unlike the Westphalian marine bands, however, Scottish Dinantian marine faunas appear to have been in part locally facies controlled (Wilson 1974), which despite some similarities between the same marine band at different localities, accounts for many dissimilarities.

9.13. Conclusions

Relays (systematic shifting of the relative importance of fossil components) are recognised using optimized similarity matrices in the sampled profiles of two fossiliferous mudrocks, inderlying the First and Second Abden limestones in the volcanically-influenced Brigantian (Dinantian) succession which crops out near Kinghorn, central Fife. The mudrocks are underlain by seat-earths which overlie subaerially weathered volcanic rocks, and are overlain by limestones containing marine fossils. The relays within the mudrocks are considered to represent changes in the composition of the fossil assemblages through a vertically sampled profile, reflecting shifts in community structure along salinity gradients inherent within a marine incursion.

The volcanics are interpreted as extrusions into shallow water environments establishing temporary land surfaces which were vegetated, resulting in the development of seat-earths. As a result of a presumed rise in sea level, however, the volcanics were transgressed and mudrocks were initially deposited. The First and Second Abden limestones are interpreted as carbonates deposited during the acme of the marine incursions. Most of the fossils in the mudrocks do not appear to have experienced a great deal of *post-mortem* disturbance, but concentrations of lingulids, fish remains (Abden Bone Bed) and shell beds interpreted as transgressive lags are exceptions. These were probably deposited during erosive phases in the early stages of the incursions.

Both the First and Second Abden shales were identified at different localities in Fife and the Lothians, and whilst the local successions in which they occur differ (e.g. the presence or absence of volcanics), the general faunal content of the shales is similar. Although marine conditions appear to have been widespread and uniform during marine incursions, the relays present at each locality cannot be clearly related to each other, suggesting disruptions of faunal distribution patterns. Although the faunal phases or 'topozones' recognised in the First and Second Abden shales were partially recognised at some of the other localities, it is concluded that local facies controls disturb regionally uniform patterns of faunal colonization, so that although some similarities within individual marine bands in different areas exist, most are only recognized as belonging to the same horizon by virtue of their respective positions in the various sequences. The stratigraphical usefulness of these so-called faunal index horizons should therefore be questioned, not least because so many of the faunas have extended time ranges throughout parts of the Strathclyde and Lower Limestone groups.

CHAPTER 10

An example of marine limestones locally removed by fluvio-deltaics; Lower Limestone Group of central Fife and East Lothian

10.1. Introduction

Washouts of coals and overlying prodeltaic and delta-front deposits are well known from the Westphalian (Silesian, Upper Carboniferous) of England (e.g. Guion 1987, p.474). Such phenomena result from delta-top distributary channels cutting down through earlier, underlying sediments deposited during delta progradation. In Yoredale-type sequences, however, where marine phases including limestones are intercalated with fluvio-deltaics, the potential exists for similar washouts to occur involving the removal of limestones (Moore 1959; Selley 1970; Anderton *et al.* 1979; Leeder and Strudwick 1987). Though reported and documented cases of such limestone washouts are scarce, the potential significance and importance of such a phenomenon cannot be underlined too strongly, despite the fact that many clear cases have often been overlooked, and the mysteries of missing marine bands in sections which are more cryptic left unsolved.

Correlation within the Dinantian Lower Limestone Group of the Midland Valley of Scotland depends largely upon the presence of geographically widespread marine limestones and associated calcareous mudrocks. When such marine phases are locally absent, mistaken correlations of the remaining limestones are often made, so the recognition of marine beds locally removed by erosion due to fluvio-deltaic channels can be critical. In general, marine limestones in the Lower Limestone Group are overlain by well-developed upward-coarsening sequences representing delta progradation. These are often capped by delta-top facies which may contain major channel sand bodies. In rare cases, such sand bodies appear to have cut down through the delta-front and prodelta facies and may have even removed the underlying marine phase. When this has taken place, a large amount of geological evidence has been locally lost, and if the sequence of events is not recognised, mistaken interpretations and correlations may be made.

In this study, the interval between the Second Abden (Hurlet) and Seafield Tower (Charlestown Main) limestones is examined in the Kinghorn-Kirkcaldy coastal section in central Fife (Figs. 10.1 and 10.2). For many years, the Second Abden Limestone has been correlated with a limestone between the Hurlet and Charlestown Main limestones in west and east Fife. Recent microfossil work (Oldroyd pers. comm.), however, has indicated that the Second Abden Limestone is the local correlative of the Hurlet Limestone in central Fife, and that the intervening limestone recognised elsewhere is missing at Kinghorn-Kirkcaldy (Fig. 10.2). The same interval in East Lothian occurs between the Upper Longcraig and Middle Skateraw limestones, which are the local equivalents of the Hurlet and Charlestown Main limestones (Fig. 10.2). Between these two limestones on the coast at Catcraig and inland in part of the Dunbar Works Quarry (Fig. 10.1), the Lower Skateraw Limestone is present, but in some parts of the quarry it is absent. These exposures were investigated and evidence is provided to suggest that the interval at Kinghorn-Kirkcaldy between the Second Abden and Seafield Tower limestones now occupied by an abnormally thick fluvio-deltaic sequence consists of a progradational deltaic sequence which was once probably overlain by a marine phase. The marine beds, however, appear to have been removed along with an overlying prodeltaic/delta-front sequence by major distributary channels on the delta-top. This has resulted in the superimposition of a delta-top succession upon an upward-coarsening prodeltaic sequence overlain by abandonment facies, on top of which the limestone should have lain, had it not been eroded away by the overlying channellised sandstones. In East Lothian, the Lower Skateraw Limestone, which is locally missing in part of the Dunbar Works Quarry also appears to have been cut out by a major heterolithic sand body with well-developed lateral accretion surfaces and a channel lag at the base. The absence of the limestone in only part of the quarry provides an extremely localised example of limestones removed by fluvio-deltaics, so that the limestone can actually be traced to the point where the overlying channel cuts down into the marine phase. This second example provides a smaller scale model illustrating how the limestone may have been removed at Kinghorn-Kirkcaldy.

10.2. Kinghorn-Kirkcaldy, central Fife; Second Abden Limestone and overlying delta-front sandstones (see Fig. 10.3).

The base of the Second Abden Limestone is considered to mark the base of the Lower Limestone Group (Fig. 10.2), and this limestone is correlated with the Hurlet Limestone of Glasgow on the basis of the presence of abundant specimens of the codiacean alga *Calcifolium punctatum* Maslov (Fig. 10.5) (Burgess 1965; Oldroyd in MacGregor 1973; Oldroyd pers. comm.). The 5.35 m thick limestone (limestone No.2 of Wright 1922, p.296) thickens to the NE (MacGregor 1973) and contains numerous colonies of the corals *Lithostrotion junceum* and *Lithostrotion irregulare* in the lower 1-2 m (Fig. 10.4B, C and D) and is characterised by the presence of the large solitary corals *Amplexizaphrentis*, *Clisiophyllum* and *Aulophyllum* in the upper part. Bioturbation and tube-like burrows are also present, along with networks of gallery-like burrows reminiscent of *Thalassinoides*. A very abundant macrofauna (Peach in Geikie 1900) and microfauna (Fig. 10.6) is characteristic of this limestone, including the foraminifera *Howchinia bradyana* (Howchin) (Fig. 10.6A), *Janischewskina* sp. (Ferguson 1962), *Bradyina rotula* (Eichwald) (Fig. 10.6C), *Palaeotextularia longiseptata* Lipina (Fig. 10.6B), *Endothyranopsis crassus* (Brady), *Tetrataxis conica* (Ehrenberg), *Earlandia pulchra* (Cummings), *Draffania biloba* Cummings (see Cummings 1957) and several species of *Eotuberitinia* (Ferguson 1962; cf. Hallet 1970). Adherent forms such as *Tetrataxis* are often attached to bioclasts in assumed life position, and algae such as *Calcifolium* commonly encrust *Lithostrotion* corallites (cf. Burgess 1965), which are also in assumed life position. Crinoid debris is common throughout the limestone (MacGregor 1973), but a layer rich in *Archaeocidaris urei* is present near the top, and the crinoid *Ulocrinus* is present at the base (Wright 1922).

The limestone is conspiciously composed of layers or pseudo-beds which average 15-30 cm in thickness (Fig. 10.4A), separated by irregular mudrock partings (MacGregor 1973) which are interpreted as pressure dissolution features formed during late stage burial resulting in the dissolution of $CaCO_3$ along surfaces where insoluble residues were deposited as stylocumulate shale horizons containing isolated bioclasts or 'idens' (largely crinoid ossicles) (cf. Logan and Semeniuk 1976; Wanless 1979; Simpson 1985). During burial, limestone beds may be subjected to stress, which at certain loci may lead to an increase in elastic strain and, hence, an increase in carbonate solubility (Bathurst

1984). Carbonate dissolution then occurs, concentrating insoluble residues along solution seams or stylolites (commonly observed on a micro-scale during petrographic study of limestone thin sections). Finer crystalline material (such as micrite or microspar) is more susceptible to solution than coarse skeletal material, which may, as a consequence, become isolated within the solution seam as an 'iden' (Logan and Semeniuk 1976).

Field and petrographic analysis reveals that the limestone is characterised by patchy, late stage diagenetic, fabric destructive dolomitization (Robertson *et al.* 1949, p.106; MacGregor 1973, p.253), which is a common feature of limestones in the Lower Limestone Group (cf. Selim and Duff 1974, p.808; Forsyth and Chisholm 1977, p.61). Other petrographic features include the presence of micrite envelopes around bioclasts (cf. Bathurst 1966; 1975, p.383), and a predominance of wackestone (cf. Dunham 1962) or biosparitic (cf. Folk 1959) textures. The dominant grains are bioclasts of marine fossils (e.g. foraminifera, algae, crinoid remains, echinoid fragments, brachiopods, bivalves, solitary and colonial corals, ostracodes and gastropods), and the algae *Calcifolium* and *Girvanella* are common. The majority of the original micrite matrix (less than 4 μ) appears to have been converted to microspar during the diagenetic process of neomorphism, with only occasional wisps of micrite matrix remaining, surrounded by coarser neomorphic spar (cf. Bathurst 1959). Because of diagenetic overprint, the original amount of deposited carbonate mud (micrite matrix), and therefore the energy of the environment, are difficult to ascertain. Although the Folk (1959) classification of the rock is as a biosparite, it should perhaps be more correctly referred to as a biomicrosparite. This is a recrystallized limestone where the 'matrix' is composed almost entirely of microspar and pseudospar, and the sparry nature is shown by cathodoluminescence (cf. Miller 1987) to be produced from aggrading neomorphism of a former bioclastic wackestone.

The Second Abden Limestone is invariably capped by sheet-like beds of crinoidal grainstones and packstones which are overlain by ?prodeltaic mudrocks (see Fig. 10.3).

The limestone is overlain by a 2.00 m thick coarsening-upward sequence (see Fig. 10.3) with 0.50 m of shaly mudrocks passing upwards into 1.50 m of fine-medium grained sandstones which are wave-rippled, cross-laminated and characterised by wavy and flaser bedding (Reineck and Wunderlich 1968) (Figs. 10.7 and 10.3). Indistinct vertical burrows are common, as are the trace fossils *Diplocraterion*, *Teichichnus*, *Skolithos* and *Asterosoma*. One prominent and distinctive sandstone bedding plane surface is characterised by numerous *Diplocraterion* burrows which show a definite (?current-aligned), NE-SW orientation. The cross-laminae indicate palaeocurrents to the east and north-east, whilst the wave-ripples indicate a palaeocurrent trend of NNE-SSW to N-S. The upper part of this unit contains occasional isolated trough cross-bed sets and *in situ* rootlets. This upward-coarsening unit is overlain by a similar unit which is also 2.00 m thick, and consists of 0.17 m of mudrocks which pass upwards through interlaminated sandstones, siltstones and shales ('striped beds') into medium to fine-grained sandstones containing *in situ* coalified rootlets. The thin sandstone beds and laminae ('ribs') in the upward-coarsening unit are cross-laminated and wave-rippled, with palaeocurrents to the N and palaeocurrent trends (from the wave-ripples) of WWN-EES to W-E. These beds are also characterised by vertical and horizontal burrows and trails and contain most of the trace fossils present in the previous unit with the addition of *Palaeophycos*. The rooted sandstones contain coalified chunks and are overlain by a thin (0.10 m thick) coal (Fig. 10.3).

The two minor upward-coarsening sequences overlying the Second Abden Limestone are succeeded by a major upward-coarsening sequence (Fig. 10.8A) capped by a thick coal and interpreted as representing the progradation of a major mouth-bar. The thin coal at the base of the sequence is overlain by 1.87 m of mudrocks (Fig. 10.8A) which coarsen-upward and contain sandstone laminae and beds which become more common towards the top (Fig. 10.8A). The mudrocks are blue-grey coloured, fissile (shaly) and contain siderite nodules of various sizes. The sandstone beds towards the base are very thin (0.5 cm) and the bases are often loaded (Fig. 10.3). Wave-ripples present in the sandstones indicate palaeocurrent trends of NW-SE and the trace fossil *Teichichnus* is present along with numerous vertical burrows. This upward-coarsening sequence is capped by 1.07 m of sandstones which are wave-rippled in the lower part (Figs. 10.8A and C and 10.9B and C) and trough cross-bedded in the upper part (Figs. 10.8A and 10.9A and B). The sandstones are medium-grained and are punctuated by thin mudrock laminae. The wave-ripples suggest palaeocurrent trends of NW-SE to W-E, and the cross-beds indicate palaeocurrents to the NW. The upper surface of this sand body is characterised by well-preserved epichnial trails of *Gyrochorte* and *Planolites* (Fig. 10.8B) and indistinct vertical burrows occur in the lower part of the sandstone. The mouth-bar sandstones pass upward into a 1.00 m thick, delta-top coarsening-upward sequence which is capped by a poorly exposed 0.50 m thick coal (Fig. 10.3). The lowest beds are 0.40 m of interlaminated sandstones and siltstones, where the fine-grained sandstones have load-casted bases and are indistinctly wave-rippled. These beds coarsen-upwards into a 0.60 m thick, medium to fine-grained sandstone which contains abundant coalified *in situ* rootlets, vertical burrows, *Skolithos*, and is overlain by a relatively thick coal. The overlying beds are massive channellised sandstones and it is suggested that the former position of the now missing limestone may have been above the coal, although no trace of its presence now remains (Fig. 10.3). The limestone also appears to be absent in a small inland exposure assumed to lie at this stratigraphic level (Fig. 10.10) and in the Seafield No.1 Colliery Shaft (Francis 1961a) (Fig. 10.11), although in the latter case a major dolerite sill is intruded into the critical part of the succession.

10.3. Second Abden Limestone and overlying delta-front sandstones; interpretation (see Figs.10.17 and 10.19)

The Second Abden Limestone represents a major marine phase (Hurlet transgression) which is present throughout much of the Midland Valley. This probably represents a major rise in sea level independent of local facies changes, establishing an open marine shelf setting of normal marine salinity and generally low energy conditions (Ferguson 1962, p.1105). Occasional packstone and grainstone textures, however, suggest periodically higher energy conditions (e.g. crinoid packstones at the top of the Second Abden Limestone developed due to ?shallowing-upwards trends associated with regression). The presence of two bands containing numerous 'pockets' of *Lithostrotion junceum* (Fleming) (Francis 1961a) suggests warm tropical or subtropical environments, as large *Lithostrotion* colonies are known to have had such environmental preferances (Ferguson 1962), and this is supported by the fauna and flora as a whole (cf. Wilson 1975; Anderton *et al.* 1979, p.152), and palaeomagnetic data, which suggests that Britain occupied an equatorial position during the late Dinantian (Smith *et al.* 1973, 1981; Turner and Tarling 1975). Most living corals (e.g. Recent scleractinians), and especially reef-builders, are similarly confined to the warm and relatively shallow waters of the tropics, and reef corals are best developed where the mean annual water temperatures are approximately 23-25 degrees C (Wells 1957). Micrite envelopes are known to be the result of photosynthetic and boring endolithic algae in shallow seas (Bathurst 1966), but in most modern environments micrite envelopes occur in shallower depths of the order of a few tens of metres (Simpson 1987). The presence of micrite envelopes, therefore, should indicate a depositional setting within the palaeophotic zone, although the use of micrite envelopes as indicators of palaeodepth is potentially unreliable (see discussions in Flugel 1982 and Lees *et al.* 1985). The depths of modern photic zones vary greatly according to the intensity and duration of light at the surface of the sea, water clarity, and motion of the water surface (Simpson 1987). Maximum depths of 100-150 m (Riding 1975) have been quoted, although it is assumed that the Second Abden Limestone was deposited in a few tens of metres of water in a generally low energy setting. The presence of *Calcifolium* suggests a shallow water depositional setting within the photic zone (Ferguson 1962; Skompski 1986), as does the occurence of *Girvanella* (Lauritzen and Worsley 1974), although *Girvanella*, like many blue-green algae may be an unreliable depth indicator (Riding 1975).

The two minor coarsening-upward sequences overlying the limestone consist of delta-front sandstones with only a thin underlying diminutive prodeltaic muddy facies developed. The dominant sedimentary structures in these beds (flaser bedding, wavy bedding and wave-ripples) suggest that the delta prograded into a shallow water setting where it was actively reworked by waves and other marine processes. Although flaser, wavy and lenticular bedding are generally associated with tidal and intertidal settings, such bedforms are known to form in a wide variety of environments (Reineck and Wunderlich 1968, p.104), with settings where the fronts of deltas prograde into marine conditions being particularly important (Reineck and Wunderlich 1968; Blatt *et al.* 1972, p.155). This type of setting is further supported by the presence of abundant marine trace fossils characteristic of shoreline-type facies. Usually, high rates of sedimentation at the delta-front deter burrowing organisms, but in delta-front sequences where basinal reworking of prograding sediments is intense, colonization of the sands by organisms is possible. These degraded delta front sand sheets were periodically abandoned and the sand ridges were vegetated accounting for the presence of the rooted beds which cap the two upward-coarsening sequences. The marine/basinal influence appears to have been strong throughout the deposition of the two minor units where wave-influenced bedforms and marine ichnogenera are common, and marine reworking of the delta may have been so strong as to restrict the development of major delta-top facies. The second upward-coarsening unit, however, is capped by a thin coal which indicates that the prograding, reworked sands had established a delta-platform which was abandoned, vegetated and organic paleosol facies (peats) developed.

The major coarsening-upward sequence above the two lower units does not display as much evidence for marine reworking of the front of the delta, suggesting that regression was perhaps taking place allowing a more constructive type of deltaic sequence to be developed. This is supported by the fact that the lower units are indicative of sheet-like sands which formed along the delta-front replacing point-concentrated mouth-bars which had become degraded by marine reworking. The major coarsening-upward sequence, however, is interpreted as a major mouth-bar developed in response to constructive, point-concentrated delta progradation (cf. elongate deltas), with only minimal marine reworking. The lower part of the succession, therefore, suggests that marine processes were dominant over deltaic, whereas in the upper part deltaic processes were dominant over marine. The controlling factor over these facies differences was probably sea level. The major mouth-bar is wave-rippled in the lower part indicating some basinal reworking (unlike Oil-Shale Group mouth-bars, see Cater (1987) and Maddox and Andrews (1987)), but the upper part of the bar contains dune-like bedforms which probably migrated in the channel with which the mouth-bar was associated. The mouth-bar is overlain by a minor upward-coarsening sequence representing interdistributary bay (Elliot 1974b), delta-top sedimentation. The sequence records the infilling and abandonment of the lake and the development of a thick peat blanket (organic paleosol) which formed in waterlogged swamp-like conditions (Fig. 10.17). This coal is quite a major paleosol and may be correlated with the 0.60 m thick Radernie Brassie Coal which underlies the St Monans Little Limestone in East Fife (Geikie 1902) and the coal which underlies the Charlestown Green Limestone in West Fife (Forsyth 1970; Chisholm 1970a). It is therefore probably a major abandonment facies which developed as a peat blanket over much of the delta-top prior to the major marine transgression which resulted in the deposition of the limestone between the Hurlet and Charlestown Main limestones. The absence of the limestone in the Kinghorn-Kirkcaldy section suggests that the major channel sandstones which overlie the coal cut into the marine beds and removed them by erosion (Fig. 10.17).

10.4. Charlestown Green/St Monans White limestone; ?former presence at Kinghorn-Kirkcaldy

Most of the major sections (both surface and subsurface) throughout Fife and the Lothians are characterised by the presence of a major marine limestone between the local equivalents of the Hurlet and Charlestown Main limestones. The only notable exceptions to this rule are the Kinghorn-Kirkcaldy coastal section (Figs. 10.2 and 10.3) and the shaft sections in the nearby Seafield Colliery (Francis 1961a) (Fig. 10. 11). The presence of only two limestones (First and Second Abden limestones) in the Kirkcaldy area below the Charlestown Main Limestone, has led to them usually being correlated with the Charlestown Station and Charlestown Green limestones (West Fife) and the St Monans Brecciated and Little limestones (East Fife) respectively (Francis

1961a; Forsyth 1970). These correlations have since been proved incorrect and the Second Abden Limestone is now known to be the correlative of the Charlestown Station and St Monans Brecciated limestones (Oldroyd in MacGregor 1973), suggesting that the Charlestown Green/St Monans Little Limestone is missing. As the limestone is a widespread marine phase, probably resulting from a rise in sea level, it is unlikely that it was never present in the Kirkcaldy area, and it is much more probable that it has been removed by channel sandstones. The former position of the limestone is drawn above the 0.50 m thick coal, as this is the point at which the section would begin to appear anomalous were not the former presence of a marine phase inferred. Comparison of this part of the section with sections in East Fife (St Monans) support such an assumption, as the St Monans Little Limestone is located at a similar position, above a major coal which caps a delta-front sandstone sequence. The fluvio-deltaic clastic interval between the Second Abden and Seafield Tower limestones at Kinghorn-Kirkcaldy is anomalously thick and contains two major deltaic (inter-marine) sequences superimposed on top of one another. This in itself suggests that a marine phase should be present between the two deltaic sequences, solving a mystery which has caused lithostratigraphic confusion as to the correlation of the major marine phases into this area for many years.

10.5. Interval between the former position of the Charlestown Green/St Monans Little and Seafield Tower (Charlestown Main) limestones (see Figs. 10.3 and 10.15).

The interval between the suspected former position of the now missing limestone and the Seafield Tower Limestone is dominated by a clastic fluvio-deltaic, delta-top sequence which is intruded by a 5.5-6.0 m thick transgressive teschenite sill which splits into three intrusive bodies separated by intervening sedimentary rocks to the south (Geikie 1900; Francis 1961a; MacGregor 1973, p. 254) (Fig. 10.3). The interval between the 0.50 m thick coal and the base of the teschenite sill is composed of a 13-14 m thick sequence which is quite poorly exposed and is dominated by fluvio-deltaic channel sand bodies (Fig. 10.12). This part of the section is also exposed in a small quarry approximately one hundred metres inland (Fig. 10.10). On the coast, however, approximately 5.5 m of white-sandy brown coloured, fine to coarse-grained sandstones with a strongly erosive base are present. These are characterised by grouped sets of trough cross-bedding, 'cut and fill' channel-like structures, and impersistent basal conglomeratic lag horizons (Fig. 10.12C and D). In the small quarry, at the top of the section, 4.50 m of coarse-medium grained, red coloured sandstones contain grouped sets of trough cross-bedding and have a major undulatory erosive base, underlain by a 0.17 m thick coal (Fig. 10.12A and B). These sandstones overlie the presumed equivalents of the channel mouth-bar facies on the coast. The channellised sandstones are succeeded by a gap of 4 m and a rooted, nodular sandstone (medium to fine-grained) is intermittently exposed. This paleosol is overlain by another gap in the succession which is 2 m thick and passes upward into 0.50 m of laminated siltstones which are overlain by the lowest part of the sill which is approximately 0.60 m thick. This is separated from the middle part of the sill (2.00 m thick) by 0.30-0.40 m of laminated siltstones. All the sedimentary rocks adjacent to the sills are baked and the sill margins are bleached and altered to 'white trap' (Geikie 1900; MacGregor 1973). The middle part of the teschenite is separated from the upper part by a 1 m thick unit of siltstones, mudrocks and intercalated thin, fine-grained sandstones which are wave-rippled suggesting a N-S palaeocurrent trend. The upper part of the sill is 4 m thick, green-coloured, veined, and weathers out as 'pseudo-pillows', reminiscent of the basalt lavas (Geikie 1900) much lower down in the Kinghorn-Kirkcaldy section.

The sill is overlain by 3.5 m of pinky-red coloured sandstones characterised by an upper 1.30 m thick, medium-coarse grained unit containing a distinctive large-scale solitary set of trough cross-bedding (MacGregor 1973, p.254) indicating southerly and southwesterly palaeocurrents (Fig. 10.13). The underlying beds consist of trough cross-laminated and ripple cross-laminated, medium-fine grained sandstone beds intercalated with small coarsening-upward units containing interlaminated sandstones and siltstones (Fig. 10.13 B and D). The massively cross-bedded sandstone unit (Fig. 10.13 A and C) is overlain by a 3.00 m thick paleosol consisting of medium-fine grained sandstones characterised by large red nodules and red coloured oxidised areas, *in situ* rootlets and large stigmarian roots. It consists of several beds and has a very uneven, slaggy, potholed weathered surface which is largely a deep red colour (Fig. 10.14D). This massive paleosol is separated from the next overlying paleosol by 2 m of delta-top interdistributary bay deposits (Fig. 10.14C). These consist of a coarsening-upward sequence (cf. Elliot 1974b) with mudrocks and siltstones containing intercalated sandstone beds and laminae, siderite nodules, abundant coalified plant remains and impersistent coal seams, passing upward into a 0.40 m thick fine-grained sandstone which is cross-laminated and characterised by vertical burrows. Some of the other minor sandstone 'ribs' are also cross-laminated and these indicate north-westerly palaeocurrents, whilst wave-rippled surfaces are also present (MacGregor 1973, p.254). This bay-fill sequence is capped by a major 3 m+ paleosol (Fig. 10.14 A and B) which consists of four beds, the upper two separated by a very thin shale. These paleosol beds are dominantly fine-grained sandstones which contain *in situ* rootlets (Fig. 10.15C), ferruginous rhizocretions, *in situ Lepidodendron* tree trunks (Fig. 10.15D), abundant stigmarian rootlets (Fig. 10.15A and B) (MacGregor 1973, p.254) and large rounded-subrounded, red-pink coloured oxidisation patches. This paleosol is separated from the overlying Seafield Tower Limestone by 1.10 m of dark fissile mudrocks which contain a thin (0.04-0.06 m) sandy limestone with pyritised specimens of *Orthoceras* sp. The limestone is underlain by approximately 1.30 m of shales which are sparsely fossiliferous and contain lingulids, ostracodes and abundant coalified material. The 0.80 m thick mudrock overlying the thin limestone passes upwards into the Seafield Tower Limestone (Francis 1961a, p.24) and contains productid brachiopods, bands of carbonate nodules and flattened solitary corals in the upper part.

10.6. Interval between the presumed position of the Charlestown Green/St Monans Little and Seafield Tower limestones; interpretation (see Figs. 10.18 and 10.19)

The massive trough-cross bedded and channellised sandstones above the 0.50 m thick coal are interpreted as the deposits of major delta-top distributary channels which cut down through previously deposited delta-front and prodelta sediments, eroding away the underlying marine limestones and associated shales (cf. Moore 1959). This erosion appears to be a feature localised in the Kirkcaldy area, as inland sections in the Rothes Colliery (Francis 1961a) and the BGS Glenrothes Borehole (Browne *et al.* 1986) show that the Charlestown Green Limestone is present. The removal of the marine and overlying prodelta and delta-front deposits has resulted in the superimposition (stacking) of two delta-top sequences and the development of an anomalously thick fluvio-deltaic sequence between the Second Abden and Seafield Tower limestones, leading some workers to question whether a limestone was formerly present but later removed by fluvio-deltaic activity (Browne pers. comm.). Although the exposure is poor above the delta-top channel sandstones, it is clear that the incompletely exposed paleosol represents abandonment of the delta-top. The wave-rippled siltstones, sandstones and mudrocks associated with, and overlying the sill are interpreted as being deposited in lakes and interdistributary bays on the delta-top (cf. Elliot 1974b). The major trough cross-bedded sandstones above the sill record the presence of delta-top distributary and/or crevasse channels which frequently shifted their courses on the delta-top, cutting across interdistributary bay tracts. The prominent 3.00 m thick paleosol is interpreted as a major delta-top abandonment facies along with the uppermost 3.00 m+ paleosol, and the thin coarsening-upward sequence between the paleosols records the brief establishment of a delta-top lake which became infilled by crevasse-splay sand tongues (cf. Elliot 1974b). These paleosols are superbly preserved and contain ferruginous rhizocretions, presumably forming around decaying roots. These are similar to iron oxide precipitates forming around decaying roots in modern plant-bearing sediments (Coleman 1966) and ancient examples described from the Namurian in Northumberland (Elliot 1976c). It is interesting to note that major paleosols are also developed below the Charlestown Main Limestone at St Monans (East Fife) and Catcraig (East Lothian), suggesting that a major, but gradual rise in sea-level affected the water table on the delta-top resulting in waterlogging and reduced sedimentation. The mudrocks which overlie the paleosol and pass upward into the Seafield Tower (Charlestown Main)

Limestone display a transition from a lingulid-ostracode, restricted marine association at the base to a fully marine productid-coral association at the top, indicating that the transgression which reached its acme in the overlying limestone was relatively slow, and quasi-marine conditions were established in its early stages (cf. Ferguson 1962; Calver 1968a, 1968b).

10.7. Tracing the Second Abden-Seafield Tower limestones interval into East Lothian

Major sections through the Lower Limestone Group in the Dunbar area of East Lothian include the Catcraig coastal section (Whyte 1973; Craig 1975; Clarkson 1986a), the Dunbar Works Quarry (Whyte 1973) and the Skateraw Borehole (Figs. 10.1 , 10.2 and 10.20). In these sections the correlatives of the Second Abden and Seafield Tower limestones are the Upper Longcraig and Middle Skateraw limestones respectively (Fig. 10.2). The succession in East Lothian, however, is much thinner than that in central Fife (Francis 1983a) and consequently the major clastic intervals between marine phases are much reduced in thickness too. On the coast at Catcraig, and in the Skateraw Borehole, the major interval between the Upper Longcraig and Middle Skateraw limestones contains a thin marine limestone (Lower Skateraw Limestone) which is correlated with the Charlestown Green/St Monans Little limestones in Fife (George *et al.* 1976; Francis 1983a). The Lower Skateraw Limestone is absent in part of the Dunbar Works Quarry, however, providing a smaller-scale, yet similar example of the local removal of this limestone by overlying deltaics.

The Upper Longcraig Limestone, like the Second Abden Limestone contains the codiacean alga *Calcifolium punctatum* Maslov (Burgess 1965). It is pseudo-bedded (cf. Simpson 1985), with thin, undulatory stylocumulate horizons (Logan and Semeniuk 1976). Petrographically, the dominant fabrics are wackestones and packstones, and framboidal pyrite is very common. An abundant macrofauna and microfauna is present (see Clough *et al.* 1910; Clarkson 1986a; Wilson in Davies *et al.* 1986; Davies *et al.* 1986) including some large solitary corals and small colonies of *Lithostrotion*.

On the coast the interval between the Upper Longcraig and Lower Skateraw limestones is poorly exposed, but is well exposed in the quarry. Here it consists of a 4-5 m thick coarsening-upward sequence (Figs. 10.20 and 10.21) consisting of 1.25 m of mudrocks at the base which contain pectinid bivalves, orthocones, specimens of *Conularia* sp. (Whyte 1973), ?coprolites and pyritized plant remains. These pass upwards into a sequence of interlaminated sandstones, siltstones and mudrocks which are predominantly wave-rippled, lenticular, wavy and flaser bedded (Fig. 10.23A and B), and characterised by trace fossils (Fig. 10.23C) (e.g. mud-filled burrows) and bioturbation. The white sandstones and associated darker silts and muds are very micaceous and rich in pyritised plant remains and pyrite chunks. Palaeocurrents of 165 degrees (SW) are suggested by cross-laminae and palaeocurrent trends of 317-137 degrees (NE-SW) are indicated by wave-ripples. Some of the lenticules of sandstone exhibit soft-sediment deformation and are convoluted, dewatered and loaded. These heterolithic deposits are overlain by a thin, 0.10 m thick coal. On the coast the limestone is underlain by a massive white-coloured 1 m thick sandstone which has sand-filled casts of stigmarian rootlets in the upper part, and the coal observed in the quarry is absent.

On the coast, the Lower Skateraw Limestone is 0.56 m thick and contains disarticulated valves of the productid *Gigantoproductus* cf. *giganteus* (J. Sowerby). It is a brown-grey dolomitised limestone which has an orange weathering top characterised by small *Diplocraterion* burrows on the upper surface, and is a relatively thin and poorly fossiliferous horizon (Davies *et al.* 1986 and Wilson in Davies *et al.* 1986). Elsewhere along the coast, at Torness Point (Longcraig), the fauna is more diverse and includes *Lithostrotion* and a few rugose corals (Davies *et al.* 1986). The limestone varies in thickness between 0.36-1.52 m throughout the area, but is generally laterally persistent and characteristically uniform lithologically. In the quarry, the limestone is 0.20 m thick and contains crinoid ossicles and large productid valves which are convex-upwards and concave-upwards. It is called the Mg-limestone by the quarrymen, who do not quarry it for cement because of the high Mg content. In the southern end of the quarry the limestone is present but is cut into by the overlying heterolithic sandstones. This undulatory erosive contact is characterised by a coarse lag consisting of plant remains and intraclasts. In the northern end of the quarry, however, the limestone is cut out altogether by the overlying sand body and the interval between the Upper Longcraig and Middle Skateraw limestones is totally occupied by clastics, as at Kinghorn-Kirkcaldy. The heterolithic sandstone which overlies the limestone and cuts it out is approximately 2 m thick and consists of intensely rooted sandstones (Fig. 10.24) which form prominent laterally accreted units in the quarry face (Fig. 10.22), and this is especialy well displayed towards the southern end of the quarry. Palaeocurrent data derived from this channellised sandstone indicates palaeocurrents from E-W to NE-SW. The sandstones containing abundant *in situ* coalified rootlets are bleached white and ganister-like, and this sand body is characterised by micaceous horizons, coal laminae, plant remains, and stigmarian rootlets. A green coloured mudstone with large desiccation cracks has been noted as a parting within these sandstones (Whyte 1973, 1981, p.243), but is not exposed at the present day. The sandstones are channellised and display erosive contacts, steep erosive surfaces, and impersistent coals are present, but are 'washed-out' preventing thicker and more persistent deposits from developing. The laterally accreted units are well displayed, but are locally steep, dipping at around 20 degrees both ways into the channel. The laterally accreted sand body is overlain by 1-1.5 m of muddy fireclay which is rhizoturbated, contains coaly chunks, varies considerably in thickness along the quarry face and is overlain by a 10-15 cm thick coal. The coal is overlain by the 4 m thick Middle Skateraw Limestone (Fig. 10.22) and the overlying marine mudrocks containing the Neilson Shell Bed (Whyte 1973, 1982, 1984). On the coast, the interval between the Lower and Middle Skateraw limestones is significantly different, and is predominantly composed of paleosol facies, the lateral accreted sand body replaced by a 2.20 m thick silty paleosol which is prominently orange weathered and contains orange coloured cornstone-type carbonate nodules and 'pipes'. The overlying rocks are almost identical to those developed in the quarry and these paleosols are probably equivalent to those developed below the Seafield Tower Limestone in central Fife.

10.8. Upper Longcraig-Middle Skateraw limestones interval; interpretation (see Figs. 10.25 and 10.26)

The Upper Longcraig Limestone contains a similar solitary and colonial coral fauna (e.g. the *Koninckophyllum echinatum* band or 'Dunbar Marble') to the Second Abden Limestone and also contains the codiacean alga *Calcifolium punctatum* Maslov. As such it is a major marine phase which represents deposition within an open marine shelf setting, created by a major marine transgression of the Midland Valley (cf. Wilson 1974). The overlying heterolithic sandstones containing a predominance of wave-dominated structures, which pass upward from marine mudrocks represent a transition from prodelta deposits to delta-front sediments, which were wave-influenced (Clifton *et al.* 1971) and reworked by marine basinal processes. This is supported by the presence of marine ichnogenera which suggest that persistent and high rates of deltaic sedimentation were not attained due to a dominance of marine influence. The sandy beds which are mud-draped suggest periodic river-generated sand incursions punctuated by quieter water (low energy) phases of sedimentation when mud was deposited from suspension onto the 'backs' of rippled sands. On the coast, the massive sandstone which caps this sequence has been reported to be channellised (Whyte 1973), suggesting delta-top sedimentation within a distributary channel which fed the delta-front sand sheets. Due to the level of marine reworking it is concluded that point-concentrated sand bars could not develop (cf. Belt 1975). The rooted nature of the upper surface of this paleosol and the development of a thin coal in the quarry suggest widespread abandonment of the channels and contemporary bays on the delta-top resulting from changes in the water table, possibly in response to a rise in sea level. The overlying Lower Skateraw Limestone, which is widespread throughout the Lothians and Fife (except where locally removed by fluvio-deltaic erosion) probably records a sea level rise resulting in the establishment of widespread shallow, open marine shelf conditions. The presence of *Diplocraterion* burrows on the top of the Lower Skateraw Limestone may record a shallowing-upwards trend, and the local absence of the limestone in part of the quarry suggests that it was removed by the overlying meandering channel (presumably in the thalweg) which eroded down into the underlying and previously deposited sediments. The sand body which is only present in the quarry and is absent on the coast and in the Skateraw Borehole represents a major meandering channel with associated point bars. The rooted nature of the sandstones suggests that the point of sediment accretion on the bar was periodically abandoned and vegetated, providing stabilisation for the relatively steep surfaces. Minor impersistant coals further indicate that parts of the sluggish river periodically became swamp-like vegetated tracts where peats (organic paleosols) developed in waterlogged conditions. Repeated river-activity, however, resulted in 'wash-outs' explaining the lateral impersistence and localised nature of the seams. Breaks in deposition within the channel also resulted in muddy drapes on the inclined point-bar surface, and heterolithic sediments are characteristic of laterally accreted sand bodies (Reineck and Singh 1975). Lateral accretion ('epsilon cross-stratification' of Allen (1963)) is common in channel sandstone coarse members (Collinson 1986, pp.53-5), and consists of low-angle cross-beds which extend as a single set over the whole thickness of the coarse member, or over a substantial part of it. The foresets dip at 90 degrees to the palaeocurrent direction obtained from smaller-scale sedimentary structures and the inclined layers are defined by fluctuations in grain size (Collinson 1986). In the Dunbar Quarry, the lateral accretion surfaces occupy the whole thickness of the sandstone body (cf. Puigdefabregas and Van Vliet 1978), and the unit is interpreted as resulting from the lateral accretion of sediments upon an inclined surface (i.e. a point bar within a meandering channel (Allen 1983)). The finer-grained intercalations, like the rooted horizons, represent flow stage fluctuations in the channel. On the coast, it is interesting to note that the channel sand body is replaced by interdistributary bay-lagoon paleosol facies which was presumably the lateral equivalent on the delta-top of the meandering distributary channels. The overlying paleosols (fireclay and coal) are probably correlatives of the paleosols below the Seafield Tower Limestone at Kinghorn-Kirkcaldy and are interpreted as a major delta-top abandonment facies developed prior to the 'Charlestown Main Limestone marine transgression'.

10.9. Comparisons between the central Fife and East Lothian sections

Although the East Lothian succession is considerably thinner than that developed in central Fife (Goodlet 1957; George *et al.* 1976; Francis 1983a), the interval between the Hurlet-Charlestown Main limestones is very similar in both areas, and major abandonment facies (e.g. paleosols) and marine phases can be correlated with some accuracy between the two districts. But perhaps the most interesting feature is the absence of an intervening limestone in central Fife and its partial absence in East Lothian (Fig. 10.2). Although it can only be inferred that a limestone was once present in central Fife, direct evidence in East Lothian shows how a limestone can be locally removed by overlying erosive channel facies. It is therefore suggested that this was the mechanism by which a limestone was removed from the Kinghorn-Kirkcaldy section, and this is supported by the general nature of the sequence which via facies analysis suggests that a major marine phase should be present in the middle of an interval which is unusual and anomalously thick. Once a reconstruction is made, however, and the limestone is assigned to its presumed former position, the sequence begins to look less anomalous and more similar to any other inter-marine part of a Yoredale-type cycle.

10.10. Discussion of paleosols

Paleosols are very common, well developed and superbly preserved in the outcrops studied and three dominant types are recognised. These are podzols, gley soils and organic soils or peats. In most cases, paleosol facies are developed below marine phases (cf. Elliot 1974a, 1975; Percival 1986), and as such probably represent reduced sedimentation on the delta-top which was rapidly becoming abandoned due to a rise in sea-level affecting the water table, and in most cases raising the base level and waterlogging the delta plain (Percival 1986). Coals (organic paleosols) and fireclays and seat-earths (gley paleosols) are most commonly developed below marine beds and are interpreted as representing hydromorphic (waterlogged) conditions on the delta plain. Such conditions are most characteristic of soils forming in deltaic environments with a low relief and a generally high water table. In some cases, however, podzols with well developed albic horizons (cf.

Percival 1986) are developed, indicating well drained delta-top settings. Such beds are invariably known as ganisters (Percival 1983) and are generally represented by hard, siliceous quartz-arenites containing stigmarian rootlets and *Lepidodendron* trunks suggesting colonization by shallow rooting club mosses (Collinson 1986). Similar paleosols indicating the periodic attainment of well-drained conditions in delta platform settings have also been noted in the Westphalian (Percival 1986), and these are often sensitive to factors such as the prevailing climate and local tectonic uplift, the latter promoting drainage (Fielding *et al.* 1986).

The paleosols studied can be clearly divided into two kinds; those that are obviously localised and merely represent the local infilling and colonization by vegetation of parts of the delta-top, and those that are more major, underlying widespread marine bands and clearly developed across the whole of the delta-top.

10.11. Conclusions

This study illustrates by two examples how a marine limestone may be removed from a section and partially removed from another. In central Fife, the absence of a limestone has caused problems in the lithostratigraphic correlation of the area with other parts of Fife, which provides an example of the importance of such a phenomenon in successions where lithostratigraphic control and correlation is of paramount importance. These are the first recorded examples of limestone 'washouts' by fluvio-deltaic channels from the Dinantian of Scotland, but it is hoped that by their recognition improvements may be made in the interpretation and correlation of the successions in which they occur.

It is perhaps also worth noting that the Charlestown Green, St Monans Little and Lower Skateraw limestones are all relatively thin units, and unlike the thicker marine phases developed in the Lower Limestone Group may be more readily and easily removed by fluvio-deltaic erosion.

CHAPTER 11

The recognition and significance of facies and thickness changes in the Charlestown Main Limestone-Lower Kinniny Limestone interval, Fife and the Lothians.

11.1. Introduction and rationale

In this study, the interval between the Seafield Tower (Charlestown Main) and Lower Kinniny limestones which crops out in the Kirkcaldy area of central Fife is described (Figs.11.1, 11.2 and 11.7). The Seafield Tower Limestone and overlying calcareous mudrocks are interpreted as a very major marine phase and the overlying major distributary channel sand body (the Seafield Tower Sandstone) is interpreted as a delta-top channel which probably cut down and eroded away a significant thickness of prodelta and delta-front sediments. This constructive, progradational fluvially-dominated deltaic phase is overlain by delta lobe abandonment facies (paleosols), succeeded by a destructive (wave-dominated) post-abandonment phase, illustrating the two-fold nature of deltaic sedimentation (cf. Scruton 1960; Elliot 1978). Within the post-abandonment facies, the Seafield Marine Band is recognised as a transgressive marine phase limited in geographical extent to the abandoned delta lobe, which probably extended throughout east and central Fife, but was largely limited to an area east of the Burntisland High, a structure which may have controlled the geographical extent of the delta lobe.

By examining the interval at other localities in parts of Fife and the Lothians (Fig.11.2), a detailed correlation of marine phases has allowed a reconstruction of prodelta, delta-front and delta-top facies in the intervening clastics, which has given an insight into the relative roles of marine and fluvio-deltaic interaction in a tectonically active setting.

11.2. Localities and stratigraphical position of the rock sequence

The sequence (interval) studied [NT 280 884] crops out on the northern shore of the Firth of Forth between Kinghorn and Kirkcaldy, central Fife (Figs.11.1, 11.2). Part of the sequence also crops out inland, along strike, at Inverteil Quarry [NT 272 898], on the outskirts of Kirkcaldy, and subsurface sections occur in the nearby Seafield Colliery [NT 278 895] (Figs.11.1 and 11.2). The sequence occurs between the Charlestown Main Limestone (locally known as the Seafield Tower

Limestone) and the Lower Kinniny Limestone (Fig.11.1), which are recognised (albeit with different names) throughout most of the Midland Valley of Scotland (MacGregor 1973, p. 33). This regional correlation is further aided by the presence within the sequence of the Seafield Marine Band (Fig.11.1) (Francis 1961a) which allows a more precise and local correlation with surface and subsurface sequences in east, central and west Fife, where the Seafield Marine Band has also been recognised (cf. Forsyth and Chisholm 1968; Forsyth 1970).

11.3. Seafield Tower Limestone (Charlestown Main Limestone)

The 3.9 m thick Seafield Tower Limestone consists of three main beds and is overlain by a thick sequence (25 m) of calcareous mudrocks (Fig.11.4D) containing septarian nodules (Fig.11.4B) and thin lensoidally-bedded crinoidal limestones (Fig.11.4A, C and D). The limestone contains an abundant marine fauna including crinoids and crinoid cups (Wright 1911, 1912), *Lithostrotion*, *Zaphrentis*, the heterocorals *Heterophyllia* and *Hexaphyllia* (Sutherland and Mitchell 1980, p. 15), *Schizophoria*, *Spirifer*, *Productus*, *Orthoceras* sp. and *Fenestella* sp. (MacGregor 1973, p. 254). Microfossils are also present including the diagnostic alga *Calcifolium okense* Maslov (Oldroyd pers. comm.), which is particularly abundant in thin sections from the inland exposure at Middlebank Road Cutting, near Inverkeithing (Fig.11.3A, B and C). The presence of this algal species suggests that this limestone is the equivalent of the Charlestown Main Limestone (west Fife), and the Blackhall Limestone in the west of the Midland Valley of Scotland (Figs.11.14 and 11.15) (Burgess 1965).

The overlying calcareous marine mudrocks do not contain the Neilson Shell Bed (Wilson 1966; Jameson 1980) which is usually found at this level throughout the Midland Valley, but otherwise this part of the sequence is similar to that developed elsewhere. Although several explanations have been forwarded as to the reason for its absence, it is likely that the nearby Burntisland Anticline may have exerted a faunal and facies control, as it is known to have influenced Namurian faunal distributions (Wilson 1967). The intercalated limestones are predominantly crinoidal (crinoid-bryozoan packstones and grainstones)

(Fig.11.4A and C), and directly below the erosive contact with the overlying Seafield Tower Sandstone, several beds of crinoid-bryozoan packstones and grainstones are crudely hummocky cross-stratified and bright pink coloured (Fig.11.5D).

11.4. Seafield Tower Sandstone; Fining-upwards unit; coarse member (Figs. 11.7)

The Seafield Tower sandstone forms a 13 m thick fining-upward unit which abruptly overlies the calcareous mudrocks and interbedded limestones above the Seafield Tower Limestone (Fig.11.5D). The fining-upward unit is divided into a lower, 8 m thick 'coarse member', and an upper, 5 m thick 'fine member' (terminology after Allen (1965)).

The coarse member consists of a thin, very coarse to coarse-grained, quartz-arenitic sandstone with a thin (0.30 m), basal conglomerate (Fig.11.6B), locally developed upon a sharp, undulatory, erosive base. The coarse member is well exposed on the Kinghorn-Kirkcaldy foreshore (upon which the ruins of Seafield Tower stand) and at Inverteil Quarry. The thin basal conglomerate is developed within clast-supported, hummocky-shaped irregularities on the base of the sandstone at Inverteil, and as a thin, matrix-supported veneer upon the less irregularly-shaped base of the sandstone at Kinghorn-Kirkcaldy. The clasts are dominantly mudrock fragments and coalified plant remains (e.g. tree trunks), although occasional clasts of crinoidal mudstone occur. The conglomerate rapidly fines-upward into a very coarse to coarse-grained, pink coloured sandstone. The sandstone is dominantly trough cross-bedded (Figs.11.5A and 11.6A) and the trough cross-bed sets, 0.5-0.7 m in thickness are grouped into cosets occasionally punctuated by major reactivation surfaces (Fig.11.5B) (cf. Collinson 1970). At Kinghorn-Kirkcaldy, the axes of three-dimensionally exhumed trough cross-bed sets (Fig.11.6A) predominantly trend NE-SW, the curved foresets dipping to the SW. These measurements contrast with those recorded at Inverteil Quarry where trough cross-bed axes trend NW-SE, the curved foresets dipping to the NW.

Within the eastern face of Inverteil Quarry, the basal 3 m of the coarse member consists of very coarse-grained sandstone containing cosets of trough cross-bedding, and is overlain by a major erosion surface. Above this, the sandstone is noticeably finer-grained and the dominant structures are large trough-shaped, channelloid scours. These scours range from approximately 6 m to 10 m in width, and their erosive bases are usually overlain by mudrock drapes. One of the scours appears to be infilled with laterally-accreted sediments (Fig.11.5C) (epsilon cross-stratification of Allen (1963)) and the lateral accretion surfaces are draped by very thin mudrock veneers. The axes of the trough-shaped scours dominantly trend WWWN-EEES. The upper part of the coarse member at both Kinghorn-Kirkcaldy and Inverteil is characterised by convoluted bedding (Fig.11.6C) and associated water-escape structures (Fig.11.6C).

In the nearby Seafield No.1 Colliery Shaft, the coarse member is reduced to a 2.40 m thick medium-grained, massive, white-coloured sandstone, which is coarse and pebbly in the lower part.

11.5. Seafield Tower Sandstone; Fining-upwards unit; fine member (Fig.11.7)

The 5 m thick fine member is only exposed on the foreshore at Kinghorn-Kirkcaldy. It consists of red coloured, medium to fine-grained sandstones, which are rooted and occasionally cross-laminated, and are interbedded with siltstones and mudrocks (Fig.11.8D). The fine member is overlain by a 0.14 m thick nodular siltstone containing rootlets (seat-earth) (Fig.11.9B) which passes upward into a very poorly exposed, 0.9 m thick coal (Fig.11.9C), which was formerly worked at outcrop (Francis 1961a, p. 26).

In the Seafield No.1 Colliery shaft, the fine member is 5.7 m thick and consists of two upward-coarsening units capped by coals. The coarse member is overlain by the first unit which consists of a 1.53 m thick mudrock which coarsens-upward and is overlain by a 0.30 m thick coal. The second unit comprises a 3.90 m coarsening-upward unit with a basal 1.80 m mudrock containing thin sandy beds and laminae (ribs) which become more common towards the top. The mudrock passes upward into silty sandstones which contain *in situ* rootlets, and the overlying 0.995 m thick coal is clearly the correlative of the 0.90 m coal which crops out on the coast (Fig.11.7).

11.6. Interpretation of the fining-upward sequence

The thin conglomerate at the base of the coarse member within the fining-upward sequence is interpreted as a channel floor lag which partially accumulated within scour pits produced in the channel thalweg (Allen 1970; Elliot 1976b; Plint 1983). The absence of a coarsening-upward prodeltaic to delta-front transition facies between the marine limestones and shales and the overlying channel lag is probably due to erosion of previously deposited sediments by the major delta-top distributary channel (cf. Belt 1975).

The decimetre-scale trough cross-bedding is interpreted as representing sinuous-crested dune bedforms which are known to be produced subaqueously in Recent rivers (Bridge 1976; Levey 1978). Cosets of trough cross-bedding are characteristic of palaeochannel fills (cf. Elliot 1976b; Okolo 1983) and may as in this example be the dominant or only 'facies' present in the coarse member (Collinson 1978). Palaeocurrent data from Kinghorn-Kirkcaldy suggests a dominant palaeoflow direction to the SW, which is in accordance with previously suggested palaeocurrent trends within the Lower Limestone Group (cf. Goodlet 1957; Belt 1975). Limited palaeocurrent data recorded from Inverteil Quarry indicates a north-westerly palaeoflow direction, which is a slight deviation from suggested palaeocurrent trends, and may indicate a meander within the distributary channel. The large-scale reactivation surfaces which punctuate the trough cross-bed sets are interpreted as surfaces most commonly developed at low water stage, when channel bedforms were dormant and emergent (Collinson 1978; Haszeldine 1983), indicating periodic, large-scale fluctuations in river level. The large-scale trough-shaped scours at Inverteil Quarry are erosional and are interpreted as small channels ('cut and fills') within a larger fluvial distributary channel setting (cf. Reineck and Singh 1975). Associated lateral accretion surfaces orientated at approximately 90 degrees to palaeoflow are interpreted as small point bars developed within the channels. The presence of smaller channels within a larger, major channel complex is suggestive of braiding, and the possibility that the Seafield Tower Sandstone represents a major braided stream deposit cannot be overruled.

Convoluted bedding and water escape structures are soft-sediment deformation features which are known to be commonly developed within channel sequences (Plint 1983). The convoluted bedding in the upper part of the Seafield Tower Sandstone coarse member probably formed through partial liquefaction and deformation of water saturated sediment under the influence of lateral shearing, possibly resulting from the movement of large bedforms over an unconsolidated substrate during high flow stages (McKee *et al.* 1962).

The overlying 5 m thick fine member is interpreted as representing the final channel fill during abandonment, leading to the subsequent colonization by vegetation and development of the seat-earth and coal. Channel abandonment often produces an overall fining-upwards trend (Kelling and George 1971), resulting from a gradual reduction in the coarse clastic sediment input, with only intermittent crevasse splay sand incursions.

The sequence developed in the colliery shafts between the Seafield Tower Sandstone (coarse member) and the major, 0.90 m thick coal is interpreted as an interdistributary bay sequence (cf. Elliot 1974b) contemporary with the major distributary channel sequence represented by the thicker sandstone on the coast and at Inverteil. In the colliery area, major channel development apparently began at the same time as it did in the coastal sequence, but channel abandonment took place much earlier leading to the development of a large bay-like lake where fine-grained muds accumulated. Occasional crevasse splay sands infilled the shallow bay-lakes and organic paleosols (peats) developed (now represented by the minor 0.30 m thick coal). These minor coals are limited to the geographically restricted bays on the delta-top and should not be confused with the more major coals which developed as areally widespread peat blankets upon the abandoned delta top (cf. Elliot 1974a, 1974b, 1975). The variation in the sequences on the coast at Seafield and Inverteil compared with the nearby Seafield Shafts illustrates the variation in styles and patterns of sedimentation on ancient delta-tops over relatively short distances, and is useful in displaying the differences between coals representing local bay abandonment which cannot be correlated over long distances, and more major coals representing major delta-top abandonment facies which are more geographically widespread.

The seat-earth and coal which overlie the fine member on the coast and in the Seafield Colliery represent the termination of the constructive progradational phase of fluvially-dominated deltaic sedimentation. The coal is interpreted as representing the proximal facies of the abandonment phase, possibly representing delta-top marsh peat development, following abandonment of a delta lobe (cf. Elliot 1975).

11.7. Lateral continuity of the Seafield Tower Sandstone (see Figs.11.14 and 11.15)

Deltaic sandstones of a fluvial distributary channel origin are known to be laterally impersistent and the Seafield Tower Sandstone is no exception, its thickness and facies equivalents varying greatly (Francis 1961a). On the coast at Seafield, the sandstone is about 15 m thick, whereas in the nearby Seafield Colliery shaft it is only approximately 3 m thick and is overlain by interdistributary bay facies (Fig.11.7), suggesting the earlier abandonment of the channel complex and the development of shallow bay-lakes which were contemporaneous (lateral equivalents) with a major channel complex on the delta top as exemplified by the thicker channel sandstone on the coast. Away from the Seafield area, some 14-16 km to the north, it is as much as 36 m thick in bores in the Thornton area, and contains paleosol facies (15 cm coal and an underlying fireclay) in its upper part (Francis 1961a, p.26). At other localities, however, the lithological continuity and homogeneity of the sandstone unit deteriorates, and near Thornton in a westerly direction, and in the Mid Strathore Bore it consists of two sandy units separated by 6 m of fine-grained beds. A similar sequence has been recorded in the Rothes Colliery where about 12 m of fine-grained rocks containing a 7.5 cm thick coal separate the two sandstone units. On the other (western) side of the Burntisland Anticline at Bowhill Colliery, 11 km to the west of Rothes, the succession is similar to Rothes, except that the intervening fine-grained beds between the two sandstone units contain the Mill Hill Marine Band (Haldane and Allan 1931; Wilson 1980; Forsyth and Wilson 1981). This suggests that the Mill Hill Marine Band is absent in central Fife, and that the marine band above the Seafield Tower Sandstone on the coast at Seafield is not the Mill Hill Marine Band as was suggested by Allan and Knox (1934) (Forsyth and Wilson 1981), but is the stratigraphically higher Seafield Marine Band (Francis 1961a).

11.8. Geographical distribution and significance of the Mill Hill Marine Band

The Mill Hill Marine Band is present throughout West Fife (Fig.11.14) (Haldane and Allan 1931, p.29; Forsyth 1970) above the lower of two sandstone units (described above), about 45 m above the Charlestown Main Limestone (Forsyth and Wilson 1981). It is absent, however, from central Fife (Fig.11.14), at all localities with the exception of the Bowhill Colliery (Francis 1961a, p.26), which is on the west side of the Burntisland Anticline, and it has never been found at a central Fife locality east of the anticline. In East Fife, the marine band has been located in subsurface sections (Forsyth and Chisholm 1968), on the eastern limb of the St Monans Syncline coastal section (Fig.11.20) (Wood 1887; Forsyth and Chisholm 1977; Wilson 1980; Forsyth and Wilson 1981), and on the coast at Elie (Forsyth and Wilson 1980). The Mill Hill Marine Band has not been identified outside Fife, and therefore it must be concluded that it is a geographically restricted marine phase limited to parts of west and east Fife.

The questions that must be posed with regard to the Mill Hill Marine Band relate to why it is geographically restricted to Fife and why it is absent at all central Fife localities west of the Burntisland Anticline. Most of the marine phases in the Lower Limestone Group and the underlying Pathhead Beds are widespread across the Midland Valley (Burgess 1965; Wilson 1966, 1974) and appear to represent rises in sea level which initiated marine transgressions. Clearly, therefore, if the Mill Hill Marine Band were the result of a major marine incursion, then it should be present across the whole of the Midland Valley, or at least over a relatively wide area. As this is not the case, then either the marine band is more widespread than has previously been recognised (and was the result of a major incursion), or the present day distribution is a true reflection of its original geographical restriction suggesting it was not the product of a major marine transgression. There is some evidence to support the former argument, as in the Seafield area it may have been removed by fluvial distributary channel erosion (cf. chapter 10). This argument, however, falls apart to some degree when the section in the Seafield Colliery shafts is investigated, in that the Seafield Tower Sandstone fluvial sand body is quite thin and is overlain by a thick interdistributary bay sequence which shows no signs of the Mill Hill Marine band, which if originally present in the area would surely be present in this part of the section. Unless the thin channel sand had removed an enormous amount of previously deposited sediment (which seems most unlikely) it appears that the Mill Hill marine phase was never present. This line of argument is also supported by the fact that the marine band is restricted to parts of Fife, and even if it was originally present in central Fife, it was clearly not present outside Fife.

Geographically restricted marine bands can result from either marine reworking of only the abandoned parts of deltas (Elliot 1974a, 1975), weak marine pulses which petered out in a landward direction, or tectonic activity restricting the extent of the marine conditions. The restriction of the Mill Hill Marine Band to parts of the delta lobe (or lobes) which were partially abandoned finds some favour with the evidence, as it is possible that whilst the Fife-Midlothian Low which runs through central Fife was the site of major delta progradation (and favoured by major channel drainage) (Fig.11.15), the west and east Fife basins were characterised by delta lobes which were abandoned and encroached upon by marine conditions, the limits of the marine incursion confined to the area of abandoned delta (cf. Elliot 1974a). This solution is supported to some degree by the facies developed in the marine band, which in parts of East Fife consist of bioturbated calcareous sandstones with relic cross-bedding (Forsyth and Wilson 1981) suggesting reworking of delta sediments in shallow marine conditions established during delta abandonment. Thick marine limestones and shales are not developed in the marine band indicating that the marine influence was not great, and such evidence is suggestive of either a very weak transgression or a localised incursion restricted only to areas of the delta complex that were not actively prograding and which had become partially abandoned.

In conclusion, it must be stated that the marine band may have been removed by fluvial channel erosion (in the Fife-Midlothian Low axial drainage system), explaining its absence in central Fife, conversely, its absence may be a genuine original environmental feature providing evidence to suggest that the deltaic complex prograded at different rates, with some areas being reworked by marine processes whilst others were still actively prograding.

11.9. Coarsening-upward unit (Fig.11.7)

The abandonment facies described above are overlain by a 10 m thick coarsening-upward unit, within which are two subordinate coarsening-upward sub-units A and B.

The lower coarsening-upward sub-unit (A) is approximately 5 m thick and is dominated by dark fissile mudrocks (Fig.11.9C) containing carbonate nodules and a thin limestone bed, all of which contain marine fossils. Mudrocks containing siderite nodules and bands (Fig.11.8B) gradually coarsen-upward into a flaggy, wave-rippled, fine-grained sandstone which is overlain by a 0.4 m thick arenaceous bioturbated limestone containing marine fossils (largely disarticulated crinoid ossicles), the degree of recognisable bioturbation increasing as the rocks coarsen. The arenaceous limestone contains abundant burrows of the marine ichnogenera *Rhizocorallium* (Fig.11.9D), *Diplocraterion* (Fig.11.9A) and *Zoophycos*, and displays hints of cross-bedding, highly disrupted by bioturbation. This coarsening-upward unit, along with the thin overlying mudrock bed at the base of the next sub-unit (B) is the Seafield Marine Band (Francis 1961a).

The overlying coarsening-upward sub-unit (B) is approximately 4 m in thickness, and conformably overlies the lower sub-unit. It begins with a 0.5 m thick mudrock bed containing siderite nodules which rapidly coarsens-upward into lenticular bedded, fine-grained sandstones, succeeded by rippled, flaser bedded sandstones. These rippled sandstones are approximately 1.5 m thick, and the ripples are well exposed upon the upper bedding surfaces. The ripple crests are straight, with minor sinuosity, and crest bifurcation is common. The crests dominantly trend in a NW-SE direction. The ripple crests are symmetrical and slightly rounded in profile, and the average ripple index is 7. Occasional trace fossils (?*Gyrochorte* trails) are present within the ripple troughs. The rippled sandstones pass-upward into 1.5 m of poorly exposed, medium-grained, trough cross-bedded sandstones which are overlain by 0.5 m of planar-bedded, fine-grained sandstones containing large stigmarian rootlets and the epichnial trails of *Gyrochorte*. The top bed of this sub-unit contains abundant coalified rootlets. These rocks are overlain by a thin coaly mudrock, which passes upward into the Lower Kinniny Limestone containing marine fossils.

11.10. Interpretation of the coarsening-upward unit

After the abandonment phase, during which the seat-earth and coal formed, the abandoned delta-top was transgressed, establishing mud sedimentation in a relatively quiet open marine environment, now represented by the fine-grained lower part of the coarsening-upward sub-unit (A) (Seafield Marine Band). The wave-ripples associated with upward-coarsening suggest wave reworking, in an environment generally starved of coarse clastic sediment input. This is supported by the presence of trace fossils. The calcarenite containing marine body fossils and well preserved trace fossils is interpreted as reflecting sediment reworking (Swift 1968) and slow depositional rates during a post-abandonment transgression over an abandoned delta-top (cf. Elliot 1975).

The overlying 4 m coarsening-upward sub-unit (B) reflects increasing input of coarse clastic sediment. The dominance of wave-ripples and lenticular and flaser bedding suggests a wave-dominated palaeoenvironment (Clifton *et al.* 1971; Belt 1975) possibly representing the advance of the wave reworked front of a delta lobe. The overlying trough cross-bedded and planar-bedded sandstones may represent delta-top facies, developed prior to the 'Lower Kinniny Limestone marine transgression'. The Lower Kinniny Limestone is interpreted as a transgressive unit, the base of which represents extensive marine reworking and bioturbation of abandoned deltaic sands during the marine incursion.

11.11. Charlestown Main Limestone-Seafield Marine Band-interval; Fife and Lothians

The Charlestown Main Limestone is readily traced throughout east, central and west Fife into the Lothians (Figs.11.14 and 11.15), south of the Firth of Forth, where it is invariably called the North Greens Limestone (Midlothian) or the Middle Skateraw Limestone (East Lothian). Together with the overlying marine mudrocks, this limestone generally forms the thickest and most widespread marine phase in the Lower Limestone Group, and is known to be characterised by carbonate buildups at some localities (Wright 1912; MacGregor 1973, pp. 246-7; Jameson 1980, 1987). It contains the diagnostic alga *Calcifolium okense* (Fig.11.3) (Burgess 1965), and is usually overlain by the Neilson Shell Bed (Wilson 1966, 1974). Another feature which is sometimes characteristic of the limestone (especially in parts of the Lothians) is the presence of *Saccaminopsis* bands (Davies *et al.* 1986; Clarkson 1986a). At all the localities studied with the exception of Kinghorn-Kirkcaldy (central Fife) and Bilston Burn (Midlothian), the Charlestown Main Limestone is overlain by marine mudrocks with interbedded limestones which gradually coarsen-upward into mudrocks and siltstones with occasional sandstone interbeds developed prior to the development of thicker sand bodies.

In the Bilston Burn (Fig.11.15), however, the North Greens Limestone (Charlestown Main Limestone) is overlain by a marine mudrock sequence which is cut into by a major erosive-based sand body (Fig.11.8A) (North Greens Sandstone) which is the local equivalent of the Seafield Tower Sandstone (Macconochie 1927, pp. 33 and 35). This sandstone is very coarse to coarse-grained, red-orange to yellow coloured, very well trough cross-bedded (grouped sets) and characterised by reactivation surfaces and dewatering structures in the upper part. Palaeocurrent data indicates a predominantly south-westerly palaeoflow and the gross lithological characteristics of the rock are virtually identical to those of the Seafield Tower Sandstone. The Bilston Burn [NT 275 645] is almost directly south of Kinghorn-Kirkcaldy within the Fife-Midlothian Low suggesting that the axis of the low may have formed an axial drainage system along which major channels drained.

All the localities studied, however, broadly display a transition from shallow marine mudrocks and limestones into deltaic facies (prodelta, delta-front and delta-top), the only differences relating to the erosion of presumed prodelta and delta-front deposits at Kirkcaldy and Bilston due to their positions along an axial drainage system where major channels developed, eroding away previously deposited sediments. The preservation rate of prodelta and delta-front deposits at the other localities appears to have been greater, although the prodelta and delta-front facies pass upward into delta-top facies.

In East Fife (Figs.11.11 and 11.12), West Fife and East Lothian (Figs.11.14 and 11.15), the Charlestown Main Limestone (Fig.11.13D) is overlain by mudrocks containing the Neilson Shell Bed which coarsen-upward through mudrocks, siltstones and sandstones (Fig.11.13A). The interbedded thin sandstone beds are often wave-rippled, ripple cross-laminated, hummocky cross-stratified (Fig.11.13B), channellised (Fig.11.13C) and display signs of bioturbation and trace fossils (Fig.11.13A) These delta-front sequences appear to have been marine reworked and marine influenced as they are characterised by marine to quasi-marine trace fossils (Forsyth 1970; Chisholm 1970b) and occasional body fossils (Davies *et al.* 1986). Thicker channel sand bodies and palaeosol facies do, however, overlie the marine-influenced delta-front deposits, which can be compared with the delta-top facies at Seafield and in the Bilston Burn, but the sequences in east and west Fife are punctuated by the Mill Hill Marine Band which is absent from central Fife, and is not known in the Lothians. Like the Seafield Marine Band, the Mill Hill Marine Band (Haldane and Allan 1934) is a geographically restricted marine phase, overlying abandonment facies (e.g. paleosols or reworked layers (Chisholm 1970a, 1970b)) and possibly representing post-abandonment marine bands which were confined to the extent of ancient delta lobes (cf. Elliot 1975). In east and west Fife the rocks between the Mill Hill and Seafield marine bands vary in character. In East Fife, 7.50-13.50 m of mainly sandy deposits (Forsyth and Chisholm 1977) which are strongly bioturbated (Chisholm 1970a) intervene between the marine bands and are capped by the lowest part of the Largoward Black Coal. In West Fife, the interval comprises a coarsening-upward sequence with siltstones and silty sandstones containing *Curvirimula* passing upward into sandstones and siltstones characterised by *Monocraterion*.

In the Lothians, the recognition and correlation of marine phases above the Charlestown Main Limestone horizon with those in Fife is doubtful and the Mill Hill, Seafield and Lower Kinniny marine phases have not been positively identified in the succession south of the Forth.

11.12. Geographical extent and significance of the Seafield Marine Band (see Fig.11.10)

The Seafield Marine Band is only positively identifiable in parts of central and east Fife, where it overlies a coal and contains a diverse marine fauna. In general it is absent west of the Burntisland Anticline, although the *Lingula* band at Annfield, West Fife (Forsyth 1970) is a correlative. The recognition of the marine band in the Lothians area does not seem possible, although the Carriden No. 4 and Lower Vexhim limestones of West Lothian and Midlothian respectively may also be correlatives. Clearly, therefore, the marine band is restricted geographically to the eastern part of the Midland Valley, and there is no evidence to suggest that it occurs within, or to the west of, the Central Coalfield. In general, marine horizons in the Lower Limestone Group are widespread throughout the Midland Valley, and may be the result of rises in sea level. The explanation of more localised marine bands (e.g. Mill Hill and Seafield marine bands) is therefore more problematical.

The Seafield Marine Band occurs above an areally widespread coal horizon, clearly marking extensive delta-top abandonment, rather than local interdistributary bay fills (cf. Elliot 1974b). The increase in faunal diversity of the marine band to the east suggests that the 'Seafield Marine Band transgression' came from this direction, presumably indicating that open marine conditions lay to the east (cf. Wilson 1974). The degeneration of the marine band to a *Lingula* band in West Fife suggests an east-west transition from fully marine conditions to marginal marine brackish water conditions, the latter developed in areas where the transgression was not fully developed and therefore defining the maximum extent of the incursion. This marine band may therefore represent a rise in sea level which was not of sufficient magnitude to extend across the whole Midland Valley (and/or inhibited by the positive tectonic influence of the Burntisland High), only marginally reaching parts of West Fife. Alternatively, the geographical restriction of the marine band could indicate a post-abandonment marine transgression, limited to the extent of the abandoned delta lobe (which was also possibly influenced by the complex intra-basinal tectonic highs and lows).

11.13. Seafield Marine Band-Lower Kinniny Limestone interval

Throughout Fife, the interval between the Seafield Marine Band and the Lower Kinniny Limestone is generally represented by an upward-coarsening sequence. In East Fife, mudrocks pass upward into sandstones which are locally silty and bioturbated, and in West Fife, shales coarsen-upward into sandstones and siltstones.

The Lower Kinniny Limestone is present in West Fife, but is absent in East Fife (Forsyth and Chisholm 1977), where it is represented by mudrocks containing a sparse marine fauna of *Lingula* and bivalves. In West Fife, the Lower Kinniny Limestone is usually underlain by an extensively bioturbated sandstone containing many recognised marine ichnogenera (Chisholm 1970a) and the horizon is very similar to that developed in the Kinghorn-Kirkcaldy coastal section (Francis 1961a). The Lower Kinniny Limestone horizon usually overlies a coal, which in East Fife is 1.4 m thick and is named the Largoward Splint Coal (Forsyth and Chisholm), and the presence of abundant and thicker coals is characteristic of East Fife, when compared with the succession elsewhere.

The coarsening-upward sequence below the Lower Kinniny Limestone horizon and the underlying palaeosol facies are interpreted as a transition from marine shelf to delta-top, via prodeltaic and delta-front facies. The coal is interpreted as a delta-top abandonment facies, and its widespread geographical extent suggests that it represents extensive delta abandonment, rather than the infilling and abandonment of a local interdistributary bay (cf. Elliot 1974a, 1974b). The overlying bioturbated sandstone which is present in central and west Fife probably represents sands that were reworked during the 'Lower Kinniny Limestone marine transgression' (see chapter 12).

11.14. Discussion

The detailed study of the interval between the Charlestown Main and Lower Kinniny limestones throughout parts of Fife and the Lothians has enabled two geographically restricted marine horizons (Mill Hill and Seafield marine bands) to be recognised and interpreted. It is clear that while marine conditions prevailed in some parts of Fife and the Lothians, constructive, delta-top conditions were present elsewhere. This is illustrated by the Mill Hill Marine Band horizon which is represented in central Fife by a thick delta-top distributary channel. The Mill Hill Marine Band is characterised by cross-bedded and bioturbated marine sandstones (Wilson 1980; Forsyth and Wilson 1981) and clearly indicates that some parts of the prograding delta complex (? small delta lobes) were being actively reworked by marine processes whilst in other areas the delta complex (?individual delta lobes) was apparently actively prograding. The level of marine reworking in the delta-front sequences is high and wave/storm reworked deposits characterised by wave-ripples and hummocky cross-stratification are common. Clearly, a simplistic model for patterns of deltaic sedimentation involving a constructive phase followed by a destructive phase cannot be applied to deltas where parts of the complex may have been prograding whilst other areas were being contemporaneously reworked by marine processes. It is possible, however, that several small delta lobes were present, and whilst one may have been actively prograding, another one may have been in the process of being abandoned or reworked. In this way it would be possible to explain the localised presence of some marine bands, restricted to small delta lobes that had been abandoned and were subsiding, being susceptible to marine reworking.

The interaction between fluvio-deltaic processes and marine conditions appears to have produced a complex series of localised sequences which are characterised by certain local idiosyncratic features. The marine/fluvio-deltaic interactions are further complicated by the influence of local tectonism. The NE-SW trending highs and lows appear to have influenced the delta lobes, the distribution of marine phases and the associated faunas, and faults probably affected local drainage patterns, reflected in the distribution, character and thickness of paleosols (e.g. greater number and thickness of coals in East Fife). The high incidence rate of soft-sediment deformation features associated with sandstones also suggests tectonic activity, centred along synsedimentary faults (cf. Ord *et al.* 1988).

11.15. Conclusions

The interval between the Charlestown Main and Lower Kinniny limestones cropping out along the coast between Kinghorn and Kirkcaldy, central Fife has been recognised at St Monans, East Fife, and in the Annfield Borehole, West Fife. The lower part of the interval is also recognised in the Bilston Burn, Midlothian and at Catcraig, East Lothian. At all localities the Charlestown Main Limestone (and the local names by which it is known) and overlying calcareous mudrocks represent a very widespread marine phase which penetrated the whole of the Midland Valley. The Neilson Shell Bed is recognised in the mudrocks above the limestone at all the localities with the exception of Kinghorn-Kirkcaldy, and the interbedded crinoidal grainstones and packstones (some of which are hummocky cross-stratified) represent higher energy (?storm) beds deposited within inner shelf settings where mud deposition from suspension usually predominated. These marine beds are overlain, or pass up into, deltaic deposits at all the localities, but at the two localities within the Fife-Midlothian Low (Kirkcaldy and Bilston Burn), the prodeltaic and delta-front deposits appear to have been cut out by a major delta-top distributary channel sand body. It is likely that as predicted by Goodlet (1957, 1959), the lows were characterised by more competent drainage than the adjacent highs, and during this particular time period, a major channel drained down the axis of the Fife-Midlothian Low but was absent elsewhere. The 13-14 m thick Seafield Tower Sandstone present at Kirkcaldy is represented in east and west Fife by quite a thick sequence of deltaics within which the Mill Hill Marine Band is intercalated. These facies and thickness changes can be interpreted as genuine facies changes, or merely the result of a great thickness of sediment (including the Mill Hill Marine Band) being removed by the Seafield Tower Sandstone at Kirkcaldy. The interval between the Seafield Marine Band and the Lower Kinniny Limestone, although not recognised in the Lothians is with the exception of subtle changes fairly uniform throughout Fife.

Recent work on Yoredale cyclothems (Leeder and Strudwick 1987) suggests that periodic basin subsidence (often along fault lines) was the controlling factor in determining the position of active delta lobes. There is, therefore, a close relationship between tectonic subsidence and the total thickness of sandstones within individual successions.

Previously, the deltaic complex which was established during the Lower Limestone Group was thought to be a predominantly wave-dominated destructive delta, similar to the present day Rhone Delta (Belt 1975). Deltaic sedimentation, however, is often a two-fold process (Elliot

1978), with a constructive progradational phase and a destructive post-abandonment phase (Scruton 1960). The term 'destructive' delta as used by Belt (1975) is misleading, as all delta lobes are constructive whilst actively prograding. The deltaic complex which developed during Lower Limestone Group times is considered to have been a lobate type, such as the Lafourche Complex of the Mississippi Delta system (cf. Galloway and Hobday 1983). This proposition is supported by several lines of evidence;

1. The alternating constructive and destructive facies are suggestive of lobate deltas (Coleman and Gagliano 1964).

2. Lobate deltas are the result of the interaction between fluvially-dominated deltas and wave activity. With increasing wave activity and marine influence initiated during the Brigantian rise in sea level in the Midland Valley, the fluvio-deltaic complex appears to have been modified from a digitate-elongate delta to a lobate type.

3. The facies patterns are very similar to other Yoredale facies (Elliot 1975), considered to have resulted from the progradation and abandonment of the lobes of a lobate delta.

Other conclusions drawn from this study are;

1. The NE-SW trending lows and highs in the eastern part of the Midland Valley appear to have exerted a profound influence upon the patterns of clastic sedimentation, with the Fife-Midlothian Low which was rapidly subsiding acting as an axial drainage system actively sought out by major fluvial distributary channels (e.g. Seafield Tower Sandstone) on the ancient delta-top. The facies patterns associated with the highs and lows suggest that they could be related to tilt-block (Grayson and Oldham 1987) or half-graben (Leeder and Strudwick 1987) structures, which are known to be characteristic of extensional tectonic regimes such as the Dinantian Midland Valley Basin (Leeder 1987). There is also a suspicion that the limited geographical extent of some marine bands (e.g. Seafield Marine Band) may have been a function of the tectonic

influence (either directly or indirectly) exerted by such structures as the Burntisland High or Anticline (Wilson 1967).

2. The Lower Limestone Group succession contains marine phases which are largely correlatable over a wide geographic area and are characterised by marine limestones and shales. Some of the thinner and more heterolithic marine horizons, however, are clearly less widespread and are restricted to localised areas. This may be due to a lack of recognition and identification, coupled with removal by distributary channels, or an original process-related feature such as a weak transgression or poorly developed marine processes restricted to the abandoned areas of deltas.

3. If the geographically restricted marine bands are related to the abandonment of deltas, then their absence in some areas where they are replaced by delta-top facies suggests variable rates of progradation, with some parts of the delta actively outbuilding whilst others were abandoned and undergoing marine reworking.

4. Despite Belt's (1975) comments which indicate otherwise, major delta-top facies (including large fluvial distributary channels) are well developed in the Lower Limestone Group, and ancient delta-top conditions may be reconstructed by comparing inter-marine clastic intervals between correlatable marine marker horizons (time lines).

5. Geological information may be lost by the downcutting of fluvial distributary chanel sands (cf. Chapter 10). This may result in the local removal of marine horizons causing mistaken correlations and erroneous palaeoenvironmental interpretations.

CHAPTER 12

Marine-modified deltaic sequences from the Brigantian of the eastern part of the Midland Valley of Scotland; Fife and the Lothians

12.1. Introduction

In the uppermost part of the Strathclyde Group (Paterson and Hall 1986) and the overlying Lower Limestone Group, Yoredale-type cycles are well-developed in the eastern part of the Midland Valley (Moore 1959; Francis 1965, 1983a). Such cycles generally consist of interbedded marine carbonates and deltaic clastics, and marine limestones and shales usually succeed delta-top abandonment facies (Elliot 1974a, 1975) which are represented by paleosols (e.g. coals, seat-earths and ganisters). This suggests that the deltas were abandoned in response to rises in sea level leading to the development of soils during periods of greatly reduced sedimentation, and the association of paleosols with marine phases has been noted throughout the British Carboniferous (Elliot 1975; Percival 1986). In some instances, however, limestones directly overlie sandstones with a gradational contact, and the upper parts of the sandstones are patchily carbonate cemented, severely bioturbated, and contain a marine fauna. Examples of such a phenomenon have been identified within the uppermost Strathclyde Group and overlying Lower Limestone Group in parts of western, central and east Fife, and East Lothian (Fig. 12.1). These were investigated, interpreted and compared and contrasted, and the results have shed light upon the impact which the Brigantian marine incursions had upon the 'background' patterns of sedimentation within the Midland Valley Basin during the late Dinantian marine 'events', which had affected most other major British Dinantian basins at a much earlier time in the Dinantian.

12.2. Rationale and localities

When delta lobes are abandoned in response to a rise in sea level, the marine facies deposited during the transgression invariably lie upon the abandonment facies of the delta, which are often represented by paleosols such as coals. In some cases, however, intervening facies between the paleosols and the marine facies are present. One such intervening abandonment facies has been identified between the Largoward Splint Coal (Forsyth and Chisholm 1977) and the Lower Kinniny Limestone in parts of central (Francis 1961a) and west Fife (Forsyth 1970; Chisholm 1970a). This is an extensively bioturbated marine calcareous sandstone which is patchily carbonate cemented and contains trace fossils such as *Zoophycos* and *Teichichnus*. When traced to the north-east into East Fife (Forsyth and Chisholm 1977), however, this horizon is absent and there are significant facies and thickness changes in the underlying and overlying strata. The sequence containing these rocks has been examined in parts of west, central and east Fife (Fig. 12.1), where it has been described and interpreted. The facies developed below the Lower Kinniny Limestone horizon are interpreted as representing abandonment facies, the nature of which varied depending upon the position on the ancient delta lobe. These facies were developed after delta abandonment and prior to the acme of the 'Lower Kinniny Limestone marine transgression'. The level of marine reworking appears to have been quite low, and only the delta-front was reworked, the upper part of the lower delta-plain being blanketed by organic paleosols (peats).

Similar facies are also recognised (but not discussed in any detail in this chapter) at the Middle Longcraig and Chapel Point limestone horizons in the Catcraig coastal section, East Lothian, and the Middle Longcraig Limestone horizon in the Skateraw and Spilmersford boreholes (Fig. 12.1). The Middle Longcraig Limestone lies at the top of the Strathclyde Group (Paterson and Hall 1986), but the Chapel Point Limestone lies close to the Lower Kinniny Limestone horizon, although it is not known whether it is a direct correlative (Davies *et al.* 1986; Wilson in Davies *et al.* 1986).

12.3. Stratigraphy

In the west of Scotland, limestones above the major Charlestown Main (Blackhall) Limestone are termed the Hosie limestones (Monro 1982a), but on occasions (and especially in the older literature) the limestones in the east at these positions have also been called by this name (Geikie 1900;. Gordon 1914). It is generally acknowledged, however, that the term 'Kinniny limestones' first coined in West Fife (Muff 1906, pp.134-7; Maufe in Peach *et al.* 1910; Dinham 1924, pp. 115-20; Haldane and Allan 1931, pp. 19-39; Allan and Knox 1934, p.21; Francis 1961a, p.19) should be applied to these limestones (generally three major limestones) in west, central and east Fife (Forsyth 1970; MacGregor 1973, p.255), but there is some uncertainty as to whether these are the correlatives of the Hosie limestones in the west. In the Bo'ness area, however, it appears to be possible to trace both the Kinniny and Hosie limestones, where they might be correlated (Haldane and Allan 1931) with the Carriden No's 1 to 3 limestones. This implies that the coal below the Mid Kinniny Limestone thickens south of the Forth to become the Victory Coal at Bo'ness, which has been correlated with the Lillie's Shale Coal in Paisley (MacGregor and Haldane 1933, p.29).

