

Thesis presented to the University of Oxford
for the degree of Doctor of Philosophy.

REGIONAL STUDIES IN THE SEDIMENTOLOGY, MINERALOGY
& GEOCHEMISTRY OF THE PENARTH GROUP ("RHAETIC") OF
BRITAIN.

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REGIONAL STUDIES IN THE SEDIMENTOLOGY, MINERALOGY & GEOCHEMISTRY OF THE PENARTH GROUP ("RHAETIC") OF BRITAIN.

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ABSTRACT.

The Upper Triassic, Penarth Group has been examined, throughout Britain, both at outcrop and in boreholes. It is divided, lithostratigraphically into a lower, Westbury Formation and an upper, Lilstock Formation. Within these units a number of regionally-and locally-applicable members are distinguished.

The Penarth Group is a predominantly marine, sedimentary sequence transitionally situated between arid or semi-arid lacustrine and fluviatile sediments (Mercia Mudstone Group and New Red Sandstone) and more fully marine strata (Lias).

Early stages of the "Rhaetic" marine incursion, principally represented by the Westbury Member, document the establishment of semi-isolated, brackish basins which were superseded by a less restricted marine environment. This transgressional advance is linked to nutrient supply and thence to phytoplankton productivity in order to explain organic carbon profiles through the Westbury Member. Offshore and nearshore zones of this sea are recognised, the latter including sediments assigned to barrier-inlet, lagoon and tidal-flat environments. Clay mineral studies reveal an enrichment of smectite in offshore areas which is ascribed to differential sedimentation processes.

Transgression was interrupted by a regressional phase marked by the lagoonal sediments of the Cotham Member. A shift in the zone of smectite deposition can be related to this regression.

The inferred shelf-lagoon carbonates of the Langport Member reflect a renewal of transgression. A local influx of sediment-laden fresh-water is believed to have been responsible for the local change to the Watchet Member Facies.

Deeper-water intermittently oxygen-deficient, marine environments are envisaged for the Pre-planorbis Beds. These spread across the Langport Member shelf-lagoon, as a result of continuing transgression, culminating in the widespread establishment of deeper-water conditions in the Lower Jurassic. An increase in kaolinite relative to smectite in these younger strata, reflects increasingly humid climatic conditions.

A regional correlation of the lithostratigraphical subdivisions is attempted leading to a series of palaeogeographical reconstructions.

LONG ABSTRACT.

The Penarth Group, a lithostratigraphical replacement for the "Rhaetic", is a widely-developed component of end-Triassic sedimentation in Britain. The unit is known at outcrop in the Hebridean area of Western Scotland, from Teesside to east Devon in England, and in South Wales, and has been recognised in numerous boreholes in both onshore and offshore areas. The Penarth Group has been defined as ... "the argillaceous, calcareous and locally arenaceous formations of predominantly marine origin which occur between the Mercia Mudstone Group and the base of the Lias..." (Warrington et al, 1980).

In this account, the Mercia Mudstone Group ('Keuper Marls') is divided into three units; the lower, Red Marls passing upwards (depending on location) into the Grey Marls or the Tea Green Marls.

The Penarth Group comprises a lower, Westbury Formation and an upper, Lilstock Formation. Throughout most of Britain the Westbury Member is the major or only component of the Westbury Formation, but it is locally replaced, wholly or partially, by units designated here as the Sully, Hapsford, Bridgend and Gribun Members. The Lilstock formation is divided here into Cotham, Langport and Watchet Members, the Cotham Member being replaced locally by a small part of the Hapsford Member. The entire Penarth Group may be represented, on the northern and western flanks of the London Platform, by the Twyford Beds (Donovan et al, 1979; Poole, 1979; Horton et al, in prepn.)

The Penarth Group is succeeded by Liassic (Lower Jurassic) strata the basal beds of which, prior to the first appearance of the ammonite Psiloceras planorbis, are here termed the Pre-planorbis Beds.

The Mercia Mudstone Group largely comprises the deposits of a hypersaline lake in an arid or semi-arid setting. Within this lacustrine milieu sedimentary structures indicative of deposition above and below normal wave-base have been distinguished (Klein, 1962) Shore-zone sediments have been recognised near the basin-margins whose interdigitation with offshore sediments, points to fluctuations of lake water level. Larger-scale fluctuations are evidenced by the extensive development of sabkha-type evaporites in offshore-zone sediments (e.g. Tucker, 1977, 1978). In South Wales shore-zone deposits pass-laterally into non-lacustrine sediments. Similar non-lacustrine facies form the complete infill of basins of deposition in north west Scotland. They include the deposits of alluvial fans (mudflows, streamfloods and braided streams), talus slopes, flood plains (low and high sinuosity streams) and playa lakes (e.g. Tucker, 1977; Steel, 1971b, 1974a,)

The red colour of much of the Mercia Mudstone Group is considered here to be the result of a slow, diagenetic formation of haematite by alteration of hydrated iron oxides and/or iron-bearing silicates minerals. Pigmentation of the Tea Green Marls is ascribed in part to higher initial contents of organic matter and also to the presence of the overlying, organic-rich mudstones of the Westbury Member. Both these factors led to reducing pore-water conditions preventing the development of haematite and allowing a weaker, grey-green colour, probably attributable to chlorite, to be discerned.

The Grey Marls of South Western Britain are believed to reflect an interplay of subaqueous lacustrine deposition, producing laminated sediments, and subaerial conditions resulting in the development of anhydrite and gypsum-bearing dolomitic sabkha deposits with mudcracks and disrupted lamination. Former evaporites are frequently witnessed by voids and by calcite and dolomite pseudomorphs containing gypsum and anhydrite relicts.

The clay mineralogy of the Mercia Mudstone Group is believed by Jeans (1978) to be a combination of detrital illite and chlorite with neoformed minerals (including sepiolite, palygorskite and corrensite) which formed at the interface of dense hypersaline waters and lighter, overriding marine waters during periods of transgression. Continuous reaction between the water masses produced a zonation of neoformed minerals broadly related to the zonation of evaporites. Whilst the present author's results from the Grey and Tea Green Marls are broadly in accordance with this model, an apparent diagenetic alteration of smectite to illite and chlorite in northern England, suggests that other processes may also have operated.

In south west England and South Wales lacustrine deposition was halted by a marine transgression documented in the Sully Member. Thus the generation of dolomitic and evaporitic deposits was replaced by the production of calcitic deposits in a shallow, sublittoral environment, which lack evaporites, but contain a fairly diverse marine macro-fauna, microflora and ichnofauna.

The Westbury Member represents the first widespread manifestation of marine conditions in the Penarth Group. Its base is generally erosional and commonly marked by a vertebrate-bearing rudaceous deposit believed to represent a beach remnant which survived the passage of transgression. Vertebrate remains dominate the fauna of the lower part of the Westbury Member which is often large in number but low in species diversity. This "Lower Unit" also exhibits marked thickness variation and a low lateral persistence of individual beds and is believed to have been deposited in a series of semi-isolated brackish basins whose location was determined by pre-existing topography.

The dark grey mudstones of the Lower Unit pass upwards into superficially similar sediments of an "Upper Unit". These rocks, however, contain a markedly more diverse fauna, dominated by molluscan elements. Thickness variations are greatly reduced and the lateral persistence of individual beds is much enhanced. All these factors point to a wider continuity of depositional environment. It is believed that transgression proceeded to permit the deposition of subtidal shelf muds below normal wave-base in an epeiric sea of near "normal" salinities, whilst storm processes led to the intercalation of a variety of arenaceous beds.

The interpretation of organic carbon profiles through the Westbury Member is made in the light of this environmental distinction between the Lower and Upper Units. A marked peak of organic carbon was detected in the basal Upper Unit from at least three, widely spaced, locations. It is contended here that this peak results from a short period of maximised phytoplankton productivity which occurred across the basin of deposition, at a point in the progress of transgression, when nutrient

supply and replenishment were optimised. Further transgression led to the formation of a basin-centre pycnocline which reduced vertical circulation, and hence nutrient recycling, causing a fall in organic carbon levels.

The Westbury Member passes laterally, towards the basin-margins, into arenaceous and rudaceous deposits believed to be nearshore equivalents deposited in a variety of sub-environments. The Bridgend Member of South Wales contains facies attributed to barrier-inlet, lagoon and tidal-flat sedimentation on the northern fringe of a small island of Carboniferous Limestone. A similar island setting is envisaged for the inferred gravel-beach deposits of the Hapsford Member in the Mendips, whilst in western Scotland, the Gribun Member is interpreted as the product of subtidal and intertidal flat deposition. Comparable milieux may have existed on the northern and western edges of the London Platform during the deposition of the Twyford Beds.

A lateral zonation of clay minerals was detected in the Westbury Member between an illite + illite-smectite + chlorite nearshore assemblage and an illite + smectite + illite-smectite + chlorite offshore assemblage. This is attributed to differential sedimentation of detrital clays in which a size segregation mechanism, comparable to that believed to operate at present off the mouth of the Amazon, (Gibbs, 1977) was probably the dominant factor.

Deposition of the Westbury Member was terminated by a regression which led to the accumulation of the Cotham Member. Effects of this regression appear to have been experienced earliest in northerly areas, remote

from the open sea, and spread slowly southwards. In the Midlands regression was gradual but in the south west the change of environment seems to have been abrupt, perhaps as a result of uplift. The Cotham Member contains an ostracod-branchiopod-plant biota of fresh or brackish water affinity. The associated presence of marine microplankton, however, indicates lagoonal rather than fresh-water environments. Proximity to open marine water is witnessed, in south western Britain by the association of a sparse marine macrofauna with ooids and glauconite. Mud-cracked ripple-marks, and the coexistence of algal stromatolites with edgewise breccias, demonstrate that fluctuating, shallow water depths prevailed. Extremely deep desiccation cracks, developed from Devon to South Wales, point to an extended period of emergence, perhaps tectonically-controlled, signifying the maximum point of regression. Strata above this level show signs of returning marine conditions.

A prominent horizon of contorted lamination occurs towards the top of the unit from Devon of Nottinghamshire and is ascribed to contemporaneous seismically induced liquefaction, an interpretation which suggests it's use as a chronostratigraphical marker horizon.

The two-fold zonation of clay minerals, described in the Westbury Member, persists into the Cotham Member but with the illite + smectite + illite-smectite + chlorite zone displaced northwards. The almost complete lack of smectite in areas which display signs of emergence does however suggest that it was still being transported to more offshore areas in the manner envisaged for the Westbury Member. The displacement of the zones can therefore be assigned to the regressive nature of

the Cotham Member.

The Cotham Member is succeeded abruptly by marine sequences testifying to rapid, renewed transgression. The available evidence suggests that the Langport Member/Watchet Member and the lower part of the Pre-planorbis Beds (of areas where the former are absent) are essentially coeval facies.

The Langport Member was deposited in a shallow, tropical or subtropical shelf-lagoon where lime-muds were the predominant sediment. Thin arenaceous and rudaceous beds accumulated during storms. Higher strontium levels preserved in the former lithologies reflect partly the high strontium contents of originally aragonitic sediments and partly increased leaching in the latter lithologies due to higher porosities. The importance of calcarenites/calclutites increases in South Wales and Somerset and is associated with desiccation cracks at one locality (Lilstock) suggesting a shallow, shoal environment. A zone of local tectonic instability, perhaps close to the platform edge, is indicated in east Devon by the common occurrence of rubbly, matrix supported calcirudites, interpreted here as subaqueous debris flows, and slump beds. Other rubbly beds, which are widespread in the Langport Member, are probably of diagenetic origin, having strikingly similar features to inferred pressure solution seams and flasers described from the English Chalk by Garrison and Kennedy (1977). Bioturbation is common in the Langport Member with Diplocraterion, Thalassinoides Spongiomorpha and Chondrites burrows being amongst those recognised. There is also evidence for early lithification, at several locations and horizons, provided by encrusting oysters, Trypanites borings

and the wrapping of sediment around underlying irregularities.

Overall the sediments and fauna of the Langport Member are consistent with deposition in very shallow, warm waters of "normal" to slight hyper-salinity.