In west, central and east Fife, the sequence studied consists of the Lower Kinniny Limestone and associated beds which lie wholly within the Lower Limestone Group (Fig. 12.2). In East Lothian, the Middle Longcraig Limestone lies at the top of the Strathclyde Group, and is located at a position subjacent to the local Hurlet Limestone correlative (Fig. 12.2) (Davies *et al.* 1986), and is therefore the equivalent of the First Abden and St Monans White limestones of central and east Fife respectively. The Chapel Point Limestone is in the overlying Lower Limestone Group, and is located above the local equivalent of the Charlestown Main Limestone (Fig. 12.2). It is probably one of the correlatives of the Kinniny or Hosie limestones (George *et al.* 1976; Francis 1983a), although reliable confirmatory evidence is lacking.

12.4. West Fife; description of the Lower Kinniny Limestone and associated beds

The Lower Kinniny Limestone is present in surface and subsurface sections in West Fife, and it was in this area that Muff (1906) first separated and named the Lower, Middle and Upper Kinniny limestones in the area around Kinniny Point, Charlestown. At Kinniny Point, the Lower Kinniny Limestone is about 0.6 m thick containing the colonial coral *Lithostrotion irregulare*, and overlying 1.2 m of bioturbated sandstone and dark mudrocks. The mudrocks are underlain by a 0.3 m thick coal, and the sandstone between the mudrocks and the limestone which is extensively bioturbated contains traces of *Zoophycos* (Haldane and Allan 1931). In the Dunfermline and Duloch area, the limestone has only been recognised in boreholes, where it is between 0.60-0.90 m thick, and is underlain by a coal, which is generally within 0.30-0.60 m of the base

(Haldane and Allan 1931). In the relatively recent BGS borehole at Annfield (Forsyth 1970), the Lower Kinniny Limestone is almost 0.60 m thick, crinoidal, and underlain by 1.6 m of bioturbated sandstone and siltstone containing many recognised marine trace fossils including *Teichichnus*, *Zoophycos* and *Chondrites* (Chisholm 1970a), and the sandstones and siltstones are underlain by a 7.5 cm thick coal. Around Balmule, east of the Lochgelly Town Council Water Works, at Lochoire, the Kinniny limestones are exposed. Approximately 0.30 m of the Lower Kinniny Limestone crops out, containing *Lithostrotion* in its upper part, although it is not fully exposed and is located at the base of the observed sequence (Haldane and Allan 1931).

In the Annfield Borehole, recrystallised *Lithostrotion* corals have been recorded from the Lower Kinniny Limestone. In the underlying bioturbated sandstone, the trace fossils recorded are known to be associated with marine body fossils in East Fife (Chisholm 1968, p.118), and their occurence in the reworked sandstone at Annfield suggests that this bed possibly represents an early manifestation of the marine conditions that prevailed in the overlying Lower Kinniny Limestone. The stratigraphical position of the sandstone between the limestone and an underlying 7.5 cm thick coal suggests that it represents a transgressive strand-line deposit, subsequently reworked during phases of slower sedimentation in deeper water, and Chisholm (1970a, p.21) has compared it to the similar reworked sandstone bed at the same horizon below the Lower Kinniny Limestone at Seafield, central Fife (see below). For detailed descriptions of the bioturbated sandstone bed in the borehole and the associated trace fossils *Teichichnus*, *Chondrites* and *Zoophycos*, see Chisholm (1970a, pp.19 and 21).

The succession including the Lower Kinniny Limestone in West Fife was studied around Charlestown by Maufe (Muff 1906, pp.134-7; Maufe in Peach *et al.* 1910, pp.116-7) and at Dunfermline by Dinham (1924, pp.115-20), and this work was used in the interpretation of the coastal section at Seafield, between Kinghorn and Kirkcaldy. Hence the so-called 'Hosie limestones' of Seafield were correlated with the Kinniny limestones of West Fife (Allan and Knox 1934; Francis 1961a, p.19).

12.5. Central Fife; description of the Lower Kinniny Limestone and associated beds

The Lower Kinniny Limestone and associated beds are only exposed at one locality in central Fife, although they are known from subsurface sections throughout the area. The single exposure of the Lower Kinniny Limestone in central Fife is on the foreshore at Seafield [NT 2800 8870], between Kinghorn and Kirkcaldy, where the limestone has been grouped together with an underlying calcareous sandstone which collectively have a joint thickness of 0.30-0.60 m. This horizon has been described as an 'impure seam' with a very sandy base (Allan and Knox 1934; Francis 1961a) (Fig. 12.3), but at the same horizon in West Fife, the limestone and underlying calcareous, bioturbated/reworked sandstone have not been grouped together (Haldane and Allan 1931; Forsyth 1970; Chisholm 1970a) and have been recorded as separate beds. The Lower Kinniny Limestone and associated beds have been discussed in a very general sense in several accounts of the geology of the area (Geikie 1900; Gordon 1914, p.38; Wright 1922, pp.292 and 294; Allan 1924, p.488; Allan and Knox 1934, pp.31-2; Francis 1960, pp.212-213, 1961a, pp.19 and 27; MacGregor 1968, 1973, p.255; Chisholm 1970a), but no detailed description has been made.

The Lower, Middle and Upper Kinniny limestones at Seafield were originally known as the 'Hosie limestones' (Geikie 1900; Gordon 1914; Allan and Knox 1934, p.21; Francis 1961a, p.19), but it was eventually realised that these limestones clearly corresponded to the Kinniny Limestones to the west (see Francis 1961a, p.19 and Fig.4, p.21), although no representative of the 41 cm thick coal ('17-in. or Lillie's Shale Coal' of Paisley) has been recognized below the Middle Kinniny Limestone.

In his original investigation of the Kinghorn-Kirkcaldy shore section, Geikie (1900) mistakenly took the Middle Kinniny Limestone to be the Lower Kinniny Limestone, and considered the Lower Kinniny Limestone to be a lower unnamed horizon, which only after some years later was eventually correlated with the Lower Kinniny Limestone (Haldane and Allan 1931) which was first recognized at Kinniny Point, West Fife (Maufe 1906). Geikie (1900, p.94), however, described what is in reality the Lower Kinniny Limestone in the following passage which despite its antiquity (being written over 87 years ago) is perhaps the best published description, based on acute field observations of the Lower Kinniny Limestone and associated beds, and has not been surpassed in subsequent brief descriptions of the beds (Gordon 1914; Allan and Knox 1934; Francis 1960, 1961a; MacGregor 1968, 1973);

> "Among the shaly sandstones which succeed these shales, another illustration of the alternation of the contrasted sediments presents itself. Above a bed of fireclay full of rootlets lies a thin seam of coal representing the vegetation which grew on the soil and sent its roots downward into it. The coal is one foot thick at the southern end of its outcrop on the beach, but thins away northward. It is covered by 2 or 3 inches of dark fireclay, above which lies a prominent bed of hard sandstone, full of vertical worm burrows. This seam, about 2 feet thick, becomes calcareous in its upper portion, and is there crowded with fragmentary crinoid stems and covered with well marked *Cauda-galli* or sea-weed impressions. This calcareous top of the bed contains numerous calcareous concretions, which eventually coalesce and form a thin continuous band of limestone. Numerous corals lie here, evidently in their original positions of growth. In one place may be seen a group of *Lithostrotion irregulare*; in another a large bunch of *Lithostrotion junceum*. Cup-corals also occur. The transition from the evidence of a surface of terrestrial or at least lagoon vegetation to such a clear sea as allowed crinoids to live is completed within a vertical space of not more than 2 feet."

The sequence of rocks underlying the Lower Kinniny Limestone can be conveniently divided into two coarsening-upward sub-units, termed A and B. Coarsening-upward sub-unit A consists of the Seafield Marine Band (Haldane and Allan 1931; Francis 1961a), which also extends upwards into the basal mudrock bed of coarsening-upward sub-unit B (Fig.12.3 and Fig.12.4D). This is approximately 4 m in thickness and conformably overlies the lower sub-unit. It begins with a 0.5-1.5 m thick mudrock bed containing siderite nodules and bands which rapidly coarsens-upwards into sandstones via a passage through lenticular-bedded fine-grained sandstones, wavy bedded heterolithic sandstones, and rippled flaser-bedded sandstones. The flaser bedded and wave-rippled sandstones consist of rippled sandstone laminae ('ribs'), where the troughs of the ripples are filled with coaly flasers of fine-grained material. The lowest part of this heterolithic sequence (i.e. the mudrock *sensu-stricto*) is the uppermost part of the Seafield Marine Band).

The heterolithic beds rapidly coarsen-upwards into rippled and occasionally flaser-bedded sandy brown to grey-white coloured, medium to fine-grained sandstones. These rippled beds (Fig. 12.4B) form thin planar-bedded sandstone 'ribs' and are approximately 1.50-2.00 m thick, the ripples being well exposed upon the upper bedding surfaces (Fig. 12.4B). These ripple crests are straight with minor sinuosity, and crest bifurcation is common. The crests predominantly trend in a NW-SE direction, and are symmetrical with a slightly rounded profile. Ripple wavelengths average 6-7 cm and ripple crest heights average 1 cm. This gives an average ripple index of 7. Occasional trace fossils (e.g. *Pelecypodichnus*) and interfacial trails (e.g. ?*Gyrochorte* and *Planolites*) are present within the ripple troughs and the sandstones are rich in plant debris (coaly plant remains).

The rippled sandstones pass upward into 1.5-2.5 m of poorly exposed, coarse to medium-grained, trough cross-bedded sandstones, which are a sandy dark brown to light grey colour. The cross-bedding is only represented by one single solitary cross-bed set, although along strike there is evidence of several grouped sets (cf. Allen 1963) forming a coset of cross-bedding. The foresets of the cross-bed sets are slightly curved and the foreset contacts with the lower bounding surfaces are tangential. Some sets also have fine-grained coaly wisps at the bases along with iron stains along foreset planes. The foresets within trough cross-bed sets largely dip to the NW, although conflicting SW and EEN directions have also been recorded. The tops of some cross-bed sets appear to have been reworked, and individual cross-bed sets measure approximately 30 cm in thickness. The sandstone is overlain by 0.5 m of planar-bedded, fine-grained sandstones containing large stigmarian rootlets (see Geikie 1900, p.94) and the epichnial trails of *Gyrochorte* (cf. Hallam 1970) and *Planolites*. These sandstones are fissile, ?rippled and silty with a bioturbated top, and are ganister-like with large aligned examples of *Lepidodendron* trunks (Fig. 12.4C). The top bed of this coarsening-upward unit (coarsening-upward sub-unit B) contains abundant coalified rootlets (Geikie 1900, p.94) and drifted plant remains (Fig. 12.4A).

The previous sandstones are overlain by a thin coaly mudrock (approximately 0.20-0.30 m thick) which contains coal laminae towards the top (four coaly laminae, each of which is 0.5 cm thick). This coaly mudrock passes into a coal and thickens along strike (along the foreshore) to the SE (seaward) (Geikie 1900; Wright 1922, p.294; Francis 1961a, p.27). The coaly mudrock contains fragmentary plant material, is slickensided, and dramatically varies in thickness (for example thicknesses of 0.20 m, 0.44 m and 0.89 m have been measured along the strike of the bed). As noted by MacGregor (1973, p.256), the coaly beds in this part of the succession are rarely exposed, although the coal beneath the Lower Kinniny Limestone was at one time worked at outcrop. The coaly mudrock/coal seam overlies a coarsening-upward sequence (Fig. 12.4D) which probably represents the progradation of a delta onto a shallow marine shelf. The coaly mudrock passes upward into 0.72 m of bioturbated calcareous sandstone which is partially cemented by carbonate (sandy limestone) and generally fines-upwards into the overlying limestone but shows a coarsening-upward trend within the bioturbated bed (Fig. 12.5A). The bioturbated sandstone is mottled and contains the trace fossils *Chondrites* Sternberg, *Teichichnus* Seilacher (burrows of *Chondrites* (Fig. 12.5C) and *Teichichnus*) (Fig. 12.7B) and *Zoophycos* Massalango (12.5C). The sandstone has a silty and extensively bioturbated base which consists of laminated bulbous 'pods' of bioturbated sandstone surrounded by anastomosing siltstone laminae (Fig. 12.5A, B andC). These 'textures' are best developed in the lower 0.31 m of the unit and are cut back as they weather preferentially. The upper part of the sandstone (topmost 0.335 m), however, is more massive (Fig. 12.5A and B) and less well bioturbated. The upper surface of the sandstone is characterised by large round-spherical shaped limestone nodules or concretions (Figs. 12.6B) which measure up to 0.35 m in diameter and coalesce to form the more continuous limestone bed (Lower Kinniny Limestone), at the base of the dip slope where it has been cut back to by present day erosion (Fig. 12.6A) (as noted by Geikie (1900), above). These bullions or domes are largely composed of dark crystalline crinoidal bioclastic limestone which is sometimes micritic (micrite matrix) and weathers cream-white to red pink. It has been suggested that these concretions are algal masses (MacGregor 1973, p.256) but no evidence has been found to support such an assumption. The thin 0.08 m thick limestone (limestone No.5 of Wright (1922, p.294)) contains crinoids, the corals *Syringopora* and *Alveolites* (Wright 1922), along with the colonial corals *Lithostrotion junceum* and *Lithostrotion irregulare*. (Geikie 1900). Traces of *Zoophycos* Massalango along with abundant aligned crinoid stems (Wright 1922, pp.292 and 294; cf. Schwarzacher 1963) (Figs 12.6B) and disarticulated ossicles (Fig. 12.6D) are present upon the upper bedding surface of the sandstone, but body fossils are absent within the main part. The body fossils on the top surface of the unit, however, are concentrated in accumulations or 'pockets', and are largely represented by crinoid ossicles. The sandstone is medium-grained, fairly hard, crystalline, ?well-cemented, and well jointed (like the overlying limestone), with dark silty wisps and silty to mud-rich horizons. The *Teichichnus* burrows and indiscriminate bioturbation give rise to a 'stick bed' (Fig. 12.5B and C) similar to that described by Donaldson and Simpson (1962), and the individual 'sticks' average 0.7 cm in width. Problematical ?*Thalassinoides*-like burrows are also present within the bioturbated sandstone.

The Lower Kinniny Limestone and underlying bioturbated sandstone and coal are in part laterally impersistent (Francis 1961a), and the limestone and bioturbated bed are not always present within surface and subsurface sections elsewhere (away from the Seafield coast section), although invariably the horizon of the Lower Kinniny Limestone is represented by a marine development of shaly mudrocks (Francis 1961a, p.27). As an illustration of its variation, the Lower Kinniny Limestone is 1 m thick in the Seafield No.2 Colliery Shaft overlying a 15 cm thick coal, whereas in the nearby Seafield No.1 Colliery Shaft, it is only represented by mudrocks (shales) containing marine fossils (Fig. 12.3). To the north, in the Rothes No.1 Colliery Shaft, the limestone is 1 m thick, but is reduced to 0.50 m in the underground bore in the pit bottom (Francis 1961a). In the Carberry, Skeddoway No.2 and Mid Strathore bores, calcareous sandy siltstones and shales are present at the Lower Kinniny Limestone horizon, but to the west in the Sauchie Bridge Bore, two thin limestone beds (0.27 m and 0.08 m thick respectively) are present, separated by approximately 2 m of dark coloured mudrocks (shales). Further to the south-west, the limestone reaches its maximum known thickness of 1.4 m in the Bowhill No.3 Colliery Shaft (Francis 1961a).

12.6. East Fife-description of Lower Kinniny Limestone horizon and associated beds.

The Lower Kinniny Limestone is absent in East Fife (Forsyth and Chisholm 1977, p.78), but the horizon of the Lower Kinniny Limestone lies within a unit represented by siltstones, silty mudrocks and mudrocks containing a sparse marine fauna of *Lingula* and bivalves. The mudrocks overlie the 1.14 m thick Largoward Splint Coal which has been extensively worked in the Largoward area. This horizon is recognized from surface and subsurface sections and the mudrocks representing the horizon crop out on either limb of the St Monans Syncline (Fig. 12.7), and at Elie. Inland, the horizon is exposed in Balcarres Den, and a mudstone containing marine fossils in the Craighall Burn [NO 4201 0958] is considered to represent the horizon (Forsyth and Chisholm 1977). Subsurface, the horizon has been recognized in the Drumcarro (Fig. 12.7), Muircambus (Fig. 12.8), Lathallana and Callange (Fig. 12.8) boreholes above the Largoward Splint Coal (Forsyth and Chisholm 1968, 1977).

The Largoward Splint Coal (see Forsyth and Chisholm 1977, pp. 77-8 for correlation and recognition; Langdale 1837; Geikie 1902, p.177) is not well exposed on the coast at either Elie or St. Monans, possibly due to former crop workings. Forsyth and Chisholm (1977, pp.77-8) provisionally correlated this coal with the second lowest coal (69 cm thick) in Langdale's (1837) Elie section. In the Muircambus Borehole the seam is 89 cm thick, and 80 cm of coal was formerly exposed at this horizon in Balcarres Den. This coal seam was by far the most extensively worked seam in the Largoward area where it is 114 cm thick and of constant high quality. Several collieries were raised in the nineteenth and early twentieth centuries, but working ended in 1914 (Forsyth and Chisholm 1977). The term 'splint' coal refers to coals which are hard with a dull lustre and uneven fracture, and which do not coke or become easily crushed in a blast furnace (Francis 1961a, p.142).

In the Callange Borehole, the marine band representing the Lower Kinniny Limestone horizon lies above a 0.35 m thick coked coal at a depth of 145.90 m (Forsyth and Chisholm 1977, p.70), and the shales contain bivalve fragments and *Lingula squamiformis* (Wilson in Forsyth and Chisholm 1968, p.82). In the Drumcarro Borehole, the Largoward Splint Coal (Geikie 1902, p.167) is represented by old workings, and the marine shale in the 'roof' of the coal is regarded as the equivalent of the Lower Kinniny Limestone of West Fife (Haldane in Haldane and Allan 1931, pp.21-4; Forsyth and Chisholm 1968, p.71). The shales contain the brachiopod *Lingula squamiformis*, and the bivalves *?Sanguinolites* and *?Streblopteria* (Wilson in Forsyth and Chisholm 1968). In the Muircambus Borehole, the Largoward Splint Coal was encountered at a depth of 81.80 m (Forsyth and Chisholm 1978, pp.71 and 74), and as at Drumcarro, Callange and St. Monans, the marine band at the horizon of the Lower Kinniny Limestone lay above it and contained crinoid ossicles, *Streblopteria ornata*, *Solenomorpha*, *?Sanguinolites abdenensis*, *Sanguinolites plicatus* and *Lingula squamiformis*. Nineteen different fossil species have been collected from the Lower Kinniny horizon throughout East Fife (see Wilson in Forsyth and Chisholm 1977, p.132) at four different localities. This assemblage is dominated by bivalves, although specimens of the articulate brachiopod *Productus* sp. are present along the monoplacophoran *Euphemites* sp.

12.7. East Lothian-?Lower Kinniny Limestone horizon

In the Haddington area of East Lothian, the limestones above the Middle Skateraw Limestone (Charlestown Main Limestone equivalent) (Fig.

12.2) are generally only known from boreholes (McAdam and Tulloch 1985), but no one borehole in the area penetrates the entire sequence. Four limestones are present above the Middle Skateraw Limestone in this area, however, and are known as the Lower Vexhim, Upper Vexhim, Bilston Burn and Top Hosie. Farther east, in the Dunbar area, there are only two major limestones above the Middle Skateraw Limestone, which are known as the Chapel Point and Barns Ness limestones (Fig. 12.2), which is unusual compared to equivalent-aged sequences elsewhere, which contain numerous rich marine bands (Wilson in Davies *et al.* 1986). A thin limestone, 3-4 m above the top of the Middle Skateraw Limestone was previously known as the Upper Skateraw Limestone, but as it is within the same cycle as the Middle Skateraw Limestone, and is only one of up to three impersistent lenticular limestones, it has been decided that this limestone should not be named (Davies *et al.* 1986). Although correlation with the Kinniny or Hosie limestones is not possible, it is considered that the Barns Ness Limestone is possibly the equivalent of the Top Hosie Limestone, although it may equate with one of the lower Hosie limestones. If the Barns Ness Limestone is the Top Hosie or Upper Kinniny limestone equivalent, then the underlying Chapel Point Limestone would equate with either the Middle or Lower Kinniny/Hosie limestone. Unfortunately, past workers have confused matters by including a third limestone, called the Dryburn Foot in the sequence above the Middle Skateraw Limestone (e.g. Whyte 1973; Francis 1983a). Recent work, however, suggests that the so-called Dryburn Foot and Barns Ness limestones are the same horizon (Clarkson 1986a), and this is supported by borehole evidence. This erroneous conclusion led Whyte (1973) to correlate the Dryburn Foot Limestone with the Lower Kinniny Limestone, and the Barns Ness Limestone with the Middle Kinniny Limestone, claiming that the Upper Kinniny Limestone equivalent was absent in this area. This does not find favour with more recent work, and for reasons suggested above cannot be upheld.

12.8. Lower Kinniny Limestone and associated beds; interpretation (see Figs. 12.9, 12.11 and 12.12)

The coarsening-upward sequence below the Lower Kinniny Limestone and the underlying paleosol-coal are interpreted as a transition from marine shelf to delta-top, via prodeltaic and delta-front facies (Fig. 12.9). The coal is interpreted as a major delta-top abandonment facies, and its widespread geographical extent suggests that it represents extensive delta abandonment, rather than the infilling and abandonment of a local interdistributary bay (cf. Elliot 1974b) (Fig. 12.11). The overlying bioturbated sandstone represents sands that were reworked during the marine transgression which resulted in the development of the Lower Kinniny Limestone and equivalent horizons. The lateral impersistence of this unit throughout central Fife and elsewhere, and its absence in East Fife (Fig. 12.10) suggests that the sands were deposited as an arcuate barrier island chain, filling localised runnels, explaining their extremely localised and patchy development (Fig. 12.9). The extensive bioturbation indicates low rates of sedimentation after the abandonment of the delta (Elliot 1974a; 1975). The ichnogenera in the sandstone are known to be associated with marine body fossils elsewhere in east and west Fife (Chisholm 1968, 1970a, 1970b) and the mottled texture of the rock indicates extensive biogenic reworking, although the burrowing organisms did not produce identifiable trace fossils (Schafer 1956; Moore and Scrutton 1957; Chisholm 1970a). Chisholm (1970a) has described the reworked sandstone unit below the Lower Kinniny Limestone in the Annfield Borehole, West Fife, which he interpreted as a strand-line deposit, subsequently reworked during phases of slower sedimentation in deeper water, and this is consistent with the interpretation presented here.

Elliot (1974a, 1975) has described very similar facies to these from equivalent-aged (Yoredale) deposits in the north of England. Abandonment facies detailed by Elliot (1974a) are almost identical to the bioturbated, marine sandstones described here, in that they are bioturbated and mottled, contain a restricted fauna of crinoids and pectinid debris, and are characterised by domes of limestone representing localised carbonate cementation and replacement (Elliot 1974a, p.363). The abandonment facies described by Elliot are invariably developed above areally widespread coals as in this case, and represent marine phases developed after delta abandonment. Elliot prefers the term 'abandonment facies' to destructive phase (Scruton

1960; Scott and Fisher 1969) as in his examples the general level of marine reworking is low. In this study, all marine facies in the Pathhead Beds and Lower Limestone Group are regarded as post-abandonment phases, and the sandy base of the Lower Kinniny Limestone represents an example of delta-front sand reworking during a transgression, which sometimes is present as an early post-abandonment/abandonment phase. The very thick post-abandonment phases described by Elliot (1975) are not recognised here, although post-abandonment coarsening-upward sequences representing barrier islands are difficult to distinguish from upward-coarsening sequences developed in wave-attenuated progradational delta-front sequences (Elliot 1986). In West Fife, the Lower Kinniny Limestone and underlying rocks are very similar to those present in central Fife and appear to represent facies developments at a similar position on the lower part of the delta plain.

The absence of the Lower Kinniny Limestone in East Fife, and its replacement by mudrocks containing a sparse-restricted marine fauna suggests that only marginal marine conditions were established in this area during the 'Lower Kinniny Limestone marine transgression' (Fig. 12.13). The bioturbated marine sandstone bodies patchily developed in parts of central and west Fife are also absent in East Fife, suggesting a palaeogeographical setting higher on the lower delta plain, away from reworked delta-front sands (Figs. 12.10, 12.11 and 12.12). Therefore, the thicker coals in East Fife which underlie the Lower Kinniny Limestone horizon were clearly contemporary with the bioturbated, calcareous marine sandstones which were being deposited in west and central Fife (Figs. 12.11 and 12.12). This suggests that while some reworking and delta 'destruction' took place along the delta-front, the more proximal part of the delta lobe was covered by an extensive peat blanket and the underlying sediments were preserved (Fig. 12.12). Depositional rates appear to have been virtually non-existent and organic paleosols accumulated in hydromorphic conditions in response to a rising water table prior to the 'Lower Kinniny Limestone marine transgression'. This is supported by the absence of the limestone in East Fife, coupled with a decrease in faunal diversity and the development of a thicker coal (named the Largoward Splint Coal) when compared with the thin coal or coaly mudrocks present to the south-west in central and west Fife. The general palaeoflow direction of the delta is considered to have been to the south-west, and East Fife appears to have occupied a slightly higher position on the delta plain than central and west Fife, which were 'down-delta' to the south-west. Therefore, the abandonment facies recognised in central and west Fife (thin coal, coaly mudrocks and bioturbated sandstones) are only represented in East Fife by a thick coal overlain by a mudrock (Fig. 12.11). This is interpreted as a transition from the lower part of the lower delta plain/delta front to the upper part of the lower delta plain.

12.9. Discussion

Unlike the abandonment facies outlined by Elliot (1974a, 1975) which appear to have resulted from a delta lobe becoming abandoned after channel switching, therefore inducing a partial marine transgression, the abandonment facies below the Lower Kinniny Limestone horizon probably resulted from delta abandonment as a result of a rise in sea level. Delineation of the marine band would not therefore mark the extent of the abandoned lobe, but would merely delineate the extent of the marine transgression. The abandonment facies, however, probably do delineate the extent of the lobe, and the different characteristics of the abandonment facies (e.g. bioturbated sands in central and west Fife, and coals in East Fife) provide useful information as to the varying processes, and therefore the morphology of the lobe and the position of the delta-front and proximal deltaic areas. The sequences below the Lower Kinniny Limestone are constructive progradational facies. The coals and other paleosols (generally rooted sandstones and siltstones) which cap these sequences are abandonment facies representing the abandonment of the delta-top due to a rise in the water table at the start of the 'Lower Kinniny Limestone marine transgression'. Once abandoned, the delta-top was largely blanketed by organic paleosols, where peats accumulated in hydromorphic swamp-marsh conditions. Near the delta-front, the peats appear to have been generally thin, and were deposited behind the delta-front sand sheets and ridges and small barrier islands which had started to form as the sea level rose. On the higher part of the lower delta plain, away from the delta-front in proximal areas, thicker peat blankets developed, during periods of zero net sedimentation, undisturbed from marine reworking at the delta-front (Fig. 12.12). As the sea level rose and the transgression began, sands at the delta-front were reworked in shallow marine conditions and deposited on top of the thin coals which had developed behind the barriers at the delta-front. As marine reworking of the lobe in general was probably quite low, the 'landward' progradation of the barrier islands was limited, and the barrier island reworked/bioturbated sands were restricted to delta-front localities and replaced higher on the delta-plain by coals (Fig. 12.11). The barrier island/strand line sands are very impersistent and patchily distributed, which is consistent with modern barrier island sands (e.g. Chandeleur Islands, Mississippi Delta (Coleman and Gagliano 1964)). The lateral equivalence of strand line marine sands and coals suggests that the transgression was slow and diachronous, with marine conditions first reaching central and west Fife, and reworking deltaic sands, whilst non-marine peat swamp conditions proliferated to the north-east in East Fife. As the transgression gained momentum, however, even the East Fife area was swamped by shallow marine conditions. In central and west Fife, fully marine conditions are indicated by the Lower Kinniny Limestone which contains a shallow open marine carbonate shelf fauna including colonial corals. In East Fife, however, the limestone is absent and a restricted marine fauna including *Streblopteria* and *Lingula* suggests that even during the acme of the incursion, the upper part of the abandoned lower delta plain in East Fife was only characterised by marginal marine conditions, indicating that the transgression was quite weak, not fully penetrating some areas and therefore failing to establish fully marine conditions (Fig. 12.13). The limestone, however, is impersistent even in central Fife, and is only represented in the Seafield No.1 Colliery Shaft by marine mudrocks. Although the Lower Kinniny Limestone is supposedly widespread throughout the Midland Valley (George *et al.* 1976; Francis 1983a),(and is possibly a correlative of the Lower Hosie Limestone (see stratigraphy)), and is therefore probably the result of a rise in sea level, it is possible that the Lower Kinniny Limestone is a localised marine phase, restricted to parts of central, west and east Fife. This would suggest that it is a true post-abandonment marine phase restricted to the limits of an ancient delta lobe, explaining its localised nature (restricted to parts of Fife), and its absence in other parts of the Midland Valley.

12.10. Conclusions

Deltas often have a two-fold history comprising a constructional phase during which the delta progrades, and a destructional or abandonment phase characterised by a reduction in the amount of sediment supplied to the delta. Although most sedimentation takes place during the constructional phase, consideration of the abandonment phase can greatly assist the interpretation of sub-recent and ancient deltaic successions. The bioturbated sandstone bed which sometimes underlies the Lower Kinniny Limestone in parts of central and west Fife is similar to recognised abandonment facies associations developed in fluvially-dominated deltas (Elliot 1986, p.141). Elliot (1986, p.141) recognises four types of abandonment facies, the character of which depends upon the respective positions of the facies upon the abandoned delta lobe.

1. Low to mid delta-front; abandonment is marked by an intensely bioturbated zone, sometimes accompanied by thin, highly fossiliferous shale or limestone beds reflecting reduced sedimentation rates.

2. Upper delta-front; abandonment facies comprises a thin unit of intensely bioturbated, quartz-rich sandstones interpreted as the transgressed remnants of Chandeleur-type barrier islands (Coleman and Gagliano 1964). These sandstones are often calcite-cemented due to the dissolution of shell fragments. Units vary in thickness from 0.5-3.0 m.

3. Mid-lower delta plain; thin unit of mudrocks and siltstones with abundant marine to brackish water fauna.

4. Upper delta plain; extensive emergent area-paleosols and other surface processes dictated by prevailing climate. In humid-tropical climates, laterally extensive coals blanket the entire upper delta-plain. These beds transgress underlying facies variations in the delta-

top sediments (Fisher and McGowen 1967; Elliot 1974a; Tewalt, Bauer and Mathew 1981; Flores and Tur 1982).

The facies developed in parts of central and west Fife correspond closely to facies 1 and 2 above, whilst the East Fife facies correspond to facies 3 and 4 above. The criterion concerning thickness and distribution of coals, however, is problematical. This is because in some cases the coals are thicker and more abundant in the upper to mid delta-plain (Ferm 1976; Horne, Ferm *et al.* 1978), but in other cases they are more abundant in the lower delta-plain (Flores 1979; Ryer 1981). The latter is particularly pronounced where the delta-front is a continuous sandstone body comprised either of coalesced mouth-bars or wave-built beaches, as the coals accumulate immediately behind the delta-front (as is the case with the thin coals in central and west Fife below the Lower Kinniny Limestone).

CHAPTER 13

The Lower Kinniny-Upper Kinniny limestones interval in Fife and the Lothians; marine influenced deltaic sedimentation on the lower delta plain, Dinantian Lower Limestone Group

13.1 Introduction

Above the Charlestown Main Limestone (and its equivalents) there are generally three major marine limestone horizons in the Lower Limestone Group, which are invariably known as the Kinniny or Hosie limestones (MacGregor 1973, p.33). These beds are often represented by impure sandy limestones, or may even be locally absent, and are often characterised by the diagnostic marine trace fossil *Zoophycos* which has a spirally arranged spreiten structure (cf. Simpson 1970). Occasionally, the number of marine limestones present in some sections may be variable, with some localities characterised by more than 3 marine horizons (e.g. limestones invariably associated with calcareous marine mudrocks), and some with less. The intervening clastics, however, vary significantly from place to place, a characteristic of many inter-marine Yoredale-type successions (Elliot 1975), but one common factor is the occurence of marine/quasi-marine trace fossils associated with trough cross-bedded sandstone facies. Within Yoredale-type cycles, the trough cross-bedded sandstones which overlie coarsening-upward sequences usually represent the fills of delta-top fluvial distributary channels, where high current velocities and low salinities appear to have deterred most organisms. Therefore, the association of marine traces with such facies suggests somewhat unusual conditions.

It has been suggested that the Lower Limestone Group sediments are characteristic of a 'destructive deltaic complex' (Belt 1975), with marine reworked, strike-aligned sand-bars at the delta-front, and a lack of major distributary channels due to intense marine influence. In such cases, the lower delta plain would become the site of strong marine influence, and recognised delta-top facies would be closely associated with marine conditions and delta-front marine influenced sediments.

In this study, the interval between the Lower and Upper Kinniny limestones is examined along the well exposed coastal section at Kinghorn-Kirkcaldy, central Fife. Comparisons are then made between this section and surface and subsurface sections in East Fife, and the interval is also investigated in the Catcraig area of East Lothian.

13.2. Kinghorn-Kirkcaldy, central Fife (Figs.13.1 and 13.3)

The interval between the Lower and Middle Kinniny limestones at Kinghorn-Kirkcaldy is approximately 12-15 m thick, compared with the 20 m thickness of the interval on the east side of the St Monans Syncline, East Fife. In other parts of central Fife, however, the interval thins dramatically, and it is known to be a mere 5.4 m thick in the Carberry Bore (Francis 1961a). The Lower Kinniny Limestone is succeeded by a 4 m thick interval which is predominantly composed of dark calcareous mudrocks containing red-coloured siderite bands and nodules which gradually coarsen-upwards into silty mudrocks with fine-grained sandstone interlaminae. This sequence is overlain abruptly by an erosive and loaded-based 0.70 m thick sandstone which contains trough cross-beds and swaley hummocky cross-stratification-like structures (Fig.13.2C). It is also characterised by the trace fossils *Rhizocorallium* (Fig.13.2D), *Skolithos* and *Diplocraterion*, and noticeably fines-upward. The remaining 8 m thick sequence between the sandstone and the Middle Kinniny Limestone is composed of four small-scale upward-coarsening sequences overlain by a 1 m thick mudrock below the limestone. These coarsening-upward sequences consist of nodular mudrocks containing siderite bands and nodules with occasional sandstone laminae ('ribs') passing upward into thin rooted sandstones.

The Middle Kinniny Limestone is a 1.86 m thick marine limestone containing an abundant fauna including crinoid ossicles (Fig.13.2B) and brachiopods in the upper part, but is devoid of fossils towards the base (Francis 1961a, p.27). It is characterised by the occurence of *Zoophycos* and the presence of thrusts trending NW-SE . The presence of small thrusts in this limestone does not only appear to be a feature of the exposure on the Kinghorn-Kirkcaldy foreshore, as they are also present at Balbougie Glen in the Dunfermline area (Allan in Haldane and Allan 1931, p.30). The limestone has a sandy base and is overlain by a 15 m thick, mudrock dominated sequence which contains two thin unnamed sandy limestones (Francis 1961a), the lower of which is characterised by abundant *Zoophycos*. This mudrock sequence is capped by a 1 m thick paleosol facies consisting of a coaly mudrock overlain by rooted sandstones, which when traced along strike along the foreshore pass into a small channellised sandstone unit which is trough cross-bedded. These are overlain by the 0.51 m thick marine Upper Kinniny Limestone, the top of which marks the base of the overlying Limestone Coal Group. The mudrock dominated sequence below the two unnamed limestones contains thin fossiliferous bands, especially towards the top and bottom, and bands of nodules, some of which have diameters of up to 37 cm. Above the two unnamed limestones, the mudrocks become increasingly silty, containing siderite nodules and sandy ribs, and broadly form a slight upward-coarsening sequence into the overlying paleosol facies. The Upper Kinniny Limestone, like the Middle and Lower Kinniny limestone horizons is fossiliferous in its upper part, but passes downwards into a faunally barren sandy base, a characteristic which is a feature of all the limestones above the Seafield Tower (Charlestown Main) Limestone horizon in this section (Francis 1961a). To the north, the Upper Kinniny Limestone becomes even more impersistent and 'impure', and is represented in bores north of Kirkcaldy by about 5 cm of calcareous argillaceous sandstones and mudrocks (Francis 1961a). Above the Upper Kinniny Limestone, the base of the Limestone Coal Group succession comprises several small coarsening-upwards sequences, into which a quartz-dolerite sill has been intruded (Fig.13.2A).

13.3. Kinghorn-Kirkcaldy; interpretation

Several significant features are present within the interval between the Lower and Upper Kinniny limestones at Kinghorn-Kirkcaldy. One is the notable absence of any major sand bodies and the domination of mudrocks, and the other is the strong marine influence throughout most of the interval, despite the relative paucity of thick marine limestones and faunally rich and diverse horizons.

The coarsening-upward sequence above the Lower Kinniny Limestone does not appear to represent a 'normal' Yoredale-type upward-coarsening clastic sequence, and the erosive and loaded-based sandstone which caps the sequence is interpreted as a prodelta/delta-front storm deposit which was subsequently reworked and bioturbated by marine ichnogenera. The four minor coarsening-upward sequences between the sandstone and the Middle Kinniny Limestone appear to record the infilling of small shallow bay-lagoons by thin sand sheets which were eventually vegetated. The uppermost of these sequences is overlain by the Middle Kinniny Limestone and associated mudrocks which represent a major marine event recognised as being areally widespread, and possibly the result of a rise in sea level. This marine event appears to have been prolonged, and most of the Middle Kinniny-Upper Kinniny limestones interval is marine, although the sequence above the unnamed limestones records a shallowing and infilling of a marine-influenced bay-lagoon which was eventually vegetated. It is interesting to note that when traced laterally along strike, the rooted paleosols pass into a trough cross-bedded sandstone facies interpreted as a delta-top channel. These facies variations imply that bay-lakes were contemporary with channels on the delta top, the latter periodically cutting into abandoned bay-fill sediments, either via crevasse events from the main channel or through channel avulsion. The paleosols below the Upper Kinniny Limestone, which is interpreted as a major marine incursion would therefore appear to represent a major abandonment facies developed prior to a rise in sea level.

The interval as a whole suggests deposition on a marine-influenced lower delta-plain, largely starved of coarse clastic influxes usually supplied via distributary channels. This accounts for the predominance of mudrocks, and the prolonged nature of the marine phases. The attenuated nature of the coarsening-upward sequences also supports such an assumption, with destructive marine processes predominating over the diminutive fluvial input. During periods of marine influence, marine muds and carbonates were deposited, the latter often being sandy due to marine reworking of the deltaics. During periods of declining marine influence, the deltaics show very little sign of constructive progradation and no major upward-coarsening sequences are present. This suggests that for some reason, this part of the lower delta plain had largely been abandoned and was therefore dominated by periods of prolonged marine influence alternating with the infilling of large abandoned pools on the lower delta-plain which were subsequently vegetated. Unlike the sequence at Kinghorn below the Lower Kinniny Limestone, the phases of deltaic sedimentation are almost negligible, and virtually no constructive delta progradation is recorded. It is not thought, however, that marine influence was any stronger during this time period, only that the deltaic phases in this area were much weaker, and that this part of the lower delta plain had effectively been abandoned. This accounts for the strong marine influence of the sequence despite the relative weakness and faunal barreness of the individual marine horizons.

13.4. Lower Kinniny-Upper Kinniny limestones interval; East Fife (Fig. 13.4)

The main difference between the Lower-Upper Kinniny limestones interval in East Fife, with the same interval at Kinghorn-Kirkcaldy, central Fife, is the presence of many more sand bodies, some of which are characteristically trough cross-stratified. On the east side of the St Monans Syncline, however, the interval is still marine-influenced and channel sandstones are often associated with diverse marine trace fossil assemblages (Chisholm 1970b), including *Teichichnus* and *Rhizocorallium*. This is especially true of the sequence developed immediately above the coarsening-upward sequence with the Lower Kinniny Limestone horizon at its base, where an erosive-based channel sandstone cuts into the marine mudrocks. This sandstone is predominantly trough cross-bedded, but also contains an abundant trace fossil assemblage including *Rhizocorallium*, *Teichichnus* and *Palaeophycos*, with plant remains such as *Lepidodendron* and *Sigillaria*. It fines-upwards into cross-laminated flaggy beds which are characterised by vertical burrows, and the cross-beds suggest palaeocurrents to the E and NE. The sandstone is overlain by an extensively bioturbated fine-grained sandstone containing plant remains, and the trace fossils *Teichichnus*, *Planolites*, *Diplocraterion*, *Phycodes* and *Asterosoma* This in turn is overlain by a small coarsening-upward unit with marine mudcks at the base containing *Streblopteria ornata*. The mudrocks coarsen-upward into siltstones with cross-laminated sandstone laminae ('ribs'), which are cut into by an erosively-based sandstone. The coarsening-upward sequence is characterised by *Teichichnus*, *Planolites*, *Diplocraterion* and wave-ripples, and the overlying sandstone is trough cross-bedded and overlain by paleosol facies. The remaining part of the Lower-Middle Kinniny limestones interval consists of paleosol facies (coals and rooted sandstones) associated with ?fluvial channel sandstones, and the dolomitised Middle Kinniny Limestone and associated marine mudrocks are underlain by paleosol (abandonment) facies, which sometimes includes a coal (Forsyth and Chisholm 1977).

The interval between the Middle and Upper Kinniny limestones is not fully exposed on the east side of the St Monans Syncline, although the 0.90 m thick Middle Kinniny Limestone (with abundant *Zoophycos*) is overlain by 9 m of mudrocks containing siderite bands and a 0.20 m thick sandstone 6 m above the base. The interval is known from subsurface BGS boreholes (Forsyth and Chisholm 1968, 1977), however, where it is composed of a thick sequence of marine mudrocks (up to 18 m thick) at the base, which coarsen-upward through siltstones and bioturbated sandstones. These are cut into at many localities by a very thick (7.5-30 m) erosive-based sandstone which sometimes contains heterolithic partings with paleosol facies and is overlain by the 0.90 m thick Marl Coal (Forsyth and Chisholm 1977). This organic paleosol facies underlies the Upper Kinniny Limestone which is up to 0.4 m thick (Cumming 1928), although at many localities in East Fife it is merely represented by a mudstone bed with a sparse marine fauna.

13.5. East Fife; interpretation

In most Lower Limestone Group sequences, there is no direct marine/deltaic interaction, and progradational deltaic sequences usually develop in response to falling sea level, so that the resulting delta plain facies are freshwater-dominated. In the lower part of this interval, however, the channel sandstones with abundant marine trace fossil influence are clearly an exception to this rule, representing marine-influenced delta-top deposition on the lowest part of the delta plain. Like the Kinghorn sequence, the marine influence appears to have been strong, but in East Fife, deltas were still constructively prograding into what was apparently a stable or relatively stable marine phase (i.e. not undergoing regression).

The Lower Kinniny Limestone horizon represents a marine transgression resulting from a rise in sea level which is recorded as a widespread marine phase. In this part of East Fife, however, marine facies and lower delta plain sediments appear to have been intimately associated, and delta plain channel sands may have been at least partially colonised by marine organisms. It is possible, however, that the channel could have been situated at the marine-influenced delta-front in an estuarine-type setting which developed on the marine-swamped lower delta plain. Channel abandonment is recorded by the thin bioturbated sandstone which caps the channel, representing marine reworking of the sandy deposits to form a shoreline facies which is succeeded by marine muds containing body fossils. This part of the succession clearly represents a temporary deltaic encroachment into a muddy marine environment which was abandoned, reworked, only for the mud-dominated marine conditions to be resumed. The presence of marine sandy substrates, however, appears to have suited the organisms responsible for the wide variety of trace fossils. Towards the top of the Lower-Middle Kinniny limestones interval, further delta progradation resulted in the establishment of more typical delta-top facies where marine influence was not so marked. Here, channel sands have 'normal' palaeoflow directions to the SW, and are intercalated with organic paleosols (peats) and rooted sands containing *in situ Lepidodendron* trunks and stigmarian roots.

The Middle Kinniny Limestone, as at Kinghorn, records a widespread marine phase, and is overlain by a thick sequence of marine muds representing prolonged muddy marine conditions. Unlike Kinghorn, however, the sequence forms a major coarsening-upward sequence suggesting active delta progradation, and is cut into by a major distributary channel sand body. This is overlain by a peat abandonment facies (Marl Coal) developed prior to the 'Upper Kinniny Limestone marine transgression'. Whilst marine influence is evidently strong throughout the Lower-Upper Kinniny limestones interval in East Fife, constructive progradational sequences are also developed. These, however, show some abnormalities suggesting deposition upon a strongly marine influenced part of the lower delta plain where even delta-top facies contain marine trace fossils and show evidence of marine influence. The thicker sequences and presence of a greater number and thickness of sandstones in East Fife points to more rapid and greater tectonic subsidence than central Fife, which encouraged active delta progradation, even during periods of sustained marine influence.

13.6. Summary of central and East Fife

Deltaic deposition is usually characterised by phases of delta progradation, followed by abandonment, and the invasion of marine conditions. This gives rise to Yoredale-type cycles where marine phases are delineated from the constructive progradational fluvio-deltaic phases. In the Lower-Upper Kinniny limestones interval, however, such a well-defined distinction between marine and fluvio-deltaic phases is not so easily recognised, and many of the so-called deltaic phases are marine influenced. What is clear, however, is that delta progradation was more active during this time in East Fife, than it was in central Fife, where the lower delta plain appears to have been at least partially abandoned. This suggests that in the case of Lower Limestone Group deltas, progradation was not uniform, and that some areas of the delta were under marine influence whilst others were still actively outbuilding under a fluvio-deltaic influence. The control on this variable progradation appears to have been variable tectonic subsidence, which still encouraged the active progradation of delta lobes when marine conditions prevailed on parts of the lower delta plain.

13.7. Catcraig, East Lothian (Figs.13.5 and 13.7)

In East Lothian, only two major marine limestones are recognized above the local equivalent of the Charlestown Main Limestone (Davies *et al.* 1986), and these are known as the Chapel Point and Barns Ness limestones. They are both well exposed in the Catcraig-Barns Ness coastal section (Craig 1975; Clarkson 1986*a*), and are known to be possible equivalents of the Kinniny limestones of Fife, although exact correlations are in doubt (Davies *et al.* 1986), due to the relative scarcity of marine horizons at this level compared with the Fife sections (Wilson in Davies *et al.* 1986). Therefore, although these marine limestones cannot be exactly correlated with those studied in

Fife, and the intervening clastic intervals compared, the sequence is broadly equivalent to the Lower-Upper Kinniny limestones interval in east and central Fife.

In the thick coarsening-upward sequence above the Middle Skateraw Limestone (local equivalent of the Charlestown Main Limestone), indistinct burrows are recognised throughout the mudrocks towards the base and the intercalated sandstones and siltstones towards the top. These are associated with *Zoophycos* and *Teichichnus* burrows and are suggestive of delta-front sediments deposited as sand sheets along the front of a wave-influenced delta. The presumed delta-top facies above the delta-front deposits, however, consist of trough cross-bedded, coarse-grained sandstones with palaeocurrents to the SW associated with numerous small *Diplocraterion burrows*. In the overlying heterolithic beds below the Chapel Point Limestone, large specimens of *Rhizocorallium* up to 50 cm in length are well preserved and the sandy base of the limestone is characterised by *Teichichnus* and *Thalassinoides*. The sandy base of the limestone contains abundant crinoid ossicles and *Zoophycos* traces are common throughout. Within the Chapel Point-Barns Ness limestones interval, giant *Diplocraterion* burrows (Clarkson 1986a) are again associated with cross-bedded sandstones, and the overlying Barns Ness Limestone is characterised by abundant *Zoophycos*.

13.8. Barns Ness Limestone

The Barns Ness Limestone was formerly called the Barness East Limestone (Clough *et al.* 1910; Whyte 1973; Craig 1975), and is the uppermost limestone horizon in the Lower Limestone Group of the Dunbar-Catcraig area. It is not known for certain, however, whether this limestone equates with the Top Hosie and Upper Kinniny limestones, the tops of which mark the upper boundary of the Lower Limestone Group elsewhere. The Barns Ness Limestone is only one of two limestones above the Neilson Shell Bed (Wilson 1966) in the Dunbar area (the other is the Chapel Point Limestone), both of which are sparsely fossiliferous, in contrast to other outcrops of the Lower Limestone Group, where numerous faunally diverse marine horizons are present at this stratigraphic level (Wilson in Davies *et al.* 1986, p.30).

The Barns Ness Limestone varies in thickness between 1.1 m and 1.8 m, and is a grey-yellow white to cream-buff weathering, impure (Clough *et al.* 1910) sandy dolomitic unit which is a darker grey colour when fresh. It is crystalline, hard, compact and finely jointed, with dolomite-filled vugs and a slaggy appearance. Numerous examples of the trace fossil *Zoophycos* are present on the upper bedding surface, but the only identifiable body fossils are fragmentary crinoid remains, and the shell hash of other marine fossils such as ?brachiopods and ?bivalves. The limestone forms the core of a syncline between Catcraig and Longcraig (Skateraw), but north of Barns Ness Lighthouse the limestone rapidly decreases in thickness and dies out completely towards low water mark. To the north of White Sands [NT 7076 7814], the limestone reaches a maximum thickness of 0.9 m folded in a gentle syncline. Here it contains crinoid remains and the trace fossil *Zoophycos*, and the sequence is repeated northwards where the limestone is absent, and the horizon is represented by a dark grey coloured, cannely shaly mudrock. This bed contains *Lingula* and overlies a ganister-like sandstone, identical to the one which underlies the limestone at Catcraig-Barns Ness, supporting the correlation of the mudrock with the limestone (Fig.13.7).

The local degeneration of the Barns Ness Limestone into a *Lingula* band suggests that the marine incursion during which the limestone was deposited may not have been a laterally persistent feature (i.e. areally widespread). This implies that any correlation with the Top Hosie and Upper Kinniny limestones (George *et al.* 1976; Francis 1965, 1983a) may be untenable. The sandy nature of the limestone implies that there was some siliciclastic input during the deposition of the limestone, which may have taken place in relatively high energy conditions on a shallow, nearshore marine shelf. The low-diversity faunal assemblages suggest possible stressful conditions, initiated due to factors such as turbulence, and low-salinity, induced by substantial freshwater runoff in coastal areas in the vicinity of deltas. The presence of abundant *Zoophycos* traces is characteristic of firm to plastic substrates, which appear to have been a persistent feature of the sandy limestones deposited near the top of the Lower Limestone Group throughout the Scottish Midland Valley.

The abandonment facies (paleosols) beneath the limestone suggest that abandonment of at least part (if not all) of the lower delta plain took place prior to the marine transgression. Such abandonment facies could have resulted from a rise in sea level, or the avulsion of an individual delta lobe. In the latter case, the lobe would subside and compact, allowing marine processes to rework the delta-front and delta-top sediments (Elliot 1974a, 1975). This may in part explain the high percentage of quartz grains, and the local transition to a *Lingula* band, as these types of delta avulsion-induced incursions are generally restricted to one individual delta lobe, and are not therefore regionally widespread.

13.9. Sandstones above the Barns Ness Limestone (Figs. 13.7 and 13.8)

The Barns Ness limestone is overlain by 30-40 m of sandstones which abruptly overlie the limestone without the usual transition from mudrocks and siltstones to sandstones characteristic of inter-marine coarsening-upward sequences present in the Lower Limestone Group (Clough *et al.* 1910, p.135). The sandstones are pale red-brown to light brown coloured and are coarse to very coarse-grained at the base, fining-upward to medium-grained rocks which constitute the bulk of the sandstone body. The dominant sedimentary structure is trough cross-bedding (Fig.13.18B), and the sets are thick and punctuated by reactivation surfaces which are related to several generations of minor channel incision. The axes of the sets trend NE-SW, the curved foresets inclined to the SW. The sandstones are clean, very well sorted (mature quartz-arenites), lack fine-grained interbeds and contain rounded to subrounded quartz grains. A prominent lag-like horizon containing angular to subrounded pink-red coloured mudclasts is present towards the base and the rocks are characterised by large cannon-ball shaped concretions ('doggers') which are rounded and are up to 3 m in diameter (Fig.13.8A and C) (Davies *et al.* 1986). The sandstones in general, and particularly the concretions, possess a characteristic microcratered or pitted appearance (Fig.13.8A and C), and soft sediment deformation structures (small folds) also occur. Sandstones at this horizon also crop out at the mouth of the Broxburn (Clough *et al.* 1910), where mudrock units containing siderite nodules, a ganister-like paleosol, and a thin (0.26 m) coal (6-9 m above the top of the Barns Ness Limestone) are interbedded with the sandstones (Fig.13.7). The mudrocks associated with the coal contain plant remains, including *Cardiopteris polymorpha* (Goppert) (Clough *et al.* 1910).

The sandstones overlying the Barns Ness Limestone clearly represent a very rapid progradational influx of coarse clastic sediment into a shallow-water, nearshore marine-shelf environment (Clarkson 1986a). The noticeable absence of a well-developed coarsening-upward unit between the limestone and the sandstone suggests that either prodeltaic to delta-front sediments were never deposited, or were eroded away by subsequent coarser clastic influxes transported by currents of a high flow velocity. Equally, such an abrupt transition from a limestone to a sandstone may represent delta progradation into a very shallow water, high energy shelf setting.

The great thickness of these rocks (up to 40 m) and the general dominating presence of sandstones near the top of the Lower Limestone Group in this area, suggests a possible rejuvenation of the hinterland source area. The persistent influx of coarse clastics is characteristic of the beginning of the Namurian Limestone Coal Group throughout the Midland Valley of Scotland (Francis 1983a), which suggests that at least part of the top of the succession may be of Limestone Coal Group age.

The sandstones above the Barns Ness Limestone are interpreted as delta-top deposits, and the general fining-upwards trend (from a very coarse-grained and lag-lined base) is consistent with deposition within a large fluvial distributary channel on the lower part of the delta plain. This is supported by the mineralogical maturity of the sandstone and the presence of trough cross-bedding, which is interpreted as the cross-sectional expression of large, sinuous-crested subaqueous sand dunes, migrating in fluvial channels at high flow stage. The reactivation surfaces represent dune modification and erosion during low flow stages, and the small channel incisions associated with the surfaces were probably cut within a larger channel regime during low flow stages, only to be infilled and abandoned during high flow periods. The south-westerly palaeocurrents suggest a north-easterly source area, which is consistent with previous work (Goodlet 1957, 1959; Greensmith 1962; Belt 1975).

The presence of thin, subordinate, interbedded mudrocks and paleosols (ganister and coal) within the sandstones exposed at the mouth of the Broxburn suggests that shallow interdistributary bays were established on the delta-top (Elliot 1974b) contemporary with major channels, which were characterised by fine-grained clastics (mudrocks), only to be abandoned and vegetated (ganister). Abandoned bays were the sites of peat accumulation (coal), which appear to represent localised abandonment facies of limited extent, as the fine-grained interbeds at the mouth of the Broxburn are absent at Catcraig.

The cannon-ball shaped concretions or 'doggers' are clearly diagenetic features, and as such have little bearing upon the interpretation of the depositional setting.

13.10. Abandonment facies associated with the Barns Ness Limestone (Figs. 13.9, 13.10 and 13.11)

The Barns Ness Limestone is underlain by an impersistent, 0.12 m thick coaly breccia (Fig.13.6A) which overlies a hard, orange weathering prominent 0.50 m thick ganister-like sandstone. The latter bed is rhizoturbated and bioturbated, and the upper bedding surface is characterised by numerous horizontal and vertically orientated rootlets (Fig.13.6B) associated with *Lepidodendron* trunks (Fig.13.6C) and stigmarian rootlets up to 0.70 m in length and 0.10 m in width. Some of the stigmarian roots appear to be *in situ*, and are characterised by small sub-rootlets which emanate from the main root at approximately 90 degrees. The ganister is coarse-grained, with quartz grains in excess of 1 mm in diameter. Stigmarian roots are also observed penetrating down from this horizon into lower beds which are possibly trough cross-bedded, although these primary sedimentary structures appear to have been highly disrupted by rhizoturbation. Although Clough *et al.* (1910) described this bed as a sandstone full of worm tubes (piped bed) containing crinoid remains, it is clear that the so-called worm tubes are rootlets, and recent work has failed to confirm the presence of crinoid ossicles.

The ganister-like sandstone is interpreted as a paleosol, deposited upon an abandoned delta-top (or part of an abandoned delta-top), after delta avulsion or interdistributary bay abandonment. As the overlying Barns Ness Limestone cannot be correlated with any confidence away from the Dunbar area, it is likely that only a local delta lobe was abandoned. The presence of bioturbation, rhizoturbation and *in situ* stigmarian rootlets suggests that the abandoned area of the lower delta plain was starved of sediment, reworked by burrowing organisms and vegetated. It is not known how widespread the rooted ganister is, although it is known to underlie the *Lingula* band, north of White Sands. Because of the problems of correlating this part of the sequence outside the Catcraig area, it is not possible to deduce whether the paleosol deposits represent the abandonment of the whole delta-top, or merely a local abandonment of a bay-lake. The presence, however, of an overlying marine limestone indicates that the former hypothesis may be the more realistic of the two alternatives. The coaly breccia which overlies the ganister is probably a penecontemporaneous accumulation, deposited originally as an abandonment/post-abandonment peat 'blanket' on the delta-top, only to be broken-up and reworked during the early, erosive phases of the 'Barns Ness Limestone marine incursion' (cf. Belt 1975). The fact that clasts of coal are present within the breccia, suggests that the deposit was at least partially lithified and coherent prior to reworking.

13.11. Clastic interval between the Chapel Point and Barns Ness limestones (Fig. 13.5)

The interval between the Chapel Point and Barns Ness limestones is occupied by approximately 14.84 m of predominantly coarse clastic sedimentary rocks which vary in thickness between 9-15 m (Whyte 1973, p.18; Davies *et al.* 1986). The rocks are predominantly sandstones containing ironstone nodules and a patchy siderite cement (Davies *et al.* 1986), some of which are characteristically cross-bedded, but subordinate siltstones and mudrocks are also present. Towards the top of the interval the sandstones contain rootlets, and the sequence is capped by the ganister-like sandstone described above. The basal 6.70 m of the interval contains sporadically exposed coarse-grained sandstones which pass upward into 0.30 m of planar and cross-bedded orange-coloured sandstones containing large specimens of *Diplocraterion* (Clarkson 1986a). These are overlain by 7.63 m of poorly exposed coaly mudrocks and siltstones which are cut into by very coarse-grained sandstones and are succeeeded by heterolithic silty sandstones up to 0.60 m thick which are coarse to very coarse-grained, micaceous, and trough cross-bedded. An overlying 0.30 m thick trough cross-bedded sandstone consists of several sets of cross-bedding grouped into cosets and the axes of the sets trend NE-SW, the curved forests dipping to the SW. These sandstones are purple-brown in colour and coarsen-upwards to coarse and very coarse-grained sandstones at the top of the unit. The sandstones are overlain by a 0.06 m thick white coloured claystone which contains coalified, black coloured rootlets and passes upwards into a 0.25 m thick silty-coaly mudrock which is black in colour and contains *in situ* rootlets. A large cast of a vertically orientated stigmarian root, now filled with sandstone is present within these beds, extending down from the overlying ganister horizon. The contact between the silty coaly mudrock and the overlying ganister-like sandstone is undulatory, sharp, abrupt and possibly erosional.

The clastic package between the Chapel Point and Barns Ness limestones is a crude coarsening-upwards sequence, although in general the interval is dominated by sandstones, with only a few finer-grained beds towards the base of the sequence. This suggests a rapid influx of coarse clastic sediment during the progradational phase of delta advance, and the presence of large *Diplocraterion* burrows suggests shallow marine to quasi-marine conditions developed during lapses in the rate of deposition at the delta-front during progradation. The bed containing *Diplocraterion* burrows, therefore, probably represents sandy deposits which were reworked by basinal processes (e.g. storms and waves) to form shoreface/beach sands at the delta-front which were inhabited by marine organisms. The poorly exposed coaly mudrocks which are cut into by channel sandstones may record interdistributary bay sedimentation on the delta-top, or alternatively delta-front/prodelta muds which were cut into by proximal channel mouth-bar deposits. The overlying claystone-mudrock-sandstone sequence is clearly a record of delta-top deposition. The claystone and mudrock beds are interpreted as paleosol-type facies, representing the abandonment of part (if not all) of the lower delta plain. The overlying sandstone (ganister bed) has an erosive base and contains hints of trough cross-bedding suggesting that it may have been a crevasse channel sand which cut into bay-fill deposits and was then rapidly abandoned and vegetated, accounting for the poor preservation of primary sedimentary structures in the sandstone. These abandonment facies were developed prior to the 'Barns Ness Limestone marine transgression', and were possibly developed in response to a rise in sea level affecting the water table on the delta-top.

13.12. Catcraig-discussion

Although this sequence can only be broadly compared with that in east and central Fife, the lithological similarity of the limestones (e.g. sandy with abundant *Zoophycos* traces) and the general stratigraphical positions of the sequence suggests that it must be approximately at the same level. It is different, however, from both the successions in east and central Fife, being much thinner and characterised by fewer marine horizons. The facies developed in the inter-marine clastics do show some similarity to those in East Fife (e.g. associations of marine trace fossils with trough cross-bedded sandstones) suggesting marine influenced delta-fronts or even delta-tops. Although the East Lothian succession is much thinner than that in central Fife, it is sandier and very few fine-grained beds are present.

13.13. Discussion

The Lower Limestone Group passes up into the overlying Limestone Coal Group, the base of which is drawn at the top of the Top Hosie or Upper Kinniny Limestone (Francis 1983a). The Limestone Coal Group predominantly consists of fluvio-deltaics, and marine horizons are quite rare (Read 1965; Read and Dean 1967). The transition from the acme of marine conditions in the 'Charlestown Main Limestone marine phase' of the Lower Limestone Group to the essentially non-marine conditions of the Limestone Coal Group takes place through a series of thinner, less pure and faunally less diverse limestones (the Kinniny or Hosie limestones) which appear to represent a declining marine influence during the major transgressive events. During this period, however, the distinction between marine phases and deltaic phases is less clear than in the lower part of the Lower Limestone Group, possibly due to an inability on the part of some transgressions to establish fully marine conditions via the drowning of deltaic complexes and effecting abandonment of the delta-top. This resulted in a 'half-way house' situation where some marine phases were not of a sufficient magnitude to prevent deltaic encroachment, resulting in the intimate association of marine and deltaic facies.

Throughout the eastern part of the Midland Valley of Scotland, limestones at the Kinniny or Hosie position are often sandy and are characterised by the presence of *Zoophycos* and associated trace fossils (cf. Geikie 1900; Macconochie 1927; Donaldson and Simpson 1962; Craig 1975;). Although *Zoophycos* and other trace fossils are associated with stratigraphically lower limestones in the Lower Limestone Group, they are never so abundant and persistent from outcrop to outcrop in their occurence. This distribution, however, almost certainly reflects a substrate rather than a stratigraphic control, emphasising the lithological similarities between the Kinniny/Hosie limestones at different localities throughout the Midland Valley.

13.14. Conclusions

The Lower-Upper Kinniny limestones interval was studied along the Kinghorn-Kirkcaldy coastal section, central Fife and was compared with the same interval in East Fife. By comparing the inter-marine clastic intervals it was possible to infer that deltas were prograding into the East Fife area whilst the central Fife area was either under marine influence, or represented a stagnant and abandoned lower delta plain.

The inter-marine clastic intervals in East Fife show evidence of marine influence even within facies assumed to represent delta-top sedimentation. Similar facies were also located at approximately the same position in the Catcraig section, East Lothian, although the anomalous nature of the East Lothian sequence precluded direct comparsion with that in Fife. The broad conclusions of this study can be summarised as follows;

1. Marine bands (and in particular limestones) are generally thin and faunally impoverished in the upper part of the Lower Limestone Group when compared with the thick and faunally rich limestones in the lower part.
2. The limestones in the upper part of the Lower Limestone Group often have sandy bases which are faunally barren, and are laterally impersistent and exhibit facies changes when traced over relatively short distances. These limestones are often associated with an abundant ichnofauna, and the marine trace fossil *Zoophycos* is particularly common.
3. The inter-marine clastic sequences show great variability between different localities, with delta-top channel sandstones being absent from some areas, whilst common in others.
4. The relative paucity and weakness of marine transgressions appears not to have acted as an effective barrier to delta progradation (as it did in the lower part of the Lower Limestone Group) and instead of delta phases and marine facies being totally separate and representing discrete and separate environmental phases, there appears to have been an intermingling resulting in marine facies and deltaic conditions being intimately associated (e.g. trace fossils associated with ?delta-top facies).
5. Some areas (e.g central Fife) appear to have been sand starved, and sedimentation on the lower part of the lower delta plain was predominantly mud-dominated. Here, marine conditions appear to have been intimately associated with marine-influenced delta deposition, and sedimentation involved the gradual infilling of fresh to ?brackish water bay-lagoons with thin sand sheets which were vegetated, abandoned and eventually transgressed by a new phase of marine sedimentation. In other areas (e.g. parts of East Fife and East Lothian), however, very

thick sandstone bodies are present suggesting a rejuvenation of hinterland clastic sources heralding the arrival of the fluvio-deltaic dominated conditions of the Limestone Coal Group.

6. Analysis of the upper part of the Lower Limestone Group (e.g. Lower Kinniny-Upper Kinniny limestones interval) is hindered, however, by the relatively limited number of exposures of this part of the sequence, the difficulties of correlating the thin and faunally sparse marine bands between different localities, the lack of distinctive marker horizons in some areas (e.g. East Lothian), and the lack of information in the literature relating to the rocks.

CHAPTER 14

CONCLUSIONS

Late Dinantian rocks studied in parts of Fife and the Lothians can be subdivided into three concurrent phases of sedimentation; (i) an initial non-marine phase, (ii) a transitional phase, and (iii) a marine-deltaic phase. These phases were developed at the eastern end of the tectonically and volcanically active Scottish Midland Valley, which is believed to have been a major extensional sedimentary basin throughout the Lower Carboniferous.

The non-marine phase is represented by the Oil-Shale Group, where facies analysis suggests that constructive elongate deltaic complexes prograded into non-marine basins or gulfs. Some of these were tectonically and volcanically demarcated, resulting in a decrease in the degree of intra-basinal 'communication'. The bay-like lakes and lagoons were the site of oil-shale deposition, the result of low rates of sedimentation, anoxic reducing conditions, and the accumulation of phytoplanktonic algal oozes. Although oil-shales appear to have been deposited during major water body expansions, prominent desiccation-cracked stromatolitic/mudflat carbonate horizons suggest that the lakes were periodically subaerially exposed. One such shallowing-upward horizon has been identified north and south of the Firth of Forth, allowing correlation of the Lower Oil-Shale Group succession. This relative time marker displays evidence of earthquake activity (soft-sediment deformation structures) and has been used as an isochronous time-line to map out facies changes in the surrounding clastics. Upper Oil-Shale Group rocks at Kingswood, central Fife, contain laterally restricted carbonate mudflat facies which developed around the margins of a bay-lagoon whilst oil-shale deposition continued uninterrupted 'offshore'. In the Upper Oil-Shale Group, widespread volcanism (intraplate and rift-related ?) resulted in the extrusion of lavas and prominent tuffaceous horizons. The tuffs appear to have fallen as ash-showers, which decimated the 'background' faunas living in the shallow water marginal tracts of the bay-lakes. A concomitant shoaling effect led to the development of shallowing-upwards cycles capped by stromatolites, and the cyanobacterial communities developed free from the destructive grazing, browsing and burrowing of other organisms.

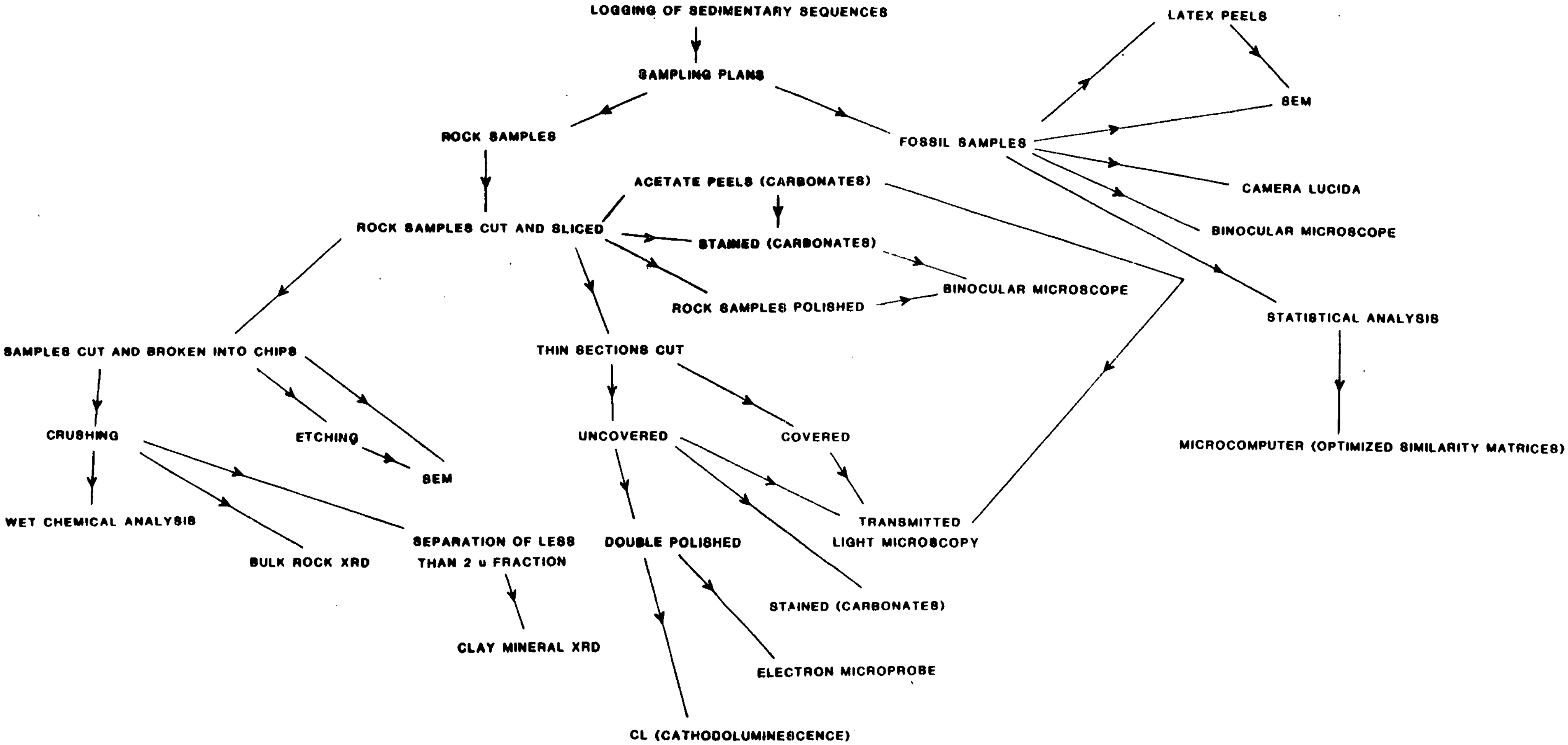
The transitional phase of sedimentation records the earliest widespread marine incursions and is represented by the Pathhead Beds. The marine horizons consist of shales and limestones, and the shales often show a series of faunal phases (a relay), recording the development of successive fossil communities during a marine advance. Although the phases or 'topozones' can be approximately traced from locality to locality, the widespread geographic distribution of recognisable communities may have been disrupted by intermittent tectonism and the presence of intra-basinal highs and lows. Even with the improved intra-basinal 'communication' afforded by the newly arrived marine conditions, uniform faunal and sedimentological regimes (facies) still appear to have been restricted. This was probably due to the presence of the tectonic highs and lows, which caused the basin to be demarcated into areas which were rapidly subsiding (lows), and adjacent tracts that were either experiencing uplift, or very little subsidence (highs). The lows are characterised by thicker inter-marine sequences containing large sand bodies, suggesting competent drainage (development of axial-channel drainage systems ?), and appear to have attracted major delta lobes. The highs, conversely, are characterised by; (i) thinner sequences which rarely contain thick sandstones, (ii) evidence for breaks in deposition (e.g. unconformities), (iii) volcanics, and (iv) limestones with emergent surfaces (e.g. karsts). The highs and lows trend NE-SW, paralleling the boundary faults of the Midland Valley Basin, and it is concluded that they could represent Dinantian tilt-block/half-graben structures, which are known to have been common in Dinantian extensional settings.

The concluding marine-deltaic phase is represented by the Lower Limestone Group, where Yoredale-type cycles contain repetitive intercalations of geographically widespread marine beds and restricted fluvio-deltaics. Declining volcanism and tectonism, coupled with widespread open marine conditions appears to have greatly improved intra-basinal 'communication', and this is reflected in the improved stratigraphy and precise lithostratigraphic correlation. The tilt-block/half-graben structures, however, still appear to have been active, and major braided channel networks (e.g. Seafield Tower Sandstone and correlatives) may have formed axial-drainage systems along the axes of intra-basinal lows. The major delta-top channels, however, occasionally cut down into the underlying marine facies, locally removing limestones and shales. This phenomenon can cause stratigraphic miscorrelation and palaeoenvironmental misinterpretation if not recognised, and examples identified in central Fife and East Lothian underline such problems. It is concluded that many similar Yoredale-type sequences have been misinterpreted and miscorrelated due to the non-recognition of limestone 'wash-outs'. In the earlier non-marine and transitional phases, major mouth-bars have been identified in delta-front sequences. In the marine-deltaic phase, however, the delta-front appears to have been largely composed of lobate sand sheets which show evidence of marine reworking. This suggests that as marine influence grew, the deltaic complex was modified from an elongate to a lobate form.

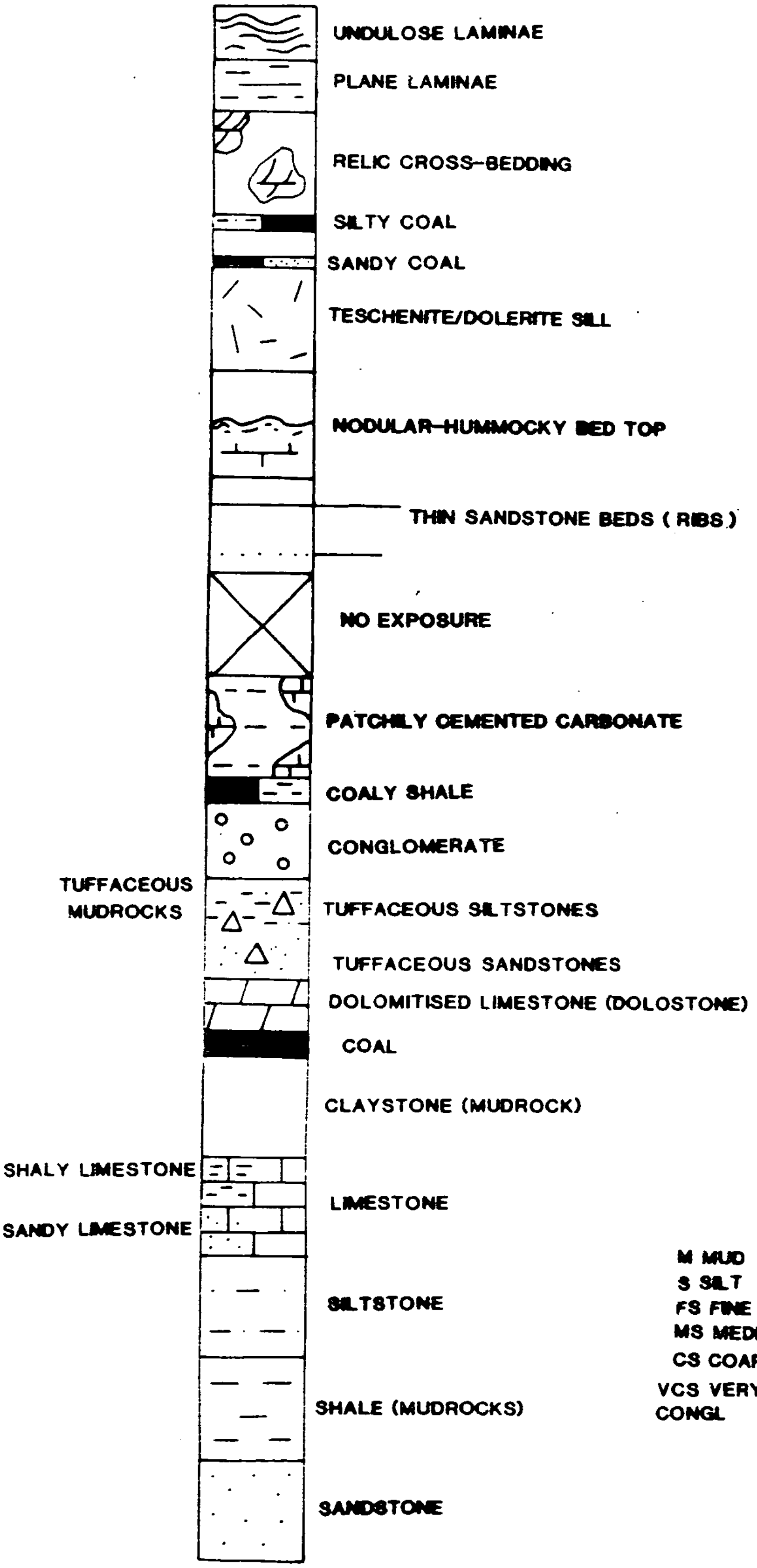
Although most of the marine horizons in the marine-deltaic phase are geographically widespread, some are laterally restricted. These appear to have resulted from either; (i) local delta lobe abandonment (overlying and associated with barrier island chains), (ii) weak marine pulses petering out landward, or (iv) seas impounded by tectonic highs. Most of the major marine bands, however, seem to have resulted from a rise in sea level, or possibly through a tectonic lowering of the Midland Valley Basin. Intermittent tectonism, however, is also suggested by the widespread development of paleosols (e.g. well-drained soils in lower delta-plain settings) and liquefaction structures in sandstones (especially in the vicinity of suspected synsedimentary faults).

Towards the end of the Dinantian, marine horizons become increasingly impoverished, and the marine-deltaic phase is succeeded by an essentially 'regressive' non-marine deltaic phase represented by the Namurian (Silesian) Limestone Coal Group.

From this study, it is evident that only an integrated model invoking the interaction of tectonic, sedimentary and sea-level controls can be used to interpret the complex patterns of sedimentation in the late Dinantian of the eastern part of the Scottish Midland Valley. The importance of the work therefore lies not only in its detailed interpretations and correlations, but in its ability to shed light on the major internal and external controls upon processes within an ancient extensional sedimentary basin.


LOGGING OF SEDIMENTARY SEQUENCES
SAMPLING PLANS
ROCK SAMPLES
FOSSIL SAMPLES
LATEX PEELS
SEM
CAMERA LUCIDA
BINOCULAR MICROSCOPE
STATISTICAL ANALYSIS
MICROCOMPUTER (OPTIMIZED SIMILARITY MATRICES)
ACETATE PEELS (CARBONATES)
ROCK SAMPLES CUT AND SLICED
STAINED (CARBONATES)
BINOCULAR MICROSCOPE
ROCK SAMPLES POLISHED
SAMPLES CUT AND BROKEN INTO CHIPS
THIN SECTIONS CUT
CRUSHING
ETCHING
SEM
UNCOVERED
COVERED
WET CHEMICAL ANALYSIS
BULK ROCK XRD
SEPARATION OF LESS THAN 2 u FRACTION
DOUBLE POLISHED
TRANSMITTED LIGHT MICROSCOPY
STAINED (CARBONATES)
CLAY MINERAL XRD
ELECTRON MICROPROBE
CL (CATHODOLUMINESCENCE)

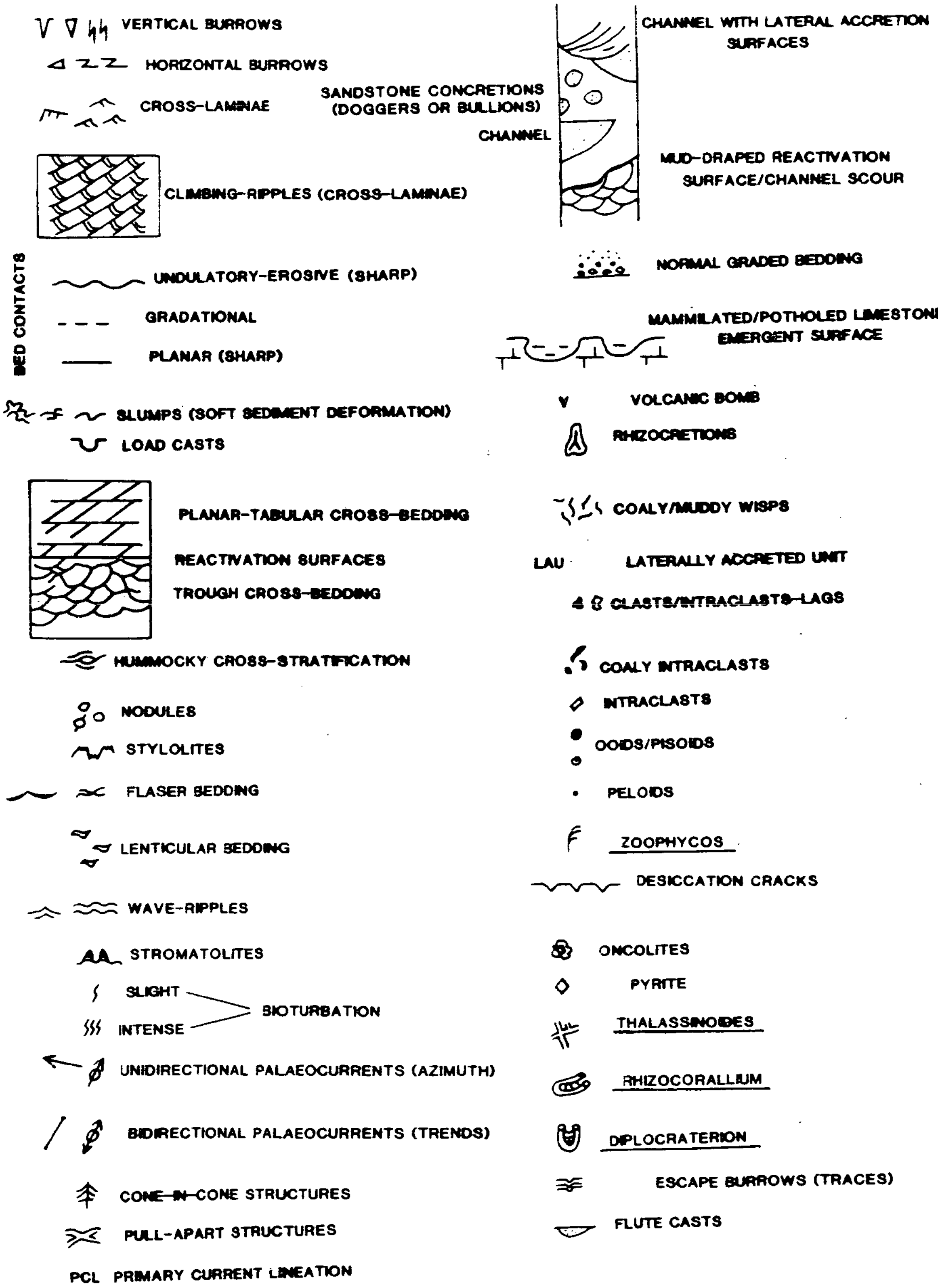
LITHOLOGY/GRAIN SIZE/SEDIMENTARY STRUCTURES



GRAIN SIZES

M	MUD
S	SILT
FS	FINE SAND
MS	MEDIUM SAND
CS	COARSE SAND
VCS	VERY COARSE SAND
CONGL	CONGLOMERATE

SEDIMENTARY AND BIOGENIC STRUCTURES AND SEDIMENTARY GRAINS



FOSSILS/TRACE FOSSILS

M MARINE FOSSILS PRESENT

STIGMARIAN ROOT

IN SITU *LEPIDODENDRON* TRUNK

SPIRORBID WORM TUBES

OSTRACODES

NON-MARINE BIVALVES (E.G. *CURVIRIMULA*)

PLANT REMAINS

PHOSPHATIC FISH REMAINS

ORTHOCONES

ROOTS

FOSSILS (UNDIFFERENTIATED)

GASTROPODS

▽ BRACHIOPODS

CORALS-SOLITARY

CORALS-COLONIAL

BRYOZOANS

BIVALVES

CRINOIDS

GONIATITE

GY *GYROCHORTE*

T *TEICHICHNUS*

HORIZONTAL *LEPIDODENDRON* TRUNK

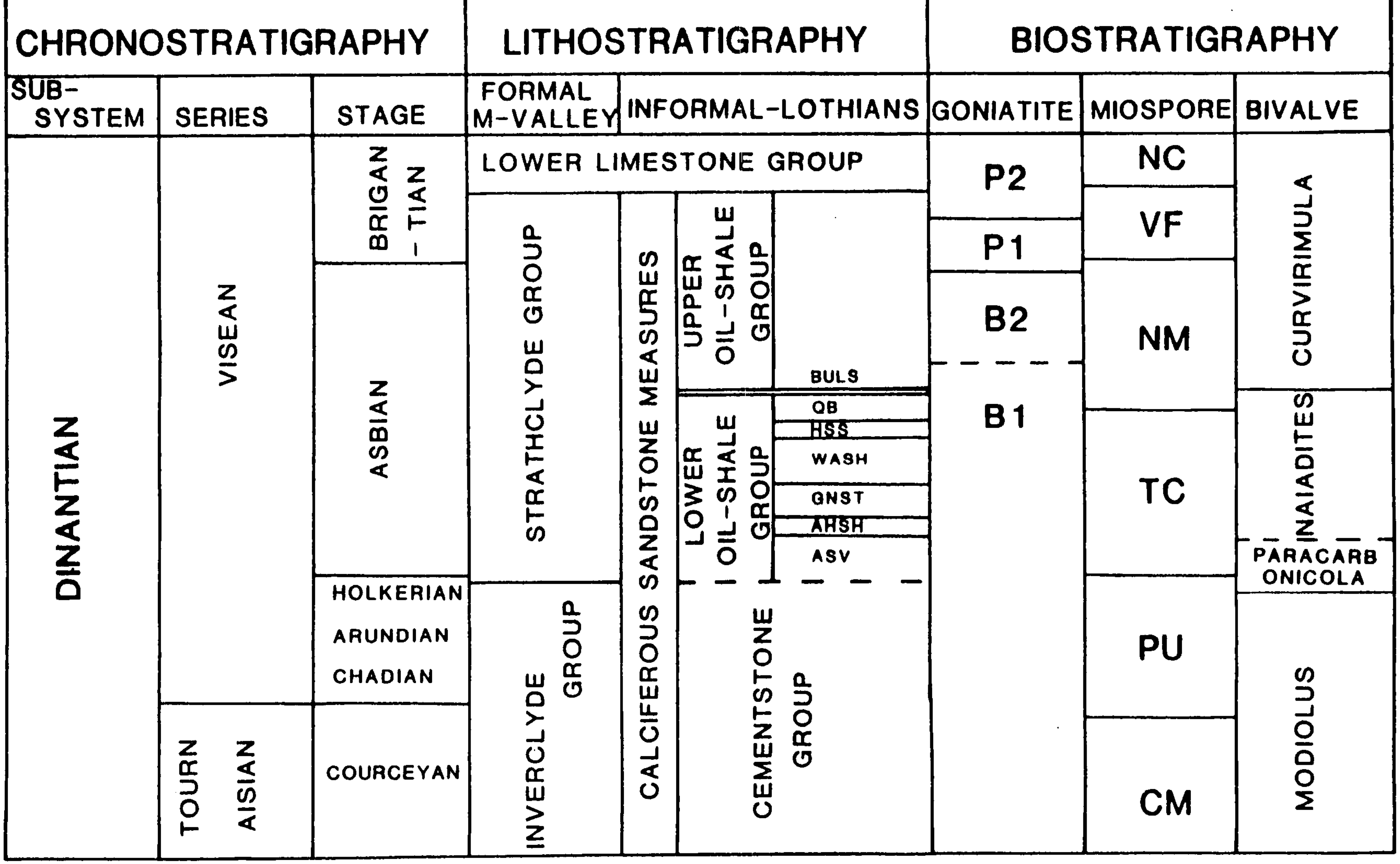
NM NON-MARINE FOSSILS

QM QUASI-MARINE FOSSILS

L *LINGULA*

Fig. 2.1.

Summary table of stratigraphy illustrating the major chrono-, litho-, and biostratigraphic divisions of the Dinantian in the Midland Valley of Scotland. The chrono- and biostratigraphic schemes are generally applicable to the whole area. The lithostratigraphical divisions of Inverclyde and Strathclyde groups also apply to the whole area, but the Oil-Shale Group and its divisions are local, informal lithostratigraphic terms applied to the Strathclyde Group succession in parts of the Lothians and Fife. The chronostratigraphic divisions are based on the work of George *et al.* (1976), whilst the biostratigraphic divisions are based on the work of Currie (1954), Neves *et al.* (1973) and Browne (1986). The lithostratigraphic divisions are after Paterson and Hall (1986) and Mitchell and Mykura (1962).



BULS	BURDIEHOUSE LIMESTONE
QB	QUEENSFERRY BEDS
HSS	HAILES SANDSTONE
WASH	WARDIE SHALES
GNST	GRANTON SANDSTONES
AHSH	ABBEYHILL SHALES
ASV	ARTHUR'S SEAT VOLCANIC ROCKS

Fig. 2.2.

Diagram illustrating the variation of the Calciferous Sandstone Measures throughout the Midland Valley of Scotland. The subdivisions in East Fife are based on the work of Forysth and Chisholm (1977), whilst the subdivisions in parts of central Fife and the Lothians are after Mitchell and Mykura (1962) and Wilson (1974). In the western part of the Midland Valley the subdivisions of the Calciferous Sandstone Measures are based on the work of Monro (1982a, 1984) and Francis (1983a).

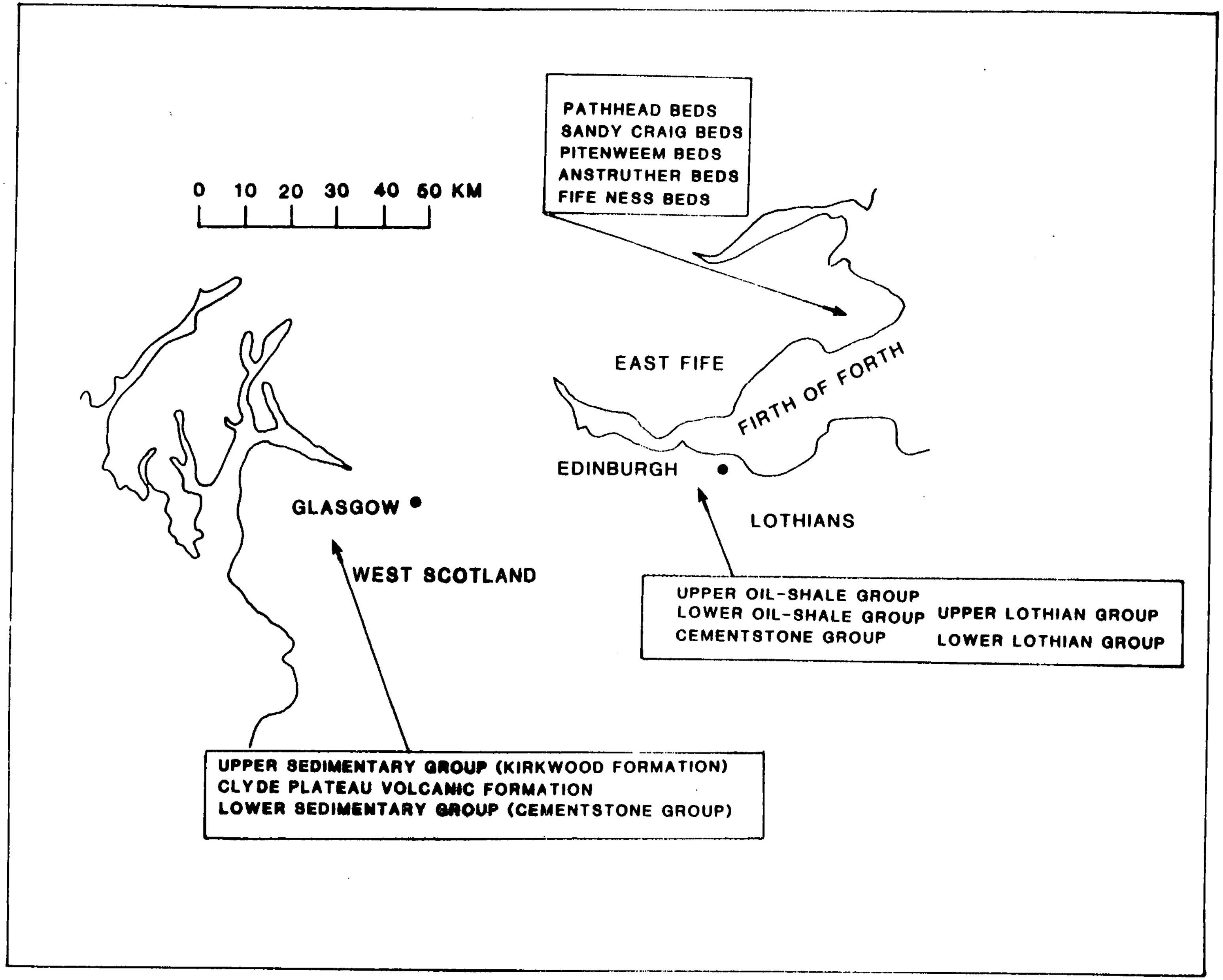

PATHHEAD BEDS
SANDY CRAIG BEDS
PITENWEEM BEDS
ANSTRUTHER BEDS
FIFE NESS BEDS
0 10 20 30 40 50 KM
EAST FIFE
FIRTH OF FORTH
EDINBURGH
GLASGOW
LOTHIANS
WEST SCOTLAND
UPPER OIL-SHALE GROUP
LOWER OIL-SHALE GROUP
CEMENTSTONE GROUP
UPPER LOTHIAN GROUP
LOWER LOTHIAN GROUP
UPPER SEDIMENTARY GROUP (KIRKWOOD FORMATION)
CLYDE PLATEAU VOLCANIC FORMATION
LOWER SEDIMENTARY GROUP (CEMENTSTONE GROUP)

Fig. 2.3.

Summary table showing the relationship between the Dinantian chronostratigraphical stages of George *et al.* (1976) and the major cycles of Ramsbottom (1973). These can be broadly related to the absolute chronology obtained from radiometric dating (Francis and Woodland 1964; Fitch *et al.* 1970; Lambert 1971). The table also shows the foraminiferan zones (after Conil *et al.* 1971 and George *et al.* 1976) of the Dinantian in Belgium, of which only the V_{3c} can be recognised in the Midland Valley of Scotland (Jameson 1980, 1987). The coral-brachiopod zones (Green and Welch 1965; Smith *et al.* 1967), like the foraminiferan zones are largely unrecognised in the Midland Valley, although the Pathhead Beds (Forsyth and Chisholm 1977) and the overlying Lower Limestone Group contain a D_2 coral-brachiopod zone fauna. Table largely after Anderton *et al.* (1979, p.139).

AGES Ma	STAGES	MAJOR CYCLES	FORAMINIFERA	CORAL-BRACHIOPOD
			BIOZONES	
325				
	BRIGANTIAN	6	V3C	D2
	ASBIAN	5	V3B	D1
	HOLKERIAN	4	V3A	S2
345	ARUNDIAN	3		C2, S1
	CHADIAN	2		C1, C2, S1
	COURCEYAN	1		K, Z
360				

Fig.3.1.

Inset-outline sketch map showing British mainland in relation to the position of Firth of Forth area (arrowed). The main sketch map shows the area of outcrop of the Oil-Shale Group in parts of West Lothian, Midlothian and the southern part of central Fife. The geographical restriction of the group to this area is clearly illustrated and the Pentland Hills inlier which is composed of Silurian and Devonian strata is outlined. Scale: 0-15 km scale bar as indicated on map.

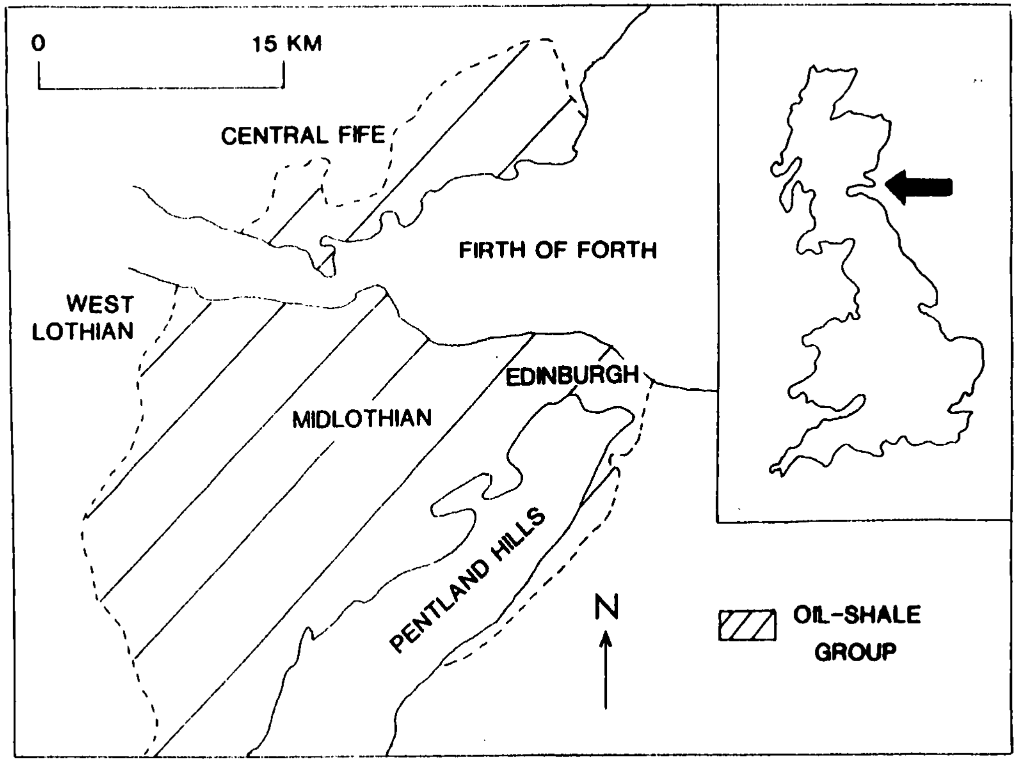
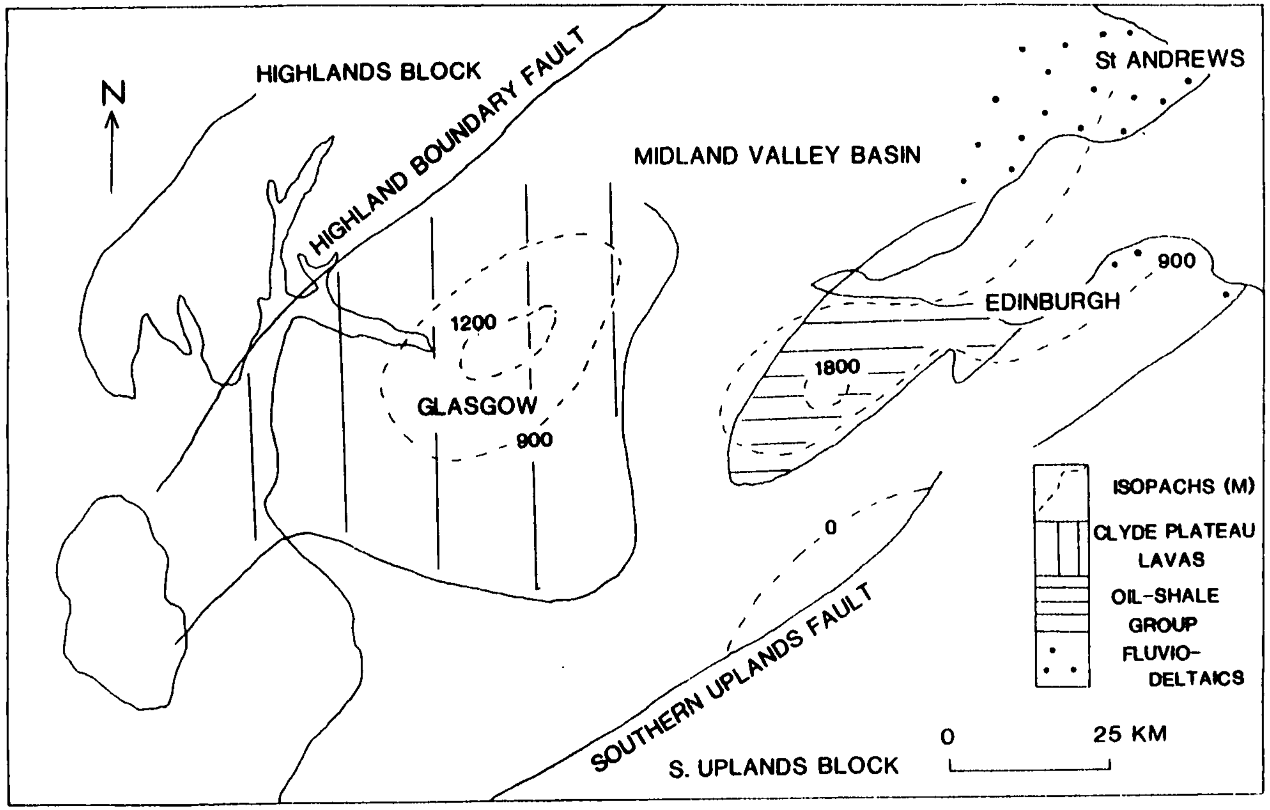

0
15 KM
CENTRAL FIFE
FIRTH OF FORTH
WEST
LOTHIAN
MIDLOTHIAN
EDINBURGH
PENTLAND HILLS
N
OIL-SHALE
GROUP

Fig.3.2.

Facies sketch map of the Midland Valley of Scotland during Oil-Shale Group times. The Midland Valley is bounded by the active Highland Boundary and Southern Upland faults which defined the margins of an intracratonic rift-like basin, with the tectonically positive Highland Block to the north of the Highland Boundary Fault and the tectonically positive Southern Uplands Block to the south of the Southern Uplands Fault. Sedimentation across the Midland Valley Basin was not uniform, and the demarcation of the basin was due to contemporaneous volcanic activity, active faults and highs and lows which were characterised by variable subsidence. In this extensional regime, patterns of variable subsidence within the basin resulted in local successions (e.g. Oil-Shale Group) which bear little resemblance to contemporaneous facies of equivalent age elsewhere in the basin. The Oil-Shale Group was restricted to the 'Edinburgh Basin' where approximately 1800 m of sediment accumulated. Contemporary with this was the development of thick and predominantly fluvio-deltaic sequences in East Fife and the development of a thick lava pile (Clyde Plateau Lavas) to the west. It has been suggested that the lavas hemmed in the Oil-Shale Group basin to the west providing an effective barrier to sedimentation between west and east. Partly after George (1958), Anderton *et al.* (1979) and Rayner (1981). Isopachytes after Goodlet (1957).


HIGHLANDS BLOCK
HIGHLAND BOUNDARY FAULT
N
MIDLAND VALLEY BASIN
St ANDREWS
1200
GLASGOW
900
900
EDINBURGH
1800
0
SOUTHERN UPLANDS FAULT
S. UPLANDS BLOCK
0
25 KM
ISOPACHS (M)
CLYDE PLATEAU LAVAS
OIL-SHALE GROUP
FLUVIO-DELTAICS

[illegible]

[illegible]

Fig.3.3.

Biofacies sketch map, showing decrease in the diversity of faunal assemblages from the Lower Oil-Shale Group MacGregor Marine Bands (Wilson 1974) when traced from east to west. The biofacies were established during one of the rare marine transgressions which penetrated the area during Oil-Shale Group times, and was responsible for the deposition of the Pumpherston Shell Bed and its correlatives (e.g. Cove Marine Bands, East Lothian). The distribution of faunas suggests that open marine conditions lay to the east (where a postulated North Sea Basin was situated, and from which the sporadic incursions emanated), and marine incursions during this period were relatively weak, degenerating into pectinoid-cephalopod beds containing *Lingula* in West Lothian. Partly after Wilson (1974). SQ=South Queensferry. Letters A to F indicate the lines of delineation of the various biofacies.

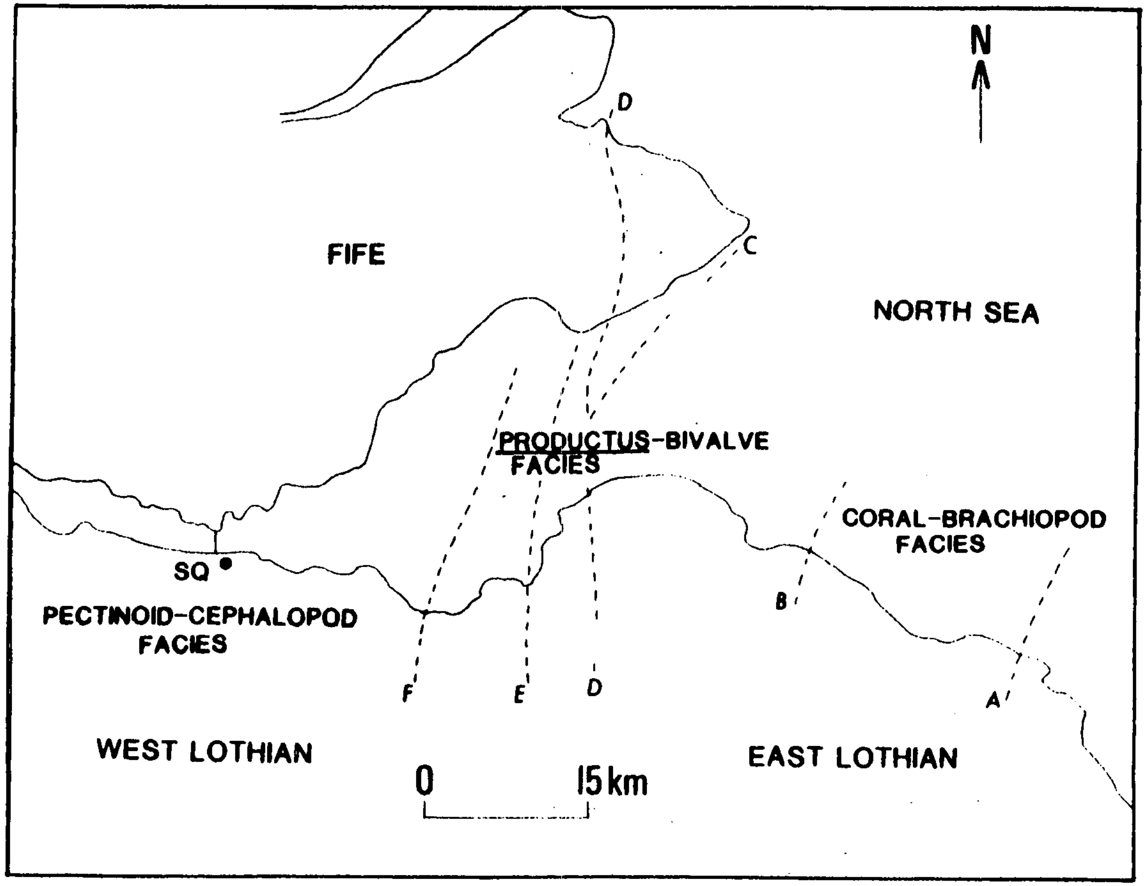

N
FIFE
NORTH SEA
D
C
PRODUCTUS-BIVALVE FACIES
CORAL-BRACHIOPOD FACIES
SQ
PECTINOID-CEPHALOPOD FACIES
B
F
E
D
A
WEST LOTHIAN
EAST LOTHIAN
0
15km

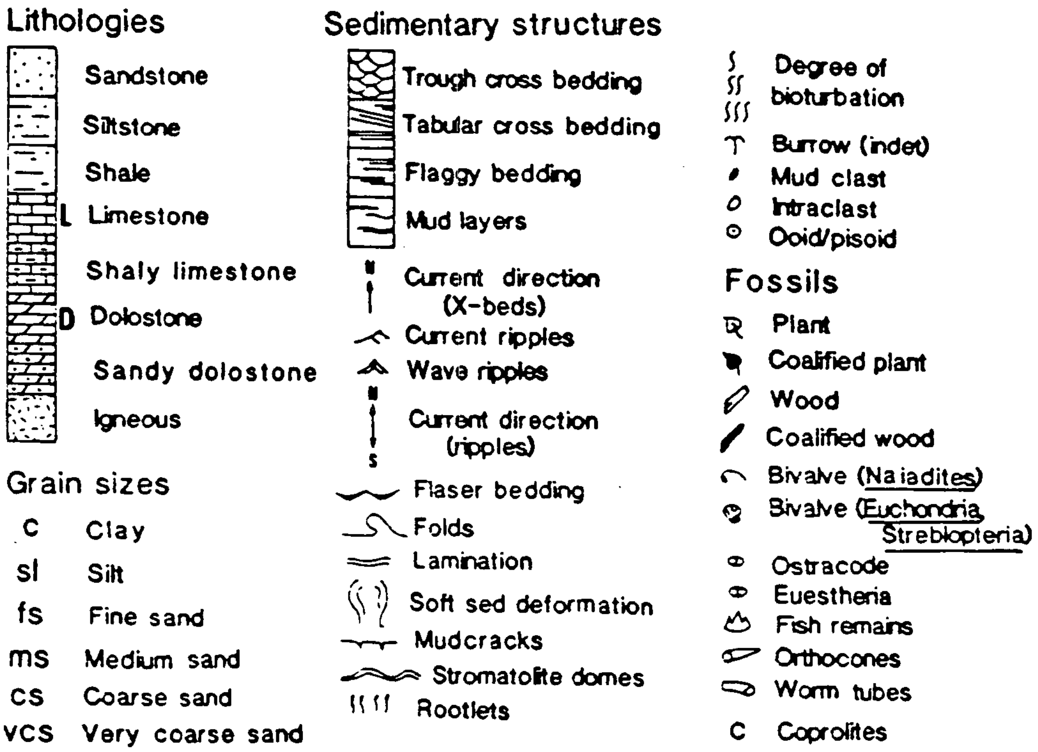
Fig.3.4.

Sumary table showing ideal or idealised cycles/cyclothems/rhythms constructed by past workers for patterns of Oil-Shale Group sedimentation. Partly after Richey (1937), MacGregor (1938), Tulloch and Walton (1958), Greensmith (1962), Francis (1965, 1983a) and Loftus (1985).

RICHEY 1937	MACGREGOR 1938	TULLOCH AND WALTON 1958	GREENSMITH 1962	FRANCIS 1965, 1983a	LOFTUS 1985
Coal	Mudstone	Seat-earth	Shale	Coal	Coal
Fireclay	Limestone	Sandstone	Oil-shale	Seat-earth	Fireclay
Sandstone	Mudstone	Shale (sandy)	Shale	Sandstone	Sandstone
Oil-shale	Mudstone (sandy)	Shale	Limestone	Shale	Siltstone
Shale	Sandstone	Oil-shale	Shale	Oil-shale	Shale
Marine-band	Mudstone	Shale	Marine shale	Shale	Oil-shale
Shale	Oil-shale	Limestone	Shale	Freshwater limestone	Shale
		Shale	Coal seam	Shale	Limestone
		Coal	Gannister	Coal	Shale
			Sandstone		Marine-band
					Shale

Fig. 4.1.

Graphic sedimentary log of the Colinswell sequence which crops out at Burntisland, central Fife. Interpretation of the depositional environments for the main divisions of the succession are also included. The black and white scale bar divisions are=1 m.


Lithologies
Sandstone
Siltstone
Shale
L Limestone
Shaly limestone
D Dolostone
Sandy dolostone
Igneous
Grain sizes
c Clay
sl Silt
fs Fine sand
ms Medium sand
cs Coarse sand
vcs Very coarse sand
Sedimentary structures
Trough cross bedding
Tabular cross bedding
Flaggy bedding
Mud layers
Current direction (X-beds)
Current ripples
Wave ripples
Current direction (ripples)
s
Flaser bedding
Folds
Lamination
Soft sed deformation
Mudcracks
Stromatolite domes
Rootlets
Degree of bioturbation
Burrow (indet)
Mud clast
Intraclast
Ooid/pisoid
Fossils
Plant
Coalified plant
Wood
Coalified wood
Bivalve (Naiadites)
Bivalve (Euchondria, Strebloptera)
Ostracode
Euestheria
Fish remains
Orthocones
Worm tubes
C Coprolites

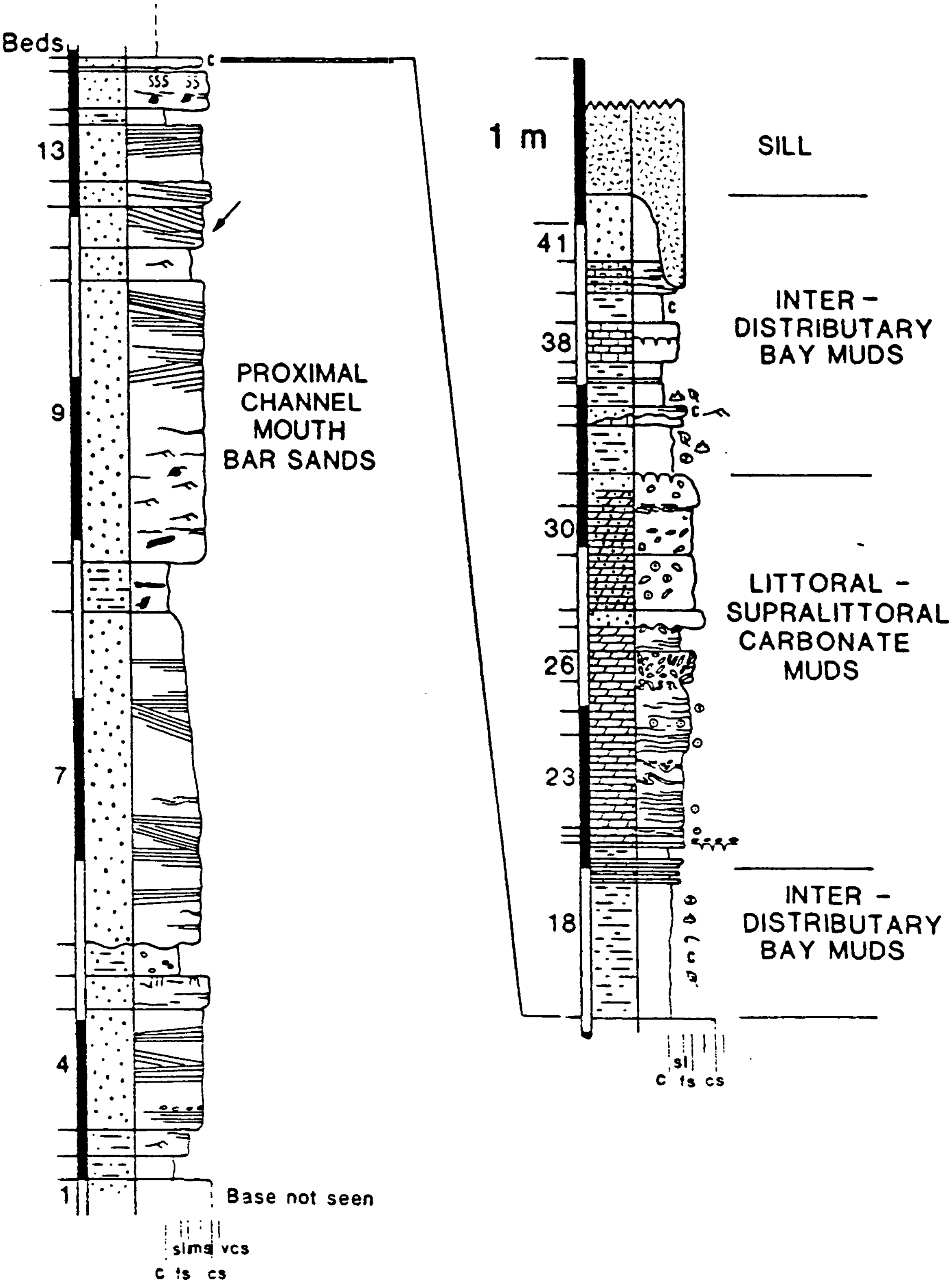

Beds
13
9
7
4
1
c
Base not seen
sl ms vcs
c fs cs
PROXIMAL CHANNEL MOUTH BAR SANDS
1 m
41
38
30
26
23
18
SILL
INTER - DISTRIBUTARY BAY MUDS
LITTORAL - SUPRALITTORAL CARBONATE MUDS
INTER - DISTRIBUTARY BAY MUDS
sl
c fs cs

Fig. 4.2.

A. A 'pocket' of intraclastic breccia (IB), outlined in ink, cutting well-laminated, oolitic-micritic dolostone (OMD). Bed 23, Colinswell, Burntisland. Scale bar=20 cm total.

B. A polished slab of dolostone showing millimetre scale laminae which have been intensely folded and fractured. The fractures are filled with a synsedimentary oolitic matrix (unlabelled arrow). Former open space has been filled by two phases of sediment. The first (G1) is an oomicritic material with a prominent geopetal surface. The second (G2) is a buff-cream coloured dolomicrite which completely fills the cavity. Bed 30, Colinswell, Burntisland. Length of scale bar=50 mm.


2 4 6 8 10 CM
OMD
IB
A

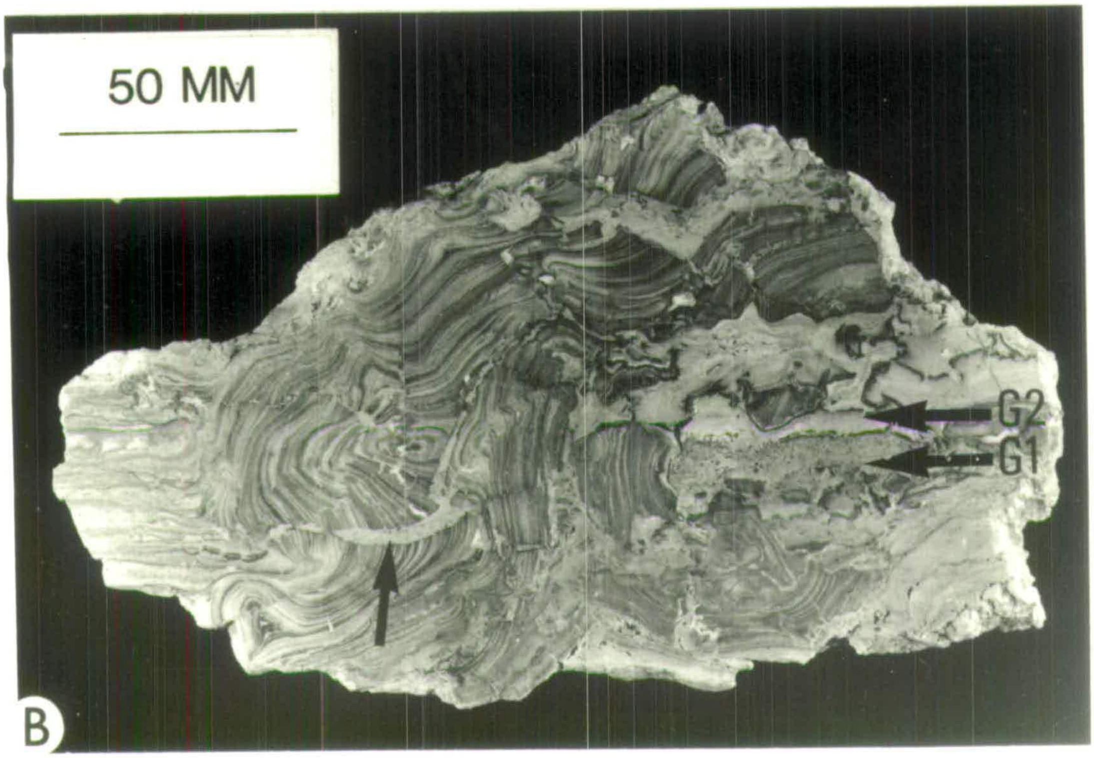

50 MM
G2
G1
B

Fig. 4.3.

A. Tubular structures approximately 20µm wide in a prominent horizon within dolomicritic laminae. The tubes are filled with an ankerite spar cement. The structures are interpreted as the filament moulds of cyanobacteria. The ragged edges to the tubes suggest some degree of dissolution enlargement during dolomitization. Bed 23, Colinswell, Burntisland. Plane polarised light (PPL). Scale: see scale bar.

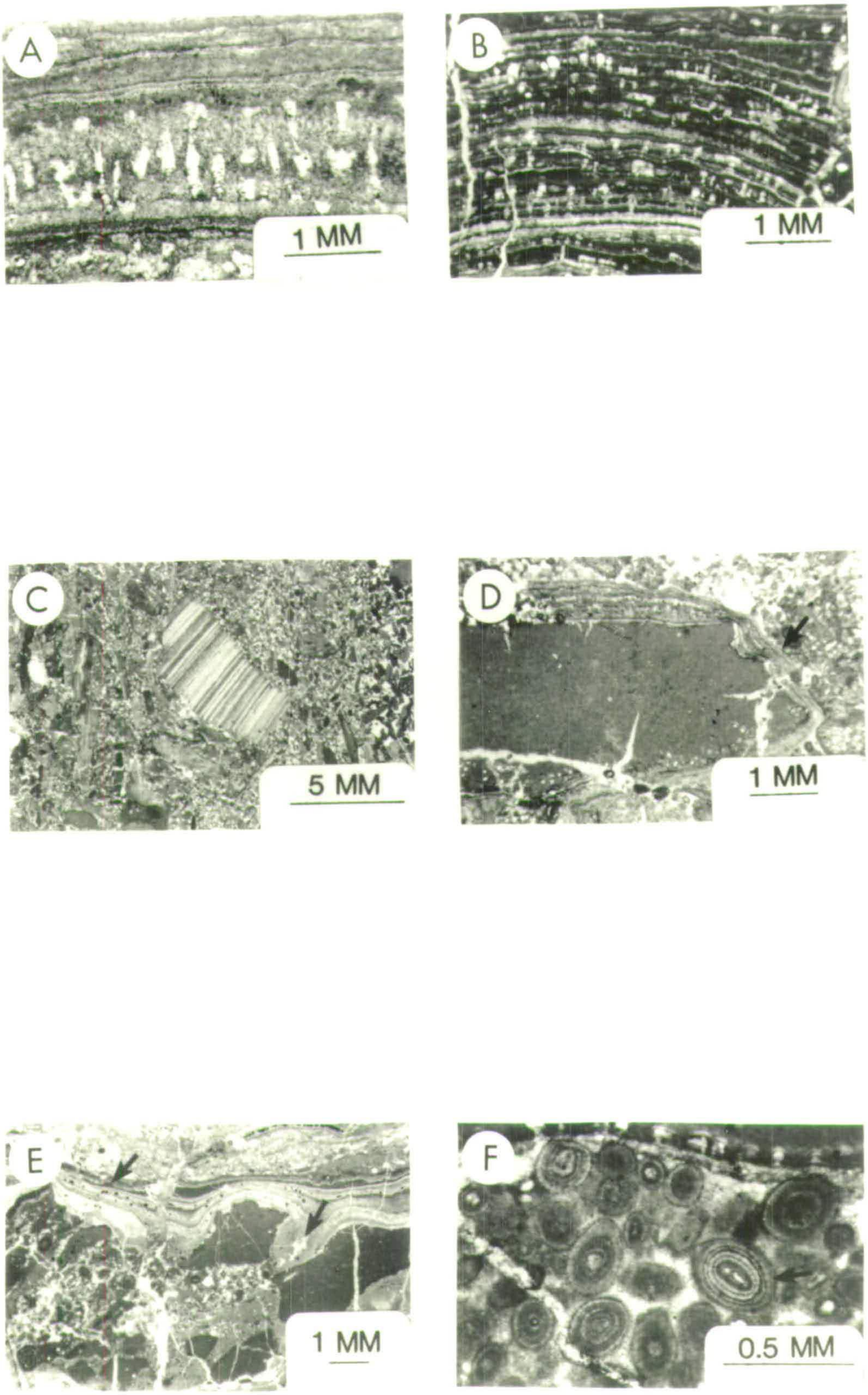
B. Alternating dolosparitic and dolomicritic laminae with distinctive micro-columnar and dome structures. These are interpreted as cryptalgal morphologies. Bed 23, Colinswell, Burntisland. PPL. Scale: scale bar.

C. Intraclast retaining the laminated structure seen in Fig. 4.3 B. The matrix is a sandy intraclast-ooid rich dolomitic packstone. Bed 26, Colinswell, Burntisland. PPL. Scale: see scale bar.

D. Micritic intraclast with tear fractures, now filled by ankerite spar cement. The intraclast has a coating of crinkly laminated microsparite and micritic dolomite (arrow). This material drapes over irregularities on the intraclast surface. It is interpreted as a cryptalgal coating on the intraclast. Toward the left hand side of the photograph this cryptalgal coat has been 'peeled off' the intraclast, probably due to mechanical abrasion. Bed 23, Colinswell, Burntisland. PPL. Scale bar.

E. Micritic intraclasts (dark patches), ooids and sand grains cemented together by a layer of dolomicritic and dolosparitic laminated material (arrow 1) as Fig. 4.2 B. This laminated material drapes into and fills the cavity formed between two intraclasts (arrow 2). The laminated material is a cryptalgal structure which has draped over and recemented the intraclasts. Bed 30, Colinswell, Burntisland. PPL. Scale bar.

F. The majority of the dolomicritic ooids seen here have a micritic cortical structure. Some of the cortical layers in the ooid arrowed retain a radial fabric. The dolomicritic matrix between ooids has been partially altered to neomorphic dolosparite. Bed 23, Colinswell, Burntisland. PPL. Scale: scale bar.


A
1 MM
B
1 MM
C
5 MM
D
1 MM
E
1 MM
F
0.5 MM

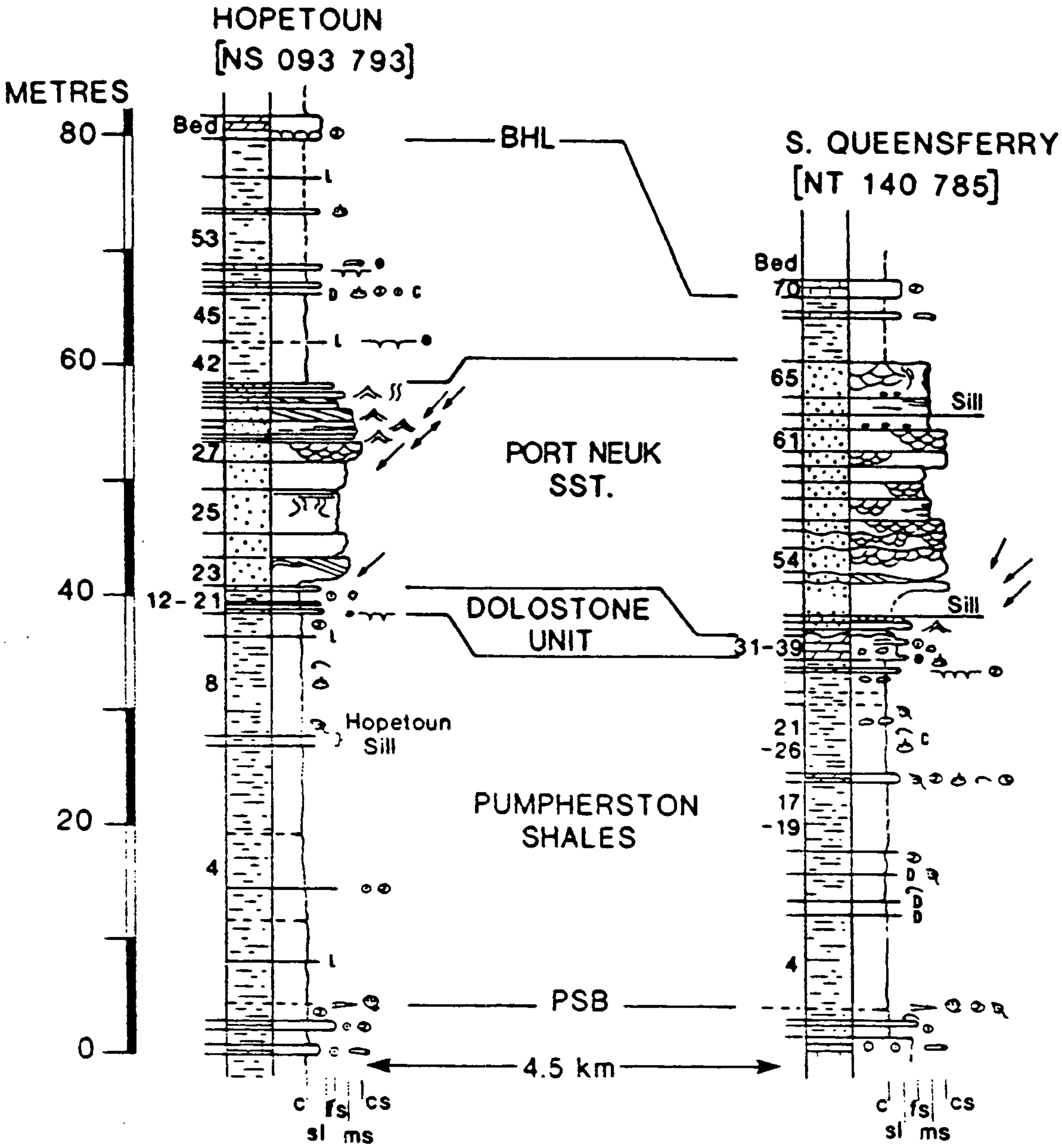

HOPETOUN
[NS 093 793]
METRES
80
60
40
20
0
Bed
53
45
42
27
25
23
12-21
8
4
L
D
C
Hopetoun Sill
BHL
S. QUEENSFERRY
[NT 140 785]
Bed
70
65
Sill
61
PORT NEUK SST.
54
Sill
DOLOSTONE UNIT
31-39
21-26
17-19
4
PUMPHERSTON SHALES
PSB
4.5 km
c sl fs ms cs
c sl fs ms cs

Fig. 4.5.

Details of the graphic sedimentary logs from Hopetoun, South Queensferry and Colinswell using the dolostone unit (DU) as a marker horizon. The Hopetoun and South Queensferry logs include the interval from the upper Pumpherston Shales to the top of the Port Neuk Sandstone (see Fig.4.4). The sandstones below the dolostone unit at Colinswell are not present at South Queensferry or Hopetoun.

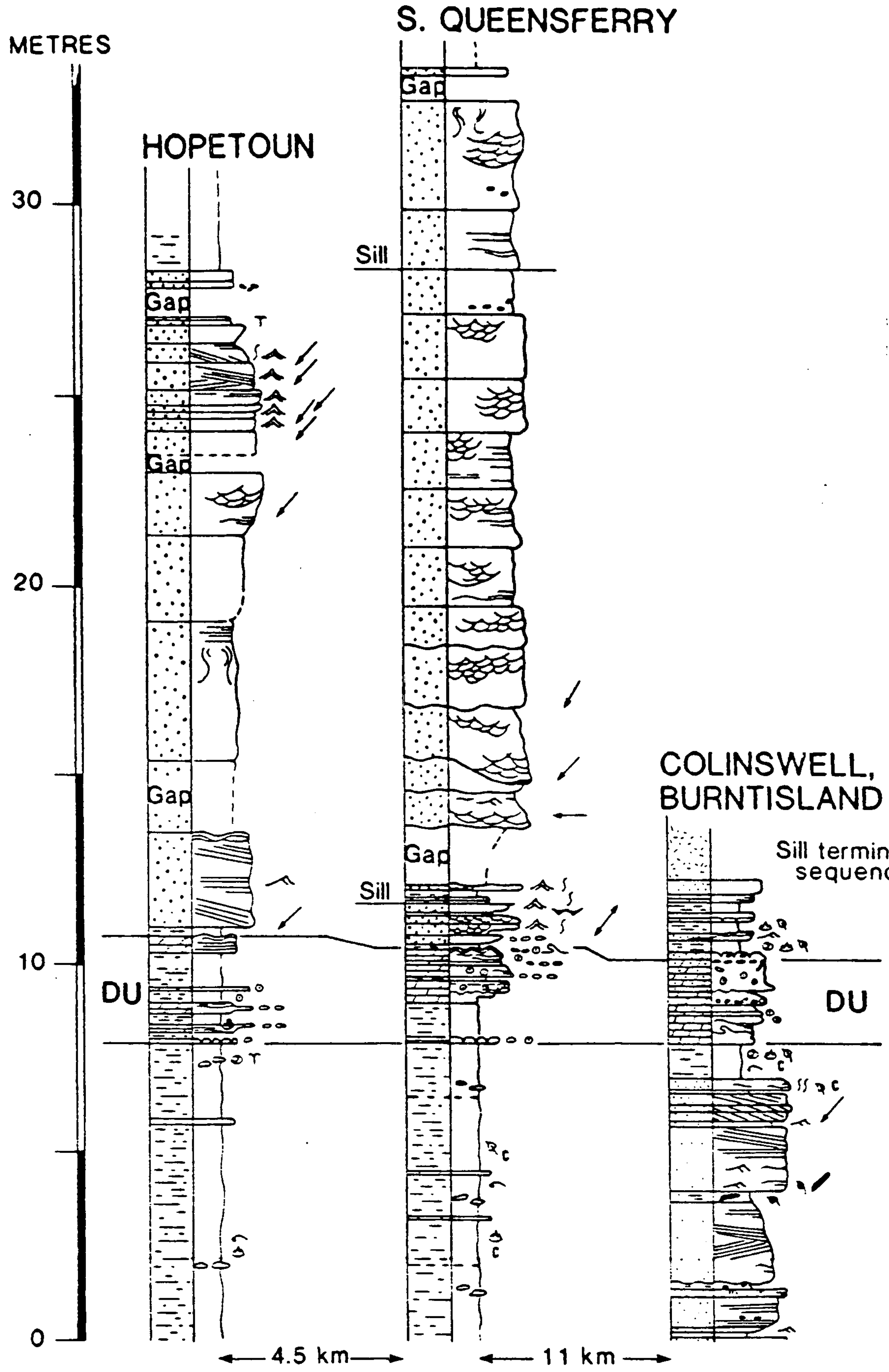
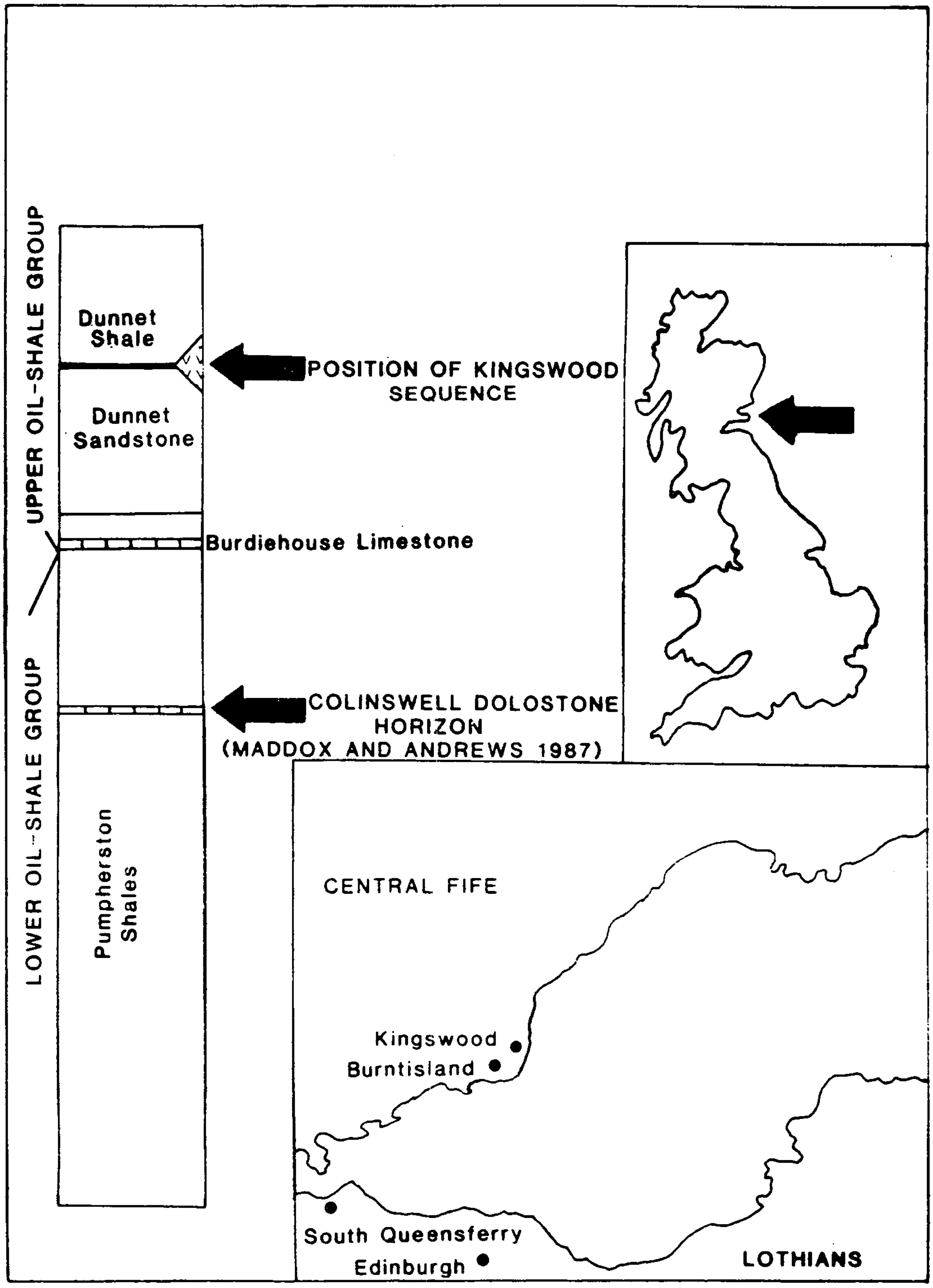

METRES
30
20
10
0
HOPETOUN
Gap
Gap
Gap
DU
S. QUEENSFERRY
Gap
Sill
Sill
Gap
COLINSWELL, BURNTISLAND
Sill terminate sequence
DU
4.5 km
11 km

Fig.5.1.

Diagram showing location of the Kingswood sequence in relation to the general Fife and Lothians area flanking the Firth of Forth. The block-column stratigraphical diagram highlights the position of the Kingswood sequence in relation to the main horizons at the top of the Lower, and bottom of the Upper Oil-Shale groups.


UPPER OIL-SHALE GROUP
LOWER OIL-SHALE GROUP
Dunnet Shale
Dunnet Sandstone
Burdiehouse Limestone
Pumpherston Shales
POSITION OF KINGSWOOD SEQUENCE
COLINSWELL DOLOSTONE HORIZON
(MADDOX AND ANDREWS 1987)
CENTRAL FIFE
Kingswood
Burntisland
South Queensferry
Edinburgh
LOTHIANS

KINGSWOOD END

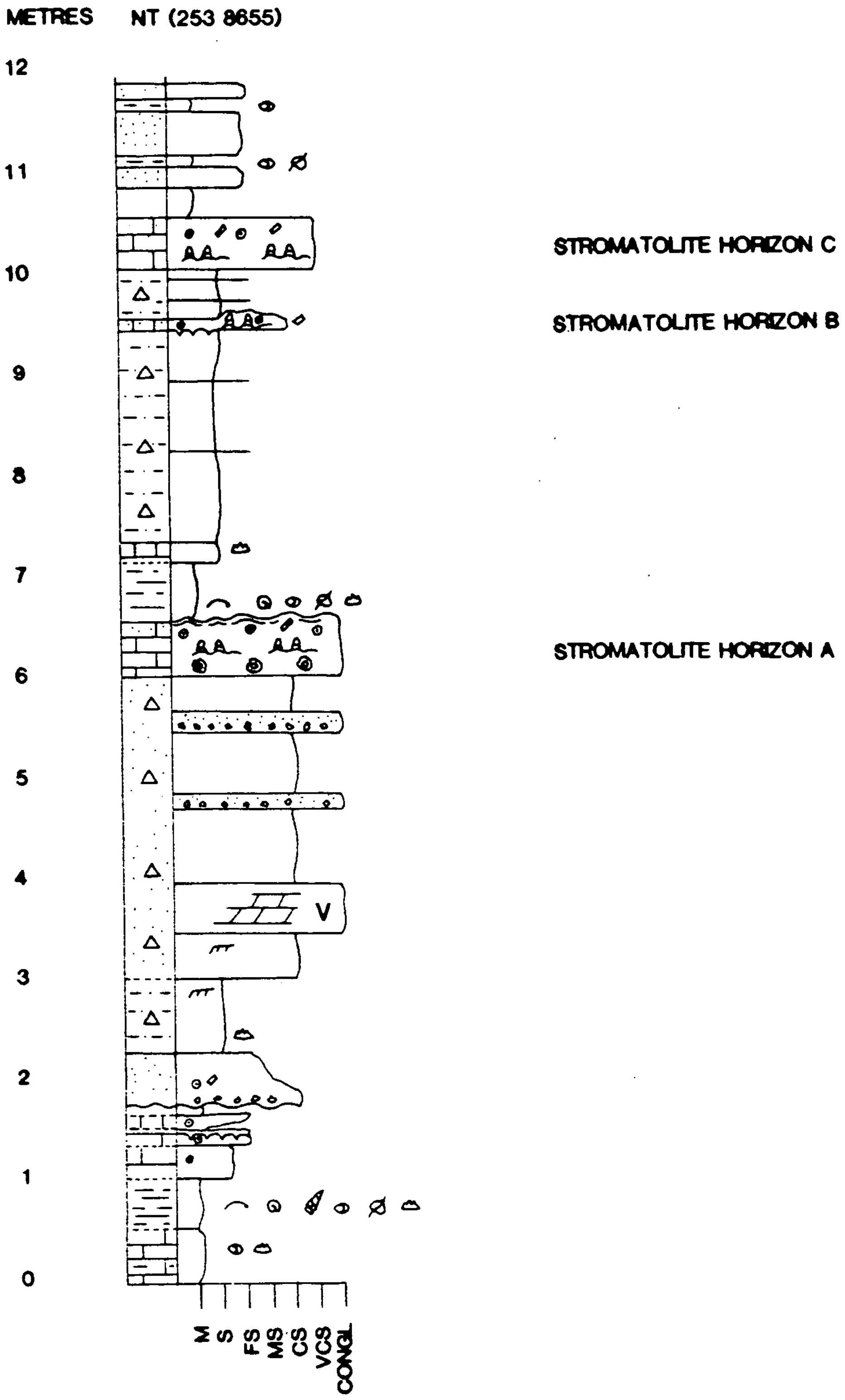
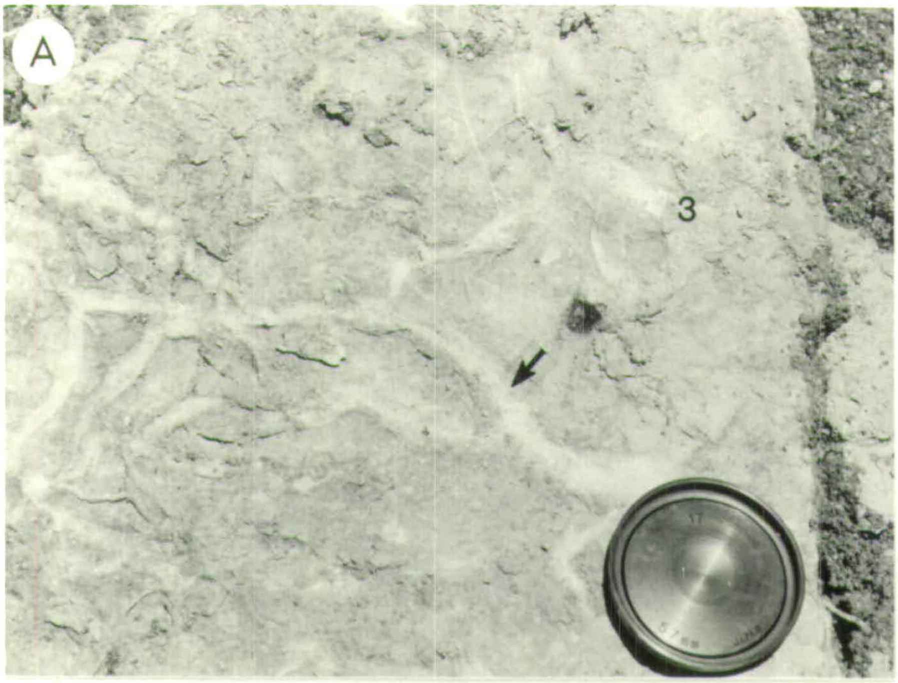


Fig.5.3.

A. Desiccation cracked lower bedding plane surface of desiccation cracked horizon at the top of bed 3 (as labelled). Desiccation cracks (arrowed) are infilled with a light coloured, coarse-grained (fine sand grade) oopelsparitic (grainstone to packstone) 'carbonate sand'. This is in contrast to the fine-grained (mud grade) micritic groundmass forming bed 3. The surface of bed 3 is covered in mud, obscuring the majority of the desiccation cracks. Scale: camera lens cap, diameter=6 cm.

B. Lowermost part of the sequence exposed in the cliffs flanking the Kingswood Hotel. Numbers 1 to 4 refer to beds 1 to 4. Arrow points to desiccation cracked upper part of bed 3, illustrated in Fig.5.3A, above. This part of the sequence consists of interbedded micritic banded limestones and laminated organic-rich mudrocks. The temporary section (in which the geological hammer is resting) was excavated by pick and shovel, to compensate for poor exposure. Scale: geological hammer, length=59 cm.


A
3


B
4
3
2
1

✓

Fig.5.4.

A. Large slab (field sample) of the lower bedding surface of the desiccation cracked horizon at the top of bed 3. Abundant, upstanding, desiccation cracks, which are slightly lighter in colour than the finer-grained groundmass are present, and these are infilled by coarse (fine sand grade) carbonate grainstones. The desiccation cracks are profuse and pervasive, forming a sub-regular pattern, which is occasionally polygonal (arrowed). A second generation of smaller, finer cracks are also present, as well as the larger and dominant first generation structures (arrowed). Scale: scale bar, length=0.04 m.

B. Cross-section through a block (field sample) of the desiccation cracked horizon at the top of bed 3 which has been cut, ground and polished. Irregular shaped desiccation cracks (arrow 2) are present which are infilled by a lighter coloured, coarser-grained packstone (a), in contrast to the finer-grained, darker, micritic groundmass (b) of bed 3. The widths of the cracks also vary considerably. Arrow 1 denotes the younging direction (points toward the upper bedding surface of bed 3). Scale: scale bar, length=4 cm.

B

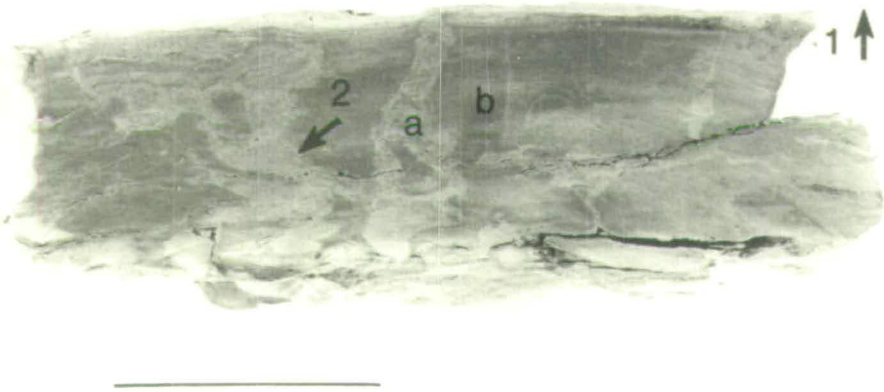
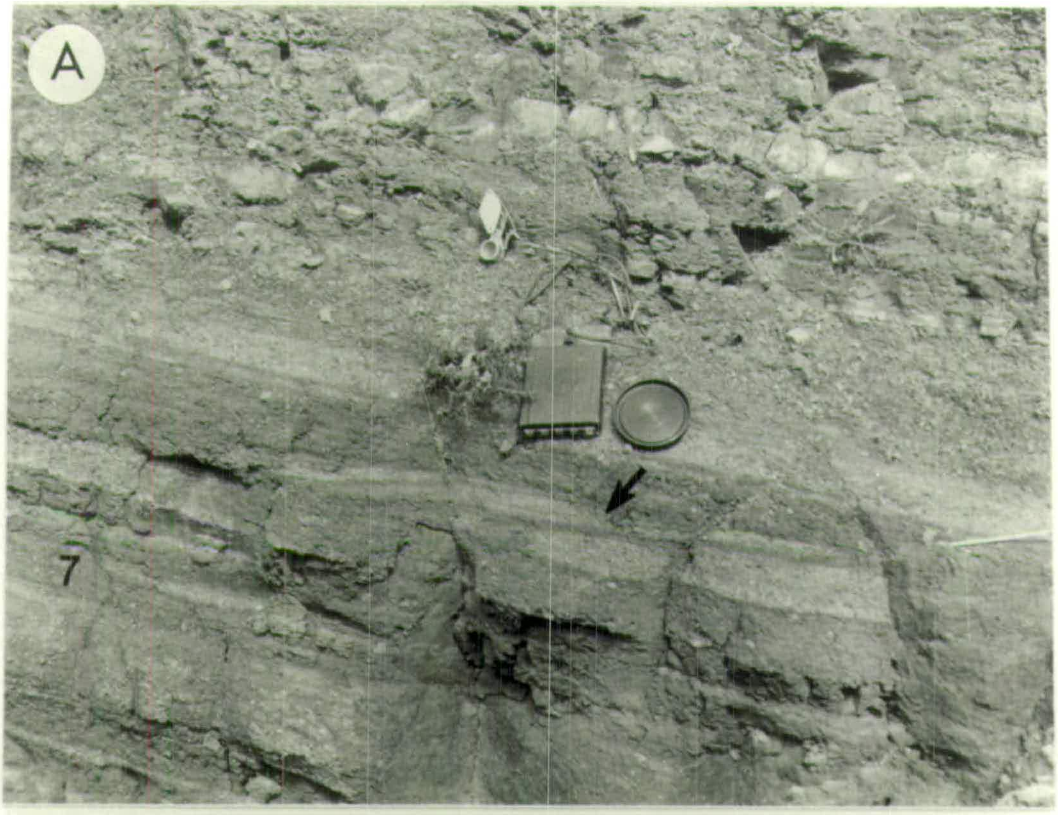


Fig.5.5.A.

View of planar/tabular cross-bedding in 3 m thick volcaniclastic unit (bed 7-labelled). The inclined foresets (arrowed) are mud-draped, and the coarser-grained (light coloured) bands are intercalated with finer-grained (darker) horizons. Scale: camera lens cap, diameter=6 cm.

B. Volcanic bomb (arrowed) lying within an impact created 'sag pit', in the middle part of bed 7 (labelled). Scale: geological compass-clinometer, length=10 cm.


A
7

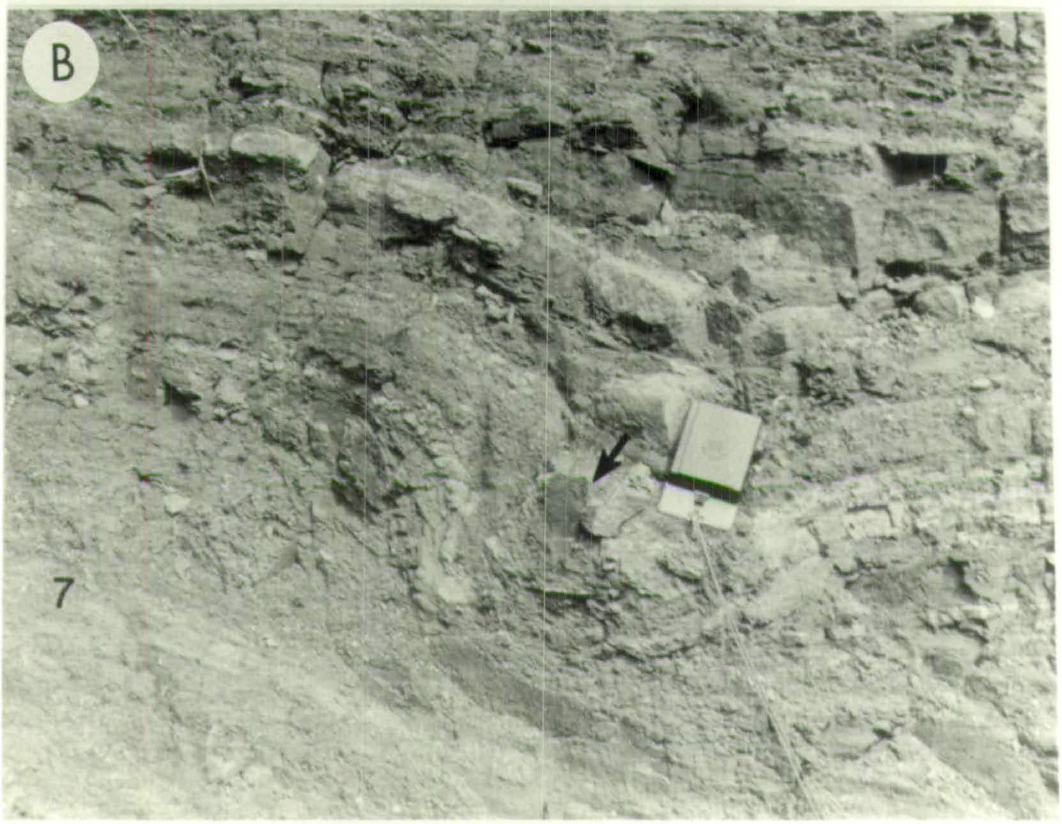
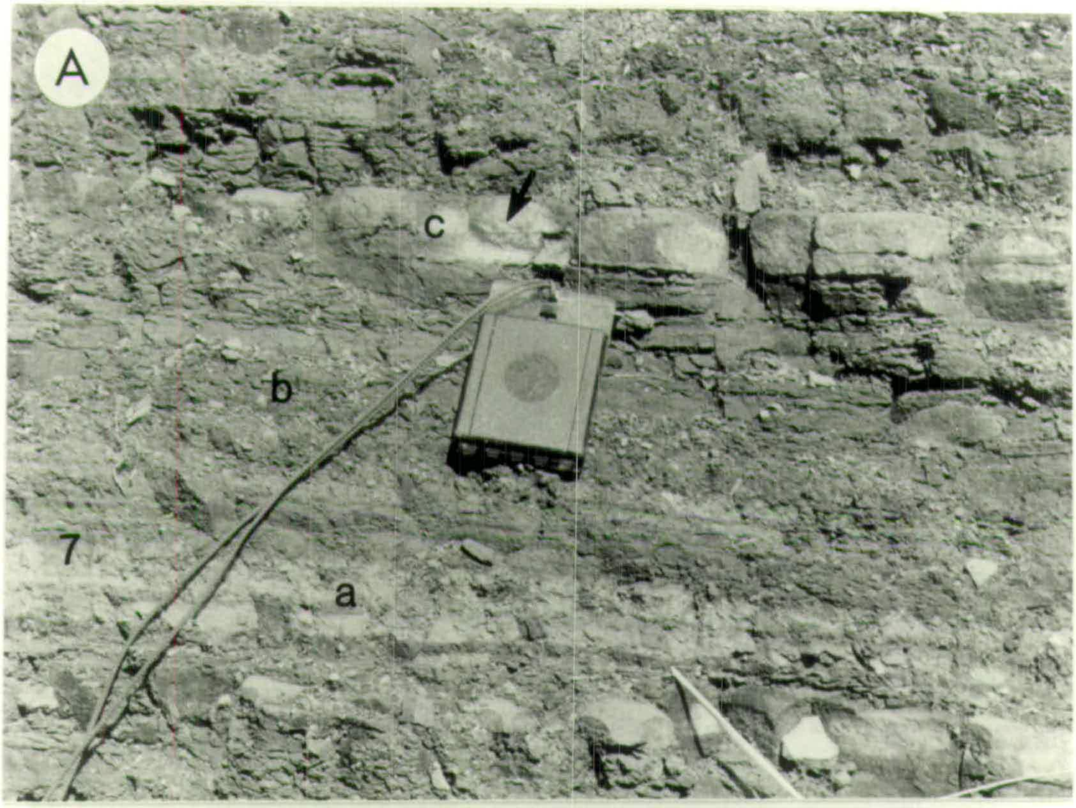

B
7

Fig.5.6.

A. Close-up view of bed 7 (3 m thick volcaniclastic unit) showing intercalation of coarse-grained lithic tuffs (a), finer-grained silty shales (b), and concretionary 'limestone' bands (c-arrowed). The coarse lithic tuffs are normally graded and fine-upwards. Scale: geological compass-clinometer, length=10 cm.

B. Close-up view of 3 m thick volcaniclastic unit (bed 7) showing coarse-grained lithic tuff bands (a) containing large lithic clasts (arrowed). The tuffs are poorly sorted, and the coarse-grained bands have sharp contacts. The coarser-grained beds are intercalated with darker, finer-grained shaly tuffs (b). Scale: geological compass-clinometer, length=10 cm.


A
c
b
7
a


B
b
7
a

Fig. 5.7.

A. Uppermost part of the sequence exposed in the cliffs flanking the Kingswood Hotel. Numbers 14 to 20 refer to beds 14 to 20. Bed 14 in the foreground is the topmost stromatolitic limestone capping the tuffaceous siltstones and sandstones of bed 13. Beds 15 to 20 are interbedded mudrocks and sandstones. The mudrocks are weathered into recessions whereas the sandstones form more prominently featured beds. Scale: geological compass-clinometer (arrowed), length=10 cm.

B. Fresh (recently fractured) cross-sectional surface of topmost stromatolitic limestone (bed 14). The successive bands of laterally-linked hemispheroid-type stromatolitic domes (arrowed) within the lower part of the bed are strikingly conspicious. The LLH-type domes are not clearly visible on weathered surfaces. The upper part of the bed is composed largely of oopelbiosparitic grainstones and packstones. Scale: compass-clinometer, length=0.10 m.


A
20
19
18
17
16
15
14


B
14

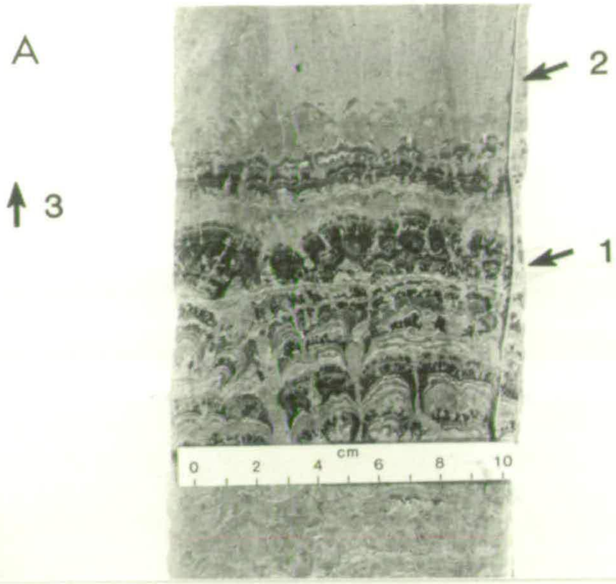
Fig.5.8.

A. Close-up view of the upper part of bed 14 (uppermost stromatolitic horizon). The stromatolitic horizon (arrow 1) shows accreting domes displaying successive detachments and reattachments with neighbouring domes. Arrow 2 points to the grainstone cap of bed 14. Arrow 3 denotes way-up. Scale: scale indicator, length=10 cm.

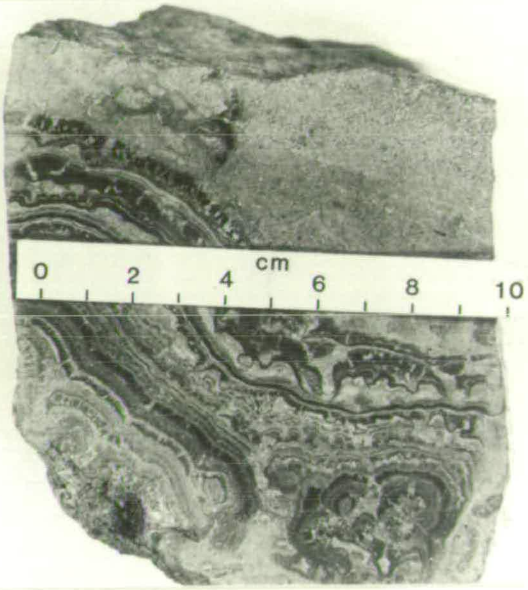
B. Close-up view of the lowermost stromatolitic unit (bed 8). A well-laminated cryptalgal fabric is present, where LLH-type domes are intercalated with planar to undulose laminae. Oncoid-type, concentrically laminated spheroidal structures are present in the lower part and the stromatolitic structures are overlain by a grainstone cap composed of coated grains. Scale: scale indicator, length=10 cm.

C. Oncoid lag-type horizon at the base of bed 8, capping the volcaniclastic unit (bed 7), containing oncoids which have tuffaceous nuclei. An undulose laminated fabric is also present, particularly towards the top of the specimen. Scale: scale indicator, length=10 cm.

A



B



C

Fig.5.9.

Cut, ground and polished slabs of the lowermost stromatolitic unit (bed 8) from Kingswood End.

A. Upper part of bed 8. The bed is composed of successive layers of laterally-linked hemispheroids. The stromatolitic domes (or hemispheroids) are internally laminated, and the laminae are often wavy. The stromatolitic cryptalgal laminae are often colour banded and are intercalated with coated grain-rich horizons. The top of the bed contains reworked cryptalgal laminae and is non-stromatolitic. Scale: pen top, length=3.5 cm.

B. Middle part of bed 8 (see A, above), showing well-laminated cryptalgal fabric, with undulose laminae forming successive layers of small- and large-scale laterally linked hemispheroids. These are intercalated with coated grain-rich laminae. Some of the laminae are planar to only slightly undulose laminated, and a prominent oncolite is present within one of the coated grain-rich horizons. Scale: pen top, length=3.5 cm.

C. Lower part of bed 8 (see A and B, above) displaying large oncolite structures consisting of concentrically laminated spheroidal structures with coarse-grained tuffaceous nuclei/cores. The concentric laminae are planar to undulose, and some of the outer laminae form laterally linked hemispherical structures. Scale: pen top, length=3.5 cm.

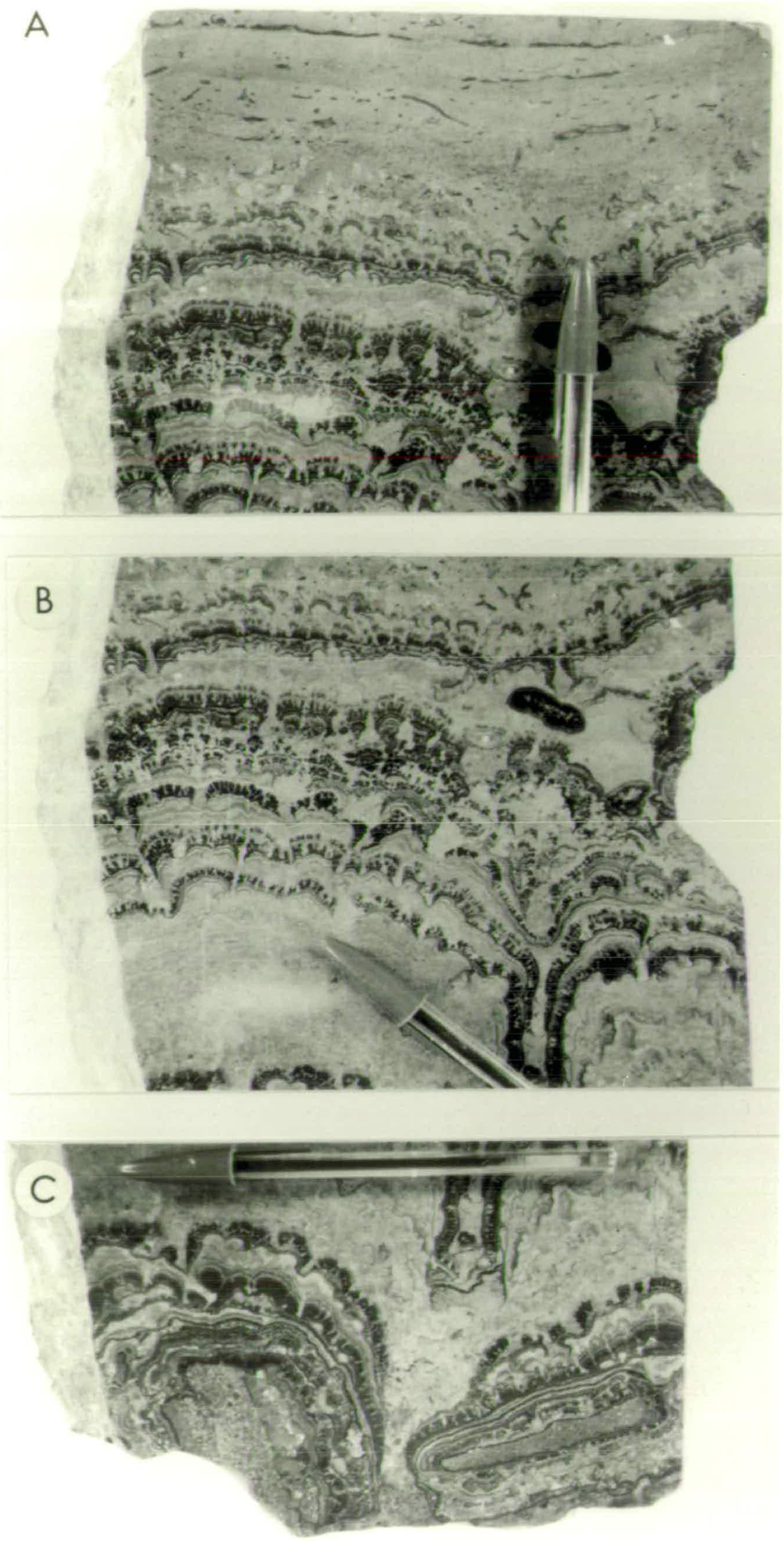
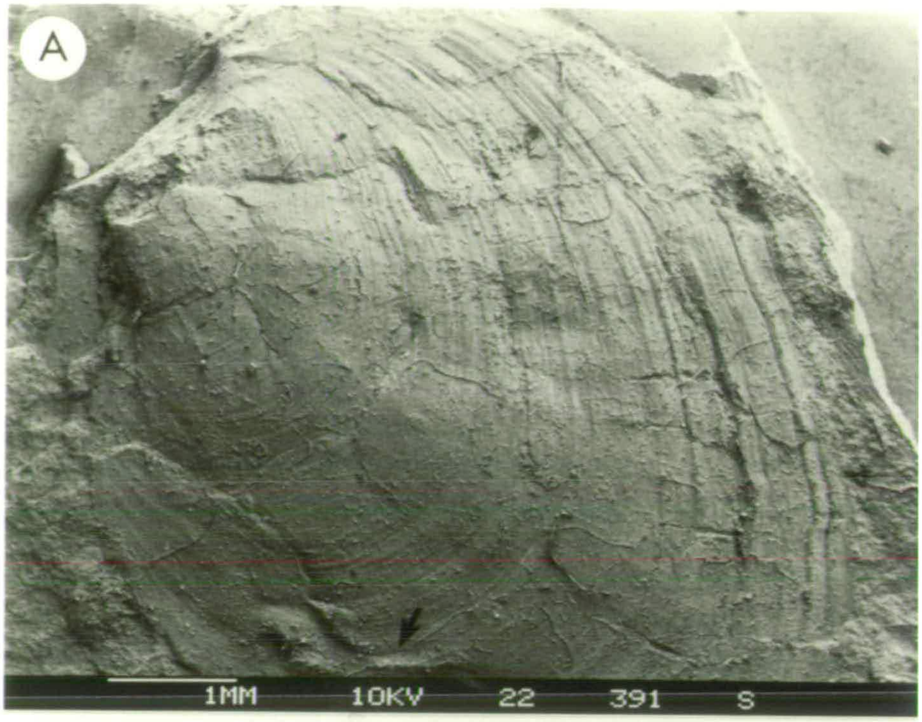

A
B
C

Fig.5.10.