The Watchet Member of Somerset and South Wales is believed to reflect deposition adjacent to a river mouth introducing fresh, sediment-laden water into the Langport Member shelf-lagoon. Thus carbonate content was lowered by dilution with clastic sediment and by reduced carbonate production due to lower sunlight penetration. The influx of freshwater was also responsible for a reduction in faunal diversity.

In the north Midlands the Langport Member appears to thin and pass northwards into the limestones and mudstones of the basal Lias. This implies a fairly subdued edge to the shelf-lagoon with pure carbonate production being gradually hampered by increasing water-depth and influx of terrigenous sediments, leading to a passage to deeper-water environments evidenced by the Pre-planorbis Beds. This Pre-planorbis facies spread over the Langport Member demonstrating a further period of transgression, which continued into the Hettangian.

In the basal Jurassic shallow-water conditions are known only from the Mendips, South Wales and parts of north west Scotland. The Sutton Stone and Southerndown Beds of South Wales represent beach and shallow sublittoral deposition (Wobber, 1965). Similar settings have been envisaged for the Downside Stone of the Mendips (Savage, 1977) and the Broadford Beds of north west Scotland (e.g. Amiri-Garroussi, 1978). In a matter of a few kilometres these nearshore deposits pass into the more extensive "Blue Lias" facies. This facies is here divided into

proximal and distal subfacies: the former typified by the limestone-shale sequence of the Dorset, Somerset and South Wales coastal exposures, whilst the latter, mud-rock dominated subfacies occurs in the north Midlands and northern England.

The spread of the ammonite Psiloceras planorbis (marking the base of the Jurassic) throughout Britain is considered to have been rapid and is used here as a chronostatigraphical marker on which to "hang" the uppermost Triassic sequence.

Clay mineralogies of the Langport Member/Watchet Member and Lower Lias are marked by an increase in kaolinite at the expense of smectite. Kaolinite appears at first only in south western England, where it may be related to the unroofing of Cornubian granites, but later becomes of widespread occurrence. This spread of kaolinite is ascribed here to a change to more humid conditions leading to more intense leaching in soil profiles: a process favouring kaolinite, and not smectite formation. Other lines of evidence support an end-Triassic change from an arid to semi-arid to a moist tropical or subtropical climate.

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INTRODUCTION

0.1 INTRODUCTION

This thesis is primarily concerned with a sedimentological study of the Penarth Group throughout the whole of Britain. The Penarth Group is taken here as the uppermost division of the British Trias following the proposals of the Geological Society of London's Triassic Working Group, reported by Warrington et al (1980) and corresponds to the "Rhaetic" of earlier authors. The term "Rhaetic" is used here as an informal synonym for Penarth Group because of the greater familiarity of the name and does not imply any more than the broadest correlation with the Rhaetian stage of the Triassic, well known in Continental Europe. The word "Rhaetic" is retained in quotes throughout the text to remind the reader that the Penarth Group is now considered to be the correct formal lithostratigraphical term for this part of the succession (Warrington et al, 1980).

The Penarth Group outcrops, in general, along a diagonal line stretching from south-western England and south Wales, across the country to the mouth of the Tees, as depicted in Fig. 0.1. A number of outliers, for example in Cheshire, indicate the originally more widespread distribution of the beds, prior to erosion, and a great deal of further information with regard to geographical spread is provided by numerous boreholes, in both onshore and offshore areas. Representatives of the Penarth Group are also known from western Scotland and from Northern Ireland.

This account utilises information gleaned from both outcrops and boreholes, but little use has been made of offshore data because this is mainly based on geophysical logs which provide only gross facies and thickness characteristics and because the actual definition of the "Rhaetic" in oil company offshore wells differs from that used onshore (Rhys, 1974, 1975).

0.2 PREVIOUS RESEARCH

This section will be kept as brief as possible, since a good historical account of "Rhaetic" research was given by Ivimey-Cook (1962). Previous research on the British Rhaetic has been almost entirely concerned with the stratigraphy and palaeontology, little detailed sedimentology having been attempted to date.

Early correlation with Alpine successions was made by Quenstedt (1858) on the basis of the equivalence of the overlying planorbis-zone marking the base of the Jurassic system. Comparison was also made on the basis of the "zone of Avicula contorta" (now Rhaetavicula contorta) which was recognised in Britain by, for example, Wright (1860).

The remainder of the nineteenth century was marked by the discovery and description (often in minute detail) of "Rhaetic" sections throughout the country. This was facilitated by the rapid expansion of the railway network, which led to the excavation of large cuttings, and enabled the documentation of many inland sections through the Penarth Group to be made. Among the more notable contributors to uppermost Triassic stratigraphy, at this time, were Brodie (1874, 1886, 1888), Etheridge (1865, 1868, 1872), Harrison (1876, 1878, 1880) and Moore (1861, 1867, 1881).

The first years of the new century were to witness the appearance of the most important contributor to "Rhaetic" knowledge to date, in the shape of Linsdall Richardson. Richardson's approach was to systematically examine all known exposures of the Penarth Group on a county-by-county basis, providing in some nine years a bed-by-bed, inch-by-inch description of each section, with a list of the contained fauna, over an area stretching from Devon and Dorset in the south, to Leicester in the north. The accumulated data were presented in a steady stream of papers (Richardson, 1903 a, b, c, d; 1904, 1905 a, b, c, 1906 a, b; 1909 , 1911, 1912) and were summarised in the regional geology handbook in 1929 (Richardson, 1929). Richardson's meticulous detail, and his coverage of virtually every outcrop in southern Britain, have been of great support to the present author in his search for exposures. It is curious, however, that Richardson, despite his eye for detail, rarely speculated as to the depositional environment of the strata he devoted so much time to examining.

In Scotland, meanwhile, an extensive survey of sediments of all ages had been carried out by Judd (1873). Following up this work the Geological Survey's officers were to find two definite, palaeontologically-datable "Rhaetic" outcrops in western Scotland. In the south a mass of dark grey shale, fortuitously preserved by its incorporation into a Tertiary vent agglomerate, was documented by Peach, Gunn and Newton (1901) whilst further north a predominantly sandy "Rhaetic" sequence was described from the Gribun area of Western Mull by Lee and Bailey (1925). These remain the only two indubitable representatives of the Penarth Group in Scotland, although other possible candidates were noted by the Survey elsewhere in the Hebridean area, and there remains the possibility (Neves and Selley, 1975) that the Dunrobin Conglomerate, outcropping on the north east coast near Golspie, Sutherland, may be of the requisite age.

After Richardson most descriptions are provided by the Geological Survey, in numerous sheet memoirs. In more recent times unpublished PhD and MSc theses have been completed in South Wales by Ivimey-Cook (1962), Willey (1966) and Moshrif (1974). Much new stratigraphical data on the east Midlands was provided by Kent (1953, 1968, 1970) and the steady trickle of papers which continues to the present includes a study of the White Lias by Hallam (1960 a), the ending of the controversy concerning the origin of the Cotham Marble by Hamilton (1961) and a fairly large volume of recent palynological data presented in the papers of Warrington (e.g. 1974 b, 1977 b, 1978 a), Orbell (1973), Morbey (1975) and Fisher (1972 a, b).

0.3 AIMS OF THE RESEARCH

Preceding research work described in the previous section has provided a wealth of stratigraphical data and has answered some of the questions posed, but very little sedimentological work has been published to date, and in general interpretative palaeoenvironmental accounts are few, and where they exist tend to be speculative rather than reaching conclusions in the light of amassed evidence. Another general feature of the earlier work is its local bias. The aim of the present work is an attempt to redress these omissions by a regional study, on a broad sedimentological front. The objective behind this project was the presentation of a palaeoenvironmental synthesis for the Penarth Group, on a regional basis, covering the whole of Britain. Northern Ireland has been largely excluded from this study both because of the time element and also, partially, because of the political unrest in the province. Within this broad

objective a number of sub-projects have been delineated; most notably these are the regional survey of the clay mineralogy (Chapter 7) which, whilst tying in with the principal aims of the study, also fills an important stratigraphical gap in British clay mineralogy (a fact noted by Perrin, 1971) and an examination of the distribution of organic matter in the dark grey argillites of the Westbury Member (Chapter 8). This latter sub-project has been undertaken in co-operation with the Organic Geochemistry Unit of Bristol University, who have investigated the detailed organic geochemistry of the organic matter as part of their programme involving a variety of organic-rich strata of differing ages.

0.4 TECHNIQUES

A fairly standard procedure has been followed throughout this study, with follow-up of selected lines of enquiry in greater detail.

In the field the emphasis has been on the evaluation of the gross characteristics of the sediments including the routine description of colour, grain size, lithology, sedimentary structures, broad palaeontological content and palaeocurrent azimuths, and the compilation of the data in the form of graphic logs of the sections examined. Continuous sampling was normally carried out on a bed-by-bed basis, this being supplemented by more closely-spaced sampling, as the need arose (for example this was necessary in the examination of the distribution of organic matter in the Westbury Member). When sampling, great care was taken, whenever possible, to obtain the specimen after the obviously weathered outer layer of material had been removed.

Improvements to the field graphic logs were made by examination of polished surfaces of sawn blocks and by a petrographic study of thin sections of all lithified samples, using a polarising microscope (staining with alizarin red-S and potassium ferricyanide was used to discriminate calcite from dolomite and ferroan carbonates from non-ferroan carbonates). The microscopy also provided information on the post-depositional history of the sediments. It was found to be extremely difficult to prepare thin-sections of the more argillaceous rocks (silty mudstones and mudstones) even when vacuum impregnation techniques were used. Their mineralogy was therefore determined by a study of cavity-mounted whole-rock powders using X-ray diffraction. Further extensive use of X-ray diffractometry was made in the regional study of the clay mineralogy.

Organic-carbon determinations on rocks from the Westbury Member were made using oxidation with hot chromic acid, the evolved carbon dioxide being measured with a gas chromatograph. Trace element geochemistry of samples from the same member was obtained by X-ray fluorescence spectrometry of pressed pellets. Strontium analyses of Langport Member limestones were also performed using the same method.

Details of techniques are given in the relevant chapters and appendices. Various other approaches were tried without success. These include an abortive attempt to elucidate the sedimentary structures of apparently massive limestones using X-ray radiography and a similarly unsuccessful search for algal filaments in acid-insoluble residues of stromatolitic limestones from the Cotham Member.

0.5 STRATIGRAPHY

The stratigraphical scheme used in this account is based on the proposals of Warrington et al (1980) who define the Penarth Group as: "the argillaceous, calcareous and locally arenaceous formations of predominantly marine origin which occur between the Mercia Mudstone Group and the base of the Lias" They subdivide the Penarth Group into two formations; a lower Westbury Formation and an upper Lilstock Formation, the latter being further split into the Cotham and Langport Members. A further subdivision of the Westbury and Lilstock Formations is made here to separate distinctive, locally-important lithological units. Thus the Westbury Formation here is principally comprised of the Westbury and Sully Members and the Lilstock Formation gains an extra component; the Watchet Member. Despite wishing to keep new terminology to a minimum, circumstances force the introduction of an additional three members to the Westbury Formation; the Gribun Member of north west Scotland, the Hapsford Member of the Mendips and the Bridgend Member of Mid-Glamorgan. These members are included in the Westbury Formation because their fossil content indicates probable biostratigraphical correlation. Their contrasting lithology, when compared to the Westbury and Sully Members, however, necessitates their designation as distinct members.

The underlying Mercia Mudstone Group is divided threefold into the Red, Tea Green and Grey Marls (the latter two equivalent to the Blue Anchor Formation of Warrington et al, 1980). This usage is adopted because of the need for a broad, regionally-applicable terminology. For this reason locally-erected lithostratigraphical classifications for the Mercia Mudstone Group, such as those of Wilson and Manning (1978) and Elliot (1961) have not been used.