A. Scanning electron photomicrograph of an exterior view of a right valve of the non-marine bivalve, *Curvirimula scotica* (R. Etheridge jun.) preserved upon a parting plane within bed 2, which is a dark, laminated, crudely fissile, organic-rich mudrock. *C. scotica* is a small, suborbicular or rotund-ovate *Curvirimula*, possessing a smoothly curved outline. The anterior margin merges without definition of anterior lobe into the uninterrupted arc of the ventral, postero-ventral and posterior margins. Distinctive growth lines occur and an encrusting spirorbid worm tube (arrowed) near the antero-ventral margin of the valve is present. Scale: scale bar, length=1 mm.

B. Scanning electron photomicrograph illustrating a closer view of a spirorbid worm tube (arrowed) attached to the exterior surface of the left valve of a specimen of *C. scotica*, as seen above (A). The worm tube has a planispiral form, and is referred to the species *Spirorbis pusillus*. Scale: scale bar, length=1 mm.

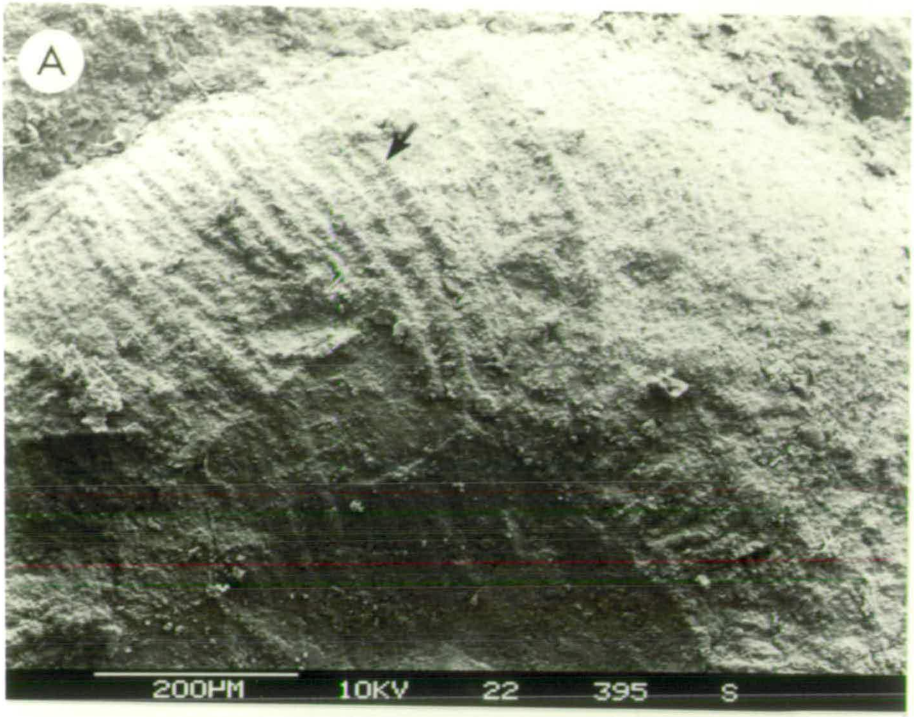

A
1MM
10KV
22
391
S


B
1MM
10KV
22
389
S

Fig.5.11.

A. Scanning electron photomicrograph, showing close-up view of the exterior surface ornamentation of the shell of a spirorbid worm tube described below (B). Distinct, upstanding rib structures (arrowed) are present, some of which appear to bifurcate. Scale: scale bar, length=200μm.

B. Scanning electron photomicrograph, showing a spirorbid worm tube, referred to the species *Spirorbis pusillus*. This specimen was recovered from a parting plane surface of an organic rich mudrock (bed 2), and was preserved, unattached, upon the sediment substrate. The tube has a planispiral form, and is characterised by distinct ribs (arrow 1) upon the exterior surface of the shell. Partially crushed ostracodes (arrow 2) are also present, as are fragments of the valves (arrow 3) of the non-marine bivalve *C. scotica*. Scale: scale bar=400μm.


A
200µM
10KV
22
395
S

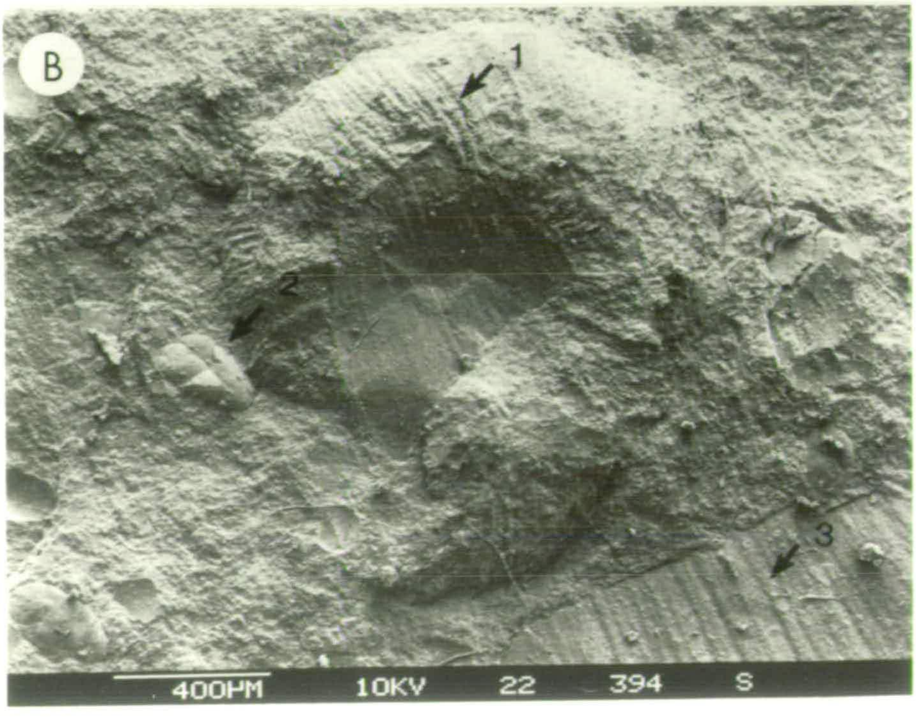

B
1
2
3
400µM
10KV
22
394
S

Fig.5.12.

A. Scanning electron photomicrograph of a gastropod, preserved upon a parting plane surface within bed 2. This specimen is tentatively referred to the species *Platyostomella scotoburdigalensis* (R. Etheridge jun.). Scale: scale bar, length=400µm.

B. Scanning electron photomicrograph of an ostracode, preserved upon a parting plane surface within bed 2. This specimen is externally ornamented, the exterior surface of the valve possessing a coarse, pitted appearance (arrowed). Scale: scale bar, length=200µm.


A
400µM 10KV 22 393 S

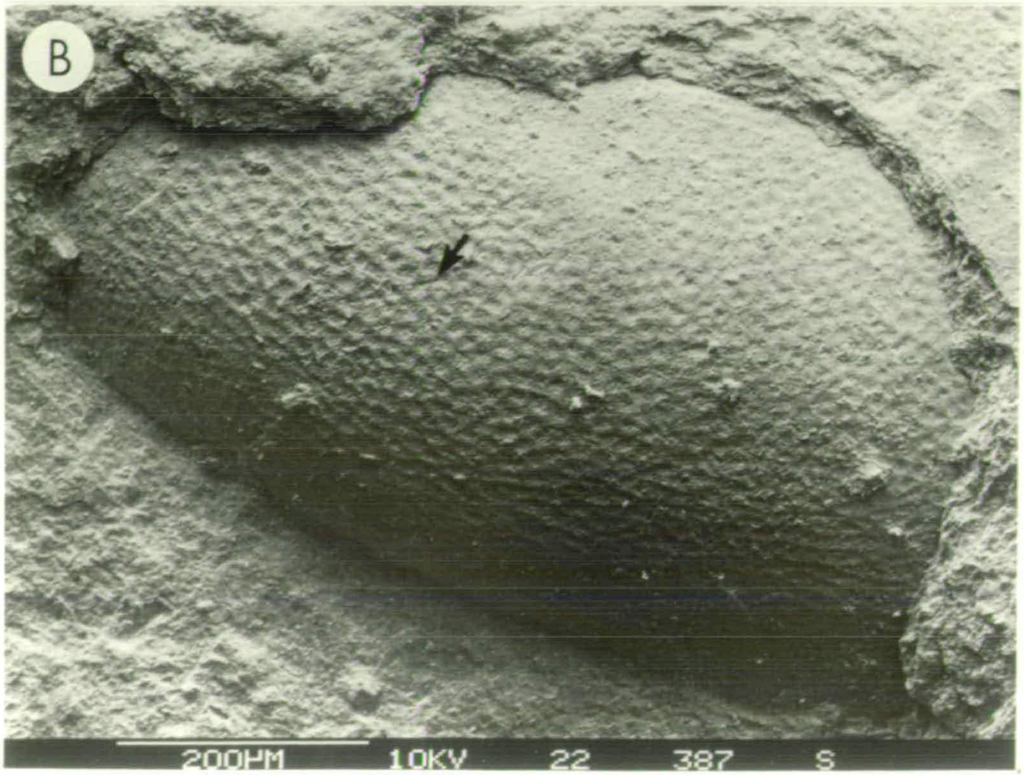
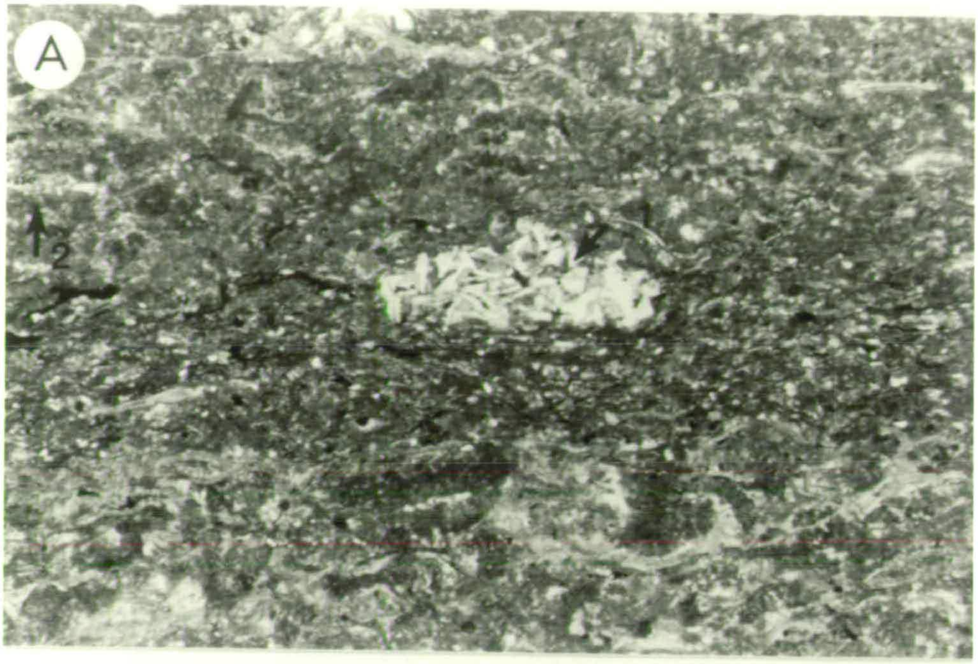

B
200µM 10KV 22 387 S

Fig.5.13.

A. Thin section photomicrograph of bed 10 (plane polarised light). This bed is composed of many thin, shelly laminae, which alternate with non-shelly laminae. The shelly laminae are largely composed of ostracode and bivalve valves. A distinctive coprolite (arrow 1) is present within a non-shelly lamina. This is a faecal pellet, composed of the remains of fish (largely phosphatic scales, teeth and spines). Abundant silt-sized quartz grains and cuticular pyrite strands occur. Arrow 2 denotes the younging direction (points toward the upper bounding surface of bed 10). Scale: horizontal field of view=8 mm.

B. Thin section photomicrograph of bed 10 (plane polarised light). A diamond-shaped, phosphatic, paleoniscoid fish scale is present (arrow 1) within a shelly lamina, rich in bivalve and ostracode valves (arrow 2). Arrow 3 denotes younging direction (points toward upper bounding surface of bed 10). Scale: horizontal field of view=4 mm.


A
1
2

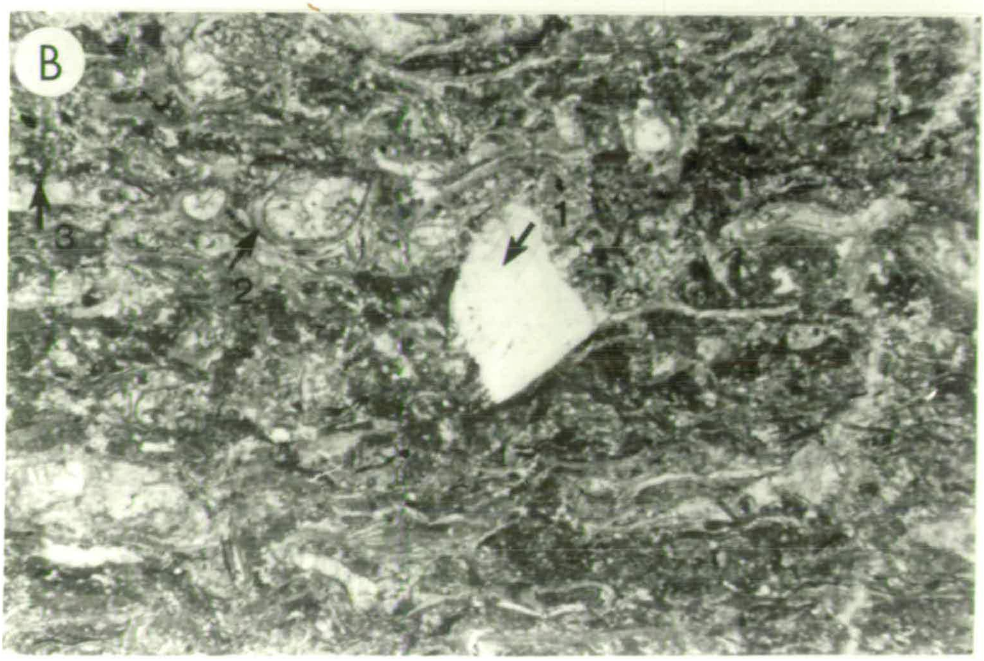
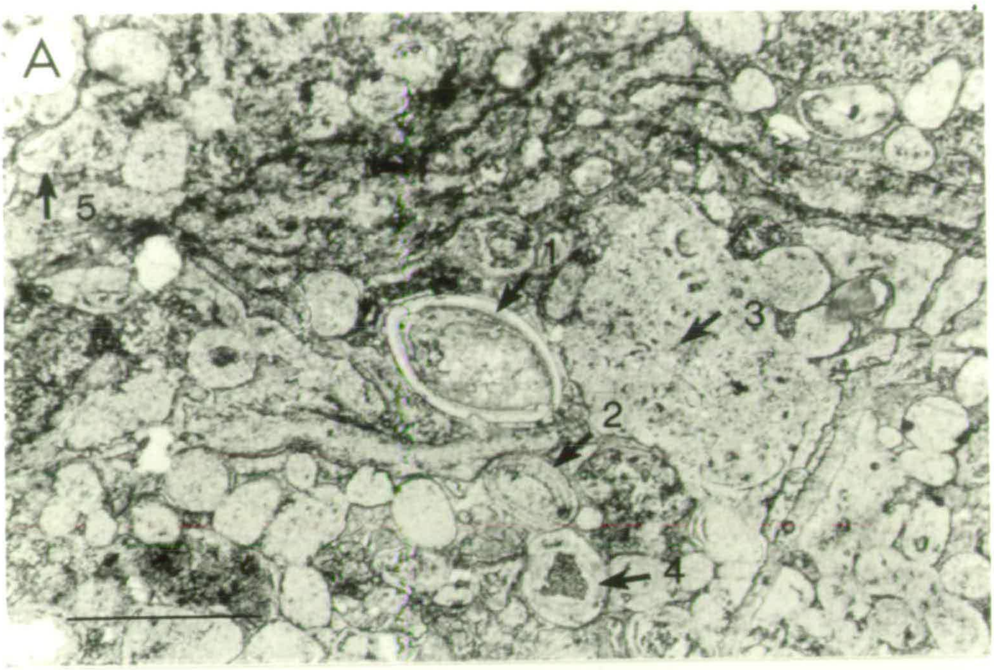

B
1
2
3

Fig.5.14.

A. Photomicrograph of stained acetate peel of the upper part of bed 12, illustrating the predominantly grainstone fabric. Bed 12 contains diminutive laterally linked hemispheroid (LLH)-type stromatolitic domes, which directly overlie a desiccation cracked surface, marking the base of the bed. The LLH-type domes are restricted to the basal part of the bed, which is composed of predominantly oopelbiosparitic grainstone fabrics. Bioclasts are present (articulated ostracode (arrow 1)), as are coated grains possessing concentrically laminated coatings (arrow 2), and coated grains with amorphous coats (arrow 4) of cryptocrystalline, dense, dark-coloured micrite. Large (greater than 1 mm) lithic clasts, however, are also present (arrow 3). Coated grains predominate, which are very closely packed, and are largely well-rounded. Arrow 5 denotes the younging direction (points toward the upper bounding surface of bed 12). Scale: scale bar, length=1 mm.

B. Photomicrograph of stained acetate peel of the upper part of bed 12. The rock is an oopelbiosparitic grainstone. A spirorbid worm tube (arrow 1) is present, longitudinally sectioned, displaying characteristically rounded to ovoid shaped chambers. The worm tube is upside down, and the ventral surface is characteristically planar. Scale: scale bar, length=1.5 mm.


A
5
1
3
2
4

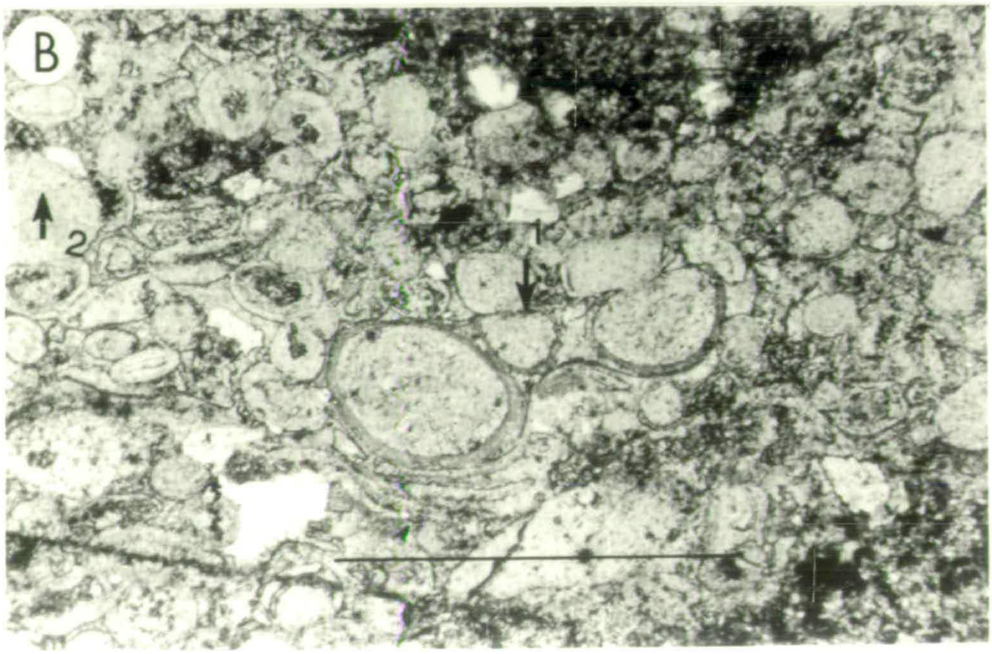
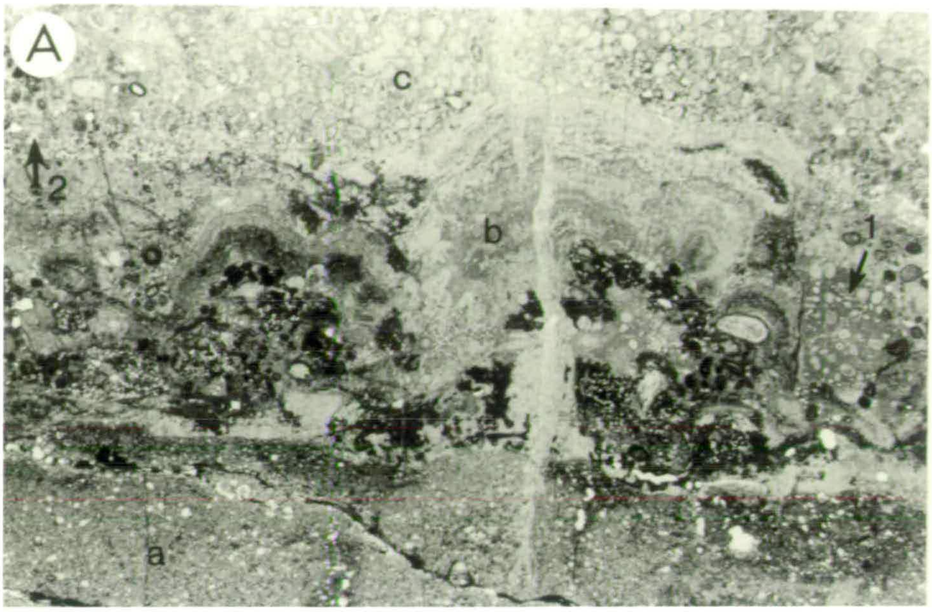

B
2
1

Fig.5.15.

A. Photomicrograph of a stained acetate peel of the basal part of bed 12 (middle stromatolitic bed). At the base of bed 12, diminutive LLH-type stromatolitic domes (b) overlie a distinctive, desiccation cracked tuffaceous siltstone (a) (underlying bed 11). The desiccation cracked tuffaceous siltstone is generally fine-grained (mud grade), but contains silt-sized quartz grains. In contrast, the desiccation cracks are infilled by coarse-grained (fine sand grade) oopelsparitic grainstones. The stromatolitic dome structures (b) emanate from the desiccation cracked surface and consist of small domes which are laterally linked. The inter-dome areas (arrow 1) are often filled with sediment characterised by coarse grainstone fabrics. The stromatolitic horizon is overlain by coarse oopelsparitic and oopelbiosparitic grainstone fabrics. Arrow 2 denotes younging direction (points toward upper bounding surface of bed 12). Scale: horizontal field of view=1.5 cm.

B. Photomicrograph of stained acetate peel of basal part of bed 12, illustrating a close-up view of two small stromatolitic domes (a and b). Domes a and b are composed of successive layers of smaller domes which are laterally linked (arrow 3), but which are also occasionally incised (arrow 5). Silt to fine sand sized coated grains have been incorporated into the stromatolitic structure (arrow 2) and subsequently 'roofed over' by further generations of algal/cryptalgal growth. The interdome area between domes a and b has been infilled by a large clast (arrow 4), which has been incorporated into the structure, and subsequently draped by laminae to form another small dome (c), between domes a and b. Arrow 1 points to a vein which along with another vein cuts across the interdome area and passes into the overlying grainstone fabric. These veins contain ferroan calcite and appear to have acted as conduits for the introduction of a late blocky, ferroan-calcite spar, which is a feature of the diagenetic history of the grainstones. The stromatolitic horizon is overlain by a coarse grainstone, which is moderately well-sorted, but contains occasional large clasts (arrow 6), which were probably derived from the underlying, basal desiccation cracked horizon. Arrow 7 denotes younging direction (points toward the upper bounding surface of bed 12). Scale: horizontal field of view=6 mm.


A
c
2
b
1
a


B
7
6
c
4
a
5
b
1
2
3

Fig.5.16.

A. The entrance to the Newbigging Mine, Burntisland. The mine entrance cuts through the horizon of the Burdiehouse Limestone, which is overlain by deltaic sandstones. The sandstone beds pinch out in a manner suggestive of channelling or lateral accretion. Scale: mine entrance is approximately 5-6 m in height.

B. Cut, ground and polished block of the Burdiehouse Limestone from the Newbigging Mine, Burntisland (see A, above). A well developed banding is conspicious. Scale: two pence coin, diameter=2.5 cm.

C. 'Cut-and-fill' channel structure in the Dunnet Sandstone (above the Burdiehouse Limestone), as exposed in the Dalachy Quarry, Burntisland. The channel base is mud-draped, suggesting initial abandonment. Scale: geological hammer, length=40 cm.

D. Trough cross-bedded Dunnet Sandstone cropping out below the Forth Railway Bridge on the southern shore of the Firth of Forth at South Queensferry, West Lothian. Scale: geological hammer, length=40 cm.

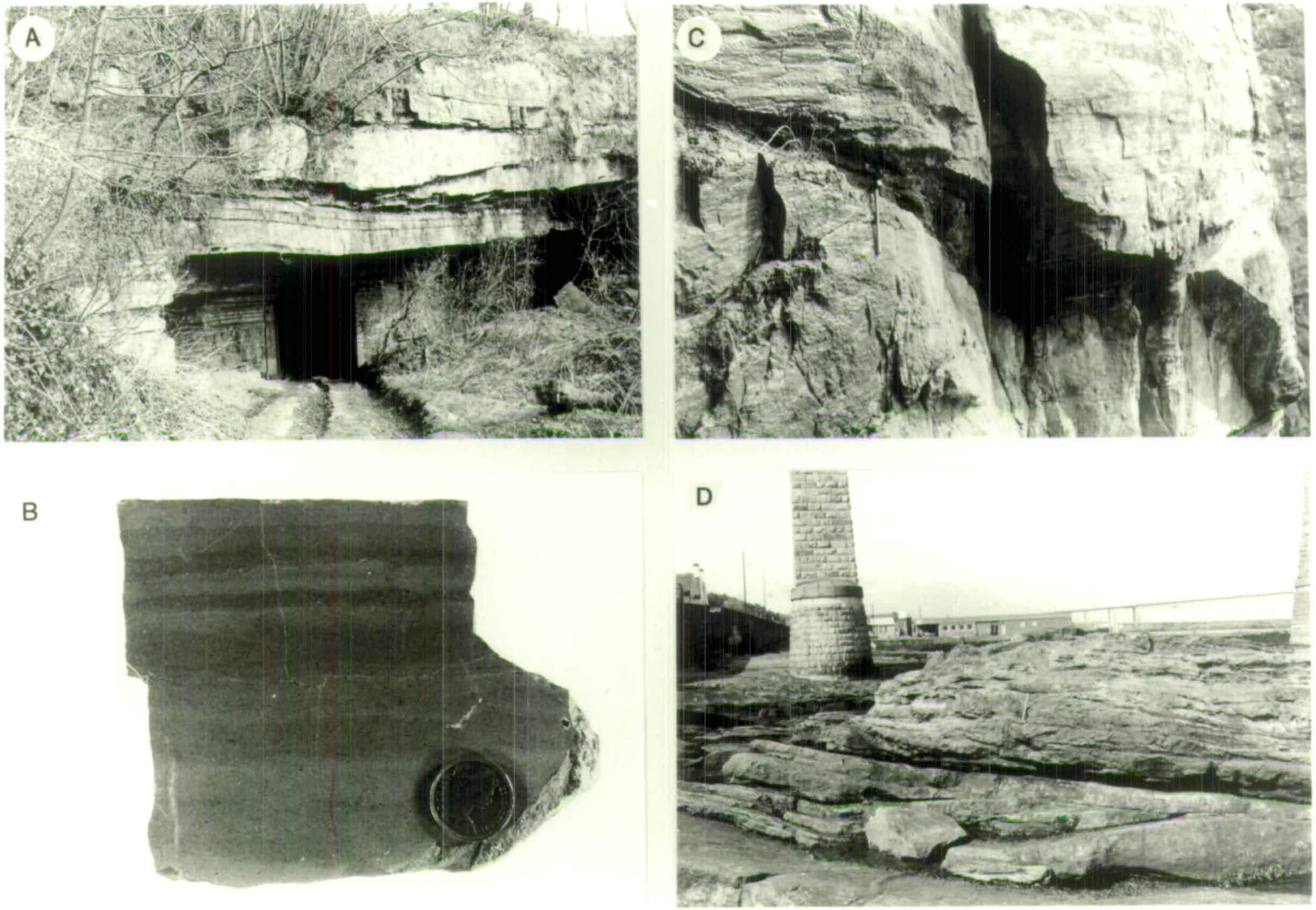

A
C
B
D

Fig. 6.1

Sketch block diagram showing an 'idealised' cycle or cyclothem of Lower Limestone Group sedimentation, with interpretations presented. The cycles are invariably between 10-30 m in thickness. Partially adapted from Duff *et al.* (1967) and Francis (1983a).

LOWER LIMESTONE GROUP
IDEALISED CYCLE

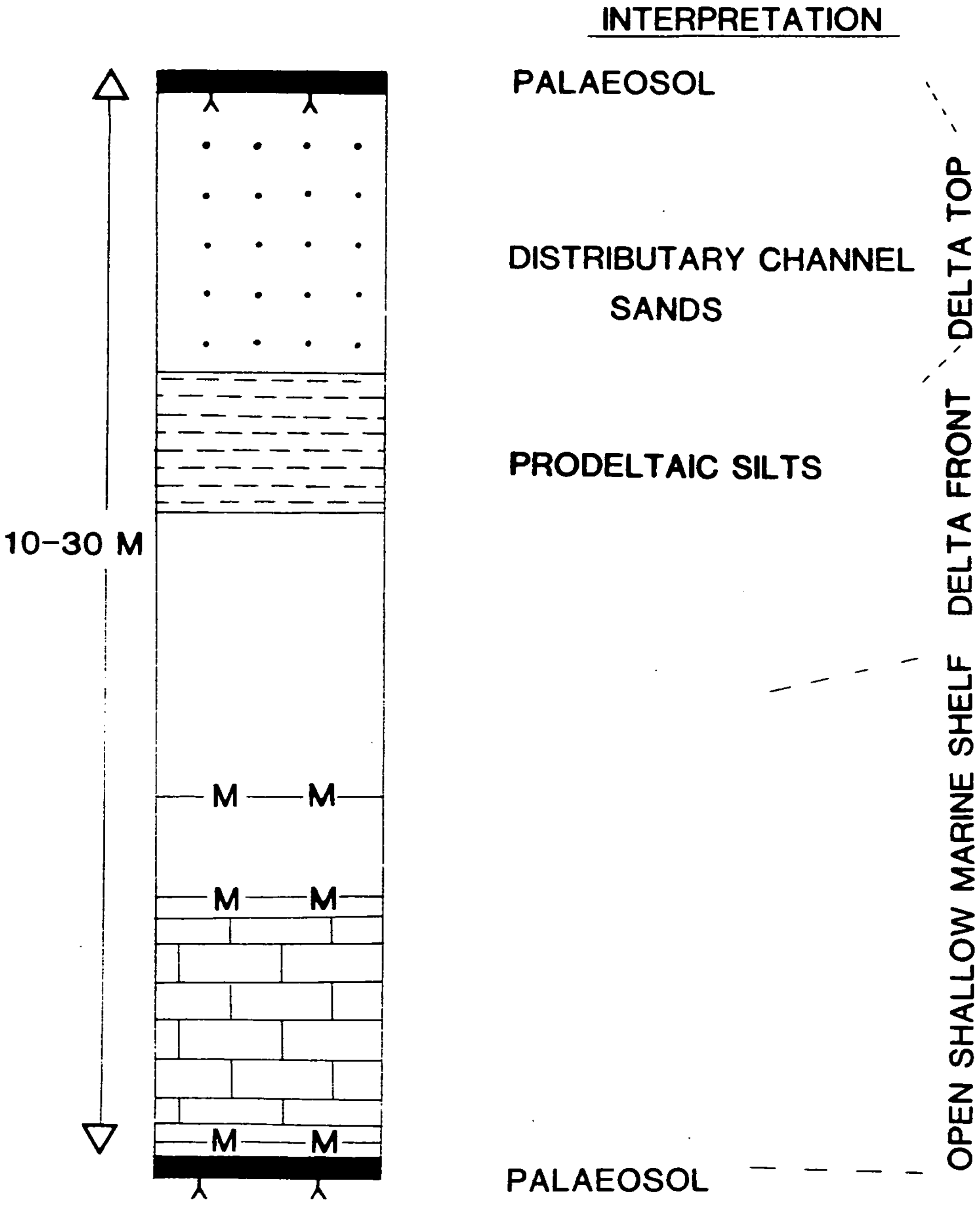


Fig.6.2

Graphic sedimentary log showing the clastic interval between the Upper Longcraig and Lower Skateraw limestones (see Chapter 10) as exposed on the foreshore between Craigielaw Point and Aberlady Point, Aberlady Bay-Kilspindie, Haddington, East Lothian. This facies transect is from the SW to the NE, and generally shows a transition from marine shelf facies (Upper Longcraig Limestone) to delta-front facies via a thin prodeltaic facies. The delta-front facies consist of wave-rippled heterolithic beds which are occasionally hummocky cross-stratified. The delta-top facies is represented by coarse-grained, trough cross-bedded and channellised sandstones which cut-down through the delta-front and prodelta facies to variable levels. At one point, the sandstone has erosively cut-down to within a short distance of the Upper Longcraig Limestone, whereas at another point it is apparently absent altogether. This indicates the variablity of deltaic processes, and the limited lateral geographic extent of delta-top distributary channel facies.

CLASTIC INTERVAL ABOVE UPPER LONGCRAIG LIMESTONE

CRAIGIELAW POINT TO ABERLADY POINT

KILSPINDIE SHORE

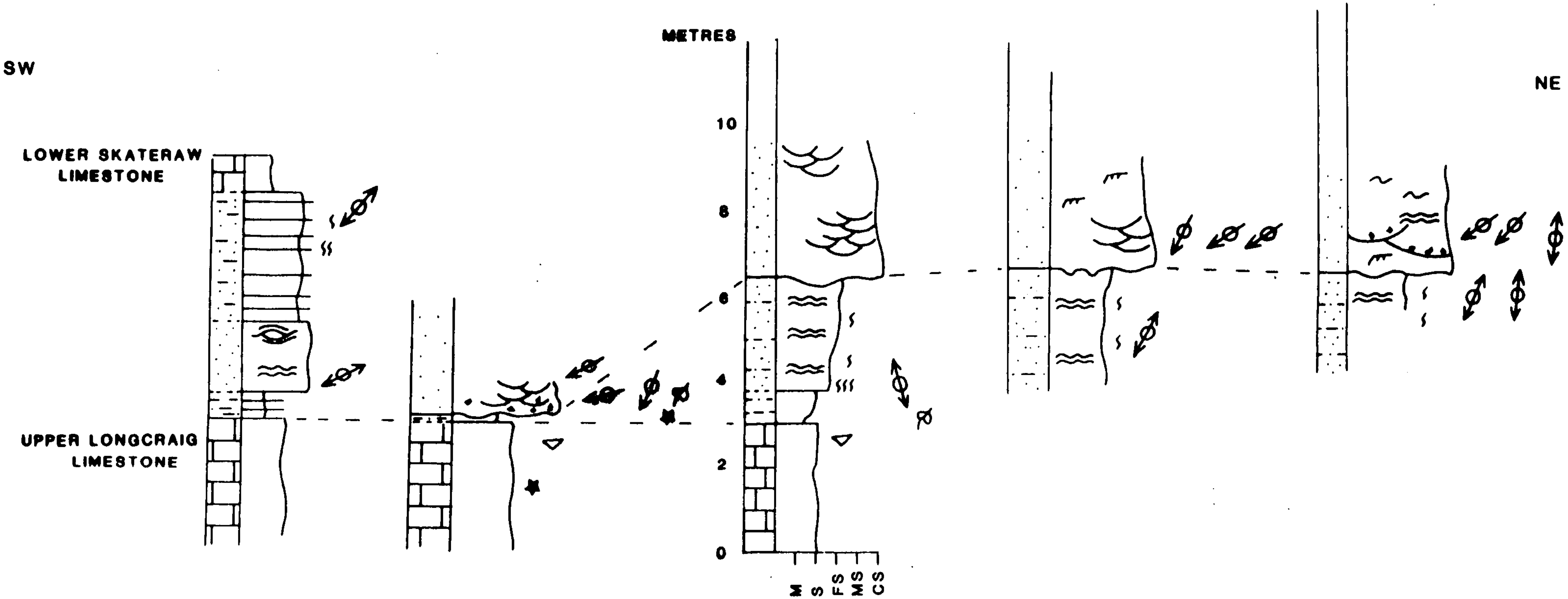
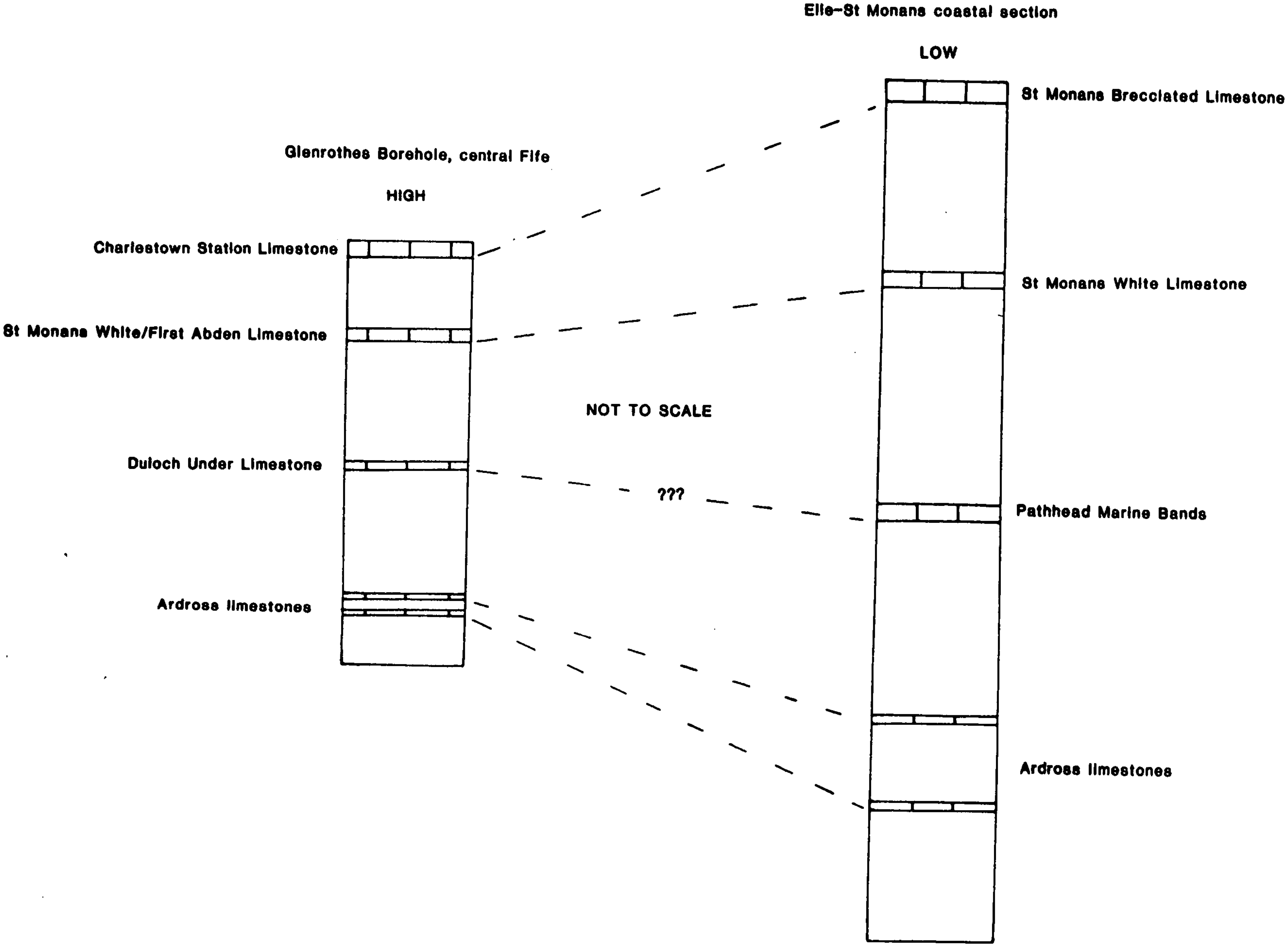


Fig.7.1.

Stratigraphic block-column diagrams showing the major marine horizons (usually limestones) at the top of the Pathhead Beds in the Glenrothes Borehole (central Fife) and the Elie-St Monans coastal section (East Fife). The Glenrothes section is much thinner than that developed in East Fife (due to thinner inter-marine clastic intervals), although the marine phases which are largely independent of local tectonic subsidence are well developed at both localities, transgressing local facies variations in the clastics. Correlations between the two areas are presented. Not to scale.



CORRELATION OF THE MAIN MARINE MARKER HORIZONS BETWEEN THE GLENROTHES BOREHOLE, CENTRAL FIFE AND THE ELIE–ST MONANS COASTAL SECTION, EAST FIFE

Fig.7.2.

Graphic sedimentary log of the major clastic sequence including the Lower and Upper Ardross limestones as exposed at Ardross, Elie, East Fife. Three major coarsening-upward sequences are present, marked A, B and C, and these are discussed in detail in the text.

MOUTH-BAR BETWEEN ARDROSS LIMESTONES,
ELIE-ARDROSS COAST SECTION, EAST FIFE

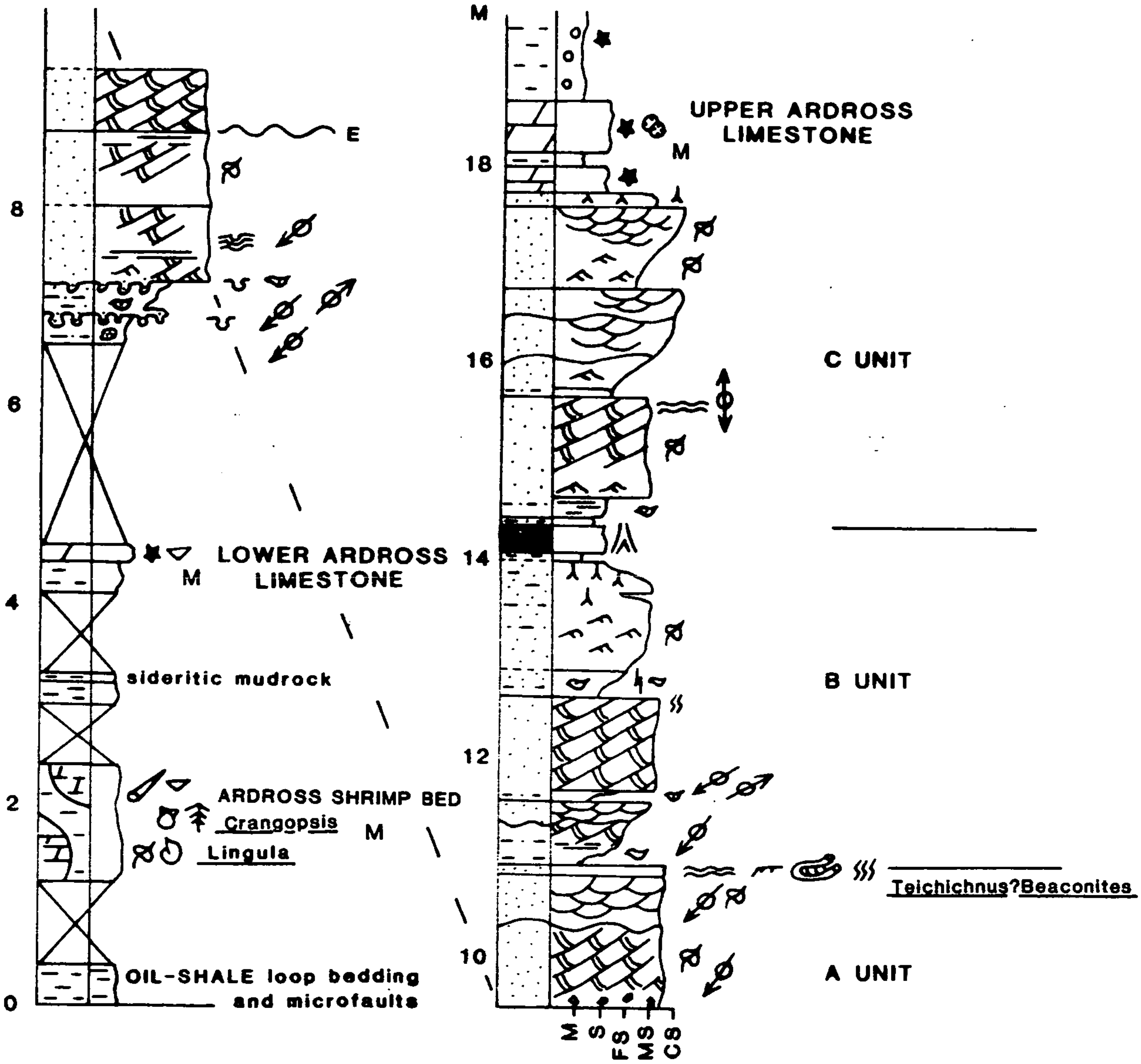
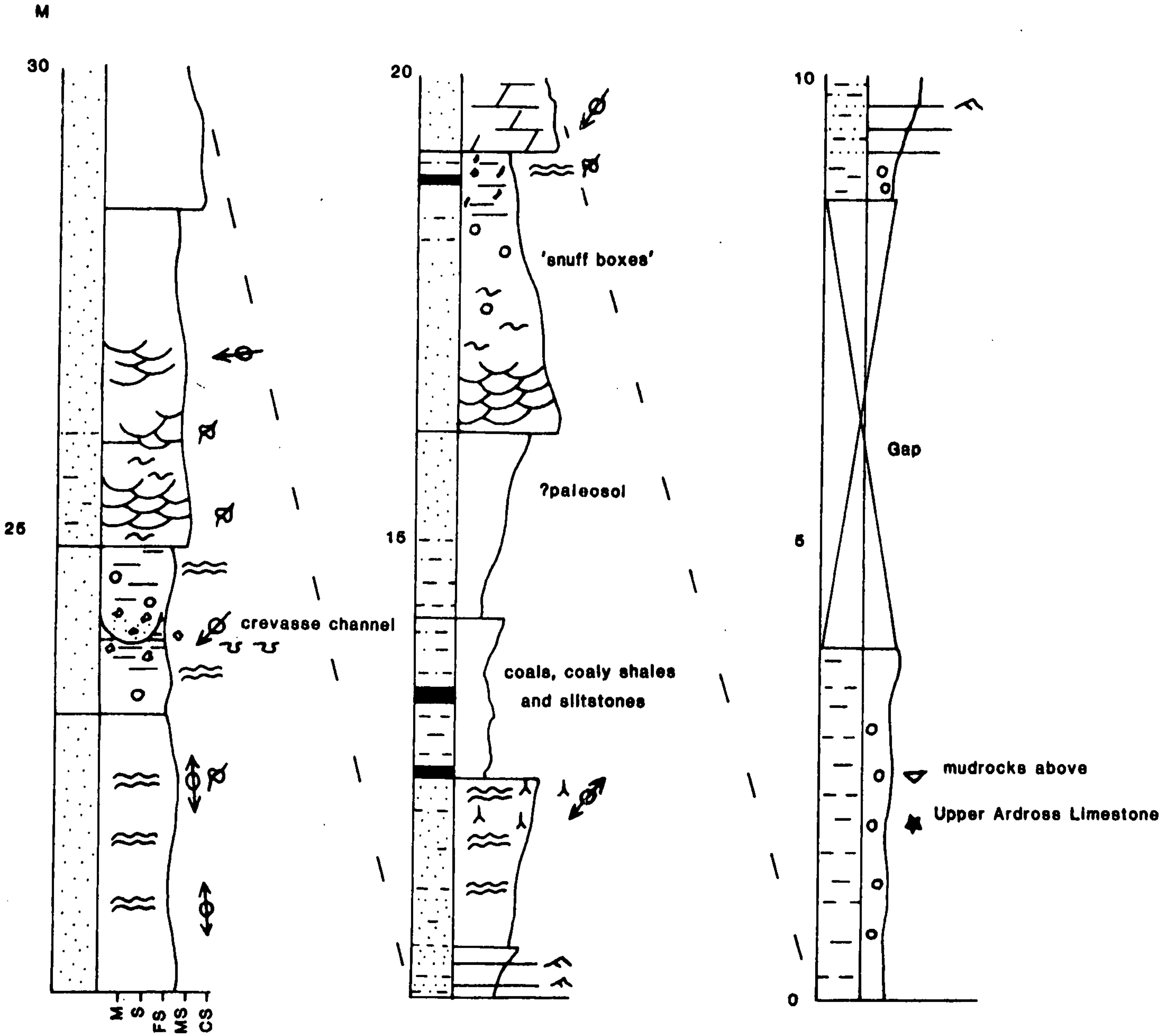


Fig.7.3.

Graphic sedimentary log of the clastic sequence above the Upper Ardross Limestone, as exposed on the coast at Ardross, Elie, East Fife. The sandstones at the top of the sequence are part of the major sandstone body which lies below the Pathhead Marine Bands in East Fife, but which is absent in the Glenrothes Borehole, central Fife.

CLASTIC SEQUENCE ABOVE UPPER ARDROSS LIMESTONE INCLUDING LOWER MAJOR SAND BODY BELOW PATHHEAD MARINE BANDS, ARDROSS-ELIE COASTAL SECTION, EAST FIFE



Clastic interval below St Monans White Limestone

, west side of St Monans Syncline

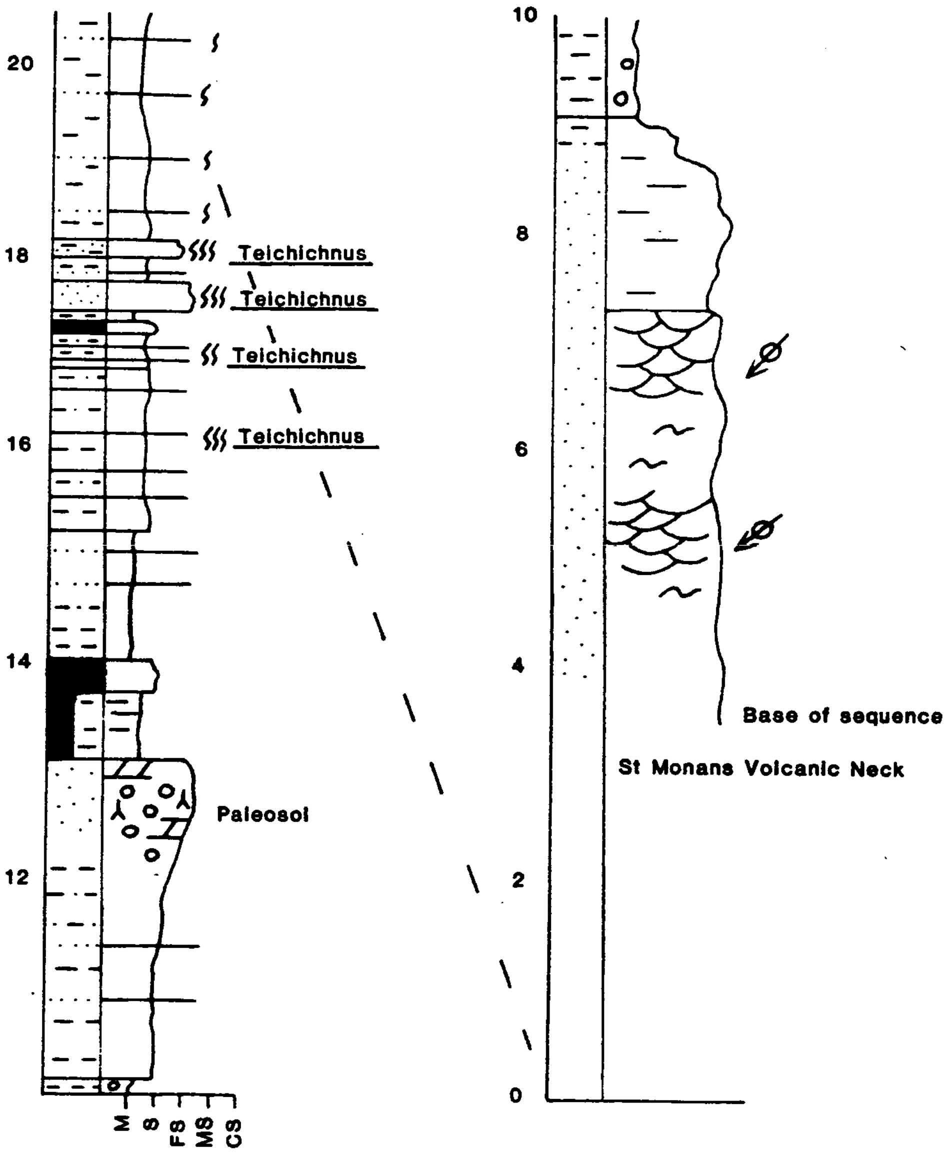


Fig.7.5.

Graphic sedimentary log of the clastic interval between the St Monans White and St Monans Brecciated limestones exposed on the west side of the St Monans Syncline, East Fife. The top of the Pathhead Beds and the base of the overlying Lower Limestone Group is drawn at the base of the St Monans Brecciated Limestone on fossil evidence (Oldroyd in MacGregor 1973).

INTERVAL BETWEEN ST MONANS BRECCIATED AND ST MONANS WHITE LIMESTONES
WEST SIDE OF ST MONANS SYNCLINE, EAST FIFE

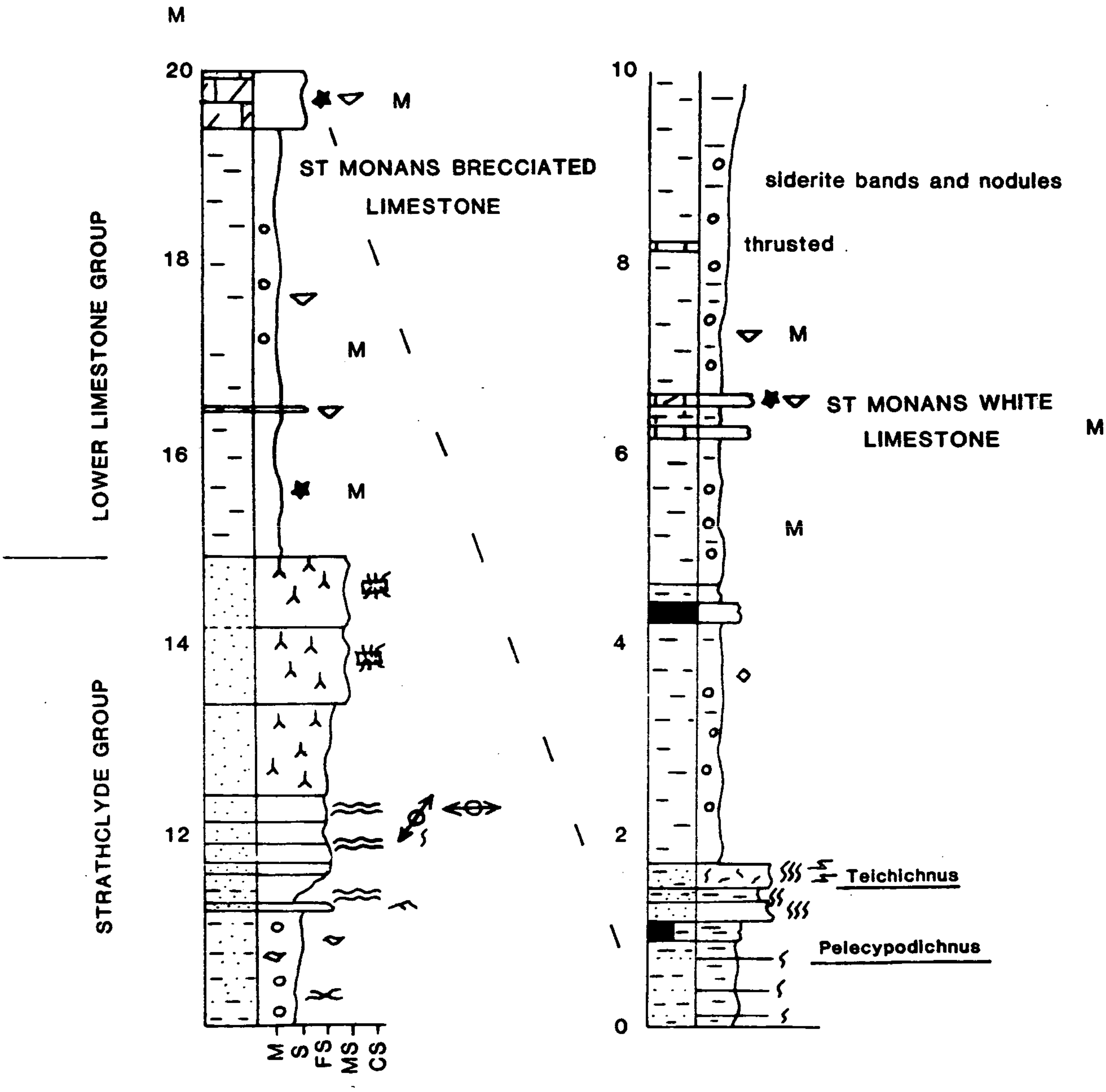


Fig.7.6.

Graphic sedimentary log of the sequence below the Charlestown Main Limestone on the east side of the St Monans Syncline, East Fife. The section is thinner than that on the western side and the sequence drawn extends down to the major sandstone identified adjacent to the St Monans Volcanic Neck on the western side of the syncline. The boundary between the Strathclyde Group (Pathhead Beds) and the overlying Lower Limestone Group is drawn at the base of the St Monans Brecciated Limestone.

SEQUENCE BELOW CHARLESTOWN MAIN LIMESTONE, EAST SIDE OF ST MONANS SYNCLINE, EAST FIFE

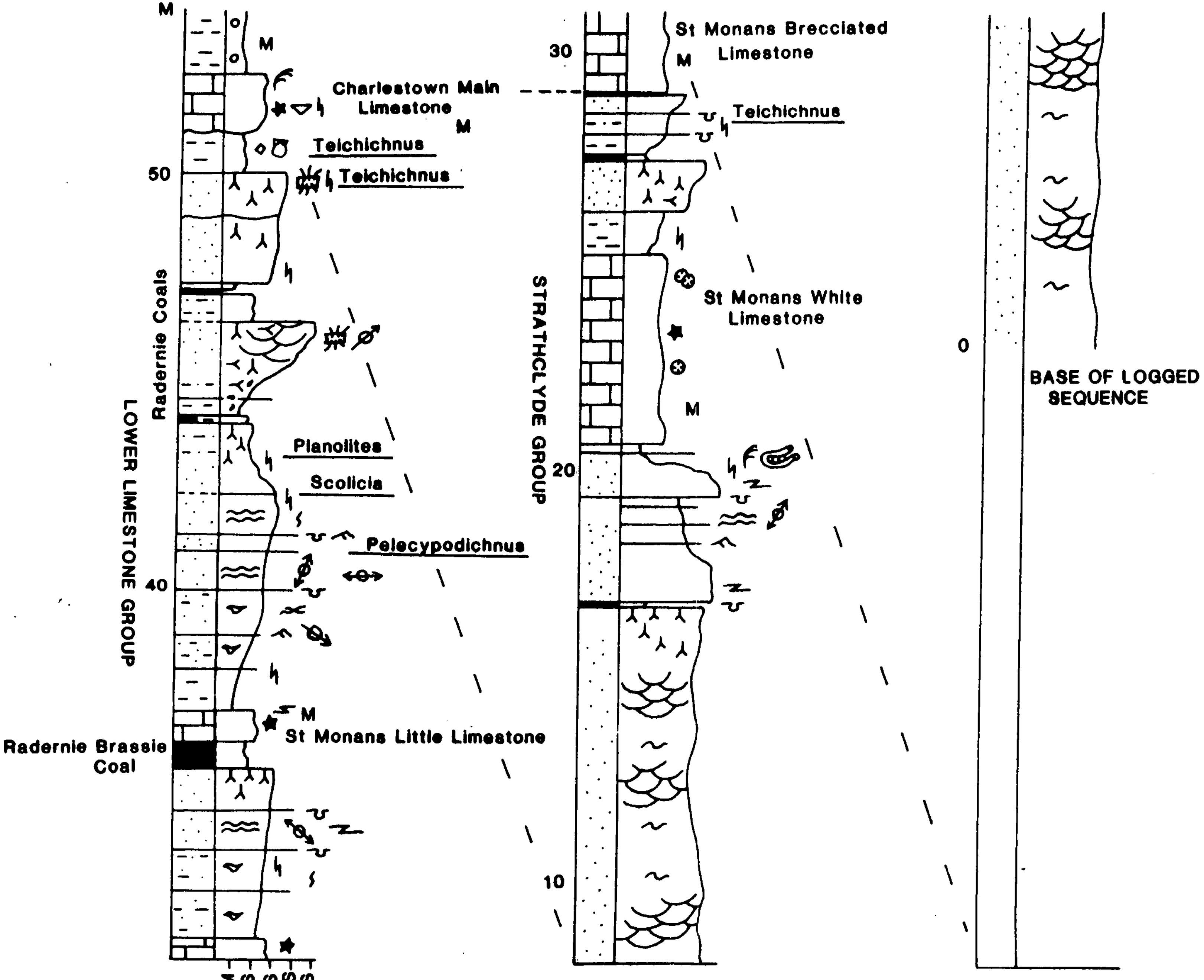


Fig. 7.7.

Graphic sedimentary log of the basal part of the attenuated Pathhead Beds sequence from the Glenrothes Borehole, central Fife. The log relates to the interval between the mudshales above the Duloch Under Limestone and the conglomerate at the base of the sequence which overlies the basal unconformity. The section contains the Lower and Upper Ardross limestones and is characterised by the lowest of the five coarsening-upward sequences in the Pathhead Beds of this section. The lowest part of the sequence forms a distinct fining-upward sequence.

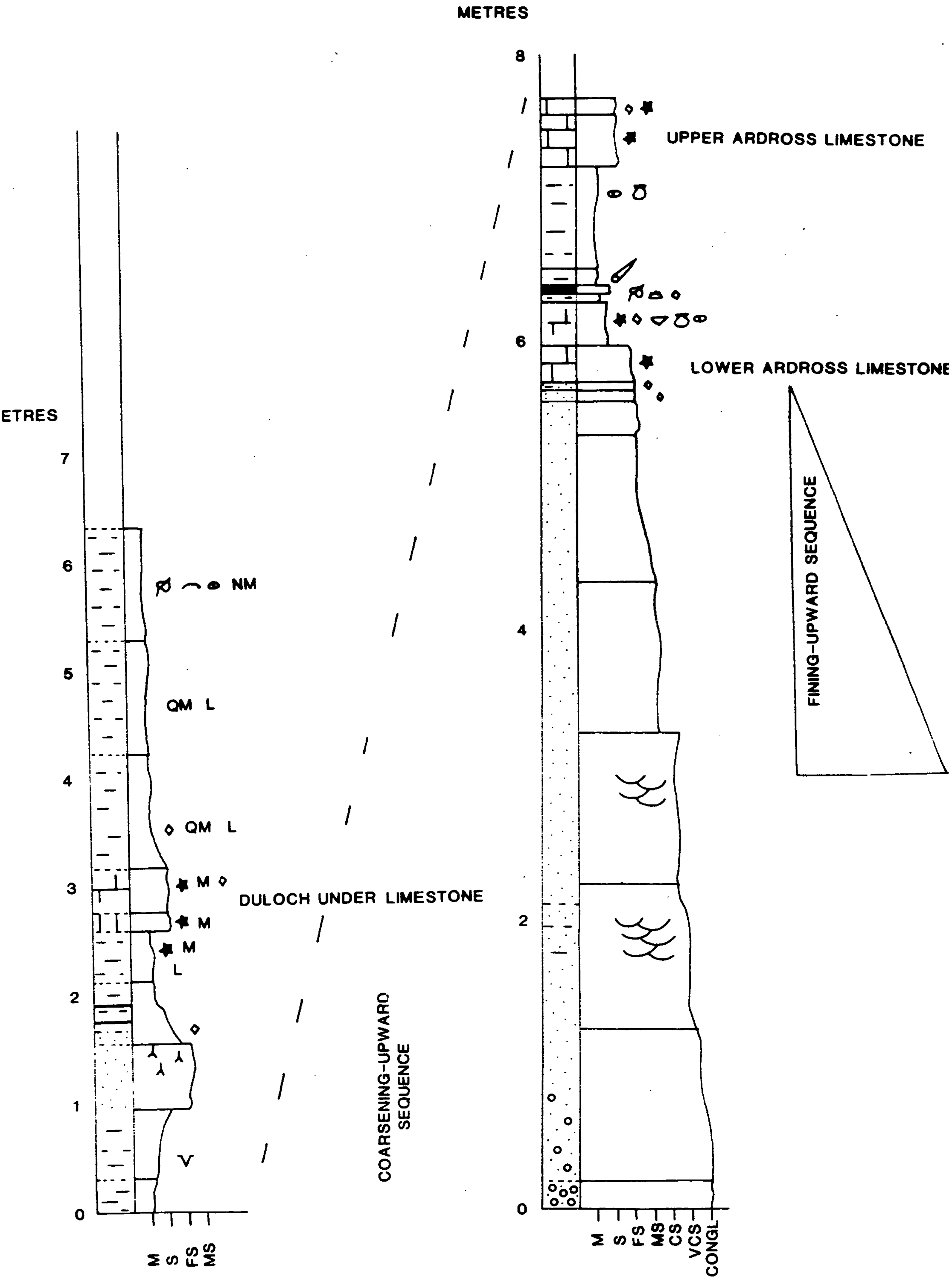

ETRES
7
6
5
4
3
2
1
0
NM
QM L
QM L
M
DULOCH UNDER LIMESTONE
M
M
L
COARSENING-UPWARD SEQUENCE
M
S
FS
MS
METRES
8
6
4
2
0
UPPER ARDROSS LIMESTONE
LOWER ARDROSS LIMESTONE
FINING-UPWARD SEQUENCE
M
S
FS
MS
CS
VCS
CONGL

Fig.7.8.

Graphic sedimentary log of the interval between the Duloch Under and St Monans White limestones (Pathhead Beds) in the Glenrothes Borehole, central Fife. This log follows on upsection from that in Fig.7.7., and contains the top of the second and the whole of the third coarsening-upward sequence.

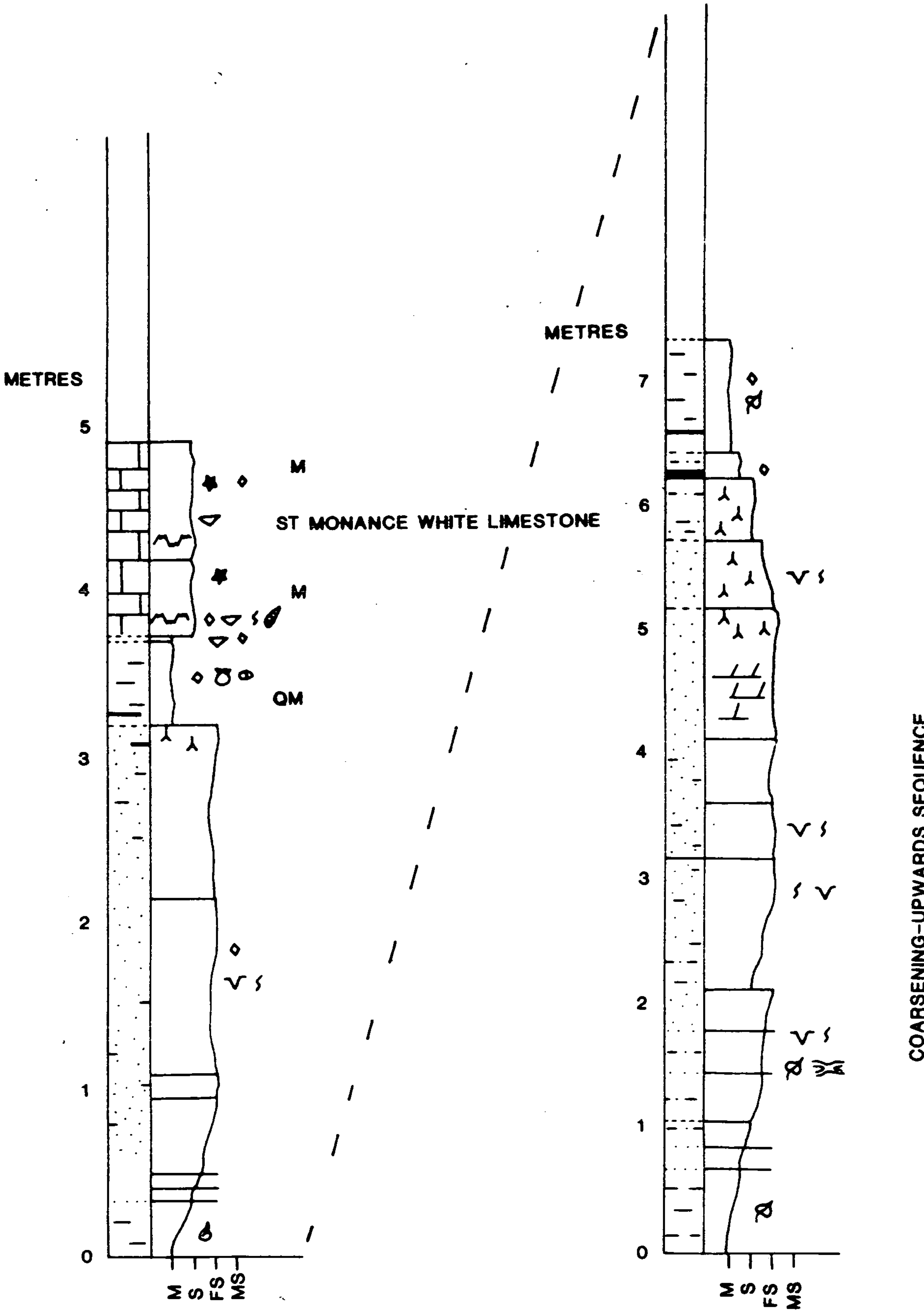

METRES
5
4
3
2
1
0
M
ST MONANCE WHITE LIMESTONE
M
QM
M
S
FS
MS
METRES
7
6
5
4
3
2
1
0
M
S
FS
MS
COARSENING-UPWARDS SEQUENCE

Fig.7.9.

Graphic sedimentary log of the interval between the St Monans White and Charlestown Station limestones in the Glenrothes Borehole, central Fife. This section includes coarsening-upward sequences 4, 5 and 6 and occurs at the top of the Pathhead Beds, the base of the Charlestown Station (or St Monans Brecciated) Limestone marking the top of the Pathhead Beds and the base of the Lower Limestone Group.

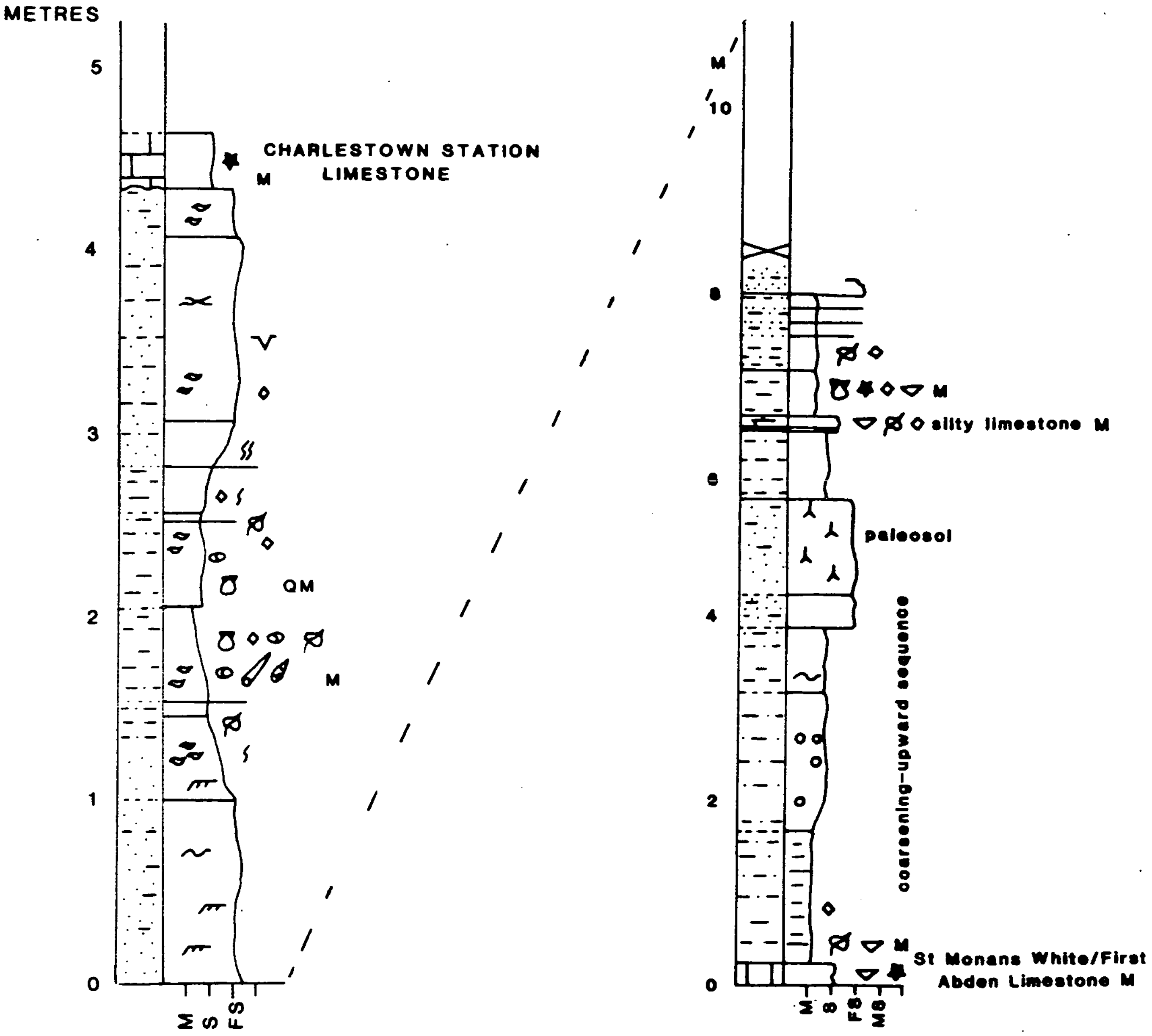
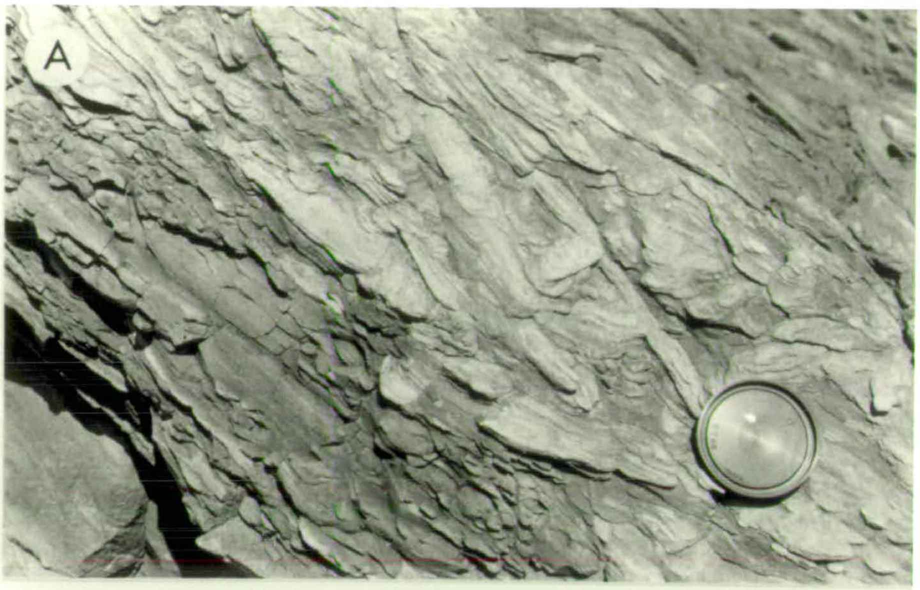

METRES
5
4
3
2
1
0
CHARLESTOWN STATION LIMESTONE
M
QM
M
M
S
FS
M
10
8
6
4
2
0
M
silty limestone M
paleosol
coarsening-upward sequence
M
St Monans White/First Abden Limestone M
M
S
FS
MS

Fig.7.10.

A. Field photograph of heterolithic, bioturbated sandy siltstones and shales with well-preserved *Teichichnus* burrows, situated in the marine-influenced sequence below the St Monans White Limestone (Pathhead Beds), on the west side of the St Monans Syncline. Scale: camera lens cap, diameter=6 cm.

B. Field photograph of mixed (heterolithic) sequence of sandy siltstones, siltstones, shales and coals below the St Monans White Limestone on the west side of the St Monans Syncline, East Fife. The light coloured sandy band in the upper right hand corner of the photograph is described above in close-up (Fig.7.10A). The geologist in the picture is pointing both geological hammers towards two small thrusts which affect the sequence, and the upper hammer underlies a thin coal seam. Scale: geologist, approximately 1.8 m in height.

C. Close-up view of thin sandy siltstones containing *Teichichnus* from the sequence illustrated above (Fig.7.10B). Scale: camera lens cap, diameter=6 cm.


A


B

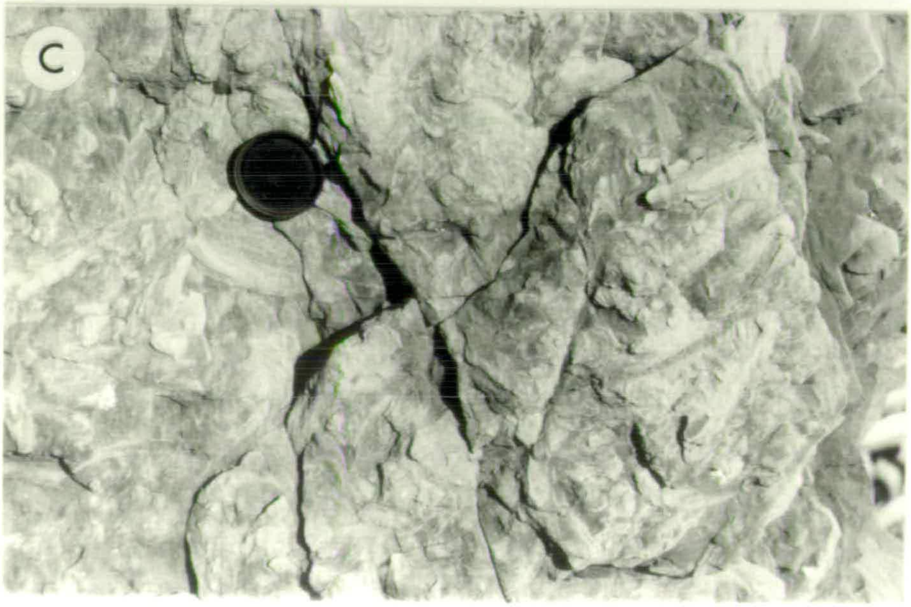

C

Fig. 8.1

Sketch outline map showing Lothians and Fife districts bounding the Firth of Forth. The Lothians area has been divided into west, mid and east Lothian, the localities studied being in the latter area. The four localities investigated (Catcraig, Skateraw Borehole, Spilmersford Borehole and Kilspindie-Aberlady Bay) are also clearly marked. Scale: provided on map=0-15 km.

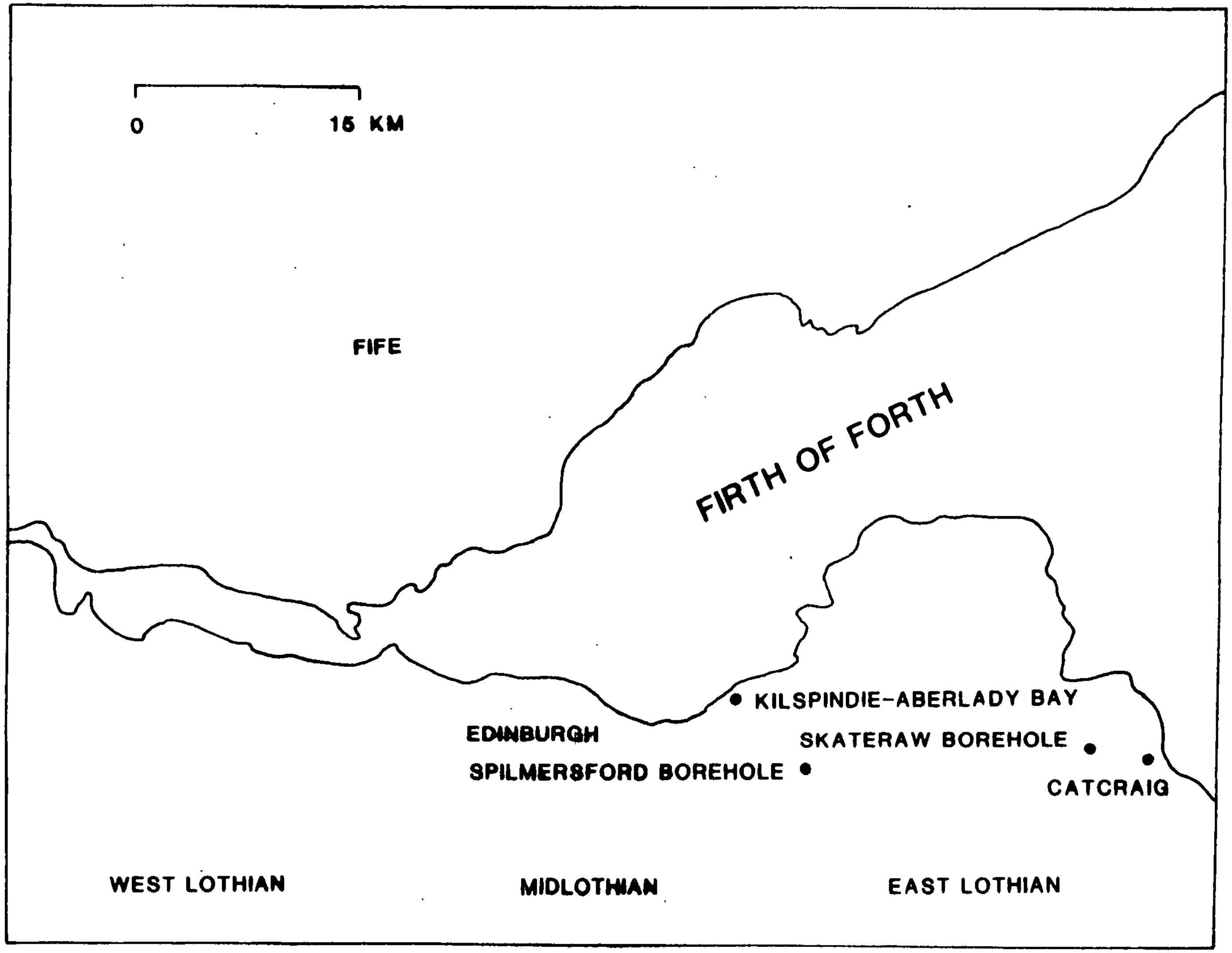

0
15 KM
FIFE
FIRTH OF FORTH
KILSPINDIE-ABERLADY BAY
EDINBURGH
SKATERAW BOREHOLE
SPILMERSFORD BOREHOLE
CATCRAIG
WEST LOTHIAN
MIDLOTHIAN
EAST LOTHIAN

Fig. 8.2.

Graphic sedimentary logs of the Middle-Upper Longcraig limestones interval on the Catcraig foreshore and in the Skateraw Borehole, East Lothian. The two sequences are generally quite similar, and both are characterised by the presence of an emergent surface on top of the Middle Longcraig Limestone. The clastic interval between the limestones, however, is thinner in the Skateraw Borehole.