The base of the Jurassic is taken, at the first appearance of the ammonite Psiloceras planorbis as recommended by Cope et al (1980), Ivimey-Cook et al (1980) and Warrington et al (1980). The term Pre-planorbis Beds is used here for the basal strata of the Blue Lias situated above the Penarth Group and below the earliest appearance of Psiloceras planorbis. The author does not use this term in a formal lithostratigraphical sense, but merely in an informal way to describe a part of the Blue Lias sequence. The name is retained here, despite the misgivings of Ivimey-Cook et al (1980) and Donovan (1980) because it is felt that an existing, familiar and highly descriptive term is preferable to the introduction of further nomenclature.

In general, the terminology used here follows that of Richardson (1911) with the exception of the Watchet Member which is used as redefined by Whittaker (1978). The lithostratigraphy utilised here is outlined in relation to older nomenclature in Fig. 0.2. Further details of individual designations can be found in the appropriate ensuing chapters.

NOTE

Throughout the text which follows grid references are not generally given for localities, they are however appended to a map (Fig. 0.3) which depicts the position of all locations referred to in the text. This map can be found in a pocket at the rear of Volume 2. A key to the symbols used in the graphic logs of this account is also to be found in this pocket and may likewise be detached for reference purposes.

CHAPTER ONE

MERCIA MUDSTONE GROUP

1.1 INTRODUCTION

The Mercia Mudstone Group is the name suggested by the Triassic working party of the Geological Society as a formal lithostratigraphical term to replace the "Keuper Marls" (Warrington et al, 1980) and hence embraces the Red Marls, Tea Green Marls and Grey Marls of earlier authors (the latter two being the Blue Anchor Formation of Warrington et al, 1980). The stratigraphical proposals of the Triassic Working Group are generally adhered to here except where a more detailed subdivision is deemed necessary. The use of the term "Mercia Mudstone Group" removes the time connotation implicit in the word "Keuper" - a term whose removal from British Lithostratigraphy is to be encouraged, since the "Keuper" Marls, in this country, range from Upper Bunter (Scythian) to Keuper (Norian) in age (Warrington, 1967, 1970, 1974 c; Stevenson and Warrington, 1971).

An appropriate subdivision of the Mercia Mudstone Group into constituent formations and members has only been attempted to date for the midlands (Elliot, 1961; Warrington, 1970) and Northern Ireland (Wilson and Manning, 1978). In the absence of a nationally-agreed terminology the names, "Red Marls", "Tea Green Marls" and "Grey Marls" are retained here in the manner of Fig. 0.1. The general appearance of this part of the stratigraphical column is shown in Plate 1.1.

1.2 RED MARLS

This unit has not been studied in detail by the present author, but a brief description of it is appropriate in providing a broader setting to Rhaetic deposition. A short account of the lowermost Lias is given, for similar reasons, in chapter six. These two sections permit the examination of the Penarth Group in a wider framework, and avoid its being discussed in a sedimentological vacuum.

The Red Marls occur throughout Britain, ranging in places (e.g. Northern Ireland, Cheshire and Yorkshire) from late Bunter to Keuper in age (Warrington, 1970, 1978b) and at other localities (e.g. the central midlands) from upper Muschelkalk to Keuper (Warrington, 1970). In Scotland the Red Marls (Auchenheew Beds) are known from the Isle of Arran where they are of late Bunter or early Muschelkalk to probable upper Keuper age (Warrington, 1973).

Lithologically the Red Marls consist of almost unfossiliferous, reddish and brownish calcareous mudstones and siltstones, with thin beds, ellipsoids and irregular patches of similar grey/green or grey material. The rocks are frequently dolomitic and are interbedded with "skerry" members consisting of typically grey or grey/green dolomitic siltstones and sandstones, which range from tens of centimetres up to a few metres in thickness.

A detailed regional examination of sedimentary structures has yet to be undertaken, but information is contained in certain papers, especially those of Elliot (1961) and Klein (1962) - who worked on the basinal,

Red Marl sequence - whilst the equivalent basin-margin facies have been described in the important contributions of Tucker (1977, 1978). Klein was able to divide the rocks, on the basis of their structures, into two groups, one deposited above normal wave-base, the other below. The criteria for this subdivision are shown below:-

Beds deposited above normal
wave-base

1. Even bedding
2. Rhythmic lamination
3. Oscillation and interference
ripple-marks
4. Current lineation
5. Rib-and-furrow structure
6. Groove casts
7. Raindrop imprints
8. Halite pseudomorphs

Beds deposited below normal
wave-base

1. Even bedding
2. Rhythmic lamination
3. Disturbed stratification
4. Graded bedding
5. Load casts
6. Pull-apart structures
7. Oscillation ripple marks

Evaporite minerals are widespread in the Red Marls. Gypsum and anhydrite are practically ubiquitous, being commercially important at certain horizons. Thick halite deposits occur in the sequence in, for example, Cheshire, Staffordshire and central Somerset (see e.g. Edwards, 1967, Evans et al, 1968; Whittaker, 1972; Warrington, 1974 a) and celestite forms significant beds in the Bristol area (Nickless et al, 1976; Cave, 1977).

Two main schools of thought exist as far as the depositional environment of the Red Marls is concerned (Wills, 1970). It was either:-

- a) Deposited on a subaerially-dominated megaplaya or desert plain
(e.g. Lomas, 1907; Bosworth, 1913; Sherlock, 1921; Wills, 1976)
- or:
- b) Deposited under mainly subaqueous conditions in a hypersaline lake or epeiric sea (Warrington, 1970; 1974 a), b); Tucker, 1977, 1978).

In either case there appear to have been periodic incursions of marine water, probably from the Tethyan area to the south (see Warrington, 1974a; Wills, 1976; Jeans, 1978). Tucker's work in the marginal Trias of South Wales indicates that the second interpretation is essentially correct, but that conditions approaching those of a megaplaya pertained during periods of lake regression. The presence of structures indicative of emergence, and of a number of lake-margin, wave-cut platforms, suggests fluctuations in the level of the "Keuper" lake.

Whilst it has been generally agreed in recent years that most of the gypsum and anhydrite formed during early diagenesis in a subaerially-exposed, continental, sabkha-type environment (e.g. Warrington, 1974 a), Nickless et al, 1976; Tucker, 1977, 1978) no such consensus of opinion has been reached concerning the genesis of the halite. Evans et al (1968) considered the halite to have formed, at a water depth of several hundred metres, from a dense, concentrated brine occurring at the bottom of a sagging epeiric basin. More recent studies by Arthurton (1973) which involved a comparison with experimentally-produced halite, and the identification of emersion features comparable to those of modern salt

flats, led him to suggest that the halite formed in pools, perhaps only centimetres deep! The latter, shallow-water origin was preferred by Warrington (1974 a)) who drew an analogy with Permian halite deposits, believed by Smith (1971) to have formed during early diagenesis on a lake-margin sabkha. Warrington concluded that the salt was probably formed during regressions by the evaporation of marine waters isolated from the sea. The celestite deposits of the Bristol area are considered to be a diagenetic replacement of pre-existing gypsum and anhydrite, the strontium being derived from the nearby Carboniferous limestone (Nickless et al, 1976; West, 1973).

The general picture of Red Marl sedimentation was therefore one of deposition in a subaqueous hypersaline lake, subject to periodic marine incursions introducing a sparse marine biota, interspersed with longer regressional phases producing evaporites on marginal sabkhas. In certain areas, such as South Wales, the Mendips and Charnwood Forest, emergent basement rocks protruded above the lake surface (Bosworth, 1913; Tucker, 1977) on which fluviatile, scree and playa lake deposits accumulated, and around whose margins were developed a series of lake-margin sediments (Bosworth, 1913; Tucker, 1977, 1978). As time went on these marginal deposits were commonly overlapped by offshore lacustrine sediments; indeed, the Charnwood Forest massif was completely inundated by the close of the Keuper (Bosworth, 1913).

Red Marl sedimentation occurred in a number of fault-bounded graben structures, which accumulated thick piles of sediment, whilst thinner sequences developed on the intervening horsts (Audley-Charles, 1970 b);

Whittaker, 1975). The control of faulting on sedimentation waned progressively, such that by Norian times the only clear-cut evidence for synsedimentary faulting occurs on the western margin of the Worcester graben and along the Puriton trough (Audley-Charles, 1970 b)).

1.3 TEA GREEN MARLS

1.3.1 DESCRIPTION

This name applies to the unit of typically grey-green siltstones and mudstones which occur at the top of the Mercia Mudstone Group. In south west England and South Wales the Grey Marls intervene between the Red Marls and the Penarth Group. In this area it is difficult to define a distinct Tea Green Marl unit, because of a gradual upward colour variation, hence the two are combined, in this account, as Grey Marls (dealt with in section 1.4). The present section deals only with the Tea Green Marls from areas where the Grey Marls are absent: the disposition of Grey and Tea Green Marls according to this usage is illustrated in fig. 1.1.

The Tea Green Marls are very similar, lithologically, to the Red Marls, presenting an outward appearance almost identical to that of the grey areas within the latter. The mineralogy is also closely comparable, with the presence of quartz, feldspars, dolomite and clay minerals (the latter discussed in chapter seven) and the notable absence of the red pigment, haematite. The grey-green colouration is almost certainly due to the ubiquitous occurrence of an iron-rich chlorite, a mineral also present in the Red Marls, but whose contribution to the colour of these rocks is masked by the stronger red colour of haematite. In addition to the above-mentioned minerals, calcite is occasionally represented, especially

in nodules, where it appears to have formed at the expense of dolomite (plate 1.2).

With the exception of an increase of CaO and MgO, as a result of the increased importance of dolomite, the chemistry of the Tea Green Marls is broadly similar to that of the Red Marls.

The junctions between the Tea Green Marls and adjacent strata are variable; the lower junction with the Red Marls is commonly transitional with an interbedding of red and grey-green strata, the contact with the Westbury Member is normally sharp, the base of the Westbury Member being sometimes erosive, but at a few localities (for example in the Eskdale boreholes, North Yorkshire; Raymond, 1955, and at Patchway, Avon) the transition is gradual, with dark grey mudstones intercalated in the uppermost few metres of the Tea Green Marls.

The Tea Green Marls showed a fairly marked thickness variation, attaining a maximum of over 16 metres in the Platt Lane borehole (Poole and Whiteman, 1966) and being locally absent in the Stratford upon Avon area (Williams and Whittaker, 1974). A plot of Tea Green Marl thickness versus thickness of the overlying Westbury Formation (fig. 1.2) indicates, in very general terms, a broad correlation, with one unit thickening in concert with the other.

Although commonly appearing to be massive, sedimentary structures are sometimes discernible, and are similar to structures detected in the Red Marls. They include horizontal lamination, broken and contorted lamination, brecciation, mudcracks and minor erosion surfaces (Raymond, 1955, Worssam, 1963; Poole and Whiteman, 1966 and the writer's personal observations).

A very sparse biota has sometimes been found from this unit, consisting of plant debris, fish teeth and scales belonging to the genera Gyrolepis and Colobodus, the branchiopod Euestheria and rare insect wings (Wilson, 1891; Green and Melville, 1956; Welch and Trotter, 1960; Worssam, 1963; Poole and Whiteman, 1966; Taylor, 1968; Warrington, 1974 b; 1976; Wilson and Manning, 1978).

The final noteworthy feature is the presence of evaporites which are a rare component of this unit. Nodular, massive and vein, gypsum and anhydrite have been described from Yorkshire by Warrington (1974 b) and Raymond (1955). Veins of gypsum have been noted elsewhere by the present author (e.g. at Aust Cliff, Avon). In this case the gypsum is almost certainly derived, by re-mobilisation, from bedded sulphates in the underlying Red Marls.

1.3.2 DISCUSSION

In any discussion of the Tea Green Marls an explanation must be sought for the colour change from red to green; this is the fundamental difference between these rocks and the Red Marls beneath. Up to now this colour change has been tied in to iron analyses of the green spots and beds in the Red Marls and not directly to analyses of the Tea Green Marls themselves. De la Beche (1846) concluded from his analytical results that the green colouration resulted from the reduction of $\text{Fe}_2\text{O}_3 \rightarrow \text{FeO}$ by the decomposition of organic matter. However, his data showed comparable levels of total iron in both red and green material, with a change only in the oxidation state, and is contradicted by later results (Maw, 1868; Moody, 1905; Sherwood and Hollis, 1966) which reveal comparable levels of FeO in both rock types, but a higher content of Fe_2O_3 (and hence of total iron) in the red lithologies.

Moody (1905) suggested that all the Keuper Marl had originally been green but that subsequent passage of iron-rich groundwaters had led to the precipitation of iron oxides and hence to red colouration.

He explained the green areas within the Red Marls as impervious patches, which did not allow the passage of the iron-bearing waters. This reasoning was based on experiments which sought to alter Red Marl to Green and vice-versa. Attempts to remove Fe_2O_3 from Red Marl proved unsuccessful due to the inhibiting effect of MgCO_3 and CaCO_3 , but Moody found that the experimental passage of iron-rich solution through green marl produced a material extremely similar to natural red marl. Contrary to Moody's results, Keller (1929) found that production of grey/green rock from red was possible providing the Fe^{2+} ions formed by a reduction reaction could be leached away. In his experiments, Keller reduced the Fe_2O_3 using hydrogen sulphide and leached the resulting Fe^{2+} with carbonic acid.

Subsequent authors have mostly considered the Tea Green Marl to be a primary green deposit reflecting the first stages of the 'Rhaetic' transgression, with accompanying reducing conditions, on the basis of the sparse fossil assemblage, the transitional passage from red → green marls, the predictability of its position relative to distinctive horizons in the underlying Red Marls (e.g. the Severnside Evaporite Bed - Cave, 1977) and its thickening and attenuation in concert with variations in the contiguous strata (e.g. Poole and Whiteman, 1966; Williams and Whittaker, 1974; Warrington, 1974 b; Wilson and Manning, 1978). The lack of fauna in the "Tea Green Marls" of IGS's Steeple Aston and Withycombe Farm borehole, and results from nearby British Gas boreholes in the Chipping Norton area, led Poole (1977, 1978) to conclude that in this area there was no Tea Green Marl, *sensu stricto*, but only an originally red sequence which had been

secondarily reduced below organic-rich mudstone of the Westbury Member.

No authors to date have considered colouration in the Mercia Mudstone Group in terms of recent studies relating to the genesis of red beds. In modern humid, tropical, arid and semi-arid regions, alluvium is grey or brown in colour and only attains a red colour owing to the diagenetic production of haematite by dehydration of hydrated iron oxides, and/or the in situ alteration of detrital, iron-bearing silicate minerals (Walker, 1967 a), b); 1974; Walker and Honea, 1969; Van Houten, 1968, 1972; Folk, 1976). Critical prerequisites for reddening are:-

1. Adequate supply of iron from iron oxides and/or silicates.
2. Suitable post-depositional conditions for the alteration of these minerals to haematite.
3. A rate of organic accumulation that is exceeded by the oxidation rate or by the rate of destruction of organic matter (in arid areas there is little organic matter whilst in humid tropical regions, high temperatures promote rapid bacterial consumption of organic matter).

(Walker, 1967 a); Folk, 1976)

The degree of reddening produced is dependent on temperature, moisture and time, alone, or in any combination (Folk, 1976).

It seems reasonable, on the basis of the above researches, to assume that neither the green or red colours in the Mercia Mudstone Group are primary, but that the original sediment was probably grey or brown. The presence of evaporites in the Mercia Mudstone Group indicates an arid or semi-arid climate and hence, by analogy with Walker's (1967 a)) studies in a similarly dry setting, reddening would have taken hundreds of thousands,

to millions of years to reach completion. This time-scale implies that much, if not all, of the Penarth Group was deposited before colouration processes in the upper part of the Mercia Mudstone Group had reached completion.

Further reference to these modern studies indicates to the present author the strong probability that colour variation in these rocks is the result of local Eh + pH conditions of the interstitial waters during diagenesis (see fig. 1.3). As the bulk of the sediment is red these conditions must have generally favoured the formation of ferric oxides and eventually, haematite. The formation of green beds and mottles must be related to local conditions of abnormal Eh/pH linked to original differences in the sediment, or to subsequent changes in pore-water chemistry. The most obvious factor responsible for these variations is the distribution of organic matter. The green spots and beds in the Red Marls are probably related to localised concentrations of organic matter, producing Eh/pH conditions in the Fe^{2+} field of fig. 1.3, thereby leading to removal of iron in solution and hence accounting for the low levels of iron in these areas. The common occurrence of grey or green zones in mudstone adjacent to sandstone and siltstone beds may be explained in terms of bleaching adjacent to a more permeable layer, whose coarser grain size may have been associated with lower levels of fine-grained ferric oxides (haematite precursors), and Eh/pH conditions in the interstitial fluids, favouring the removal of iron in solution (compare, for example, the alternating green/red, silt/clay couplets of Braunagel and Stanley, 1977).

Bleached spots surrounding a black, radioactive core are a special case.

In a recent study of similar phenomena in a comparable, but older part of the British New Red sequence (?Permian, Littleham Mudstone Formation of Devon) Durrance et al (1978) concluded that these, "fish-eyes" formed after

1,000-1,300 m of covering strata had been deposited, and that they were the result of late-stage diffusion of uranium to sites of remanent organic matter. This organic material was responsible for reduction of the uranium and hence its precipitation as small radioactive nodules. The green colour of the surrounding spot resulting from the local concentration of organic matter. The great similarity of the Permian and Red Marl "fish-eyes" suggests that a comparable mode of formation may be invoked.

These ideas can be extended to the Tea Green Marls although a word of caution is appropriate. These conclusions must be regarded as tentative in that they lack detailed geochemical back-up. Total iron analyses made by the author on ten Tea Green Marls samples (see table 1.1) were scattered about the mean of 4.3% obtained by earlier workers (Maw, 1868; Moody, 1905; Sherwood and Hollis, 1966) for the Red Marls and therefore do not necessarily show the lower level of total iron anticipated by the model for Tea Green Marl colouration that follows. The proper test for this model would be a detailed study of the iron content in sections through the Red and Tea Green Marls - a study beyond the scope of the present investigation. As previously stated much of the Penarth Group was probably deposited prior to completion of the pigmentation process. The available evidence suggests that the green colouration is partially the result of a relatively high content of organic matter in this unit, due to changing conditions accompanying the onset of transgression, and was also partly controlled by Eh/pH conditions induced in the ground water by the presence of the overlying Westbury Member. The sparse fauna and the predictability of position and thickness variations in the Tea Green Marls are support for the first mechanism, whilst the high levels of organic matter in the Westbury Member (see Chapter 8) would be expected to lead to Eh/pH conditions lying in the Fe^{2+} field, in adjacent strata, and hence point to

TABLE 1.1 IRON CONTENTS OF SAMPLES FROM THE GREY AND TEA GREEN MARLS.

A. TEA GREEN MARLS.

<u>SAMPLE</u>	(DEPTH)	<u>% TOTAL IRON. (As Fe_2O_3)</u>
SCALLA MOOR BOREHOLE	(c. 47.6 m.)	2.82
COCKLE PITS BOREHOLE	(116.64-117.60 m)	3.34
BLYBOROUGH BOREHOLE	(155.10-156.00 m)	6.00
THORPE-BY-WATER BOREHOLE	(234.23 m)	6.06
WITHYCOMBE FARM BOREHOLE	("TEA GREEN MARL")	5.95
STEEPLE ASTON BOREHOLE	(590')	5.34
STOWELL PARK BOREHOLE	(2083'10")	3.79
UPTON BOREHOLE	(604'10")	2.71
WAINLODE CLIFF	(TEA GREEN MARL)	3.51
PATCHWAY	(TEA GREEN MARL)	4.96

B. GREY MARLS.

LAVERNOCK POINT	(4.35 m. below Westbury Member).	2.71
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(Analyses obtained by x-ray fluorescence spectrometry).

the operation of the latter mechanism. In fact, correlation between Westbury Member and Tea Green Marl thicknesses might be explained in terms of the quantity of soluble organic matter available; the larger the volume of soluble organic material, the thicker the zone of Mercia Mudstone Group with pore-waters lying in the Fe^{2+} , Eh/pH field. Further support for the development of a reducing environment in interstitial waters in the Tea Green Marls, as a result of the high organic content of the Westbury Member, comes from British Gas boreholes in the Chipping Norton area, where the Tea Green Marls descend the stratigraphy relative to geophysical marker horizons (Horton, pers comm, 1979 and Horton et al, in prepn). Poole (1977, 1978) interpreted this in terms of a secondary reduction of originally red mudstone, the present author prefers to consider it in terms of reducing pore-water conditions leading to removal of iron as Fe^{2+} , rather than permitting the maturation of iron oxides and silicates to haematite.

The colour of the Tea Green Marls, therefore, is probably only a partial reflection of a change in depositional environment. The strong contrast of pigment with the underlying Red Marls should not be taken as evidence of a profound environmental change. This unit has a greater affinity with the Red Marls than with the Penarth Group and is interpreted here as having been deposited, similarly, in a lacustrine setting. The faunal evidence does, however, point to the beginnings of a marine influence - a hint of things to come. The gypsum and anhydrite described from this unit, in Yorkshire by Warrington (1974 b) and Raymond (1955) was probably, like that of the Red Marls, deposited in a lake-margin sabkha environment.

1.4 GREY MARLS

1.4.1 DESCRIPTION

As explained in section 1.3.1, the Grey Marls are taken here as the entire upper unit of the Mercia Mudstone Group overlying the Red Marls, in south and south west England, and South Wales (the distribution of this facies is shown in fig. 1.1). Representative sections of this facies are illustrated in fig. 1.4 and 1.5.

The Grey Marls consist of a series of typically dolomitic, rarely dolomitic and calcareous mudstones and siltstones, usually various shades of grey in colour, more rarely grey/green, buff or red/brown. The mudstones are mostly dark grey dolomicrites with rare detrital grains of silt grade (predominantly quartz) and scattered, comminuted organic material. The siltstones are generally lighter in colour consisting mainly of subangular grains of quartz, feldspars and micas cemented by sparry, occasionally rhomboidal, dolomite.

Two types of rock predominate in this unit: one is regularly laminated, the other chaotic. The former comprises ferroan dolomicrite laminated on a mm/cm scale with dolomitic siltstone, the siltstone being frequently lenticular and micro-cross-stratified (plates 1.3, 1.4). This lithotype is sometimes burrowed by simple vertical or U-structures (Arenicolites) (plate 1.5) and the bedding is disturbed by irregular, fluid-escape structures (plate 1.3) typically infilled with silty material (plate 1.6) suggesting upward injection of water-saturated sediment. More spectacular water-escape features produce a brecciated fabric (plate 1.7). The

second major lithology consists of usually dark grey, rather chaotic mudstones with subordinate siltstone (plate 1.8). The common mottled appearance of this lithotype is similar to burrow mottling, but seems, in this instance, to grade imperceptibly into recognisable fluidisation structures, and is therefore more probably attributable to this mechanism. No sharp demarcation exists between the main lithotypes, they tend to pass vertically into each other (see plate 1.8).

Further disturbances to the sediment have been produced by abundant normal microfaults (plate 1.8) by desiccation cracks (plate 1.9) and by the displacive development of evaporites.

Evaporites, or replacements after evaporites, are common in the Grey Marls, occurring in both the main lithotypes, but being more common in the chaotic mudstones. The principal evaporite mineral now present is gypsum which occurs both in nodular form, and redistributed as fibrous infills of veins and tension gashes (see plates 1.10, 1.11, 1.12). Textural evidence suggests that the nodular gypsum is a replacement of anhydrite (Stevenson and Warrington, 1971). This is supported by the occurrence of nodular, and apparently bedded anhydrite, in the IGS Burton Row borehole (IGS unpublished log) where gypsum is absent, and by chicken-wire and enterolithic textures typical of modern and ancient anhydrite (see discussion). Evaporites are best displayed at Blue Anchor (Somerset) where gypsum is abundant in the cliff section; in other surface exposures evaporites are rare or entirely absent. Their former presence is, however, indicated by the occurrence of nodular-shaped cavities (plate 1.13) and by replacement by dolomite and calcite. In one interesting case, small

clusters of pinkish quartz crystals occur, in the absence of gypsum, at St. Audries (Somerset) which are identical to examples occurring within gypsum nodules, at the adjacent section at Blue Anchor (plate 1.12).