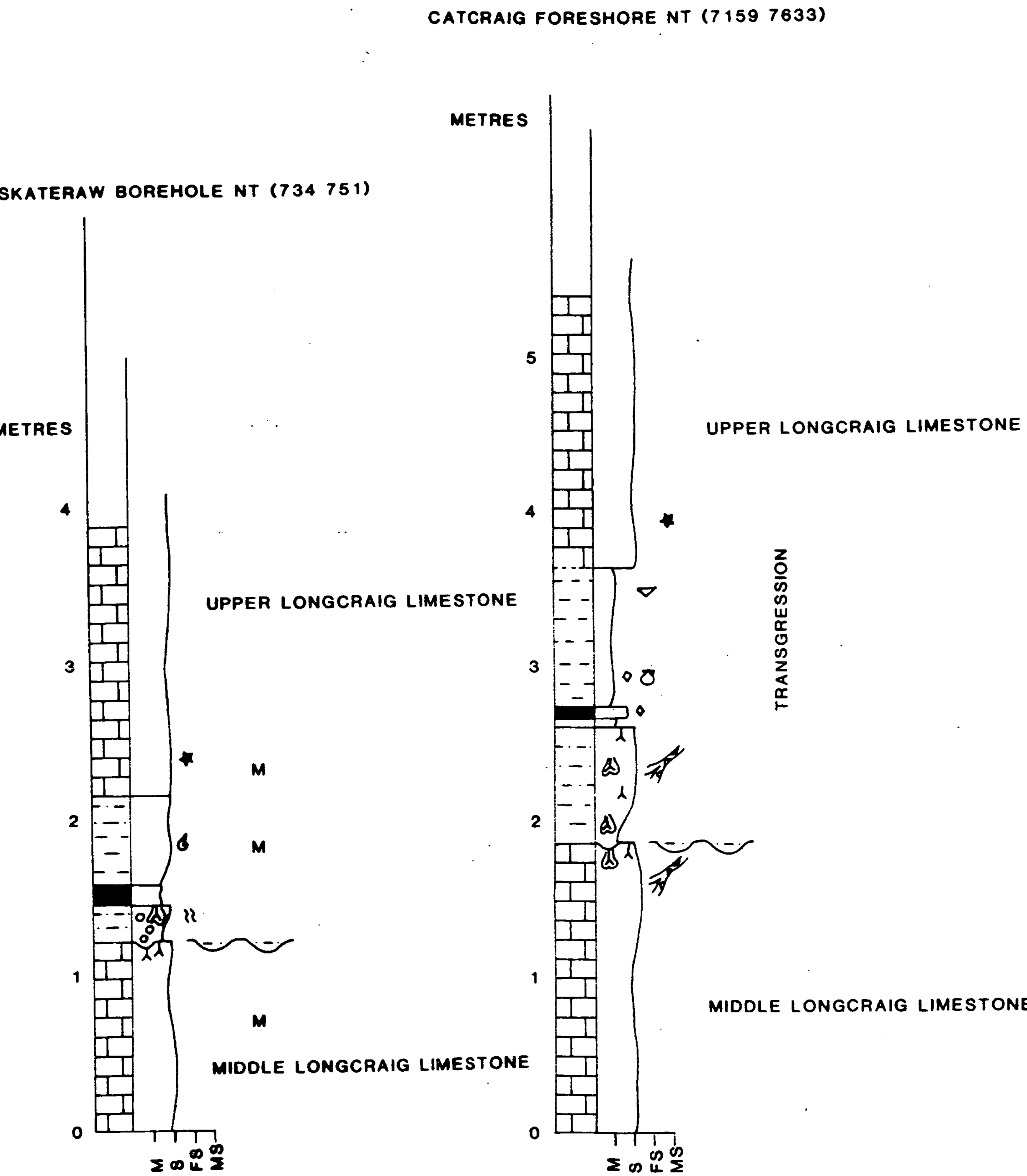

SKATERAW BOREHOLE NT (734 751)
ETRES
4
3
2
1
0
UPPER LONGCRAIG LIMESTONE
M
M
M
MIDDLE LONGCRAIG LIMESTONE
M
S
FS
MS
CATCRAIG FORESHORE NT (7159 7633)
METRES
5
4
3
2
1
0
UPPER LONGCRAIG LIMESTONE
TRANSGRESSION
MIDDLE LONGCRAIG LIMESTONE
M
S
FS
MS

Fig. 8.3.

A. Large regular spaced basin-shaped hollows/pits (arrowed) infilled with the overlying fireclay on the top surface of the Middle Longcraig Limestone at the Catcraig coastal section, East Lothian. The upper surface of the limestone is very slaggy weathering and the limestone surface forms an extensive wave-cut platform at low tide. The depressions average 1.4 m in diameter and 0.5 m in depth and are interpreted as hollows which formed around the root systems of large club mosses and were possibly enlarged during vadose diagenesis. Scale: geologist, height=1.60 m.

B. Close-up view of the surface of the Middle Longcraig Limestone showing small *in situ* stigmarian rootlet (*Stigmaria ficoides*) (arrow 2), providing evidence of an *in situ* vegetation inferred from A, above. Small rhizocretions (arrow 1) are also present. Scale: camera lens cap, diameter=6 cm.

C. Close-up view of vertically orientated, cylindrical rhizocretions in the top of the Middle Longcraig Limestone (arrowed 1 and 3). Paler-coloured inner 'cores' or nuclei which often contain coalified wispy rootlets are present, and darker red-brown to orange coloured outer concentric laminae representing the ferruginous sphaerosideritic rhizocretion (Hemingway 1968) are conspicious. Scattered crinoid debris (arrow 2) is also present. Scale: lens cap, diameter=6 cm.

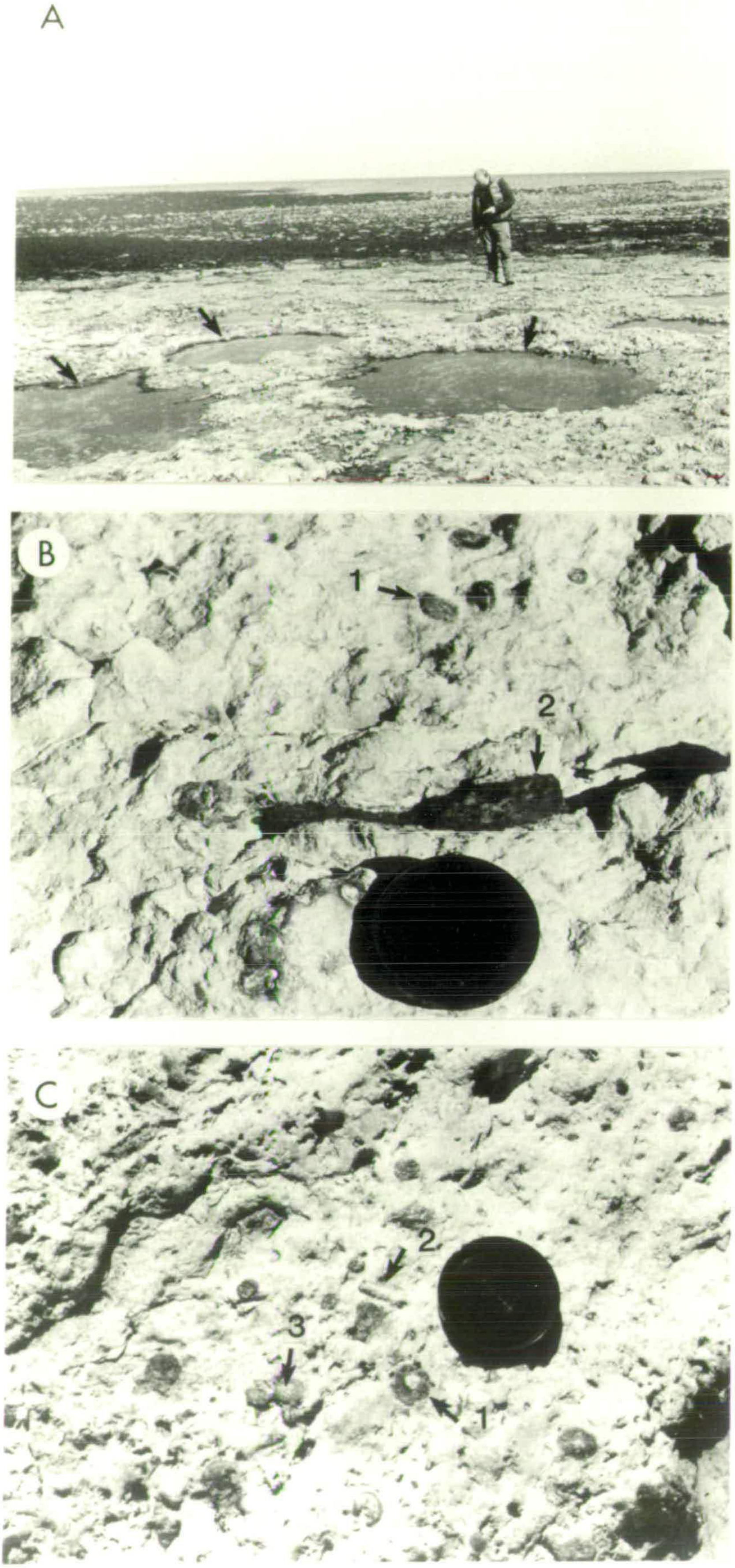

A
B
1
2
C
2
3
1

Fig. 8.4.

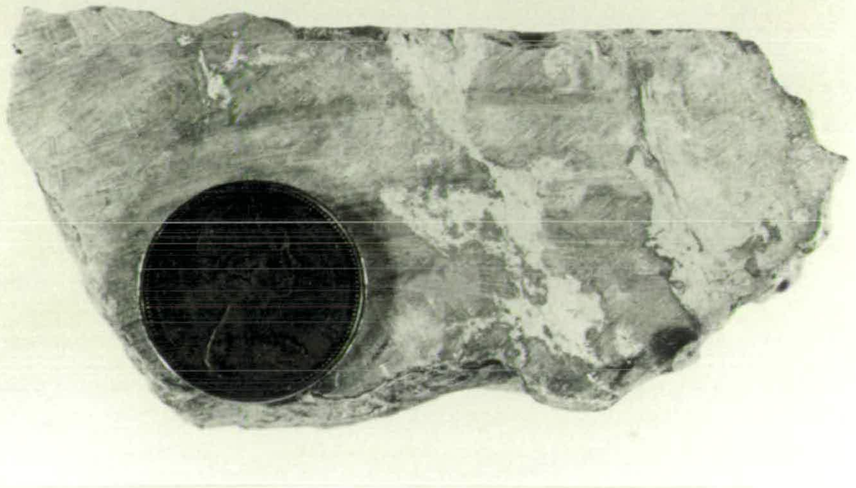
A. Sliced block of the upper part of the Middle Longcraig Limestone showing the prominent irregular shaped cavities filled with cream-white coloured kaolinite. This is interpreted as a pedogenic deposit which has infilled ?dissolution created vugs and voids. The surrounding limestone is relatively unaltered, but is characterised by small kaolinite-filled voids representing an interlinked network of internal sediment filled cavities. Scale: two pence coin, diameter=2.5 cm.

B. Sliced block of the upper part of the Middle Longcraig Limestone showing kaolinite filled cavities with red-brown coloured (stained) margins. On weathering, the softer kaolinite usually preferentially weathers out to leave an empty void which collapses to give a very slaggy and pseudo-brecciated appearance to the upper surface of the limestone. Scale: two pence coin, diameter=2.5 cm.

C. Sliced block of the upper part of the Middle Longcraig Limestone with kaolinite-filled voids associated with thin, wispy coalified rootlets. The shapes of the voids are irregular, and the contrast between the creamy colour of the clay and the darker blue-grey colour of the limestone is conspicuous. Scale: two pence coin, diameter=2.5 cm.

A

B



C

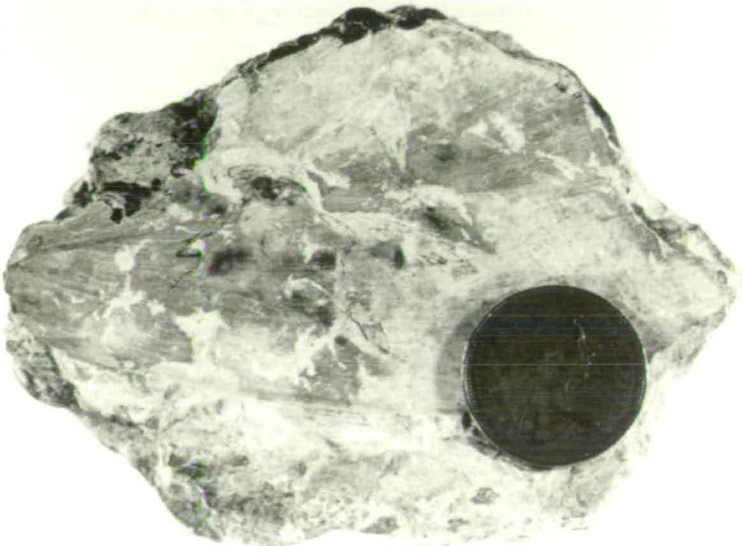
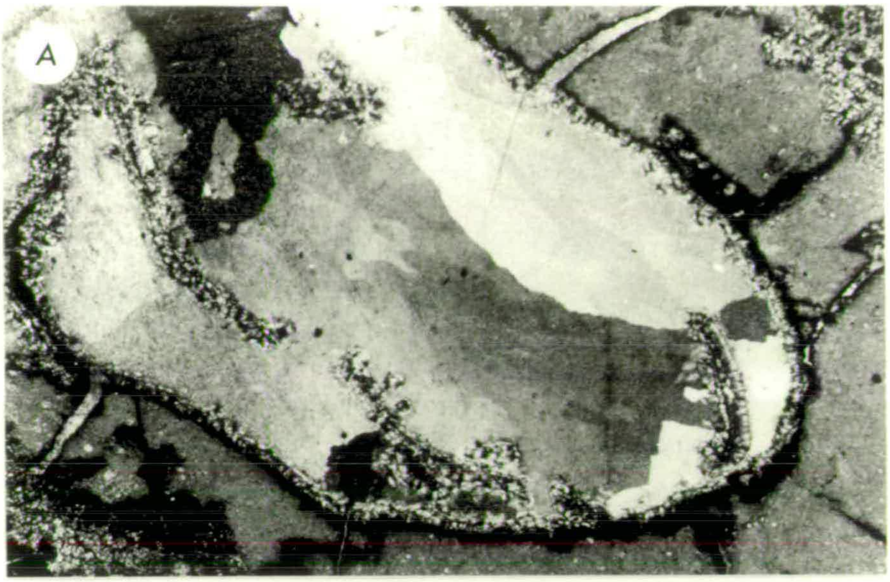


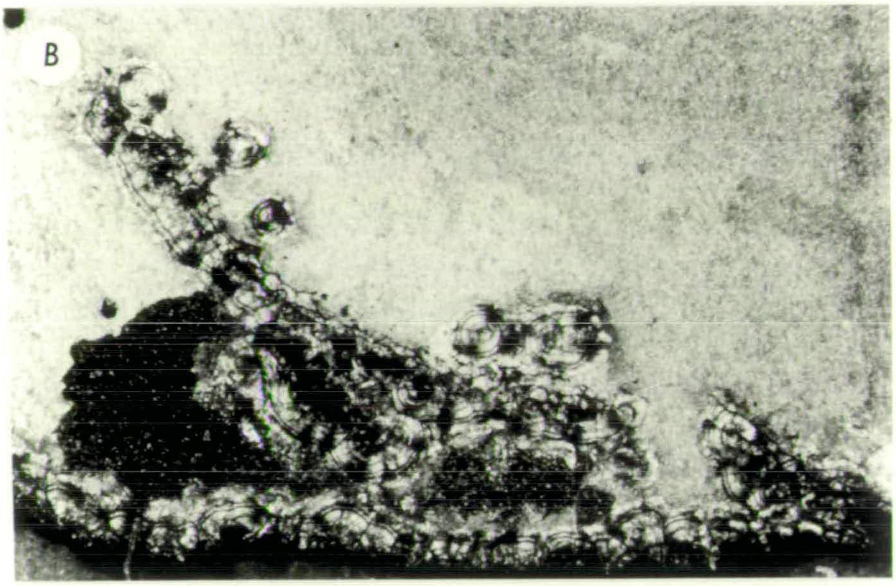
Fig. 8.5.

A. Photomicrograph of a thin section (crossed-polars) of the upper part of the Middle Longcraig Limestone (Catcraig foreshore) showing a fossil cavity which has been infilled with carbonate cements and associated sphaerosiderite. The sphaerosiderite lines the margins of the cavity which suggests that it precipitated at an earlier point in time. The void was probably created by an early dissolution phase only to be later filled by sphaerosiderite and late diagenetic carbonate cements. Scale: field of view=1 cm.

B. Photomicrograph of a thin section (crossed-polars) of the upper part of the Middle Longcraig Limestone showing a close-up view of sphaerosiderite (see A, above) displaying a characteristic spherulitic fibrous texture (Tucker 1983). The sphaerosiderite is earlier than the calcite and is known to form in brown seat-earths underlying thin coal seams which are thought to represent less water-saturated and partially emergent soils (Collinson 1986, p.51). Scale: field of view=3.5 mm.

C. Photomicrograph (crossed-polars) of close-up of above (B), showing clusters or aggregates of spherulitic sphaerosiderite. Their presence in the limestone and the overlying seat-earth (Hemingway 1968) is interesting because it suggests partial emergence of the soil profile, which is consistent with the general inferred setting. Scale: field of view=3.5 mm.


A


B

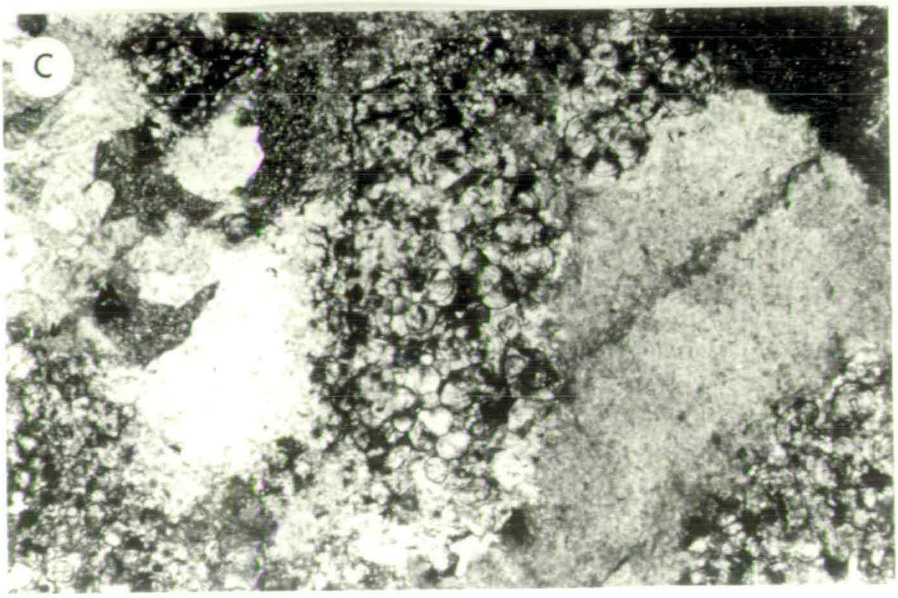
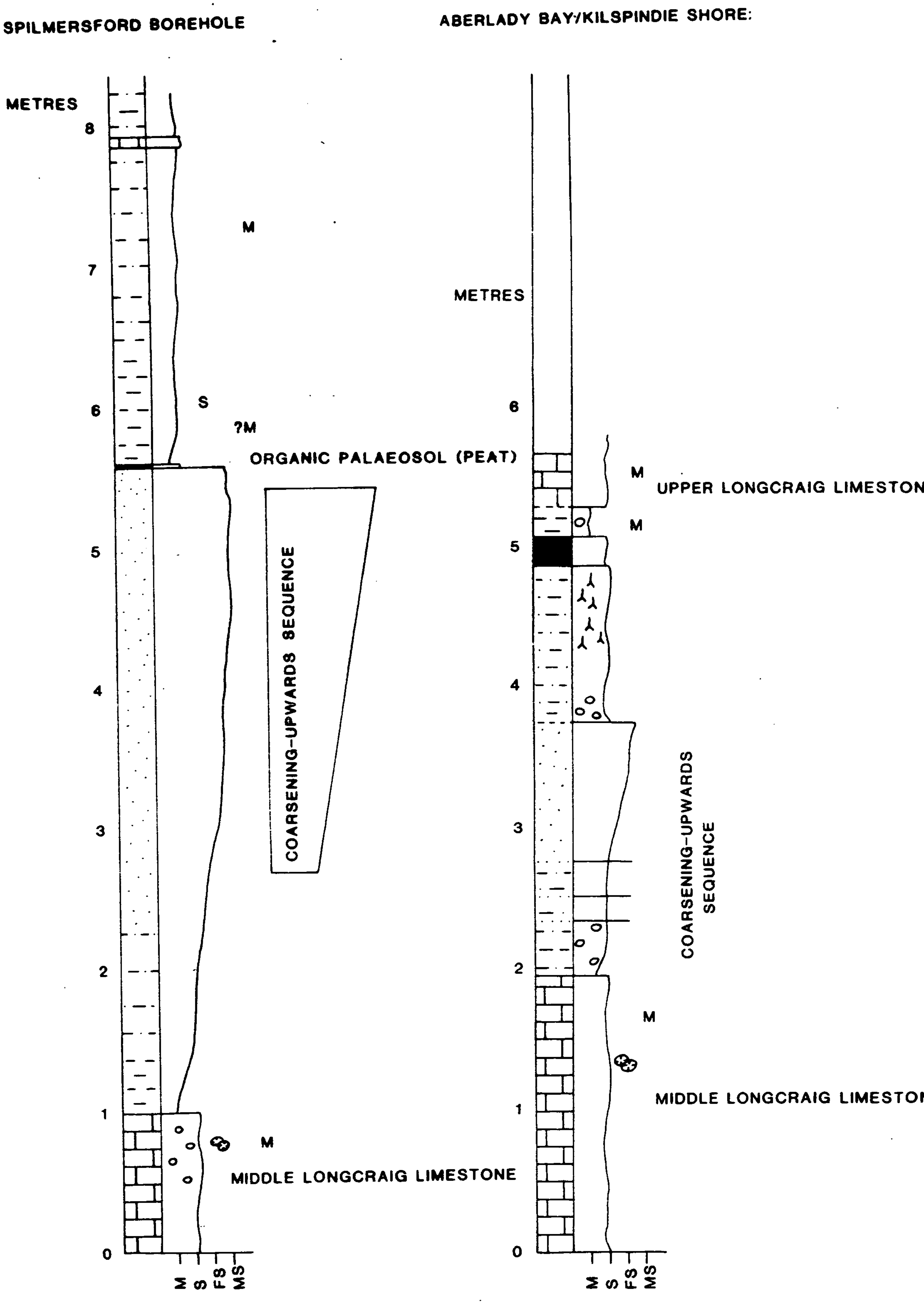

C

Fig. 8.6.

Graphic sedimentary logs of the Middle Longcraig-Upper Longcraig limestones interval in the BGS Spilmersford Borehole (Davies 1974), and the Aberlady-Kilspindie shore section, Haddington, East Lothian. The emergent surface noted on top of the Middle Longcraig Limestone in the Oldamstocks Basin is not present at these localities outside the basin, and the interval between the limestones is occupied by a progradational deltaic coarsening-upward sequence rather than a predominance of paleosol facies. These facies and thickness differences suggest that the Haddington area was undergoing more rapid tectonic subsidence than the Dunbar-Catcraig area, encouraging delta progradation and discouraging the development of a limestone emergent surface and overlying paleosol facies.


SPILMERSFORD BOREHOLE

ABERLADY BAY/KILSPINDIE SHORE:

Fig. 8.7.

Sketch cartoon showing a simplified interpretation of the facies and thickness changes involving the Middle Longcraig Limestone and the overlying clastic interval. The half-graben model as postulated by Leeder and Strudwick (1987) may be used to explain such patterns of variable subsidence in an extensional tectonic regime.

PALAEOGEOGRAPHIC RECONSTRUCTION FOR TIME INTERVAL BETWEEN MIDDLE AND UPPER LONGCRAIG LIMESTONES

HALF-GRABEN CONTROL ON YOREDALE CYCLES

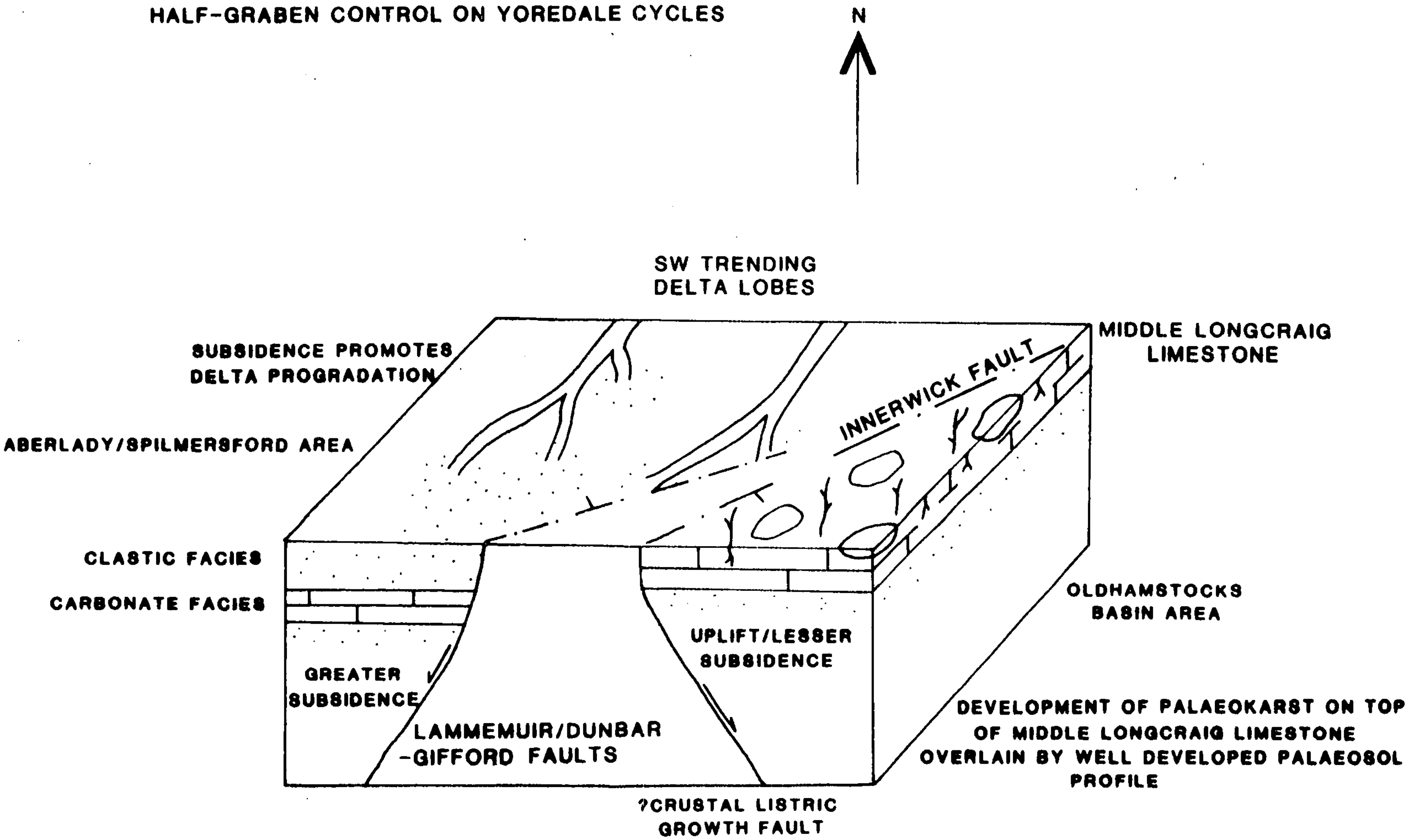


Fig. 9.1.

Sketch diagram showing the position of the Firth of Forth area in relation to the rest of the British Isles mainland, with an insert map showing a close-up of the Firth of Forth area. Close-up shows location of Kinghorn-Kirkcaldy coastal section, central Fife in relation to Edinburgh and the Firth of Forth. Stratigraphic column diagram illustrates the relative positions of the major marine limestones (marker bands) in the Lower Limestone Group of the Kinghorn-Kirkcaldy area of central Fife. The First Abden Limestone is located at the top of the underlying Strathclyde Group (Paterson and Hall 1986), and the base of the Second Abden Limestone marks the base of the Lower Limestone Group. The position of the sequence studied in this chapter is also outlined.

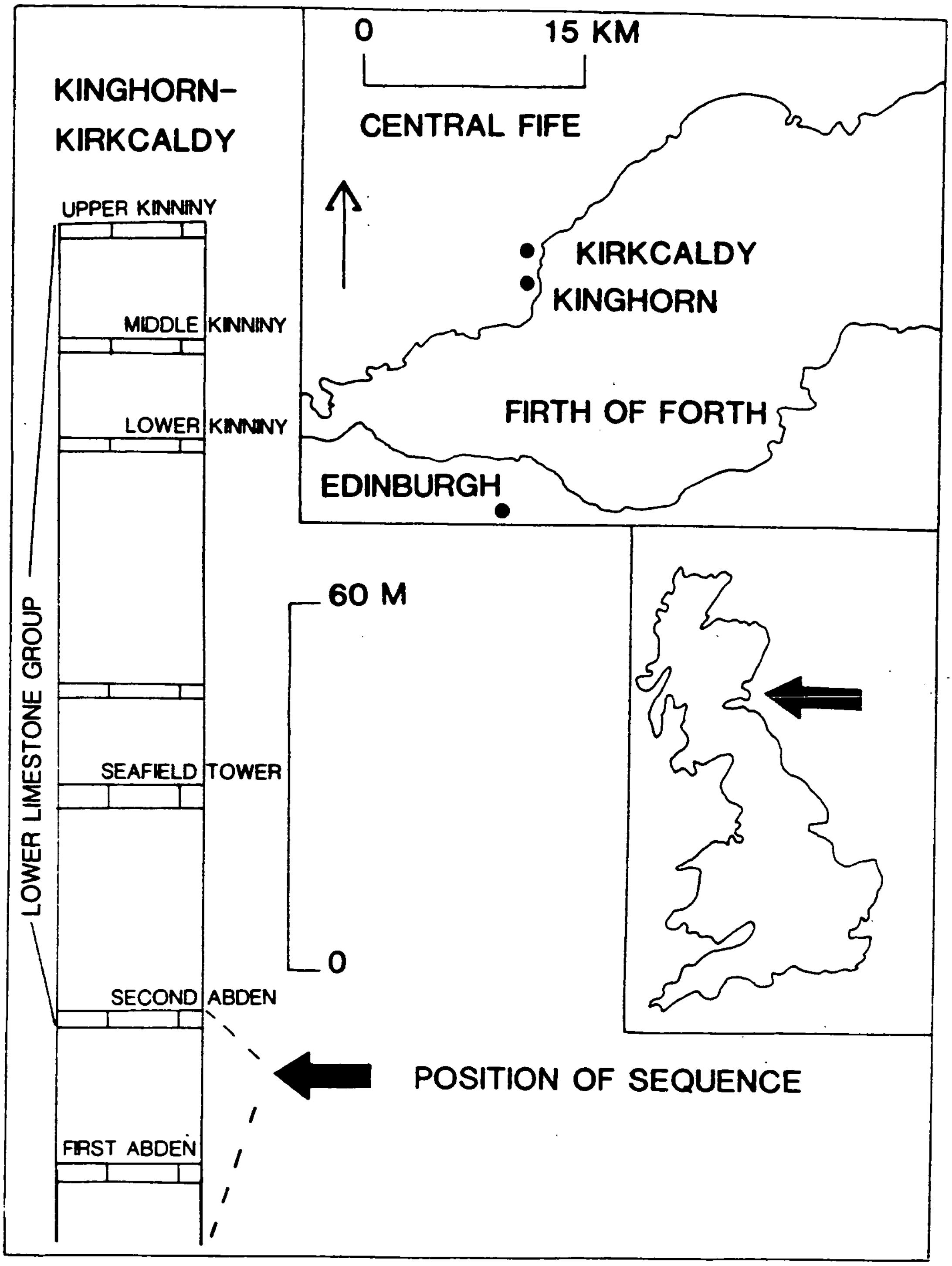
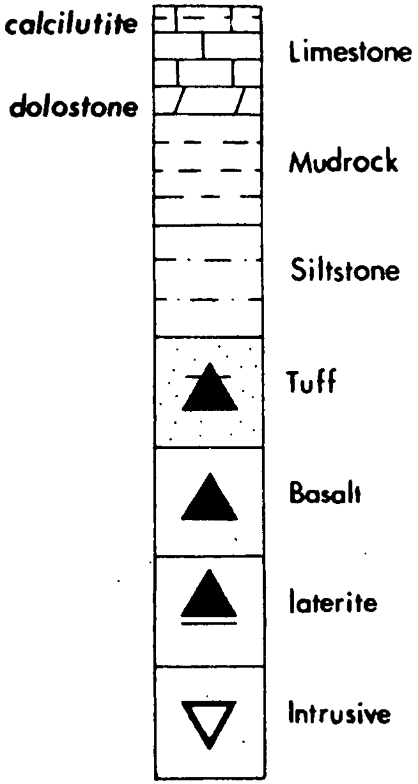

KINGHORN-
KIRKCALDY
UPPER KINNINY
MIDDLE KINNINY
LOWER KINNINY
SEAFIELD TOWER
SECOND ABDEN
FIRST ABDEN
LOWER LIMESTONE GROUP
60 M
0
0
15 KM
CENTRAL FIFE
KIRKCALDY
KINGHORN
FIRTH OF FORTH
EDINBURGH
POSITION OF SEQUENCE

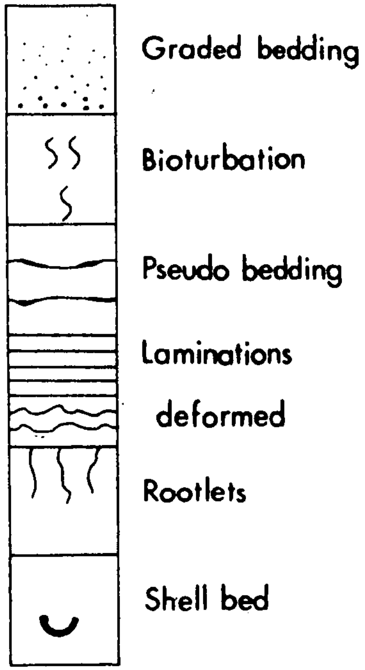
Fig. 9.2.

Graphic sedimentary log showing the sequence containing both the First and Second Abden limestones. The two transgressive mudrocks studied below the First and Second Abden limestones respectively are labelled A and B. Interpretations are presented on the right hand side of the diagram.

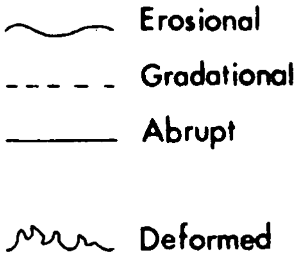
LITHOLOGIES



SEDIMENTARY STRUCTURES



BED CONTACTS



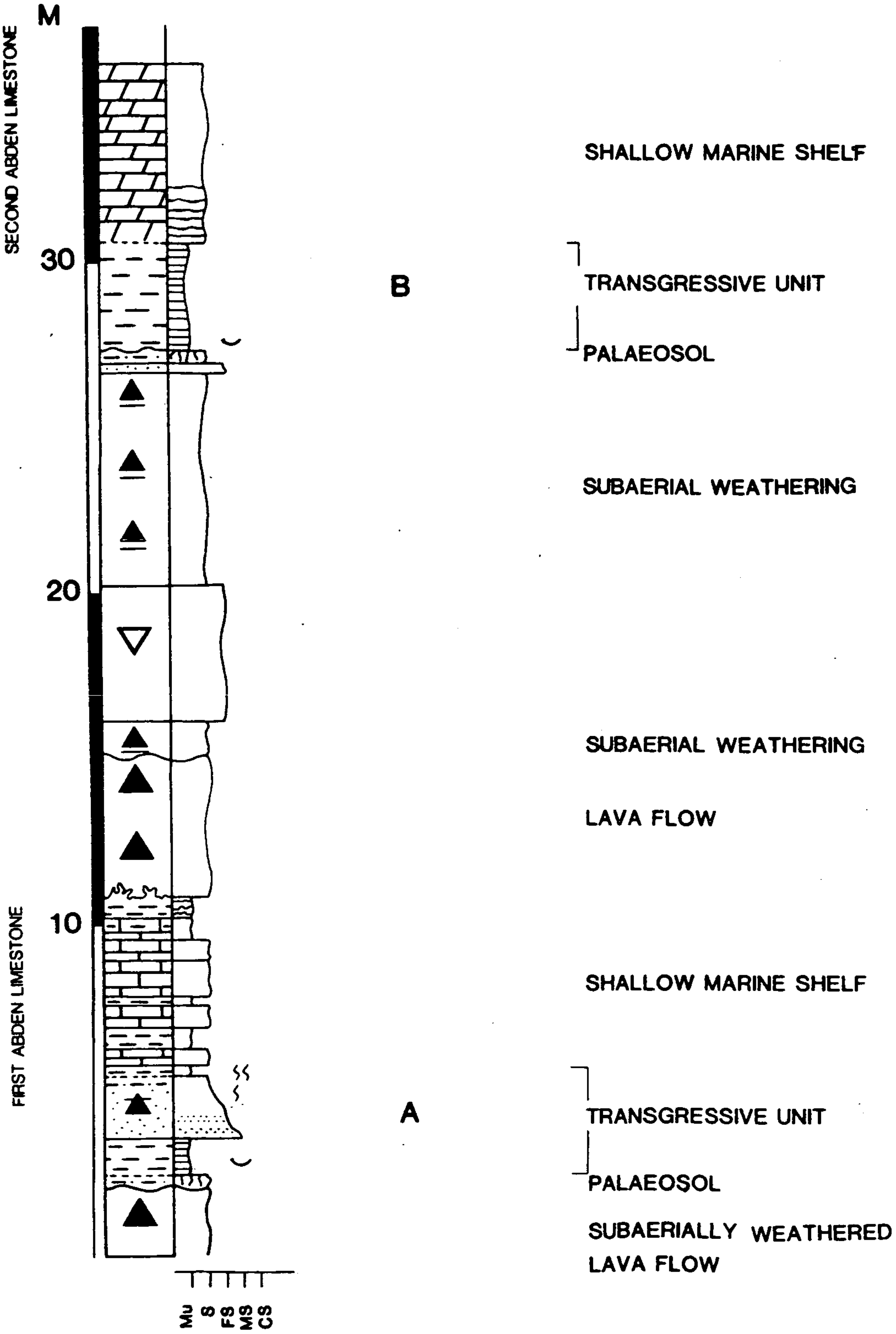

M
SECOND ABDEN LIMESTONE
30
20
10
FIRST ABDEN LIMESTONE
Mu
S
FS
MS
CS
B
A
SHALLOW MARINE SHELF
TRANSGRESSIVE UNIT
PALAEOSOL
SUBAERIAL WEATHERING
SUBAERIAL WEATHERING
LAVA FLOW
SHALLOW MARINE SHELF
TRANSGRESSIVE UNIT
PALAEOSOL
SUBAERIALLY WEATHERED
LAVA FLOW

Fig. 9.3.

Optimized matrix (Jaccard matrix for file FIFEDATA/AC:1) of Jaccard similarity coefficients corresponding to presence/absence data for fossil parameters outlined (1-13) from 187 shale slabs randomly spot sampled from the First Abden Shale (transgressive unit A). The matrix of Jaccard coefficients can be calculated using Jaccard's (1908) coefficient of community, called Jaccard's coefficient (Sokal and Sneath 1963). This enables the degree of association between two components to be calculated in a suite of samples (see Hennebert and Lees 1985, p.124), and this was undertaken along with the optimization by a microcomputer using a BASIC program. Optimization of the matrix of Jaccard coefficients involves the perfect ordering of the matrix so that the maximum number of high values is situated near the diagonal. Each parameter has been given a number (see key to parameters) and the numbers in the brackets=number of samples possessing the parameter out of the total number of samples (187). The matrix is symmetrical, and the degree of association between fossil parameters decreases as the distance between them along the matrix increases. This shows that the process of ordering known as optimization has been completed. The optimized matrix reveals the presence of a relay (Hennebert and Lees 1985), involving the systematic shifting of the relative importance of the fossil parameters throughout the sampled profiles.

Abden Shale

```
                Key to parameters

 1  Product.      2  Actinopt     3  Ostracod     4  Brachiop     5  Sanguino
 6  Plants..      7  Hi-Spire     8  Lingulid     9  Naiadite    10  Lo-Spire
11   Promytil    12  Streblop    13  Bivalves

                          Jaccard Matrix for file FIFEDATA/AC:1

               4    1    2    3   13    6    5    7   12    9    8   10   11
          ---------------------------------------------------------------------
    4 :     100   33   22   19    3    2    0    2    0    0    0    0    0
    1 :      33  100   42   36   14    2    0    3    0    0    0    0    0
    2 :      22   42  100   34   23   13   13    8    7    3    0    0    0
    3 :      19   36   34  100   26   10    7    8    3    0    2    2    2
   13 :       3   14   23   26  100   30    8   15    5    0    0    0    0
    6 :       2    2   13   10   30  100   19   31    9    0    2    0    0
    5 :       0    0   13    7    8   19  100   34   25    4    0    0    0
    7 :       2    3    8    8   15   31   34  100   27    0    0    0    0
   12 :       0    0    7    3    5    9   25   27  100    0    0    0    0
    9 :       0    0    3    0    0    0    4    0    0  100   15    0    5
    8 :       0    0    0    2    0    2    0    0    0   15  100   14   38
   10 :       0    0    0    2    0    0    0    0    0    0   14  100   25
   11 :       0    0    0    2    0    0    0    0    0    5   38   25  100


    4        Brachiop ( 20)                     11       Promytil (  4)
    1        Product. ( 49)                     10       Lo-Spire (  1)
    2        Actinopt ( 87)                      8       Lingulid (  7)
    3        Ostracod ( 60)                      9       Naiadite ( 16)
   13        Bivalves ( 82)                     12       Streblop (  9)
    6        Plants.. ( 39)                      7       Hi-Spire ( 24)
    5        Sanguino ( 31)                      5       Sanguino ( 31)
    7        Hi-Spire ( 24)                      6       Plants.. ( 39)
   12        Streblop (  9)                     13       Bivalves ( 82)
    9        Naiadite ( 16)                      3       Ostracod ( 60)
    8        Lingulid (  7)                      2       Actinopt ( 87)
   10        Lo-Spire (  1)                      1       Product. ( 49)
   11        Promytil (  4)                      4       Brachiop ( 20)
```

Number in brackets = number of samples possessing the parameter out of the total of 187

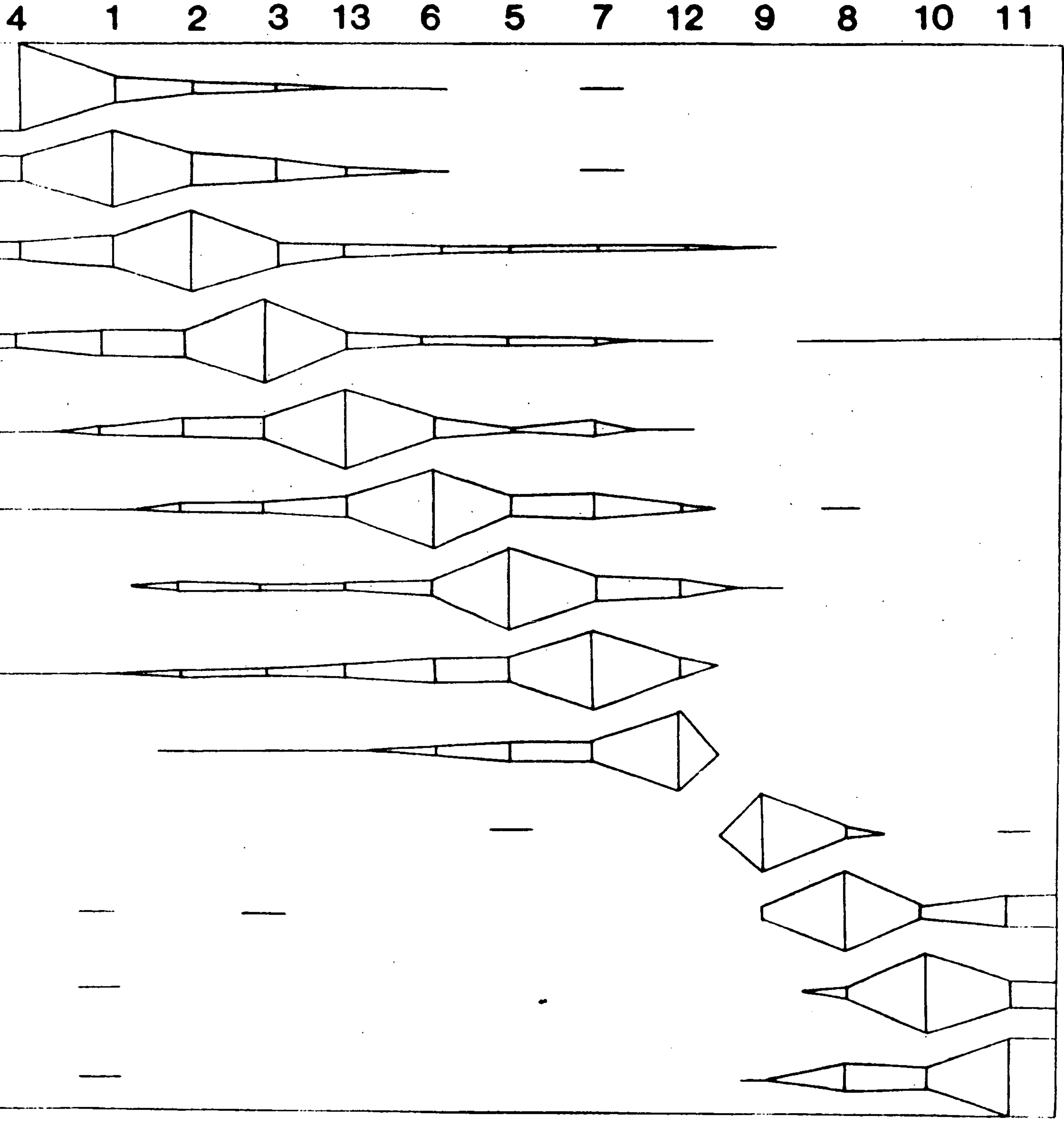
Fig. 9.4.

Optimized matrix (Jaccard matrix for file FIFEDATA/ab:0) of Jaccard similarity coefficients corresponding to presence/absence data of defined fossil parameters from 175 shale slabs randomly spot sampled from the Second Abden Shale (transgressive unit B). Some of the parameters differ from those defined for the First Abden Shale, although many of the faunal elements are common to both shales.

```
                 Jaccard Matrix for file FIFEDATA/ab:0

          9   2  10   6  12   8  15   3   1   4  18  16  14  13  17
        ------------------------------------------------------------
  9 :   100   0   0   0   3   2   0   0   0   0   0   0   0   0   0
  2 :     0 100   9   0   4   7   4   4  10   0   4   0   0   0   0
 10 :     0   9 100   4   7   8   2   2   5   0   2   0   0   0   0
  6 :     0   0   4 100  10  11  21  17   3   0   0   0   0   0   0
 12 :     3   4   7  10 100  42  13  11   5   0   0   0   0   2   0
  8 :     2   7   8  11  42 100  16  14  13   0   6   0   0   3   0
 15 :     0   4   2  21  13  16 100  76  11   4   3   3   7   0   0
  3 :     0   4   2  17  11  14  76 100  17   5   6   8  29   0   2
  1 :     0  10   5   3   5  13  11  17 100  14  29  25  11   2   2
  4 :     0   0   0   0   0   0   4   5  14 100  15  14   0   0   0
 18 :     0   4   2   0   0   6   3   6  29  15 100   8   8   4   0
 16 :     0   0   0   0   0   0   3   8  25  14   8 100   6   2   5
 14 :     0   0   0   0   0   0   7  29  11   0   8   6 100   0   6
 1  :     0   0   0   0   2   3   0   0   2   0   4   2   0 100   0
 17 :     0   0   0   0   0   0   0   2   2   0   0   5   6   0 100

            9      Naiadite (  2)                17      Corals   (  4)
            2      Actinopt ( 14)                13      Bivalves (  6)
           10      Lo-Spire ( 10)                14      Bairdid  ( 13)
            6      Plants.. ( 18)                16      Crinoids ( 37)
           12      Streblop ( 37)                18      Crurith. ( 41)
            8      Lingulid ( 61)                 4      Brachiop ( 19)
           15      Paraparc ( 34)                 1      Product. ( 97)
            3      Ostracod ( 45)                 3      Ostracod ( 45)
            1      Product. ( 97)                15      Paraparc ( 34)
            4      Brachiop ( 19)                 8      Lingulid ( 61)
           18      Crurith. ( 41)                12      Streblop ( 37)
           16      Crinoids ( 37)                 6      Plants.. ( 18)
           14      Bairdid  ( 13)                10      Lo-Spire ( 10)
           13      Bivalves (  6)                 2      Actinopt ( 14)
           17      Corals   (  4)                 9      Naiadite (  2)

Number in brackets = number of samples possessing the parameter out of the total
 of 175
```

Fig. 9.5.

Graphic representation of the optimized matrix for Jaccard coefficients from the file FIFEDATA/AC:1 (transgressive unit A) calculated from presence/absence data of 187 shale slab samples from the First Abden Shale (transgressive unit A). The column to the left and the row above the diagram indicate the numbers which refer to fossil parameters. Fully marine fossil parameters such as productids (4) and other articulate brachiopods (1) are closely associated at one end of the graph, whereas postulated lower salinity faunal elements such as *Promytilus* (11), gastropods (10) and *Lingula* (8) are closely associated at the opposite end of the graph, suggesting dissociation of these two broad groups of faunas. This mutual exclusion is expressed in the 'stratigraphical' distribution of the faunas in the shale bed, where the latter group occur towards the base, and the former group occur towards the top, closer to the limestone. As most of the fossils do not appear to have been subjected to a great deal of *post-mortem* disturbance, the relay (Hennebert and Lees 1985) would suggest the preservation of an original environmental profile, with restricted marine fossil assemblages at the base and more open marine assemblages towards the top.


4
1
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11

Fig. 9.6.

Graphic representation of the optimized matrix for Jaccard coefficients from the file FIFEDATA/ab:0 (transgressive unit B) calculated from the presence/absence data of 175 shale slab samples from the Second Abden Shale (transgressive unit B). The numbers in the column to the left of the graph and the row above it refer to the fossil parameters. As in the First Abden Shale, a relay is revealed, with a clustering of corals (17), marine bivalves (13) and marine ostracodes (14) which are closely associated at one end of the graph, and a clustering of lower salinity elements such as *Naiadites* (9), *Actinopteria* (2) and certain gastropods (10) towards the other end of the graph. The dissociation between these broad groups of fossils is reflected in the shale, where elements such as *Naiadites* occur towards the base, whereas corals occur towards the top. As is the case with the First Abden Shale, the detection of a relay would appear to suggest that an environmental profile representing a series of faunal assemblages adapted to the different stages of a marine transgression has been preserved (Ferguson 1962). The faunas towards the base of the shale are therefore indicative of brackish to brackish-marine salinities, whereas the fossils at the top of the unit record more open marine conditions, similar to those expressed by the fossils in the Second Abden Limestone.

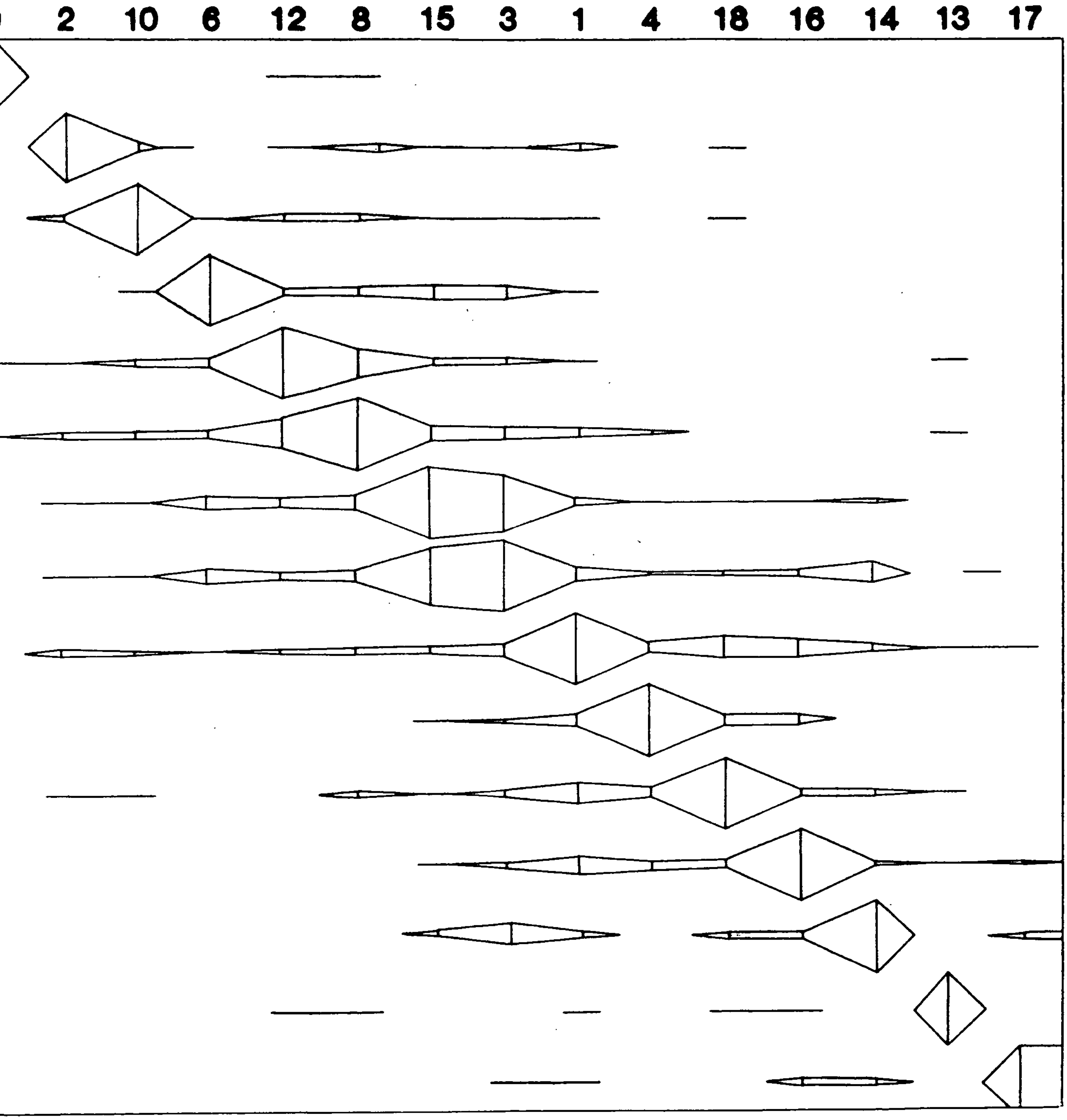
2
10
6
12
8
15
3
1
4
18
16
14
13
17

Fig. 9.7

A. Poorly preserved *Spirorbis* worm tube from near the base of the First Abden Shale ('*Promytilus* biofacies' between the Abden Bone Bed and the *Naiadites crassus* Fleming shell bed). This part of the shale is dominated by the restricted marine/quasi-marine bivalve *Promytilus* sp., with subordinate lingulids, fish remains, ostracodes, plants, *Curvirimula* and spirorbid worm tubes. This specimen of *Spirorbis* is covered with coarse white granular calcite, which obscures detail of the shell structure etc. Scale: horizontal field of view=1 mm.

B. Poorly preserved specimen of *Curvirimula scotica* (R. Etheridge jun.) (left valve) from the '*Promytilus* biofacies' towards the base of the First Abden Shale. Coarse, white granular calcite covers the valve, partially obscuring the growth lines. It is possible that spirorbid worm tubes (as in A, above) were attached to *Curvirimula*, as both occur in the same part of the shale, although none were observed adhered. Scale: horizontal field of view=2 mm.

C. Ostracode from the '*Promytilus* biofacies' of the First Abden Shale. Scale: horizontal field of view=1 mm.

D. Left valve of the marginal marine bivalve *Promytilus* from the '*Promytilus* biofacies' of the First Abden Shale, where this form occurs in large numbers upon parting plane surfaces in association with few other fossils, constituting monotypic assemblages (cf. Hudson 1980). Scale: horizontal field of view=3 mm

E. Specimen of the inarticulate brachiopod *Lingula squamiformis* Phillips from the '*Promytilus* biofacies' of the First Abden Shale, with some of the original chitinophosphatic valve preserved (cf. Graham 1970). Scale: horizontal field of view=4 mm.

F. Disarticulated paleoniscoid phosphatic fish scale from the '*Promytilus* biofacies' of the First Abden Shale. Scale: horizontal field of view=2 mm.

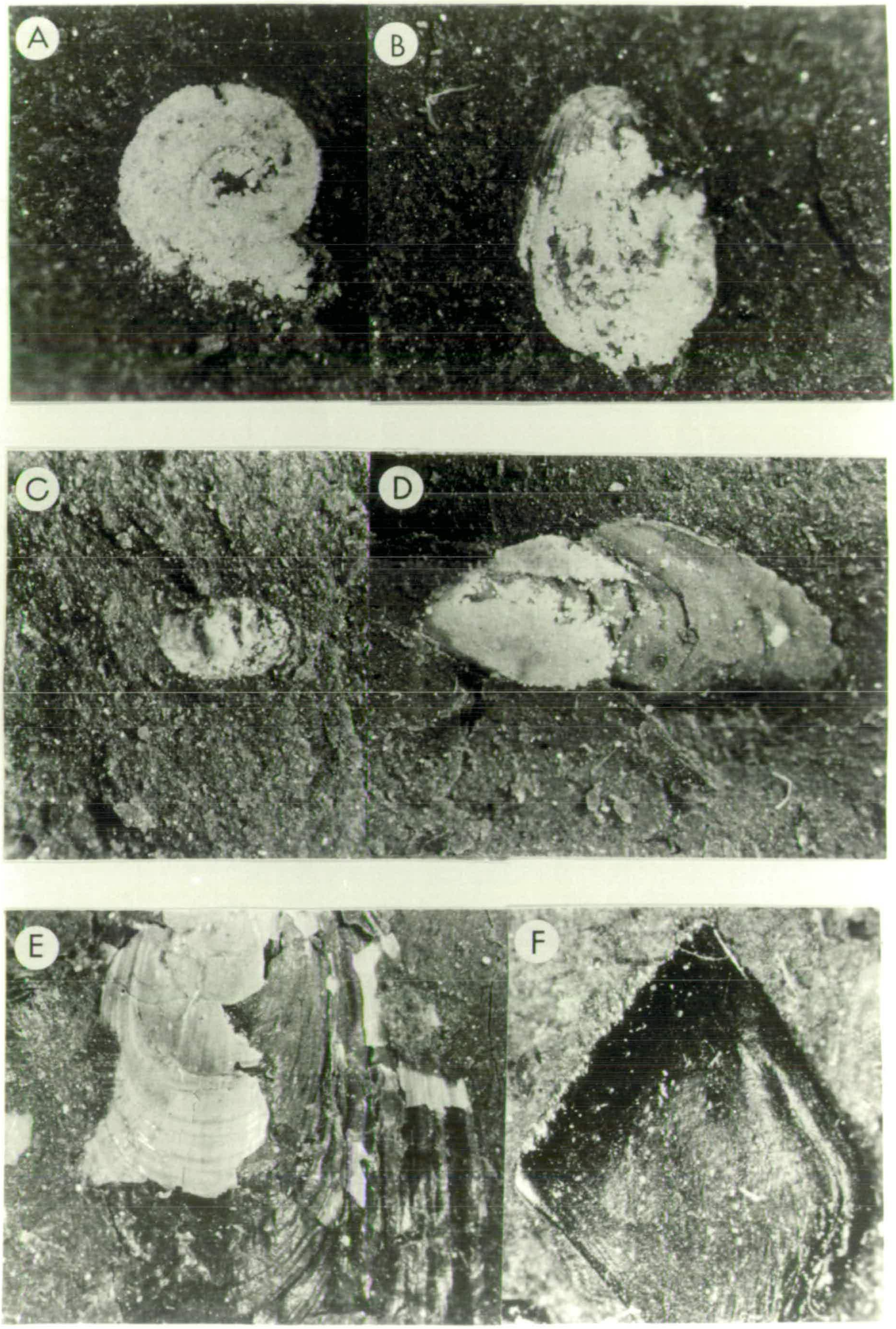
A
B
C
D
E
F

Fig. 10.1.

Sketch map of Fife and the Lothians area bordering the Firth of Forth at the eastern end of the Scottish Midland Valley, showing locations of localities studied. In central Fife, the sections on the coast between Kinghorn and Kirkcaldy and in the Seafield Colliery were examined, whilst in the Lothians, the Catcraig coastal section, the Dunbar Works Quarry, and the Skateraw Borehole sections were investigated.

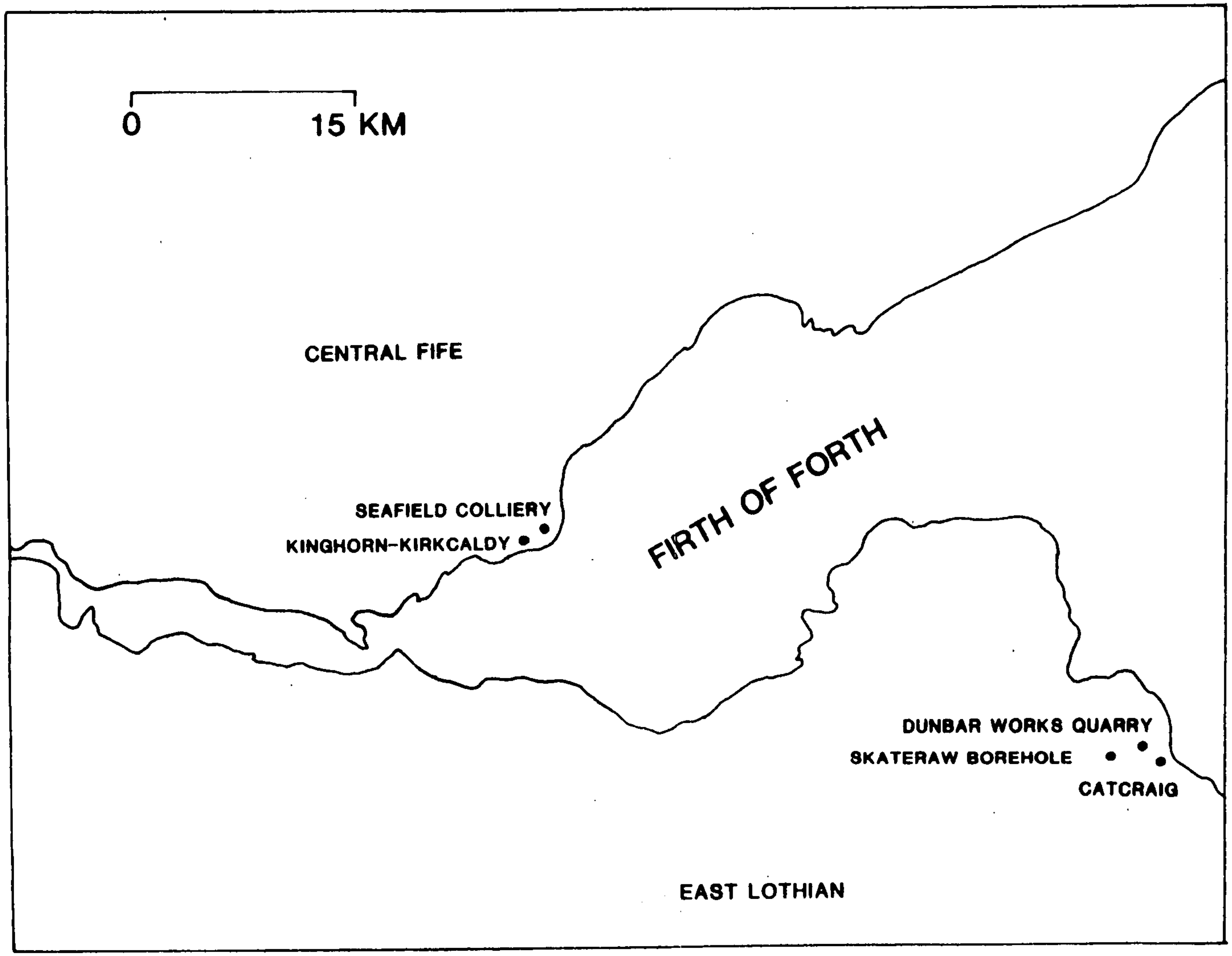
0
15 KM
CENTRAL FIFE
SEAFIELD COLLIERY
KINGHORN-KIRKCALDY
FIRTH OF FORTH
DUNBAR WORKS QUARRY
SKATERAW BOREHOLE
CATCRAIG
EAST LOTHIAN

Fig. 10.2.

Table showing major marine limestone horizons in the lower part of the Lower Limestone Group in West Fife, central Fife, East Fife and East Lothian (not to scale). The base of the Lower Limestone Group is drawn at the base of the Second Abden Limestone (central Fife) and equivalent limestones (e.g. Charlestown Station, St Monans Brecciated and Upper Longcraig limestones), whilst the major Seafield Tower Limestone (central Fife) towards the middle of the group is correlated with the Charlestown Main, 'Five Foot' and Middle Skateraw limestones. The Charlestown Green Limestone of West Fife occurs in a position between the two major limestones which occur at the base and towards the middle of the Lower Limestone Group, and is correlated with the St Monans Little Limestone of East Fife and the Lower Skateraw Limestone of East Lothian. This limestone, however, is absent in central Fife (assuming the correlations of the Seafield Tower and Second Abden limestones are correct) and is partially absent in East Lothian. These absences have caused problems in correlation in the past, as the Second Abden Limestone has sometimes been correlated with the Charlestown Green and St Monans Little limestones. It is now assumed, however, that the limestone has been removed by fluvio-deltaic processes in central Fife, and partially removed by the same processes in East Lothian.

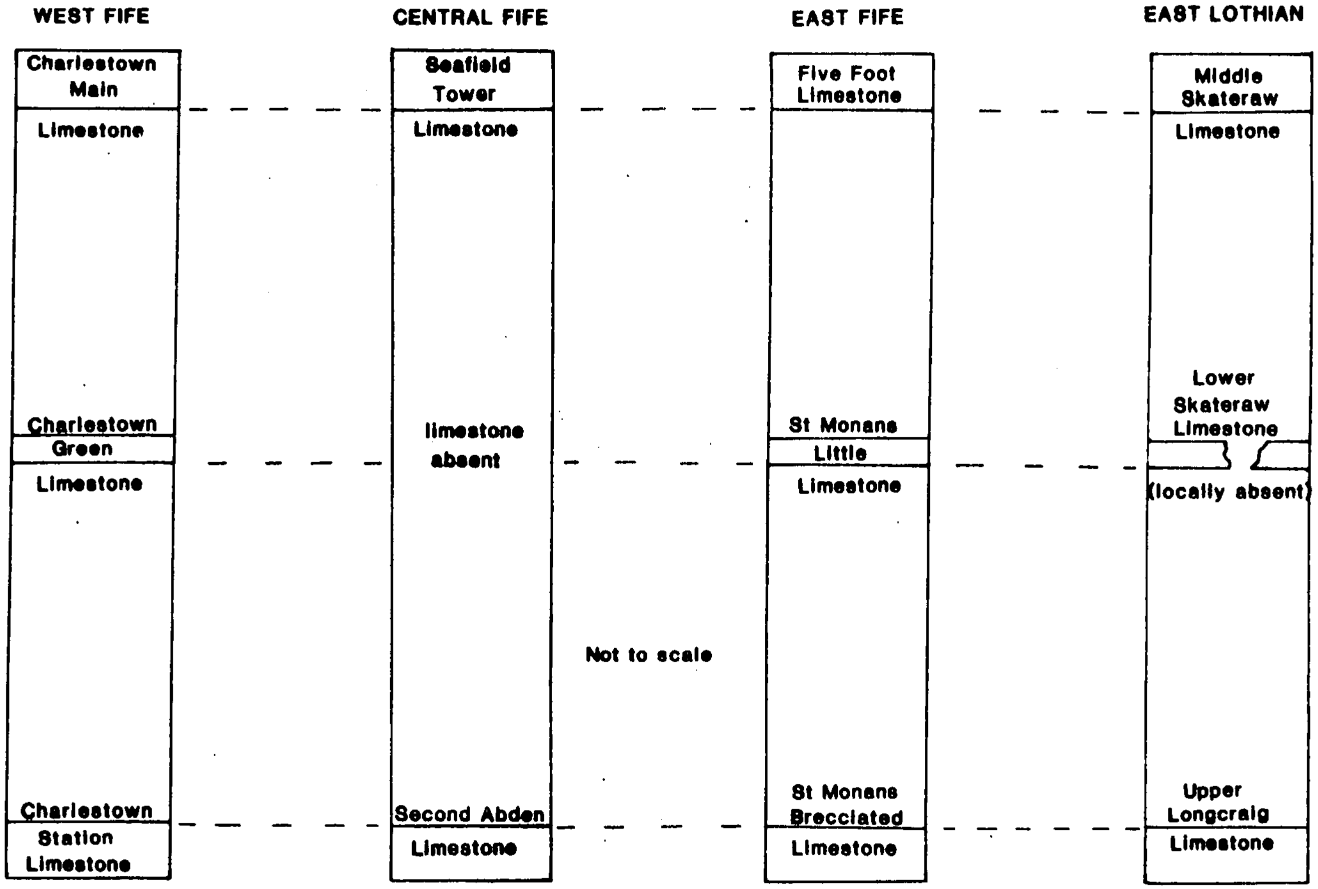
WEST FIFE
CENTRAL FIFE
EAST FIFE
EAST LOTHIAN
Charlestown Main Limestone
Seafield Tower Limestone
Five Foot Limestone
Middle Skateraw Limestone
Charlestown Green Limestone
limestone absent
St Monans Little Limestone
Lower Skateraw Limestone
(locally absent)
Not to scale
Charlestown Station Limestone
Second Abden Limestone
St Monans Brecciated Limestone
Upper Longcraig Limestone

Fig. 10.3.

Graphic sedimentary log of the interval between the Second Abden and Seafield Tower limestones as exposed in the Kinghorn-Kirkcaldy coastal section, central Fife. The postulated former position of the thin Charlestown Green Limestone has been placed above a major paleosol (abandonment facies) horizon, and below a major channel sandstone sequence which has presumably removed it. The 'slotting in' of the limestone into its presumed former position helps to explain the anomalously thick non-marine interval noted by previous workers (Geikie 1900; Gordon 1914; Wright 1922; Allan 1924; Allan and Knox 1934; Francis 1960, 1961a; MacGregor 1968, 1973). Two to three coal seams have also been identified on the coast, and three seams are also present at this level in the Seafield Colliery Shaft (Francis 1961a, p.25). Previous workers have tended to neglect the clastic sequences in the succession and invariably this interval has been merely noted down as 25.50 m (the thickness is actually nearly 50 m) of sandstones and shaly sandstones (Francis 1961a, p.19; MacGregor 1973, p.254) or 30 m of 'strata' (Wright 1922, p.295), and this has resulted in the lack of recognition of the former presence of the now missing limestone. Because most of the pre-1950's-60's geologists were mainly intersested in the fossil-bearing horizons (marine shales and limestones) little is known of the clastic rocks.

CLASTIC INTERVAL BETWEEN SECOND ABDEN AND SEAFIELD TOWER LIMESTONES, KINGHORN-KIRKCALDY COASTAL SECTION, CENTRAL FIFE

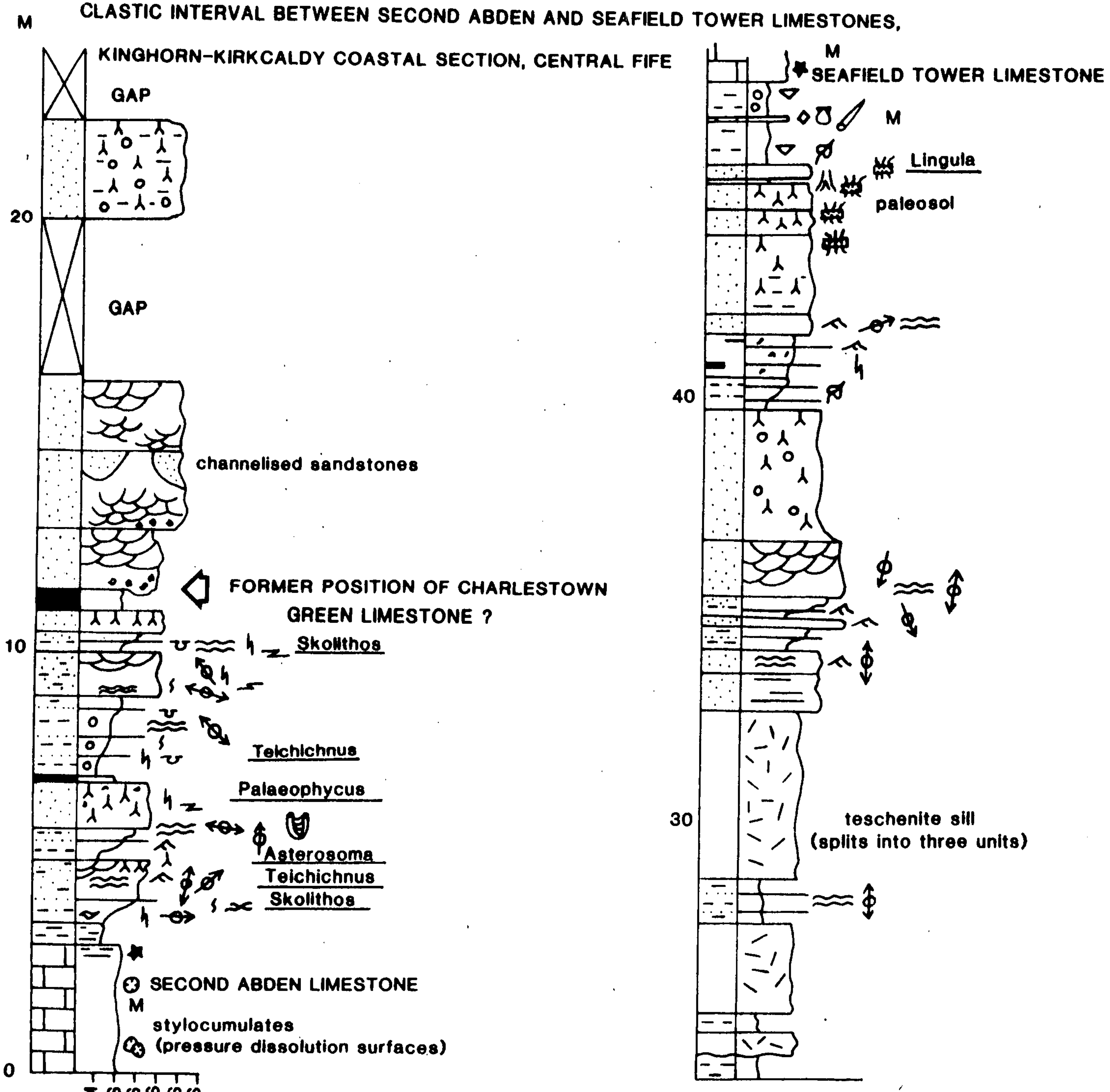

Fig. 10.4.

A. Outcrop of the Second Abden Limestone on the foreshore below Abden House, on the coast between Kinghorn and Kirkcaldy, central Fife. The well pseudo-bedded nature of the limestone is conspicuous, as is the undulatory-hummocky nature of the pseudo-bed contacts. These contacts are characterised by shaly stylocumulates with a crude lamination, flattened fossils and crinoid ossicle 'idens' (Logan and Semeniuk 1976), which weather out preferentially. The dark rusty brown iron-stained discolouration of the limestone which has been dolomitised (late diagenetic ferroan dolomite) is noticeable in the vicinity of a series of dip faults which displace the outcrop dextrally and are characterised by limestone breccias along the fault planes. Scale: camera bag, length=24 cm.

B. Hummocky-nodular pressure-dissolution surface in the Second Abden Limestone (see A, above), displaying large colonies of the colonial coral *Lithostrotion junceum*. Some of the colonies are characterised by a central zone of erect, vertically orientated corallites, whilst the corallites splay-out in a radial fashion around the edge of the colony. These colonies are evidently *in situ* and are classified as coral biolithites or boundstones. *Lithostrotion* is most common in the lower part of the limestone, where colonies occur as 'pockets' in two distinct bands (Francis 1961a). Scale: geological hammer, length=40 cm.

C. Close-up view of a *Lithostrotion* colony from the Second Abden Limestone, showing horizontally orientated corallites which radiate away from a central core, where corallites are erect. Scale: geological hammer, length=40 cm.

D. Close-up view of a *Lithostrotion* colony in the lower part of the Second Abden Limestone, showing central part of an individual colony characterised by *in situ*, vertically orientated corallites (where camera lens cap is placed). The corallites around the edge of the colony form a fan-like radial pattern around the central core. Scale: camera lens cap, diameter=6 cm.

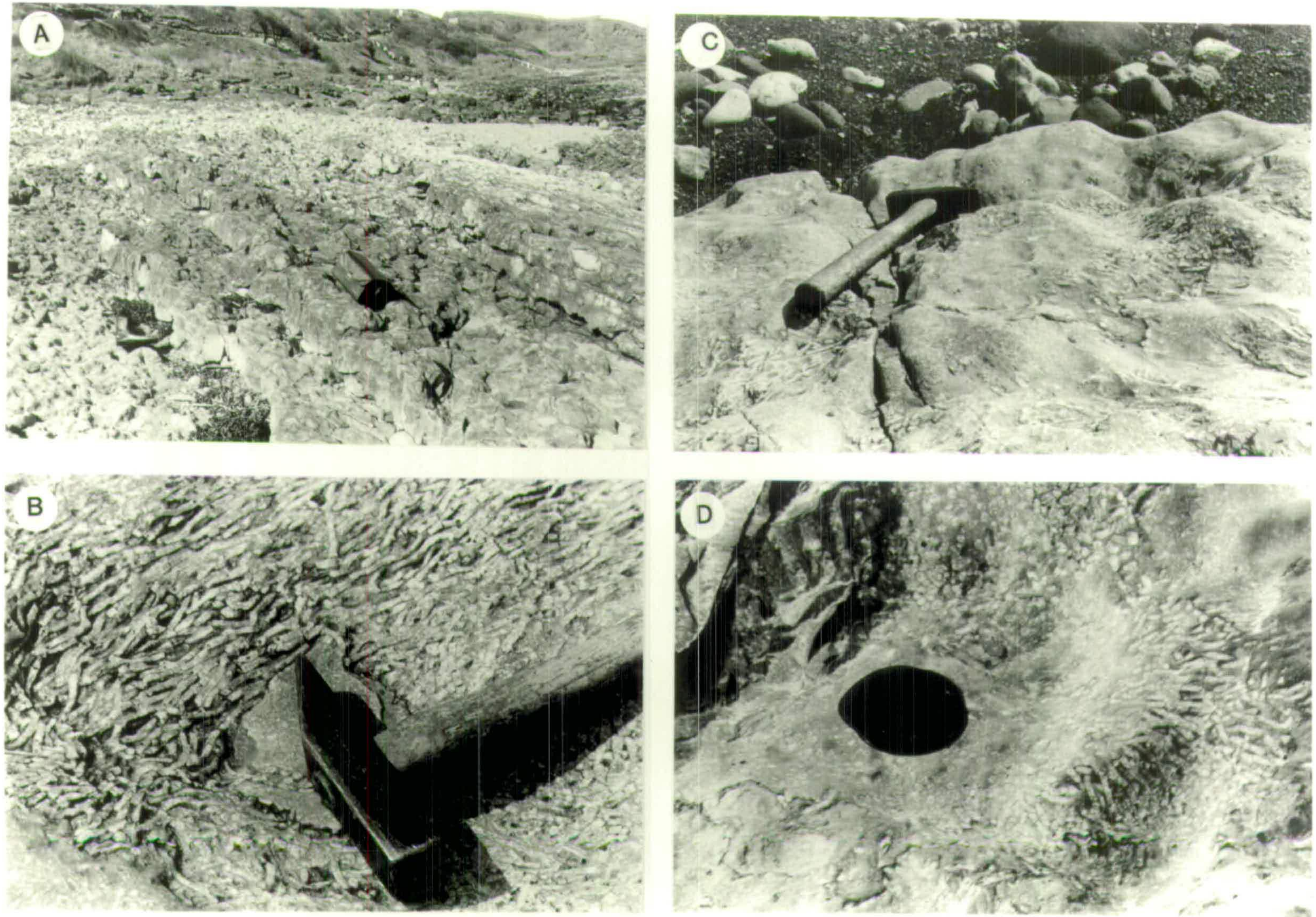
A
C
B
D

Fig. 10.5.

A. Photomicrograph of a thin section of the lower part of the Second Abden Limestone, showing *Lithostrotion* corallites and the encrusting alga, *Calcifolium punctatum* Maslov. Preservation of the internal structure of the corallite is generally poor, although septae are clearly visible. Foraminifera such as *Howchinia bradyana* in the top right hand corner are present. The fine-grained micritic nature (almost dark black in colour) of the thallus (less than 1μ) which causes it to appear dark in thin section is also conspicious. The stem wall is pierced by a network of longitudinal canals. The lateral plates (cf. Burgess 1965) appear as dark, ragged strips where they encircle the corallites and then veer away to give rise to complex branches. Scale: field of view=6 mm across.

B. Thin section photomicrograph (Second Abden Limestone) showing close-up of contact between encrusting *Calcifolium* and a *Lithostrotion* corallite. The dark micritic nature of the algal thallus is distinctive, and the lighter coloured, coarser-grained micritic fabric of the corallite wall and septae is conspicious. Very few of the longitudinal canals which pierce the stem wall of the alga are actually visible. The septae and tabulae of the corallite are well preserved, although partially pyritized, and small pyrite specks are abundant. The corallite has also been infilled with a coarse, clear sparry cement. Scale: field of view=3 mm across.

C. Thin section photomicrograph of Second Abden Limestone showing the codiacean alga *Calcifolium punctatum* Maslov. The dark colour of the micritic thallus is distinctive, and the canal system, which takes the form of a network and fills the thickness of the stem wall and the lateral plates is noticeable. Other bioclasts in the field of view are filled with blocky, clear spar and the matrix is micritic. Pyrite is present, as are cross-sections through brachiopod spines. The spar is a cement which was probably precipitated in the bioclasts after a dissolution event (?aided by micrite envelopes which created a moldic porosity). Scale: field of view=4-5 mm.