These quartz crystals contain anhydrite relics (M. Mayall, pers comm, 1979) lending further support to the contention that anhydrite was originally the most important evaporitic mineral. Unusual nodular dolomite, and more rarely calcite, beds are fairly common in the Grey Marls. The presence of laths of quartz and carbonate after anhydrite and gypsum, and of relict gypsum and anhydrite, and the close resemblance of the nodular and enterolithic textures to those of the gypsum nodules, indicate that these unusual carbonates are evaporitic replacements (see plates 1.14-1.17). They appear to be similar to evaporites in the slightly older marginal 'Keuper' of South Wales described by Tucker (1978).

Spectacular secondary mobilisation of gypsum is apparent at Blue Anchor in the form of the fibrous "satin-spar" infillings of arrays of tensional veins. These veins are usually subvertical and commonly occur as conjugate sets (plate 1.10).

With the exception of plant fragments, and the sparse evidence of a burrowing infauna (?worms) the Grey Marls, as defined in this account, are devoid of biota.

1.4.2 DISCUSSION

The nature of the evaporites in this unit is critical to its environmental interpretation. The presence of nodular anhydrite displaying chicken-wire

and enterolithic fabrics, and of various replacements after anhydrite is comparable with anhydrite fabrics developed in modern sabkhas (Shearman, 1966; Kinsman, 1969a; Butler, 1969; Bush, 1973). In Recent Persian Gulf sabkhas gypsum normally develops as a mush within the sediment, being replaced landwards by anhydrite. Later primary diagenetic anhydrite develops on this early replacement of gypsum, forming nodules which coalesce, entrapping sediment, and leading to a chicken-wire texture (Kinsman, 1969; Bush, 1973). Competitive growth leads to enterolithic folds (Shearman, 1966; Till, 1978). All modern sabkha anhydrite forms in the supratidal zone, implying, by analogy, that the Grey Marls were emergent at the time of anhydrite formation; a contention supported by the occurrence of mudcracks and halite pseudomorphs. A further similarity to modern sabkhas is the extensive development of micritic dolomite; in the Recent this forms in the sabkha as a replacement of fine-grained aragonite. The precipitation of aragonite and gypsum removes Ca^{2+} from the interstitial brines, causing the $\text{Mg}^{2+}/\text{Ca}^{2+}$ ratio to increase. When this ratio reaches and exceeds 10, aragonite is replaced by dolomite (Bush, 1973). The replacement of anhydrite by dolomicrite in the Grey Marls suggests, in view of the extensive dolomitisation occurring at an early stage in modern sabkhas, that this was probably an early diagenetic process.

Comparison of the Grey Marls with modern, Trucial Coast sabkhas has previously been made by Sellwood et al, 1970; Stevenson, 1970; Stevenson and Warrington, 1971; and Anderton et al, 1979. These authors all interpreted the Grey Marls as a marine coastal sabkha, on the basis of Arenicolites and marine microplankton. However, according to the litho-stratigraphic usage of this account, all the marine biota occurs in the

Sully Member, with the exception of Arenicolites. This structure is almost certainly produced by worms, or worm-like organisms (Häntzschel, 1975) both of which are known from modern lacustrine environments (Beadle, 1974; Hardie, Smoot and Eugster, 1978) suggesting that Arenicolites burrows are not a marine indicator. For these reasons the Grey Marls are here interpreted in terms of deposition on a lake-margin sabkha.

The tendency for evaporites to be preferentially developed in the chaotic mudstone lithotype is instructive; the laminated dolomite/siltstone lithotype represents the alternation of sedimentation from tractional currents or waves, with deposition from suspension, and is interpreted here as having formed in a sublittoral lacustrine environment. This is consistent with the less common occurrence of gypsum in this rock type. The chaotic mudstone lithotype is interpreted as a largely emergent facies representing the onshore equivalent of the laminated sediments, the disturbance to bedding being produced by water escape and by the displacive development of evaporites. The occurrence in the laminated siltstone/mudstone lithofacies of nodular evaporites indicates periods of lake shoreline regression bringing subaqueous sediment above water level and permitting the development of desiccation cracks and sabkha-type evaporites. Subsequent transgression allowed the development of a number of sabkha cycles, comparable to those of the Persian Gulf (Shearman, 1966) with the exceptions that the offshore-zone is comprised of lacustrine mixed carbonate and siliciclastics, and that no clear-cut equivalent of the intertidal algal mat facies is present (although occasionally a micro-fabric consisting of dolomicrite and dolomitic microspar alternating on a mm scale occurs which is suggestive of the presence of algal mat - see plate 1.18).

Lake-level fluctuations may be controlled by tectonics or climatic change (Tucker, 1978). There is evidence for the former in the prevailing extensional tectonics of the British area in the Triassic (e.g. Audley-Charles, 1970 b; Hallam, 1971; Steel, 1971 a, b); the extent of the latter process is more difficult to assess, but it is possible that it may also have had a significant effect.

Vein-filling fibrous gypsum is clearly a secondary mobilisation feature. Shearman et al (1972) believe it to be related to the volume increase resulting from hydration of anhydrite, whilst this process may have operated to some extent in the Grey Marls, the relation of the conjugate gypsum veins at Blue Anchor to the stress associated with anticlinal folding (Bradshaw and Hamilton, 1967) indicates that it was not the dominant process. The opening of tensional cracks by tectonic compressional stresses would be expected to permit the freer movement of groundwater and thus to enhance the process of gypsum hydration, the excess volume being taken up by the formation of fibrous gypsum vein infills.

1.5 SUMMARY

The depositional phase described in this chapter documents the latter stages of a long, essentially continental, Permo-Triassic period.

The Red Marls were deposited in a generally hypersaline lake, subject to numerous fluctuations of water level, probably related to both tectonic and climatic controls (Tucker, 1978). Lake shore-line regression allowed the formation of gypsum and anhydrite in broad, inland sabkhas. Halite deposits also seem to have formed during periods of the low lake-level, whilst celestite is apparently a replacement of gypsum and anhydrite.

The Tea Green Marls are essentially similar to the Red Marls but show signs of marine influence; their colour is probably related to reducing conditions in the interstices of the sediment, induced by a higher content of organic matter and also by the presence of the organic-rich mudstones of the overlying Westbury Member.

The Grey Marls record deposition in a lake-margin setting, with an interplay between emersion and emergence; the emergent periods produced evaporites and pervasive dolomitisation in an inland sabkha, whilst laminated sediments formed during periods of emersion, the lamination being disturbed by the activity of worm-like organisms.

The broad palaeogeography of this period is summarised in fig. 1.6.

CHAPTER TWO

WESTBURY FORMATION: SULLY MEMBER

2.1 INTRODUCTION/DESCRIPTION

This unit is restricted geographically to South Wales and south western England, essentially occurring in the same area as the Grey Marls (see fig. 1.1). The Sully Member is not always easy to define but, in this account, is the topmost few metres of the Grey Marls sequence which contains a Rhaetic, marine fauna, is often extensively bioturbated, is usually calcareous rather than dolomitic, and does not contain evaporites, with the exception of gypsiferous veins which are clearly related to evaporites in the Grey Marls beneath, and are not of primary depositional significance. This definition essentially follows that of Richardson (1911) with some minor modifications.

The Sully Member is most clearly seen on the foreshore of the Somerset coastal sections at Blue Anchor and St. Audries and in the cliffs at Lilstock. The original type-locality of St. Mary's Well Bay (Sully), Glamorgan, famous for the occurrence of the early oyster, "Ostrea bristovi" is now obscured by landslipping. In the Somerset exposures the base of the Member is taken at a slight erosional surface separating darker, gypsiferous dolomitic rocks from lighter, bioturbated, fossiliferous and predominantly calcareous strata. The top of the unit is marked by a strongly erosional contact overlain by the basal vertebrate-bearing breccia of the Westbury Member (see graphic log fig. 2.1). Whilst this upper boundary can usually be readily distinguished the lower boundary is

somewhat arbitrary outside North Somerset, being drawn here between the disappearance of evaporites and the appearance of calcareous rocks with Rhaetic faunas.

The Sully Member consists of grey (usually light to mid grey) commonly calcareous, more rarely dolomitic mudstones and siltstones and silty or argillaceous limestones (a typical lithology is illustrated in plate 2.1). These show a fine lamination which is commonly extensively disturbed by bioturbation. A diverse trace-fossil assemblage occurs in this unit including Diplocraterion, Rhizocorallium, Arenicolites and Siphonites (see plates 2.2-2.5).

Body fossils are normally poorly preserved but include bivalves, gastropods, fish, "amphibian", reptilian, mammalian and plant remains (Dawkins, 1864; Storrie, 1895; Richardson, 1905 b, 1911; Ivimey-Cook, 1974; Warrington, 1976). A list of the biota is given in Table 2.1. The microflora consists of miospores and a marine microplanktonic contribution from acritarchs and dinoflagellates (Warrington, 1971, 1974 b, 1976).

2.2 DISCUSSION

An initial examination of the Sully Member suggests a strong similarity to the Grey Marls; this first appearance is dispelled by closer study which reveals that, whilst the gross lithology is not unlike that of the Grey Marls, the fauna is comparable to that of the overlying Westbury Member. Taken together these features indicate the transitional nature

TABLE 2.1 SULLY MEMBER: BIOTA (After Dawkins, 1864; Storrie, 1895; Richardson, 1905 b, 1911 : Ivimey-Cook, 1962, 1974).

MOLLUSCA

Rhaetavicula contorta (Portlock)

Modiolus hillanoides (Chapnis & Dewalque)

Chlamys valoniensis (Defrance)

"Gervillia" praecursor (Quenstedt)

Eotrapezium cencentricum (Moore)

Protocardia rhaetica (Merian)

Liostrea bristovi (Richardson)

Myacites striato-granulata, Moore

also unidentified gastropods.

Reptilia

Gyrolepis alberti, Agassiz

Acrodus minimus, Agassiz

Sargodon tomicus, Quenstedt

Birgeria acuminata (Agassiz)

Sphaerodus

Palaeosaurus

Trematosaurus

Lepidotus?

also, unidentified fish teeth and scales, coprolites and bone fragments.

Mammalia

"Hypsiprymnopsis rhaeticus" Dawkins.

In addition to the above; wood fragments and microflora (see Warrington, 1971, 1974 b, 1976).

of the Sully Member between the Grey Marls and the Westbury Member. The faunal content, and the varied ichnofossil assemblage, show the earliest signs of a marine influence which is the crucial factor in assigning this unit to the Penarth Group.

The marine transgression in south western Britain responsible for the deposition of these sediments was accompanied by the halt of the development of evaporites and by the ending of extensive dolomitisation. These facts point to a marked reduction in water salinity which allowed the influx of a somewhat restricted marine fauna, amongst which were a number of infaunal, burrowing organisms. The position of this unit, lying transgressively above deposits interpreted as having been laid down by an interplay of subaqueous and emergent processes in a lake-margin sabkha suggests that it was largely deposited in a shallow, subtidal setting. This interpretation is consistent with the ichnofaunal assemblage and with the absence of structures indicating emergence.

2.3 SUMMARY

The long spell of essentially continental sedimentation which prevailed throughout the Permo-Trias was ended in uppermost Triassic times, in south western Britain, by the first signs of a marine influence which led to the deposition of the Sully Member. The general absence of evaporites, the lack of pervasive dolomitisation and the influx of a marine fauna indicate a reduction of salinity. A moderating of climate may also have played a part by lowering evaporation rates. Support for this proposal is given elsewhere in this account and also comes from the absence of concretion (fossil caliche soils) in overbank, fluvial deposits of late Triassic age studied in western Scotland by Steel (1974 a,b).

CHAPTER THREE

THE WESTBURY MEMBER AND LATERAL EQUIVALENTS

3.1 INTRODUCTION

This member combines with the Sully Member (described in the previous chapter) to form the Westbury Formation, which is the older component half of the Penarth Group.

The Westbury Member is equivalent to the "Avicula contorta-shales" (or "Pteria contorta-shales") of the early workers (e.g. Wilson, 1891; Wright, 1860; Moore, 1861). The term "Westbury Beds" was introduced by Richardson (1911); the name being derived from Westbury-on-Severn, where these rocks are well exposed in the, so-called, "Garden Cliff". The Westbury Member, as used here, is a direct equivalent of Richardson's Westbury Beds.

This unit is geographically widespread, occurring throughout the entire Anglo-Welsh outcrop, from the Devonshire coastal exposures west of Lyme Regis, to the mouth of the Tees. Further north it exists as a fragment fortuitously preserved in a Tertiary vent-agglomerate (Peach et al, 1901) and as sporadically exposed remnants beneath the Antrim plateau basalts of Northern Ireland. The Westbury Member has also been encountered, down-dip in a multitude of boreholes.

Normally composed of mainly argillaceous rocks, the member passes laterally into predominantly arenaceous facies in the Bridgend area of South Wales, on the Inner Hebrides in Scotland, and in a series of boreholes on the northern and western flanks of the London Platform. In the Mendips and in parts of South Wales, the lateral equivalent of the Westbury Member is a conglomeratic facies, occurring where the Penarth Group thins against Carboniferous strata and is overlapped by younger, Jurassic rocks. These coarse-grained lithofacies have been designated by local Member names in this account (see Introduction) with the Westbury Formation retained as the overall lithostratigraphic unit. The areal distribution of the members, according to this usage, is illustrated in fig. 3.1.

3.2 WESTBURY MEMBER

3.2.1 INTRODUCTION

This member is by far the most areally important component of the Westbury Formation (see fig. 3.1). It is composed predominantly of dark grey, locally black, silty, carbonaceous shales and mudstones with subordinate thin conglomerates, sandstones, siltstones and limestones (see plate 3.1). It rests either on beds belonging to the Sully Member (in south west England and South Wales) or directly on the underlying Tea Green Marls. This junction is occasionally transitional, with dark shales interbedded with grey green calcareous siltstones (as for example in the Eskdale boreholes, North Yorkshire, Raymond, 1955), but is more normally sharp and erosive. A coarse arenaceous or rudaceous, vertebrate-bearing horizon is often developed at the base, frequently containing clasts of the underlying material (for example at Westbury Garden Cliff, Lavernock, Penarth Cliff, Sedbury Cliff, Aust Cliff, Patchway, Blue Anchor and Culverhole). At

Patchway, Culverhole and in the Stæeple Aston, Blyborough and Thorpe-by-Water boreholes, the contact is burrowed by Diplocraterion-type structures (plate 3.2) and also, at Culverhole, by Thalassinoides. In South Nottinghamshire the basal sandstone fills desiccation cracks in the underlying Tea Green Marls (Kent, 1968; Johnson, 1950).

The Westbury Member can be divided, vertically, into two units based on lithological and faunal characteristics. The Lower Unit comprises mudstones with a moderately high proportion of coarser grained rocks, which are mainly sandstones, commonly rippled or showing flaser/lenticular bedding, and subordinate shelly limestones. This unit is dominated by a vertebrate fauna, with only a few invertebrate, bivalve and gastropod genera, and a high proportion of plant debris. The Upper Unit, on the other hand, has a more diverse fauna, dominated by bivalves but also containing brachiopod, ophiuroid and echinoid representatives. Fish and other vertebrates are of lesser significance. Lithologically, the Upper Unit contains a larger proportion of argillites and the coarser grained sediments are more usually bioclastic limestones with, less commonly, sandstones.

The Lower Unit shows marked lateral thickness variations and it is difficult to correlate its component beds over even short distances (see Fig. 3.2). In contrast the Upper Unit varies much less in thickness and individual beds can be traced over comparatively large distances - a feature noted previously by Richardson (1904).

3.2.2 THE LOWER UNIT

3.2.2.1 Sedimentological Description

A number of representative sections are illustrated in Fig. 3.3. Several

features are readily apparent from these sections:-

1. The marked variation in thickness and discontinuity of individual beds.
2. An overall upward decrease in grain size marked by a general decrease in the number, thickness and grain size of the beds composed of pebble, granule and sand-sized material.
3. An increase in the importance of bioclastic limestones relative to sandstones in the thicker sequences; seen, for example, at Blue Anchor.
4. In some sections, such as Patchway and Aust Cliff, a cyclicity can be seen in the form of small, fining-upwards cycles (typically about 1 m thick) which commence with sandstone or conglomerate and fine through siltstone to silty mudstone. These cycles have been previously described by Hamilton (1962, 1977). Similar cyclicity was seen in the Lavernock, Penarth and St. Mary's sections of South Wales by Ivimey-Cook (1962). However, the present writer could only detect this upward-fining repetition in a few instances at the above localities, where a simple alternation of mudstones with limestones or sandstones, appears to be the general rule.

Sedimentary structures are difficult to detect in the mudstones, although occasionally thin (mm scale) silt laminae are visible and suggest that most of these rocks are horizontally bedded. Because of the lithological homogeneity of the mudstones, the extent of bioturbation is difficult to assess.

Within the interdigitated sandstones flaser, lenticular and ripple drift structures are commonly seen (e.g. plate 3.3).

On bedding-plane surfaces the ripples are invariably symmetrical, with straight or slightly sinuous crests of great lateral continuity and with common Y-shaped crestal bifurcations; all features typical of wave-generated ripples (Reineck and Singh, 1973; de Raaf et al, 1977). Interference ripples formed by two, near-perpendicular oscillatory systems are also common, often forming a complex, "Tadpoles nest" type of pattern (see plate 3.3). Current ripples are rather rare. Cross sections through the ripples exhibit the features (form discordancy, swollen lens-like sets, draping sets, undulating set boundaries, bundled lenses, etc.) described by de Raaf et al (1977) and confirm that the ripples were wave-generated. The sand lenticles are also believed, on the same criteria, to have been wave-generated, in a situation of limited sand supply (Reineck and Wunderlich, 1968). Both the connected and disconnected lens types of Reineck and Wunderlich (1968) have been recognised, reflecting variations in sand supply. Wave ripple crest azimuths are illustrated in fig. 3.4. This shows a large variance in the direction of the prevailing oscillatory regime, superimposed onto which are two principal orientations; one NW-SE, the other NE-SW. These may well correspond to onshore and longshore wave systems. The wide overall variance can be explained in terms of the complex wave patterns generated in a shallow water setting (Reineck and Singh, 1973).

Trace fossils, usually very fine tracks and trails, are preserved on the surfaces of the sandstones, the under surfaces commonly show tool marks and occasionally, gutter casts (plate 3.4) and the internal structure is frequently disturbed by bioturbation.

Microscopic examination of the sandstones reveals quartz, occurring normally as subangular-subrounded grains, to be the dominant component, with lesser amounts of white mica, biotite, plagioclase, alkali feldspars and glauconite. This mineralogy places most of the sandstones in the quartz-arenite pigeonhole of Pettijohn et al's 1973 classification (modified after Dott, 1964). Sorting is very variable from good to poor, this probably being related to the degree of post-depositional reworking. Syntaxial quartz overgrowths are fairly common as an early cement (see Plate 3.5) but most commonly the pore space is obliterated by later sparry calcite and/or pyrite. The carbonate is presumably derived from the dissolution of molluscan shells in the immediately overlying and underlying mudrocks, and within the sandstones themselves. Support for this contention comes from the common preservation of molluscan shells as pyritic casts, a phenomenon which may be caused by the diffusion of Fe^{2+} and SO_4^{2-} to organic-rich regions (for example decaying organisms (Berner, 1971)). Pyrite, when present in the sandstones, commonly shows a replacive relationship to grains and earlier cement (plate 3.6). Pyrite is also present in the mudstones as isolated cubes. It is the stable iron mineral under low Eh and pS^{2-} conditions such as occur in fine grained marine sediments, rich in organic matter, where bacterial sulphate reduction is active. It may also form at or above the sediment/water interface in euxinic marine basins where waters overlying the sediment contain H_2S (as for example in the Black Sea). Iron for pyrite formation is mostly derived from detrital iron minerals which become solubilised in an anaerobic environment by bacterial or inorganic processes (Berner, 1971). Experimental work has shown that it forms via other metastable iron sulphides, such as mackinawite ($\text{Fe}_1 + \text{x}^5$) and greigite (Fe_3S_4) (Berner, 1971).

X-ray Diffraction studies of the mudstones show the mineralogy to be quartz, feldspars and various clay minerals (described in detail in Chapter 7) in addition to pyrite mentioned above. Occasionally molluscan shells are preserved as original aragonite. This preservation of the unstable calcium carbonate polymorph has been suggested to be related to adsorption of amino acids onto the aragonite surface. The amino acid layer prevents access of water to the aragonite (Kennedy and Hall, 1967) and hence only dry inversion of aragonite to calcite is able to take place. This process has been demonstrated to be slow, even by geological standards, taking at least tens of millions of years to reach completion (Bathurst, 1975, p 239).

Limestones, interbedded in the mudrocks of the Lower Unit are of two types: biomic sparrites and biosparrites (using Folk's 1959 classification). The biomic sparrites are poorly sorted and contain a rather chaotic mixture of mud, silt and sand-sized terrigenous material in addition to the carbonate present. The biosparrites consist almost wholly of fragmental shell material with little associated clastic sediment. In both cases the biogenic component is made up of bivalve and gastropod shells with a variable vertebrate content (mainly fish teeth and scales). Both limestone varieties contain current-stable, convex-up bivalve debris.

Features indicative of primary and secondary limestone development are both present. Shell concentration and orientation and the presence of associated coarse-clastic sediment are depositional phenomena, whilst the nodularity of many beds and the common development of cone-in-cone calcite ("beef") on both upper and lower surfaces of the limestone illustrate

the part played by post-depositional concretionary processes (the contrast between depositional and diagenetically-formed limestones is illustrated in plate 3.7). Other interesting diagenetic features are revealed by microscopic study. In many cases the original skeletal structures (for example: prismatic, foliated, cross lamellar) of the bivalve shells are at least partially preserved, usually as pseudo-pleochroic calcite (Hudson, 1962) even though the shell wall may be totally recrystallised (plate 3.8). Very commonly the sparry calcite replacing the shell wall is non-ferroan whereas void-filling spar of ?later date is ferroan. Occasionally the converse is true. The typical matrix material is a completely recrystallised fabric of spar or microspar, the latter probably replacing an original micrite (as in plate 3.8). Occasionally a number of cement generations can be seen. One such example from Blue Anchor, Somerset contains voids fringed with an early ?radial-fibrous calcite cement - a possible replacement of an acicular aragonite or high Mg-calcite, marine rim cement (Kendall and Tucker, 1973) and later partially, or completely, infilled by micrite, with any remaining space being occupied by blocky, ferroan calcite. The iron for the ferroan calcite is probably derived from the clay minerals within the mudstones, in the manner suggested by Oldershaw and Scoffin (1967) for the Halkin and Wenlock limestones.

The abundance of Fe^{2+} is further attested to by the common occurrence of pyrite.

3.2.2.2 Palaeontological Description

The fauna of the Lower Unit is dominated by vertebrates including both terrestrial and marine representatives, with a few species of marine bivalves such as Rhaetavicula Contorta, Eotrapezium concentricum and Pleurophorus elongatus, and small gastropods (see Richardson, 1903 b, 1903 c, 1904, 1905 a, 1905 b, 1905 c, 1906 b, 1909, 1911, 1912, 1929; Ivimey-Cook, 1962). These molluscs occur in large numbers at certain horizons whilst other levels are completely unfossiliferous.

Vertebrates occur throughout the Lower Unit, but are concentrated in a number of 'Bone beds' (described and discussed in Section 3.2.2.2.3).

The vertebrate fauna may be divided into two elements: reptiles and fish.