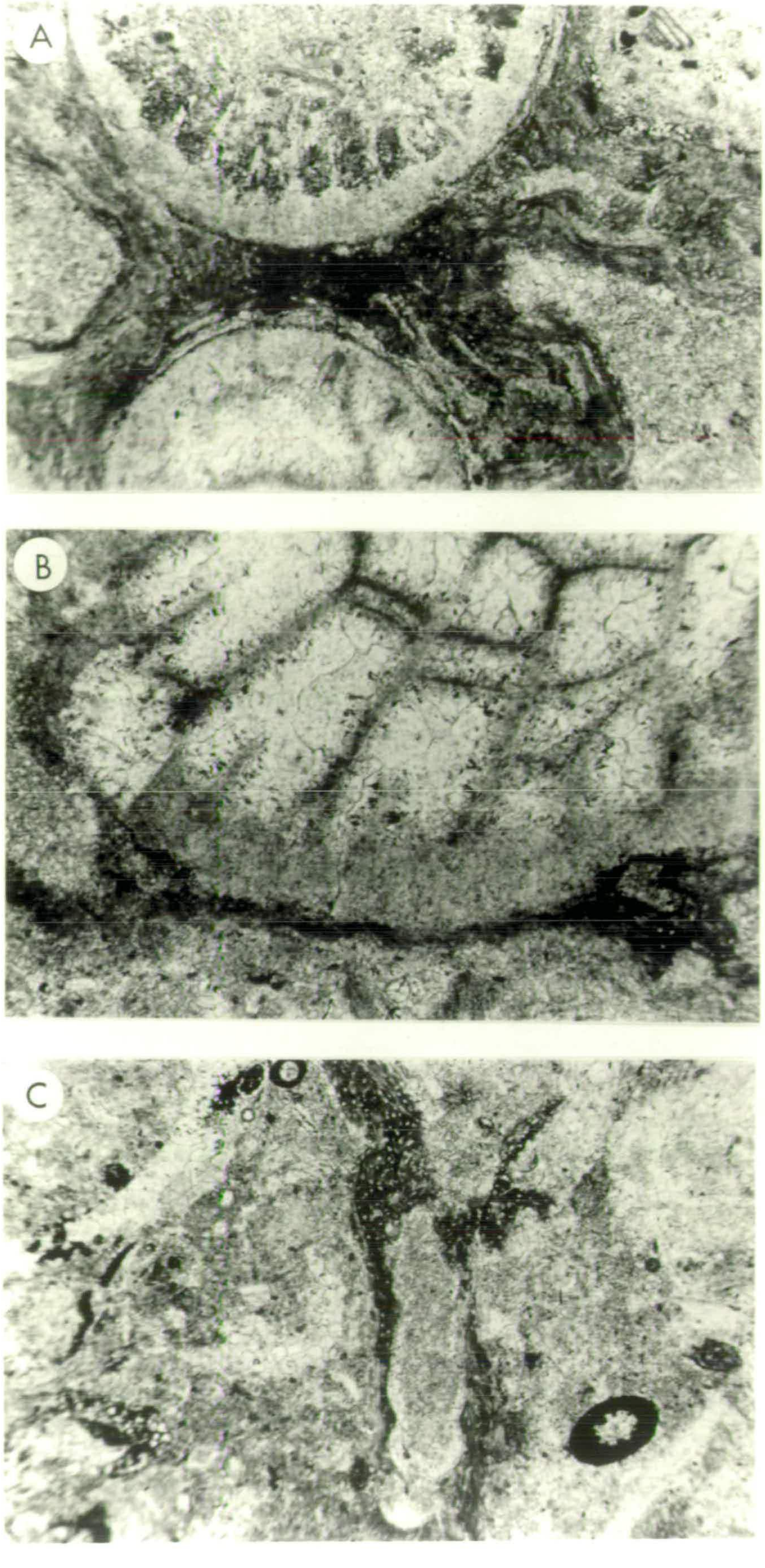
A
B
C

Fig. 10.6.

A. Thin section photomicrograph of the Second Abden Limestone showing the foraminifer *Howchinia bradyana* (Howchin) (Howchin 1888; Davies 1951). The good preservation of such a foraminifer compared with other fossils and bioclasts in the limestone is evident. *Howchinia* has a trochoid test and consists of a spiral tube wound round a conical umbilical core of microcrystalline shell structure. This foraminifer has a stratigraphical usefulness (Davis 1951) and is commonly associated with other foraminifera and algae. The limestone is a biosparite, with spar infilling bioclasts (blocky cement) and some neomorphic spar. Micrite is still present, however, though largely as relics of a more widespread micrite matrix. Pyrite is present, as are 'ghosts' of bioclasts which are now mere spar-filled outlines. Scale: field of view=4 mm

B. Thin section photomicrograph of the Second Abden Limestone showing a close-up of the foraminifer *Palaeotextularia longiseptata* Lipina. This foraminifer diplays a biserial growth pattern and has a two-layered wall. The walls are composed of dark, fine-grained micrite and the chambers are infilled with clear blocky spar. The 'matrix' is largely sparry, with only a few relic micrite patches. Scale: field of view=4 mm

C. Thin section photomicrograph of the Second Abden Limestone showing the foraminifer *Bradyina rotula* Eichwald. It is infilled by a coarse blocky spar cement and the outer wall structure is partially preserved. Bioclasts in the matrix surrounding the foraminifer are mere spar-filled outlines ('ghosts') although the surrounding micrite matrix is still present. *Bradyina* along with *Howchinia* and cibrate palaeotextularids such as *Palaeotextularia* and *Janischewskina* are particularly characteristic of the V_{3c} foraminiferan zone in Belgium (Conil *et al.* 1971; George *et al.* 1976; Jameson 1980). All these forms occur in the Second Abden Limestone and have also been noted from the Petershill Formation (Seafield Tower Limestone equivalent) near Bathgate, West Lothian (Jameson 1980, 1987). Scale: field of view=4 mm.

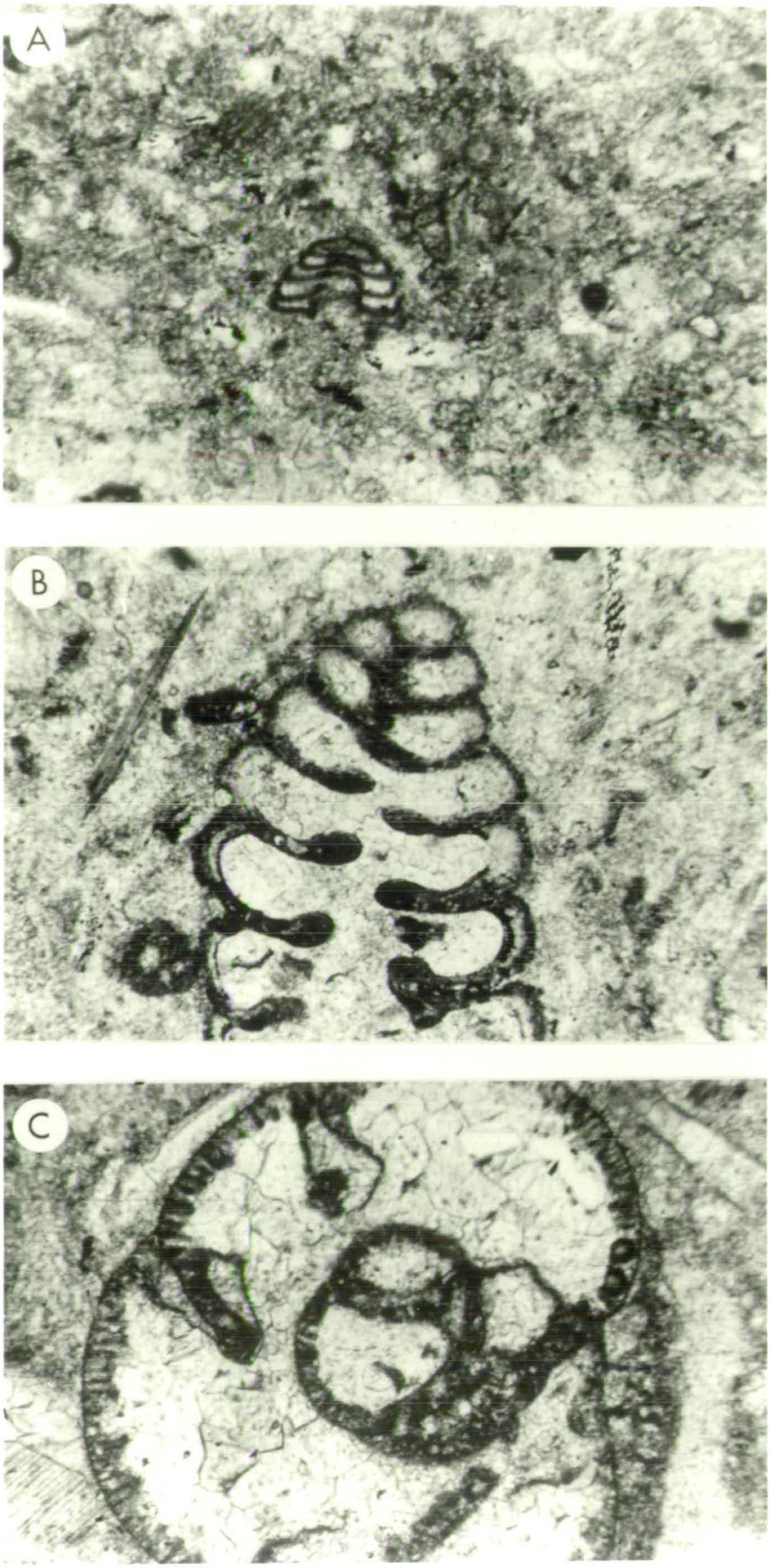
A
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Fig. 10.7.

A. View of delta-front, thinly-bedded sandstones overlying the Second Abden Limestone on the foreshore below Abden House, Kinghorn-Kirkcaldy coastal section, central Fife. Other than a thin intervening mudrock bed containing crinoid debris, the delta-front sandstones directly overlie the limestone. The wafer-like nature of the thin sandstone beds which are intercalated with very thin mudrock laminae are distinctive. This part of the succession has been displaced by a small dip-fault which has an upthrow side to the N. Scale: camera bag, length=24 cm.

B. Close-up view of delta-front sandstones above the Second Abden Limestone (see A, above). The wavy-undulatory nature of the thin sandstone beds and laminae, which are extensively wave-rippled, lenticular, wavy and flaser bedded is conspicious. At this point in the sequence (lower part) sandstone lenticles (starved ripples or linsen) are common. Scale: camera bag, length=24 cm.

C. Close-up view of fresh surface face of flaser-bedded delta-front sandstones above the Second Abden Limestone. The thin sandstone beds are extensively wave-rippled, with internal cross-laminae, and the ripple troughs, between the crests are infilled with a thin mudrock smear. These flaser beds overlie the lenticular and wavy beds and are bioturbated and characterised by shallow marine trace fossil faunas such as *Diplocraterion* and *Skolithos*.
Scale: camera lens cap, diameter=6 cm.

A

B

C

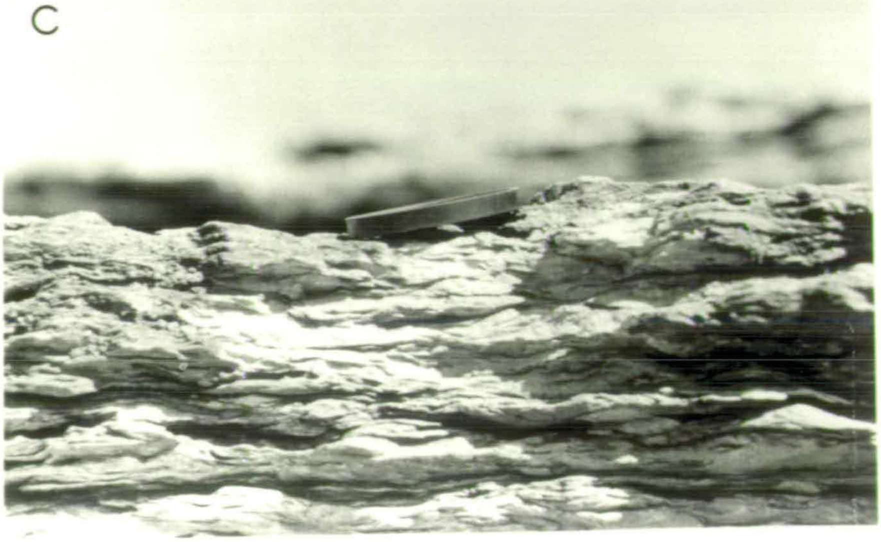


Fig. 10.8.

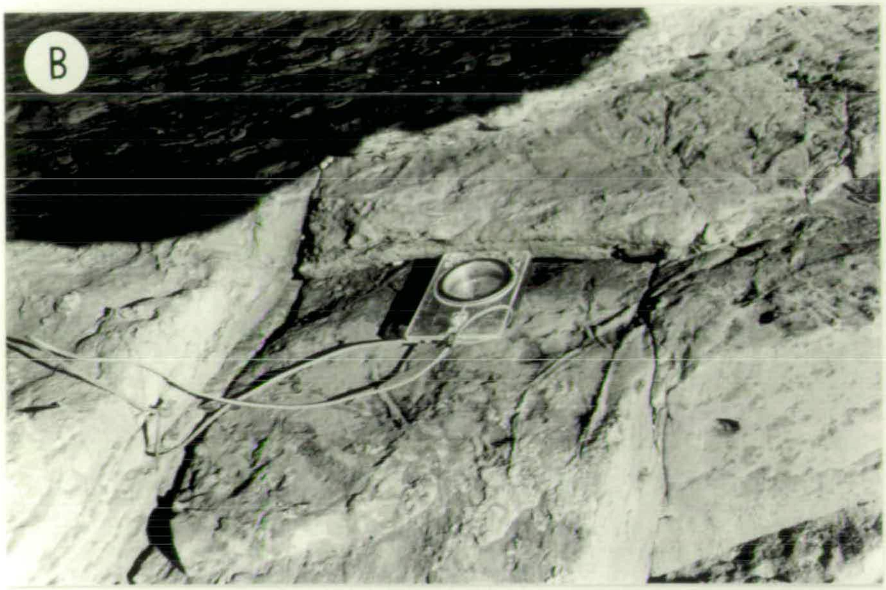
A. View of the coarsening-upward sequence capped by sandy mouth-bar deposits above the wave-reworked delta-front sandstones overlying the Second Abden Limestone, Kinghorn-Kirkcaldy coastal section, central Fife. The lower part of the sequence contains several smaller coarsening-upward sequences which are capped by sandstones, but largely consist of dark, fissile shales. The overall coarsening-upward trend is interpreted as representing the constructive progradation of a mouth-bar. Also, in general, the lower part of the sequence (foreground of the photograph) is mudrock dominated, whereas the upper part of the sequence is sandstone dominated (background of the picture). This is interpreted as a transition from distal mouth-bar deposits to proximal mouth-bar facies. Scale: coarsening-upward sequence approximately 4 m in thickness.

B. Close-up view of bioturbated/trace fossil-rich abandonment facies which caps proximal abandoned mouth-bar sandstones (see A, above). The presence of interfacial epichnial trails of *Gyrochorte* and *Planolites* is conspicious as well as numerous other trace fossils and more indiscriminate bioturbation. Similar abandonment facies have been described capping other mouth-bars presumed to have formed in elongate deltas (e.g. De Raaf *et al.* 1965: Elliot 1976a), and appear to have been formed during low rates of sedimentation, biogenic reworking and subsidence after abandonment of the distributary channel and associated mouth-bar. Scale: geological compass-clinometer, length=10 cm.

C. Wave-rippled sandstones with interfacial epichnial trails of *Gyrochorte* and *Planolites* from the upper, sand-dominated member of the mouth-bar facies (see A, above). Although mouth-bars show little marine influence and no evidence of wave-reworking in the underlying Oil-Shale Group (Cater 1987; Maddox and Andrews 1987), in the overlying Lower Limestone Group (as in this case) ?marine, wave-reworking is evident. The presence of vertical pipe-like burrows and U-shaped tubes is evident, the burrow entrances of which are seen on the bed top. The wave-ripple crests are symmetrical, rounded and laterally continuous. Scale: geological compass-clinometer, length=10 cm.

A

B



C

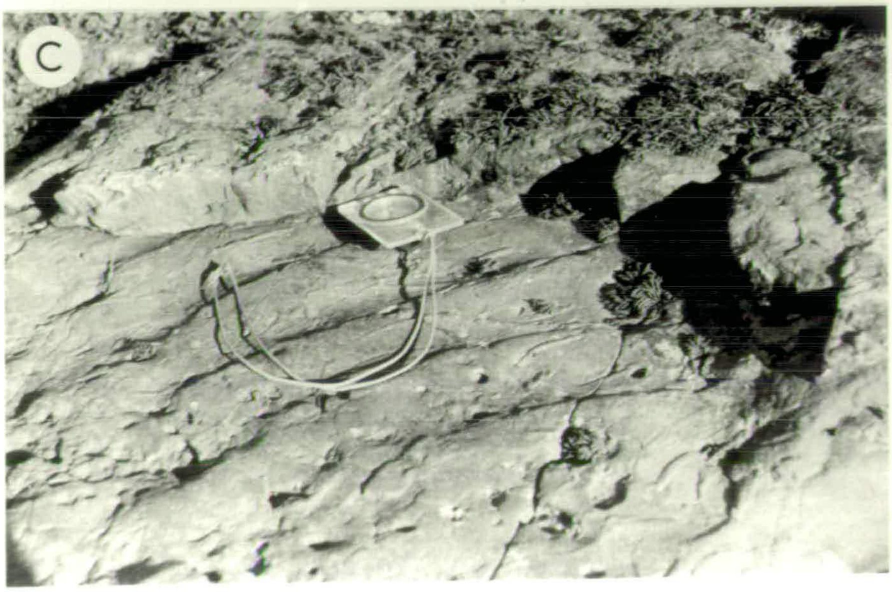


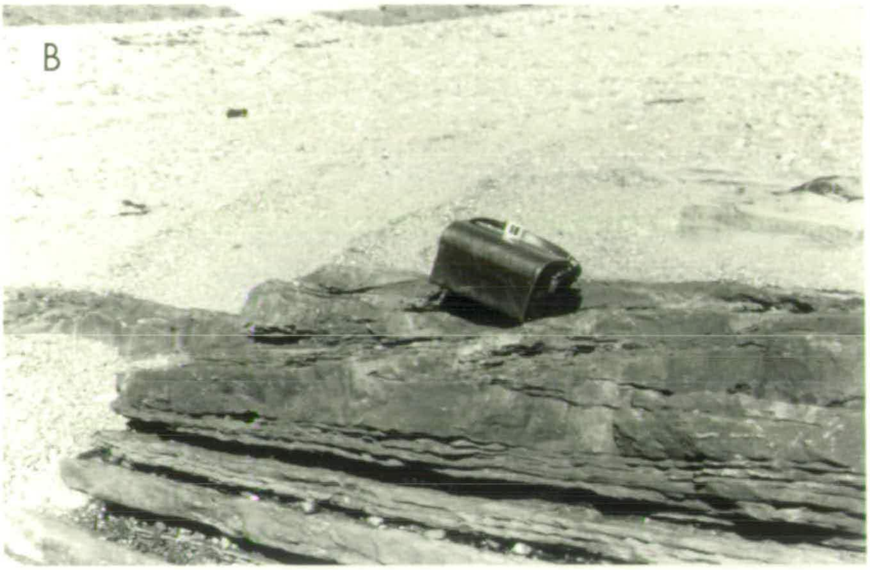
Fig. 10.9.

A. Trough cross-bedded sandstone facies of the upper sand-dominated member of the mouth-bar facies capping the major coarsening-upward sequence above the delta-front sandstones overlying the Second Abden Limestone, Kinghorn-Kirkcaldy coastal section, central Fife. The cross-bedding forms a single solitary set which overlies a lower wave-ripple bedded facies. Scale: camera bag, length=24 cm. Interpretation: cross-bedded facies is interpreted as representing the proximal mouth-bar facies where channel bedforms such as curve-crested dunes migrated at high flow stage in the channel feeding the mouth-bar and were deposited on top of, and cut into earlier deposits (note sharp base to cross-bedded sandstone).

B. Close-up view of massive trough cross-bedded proximal mouth-bar sandstones overlying extensively wave-rippled flaggy sandstones on the foreshore between Kinghorn-Kirkcaldy, central Fife. A small erosive 'cut-and-fill' channel is present which cuts into curved foreset surfaces in the solitary cross-bed set (upon which the camera bag is positioned). Scale: camera bag, length=24 cm.

C. Extensive wave-rippled upper bedding surface of flaggy bedded sandstones underlying trough cross-bedded sandstone facies (see B, above) in upper sand-dominated member of the mouth-bar. The lateral continuity, occasional bifurcation, crest symmetry and rounded profiles of ripple crests are evident. Scale: geological compass-clinometer, length=10 cm.


A


B


C

Fig. 10.10.

Graphic sedimentary log of the small quarry section exposing the top of the mouth-bar facies (above the major coarsening-upward sequences overlying the delta-front sandstones which cap the Second Abden Limestone) and overlying sandstones which are presumed to have removed the Charlestown Green Limestone. Kinghorn-Kirkcaldy coastal section, central Fife. A coal is present (paleosol-abandonment facies) which is also recognised on the shore at this position.

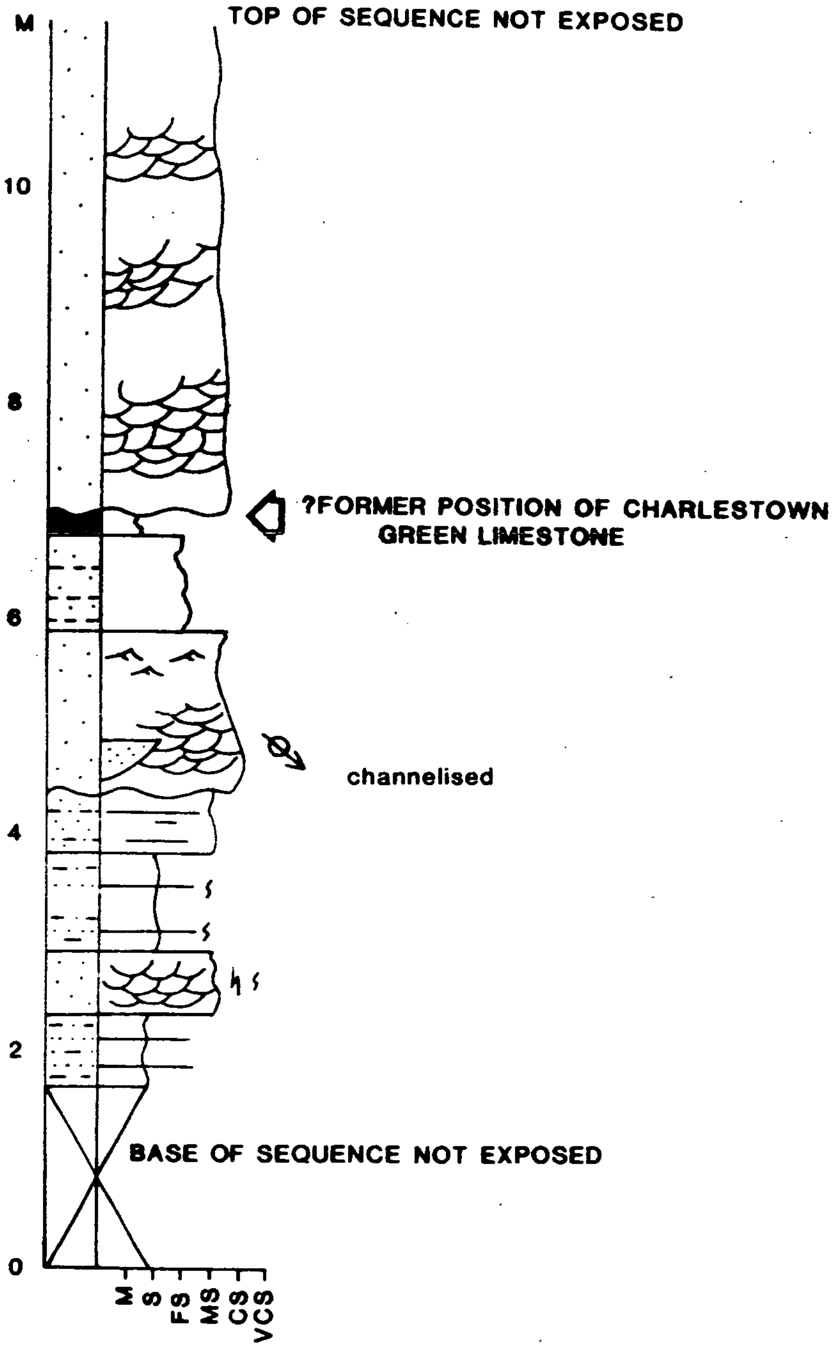

M
10
8
6
4
2
0
TOP OF SEQUENCE NOT EXPOSED
?FORMER POSITION OF CHARLESTOWN GREEN LIMESTONE
channelised
BASE OF SEQUENCE NOT EXPOSED
M
S
FS
MS
CS
VCS

Fig. 10.11.

Graphic sedimentary log of the interval between the Second Abden and Seafield Tower limestones from the Seafield No.1 Colliery Shaft, central Fife (Francis 1961a). Three coals are present (as on the coast) and the presence of a major dolerite sill is evident. This occurs in the part of the sequence where the Charlestown Green Limestone is assumed to have been situated.

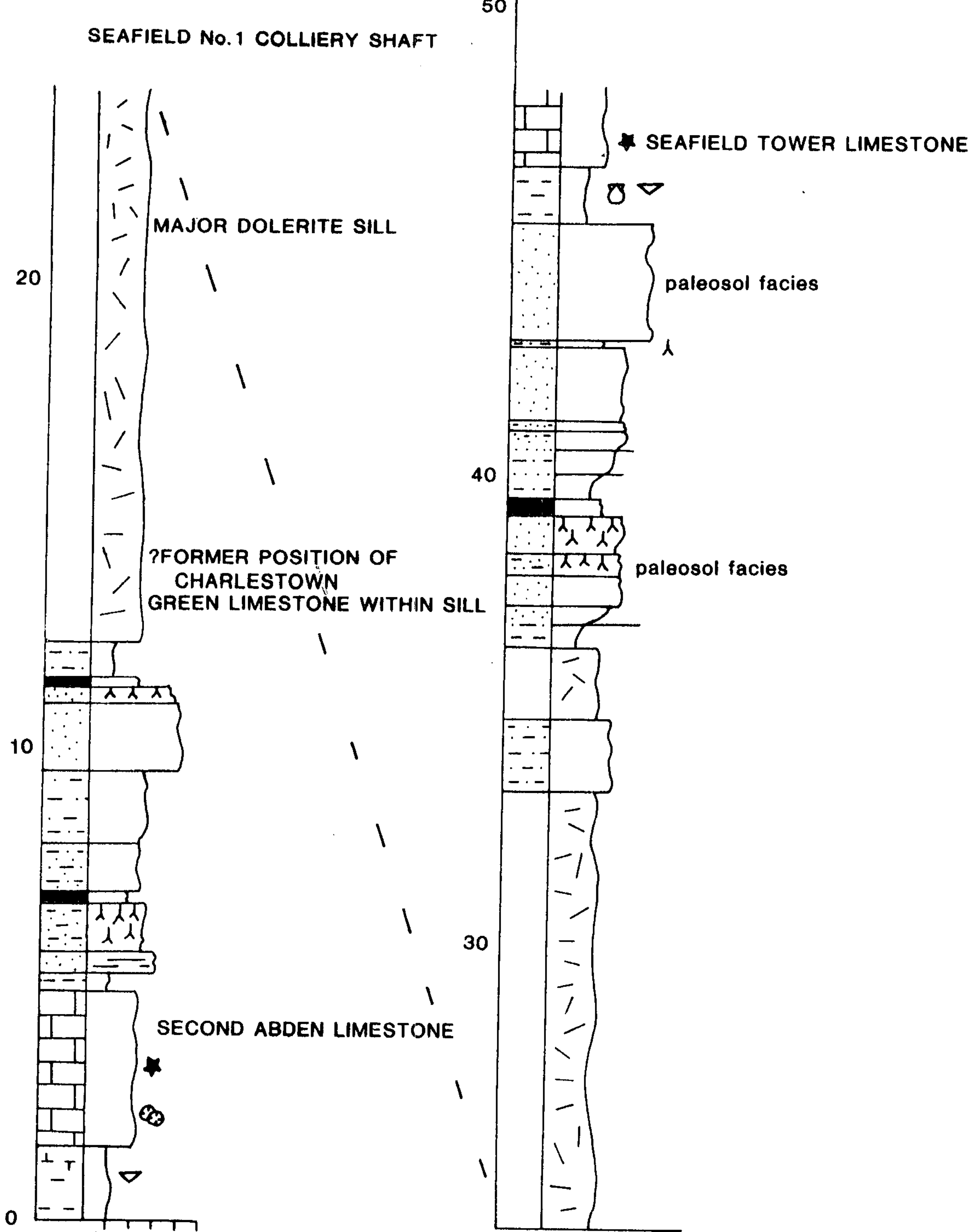

SEAFIELD No.1 COLLIERY SHAFT
MAJOR DOLERITE SILL
20
?FORMER POSITION OF
CHARLESTOWN
GREEN LIMESTONE WITHIN SILL
10
SECOND ABDEN LIMESTONE
0
50
SEAFIELD TOWER LIMESTONE
paleosol facies
40
paleosol facies
30

Fig. 10.12.

A. Small quarry adjacent to the Kinghorn-Kirkcaldy shore section, exposing the trough-cross bedded and channellised sandstones which overlie the mouth-bar facies and coal and are assumed to have cut out the Charlestown Green Limestone. The grouped sets of trough cross-bedding (with curved foreset surfaces) form cosets separated by reactivation surfaces (cf. Collinson 1970). Scale: geological compass-clinometer, length=10 cm.

B. Small quarry adjacent to the Kinghorn-Kirkcaldy shore section showing the top of mouth-bar facies, the overlying coal (where the camera bag is lain) and the overlying trough cross-bedded, channel sandstones (see A, above) which have an erosive, irregular base.

C. Coarse to medium-grained trough cross-bedded and channellised sandstones overlying mouth-bar facies and presumably cutting out the Charlestown Green Limestone. Broad, shallow 'cut-and-fill' channels are conspicious and poor exposure between the sandstones in the foreground and the presence of a teschenite sill in the background are evident. Scale: geological compass-clinometer, length=10 cm.

D. Close-up view of trough cross-bedding in the massive channel sandstone facies which has eroded away the Charlestown Green Limestone. Curved foreset surfaces within trough cross-bed sets are present and steep-sided channels with impersistent mudrock linings also occur. A teschenite sill and the ruins of Seafield Tower are evident in the background. Scale: camera bag, length=24 cm.

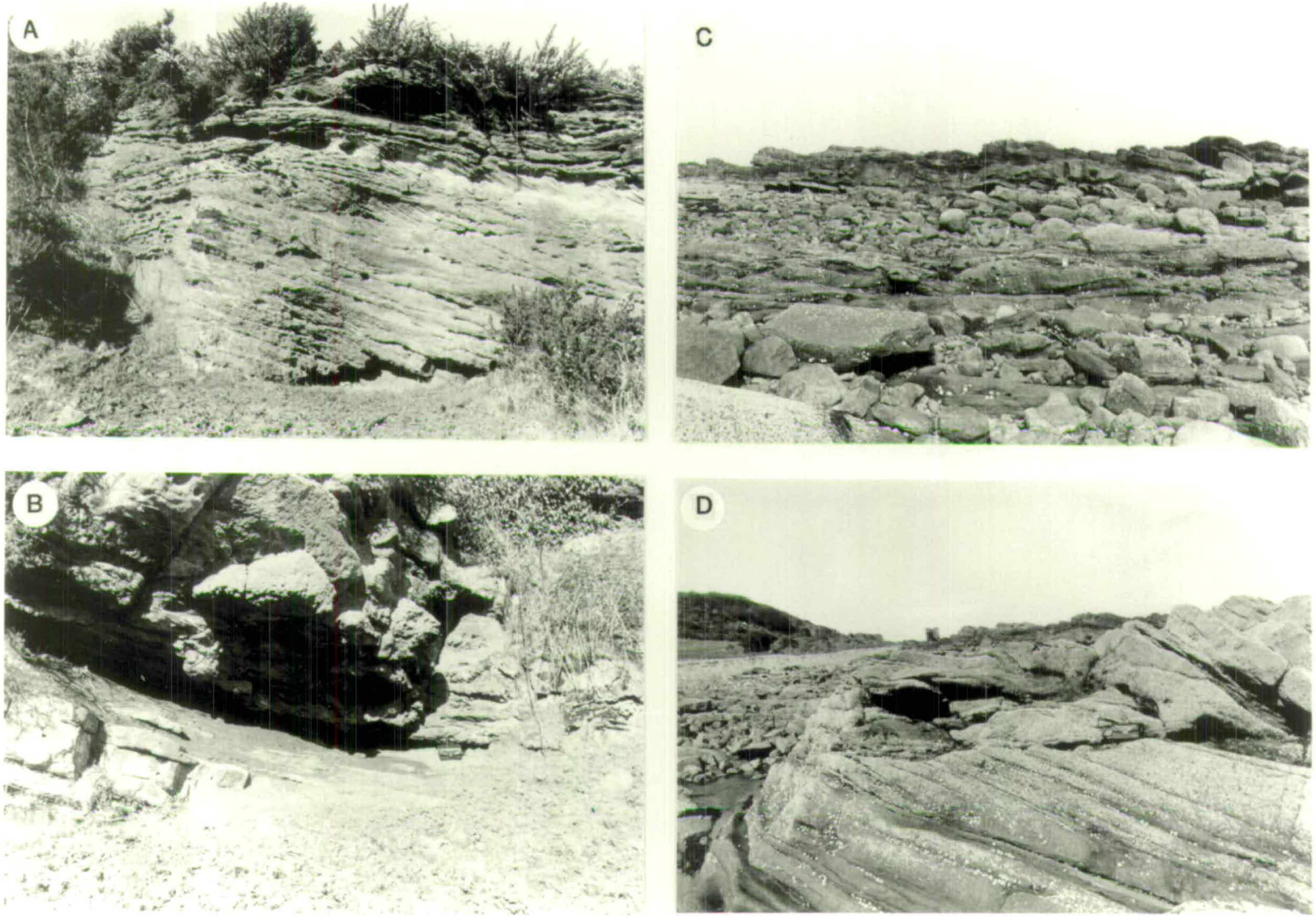

A
C
B
D

Fig. 10.13.

A. Delta-top facies developed above the teschenite sill on the Kinghorn-Kirkcaldy foreshore below the Seafield Tower Limestone. A distinctive coarsening-upward sequence with a transition from mudrocks at the base via cross-laminated sandstones into a coarser-grained massive sandstone with grouped sets of spectacular trough cross-bedding (note the curved nature of the foresets within the sets) is evident. This sequence represents a transition from small to large bedforms (in response to an increasing flow velocity) concomitant with a distributary or crevasse channel switching into an area formerly dominated by fine-grained overbank fines in a delta-top lake. Scale: camera bag, length=24 cm.

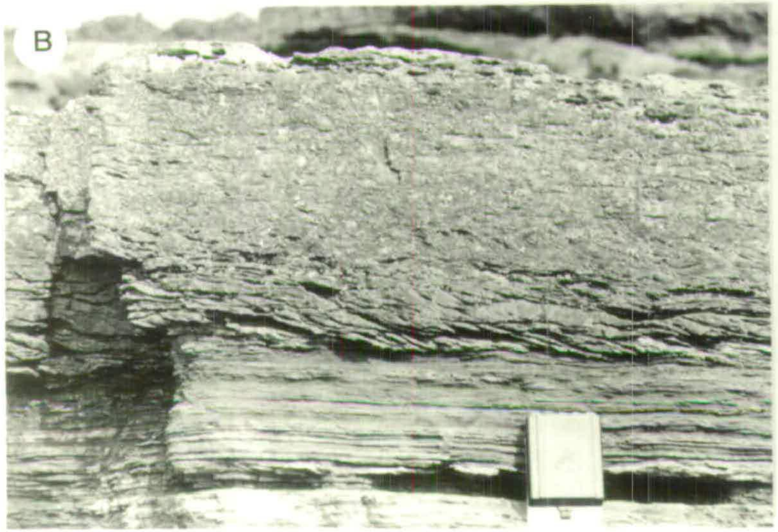
B. Close-up view of cross-laminated sandstone facies below major trough cross-bedded sandstone (see A, above). A transition from lower phase plane beds into cross-laminated (climbing rippled) sandstones is present. Such a transition suggests ever increasing flow velocities initiated during ?crevasse splay sand events into a delta-top lake/bay. Scale: geological compass-clinometer, length=10 cm.

C. View of massive, solitary, large-scale trough cross-bed set in a sandstone, Kinghorn-Kirkcaldy coastal section, central Fife (see A, above). This represents the preserved lee-slope slip faces of large curve-crested dune-like bedforms which migrated at high flow-stages (flood events) in the distributary channels which meandered across the delta-top. The set lies at the top of a coarsening-upward sequence indicating higher flow velocities during channel avulsion. In the background of the photograph, the delta-top sequence is capped by massive, slaggy weathering sandy podzols (paleosols) which lie below the Seafield Tower Limestone and terminate delta-top sedimentation. Scale: camera bag, length=24 cm.

D. Close-up view of ripple cross-laminated sandstones overlying planar-bedded lower phase plane beds and capping a minor coarsening-upward sequence on the delta-top. Another coarsening-upward sequence overlying it is present (depicted in A, B and C). Scale: compass-clinometer, length=10 cm.

A

C


B

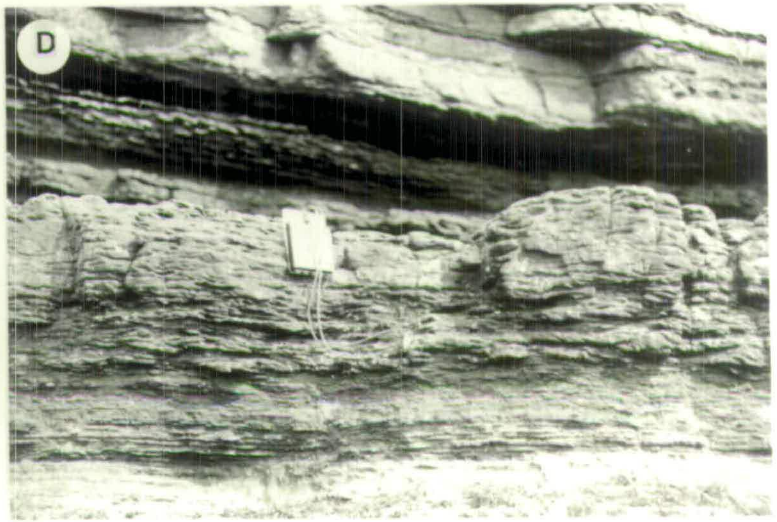

D

Fig. 10.14.

A. Podzolic sandstone paleosol below the Seafield Tower Limestone and associated shales, Seafield, Kinghorn-Kirkcaldy shore section, central Fife. The extremely irregular lower surface of the topmost sandstone bed is interpreted as the result of leaching and the deposition of clays lower down in the profile (illuviation) to leave behind a hard ganister-like sandstone free from impurities which forms a bleached albic horizon (cf. Percival 1986). This paleosol is interpreted as having developed in relatively well-drained conditions in what was otherwise a waterlogged delta plain/lower delta plain. Scale: camera bag, length=24 cm, geological hammer, length=30 cm.

B. Close-up view of the paleosol described above (A). The bleached white nature of the sandstone is conspicious, suggesting strong leaching by downward percolating water in a well-drained site. Large horizontally orientated casts of *Lepidodendron* trunks are present. In the lower left hand side of the photograph, small sandstone casts of rootlets are also evident. Scale: geological hammer, length=30 cm.

C. Coarsening-upward sequence representing bay-lake fill on the delta-top, 'sandwiched' between two podzol paleosols (see Fig. 10.17). A transition from intercalated shales, siltstones and sandstones into a more massive cross-laminated sandstone which caps the sequence is present. This is interpreted as the fill of a delta-top lacustrine bay/lake by crevasse splay sands which broke through the banks of major channels during flooding events to establish small 'offshoot' channels. Scale: geological compass-clinometer, length=10 cm.

D. Lower of the two major podzol paleosols. Like the upper podzol (seen in background overlying bay-fill sequence described above-C) it has a very undulatory, irregular lower surface which suggests leaching in a well-drained setting to form an albic horizon. The paleosol is a white, pure, bleached ganister-like sandstone with large 'potholes' and red-coloured oxidisation patches. It is slaggy weathering and contains *in situ* roots and rootlets. Scale: geological compass-clinometer, length=10 cm.

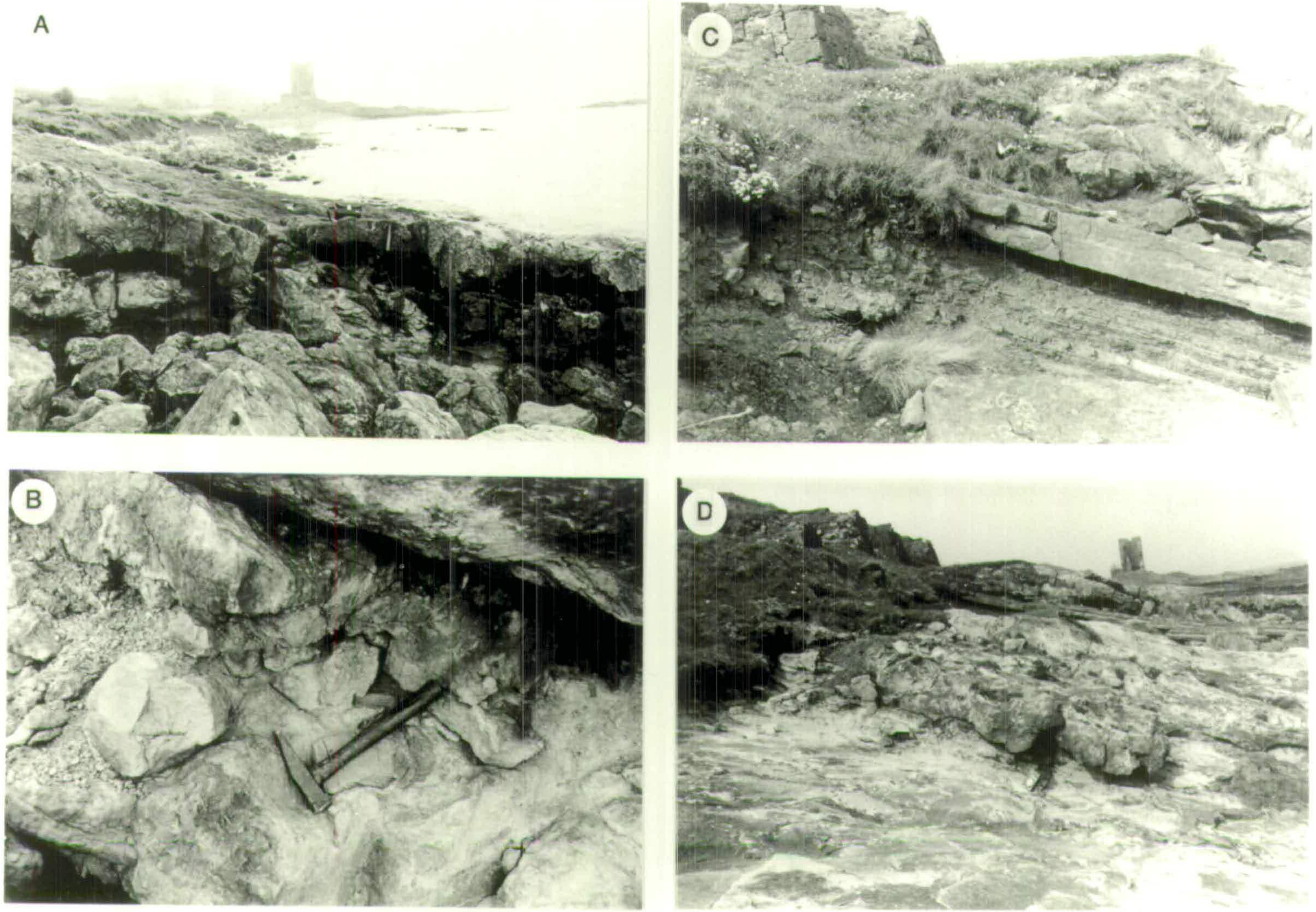

A
B
C
D

Fig. 10.15.

A. Close-up view of the upper podzolic paleosol below the Seafield Tower Limestone, as exposed on the foreshore in the Kinghorn-Kirkcaldy coastal section, central Fife. Well preserved, horizontally orientated stigmarian roots are present, along with the broken stump of an *in situ* *Lepidodendron* trunk (top of photograph). These provide evidence that the well-drained paleosol was the site of a prolific vegetation, dominated by large club mosses. Similar paleosols have been described from the Carboniferous of Ireland (Hubbard 1966). Scale: camera lens cap, diameter=6 cm.

B. Large stigmarian rootlet cast (sandstone-filled) in the albic podzol below the Seafield Tower Limestone. The bleached white colour of the sandstone, free from impurities is due to excessive leaching. The rootlet is well preserved and shows prominent rootlet scars. Towards the bottom left of the picture, small sub-rootlets are seen to branch off the main root at 90 degrees, suggesting that although horizontally orientated the root is *in situ* (cf. Hubbard 1966). As is the case with most root-systems of Carboniferous club-mosses, these examples appear to have been shallowly rooted (Collinson 1986). Scale: camera lens cap, diameter=6 cm.

C. Albic horizon in podzol described above (A and B). Conspicious features are the bleached white nature of the sandstone and the presence of abundant, *in situ*, vertically orientated sandstone-filled rootlet casts. These are located at the highly undulatory base of the bed (cf. Percival 1986). Scale: camera lens cap, diameter=6 cm.

D. *In situ*, large, obliquely orientated *Lepidodendron* trunk in podzol below the Seafield Tower Limestone (described above-A, B and C). The structureless nature of the sandstone is evident, which is the result of rhizoturbation and percolating (draining) water. The presence of such a well-drained podzol on what should have been a waterlogged delta plain suggests that there may have been some tectonism which resulted in uplift and the development of well-drained depositional sites.

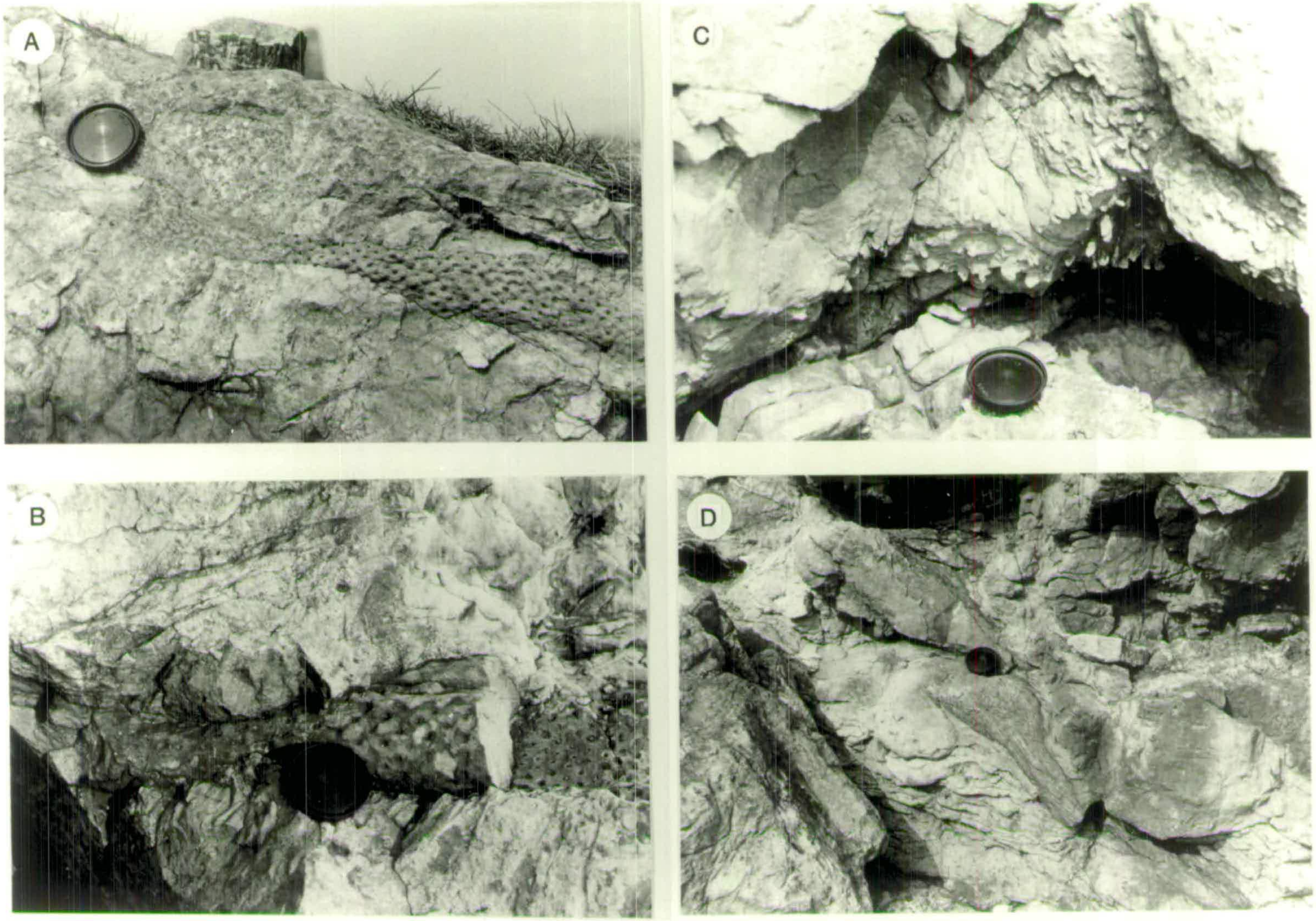

A
B
C
D

Fig. 10.16.

Detailed graphic sedimentary log of delta-top sedimentary rocks below the Seafield Tower Limestone as exposed on the shore near Seafield, Kinghorn-Kirkcaldy. This log was drawn to illustrate the two major podzolic paleosols which are developed with a thin intervening delta-top, bay-fill coarsening-upwards sequence in between. Both paleosols clearly formed in well-drained delta-top conditions (hence the absence of any major coals) and terminate delta-top sedimentation prior to the major 'Seafield Tower Limestone marine transgression'. The shales which overlie the upper paleosol and underlie the limestone contain a low-diversity restricted marine/quasi-marine fauna of ostracodes, and *Lingula* towards the base, and were described as lagoonal non-marine deposits by Geikie (1900). These are interpreted as representing marginal/restricted marine conditions which were developed prior to the acme (cf. Wignall 1987) of the 'Seafield Tower Limestone marine transgression'.

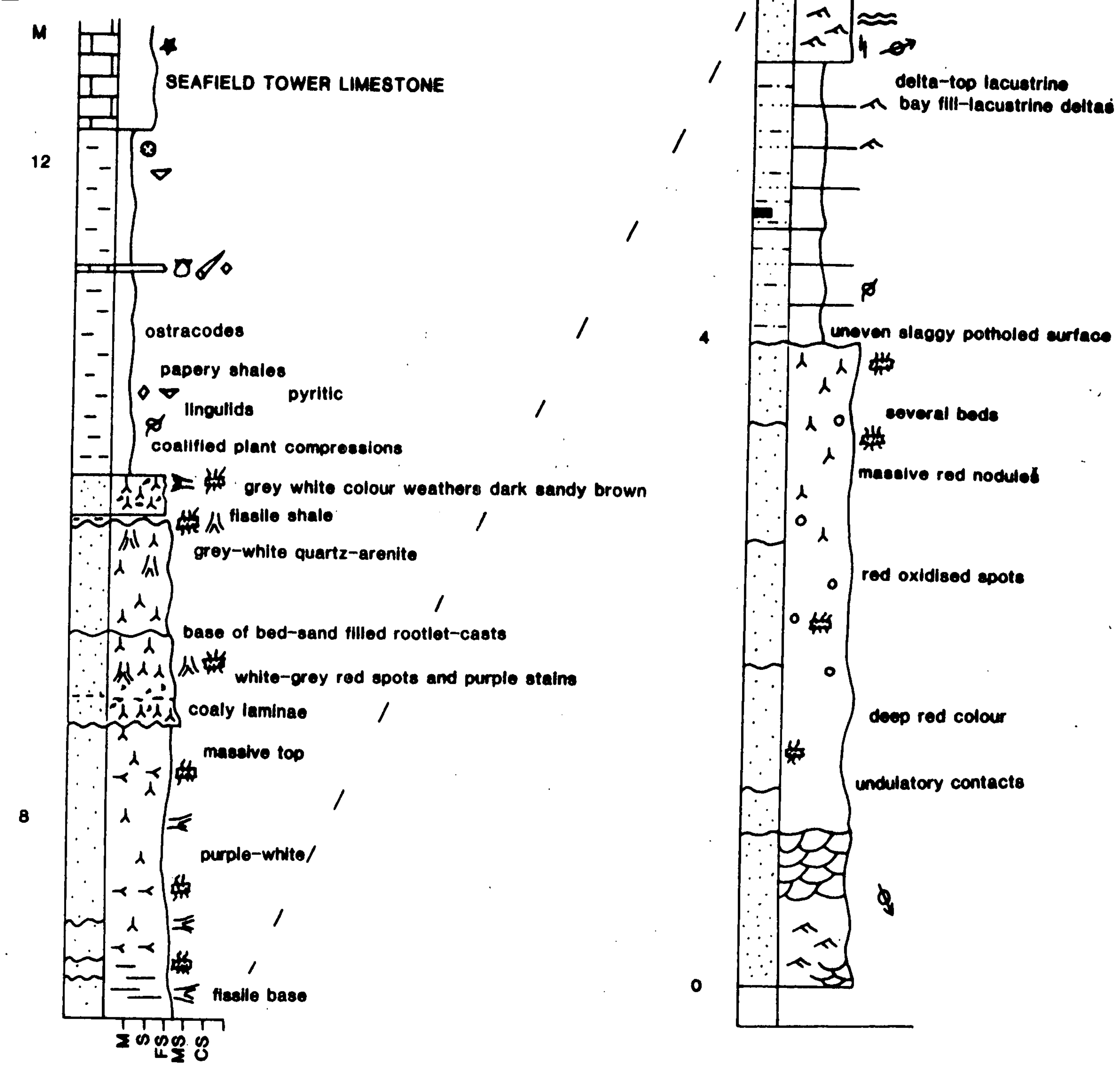

M
SEAFIELD TOWER LIMESTONE
12
ostracodes
papery shales
pyritic
lingulids
coalified plant compressions
grey white colour weathers dark sandy brown
fissile shale
grey-white quartz-arenite
base of bed-sand filled rootlet-casts
white-grey red spots and purple stains
coaly laminae
massive top
8
purple-white
fissile base
M
S
FS
MS
CS
delta-top lacustrine
bay fill-lacustrine deltas
4
uneven slaggy potholed surface
several beds
massive red nodules
red oxidised spots
deep red colour
undulatory contacts
0

Fig. 10.17.

Sketch diagram showing postulated sequence of events and depositional environments developing in the sequence involving the Second Abden Limestone, overlying delta-front sandstones and the succeeding coarsening-upward sequence capped by the mouth-bar.

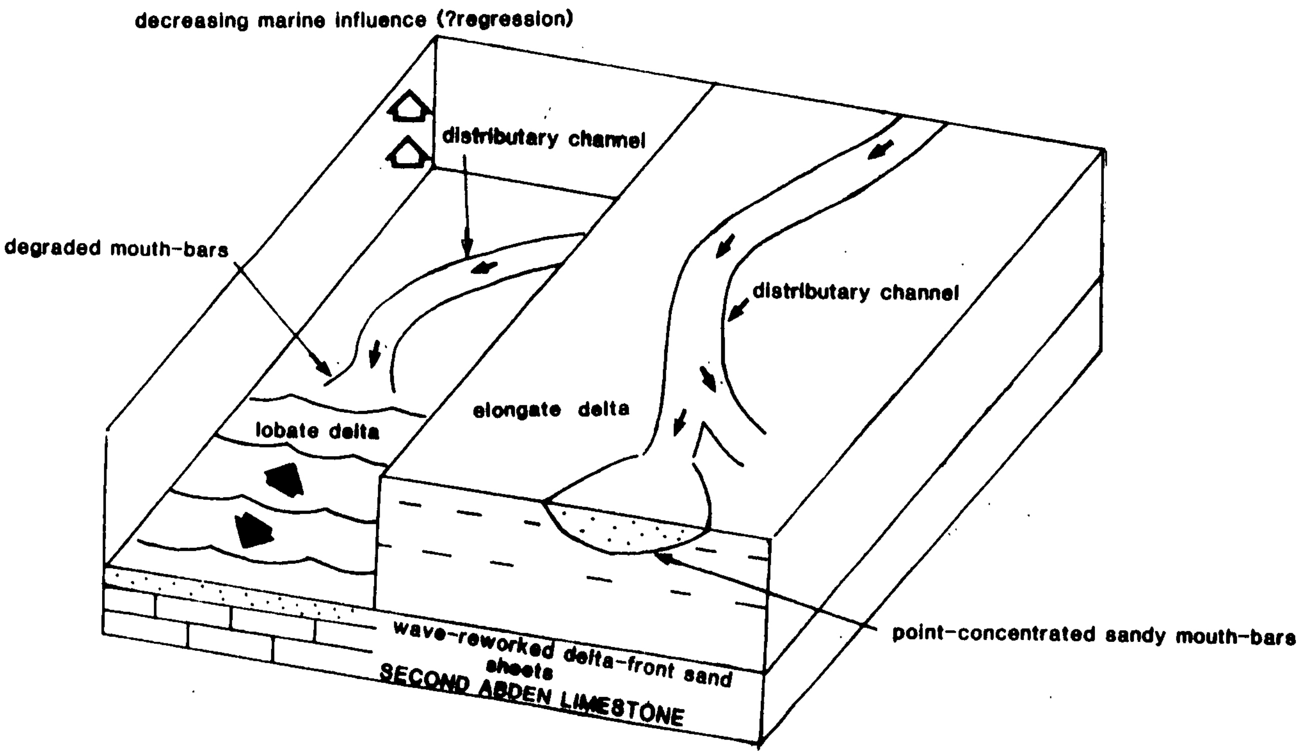

decreasing marine influence (?regression)
distributary channel
degraded mouth-bars
distributary channel
lobate delta
elongate delta
point-concentrated sandy mouth-bars
wave-reworked delta-front sand sheets
SECOND ABDEN LIMESTONE

Fig. 10.18.

Sketch interpretation diagram showing postulated depositional environments and events associated with the sequence directly above the mouth-bar (e.g. coal abandonment facies) and the overlying delta-top, trough cross-bedded, channellised sandstones involved in removing the Charlestown Green Limestone.

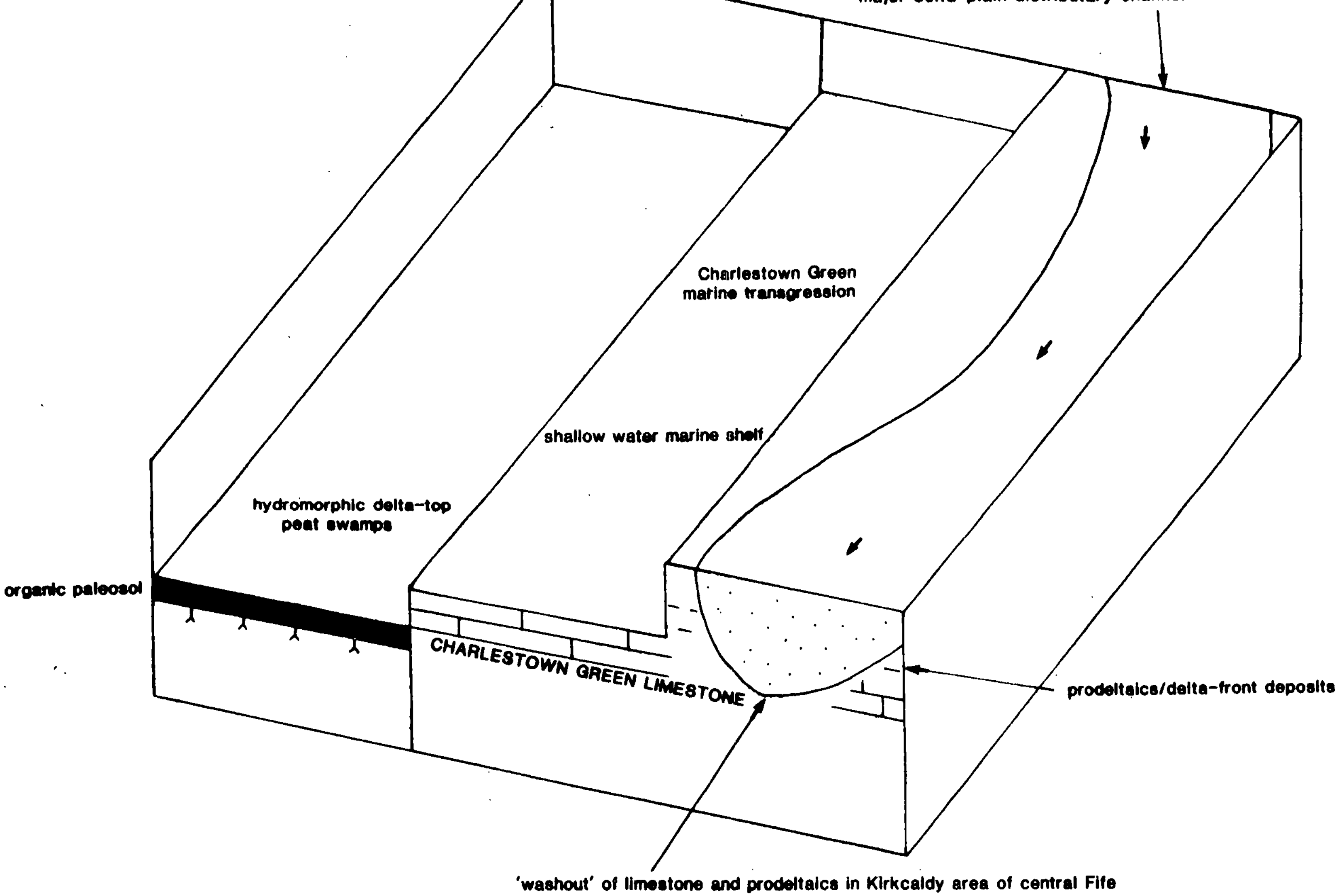
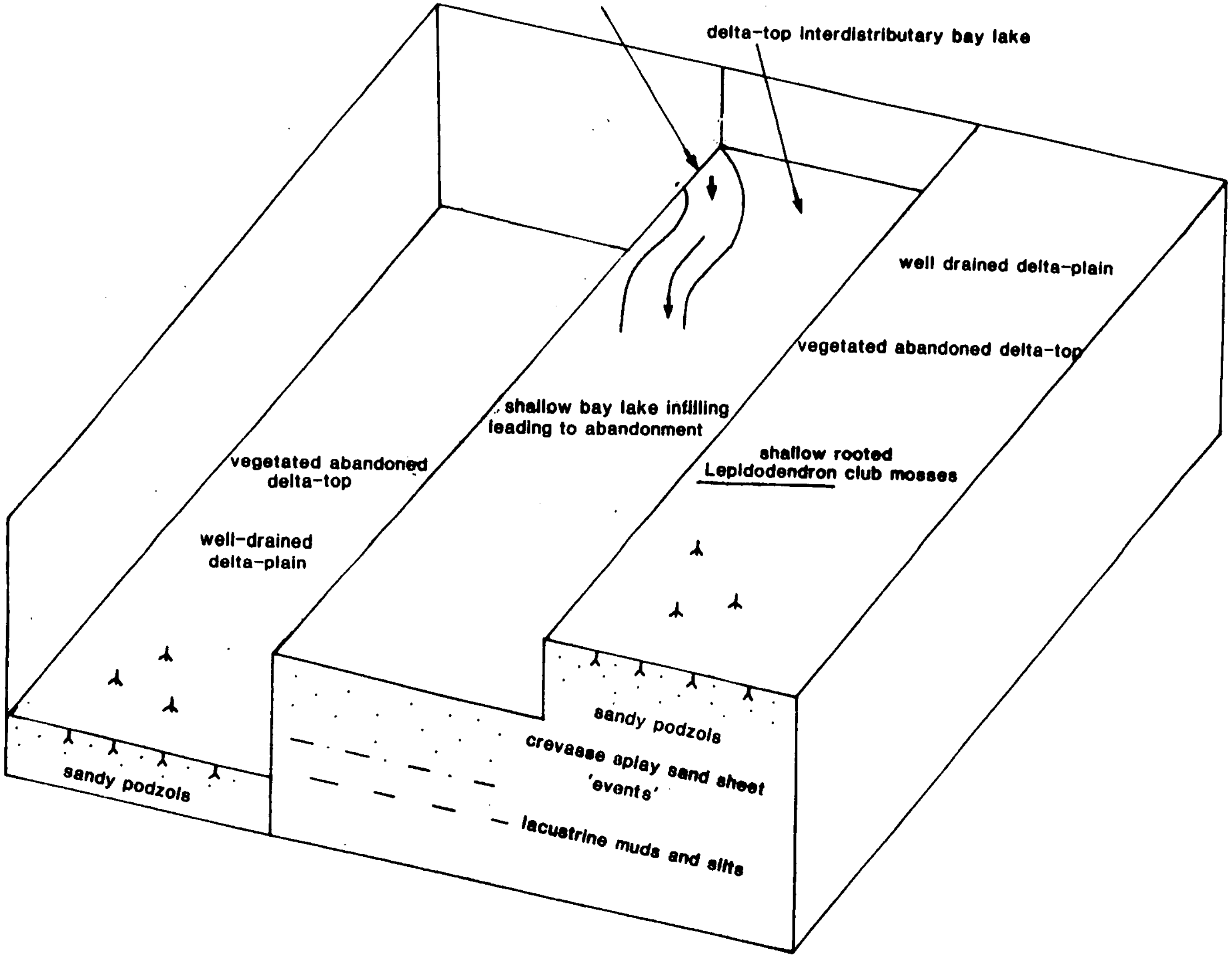

Charlestown Green
marine transgression
shallow water marine shelf
hydromorphic delta-top
peat swamps
organic paleosol
CHARLESTOWN GREEN LIMESTONE
prodeltaics/delta-front deposits
'washout' of limestone and prodeltaics in Kirkcaldy area of central Fife

Fig. 10.19.

Interpretative sketch diagram illustrating the series of events and associated depositional settings in the delta-top facies above the teschenite sill and below the Seafield Tower Limestone involving the two major podzolic paleosols.


delta-top interdistributary bay lake
well drained delta-plain
vegetated abandoned delta-top
shallow bay lake infilling leading to abandonment
shallow rooted
Lepidodendron club mosses
vegetated abandoned delta-top
well-drained delta-plain
sandy podzols
sandy podzols
crevasse splay sand sheet 'events'
lacustrine muds and silts

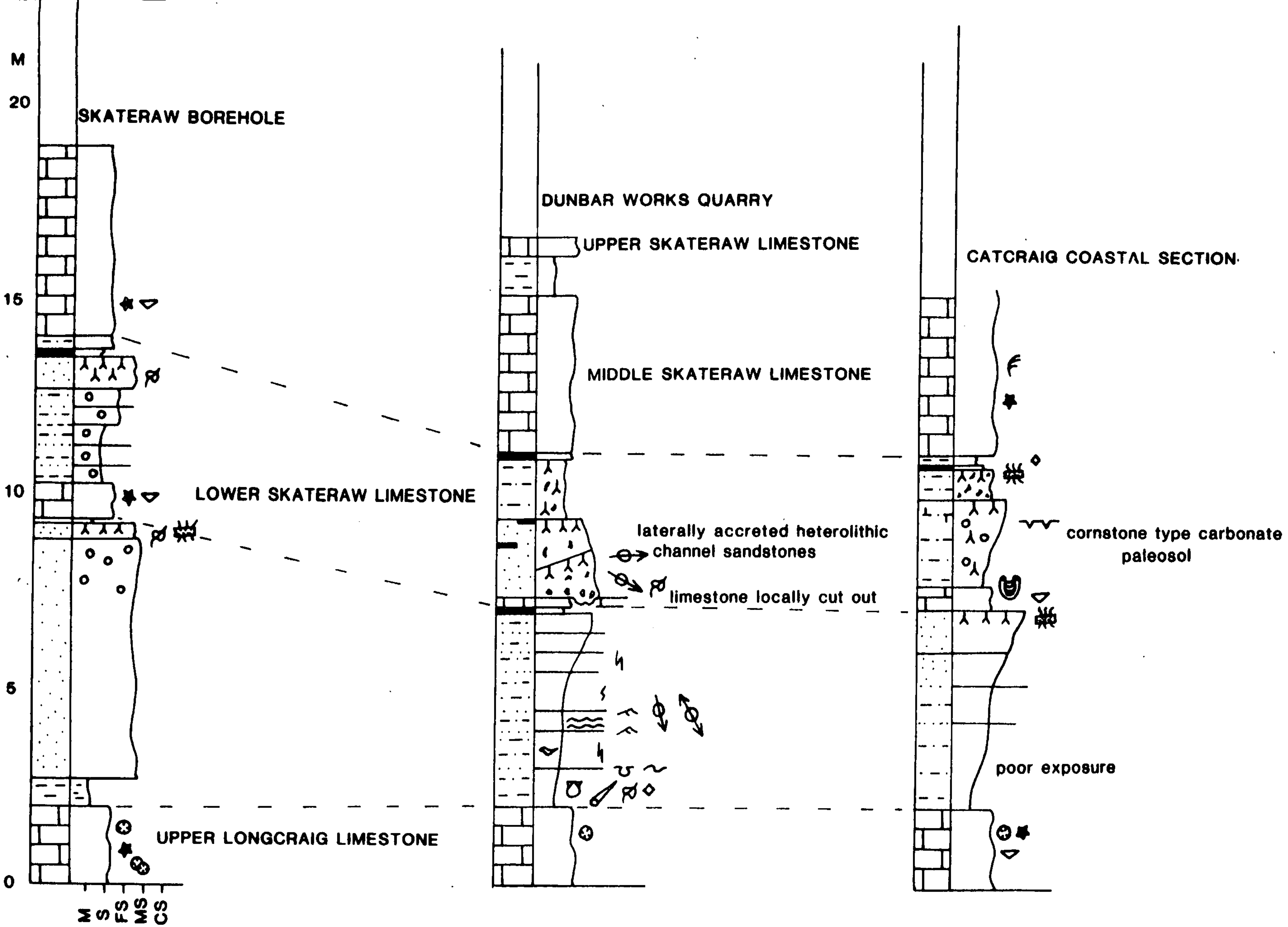

M
20
15
10
5
0
SKATERAW BOREHOLE
DUNBAR WORKS QUARRY
UPPER SKATERAW LIMESTONE
MIDDLE SKATERAW LIMESTONE
CATCRAIG COASTAL SECTION
LOWER SKATERAW LIMESTONE
laterally accreted heterolithic channel sandstones
limestone locally cut out
cornstone type carbonate paleosol
poor exposure
UPPER LONGCRAIG LIMESTONE
M
S
FS
MS
CS

Fig. 10.21.

Panorama/montage of photographs of rock face in the northern part of the Dunbar Works Quarry, East Lothian. The base of the sequence (at the foot of the quarry face) is occupied by the Upper Longcraig Limestone. This is overlain by a coarsening-upward sequence which is capped by a major channellised sandstone body which cuts out the Lower Skateraw Limestone. This sandstone is overlain by a fireclay abandonment facies which is capped by the major Middle Skateraw Limestone at the top of the quarry face. Explanations; A=Upper Longcraig Limestone, B=coarsening-upward sequence, C=channel sandstone, D=fireclay abandonment facies, and E=Middle Skateraw Limestone. Scale: quarry face=approximately 15-20 m in height.


e
d
c
b
a

Fig. 10.22.

Panorama/montage of photographs of the rock face in the southern part of the Dunbar Works Quarry, East Lothian. The quarry floor (upon which the quarrymen and the machines are stood) is formed by the top surface of the Upper Longcraig Limestone, whilst the massive unit at the top of the quarry is the Middle Skateraw Limestone. The interval between these two limestones is equivalent to the Second Abden-Seafield Tower limestones interval at Kinghorn-Kirkcaldy, central Fife (Fig. 10.2). Here the interval is approximately 6-7 m in thickness compared with nearly 40 m in central Fife. This is due to differential tectonic subsidence which affected the Midland Valley during the Dinantian (Goodlet 1957, 1959; Ramsbottom 1981; Francis 1983a). The Kinghorn-Kirkcaldy section is in the Fife-Midlothian Coalfield or low (cf. Grayson and Oldham 1987), whereas the East Lothian area lay nearer to a syndepositional axis or high. As the lows were subsiding at a greater rate, they acted as sediment traps, encouraging the progradation of deltas (cf. Leeder and Strudwick 1987) and therefore accumulating thicker clastic sequences. The highs on the other hand subsided at a slower rate and therefore have greater carbonate:clastic ratios than the lows, as at Catcraig and the Dunbar Works Quarry. Above the Upper Longcraig Limestone, there is a coarsening-upward sequence capped by a thin coal. This coal is overlain by the Lower Skateraw Limestone which is absent in the southern part of the quarry (see Fig. 10.21). The limestone is abruptly succeeded by a major heterolithic sandstone with prominently dipping lateral accretion surfaces. This is succeeded by a dark fireclay which varies in thickness laterally over short distances and passes upwards via a thin coal into the Middle Skateraw Limestone at the top of the quarry. Explanations; A=Upper Longcraig Limestone, B=coarsening-upwards sequence, C=coal, D=Lower Skateraw Limestone, E=heterolithic channel sandstone, F=fireclay-coal, and G=Middle Skateraw Limestone. Scale: quarry face is approximately 15 m high. Men standing on floor of quarry=approximately 1.8 m in height.

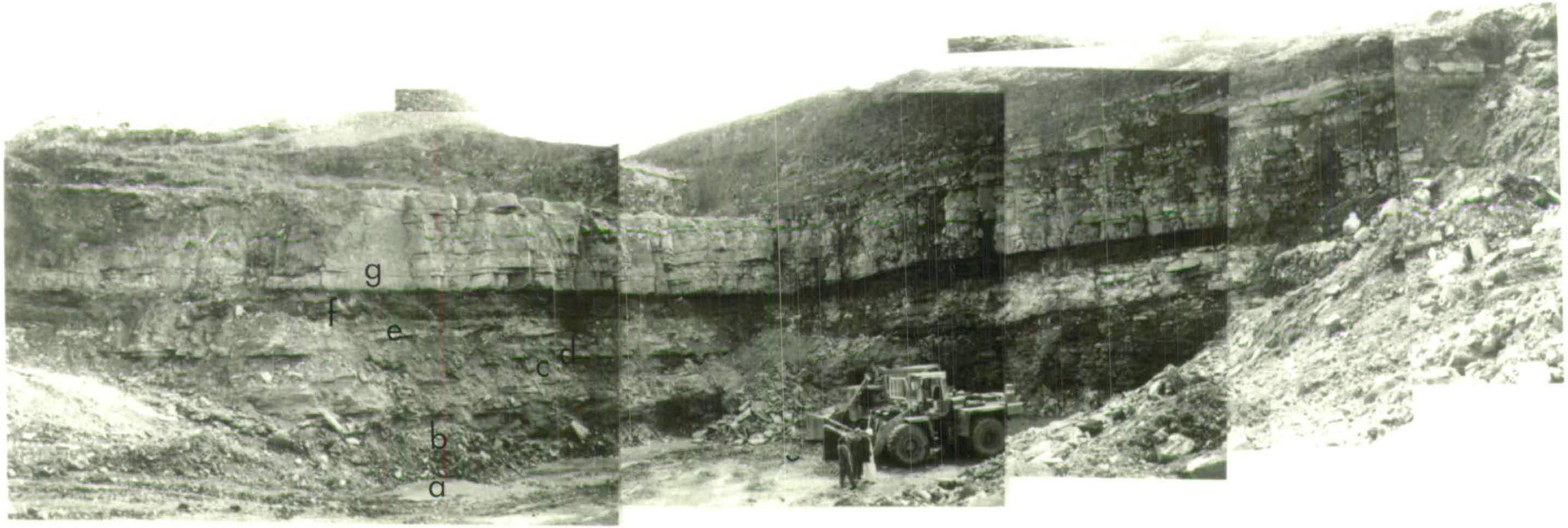

g
f
e
d
c
b
a

Fig. 10.23.

A. Wavy-bedded and lenticular bedded heterolithic sandstones and silty shales in coarsening-upward sequence above the Upper Longcraig Limestone, northern end of the Dunbar Works Quarry. The sandstones in the lower part are restricted to isolated lenticles (starved ripples) whereas in the upper part they are more continuous (transition from lenticular to wavy bedding) (see Reineck and Wunderlich 1968). Scale: camera lens cap, diameter=6 cm.

B. Loose block of lenticular-wavy bedded heterolithic sandstones and silty shales. Sandstone lenticles are isolated and 'starved' (some are loaded-soft sediment deformation), and mudrocks predominate. Location; northern end of quarry. Scale: camera lens cap, diameter=6 cm.

C. Upper bedding plane surface showing mudrock veneer on top of an underlying wave-rippled sandstone. Cross-sections through numerous vertically orientated, sandstone-filled burrows (?*Skolithos*), which extend down into the underlying sandstone are conspicious. Northern end of Dunbar Works Quarry. Scale: camera lens cap, diameter=6 cm.

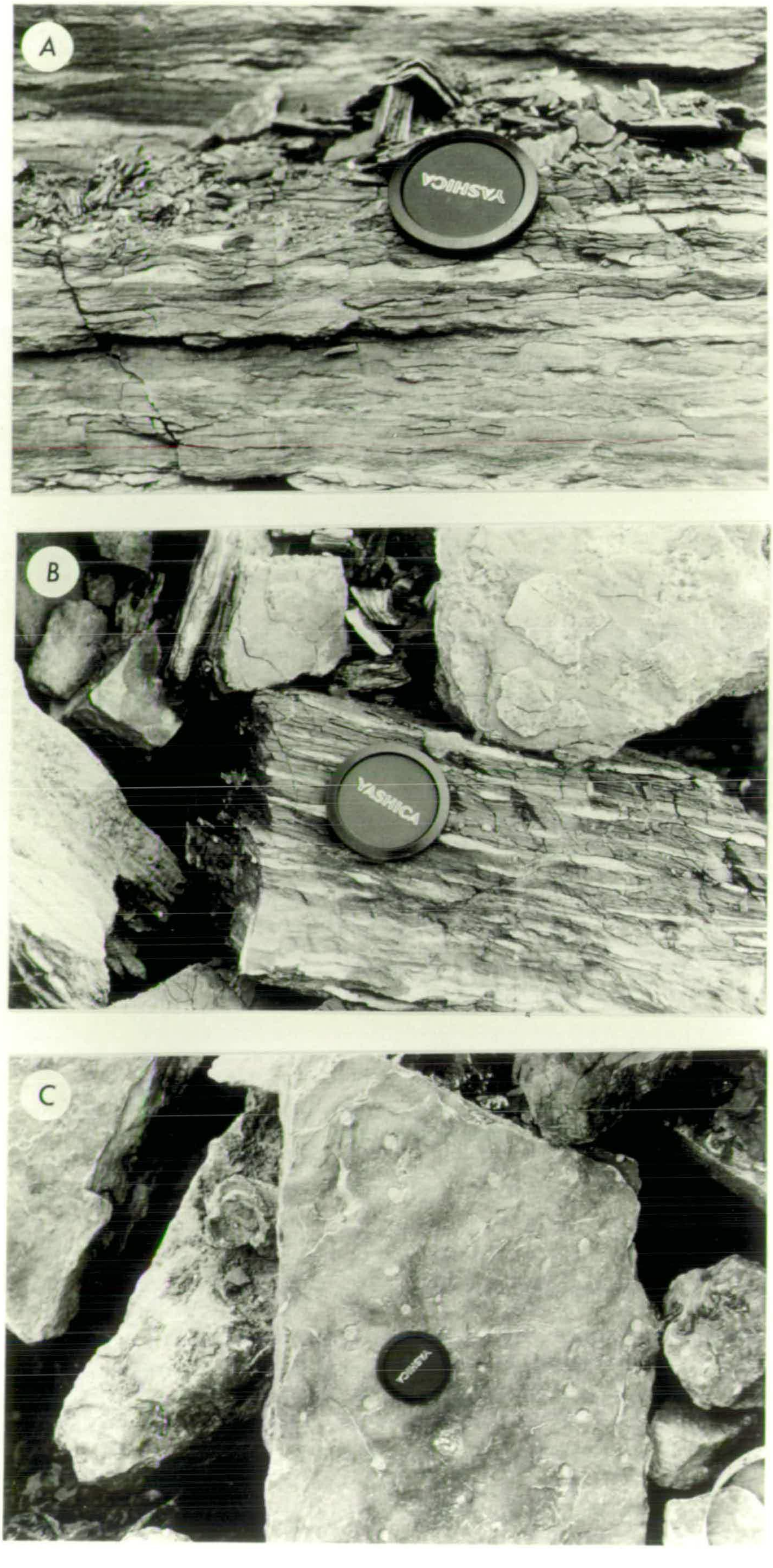

A
YASHICA
B
YASHICA
C
YASHICA

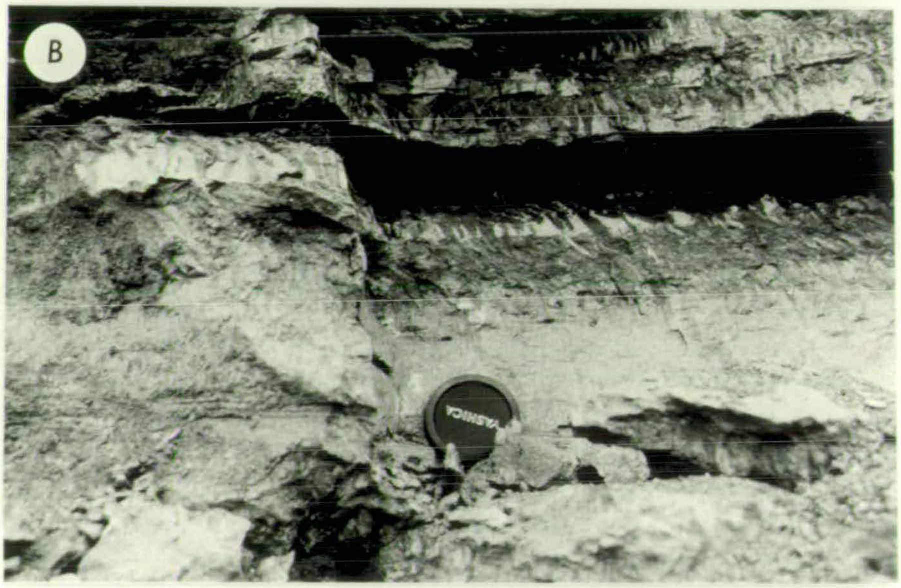
Fig. 10.24.

A. Intensely rooted sandstone in heterolithic, laterally accreted sandstone facies above the Lower Skateraw Limestone at the southern end of the quarry. The rootlets are coalified/carbonised and are associated with laterally accreted sandstones intercalated with fines. Scale: camera lens cap, diameter=6 cm.

B. View of successive rooted horizons in laterally-accreted sandstones above the Lower Skateraw Limestone in the southern part of the quarry. The densely populated coalified/carbonised rootlets are *in situ* (vertically orientated) and are developed at bleached white sandstone horizons (ganister-like deposits). The associated sandstones are largely structureless, probably as a result of extensive rhizoturbation. Scale: camera lens cap, diameter=6 cm.

C. Close-up view of individual rooted horizon (from B, above) showing development of a bleached white albic-type horizon above a dirty carbonaceous, densely rooted sandstone below. This may have resulted from draining and leaching of the upper horizon and accumulation of clays etc. at the lower horizon. Well preserved, erect, *in situ* rootlets are present within the bleached white sandstone horizon. These rooted horizons probably developed within the channel during temporary abandonment at low flow stage, and may have helped to stabilise steeply dipping point bar lateral accretion surfaces. Scale: camera lens cap, diameter=6 cm.