The reptiles are represented by the vertebrae of ichthyosaurs and plesiosaurs with, more rarely, fragments of their limb bones. In addition there may be possible representatives of terrestrial dinosaurs (Hamilton, 1977). The fish present are elasmobranch sharks (for example the teeth and fin spines of Acrodus and Hybodus), Chondrosteian ganoids (as exemplified by the teeth, and rarely, jaws of Birgeria acuminata, Savage and Large, 1966: the teeth termed 'Sargodon', and 'Gyrolepis' scales, probably belonging to the same fish, Hamilton, 1977) and dipnoans or lungfish (represented by the dental batteries of Ceratodus). In addition to body fossils, fish and reptilian coprolites occur, and possibly phosphatic nodules. Contrary to earlier opinion (e.g. Reynold's, 1946) there are probably no labyrinthodont amphibian remains present (Savage and Large, 1966).

Bone-Beds

The first comprehensive, non-genetic classification of bone-beds has been recently made by Antia (1979) (see fig. 3.5). In this scheme a bone-bed is defined as containing $> 4.5\%$ phosphatic material of which $> 30\%$ is vertebrate material. Most vertebrate-rich beds from the 'Rhaetic' therefore qualify and, in the more detailed classification, fall within the litho bone-bed, pel bone-bed and vertebrate-rich phosphorite categories. In addition, the mudstones of the Lower Unit are also locally sufficiently rich in fish teeth and scales to be termed bone-beds.

Lithologically bone beds in the Lower Unit of the Westbury Member show great variety. They include all the coarse-grained rudaceous, arenaceous and calcareous lithologies described in section 3.2.2.1. This diversity is illustrated in plates 3.9-3.12.

Early workers (for example Jukes-Browne, 1892) believed bone-beds to be the result of a catastrophic mass mortality of fish and reptiles resulting from the saline incursions of the 'Rhaetic' Sea. In 1904 this idea was refuted by three separate authors, each of whom proposed an alternative, formative mechanism. Wickes (1904) suggested they were formed as "submarine guano beds" consisting of the victims of saurians and carnivorous fishes - in other words the debris accumulated in aquatic feeding grounds. He attributed the multiplicity and lateral incontinuity of the bone-beds to the migration of the carnivores and their prey. Short (1904) believed the bone-bed (presumably he was referring to the basal, rudaceous bone bed as occurs at Aust Cliff) was a storm deposit thrown up onto supratidal flats, whilst Richardson (1904) resurrected the theory of Strickland (1858) that this bone bed was a condensed deposit accumulating

over a long period of time during which deposition was either extremely slow, or any sediment was winnowed away by subsequent waves and currents.

This explanation gained widespread acceptance, being cited by Richardson (1929) and Arkell (1933) and later extended to explain all 'Rhaetic' bone beds by Neaverson (1928) and Wills (1929). It went unchallenged until 1968 when Kent pointed out that sequences containing several bone beds (for example Blue Anchor and Lea cutting, Gainsborough) were in fact thicker than average and not, as this hypothesis would predict, thinner. Kent (1968) reverted to the idea of mass mortality, this time however, induced by sudden influxes of fresh water on a local scale. An alternative suggested by Warrington (1974c) is that the vertebrates died as a result of blooms of the motile stages of dinoflagellates.

The basic problem concerning bone-bed genesis in the Penarth Group is that explanations put forward for one particular bone-bed (the principal bone-bearing horizon containing Ceratodus) have later been applied to all the bone beds. However, as stated earlier the great diversity of vertebrate-rich lithologies in the Westbury Member precludes their formation being ascribed to a single process. Antia (1979) concludes (p. 151) that "no single mode of bone-bed formation will suffice".

The fact that the whole of the Lower Unit contains vertebrate fossils is a point worth emphasising. These remains show a strong positive correlation to the grain size of the enclosing sediment. Large bone fragments and coprolites occur only rarely in the mudstones and are concentrated in the coarser grained rocks. In general the largest fragments occur in the

conglomeratic bone-beds. This suggests to the writer that the distribution of vertebrate remains is related to a size sorting dependent on the energy level at the time of deposition. The occasional large fragments in the argillaceous lithologies result from normal vertebrate mortality, whilst in the arenaceous and rudaceous rocks prevailing current and/or wave action is such that fine sediment and fossils are winnowed away, leaving a coarse sediment/vertebrate concentrate. The model proposed here does not, necessarily, depend on large-scale vertebrate mortality. It is, however, possible that a high level of turbulence may induce a certain degree of vertebrate mortality and therefore enhance the vertebrate content of bone-beds. This mechanism can operate in one of two ways; either mixing of water masses or a storm-stranding effect. During storms adjacent relatively warm and cool water masses may mix to produce thick layers of vertebrates over a large area (Antia, 1979, p 111); alternatively they may cause the stranding of nearshore fish shoals in narrow creeks or on tidal flats, as occurs at present near the Elbe and Weser Estuaries in Northern Germany (Mohr, 1952).

There is clearly an element of truth in some of the earlier hypotheses. Short (1904) recognised the high energy level of bone-bed deposition, but his storm-deposit interpretation does not afford the best explanation for the basal bone-bed (of the Bristol area) for which it was intended. This conglomerate is typically laterally impersistent, occupies shallow (up to 30 cm deep) erosional hollows and contains clasts of Tea Green Marl, limestone and round quartz pebbles, (these may well be fish or reptile stomach stones (gastroliths) - see Wickes, 1904; Short, 1904). The fauna is a mixture of terrestrial (dipnoan + ? dinosaur) and marine elements and suggests, along with the lithological characters and position of the

bed, that it is a transgressive strandline deposit from which the finer detritus has been winnowed away (a contention supported by Donovan, 1955; Hamilton, 1962; and Sellwood et al, 1970). This model is probably applicable to all such basal, conglomeratic bone-beds in the Westbury Member, which is not to suggest that they are contemporaneous, but rather that they record an early stage in the drowning of Keuper sabkha and lake environments and were themselves drowned as the transgression proceeded. In a sense they do represent condensed deposits and hence the interpretation of Richardson (1904) is at least partly vindicated.

Higher bone-beds in the sequence are here interpreted as representing turbulent conditions in a mainly tranquil depositional setting. Those conditions may be the result of storms or of reduction of water depth.

The model proposed by Wickes (1904) that bone-beds represent vertebrate concentrations in aquatic feeding grounds does not explain the presence of abundant clastic detritus that occurs in many bone-beds, the majority of which does not possess the features (rounding and polish) typical of gastroliths.

Warrington (1974 c) questions the freshwater influx/mass mortality model of Kent (1968) on the basis that it would be extremely difficult, on the peneplained land areas of the late Triassic, to generate sufficient surface run-off to produce, even locally, disastrous salinity changes. Warrington's alternative dinoflagellate bloom mechanism suffers from the same fault as Wickes' (1904) model in that it does not account for the coarse clastic detritus that accompanies the vertebrate remains, unless the bloom is caused by the increase in turbulence that introduces the detritus. Whilst

support is lent to Warrington's contention by the presence of significant quantities of dinoflagellate cysts in the Lower Unit of the Westbury Member, dinoflagellate remains also occur in both the upper unit of the Westbury Member and in the overlying Cotham Member, neither of which contain bone-beds.

Bone-beds: prefossilisation

It has been suggested that many bone-beds are prefossilised deposits (Reif, 1971, 1974, 1976; Duffin and Gazdzicki, 1977), that is, the vertebrate material has been buried, diagenetically phosphatised (prefossilised) and then exhumed, concentrated and redeposited in a bone-bed (for a good review of prefossilisation see Antia, 1979). Criteria for recognising prefossilised vertebrate remains were suggested by Reif (1969, 1971):-

1. Prefossilised bone has smooth fracture surfaces, fresh recent bone displays fibrous fractures.
2. Recent bone is less dense than quartz, whilst prefossilised bone is as dense, or denser than quartz. Therefore size distributions of quartz and vertebrate fragments would be similar if the bone is prefossilised.
3. Prefossilised bone has polished surfaces.
4. Bone phosphatisation reduces its elasticity and hence fossil bones are less likely to be well rounded.

These criteria were critically examined by Antia (1979) and doubt was cast on their validity:-

1. Fracture patterns observed may be the result of processing of the material. Also no studies of fractures of teeth and scales (the dominant component of many bone-beds) have been made.
2. Unaltered recent vertebrate material may possess the same size distribution as the co-existing quartz grains (Schäfer, 1972) due either to infill of pores by clay or the different hydrodynamic properties of bone and quartz. In fact a number of size analyses of Rhaetic bone-beds show significant differences in the size distribution of vertebrate remains and quartz (fig. 3.6). Typically the vertebrate fragments are coarser grained, a fact which does not support pre-fossilisation. However, before any firm conclusions can be drawn from the study of this parameter the hydrodynamic properties of teeth, scales and bone must be thoroughly examined.
3. Grain polish may be produced by diagenetic mineral coatings (Antia, 1979).
4. Antia (1979) notes that so-called prefossilised teeth from the Muschelkalk Grenz bone-bed of Germany show all abrasive states from rounded to very angular, suggesting that the inherent elasticity has not been markedly affected.

Clearly, as emphasised by Antia (1979), a good deal more work, principally using scanning electron microscopy and size and shape analysis in addition to study of the hydrodynamic behaviour of vertebrate particles, is needed before the arguments for and against prefossilisation can be resolved. This work on British, Penarth Group bone-beds would constitute a whole research project, in its own right, and is therefore clearly beyond the scope of the present study.

Bone-beds: summary

The basal, conglomeratic bone-bed of the Westbury Member is here considered to represent a transgressive, strandline deposit. Higher bone-beds in the sequence are believed, by the present author, to have been produced by a concentration of coarse vertebrate and clastic material during intense wave and current activity, that removed fine grains. This turbulence may have produced vertebrate mortality and hence enhanced the vertebrate content of the bone beds. These relatively high energy levels resulted from either storms or a reduction of water depth.

3.2.2.3 Discussion and Interpretation

The Westbury Member marks the earliest widespread marine invasion of the British Rhaetian. The transgression inundated continental, lacustrine deposits throughout most of England, but was preceded in the south west by the intertidal and shallow subtidal deposits of the Sully Member (see Chapter 2). The relative completeness of the sequence in the south west, and the evidence of an early marine influence in the Sully Member, suggests

that the transgression advanced from this direction. Corroboration for this is also found in that the fullest development of the Lower Unit of the Westbury Member occurs in the Bristol Channel area.

The large thickness variations and the lack of lateral continuity of individual beds suggests that the Lower Unit was deposited in a series of small, isolated basins, the extent and position of which was probably determined by pre-existing topography. The restricted nature of the basins is witnessed by the lack of faunal variety, the fauna being dominated by a few marine and terrestrial vertebrate genera, with associated marine molluscs (bivalves and gastropods) being low in species, although sometimes great in number. Further evidence is provided by the abundance of plant debris. The low-diversity fauna has parallels with the fauna of modern brackish basins (see e.g. Segerstrale, 1957; Heckel, 1972). Stunting was not found by Ivimey-Cook (1962), suggesting, by comparison with the modern Baltic Sea, that salinities were above the 10‰ level (see Segerstrale, 1957). Whilst low-diversity faunas also exist in hypersaline environments, the occurrence of darwinulid ostracods, reported by Anderson (1964), favours hyposaline conditions. Present-day darwinulids being restricted to fresh and brackish-water settings (Benson et al, 1961).

The basal bone-bed of many localities is here interpreted as a transgressive strandline deposit, representing a beach-lag remaining after the process of ravinement (see Swift, 1968) which occurs as the shorezone migrates landwards in response to continuing marine invasion, had caused the removal, through erosion, of much of the nearshore sedimentary record. This interpretation is analogous to that made by Stanley (1969) for

similar basal, vertebrate-bearing rudites from the Pleistocene and the Devonian-Mississippian (Chattanooga Shale) of the United States.

The flaser and lenticular-bedded sandstones which occur in the lower portion of the unit represent alternating sediment transport and settling of fine sediment during slack-water periods (Reineck and Wunderlich, 1968). They contain wave ripples, frequently produced by simultaneous oscillatory systems, of unequal strength, operating at right angles. These ripples are normally produced in shallow water (Reineck and Singh, 1973). On the whole these sediments, and the interbedded shelly bioclastic limestones are reminiscent of sediments of the transition zone (shallow, subtidal) of the German North Sea tidal flats (Reineck and Singh, 1973). The lack of current ripples further suggests that the depositional environment was restricted or that tidal range was small.