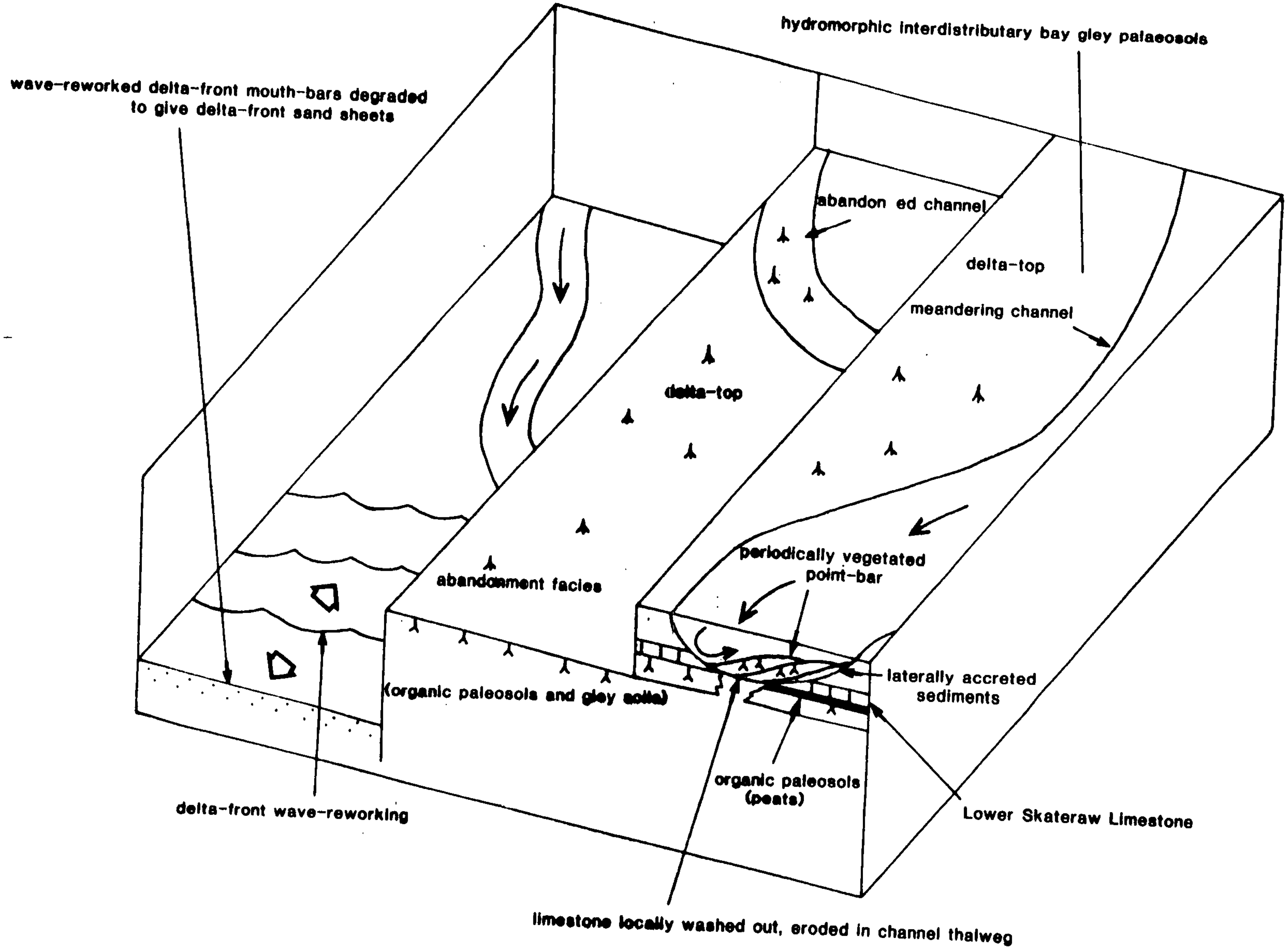

A

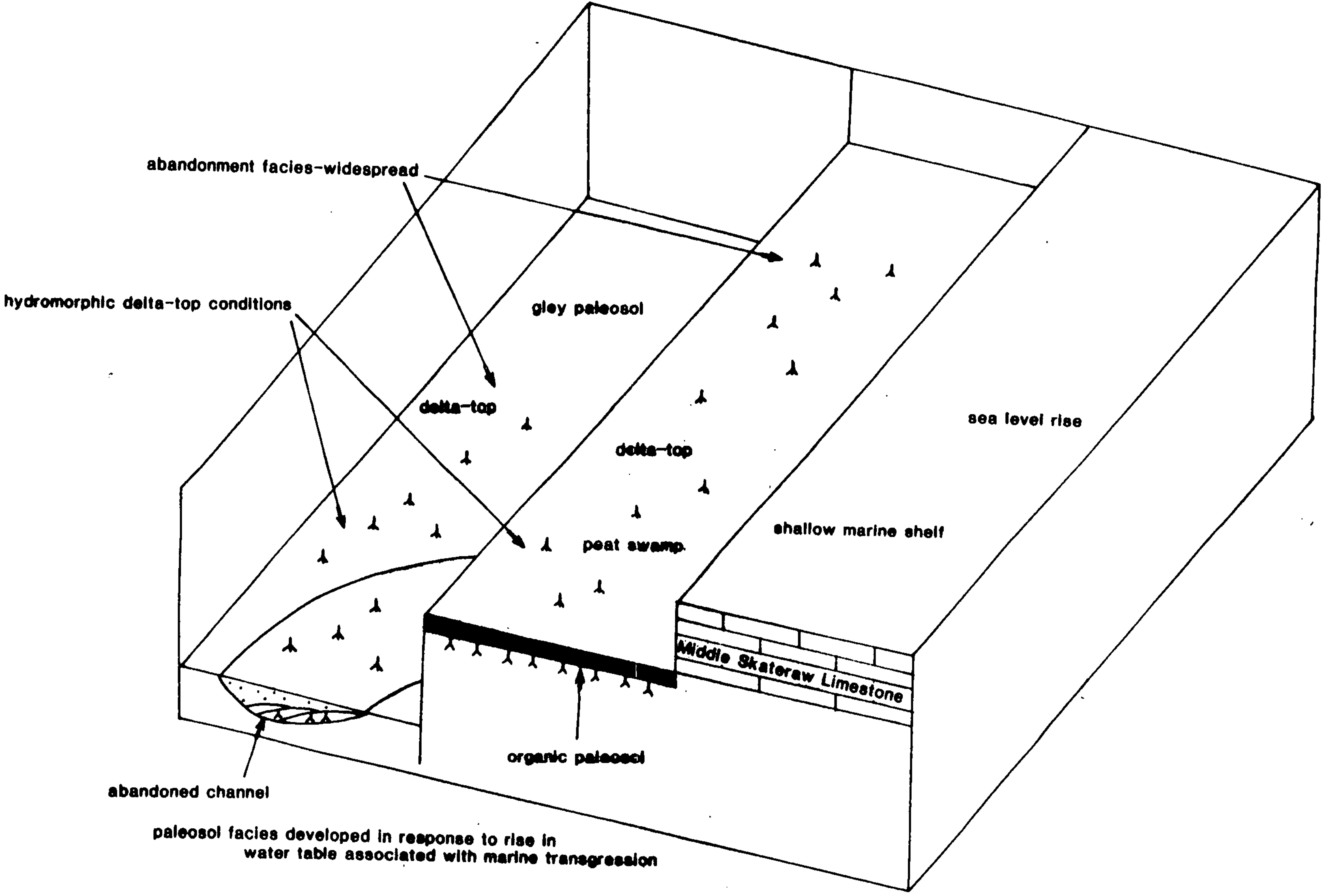

B
YASHICA


C
YASHICA

Fig. 10.25.

Interpretative sketch diagram showing postulated environments and events in the interval between the Upper Longcraig Limestone and the major heterolithic, laterally accreted sandstone above the Lower Skateraw Limestone. This diagram gives an explanation for the impersistence and absence of the limestone in the northern part of the quarry (cut out by the channel sandstone).


hydromorphic interdistributary bay gley palaeosols
wave-reworked delta-front mouth-bars degraded to give delta-front sand sheets
abandon ed channel
delta-top
meandering channel
delta-top
periodically vegetated point-bar
abandonment facies
laterally accreted sediments
(organic paleosols and gley soils)
organic paleosols (peats)
Lower Skateraw Limestone
delta-front wave-reworking
limestone locally washed out, eroded in channel thalweg



paleosol facies developed in response to rise in
water table associated with marine transgression

Fig. 11.1.

Sketch diagram showing; (i) general outline map of mainland Britain with a black arrow pointing to the Firth of Forth area (A), (ii) detailed sketch map of Firth of Forth area (showing position of the main localities studied in central Fife) (B), and (iii) block stratigraphic diagram highlighting the main marine bands in the local Lower Limestone Group succession and the stratigraphical position of the studied sequence (black arrow) (C). On the detailed sketch outline map of the Firth of Forth, the positions of the three main localities studied in central Fife (Kinghorn-Kirkcaldy coastal section, Seafield Colliery and Inverteil Quarry) are all marked. The location of Edinburgh is also marked. In the stratigraphical block diagram of the Lower Limestone Group succession in the Kinghorn-Kirkcaldy coastal section, the base of the Group is drawn at the base of the Second Abden Limestone and the sequence studied occurs between the Seafield Tower and Lower Kinniny limestones, and includes a 1 m thick coal and the overlying Seafield Marine Band.

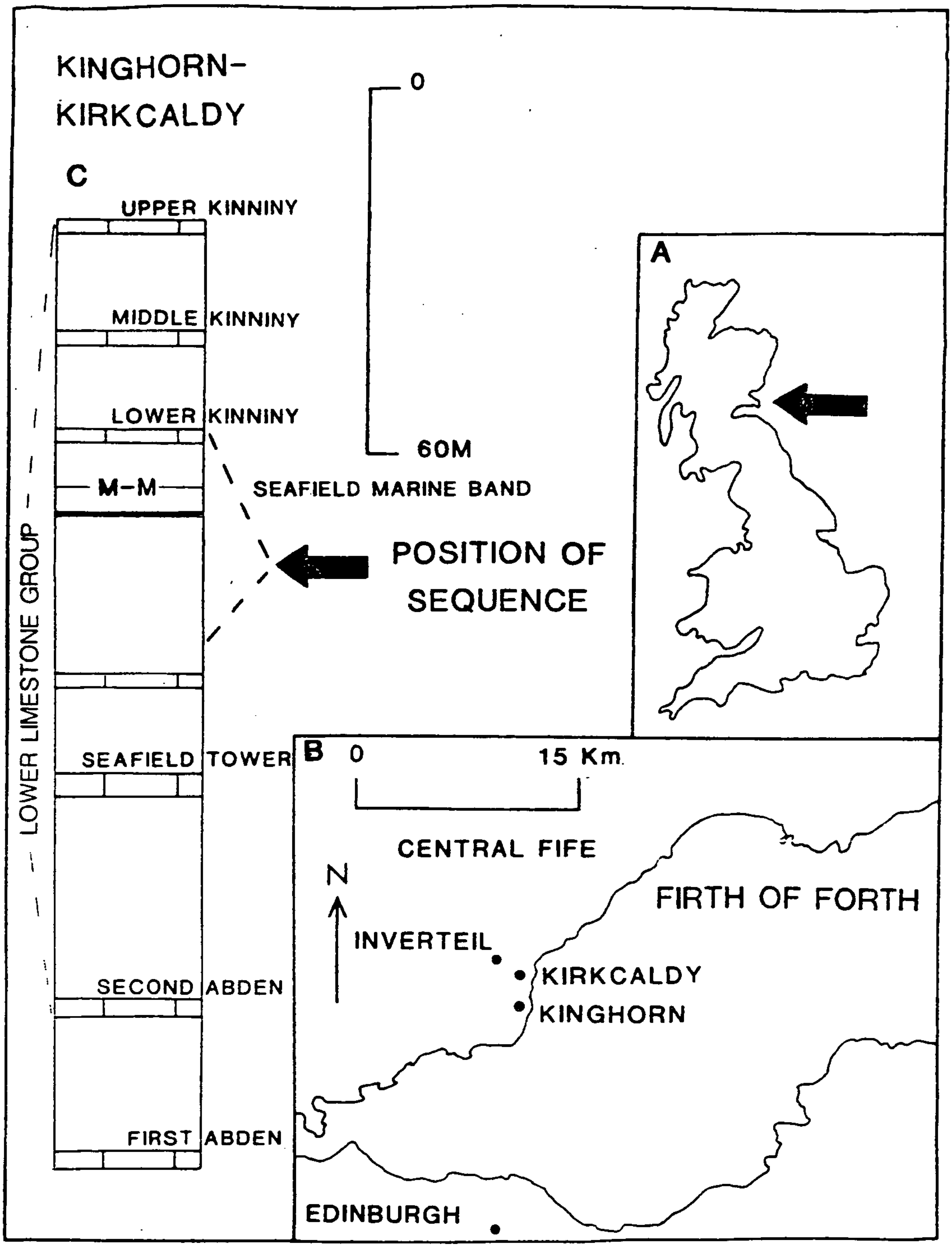

KINGHORN-
KIRKCALDY
C
UPPER KINNINY
MIDDLE KINNINY
LOWER KINNINY
M-M
SEAFIELD MARINE BAND
SEAFIELD TOWER
SECOND ABDEN
FIRST ABDEN
LOWER LIMESTONE GROUP
0
60M
POSITION OF
SEQUENCE
A
B
0
15 Km.
CENTRAL FIFE
N
FIRTH OF FORTH
INVERTEIL
KIRKCALDY
KINGHORN
EDINBURGH

Fig. 11.2.

Sketch outline map showing the Firth of Forth area, highlighting Fife and Lothians districts where localities studied are situated. Localities are; (i) St Monans coastal section, East Fife, (ii) Seafield Colliery Shafts and Kinghorn-Kirkcaldy coastal section, central Fife, (iii) Annfield Borehole, West Fife, (iv) Bilston Burn stream section, Midlothian and (v) Catcraig coastal section, East Lothian. Scale: 0-15 km as indicated on map.

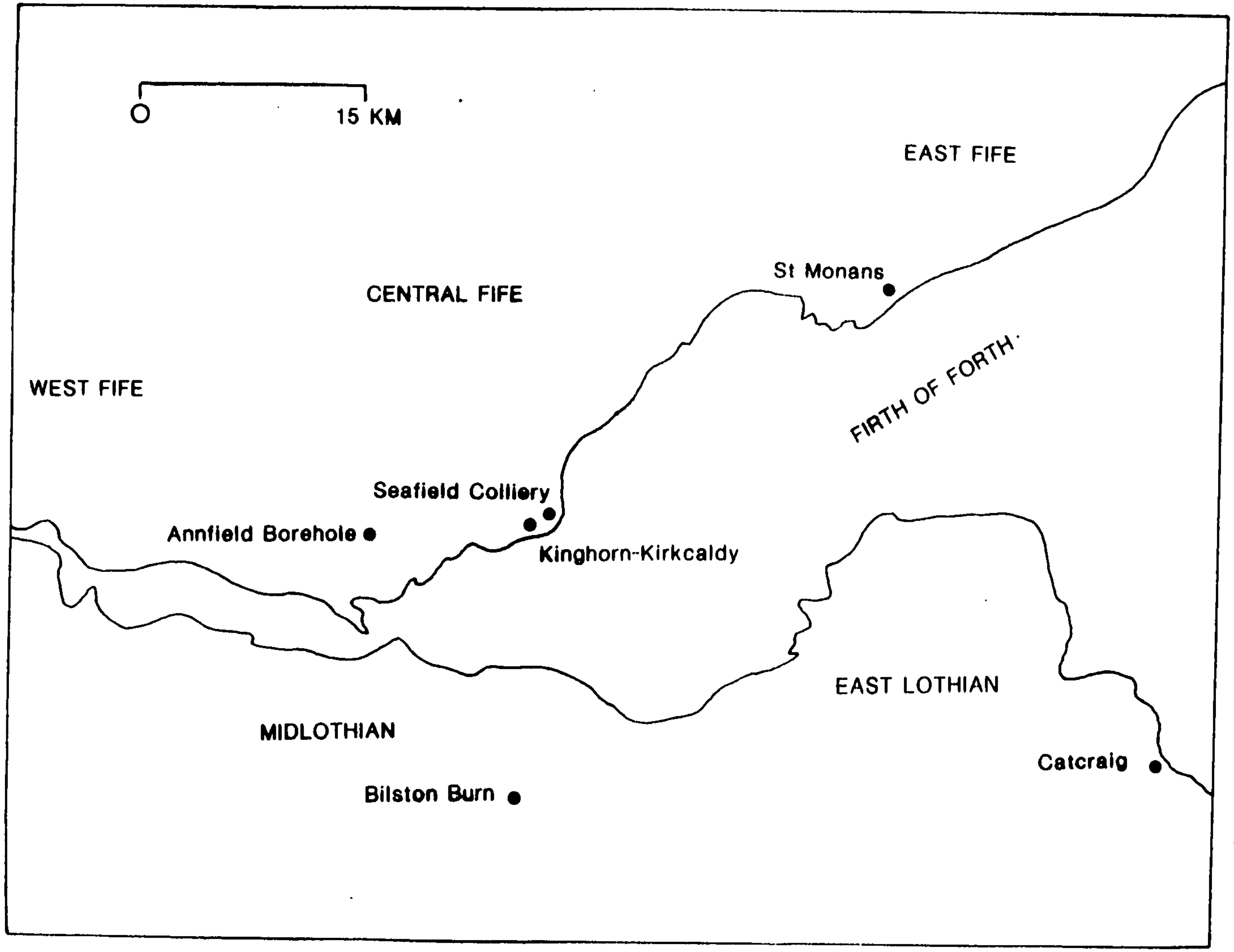

0
15 KM
EAST FIFE
CENTRAL FIFE
St Monans
WEST FIFE
FIRTH OF FORTH
Seafield Colliery
Annfield Borehole
Kinghorn-Kirkcaldy
EAST LOTHIAN
MIDLOTHIAN
Catcraig
Bilston Burn

Fig. 11.3.

Thin section photomicrographs (plane polarised light) of the Charlestown Main (Seafield Tower Limestone) from the Middlebank Road Cutting, Inverkeithing, central Fife.

A. Bioclastic wackestone containing abundant specimens of the codiacean alga *Calcifolium okense* Maslov, comminuted and broken valve (?brachiopod) fragments, and foraminifera. The bioclasts are often filled with a clear spar, and are embedded in a micrite matrix. Pyrite is also present and some of the bioclasts are partially replaced by dolomite rhombs. The alga is characteristic of the Charlestown Main Limestone and its correlatives in the Midland Valley of Scotland (Burgess 1965). The micritic thallus has a distinctive dark colour and a single series of canals lie close to the inner surface of the tubular stem in this cross-sectional view. Scale: horizontal field of view=8 mm.

B. Bioclastic wackestone (biomicrosparite) showing cross-sectional view of *C. okense* associated with foraminifera and other bioclasts. Scale: horizontal field of view=4 mm

C. Close-up view of bioclastic wackestone (biomicrosparite) showing tangential section of a plate of *C. okense*. The dark micritic thallus has been partially replaced by dolomite rhombs. Scale: horizontal field of view=3 mm.

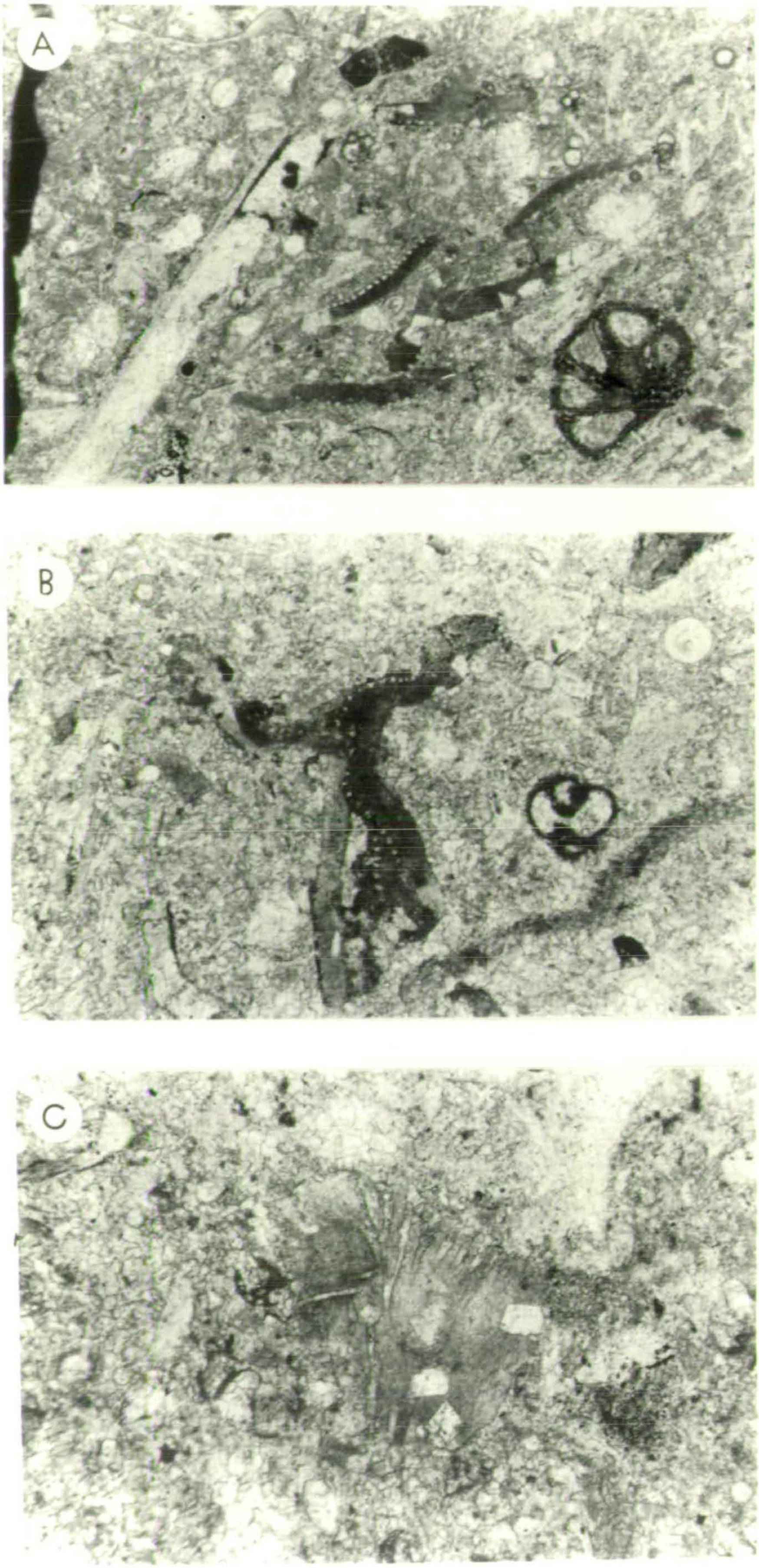

A
B
C

Fig. 11.4.

Field photographs and thin section photomicrograph showing aspects of the marine shale and limestone sequence above the Seafield Tower Limestone as exposed on the Seafield foreshore between Kinghorn and Kirkcaldy.

A. Upper bedding plane surface of a thin bed of crinoidal limestone (packstones and grainstones) developed as an intercalation within the calcareous shales. Large and abundant disarticulated crinoid ossicles and crinoid stalk fragments composed of articulated ossicles are present. Scale: metal tape measure, length=8 cm.

B. Subrounded septarian nodule from calcareous marine shales interbedded with thin limestones. Scale: camera lens cap, diameter=6 cm.

C. Thin section photomicrograph (plane polarised light) of crinoidal packstone-grainstone. The limestone is composed of disarticulated crinoid ossicles, some of which show undulatory, stylolitic pressure dissolution contacts developed due to post-depositional burial compaction. Some matrix is present and the poor sorting of the crinoid ossicles is conspicious. Scale: horizontal field of view=1.3 cm.

D. Interbedded mudrock-limestone sequence developed above the Seafield Tower Limestone. Nodules are present (many of which contain a septarian structure) in the dark fissile shales, and the lensoidal nature of the thin limestone beds is conspicious. The jointing in the limestone is a prominent feature and the base of the trough cross-bedded Seafield Tower Sandstone is present in the extreme background (far left hand side corner). Scale: camera bag, length=24 cm.

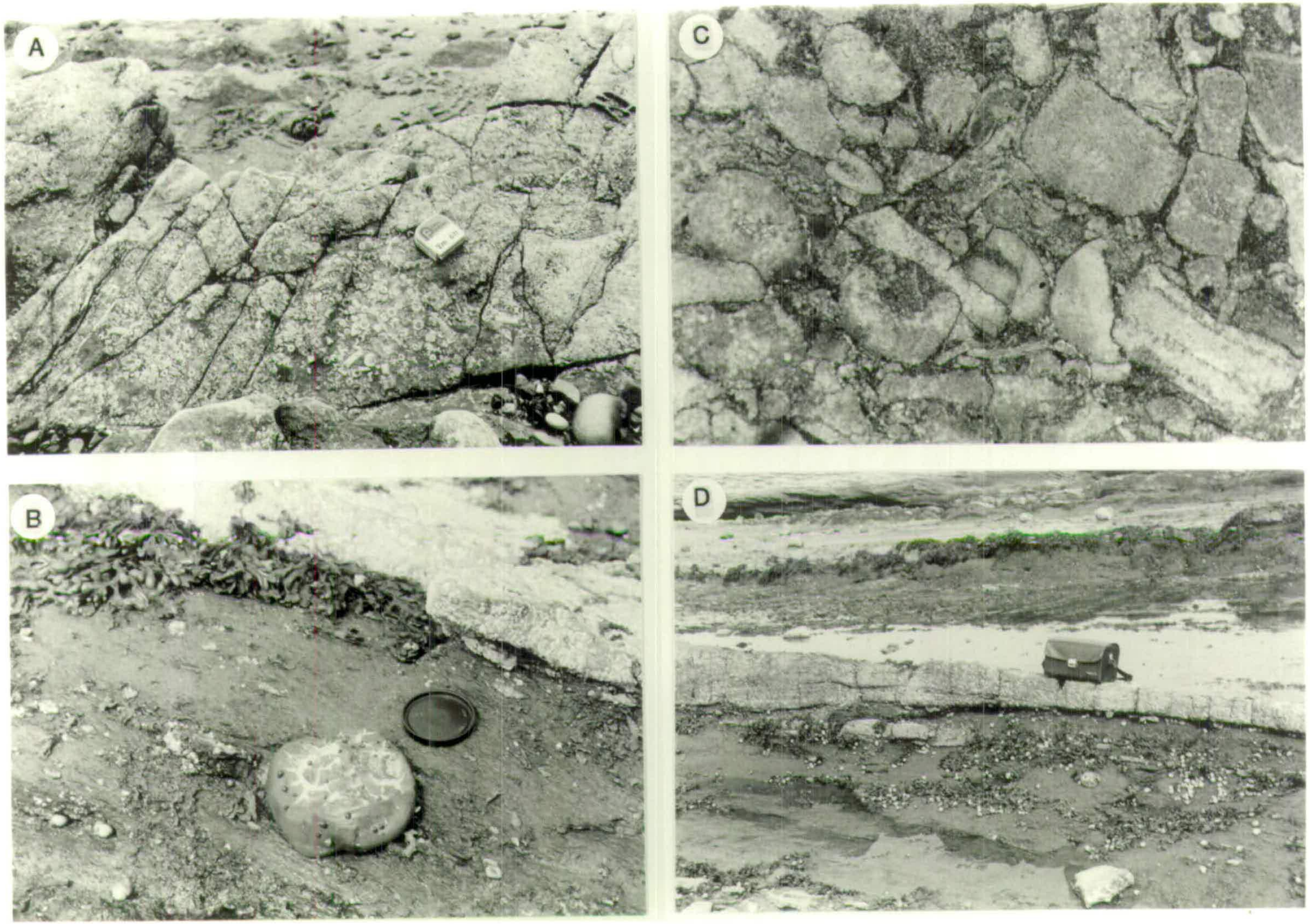

A
C
B
D

Fig. 11.5.

Field photographs of the coarse member of the Seafield Tower Sandstone at the base of the fining-upward unit which it forms, as exposed on the coast at Seafield (Kinghorn-Kirkcaldy) and inland in Inverteil Quarry.

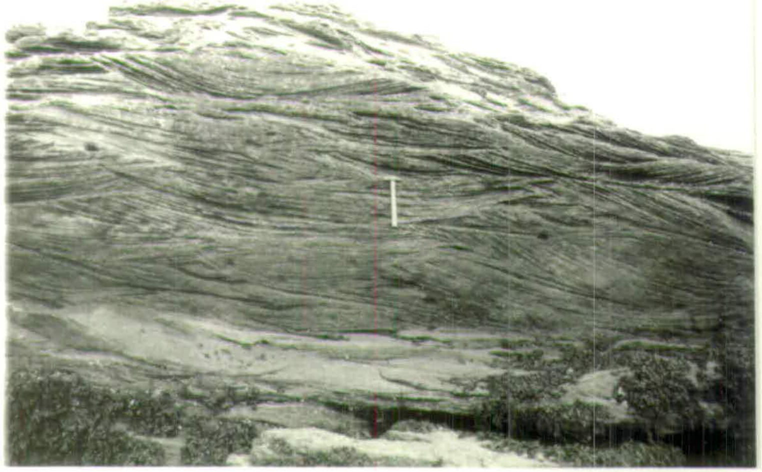
A. Prominent well exposed grouped sets (cosets) of spectacular massive, large-scale trough cross-bedding in the lower part of the Seafield Tower Sandstone coarse member at Seafield. The curved nature of the foresets within the curved, trough-shaped sets is conspicious, and the palaeocurrent direction (to the SW) is along the trough axes, in the direction towards which the foresets dip (i.e. out of the photograph towards the reader/observer). Scale: geological hammer, length=40 cm.

B. Prominent erosive, irregular and slightly undulatory reactivation surface located towards the middle of the coarse member of the sandstone at Seafield. These surfaces punctuate the cosets of trough cross-bedding and are interpreted as an erosive modification of the large curve-crested dune bedforms at low flow stage within the palaeochannel. Scale: geological hammer, length=30 cm.

C. Prominent and spectacular laterally accreted foresets dipping at low angles within a channel in the upper part of the coarse member in the eastern quarry face at Inverteil Quarry. These foresets (epsilon cross-stratification of Allen (1963)) dip at 90 degrees to the palaeocurrent (palaeocurrent-out of the photograph towards the reader/observer) and are separated by thin fine-grained beds which have largely been eroded away. Scale: geological hammer, length=59 cm.

D. Base of the coarse member of the cross-bedded Seafield Tower Sandstone on the shore at Seafield. It is underlain by red-pink coloured swaley, crudely ?hummocky cross-stratified crinoidal grainstones and packstones interbedded with shales. The sandstone has an undulatory and erosive base which has cut down through former delta-front and prodelta sediments into the marine shale and limestone sequence above the Seafield Tower Limestone. Scale: camera bag, length=24 cm.

A



C

B

D

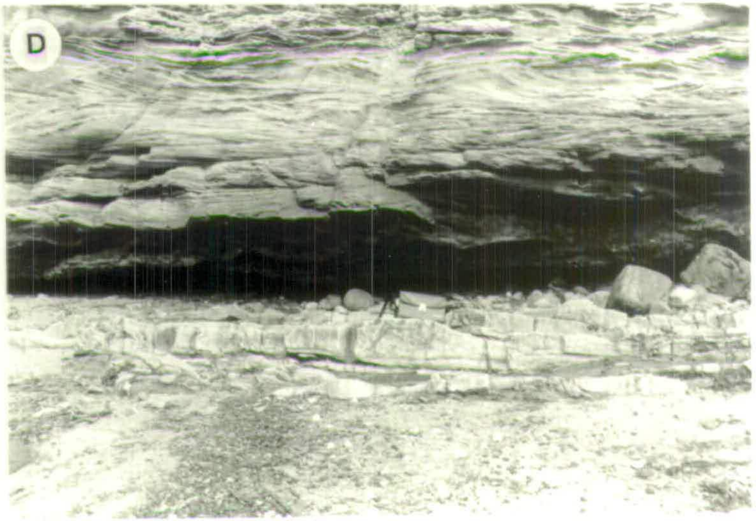


Fig. 11.6.

Field photographs showing aspects of the coarse member of the Seafield Tower Sandstone from exposures on the coast at Seafield (A and C) and inland at Inverteil Quarry (B and D), Kirkcaldy.

A. Spectacularly exhumed trough cross-bed set from the lower part of the coarse member as exposed on the foreshore at Seafield. The curved foresets within the set dip away from the reader/observer into the photograph. The palaeocurrent direction is along the axis of the set in the direction towards which the foresets dip (into the photograph, to the SW). This massive, large-scale set is just one of a whole group of large trough cross-bed sets which form a coset of trough cross-bedding (grouped trough cross-bed sets). Scale: camera bag (sits on top of exhumed trough cross-bed set), length=24 cm.

B. Loose block of conglomeratic sandstone from the lag horizon developed within pod-like scour pits on the irregular, undulatory base of the Seafield Tower Sandstone coarse member in Inverteil Quarry. The conglomeratic lag is characterised by poor sorting and the presence of mudrock clasts, coaly 'rafts', coalified plant material and a very coarse-grained sandstone matrix. This lag also contains reworked siderite nodules, crinoidal mudclasts and large drifted logs and tree trunks. Scale: pencil, length=14.5 cm.

C. Exposure of the upper part of the coarse member of the Seafield Tower Sandstone as exposed on the Seafield foreshore. Pervasively developed convoluted bedding/lamination is present, forming small, and largely symmetrical fold structures with peaks/crests and troughs. Scale: geological hammer, length=30 cm.

D. Eastern quarry face at Inverteil, showing development of large channels (4-6 m in width and outlined in ink) in the upper part of the coarse member of the Seafield Tower Sandstone. Scale: camera bag, length=24 cm.

A

B

C

D

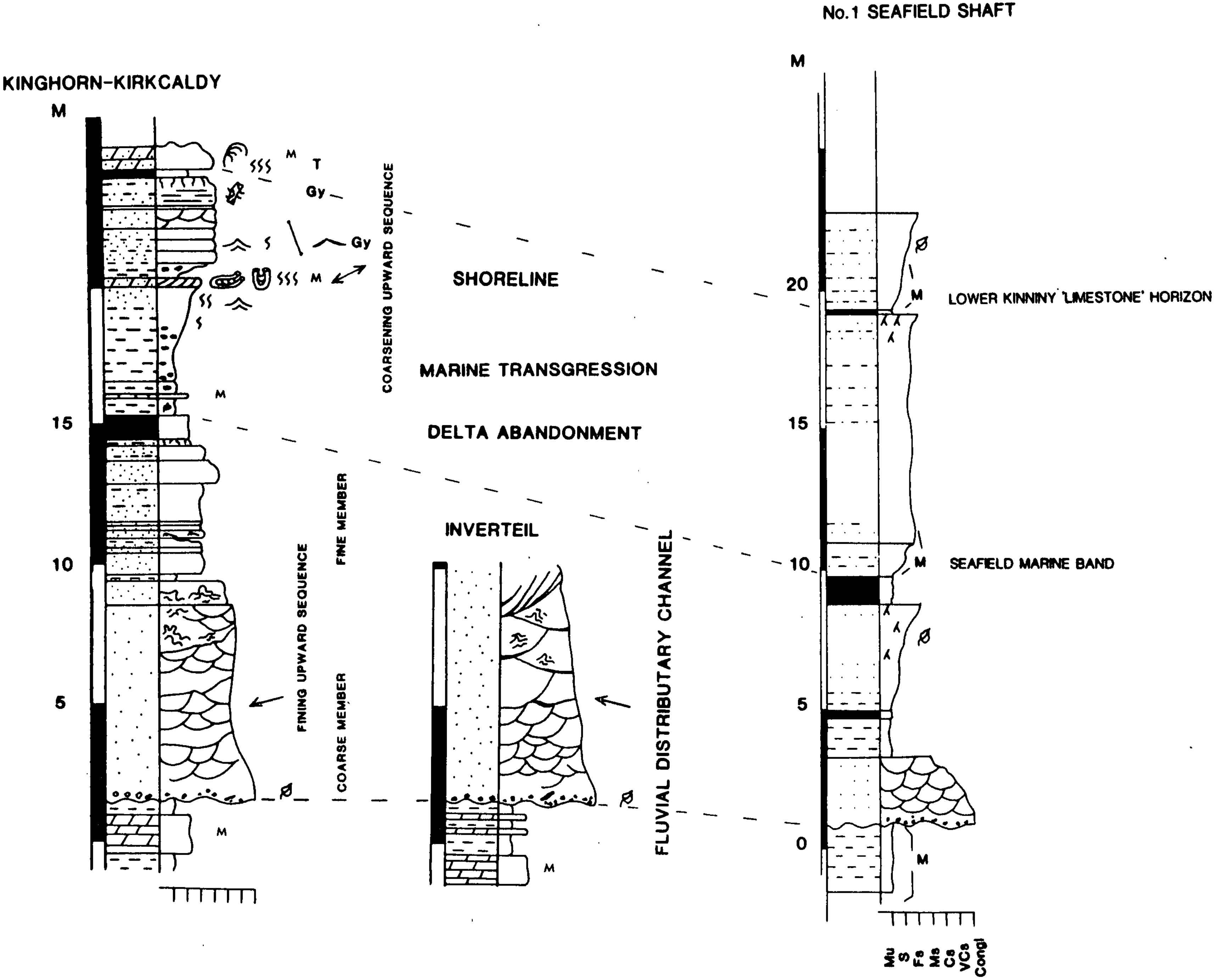

No.1 SEAFIELD SHAFT
KINGHORN-KIRKCALDY
M
M
T
Gy
Gy
M
M
COARSENING UPWARD SEQUENCE
SHORELINE
MARINE TRANSGRESSION
DELTA ABANDONMENT
FINE MEMBER
FINING UPWARD SEQUENCE
COARSE MEMBER
INVERTEIL
FLUVIAL DISTRIBUTARY CHANNEL
M
M
LOWER KINNINY 'LIMESTONE' HORIZON
SEAFIELD MARINE BAND
M
M
15
10
5
20
15
10
5
0
Mu
S
Fs
Ms
Cs
VCs
Congl

Fig. 11.8.

A. Field photograph showing the erosive base of the North Greens Sandstone (Seafield Tower Sandstone correlative) cutting into the calcareous mudrocks and limestones above the North Greens Limestone (Seafield Tower Limestone equivalent) in the Bilston Burn, Midlothian. The sandstone is in the foreground (bottom left hand corner of the photograph) and the undulatory erosive base is marked by the position of the geological hammer. The underlying strata (upstream towards the top right hand side of the photograph) comprise interbedded shales and limestones. The harder and more weathering resistant limestones form small 'waterfalls' in the stream bed. Scale: geological hammer, length=59 cm.

B. Bands of elliptical-shaped, flattened siderite nodules in dark fissile shales in the middle part of the coarsening-upward sub-unit A (Seafield Marine Band) above the coal which caps the Seafield Tower Sandstone. Seafield foreshore, central Fife. Scale: camera lens cap, diameter=6 cm.

C. Water escape structure (pipe) with associated deformed laminae/beds in the upper part of the coarse member of the Seafield Tower Sandstone, Seafield foreshore, Kinghorn-Kirkcaldy coastal section, central Fife. These soft sediment deformation structures are associated with other soft sediment deformation (liquefaction) structures such as convolute bedding/lamination. Scale: geological hammer, length=30 cm.

D. Fine member of the Seafield Tower Sandstone showing interbedded sandstones and mudrocks. The area in the background is the coarsening-upward sequence forming the middle part of the Seafield Marine Band, whilst the boulder strewn area in the middle ground marks the position of the 1 m thick coal which was once worked at outcrop and is now seldom exposed. Scale: camera bag, length=24 cm.

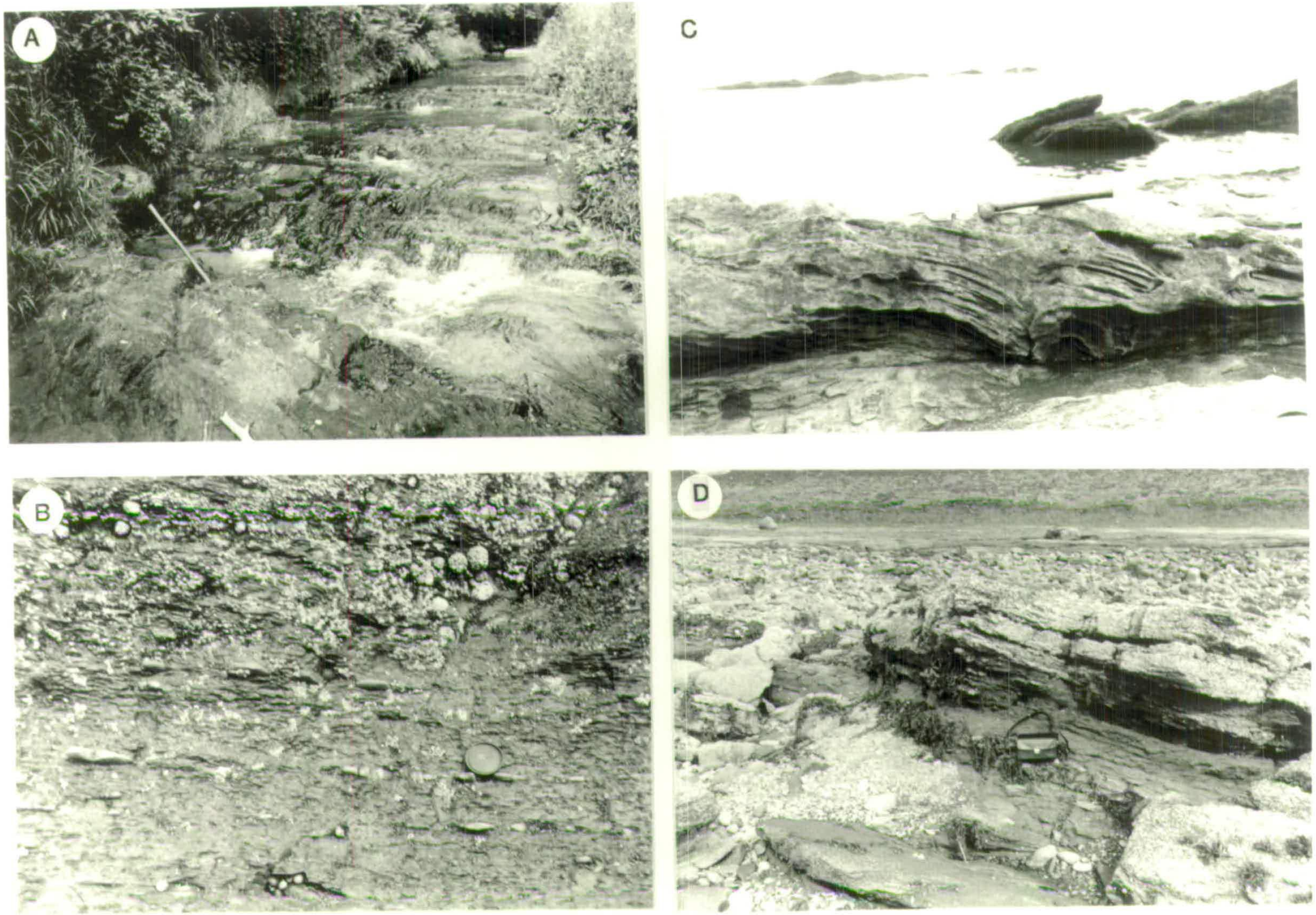

A
C
B
D

Fig. 11.9.

Field photographs showing aspects of the coarsening-upward sub-unit A (Seafield Marine Band) and underlying abandonment facies as exposed on the shore at Seafield.

A. Upper bedding plane surface of thye thin sandy limestone capping coarsening-upward sub-unit A. Aligned/sub-aligned *Diplocraterion* burrows are present, which have been eroded to form a characteristic 'doggy bone' shape. The surface of the limestone is slaggy weathered, and this has developed due to extreme bioturbation. Scale: pencil, length=13 cm.

B. Upper bedding plane surface of paleosol (seat-earth) below the 1 m coal which caps the fine member of the Seafield Tower Sandstone in the Seafield shore section, Kinghorn-Kirkcaldy. Coalified rootlets are present and the structureless nature of the silty/muddy host rock is conspicious. Scale: camera lens cap, diameter=6 cm.

C. Coarsening-upward sub-unit A above the fine member of the Seafield Tower Sandstone. The boulder strewn area in the foreground covers a 1 m thick coal, and the camera bag sits upon a very thin and impersistent marine limestone near the base of the Seafield Marine Band. A coarsening-upward trend is present in the sequence with shales passing upwards through interbedded sandstones, shales and siltstones. This sequence is capped by a thin marine sandy limestone (see A, above) which is just visible towards the top of the photograph (background). Scale: camera bag, length=24 cm.

D. Bedding plane surface of the thin sandy marine limestone which caps coarsening-upward sub-unit A of the Seafield Marine Band. Very large, protrusive *Rhizocorallium* burrows with well-preserved internal spreiten strucrtures are present. Disarticulated crinoid ossicles (crinoid debris) are also present, and the slaggy, bioturbated nature of the limestone is conspicious. Scale: geological hammer, length=30 cm.

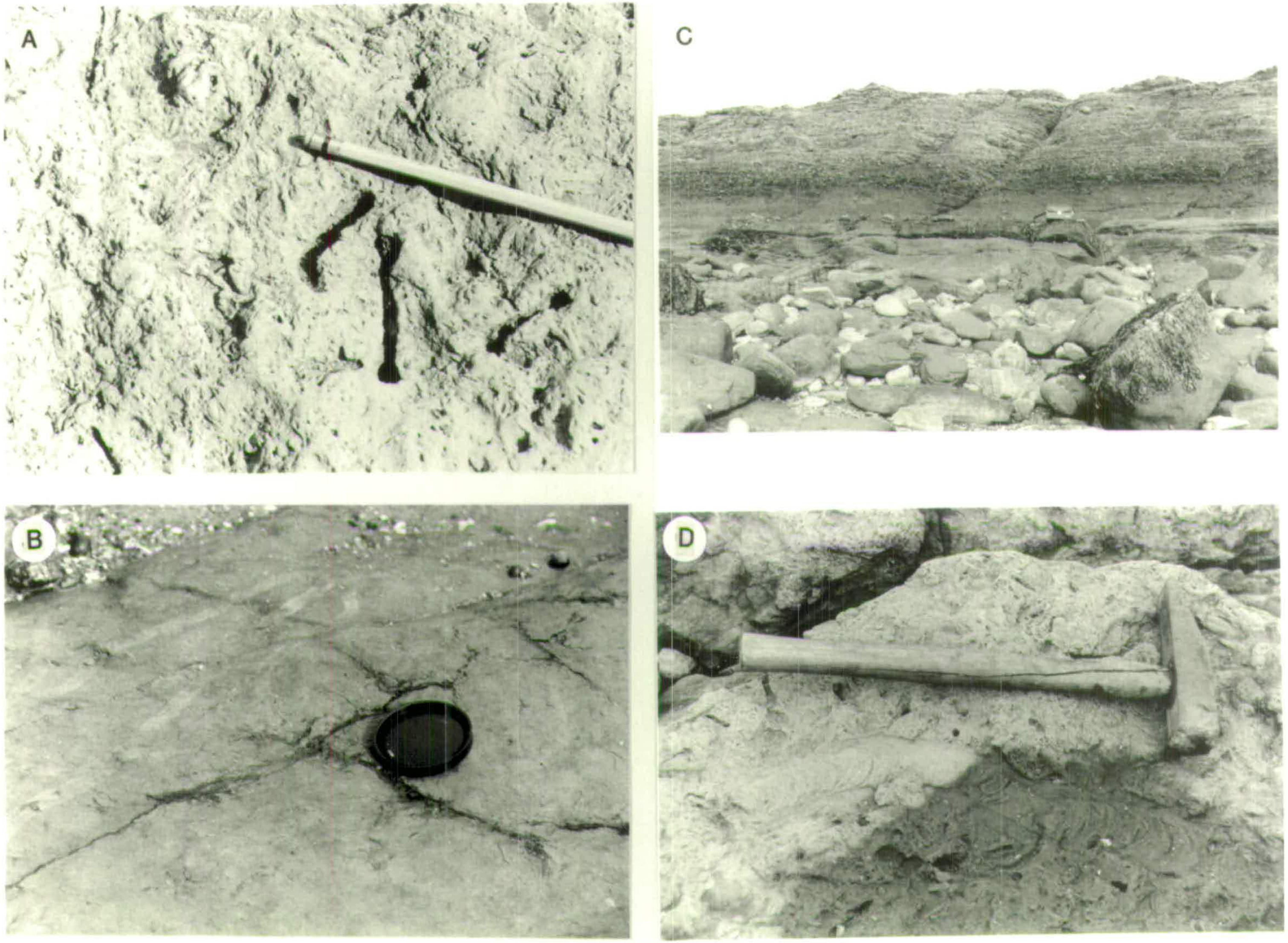
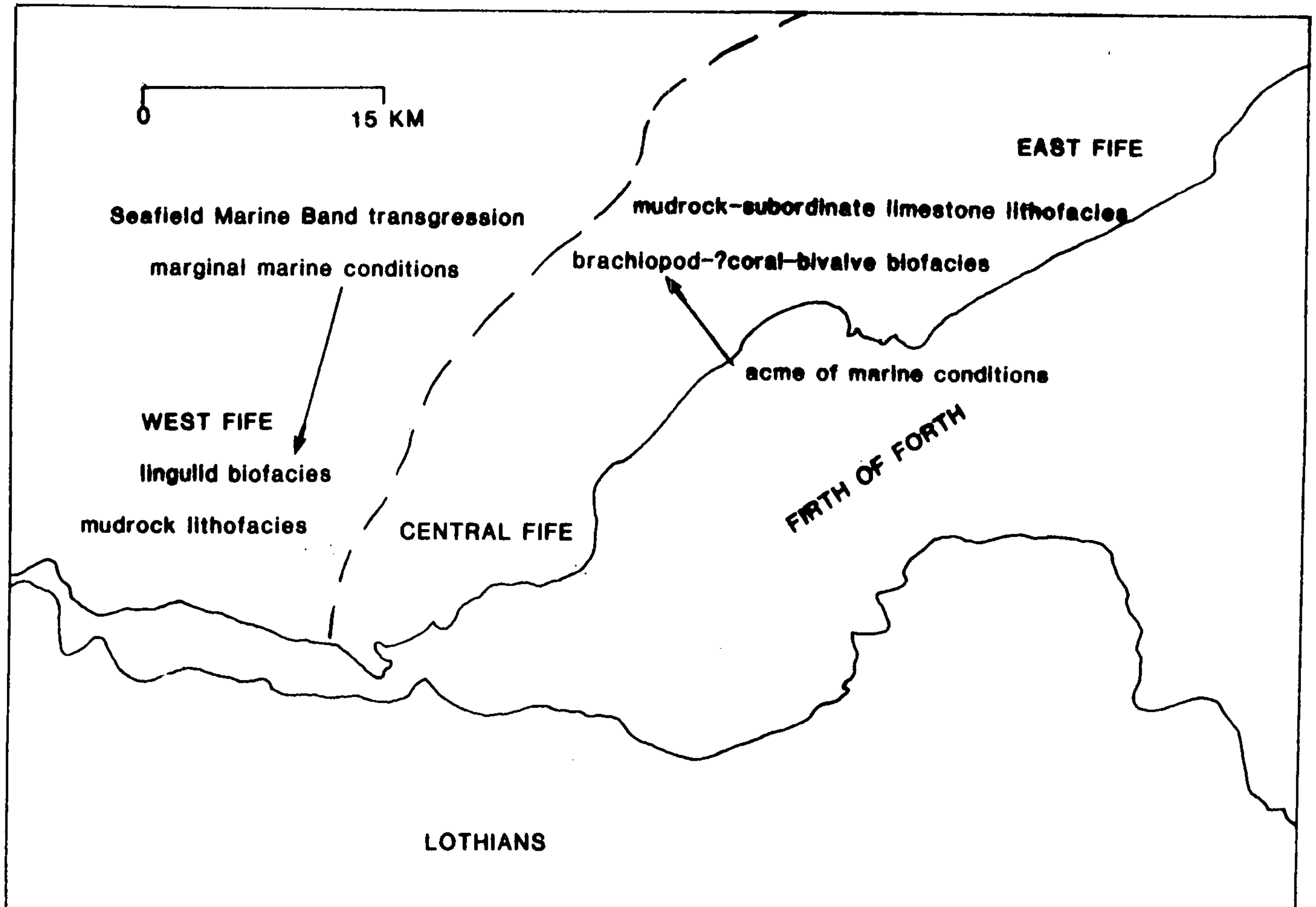
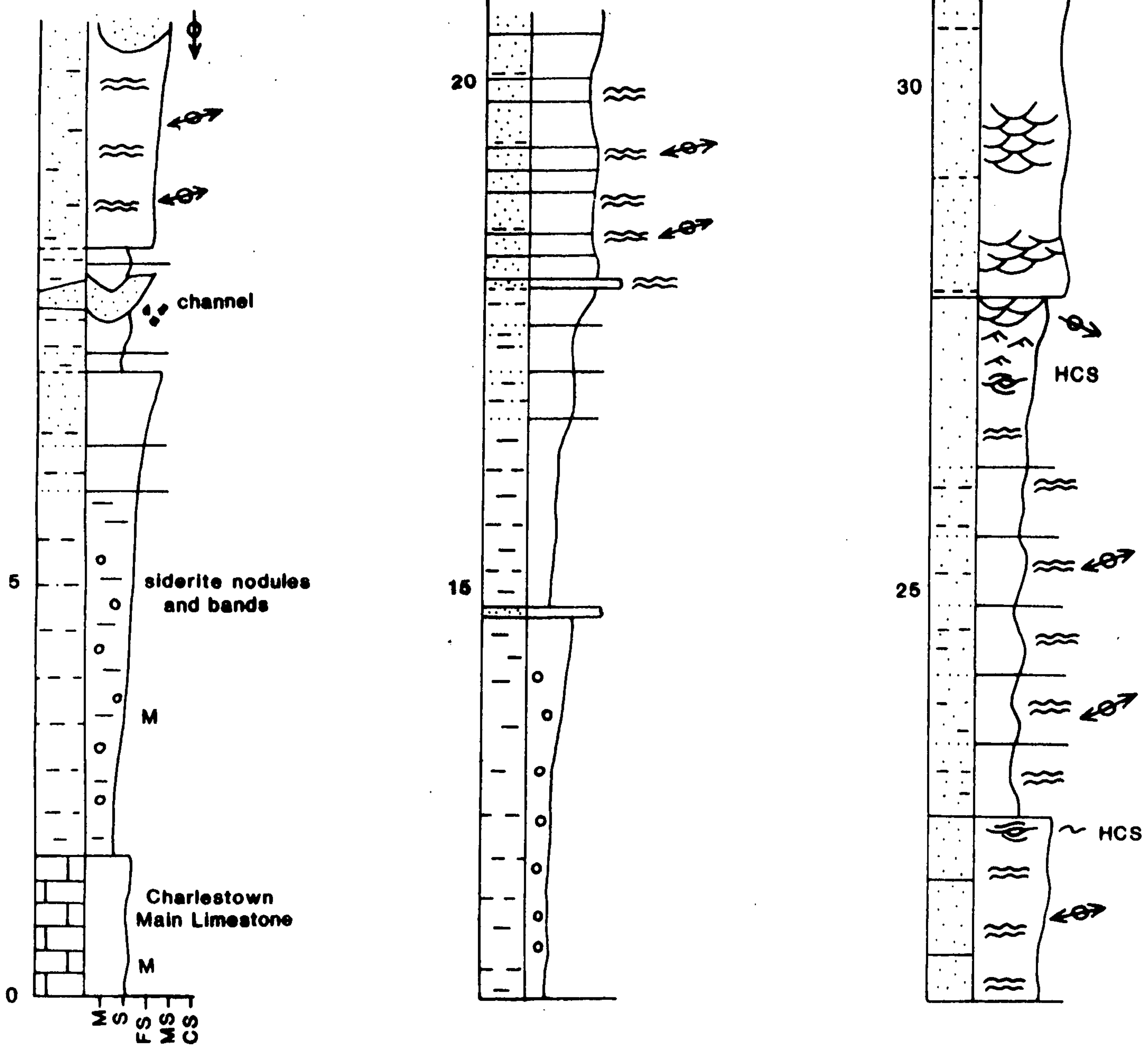

A
B
C
D

Fig. 11.10.

Interpretative sketch map showing a reconstruction of the bio- and litho- facies developed during the 'Seafield Marine Band marine transgression' throughout Fife. The acme of the marine conditions appears to have been reached in East Fife (presumably suggesting more open marine conditions to the E) whilst the marine conditions apparently petered out to the W so that the marine band degenerates to a *Lingula* band in West Fife. The barrier to the marine transgression spreading extensively into the W is considered to have been the tectonically positive Burntisland Anticline.



BIO-AND LITHO-FACIES DEVELOPED DURING SEAFIELD MARINE BAND TRANSGRESSION



CHARLESTOWN MAIN LIMESTONE AND OVERLYING COARSENING SEQUENCE

CHARLESTOWN MAIN–MIDDLE KINNINY LIMESTONES INTERVAL, EAST SIDE OF ST MONANS SYNCLINE, EAST FIFE

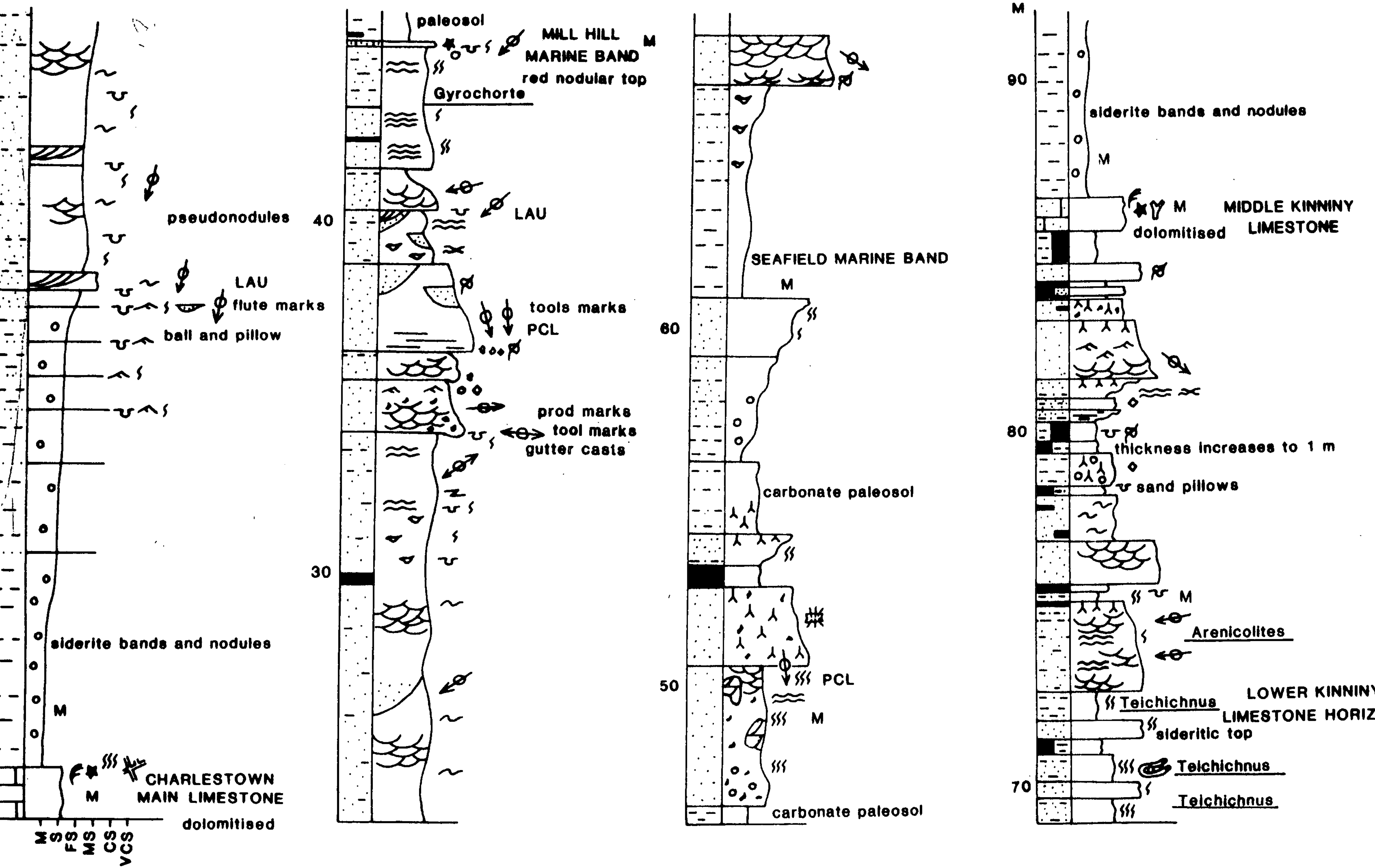


Fig. 11.13.

Field photographs showing aspects of the Charlestown Main Limestone and overlying coarsening-upward sequence as developed along the East Fife coastal section on both limbs of the St Monans Syncline.

A. Intercalated thin sandstones, shales and siltstones at the base of the coarsening-upward sequence above the Charlestown Main Limestone on the east side of the St Monans Syncline. The undersides of the sandstone beds are extensively bioturbated, characterised by trace fossils and display sole marks (see slab held in a vertical attitude by geologist). Scale: geologist, height approximately=1.8 m.

B. Hummocky cross-stratification developed in thin sandstone beds which are closely associated with wave-rippled sandstones. Middle to upper part of the coarsening-upward sequence above the Charlestown Main Limestone on the west side of the St Monans Syncline, East Fife. Scale: geological hammer shaft in picture, length=approximately 50 cm.

C. Channel sandstone in delta-front coarsening-upward sequence above the Charlestown Main Limestone on the west side of the St Monans Syncline, East Fife coastal section. The sandstone pinches out over a short distance laterally (towards the channel margins) and thickens towards the centre of the channel. This channel cuts into prodeltaic and delta-front siltstones, shales and thin sandstones. Scale: tape measure holder, diameter=18 cm.

D. Upper bedding plane surface of the Charlestown Main Limestone as exposed along the coastal section on the east side of the St Monans Syncline. A gallery-like network of *Thalassinoides* burrows is present along with extensive bioturbation. Scale: geological hammer, length=59 cm.

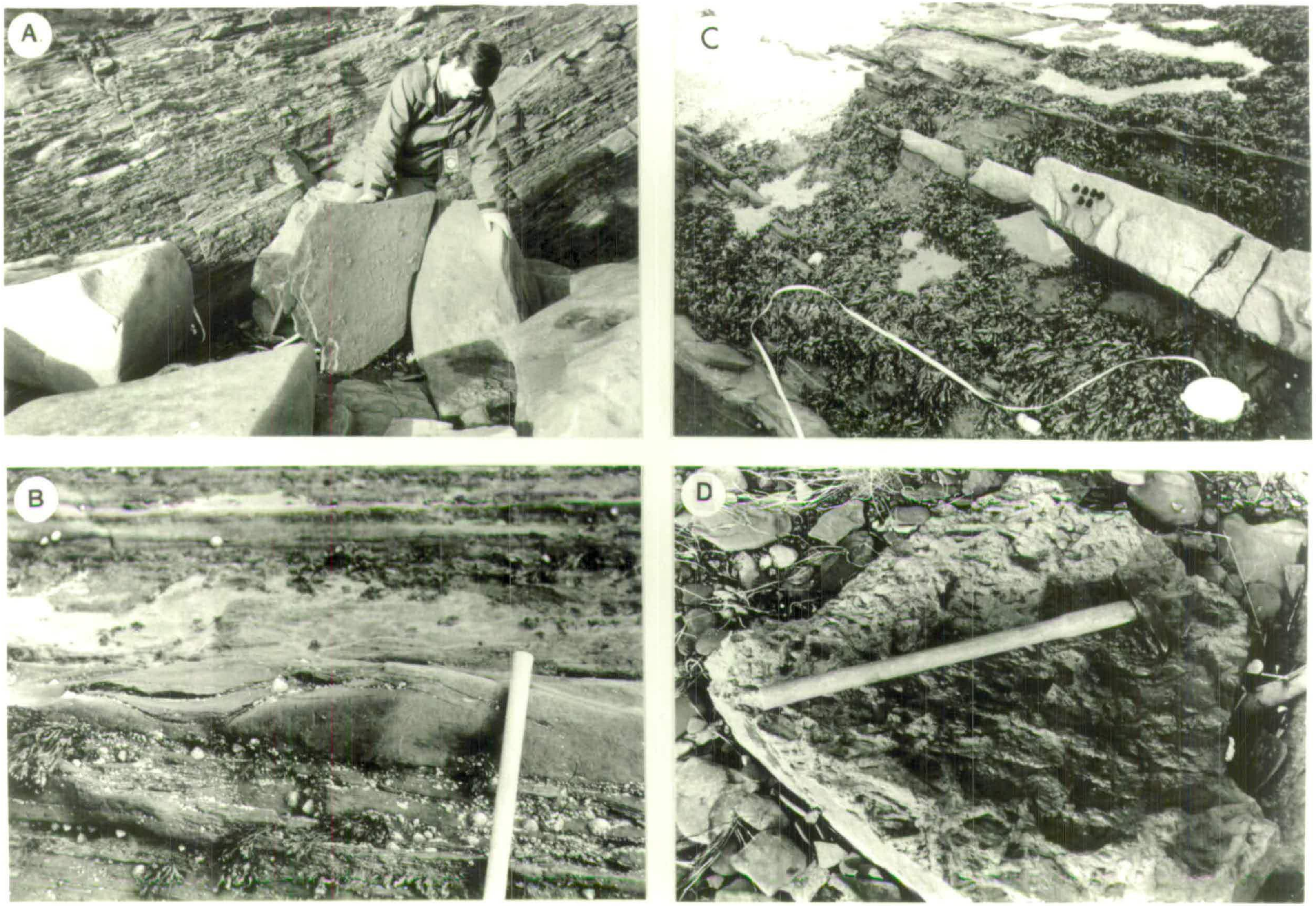

A
B
C
D

Fig. 11.14.

Large-scale graphic sedimentary logs of sedimentary sequences above the Charlestown Main Limestone (throughout Fife) from the Annfield Borehole, West Fife, the Kinghorn-Kirkcaldy coastal section, central Fife and the St Monans coastal section, East Fife. The Mill Hill Marine Band is absent in central Fife, but the general correlation of the three sections is possible. The major fluvial distributary channel Seafield Tower Sandstone is only present in central Fife which probably marks the site of a major axial drainage system which formed in the Fife-Midlothian Low but was absent to the west (W of the Burntisland Anticline) and to the east (E of the ?Cousland Axis).

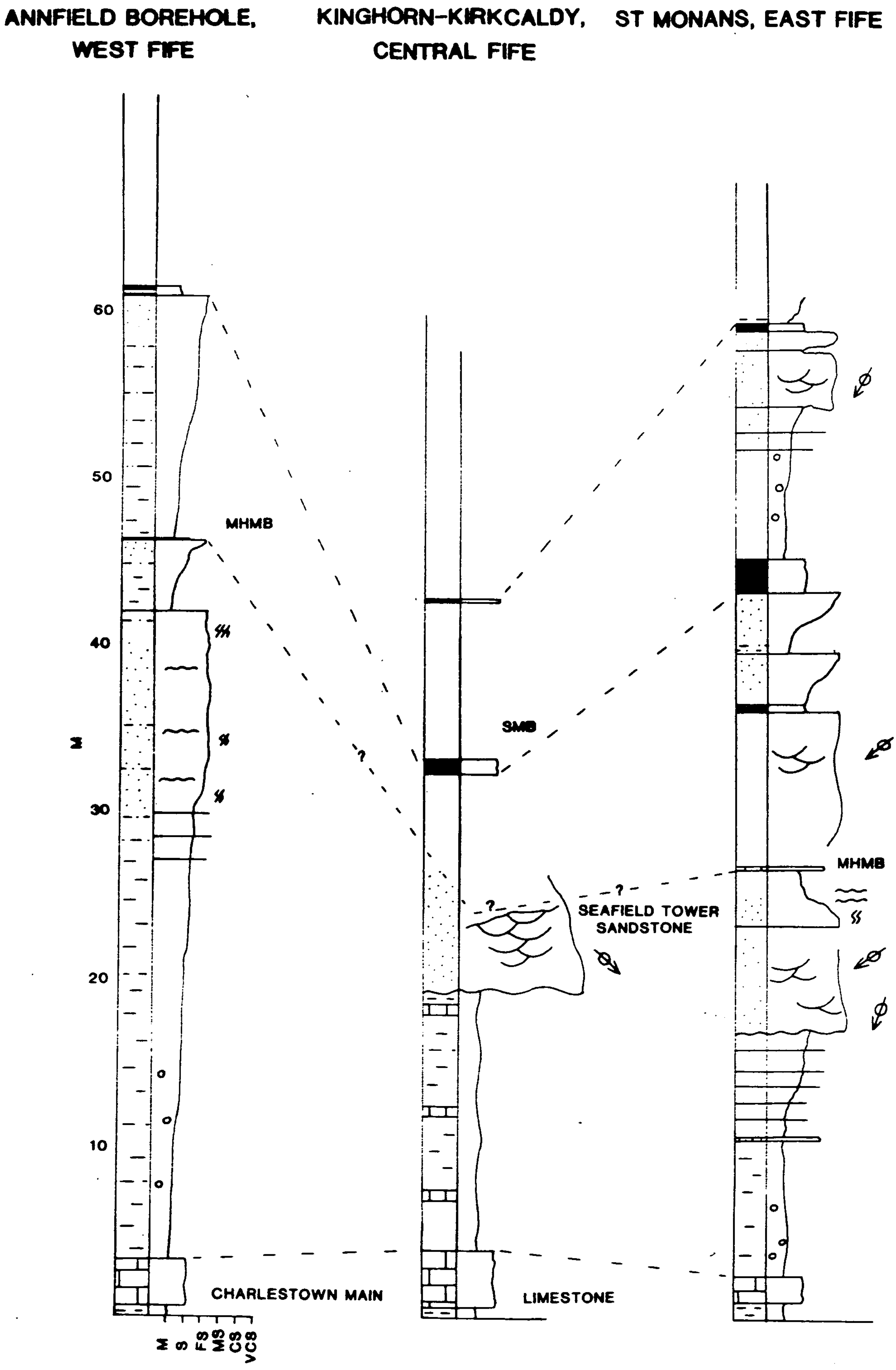

ANNFIELD BOREHOLE, WEST FIFE
KINGHORN-KIRKCALDY, CENTRAL FIFE
ST MONANS, EAST FIFE
60
50
40
M
30
20
10
MHMB
SMB
?
SEAFIELD TOWER SANDSTONE
MHMB
CHARLESTOWN MAIN
LIMESTONE
M
S
FS
MS
CS
VCS

Fig. 11.15.

Large-scale graphic sedimentary logs of the sedimentary sequences in the Lothians area above the Charlestown Main Limestone as exemplified by the Bilston Burn stream section, Midlothian and the Catcraig coastal section, East Lothian. Above the Charlestown Main Limestone (at the base of the graphic logs) the sequences are difficult to correlate. The major fluvial distributary channel North Greens Sandstone is correlated with the Seafield Tower Sandstone and as this locality is directly to the south of the Seafield locality, it appears that the channel flowed down the axis of the Fife-Midlothian Low which passes through these two areas.

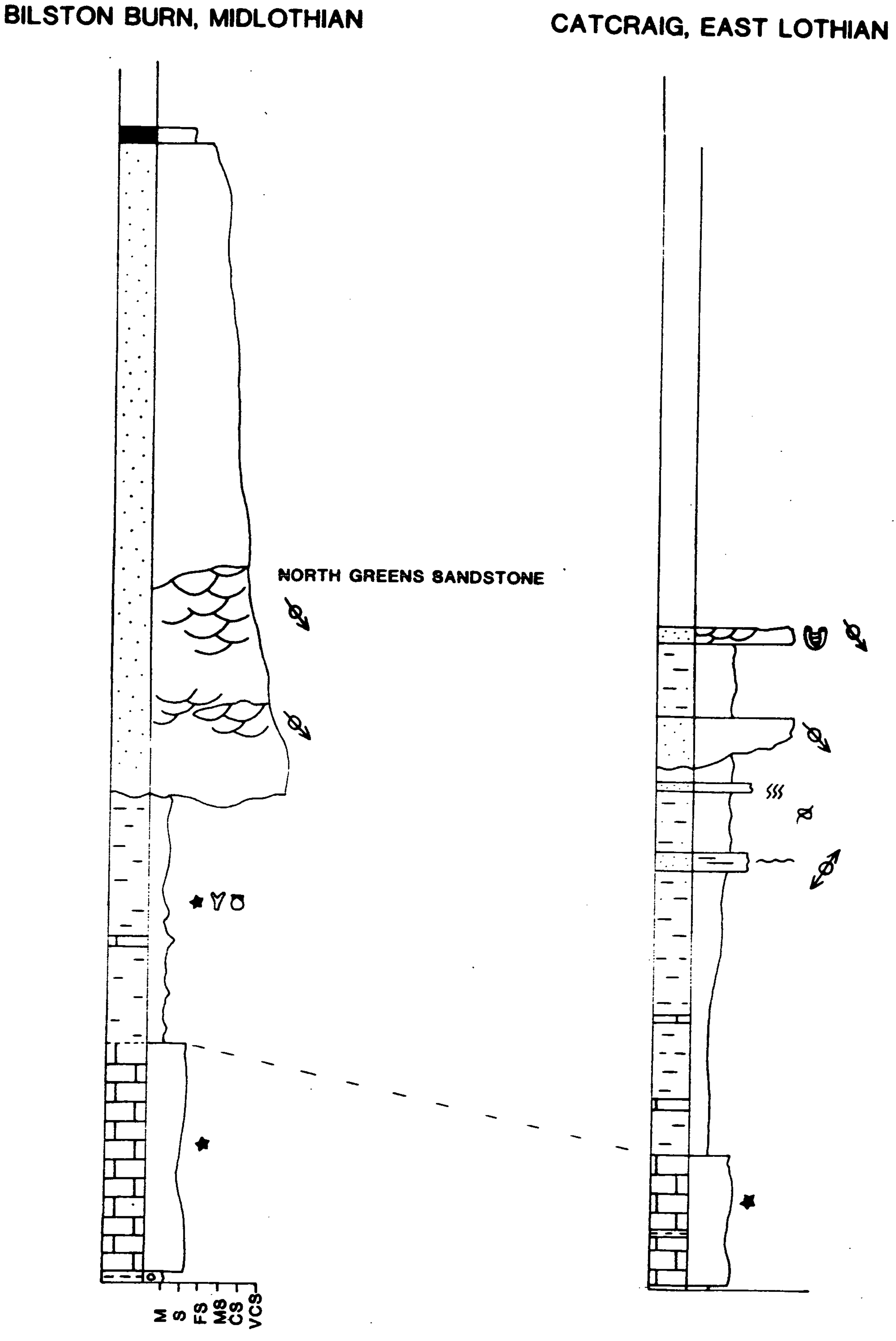

BILSTON BURN, MIDLOTHIAN
CATCRAIG, EAST LOTHIAN
NORTH GREENS SANDSTONE
M
S
FS
MS
CS
VCS

Fig. 11. 16.

Interpretative sketch diagram showing position of major axes or highs (BA=Burntisland Anticline, CA=Cousland Axis) and adjoining lows and their interpretation as major tilt-block/half-graben structures which are present at depth and have been overprinted by Hercynian folds to give rise to the present day structural configuration. The major sandstones are found within the lows (e.g. Seafield Tower-North Greens Sandstone in Fife-Midlothian Low between the Burntisland and Cousland axes) where the clastic:carbonate ratios are greater than on the highs. The adjacent highs are characterised by lower clastic:carbonate ratios and are volcanic prone (e.g. vocanic vents and plugs forming along the Burntisland Anticline). The lows were evidently subsiding at a greater rate than the adjacent highs and were therefore characterised by major delta lobes which prograded into such tracts, where axial drainage systems formed. The delta-tops of these lobes are characterised by major channel sandstone bodies (e.g. Seafield Tower-North Greens Sandstone). The underlying sketch outline map is of the Firth of Forth area at the eastern end of the Midland Valley of Scotland. Scale: 0-20 km, as indicated on the map.

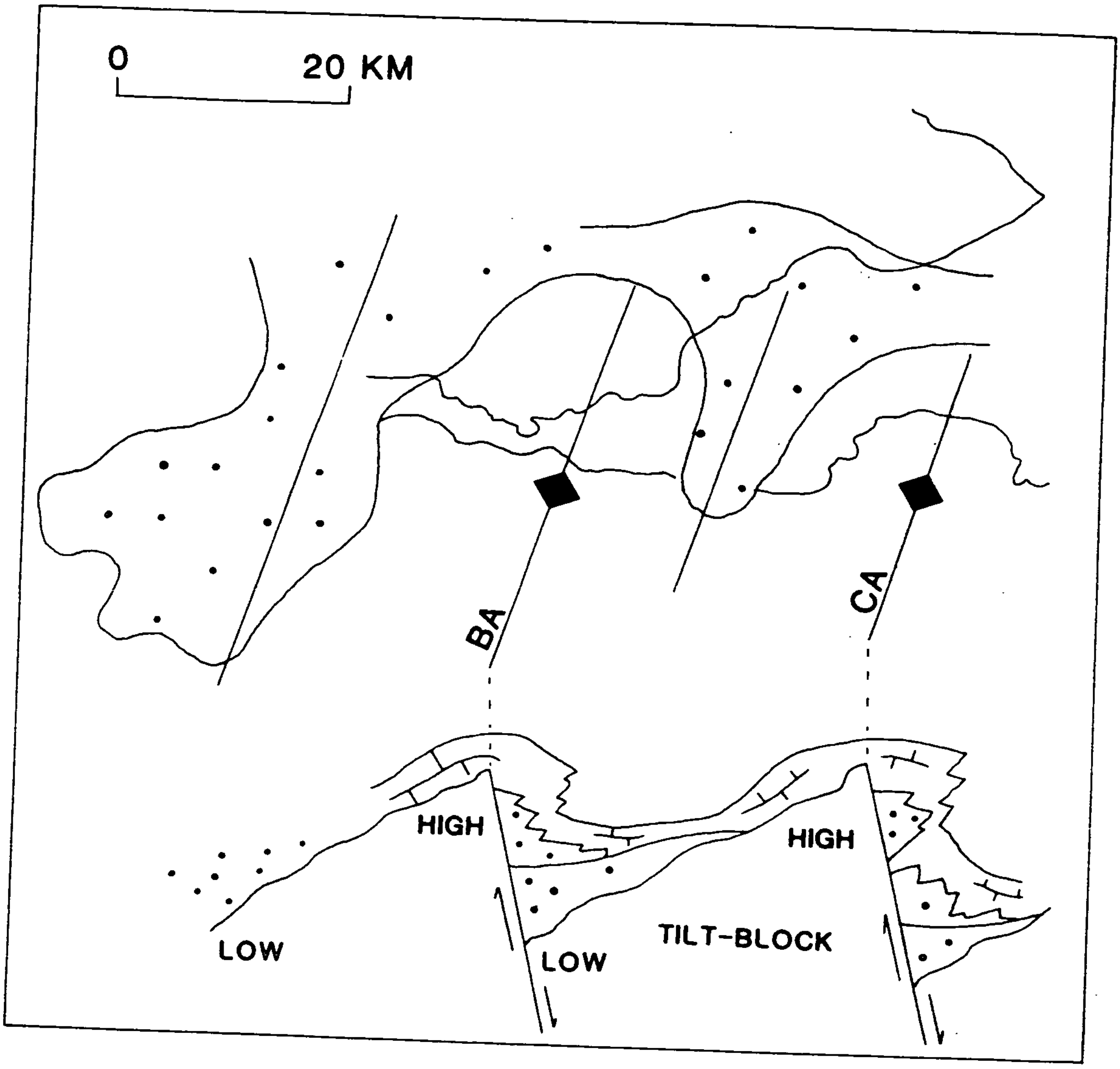

0
20 KM
BA
CA
HIGH
HIGH
LOW
LOW
TILT-BLOCK

Fig. 12.1.

Sketch map of the Fife and the Lothians area showing position of the localities where specific parts of the Strathclyde Group and the overlying Lower Limestone Group were studied.

(i)East Fife; Drumcarro, Callange and Muircambus boreholes (cf. Forsyth and Chisholm 1968) and the St Monans coastal section (cf. Forsyth and Chisholm 1977). (ii) Central Fife; Seafield No.1 Colliery Shaft and Kinghorn-Kirkcaldy coastal section (Francis 1961a). (iii) West Fife; Annfield Borehole (cf. Forsyth 1970). (iv) East Lothian; Spilmersford Borehole (Davies 1974), Skateraw Borehole and Catcraig coastal section (Davies *et al.* 1986).

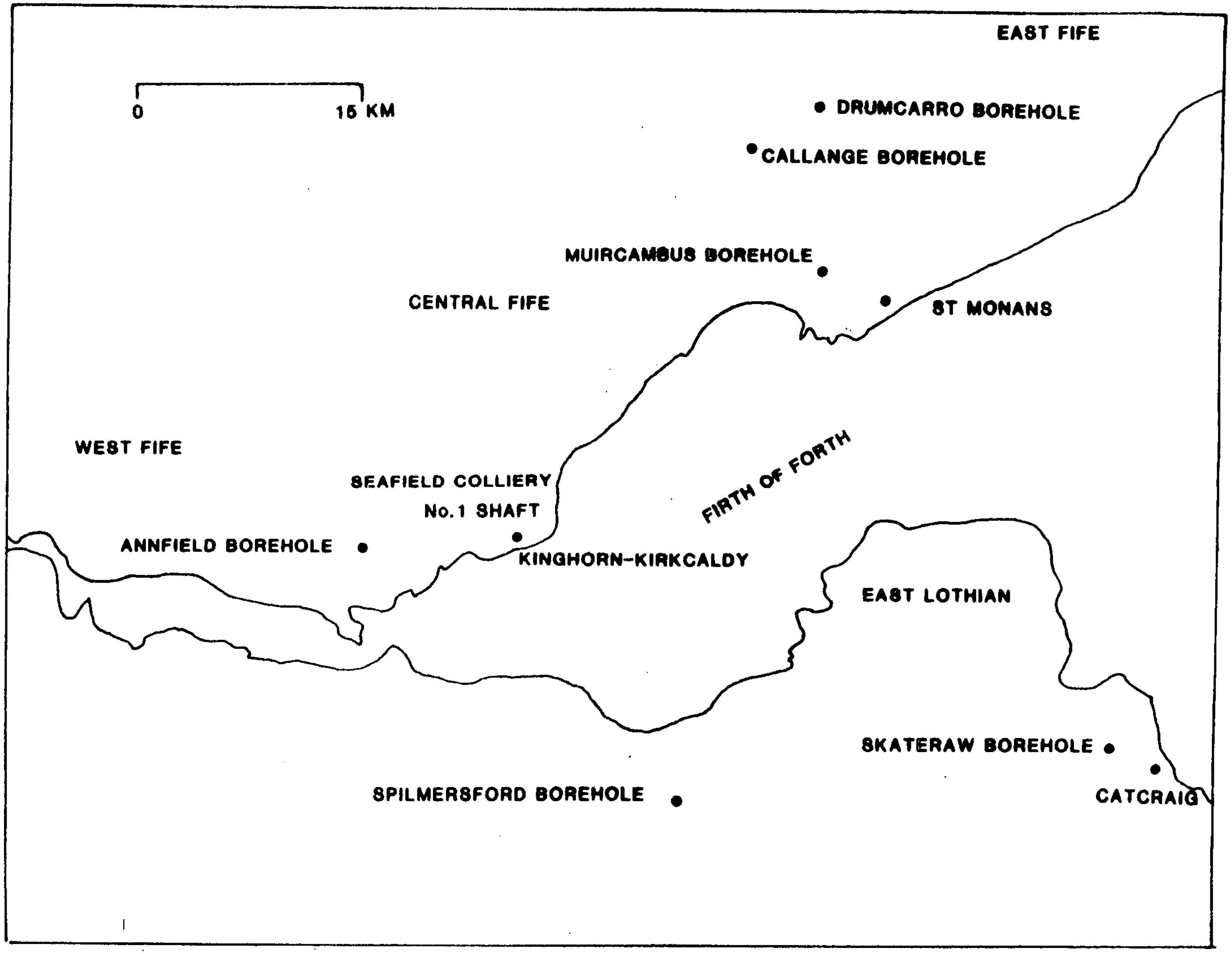
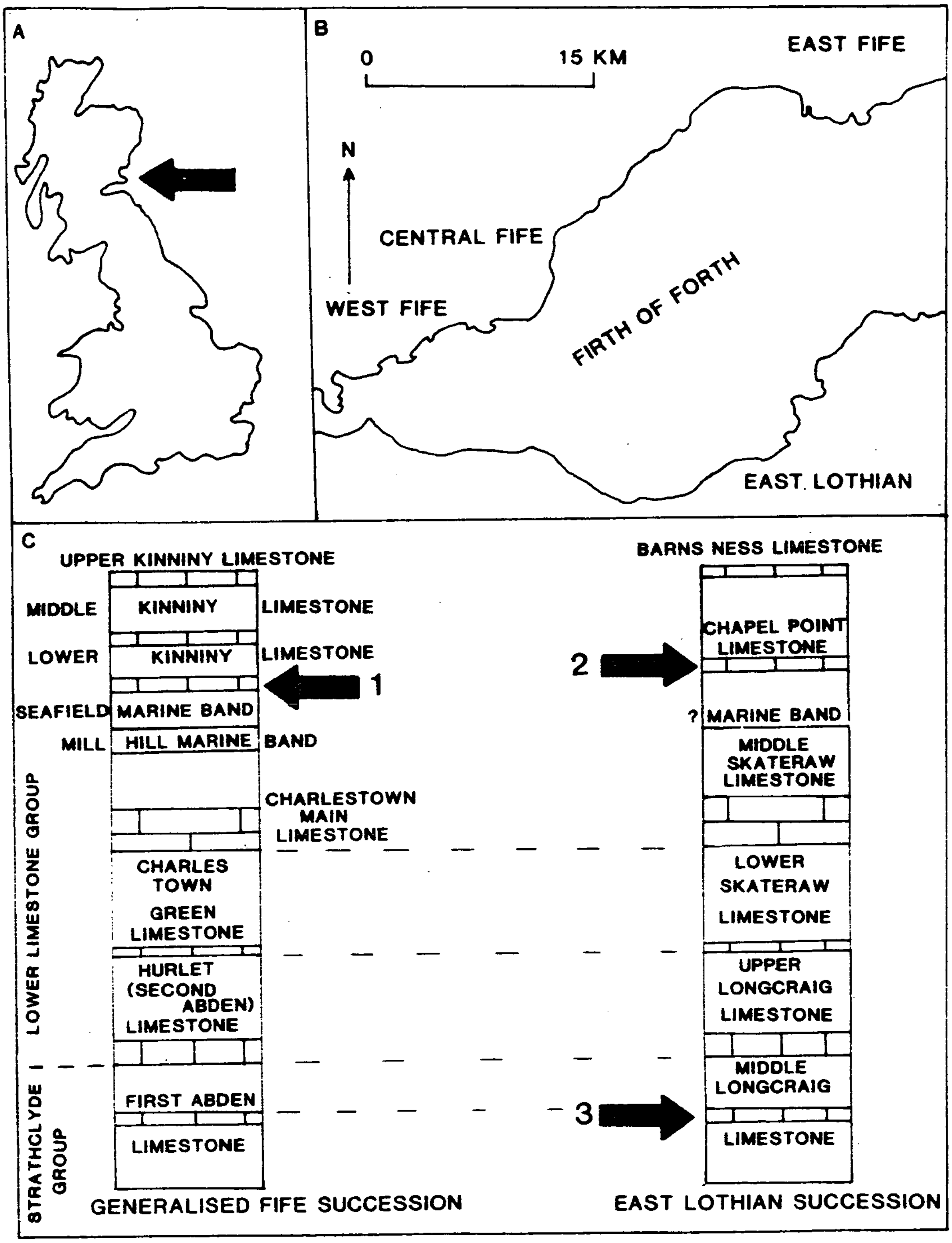

EAST FIFE
0
15 KM
DRUMCARRO BOREHOLE
CALLANGE BOREHOLE
MUIRCAMBUS BOREHOLE
CENTRAL FIFE
ST MONANS
WEST FIFE
FIRTH OF FORTH
SEAFIELD COLLIERY
No.1 SHAFT
ANNFIELD BOREHOLE
KINGHORN-KIRKCALDY
EAST LOTHIAN
SKATERAW BOREHOLE
SPILMERSFORD BOREHOLE
CATCRAIG

Fig. 12.2.

A. Outline sketch map of mainland Great Britain (excluding Ireland) showing approximate position of Fife and the Lothians (areas adjacent to the Firth of Forth) in relation to the rest of Britain.

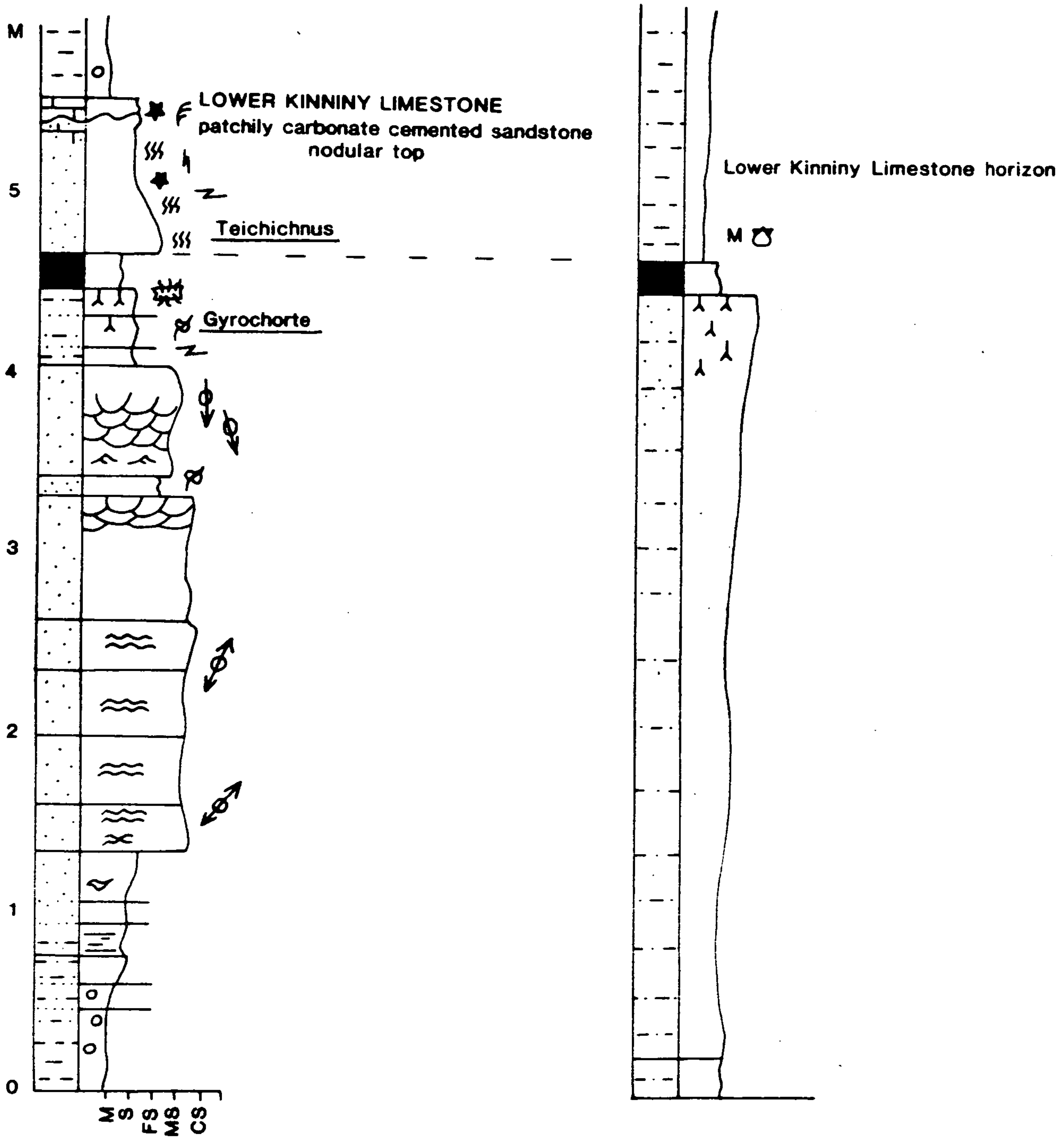
B. Sketch map of the Fife and the Lothians area showing the relative positions of east, west and central Fife and East Lothian in relation to the Firth of Forth.

C. Diagram showing the positions of the main marine marker horizons in the generalised Fife and East Lothian successions. The lower marine bands (up to the level of the Charlestown Main-Middle Skateraw Limestone horizon) are easily correlated, whereas above the critical Charlestown Main-Middle Skateraw Limestone position correlation is not feasible. Arrow 1 points to the Lower Kinniny Limestone horizon which was investigated throughout Fife, whilst arrows 2 and 3 refer to the Middle Longcraig and Chapel Point limestones, similar facies which were identified in East Lothian.


A
B
0
15 KM
EAST FIFE
N
CENTRAL FIFE
WEST FIFE
FIRTH OF FORTH
EAST. LOTHIAN
C
UPPER KINNINY LIMESTONE
MIDDLE KINNINY LIMESTONE
LOWER KINNINY LIMESTONE
1
SEAFIELD MARINE BAND
MILL HILL MARINE BAND
CHARLESTOWN MAIN LIMESTONE
CHARLES TOWN GREEN LIMESTONE
HURLET (SECOND ABDEN) LIMESTONE
FIRST ABDEN LIMESTONE
LOWER LIMESTONE GROUP
STRATHCLYDE GROUP
GENERALISED FIFE SUCCESSION
BARNS NESS LIMESTONE
CHAPEL POINT LIMESTONE
2
? MARINE BAND
MIDDLE SKATERAW LIMESTONE
LOWER SKATERAW LIMESTONE
UPPER LONGCRAIG LIMESTONE
MIDDLE LONGCRAIG LIMESTONE
3
EAST LOTHIAN SUCCESSION

12.3.

Graphic sedimentary log of the Lower Kinniny Limestone horizon and associated beds from the Kinghorn-Kirkcaldy coastal section and the Seafield No. 1 Colliery Shaft, central Fife. The Lower Kinniny Limestone and the underlying bioturbated sandstone bed are present in the coastal section, but are absent in the nearby colliery shaft. Below the major coal, both sequences broadly coarsen-upward, representing delta progradation into shallow marine conditions established by the underlying 'Seafield Marine Band marine transgression'. The prodelta facies at the base consists of mudrocks with siderite nodules and thin sandstone laminae which pass upward into lenticular, flaser and wavy bedded silty sandstones and sandstones with thin mudrock laminae. These prodelta to delta-front sandstones pass upward into the main delta-front sandstones which are flaser bedded and predominantly wave-rippled indicating wave-reworking of the delta-front. The overlying trough cross-bedded sandstones record delta-top distributary channel deposition. These delta-top channel sands are capped by a unit of interbedded siltstones and sandstones ('striped beds' cf. Kelling and George (1971)) which contains *in situ* rootlets, stigmarian and *Lepidodendron* remains, drifted plant fragments and the horizontal, interfacial epichnial trails of *Gyrochorte* and *Planolites* (cf. Hallam 1970) indicative of freshwater conditions (Anderton *et al.* 1979, p. 162). These beds are interpreted as delta-top bay fill facies, representing abandonment and the establishment of an *in situ* vegetation due to reduced rates of sedimentation during abandonment. The overlying coal/coaly mudrock also records delta abandonment, although at a slightly later and more advanced stage, when waterlogged (hydromorphic) conditions were established on the delta-top, where organic paleosols accumulated and organic matter was protected from bacterial destruction by waterlogged conditions (cf. Anderton *et al.* 1979). The overlying bioturbated calcareous marine sandstone is sometimes laterally impersistent, even over apparently short distances (e.g. between the coast section at Kinghorn-Kirkcaldy and the Seafield No.1 Colliery Shaft). It is interpreted as a reworked delta-front sand sheet which migrated 'landward' over the abandoned delta-top in response to marine reworking at the start of the transgression.



Kinghorn–Kirkcaldy coastal section

Seafield No. 1 Colliery Shaft

12.4

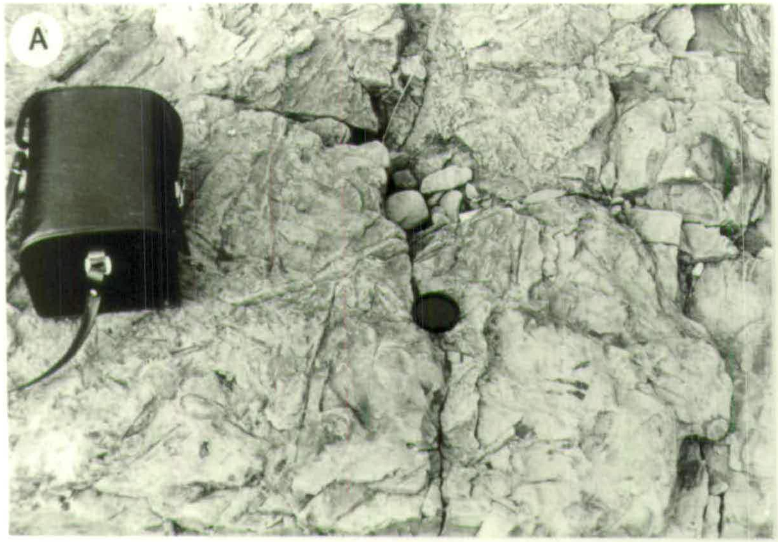
A. Drifted plant remains in interbedded sandstones and siltstones at the top of the coarsening-upward sequence below the Lower Kinniny Limestone (subjacent to the coal below the Lower Kinniny Limestone). Foreshore, north-east of Seafield Tower, Kinghorn-Kirkcaldy coastal section, central Fife. Scale: camera lens cap-diameter=6 cm, camera bag=24 cm in length.

B. Extensive wave-rippled surface of a sandstone in the middle part of the coarsening-upward sequence below the Lower Kinniny Limestone. The ripple crests are rounded, symmetrical, laterally continuous and occasionally slightly bifurcate. Scale: geological hammer, length=40 cm.

C. Flattened (compressed) impression of *Lepidodendron* tree trunk preserved in sandstones and interbedded siltstones ('striped beds') at the top of the coarsening-upward sequence below the Lower Kinniny Limestone. Scale: camera lens cap, diameter=6 cm.

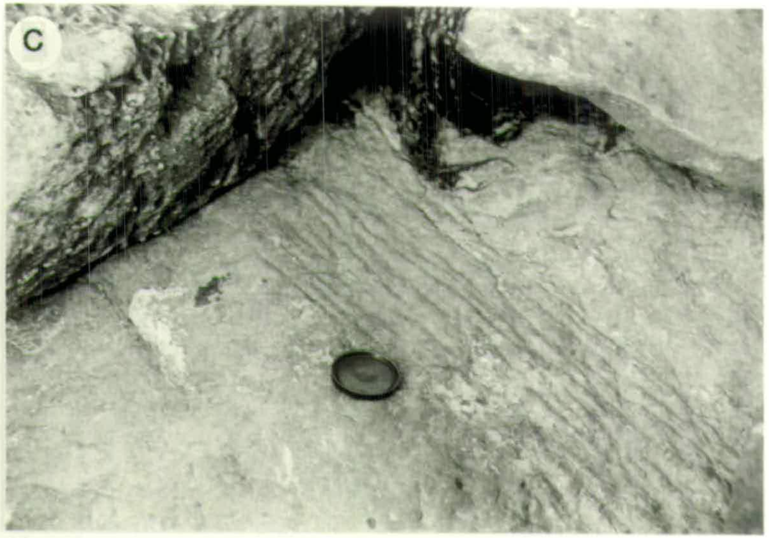
D. Small-scale coarsening-upward sequence developed below the Lower Kinniny Limestone (the bioturbated calcareous sandstone below the limestone is the prominent, thick, dark rocky 'ridge' in the background of the picture). At the base of the sequence (foreground of the picture), mudrocks containing siderite nodules gradually coarsen-upward via mudrocks and siltstones with intercalated sandstone laminae and lenticular bedding into wave-rippled, wavy and flaser bedded sandstones which are overlain by delta-top distributary channel (trough cross-bedded) sandstones. These pass upward into a plant-rich abandonment sandstone-siltstone facies and a thin coal (weathered recess below the bioturbated sandstone ridge), which are overlain by the bioturbated sandstone which grades upwards into the Lower Kinniny Limestone. Scale: camera bag, length=24 cm.

A



B

C



D

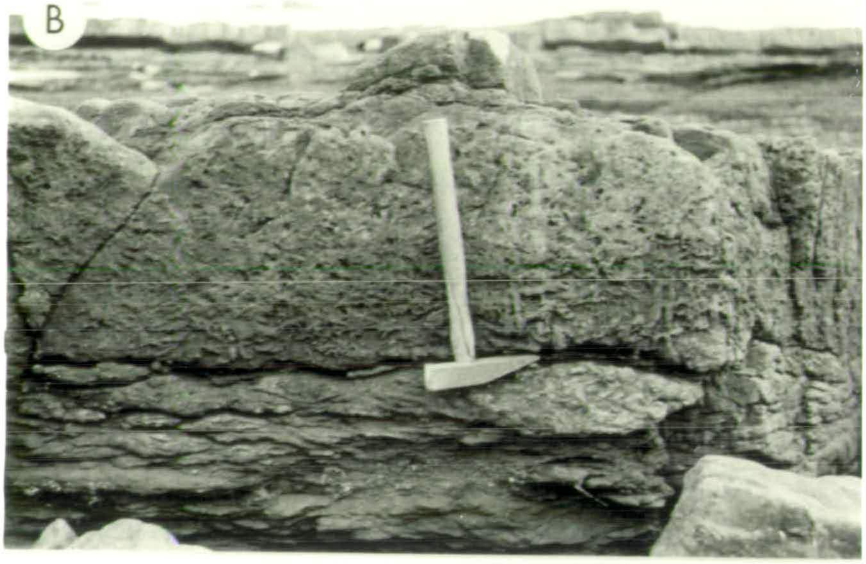
12.5

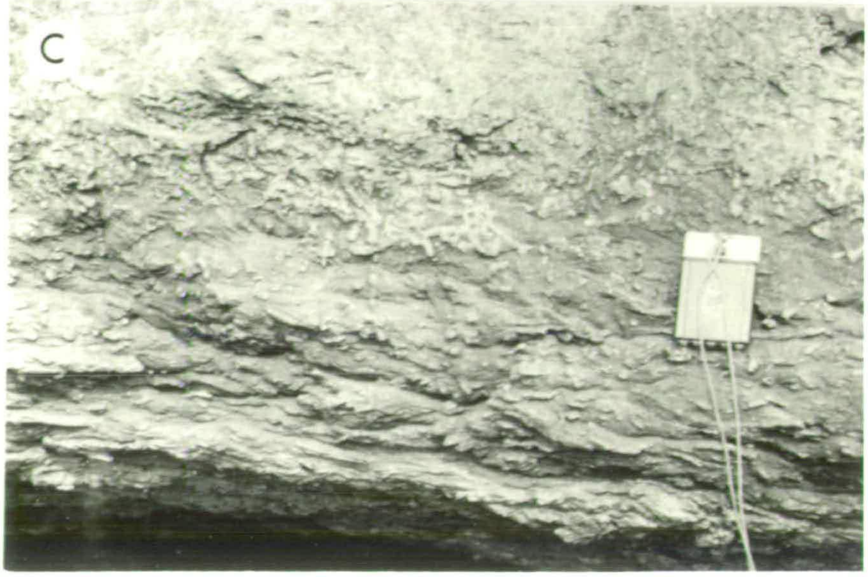
A. General view of the bioturbated sandstone bed below the Lower Kinniny Limestone, Seafield foreshore, Kinghorn-Kirkcaldy, central Fife. The softer coaly mudrocks and coals which underlie the sandstone recessively weather and are obscured by boulders, pebbles and fallen rocks. The lower part of the sandstone is extensively bioturbated and is composed of a silty sandstone which has a pod-like, lensoidal form. The upper part of the bed in contrast is quite massive, but is still characterised by bioturbation and trace fossils and is quite well jointed. Scale: camera bag, length=24 cm. Interpretation: post-abandonment facies developed as a series of marine sand barriers after delta lobe abandonment and prior to and during the early stages of transgression.

B. Close-up view of the bioturbated sandstone bed described above showing the contact with the lower lenticular-lensoidally bedded part of the sandstone and the more massive upper part. In the lensoidally bedded member, isolated lenticular or 'augen' shaped pods of very well bioturbated sandstone are separated by anastomosing-like silty sandstone laminae. The change upward to a more massive sandstone reflects a greater availability of sands during later stages of the transgression when more sediment had been reworked from the abandoned and degraded former delta-front, and also a lesser degree of bioturbation and biogenic reworking. The upper part of the sandstone (more massive member) contains *Teichichnus*. Scale: geological hammer, length=40 cm. Interpretation: as above.

C. Close-up view (taken with macro-lens) of the lower part of the bioturbated reworked sandstone (described above) displaying the trace fossils *Chondrites* and *Teichichnus* which have also been described from the same bed in the West Fife Annfield Borehole (Chisholm 1970a). The disturbed bioturbate texture is conspicious, as is the silty nature of the sandstone which is characteristic of the extreme bioturbation at the base of the unit. Scale: compass-clinometer, length=10 cm. Interpretation: as above (i.e. Fig. 12.7A).

A





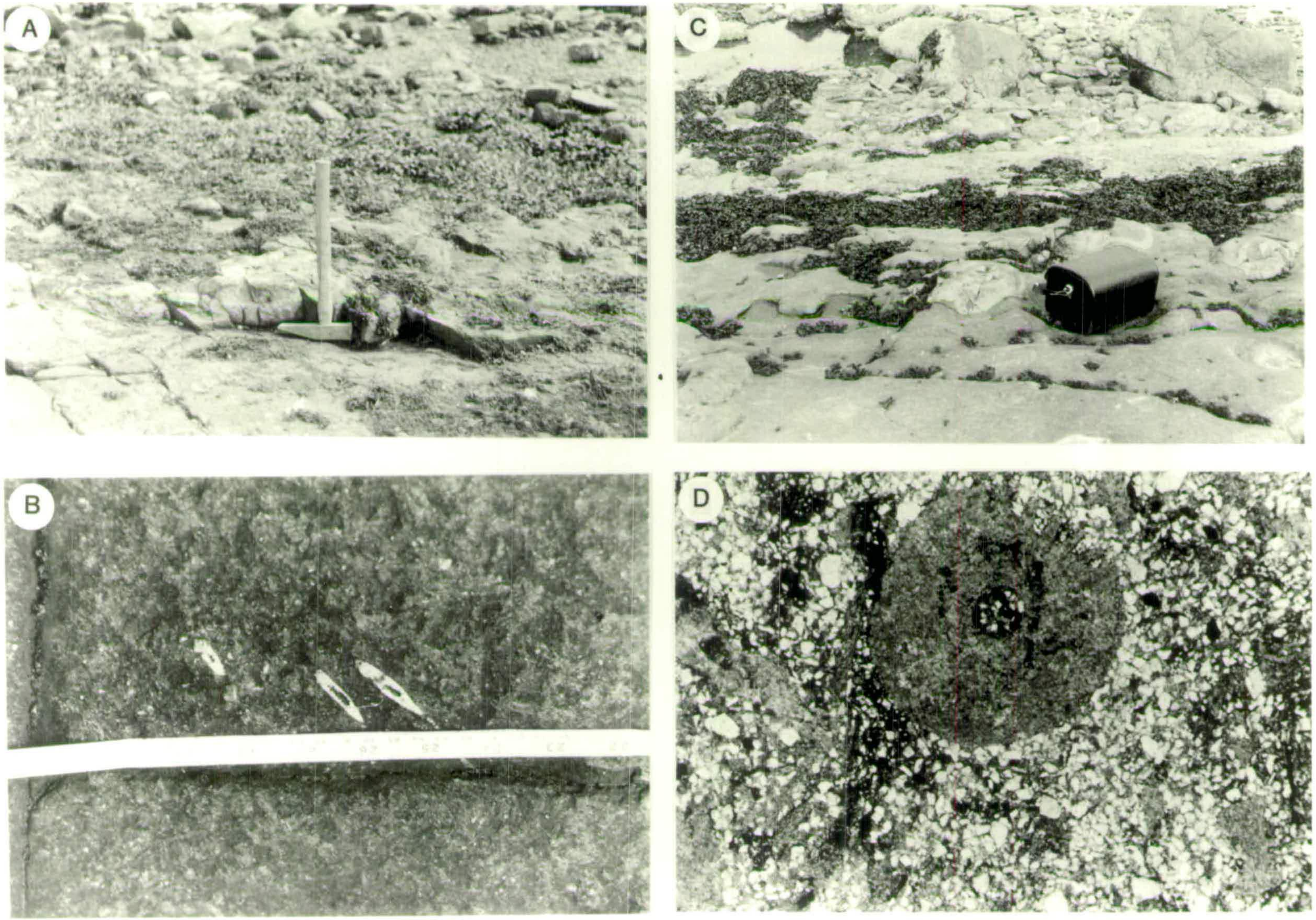
12.6.

A. Photograph showing the contact between the Lower Kinniny Limestone and the underlying bioturbated sandstone (upon which the hammer head rests), Seafield foreshore, Kinghorn-Kirkcaldy coastal section, central Fife. The Lower Kinniny Limestone has been weathered back to its position at the base of the dip-slope and is easily removed by erosion due to its sharp abrupt contact with the underlying sandstone. The limestone itself has formed as a result of the coalescing of patchily carbonate-cemented domes (Geikie 1900). Geological hammer for scale, length=40 cm.

B. Crinoid stalks (stems) on the upper bedding plane surface of the bioturbated calcareous sandstone below the Lower Kinniny Limestone. There is a preferred alignment of the three stalks (cf. Schwarzacher 1963) and small, scattered, disarticulated ossicles are present on the bed top (Wright 1922). Scale: metal tape measure (ruler), upper scale in centimetres, lower scale in inches.

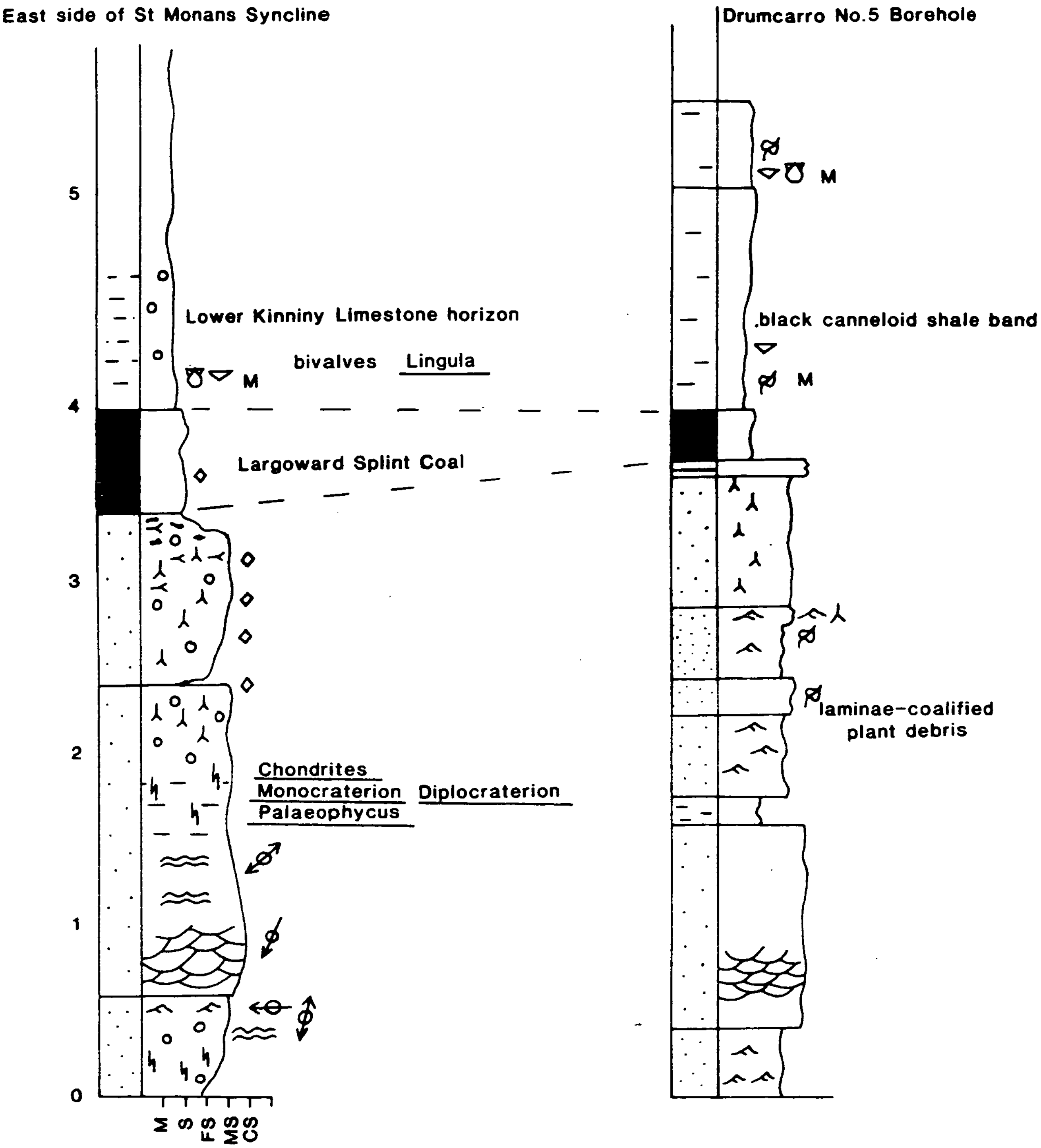
C. Carbonate domes or bullions (cf. Elliot 1974a, 1975) on top of the bioturbated calcareous sandstone, which coalesce at the base of the dip slope to form the diminutive Lower Kinniny Limestone. These domes or pods are spherical, rounded to cannon-ball shaped and when eroded out leave a circular-subcircular depression. This gives the upper bedding plane surface a hummocky-undulatory appearance with numerous empty hollows where the domes have been weathered out. Scale: camera bag, length=24 cm.

D. Thin section photomicrograph (transmitted, plane-polarised light) of the calcareous bioturbated sandstone showing a swirly, strongly bioturbated fabric, with dark-coloured clay-rich laminae lining burrows of *Zoophycos*, together with occasional pyritized faecal pellets. Prominent in the field of view is a large disarticulated crinoid ossicle, and crinoid fragments are the dominant fossils in this faunally sparse deposit. Scale: horizontal field of view=4.5 mm.


A
B
C
D

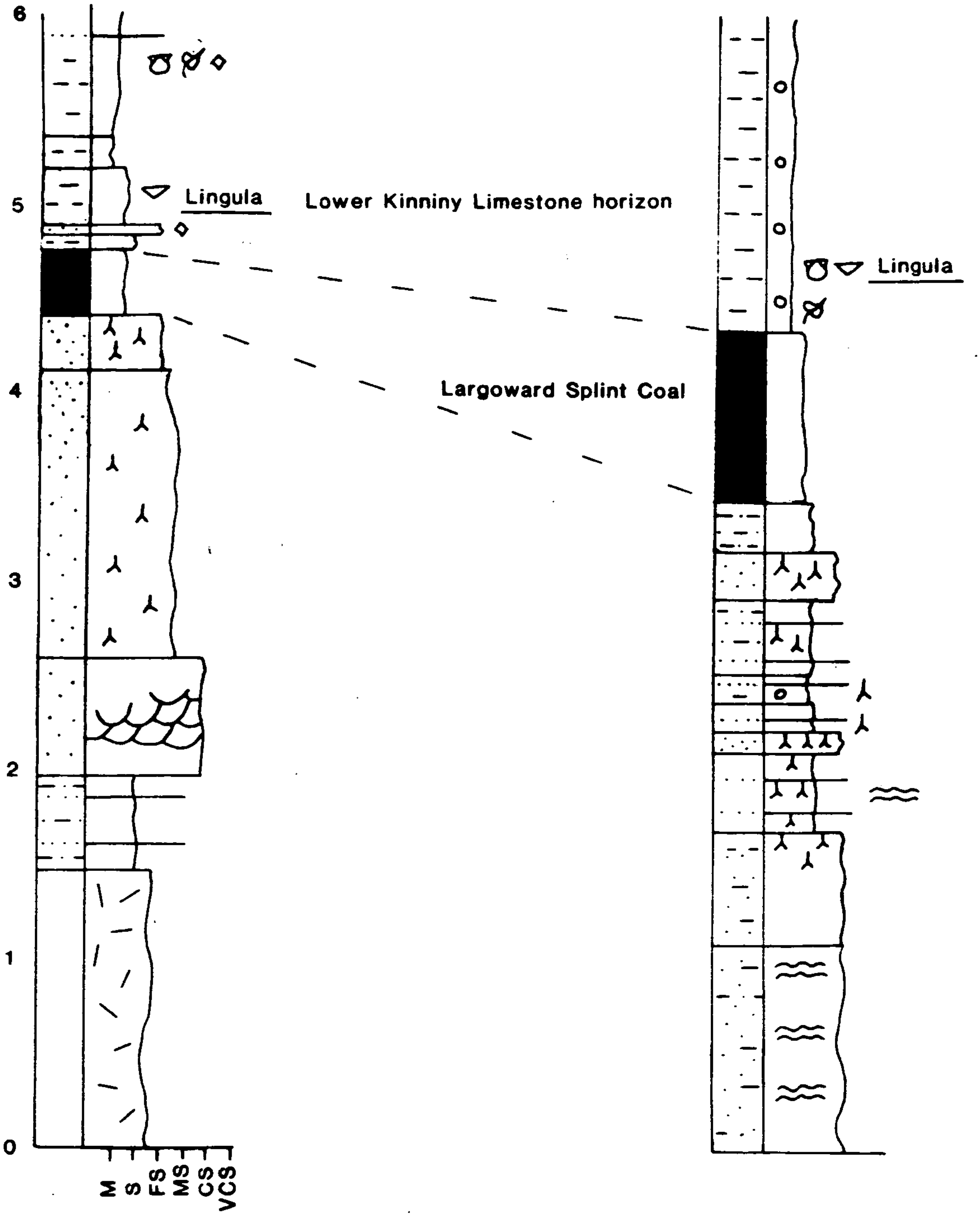
12.7.

Graphic sedimentary logs of the Lower Kinniny Limestone and associated beds from the coastal section on the east side of the St Monans Syncline (Forsyth and Chisholm 1977) and the BGS Drumcarro Borehole, East Fife (Forsyth and Chisholm 1968). The sequence developed directly below the coal is a broadly fining-upwards sequence (Allen 1964, 1970), with a transition from delta-front and delta-top sandstones into rooted paleosols. The sandstones are interpreted as delta-top distributary channel/crevasse channel deposits, whilst the delta-front sandstones possibly represent crevasse splay delta-fronts which were wave-reworked whilst prograding into a non-marine interdistributary bay on the delta-top (cf. Haszeldine 1984). The tops of the fining-upward sequences contain abundant rootlets suggesting delta abandonment prior to the development of the Largoward Splint Coal in hydromorphic (waterlogged) conditions prior to the 'Lower Kinniny Limestone marine transgression'. The overlying marine mudrocks contain a sparse marine fauna and were probably deposited in marginal marine conditions.


East side of St Monans Syncline
Drumcarro No.5 Borehole
5
4
3
2
1
0
Lower Kinniny Limestone horizon
bivalves
Lingula
M
Largoward Splint Coal
Chondrites
Monocraterion
Diplocraterion
Palaeophycus
M
S
FS
MS
CS
black canneloid shale band
M
M
laminae-coalified plant debris

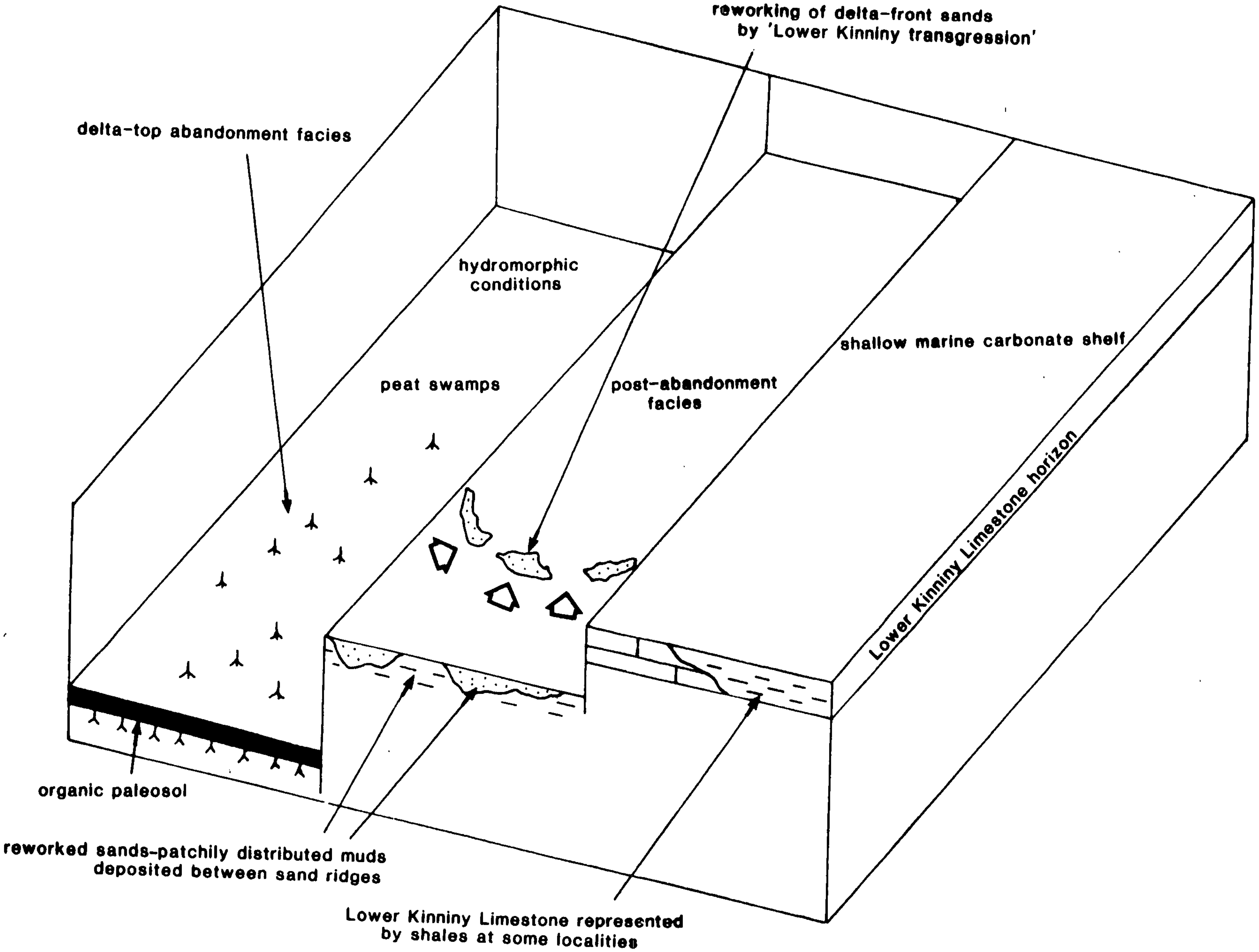
12.8.

Graphic sedimentary logs of the Lower Kinniny Limestone horizon and associated beds in the BGS Callange and Muircambus boreholes, East Fife. Both sequences broadly fine-upwards with wave-reworked delta-front facies (?prograding into interdistributary bays) and delta-top distributary channel facies developed below rooted abandonment facies sandstones and the Largoward Splint Coal (Landale 1837; Geikie 1900), which as elsewhere in East Fife is developed below the marginal marine mudshales. A dolerite sill is present at the base of the Callange Borehole.

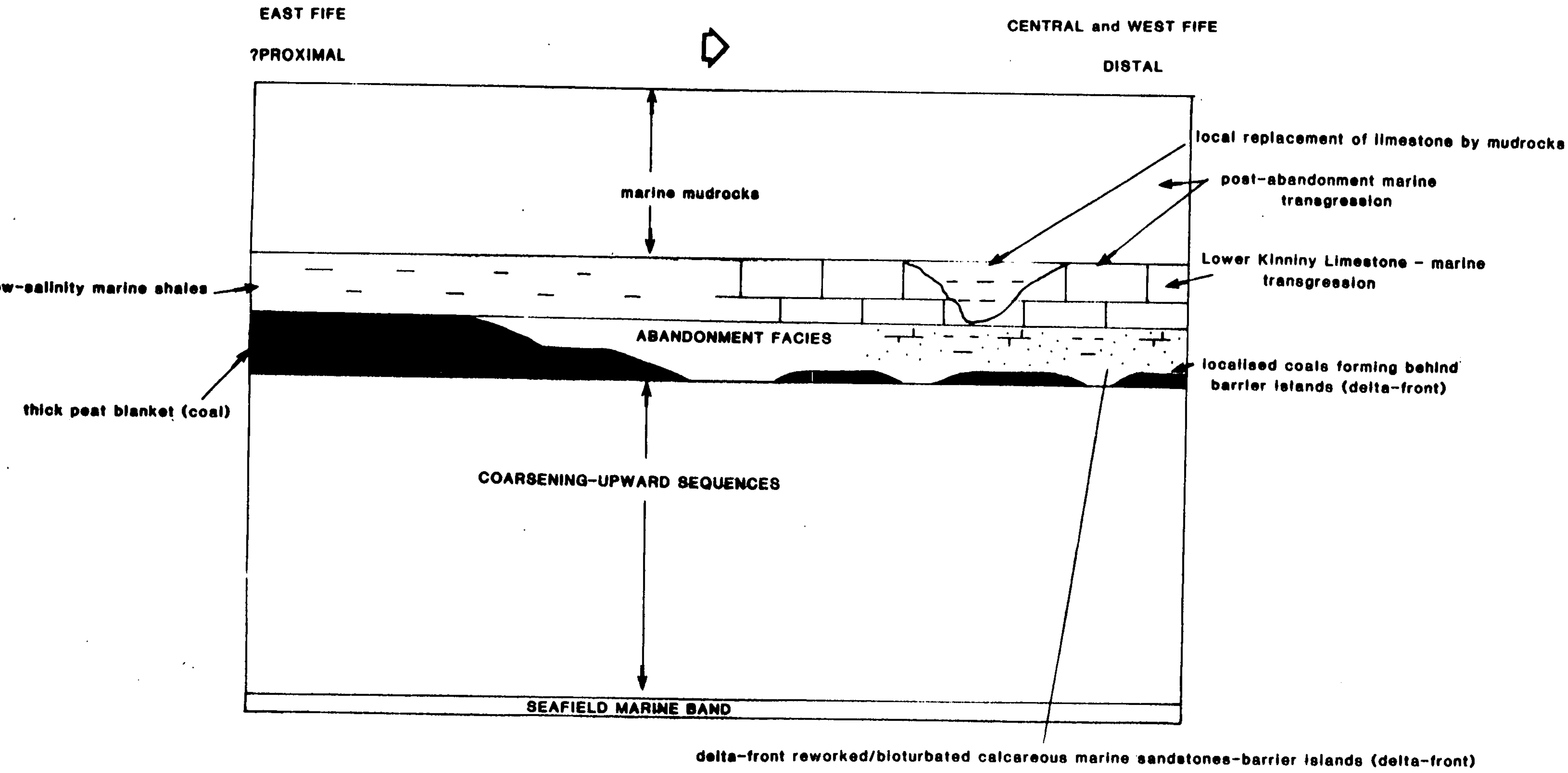


Callange No.3 Borehole

Muircambus No.8 Borehole

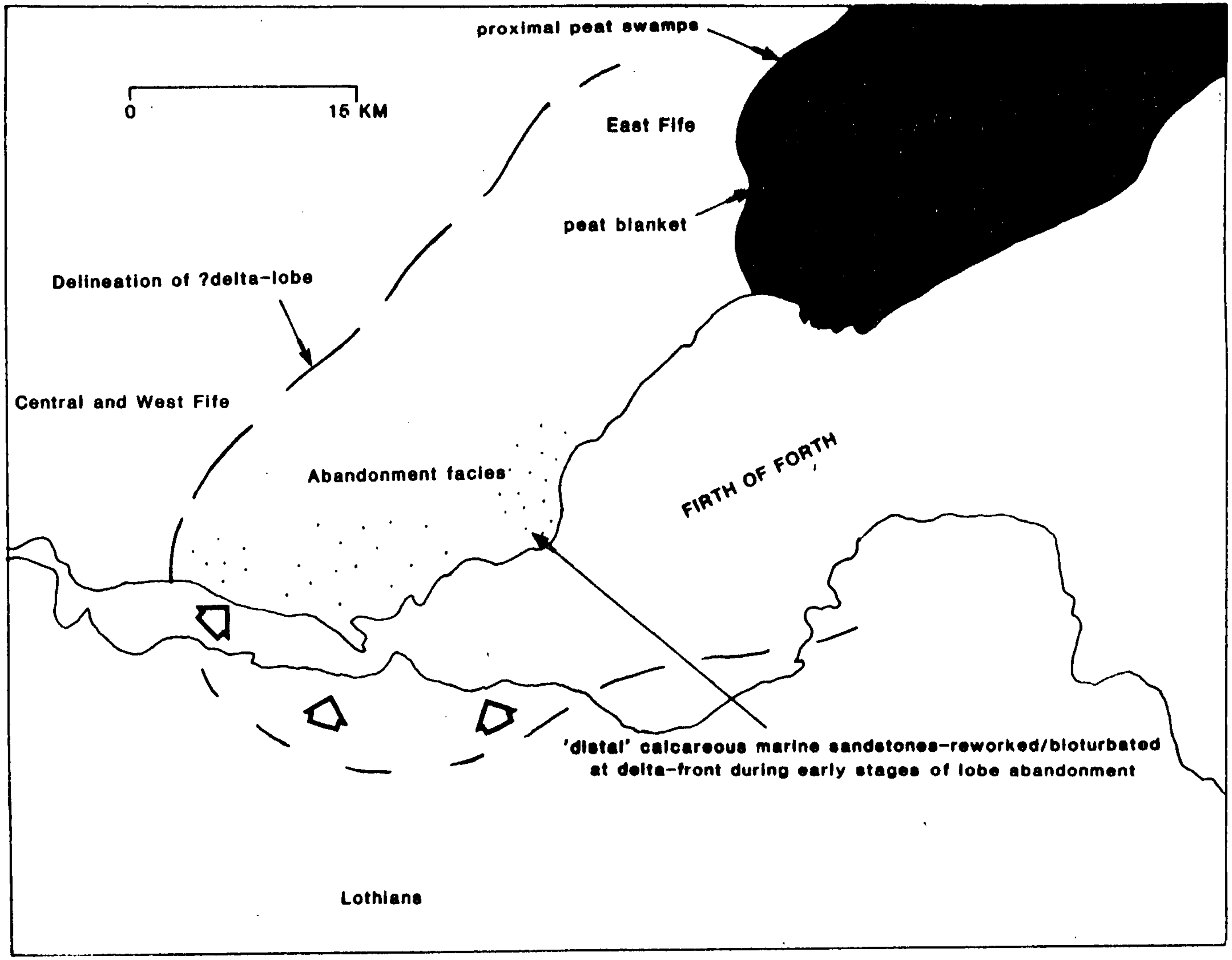

reworking of delta-front sands
by 'Lower Kinniny transgression'
delta-top abandonment facies
hydromorphic conditions
shallow marine carbonate shelf
peat swamps
post-abandonment facies
Lower Kinniny Limestone horizon
organic paleosol
reworked sands-patchily distributed muds
deposited between sand ridges
Lower Kinniny Limestone represented
by shales at some localities

	WEST FIFE	CENTRAL FIFE	EAST FIFE
LOWER KINNINY 3 LIMESTONE	present	present	absent-replaced by mudrocks containing low-diversity marine fauna
2 BIOTURBATED SANDSTONE	present	present but impersistent	absent
1 COAL	thin	thin-impersistent	thick-persistent


EAST FIFE
?PROXIMAL
CENTRAL and WEST FIFE
DISTAL
marine mudrocks
local replacement of limestone by mudrocks
post-abandonment marine transgression
Lower Kinniny Limestone - marine transgression
w-salinity marine shales
ABANDONMENT FACIES
localised coals forming behind barrier islands (delta-front)
thick peat blanket (coal)
COARSENING-UPWARD SEQUENCES
SEAFIELD MARINE BAND
delta-front reworked/bioturbated calcareous marine sandstones-barrier islands (delta-front)

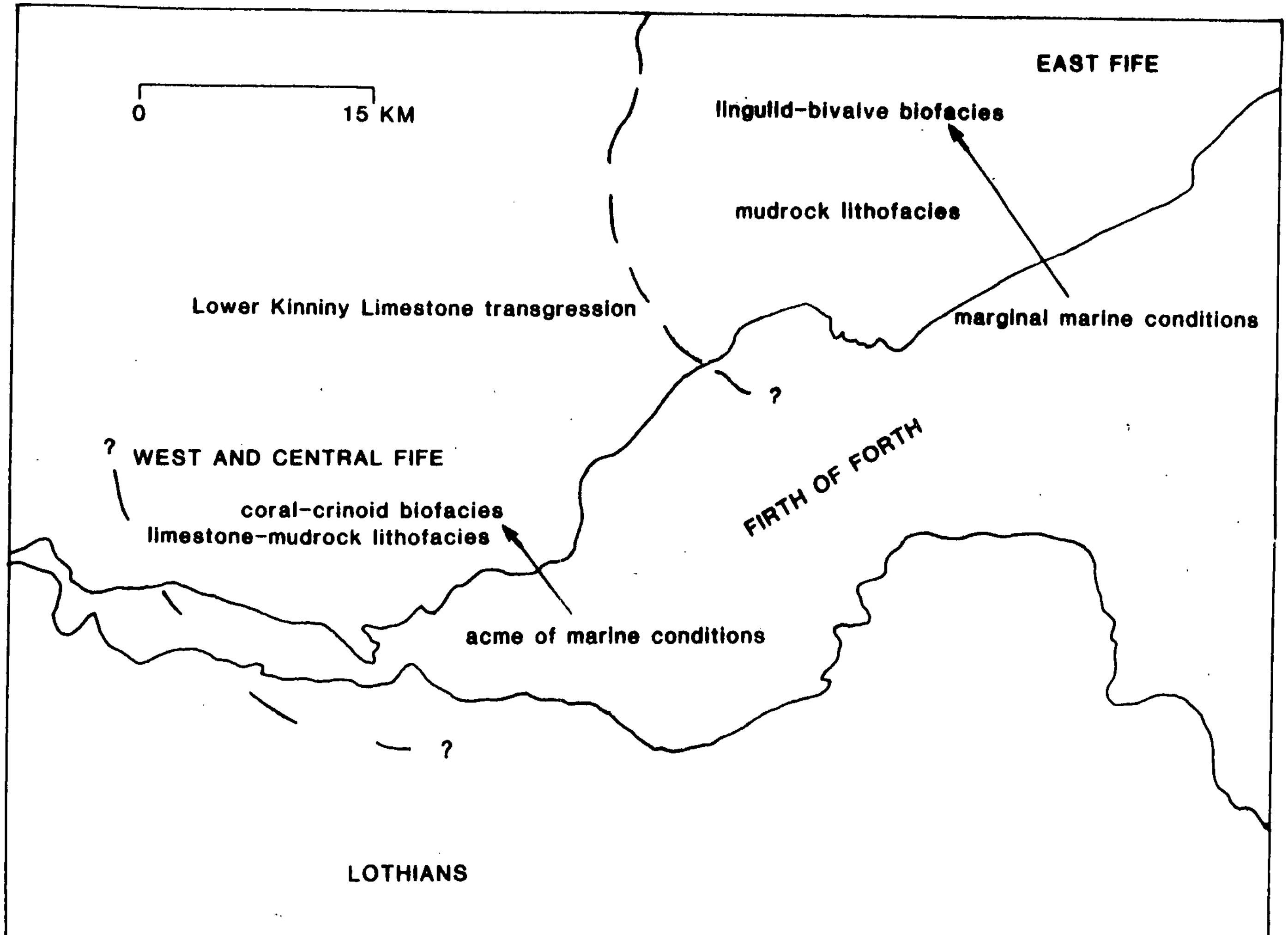
12.12.

Palaeogeographic reconstruction of postulated delta lobe developed prior to the 'Lower Kinniny Limestone marine transgression'. Delta-front facies were reworked during abandonment and the ensuing transgression in central and west Fife, whilst organic paleosols were accumulating during periods of reduced sedimentation in East Fife.


proximal peat swamps
0
15 KM
East Fife
peat blanket
Delineation of ?delta-lobe
Central and West Fife
Abandonment facies
FIRTH OF FORTH
'distal' calcareous marine sandstones-reworked/bioturbated at delta-front during early stages of lobe abandonment
Lothians

12.13

Bio- and litho- facies variations established during the 'acme' of the 'Lower Kinniny Limestone marine incursion'. Only marginal marine conditions were established in East Fife suggesting that the maximum extent of the transgression was in this area, compared to the more open marine conditions developed in west and central Fife to the south-west.



BIO-AND LITHOFACIES DEVELOPED DURING LOWER KINNINY LIMESTONE TRANSGRESSION

Fig. 13.1.

Graphic sedimentary log of the sequence from the Seafield Marine Band (at the base) to the Middle Kinniny Limestone (at the top-left hand side of the diagram) as exposed on the Seafield-Tyrie foreshore along the Kinghorn-Kirkcaldy coastal section, central Fife. This section includes the Lower Kinniny Limestone. Between the Lower and Middle Kinniny limestones the sequence consists of several small-scale coarsening-upward units, and one unit is capped by a hummocky cross-stratified bioturbated sandstone. This log lies directly below (and is linked to) the next log (Fig. 13.3) which starts at the Middle Kinniny Limestone.

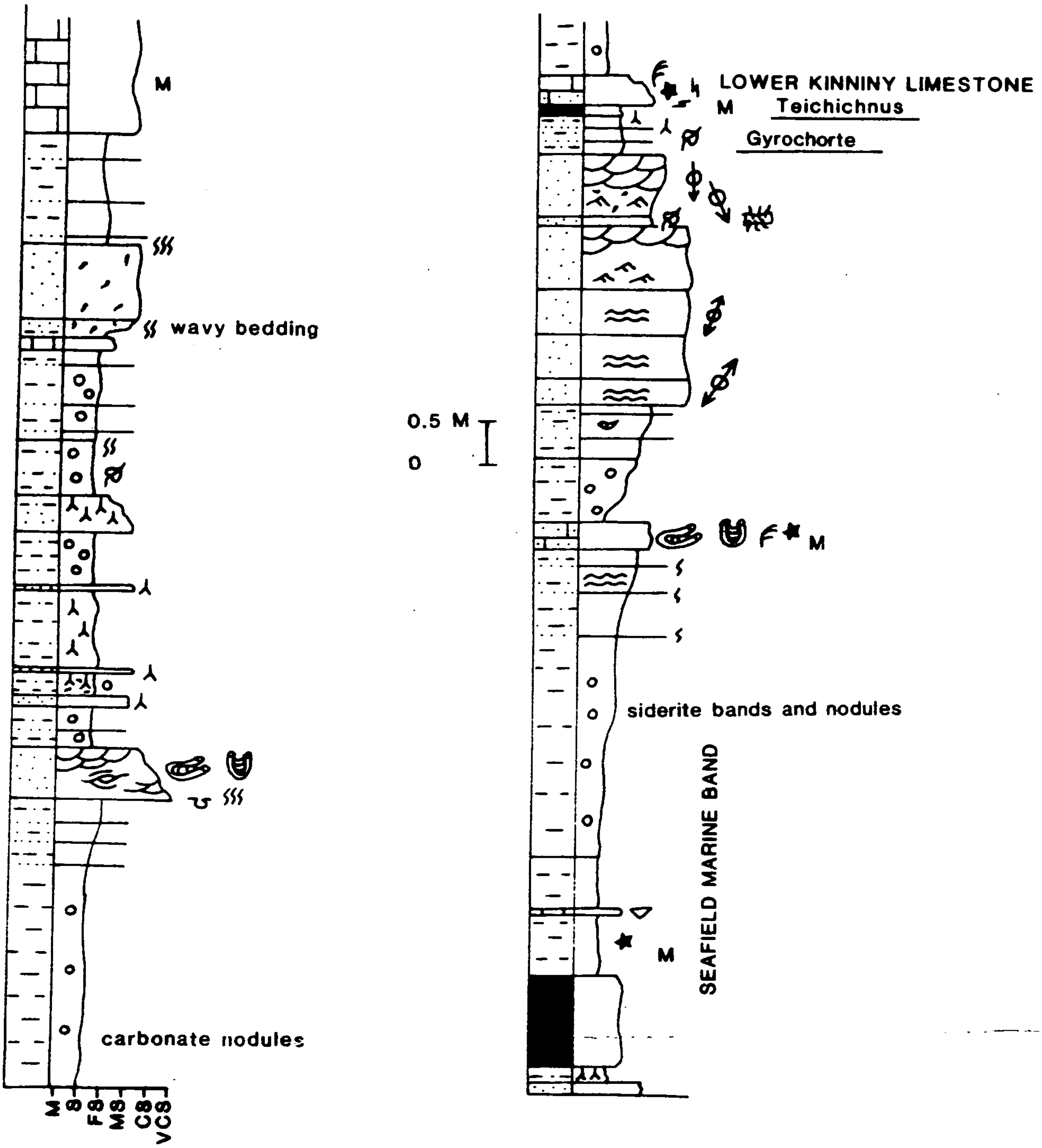

M
wavy bedding
carbonate nodules
M
S
FS
MS
CS
VCS
0.5 M
0
LOWER KINNINY LIMESTONE
M
Teichichnus
Gyrochorte
M
siderite bands and nodules
SEAFIELD MARINE BAND
M

Fig. 13.2.

Features of the section above the Lower Kinniny Limestone exposed on the Seafield-Tyrie foreshore along the Kinghorn-Kirkcaldy coastal section, central Fife.

A. View of a coarsening-upward sequence (capped by a coal) at the base of the Limestone Coal Group. The massive unit in the background is the quartz-dolerite sill which forms the East Vows. Scale: camera bag=24 cm in length.

B. Scattered accumulations of large crinoid stalks and some disarticulated ossicles forming fossil bands at the base of the thick marine mudrock which overlies the Middle Kinniny Limestone. Scale: camera lens cap, diameter=6 cm.

C. Swaley, hummocky cross-stratified sandstone which is extensively bioturbated and caps the lowest (first) coarsening-upward sequence above the Lower Kinniny Limestone. This bed is interpreted as a storm deposit Scale: camera bag, length=24 cm.

D. Close-up view of the surface of the storm deposited sandstone (see C, above) showing well-preserved protrusive *Rhizocorallium* burrows. Scale: camera lens cap, diameter=6 cm.

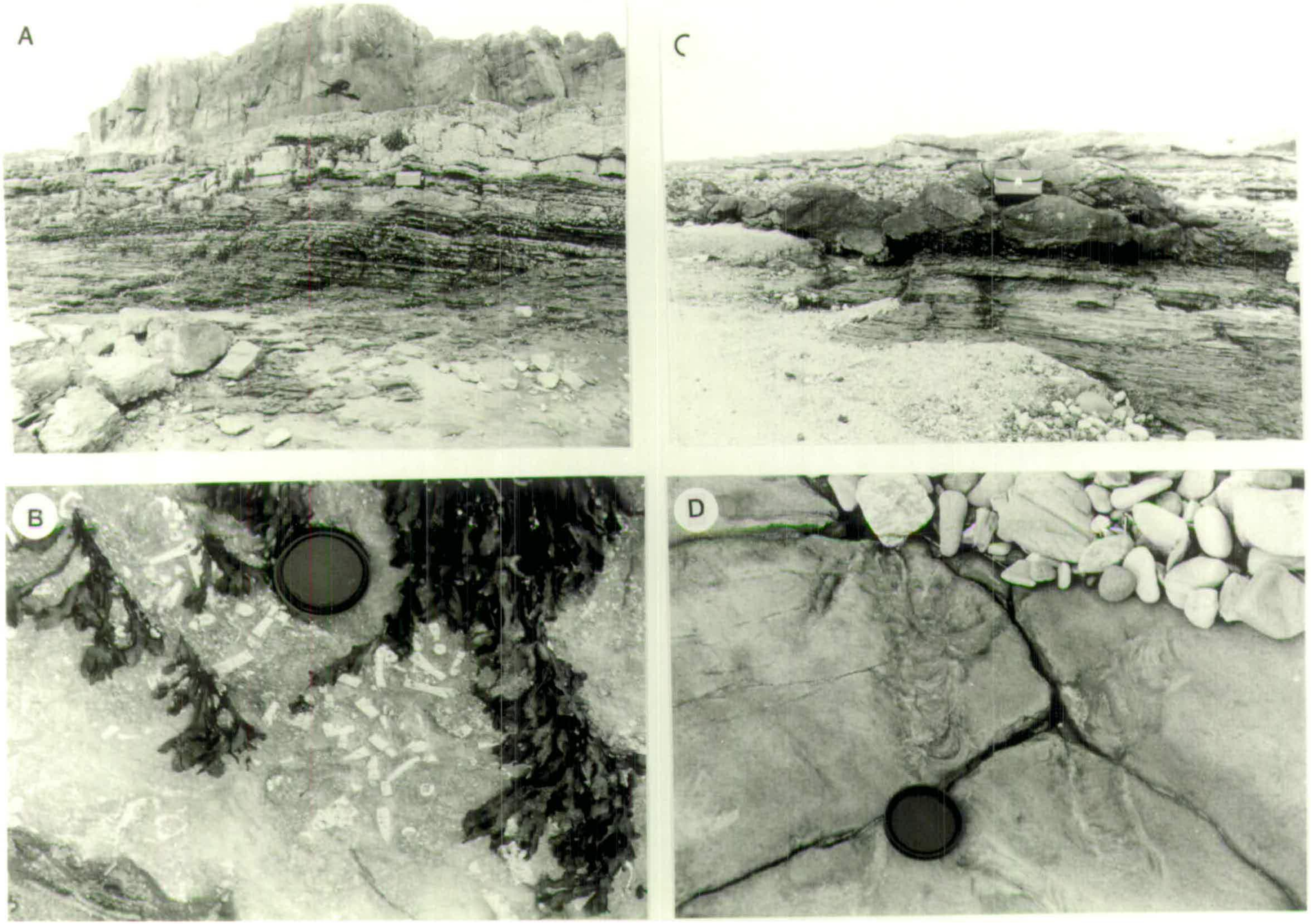
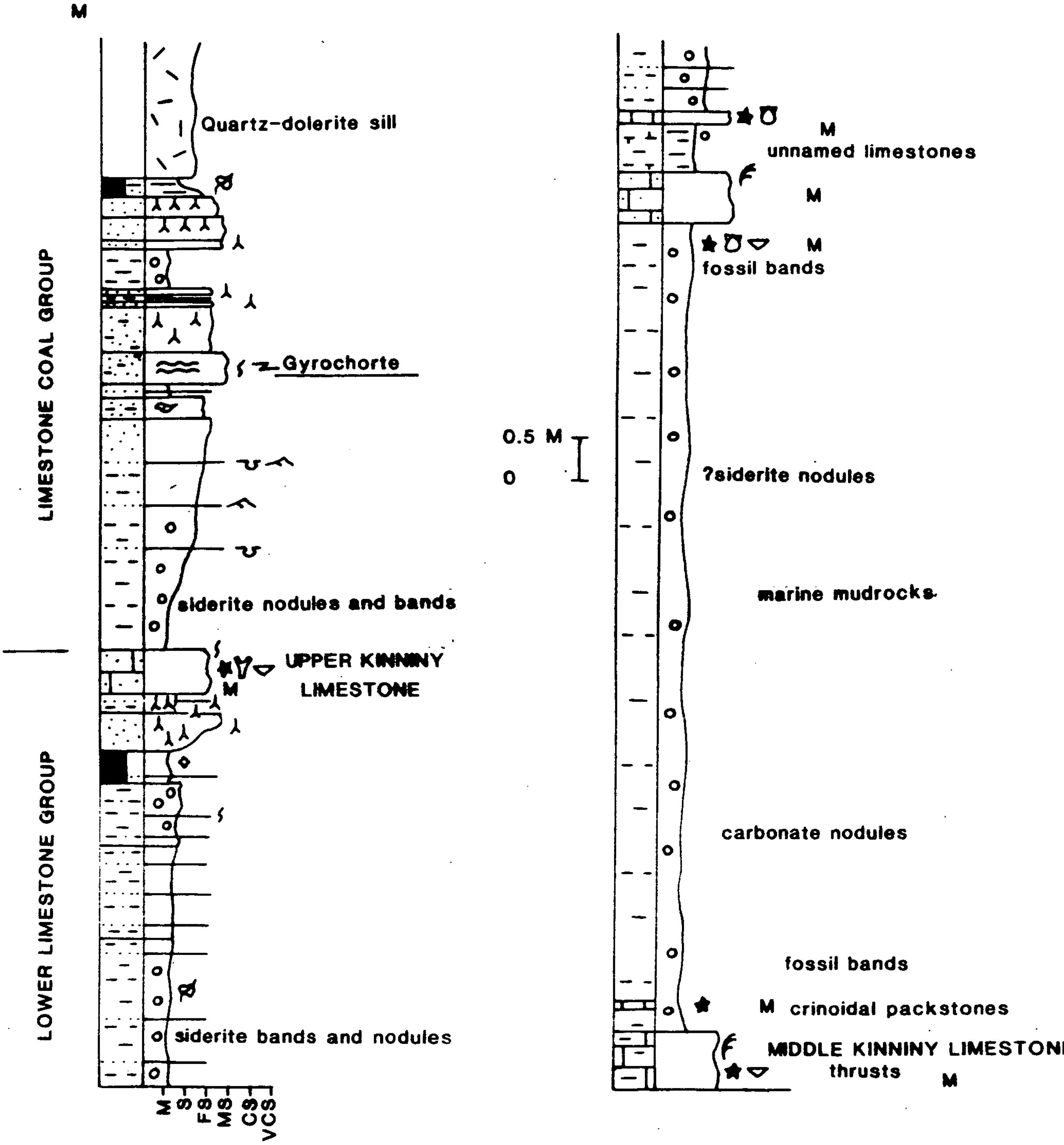

A
C
B
D

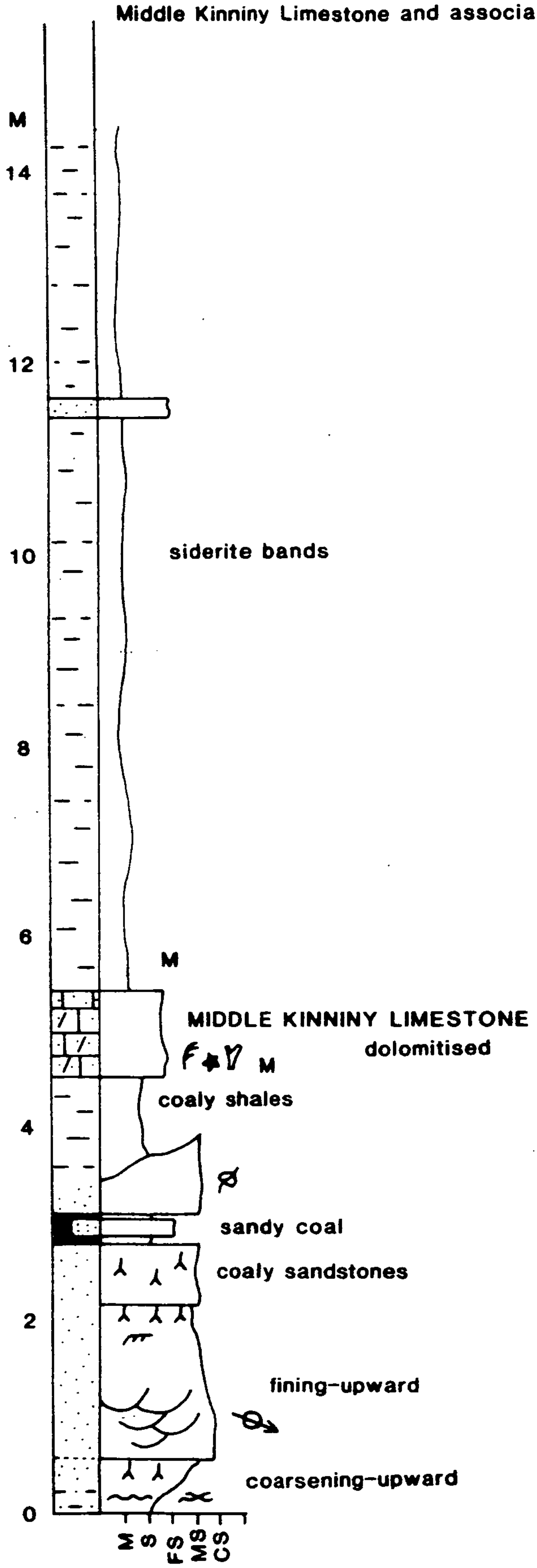
Fig. 13.3.

Graphic sedimentary log of the sedimentary sequence between the Middle Kinniny Limestone and the quartz-dolerite sill (forming the East Vows) which is intruded into the basal part of the Limestone Coal Group succession, as exposed on the Seafield-Tyrie foreshore, Kinghorn-Kirkcaldy coastal section, central Fife. The section includes the Upper Kinniny Limestone (the top of which marks the top of the Lower Limestone Group) and two unnamed limestones at the top of the thick mudrock unit above the Middle Kinniny Limestone.


M
Quartz-dolerite sill
LIMESTONE COAL GROUP
Gyrochorte
siderite nodules and bands
UPPER KINNINY LIMESTONE
M
LOWER LIMESTONE GROUP
siderite bands and nodules
M
S
FS
MS
CS
VCS
0.5 M
0
M
unnamed limestones
M
M
fossil bands
?siderite nodules
marine mudrocks
carbonate nodules
fossil bands
M crinoidal packstones
MIDDLE KINNINY LIMESTON
thrusts
M

EAST SIDE OF ST MONANS SYNCLINE, LOWER LIMESTONE GROUP, EAST FIFE.

Middle Kinniny Limestone and associated beds. NO (52790158).



UPPER PART OF CLASTIC INTERVAL BETWEEN SKATERAW
MIDDLE LIMESTONE AND CHAPEL POINT LIMESTONE
CATCRAIG FORESHORE (BARNS NESS) NT (7210 7733)

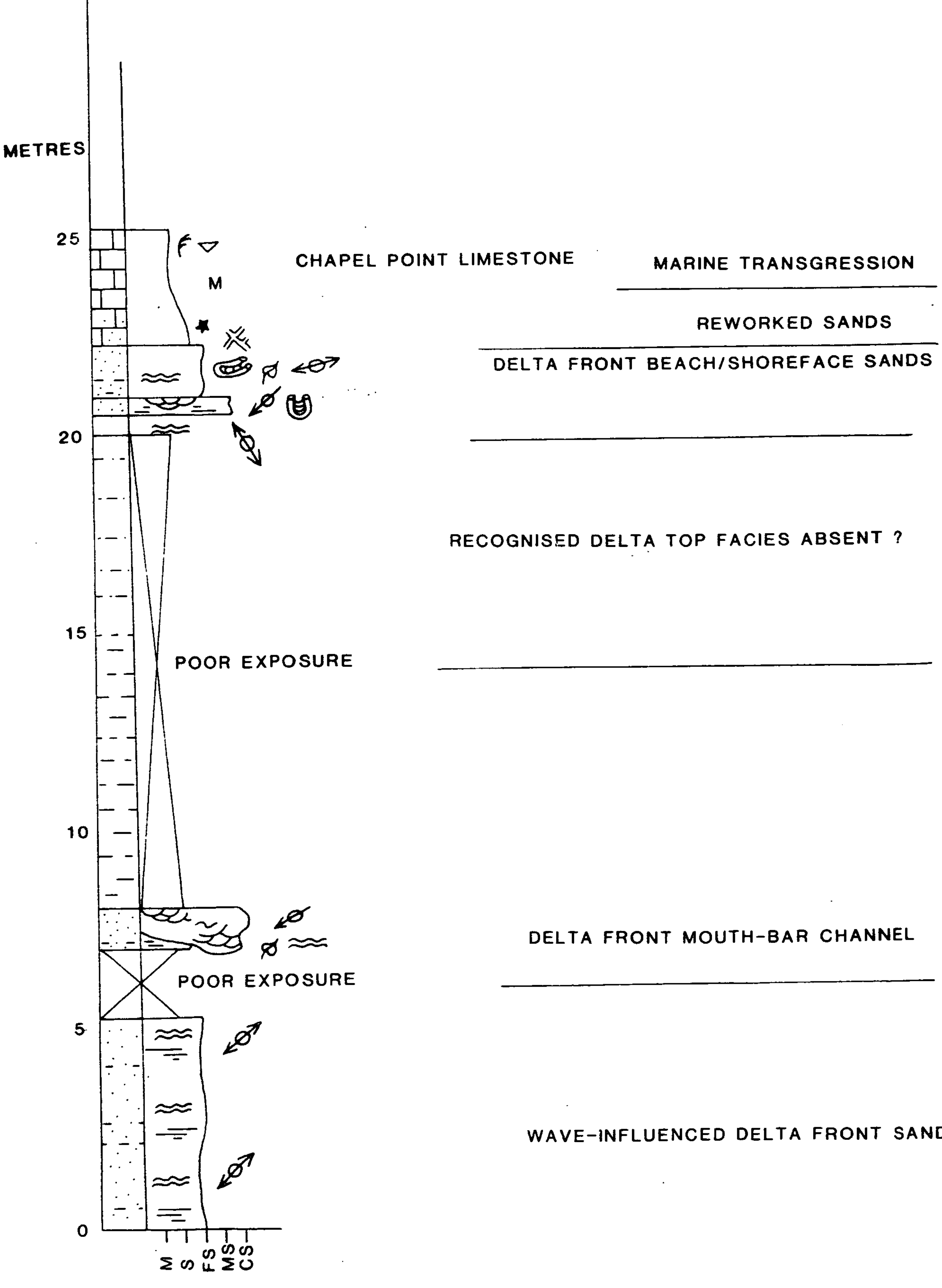


Fig. 13.6.
Field photographs showing aspects of the abandonment facies below the Barns Ness Limestone, Catcraig-Barns Ness foreshore, East Lothian.

A. Thin coaly breccia developed below the Barns Ness Limestone. Scale: camera lens cap, diameter=6 cm.

B. Intensely rooted, rhizoturbated ganister bed developed below the coaly breccia which underlies the Barns Ness Limestone. Scale: camera lens cap, diameter=6 cm.

C. Large *Lepidodendron* trunk impression in ganister bed below coaly breccia which underlies the Barns Ness Limestone. Scale: geological hammer, length=59 cm.

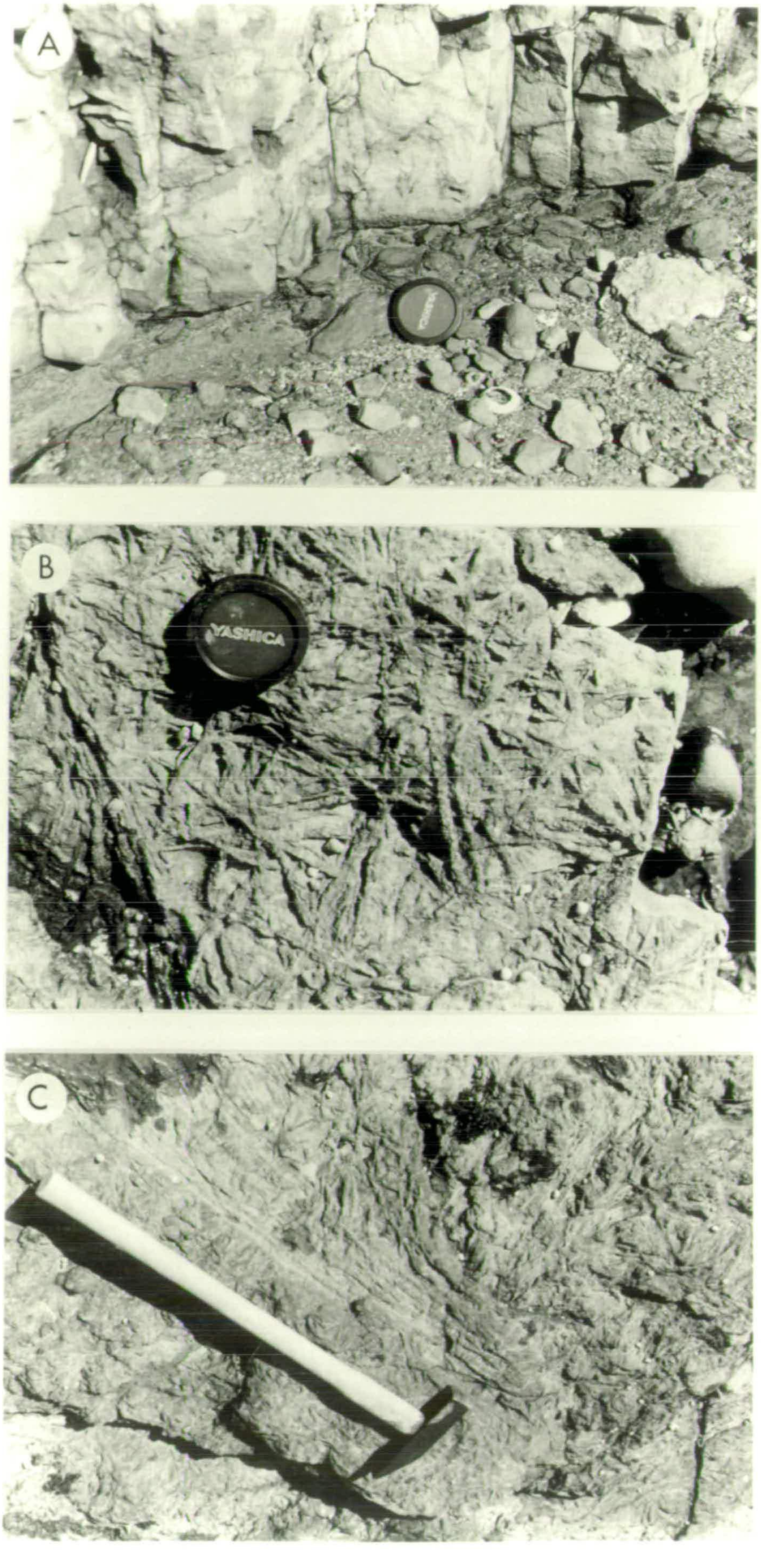

A
B
YASHICA
C

Fig. 13.7.

Graphic sedimentary log showing lateral variation of the Barns Ness Limestone and overlying sandstone from localities at Catcraig-Barns Ness to north of White Sands and the mouth of the Broxburn. The limestone degenerates to a *Lingula* band preserved in cannely shales, and the sandstones contain a paleosol (coal-fireclay) parting when traced laterally.

CLASTIC INTERVAL ABOVE BARNS NESS LIMESTONE

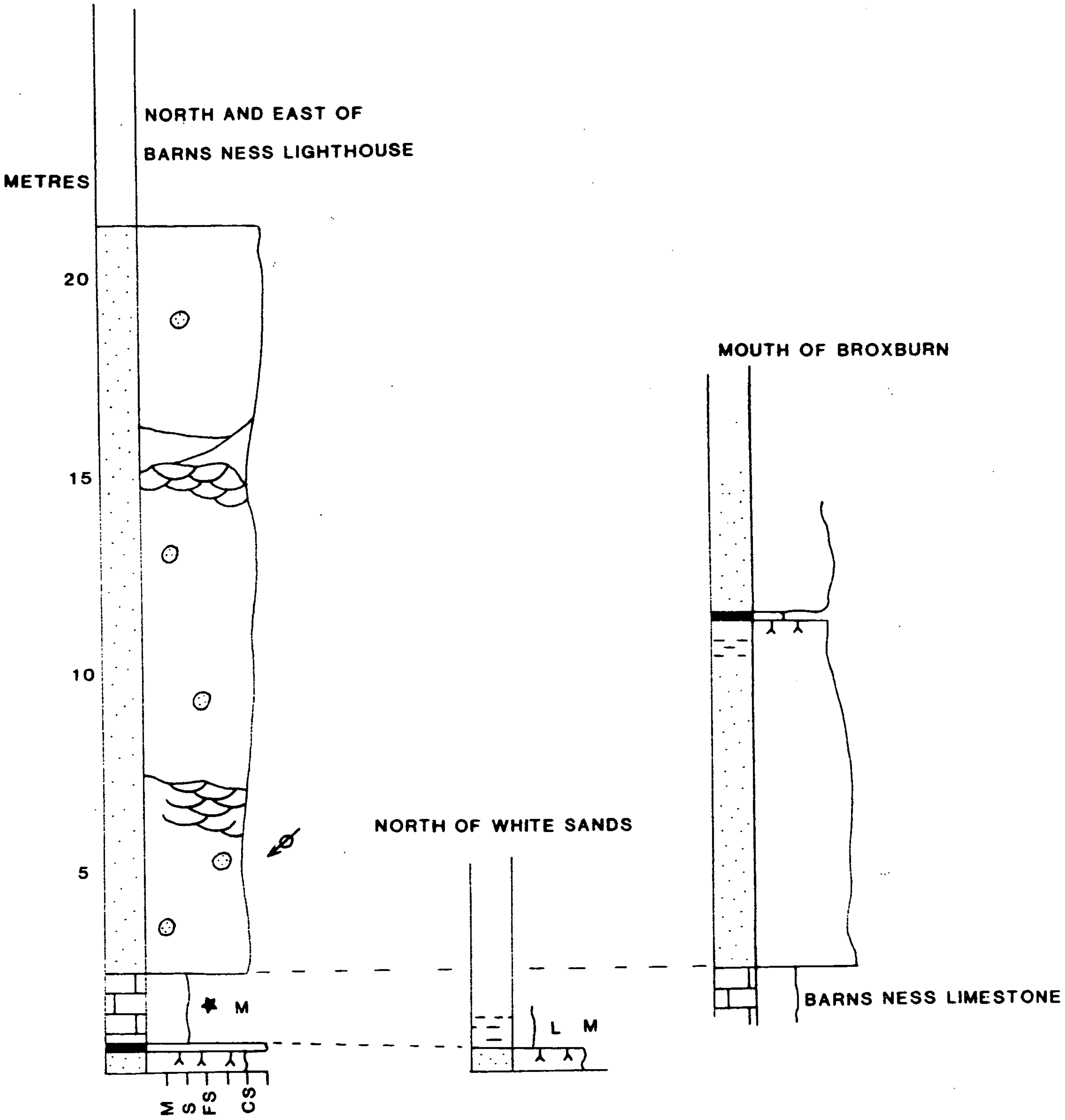


Fig. 13.8.

Field photographs showing aspects of the sandstones overlying the Barns Ness Limestone at Barns Ness-Catcraig.

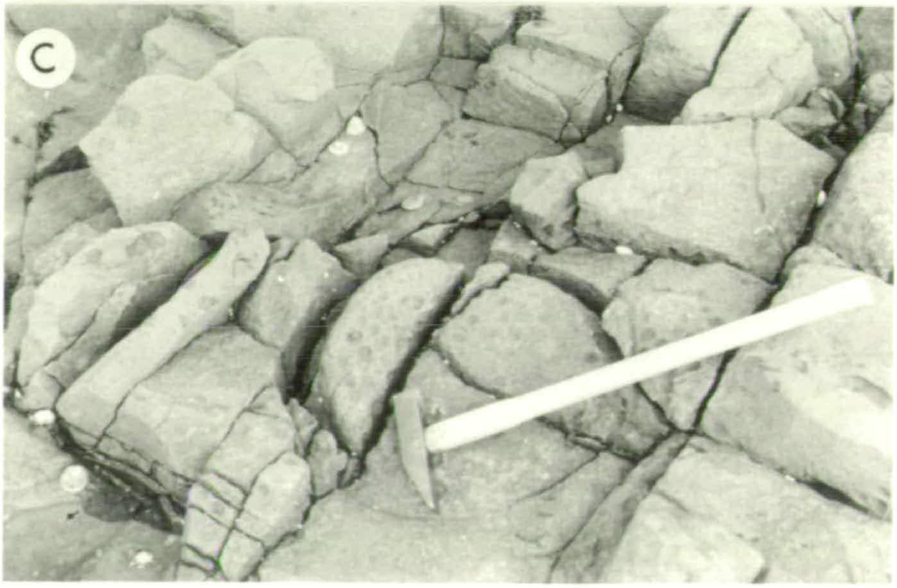
A. Cannon ball-shaped 'doggers' or bullions (concretions) in the massive sandstones above the Barns Ness Limestone. The pitted or microcratered appearance of the concretions is a conspicious feature of these rocks. Scale: geological hammer, length=59 cm.

B. Trough cross-bedding in the sandstones above the Barns Ness Limestone. The curved nature of the foresets is conspicious. These cosets of cross-bedding overlie a lag horizon consisting of pink-red coloured reworked mudclasts. Scale: geological hammer, length=59 cm.

C. Close-up view of a rounded-spherical shaped 'dogger' in the sandstone above the Barns Ness Limestone. Scale: geological hammer, length=59 cm.


A


B


C

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