An overall upward fining of the sediments can be detected (Fig. 33). This is due to either a progressive increase of depth, to a gradual decrease in supply of coarse detritus, or, more probably, to a combination of both processes. The fining-upwards cycles in the Bristol area may be attributed to increasing water depth, with each new cycle being generated by (? tectonically controlled) shoaling.

The general picture is therefore one of gradual transgression of the Keuper land surface with a progression from strandline → offshore environments in a series of small, semi-isolated, probably brackish basins, that occupied the sites of pre-"Rhaetic" topographic lows.

3.2.3 THE UPPER UNIT

3.2.3.1 Sedimentological Description

The Upper Unit of the Westbury Member differs from the lower in the increased proportion of mudstone relative to sandstone and limestone and in the preponderance of limestones, rather than the sandstones, which typify the lower unit. Apart from the above-mentioned differences and the more marked faunal variation between the two units (described in the following section) there are strong similarities of a petrographical nature. This section will therefore concentrate on the differences between the units: features such as mineralogy, which do not vary between the two, will not be redescribed here.

The Upper Unit (see Fig. 33 for representative sections) is principally composed of dark grey mudstones with a few, thin bioclastic limestones, and more rarely oscillation-rippled or lenticularly-bedded sandstones or siltstones. Two principal limestones occur in the Bristol area, the so-called 'Pecten' beds (see for example Hamilton, 1977) with their characteristic abundance of Chlamys (Pecten) Valoniensis (Defrance). Further north, in Warwickshire, Worcestershire and Lincolnshire only one Pecten bed is present (Richardson, 1903a, 1904; Kent, 1968) whilst in most Nottinghamshire sections and in those in North Yorkshire, no Pecten bed occurs. In these latter sections the monotony of the mudstones is only broken by occasional thin sandstones and siltstones. These often show oscillation ripple form sets, occasionally bearing evidence of two perpendicularly-opposed wave systems (see Plate 3.13).

The limestones may be of two types: biosparrites (composed almost wholly of fragmented bivalve material) or silty biomic sparrites with a significant silt/mud component. The former (see Plates 3.14 and 3.15) may also contain occasional gastropod or fish fragments whilst the latter (Plates 3.16 and 3.17) are fairly often nodular and hence at least partially of diagenetic origin. Both types are commonly bounded by bands of "beef" (cone-in-cone calcite) which are clearly of secondary origin. Skeletal fragments in both limestone types are usually completely recrystallised as sparry calcite with original wall structures being preserved, not infrequently, as pseudo-pleochroic calcite (Hudson, 1962). Pyrite occurs fairly commonly as a replacive medium, sometimes infilling small (? algal) borings.

Oriented bivalves occur on the surfaces of some of the limestones. A long axis orientation plot for specimens of Pleurophorus elongatus from a limestone at Blue Anchor (Plate 3.14) is shown in Fig. 3.7. This exhibits two clear, diametrically-opposed maxima of the type described by Nagle (1967) as being typical of wave-generated alignment. Data from Brenchley and Newall (1970) and Kelling and Williams (1967) shows that such an orientation pattern may also be produced by lower flow regime currents, with fossils lining-up perpendicular to the flow direction. However, the presence of oscillation ripples throughout the Westbury Member, and the almost total lack of current ripples strongly supports a wave-alignment for the bivalves, and implies an oscillatory system operating in a NE-SW direction. This azimuth is consistent with wave-ripple orientations described from the lower unit in section 3.2.2 (see Fig. 3.4).

As in the Lower Unit, sedimentary structures are difficult to pick out in the mudstones, except when lamination is revealed by thin silt bands - a

common feature at certain localities, such as Barnstone in Nottinghamshire.

Whilst the lower boundary of this Unit is fairly sharply delineated, usually by a limestone containing a diverse molluscan fauna, the upper boundary (with the Cotham Member) is of a more variable nature. It is marked in the south west by a sudden lithological break from dark grey, non-calcareous mudstones to light grey calcareous mudstones and siltstones. Further north (at Westbury Garden Cliff and beyond) this lithological distinction is more diffuse with a gradual passage between the Westbury and Cotham Members being displayed both at outcrop and in boreholes (Poole and Whiteman, 1966; Poole, 1969; Ivimey-Cook and Elliot, 1969; Green and Melville, 1956; Poole, 1977; Poole, 1978). The faunal break across the boundary is very often not concordant with the lithology, but rather a typical Westbury Member fauna may extend into the Cotham Member, even when the junction is visually well defined (for example Ivimey-Cook, 1974). These atypical fossils may, however, in certain circumstances at least, be derived (Poole, 1977).

3.2.3.2 Palaeontological Description

In contrast to the Lower Unit the upper possesses a more diverse fauna, principally bivalves, with a few representatives of relatively stenohaline phylla, notably echinoids, ophiuroids and a brachiopod. The vertebrate genera of the Lower Unit are still present, but of greatly reduced numerical importance.

The bivalves include: Rhaetavicula contorta, Portlock; Protocardia rhaetica, Merian; Pleurophorus elongatus, Moore; Chlamys valoniensis, DeFrance; Eotrapezium concentricum, E. ewaldi, Bornemann; Placunopsis alpina, Winkler; Tutcheria cloacina, Quenstedt; Cardinia regularis Terquem, Lyriomorphoria postera, Quenstedt; Atreta intusstriata, Emmrich; Modiolus hillanus, J. Sowerby; Modiolus c.f Langportensis, Richardson and Tutcher; Plagiostoma valoniense, DeFrance; Cercomya sp. and others of lesser import, and more dubious nomenclature. A small number of gastropod genera are also present for example 'Natica' Opelli (Moore), Actaeonina and Chemnitzia. In addition the brachiopod, Orbiculoidea townshendi (Forbes) occurs rarely, the ophiuroid Ophiolepis is widespread, echinoid fragments fairly common and the polymorphinid foraminifera Eoguttulina has been recorded from Lavernock by Ivimey-Cook (1962, 1974). Faunal details may be found in: Ivimey-Cook (1962, 1974, 1975), Green and Melville (1956), Poole and Whiteman (1966), Poole (1969, 1977, 1978), Moore (1861) and the multitudinous works of Richardson (e.g. 1903 a) b) c) d), 1905 a) b), 1906, 1909, 1911, 1912).

3.2.3.3 Discussion and Interpretation

The increased lateral continuity of individual beds and greatly reduced thickness variations indicate a uniformity of depositional conditions which was absent from the Lower Unit. The enhanced faunal diversity also bears witness to a much less restricted environment which, from the presence of echinoids and ophiuroids, must have had salinities approaching those of 'normal' marine waters. The total absence of ammonites and the occurrence of only one brachiopod species does, however, suggest that conditions were perhaps still sufficiently hyposaline to exclude these organisms.

On the other hand salinities were not low enough to induce stunting of the bivalves (Ivimey-Cook 1962, 1974); a phenomenon described from the brackish waters of the Baltic by Segerstrale (1957). Average salinities therefore probably lay within the 20-30‰ "transitional restricted marine" zone of Heckel (1972). Slightly reduced salinity may be attributed to dilution by freshwater run off and rain input in an epicontinental sea at some distance from the open ocean.

The Upper Unit succeeds beds compared to modern transition zone sediments (section 3.2.2.3) in a sequential manner. This position, coupled with its wide lateral uniformity, enhanced faunal variability, the disappearance of terrestrial fossil representatives and the generally finer grain-size (as compared to the Lower Unit) strongly suggests that deposition occurred in a more offshore position than that of the Lower Unit. In fact it may be favourably compared to modern shelf muds described from the Gulf of Gaeta by Reineck and Singh (1971) and off the Elbe Estuary (see Reineck and Singh, 1973). Similar ancient sediments have been interpreted as shelf muds by Brenner and Davies (1973, 1974) from the Oxfordian of the USA and from the British Silurian by Bridges (1976). The bioclastic limestones interbedded with the mudstones of the Upper Unit are here interpreted as storm deposits. The biosparites are comparable to the inferred "storm lag" deposits of Brenner and Davies (1973) whilst the biomicosparites may be "swell lags" formed by occasional intense swells that took shelly mud into suspension and produced concentrates of skeletal material as the shells settled more rapidly than the mud, following the passage of the wave. The fine silt laminations occurring at locations where shelly limestones are absent, are also interpreted as storm deposits, probably representing relatively distal accumulations. In the case of the latter, and of the

presumed "storm-lag" limestones the coarse-grained material is believed to have been transported from nearshore zones by storm-surge ebb - a process shown to be important in bringing sand-sized particles into a mud-dominated setting by Hayes (1967 a), Reineck et al (1967, 1968) and Gadow and Reineck (1969).

The Upper Unit therefore reflects the gradual progression of the 'Rhaetic' transgression with the establishment of more widespread and uniform marine conditions following the infill of original topography by the deposits of the Lower Unit, and accompanied by increasing water depth. The environment was a shallow shelf sea with an interplay of fair-weather and storm processes.

3.3 BRIDGEND MEMBER

3.3.1 INTRODUCTION

Unusually thick sandstones in the Bridgend area were first noticed by De la Beche (1846). The first detailed account of this facies was made by Strahan and Cantrill (1904) following mapping by the Geological Survey. The sandstones were subsequently described by Richardson (1905 b) and the full succession was finally determined, using mapping and borehole records, by Francis (1959).

In general, exposure of these rocks is poor, limited mostly to small disused quarries and stream sections. However, in the late spring and summer of 1979 a unique opportunity to examine the Bridgend Member at

Stormy Down, was made possible by the extension of the M4 Motorway from Pencoed. In excavations made to allow the motorway to be bridged by the A48 at the west end of Stormy Down practically the whole of the lower part of the Penarth Group was exposed. It was possible here, and in the cutting through the Down, to confirm the three-fold subdivision of Francis (1959) consisting of upper and lower sandstones separated by green and brown mudstones. The topmost part of the upper sandstone was not exposed, however, and relations with the underlying Keuper and Carboniferous Limestone were obscured by structural disturbances. A graphic log of the visible section is shown in Fig. 3.8, and the general nature of the exposure is illustrated by Plate 3.18.

3.3.2 THE LOWER SANDSTONE

Beds assigned to the Tea Green or Grey Marl Members are sharply overlain by the Lower Sandstone. This is the most lithologically homogeneous of the three components of the Bridgend Member, consisting of medium-grained, pale grey quartz arenites, with minor quartzitic lithic fragments and degraded feldspars and a small amount of grain-rimming clay matrix. The rock is well indurated with sutured grain contacts, presumably resulting from pressure solution effects, and with syntaxial quartz overgrowths visible in places (Plate 3.19).

Large- and medium-scale cross-lamination is typically present, the sets normally being tabular (Plate 3.20) with only occasional troughs, indicating the migration of mainly straight crested megaripples. Ripples

(probably of wave origin) were seen at a number of horizons, often enhanced by iron staining, and commonly showing two interfering, near perpendicular, ripple sets (Plate 3.21).

Fragments of compressed wood and other plant material are common in the Lower Sandstone, especially towards the top, where individual stem fragments attain lengths of over a metre (Plate 3.22). Animal remains have been recorded from only one locality near Coity (Grid Ref. SS 929, 306) where Eotrapezium sp, Lyriomorphoria postora (Quenstedt) and "Gervillia" praecursor (Quenstedt) were reported by Francis (1959). On this basis the Lower Sandstone was tentatively correlated with either the Sully Member or lowermost Westbury Member (Francis, 1959).

The top of the Lower Sandstone is extensively reworked by Diplocraterion (Plate 3.23) and Skolithos (Plate 3.24) burrows and is overlain by a pebbly deposit, containing fish and saurian remains and plant material, which marks the sudden change into the overlying mudstones (Plate 3.24).

3.3.3 THE INTER-SAND MUDSTONES

As stated above the mudstones sharply overlies the Lower Sandstone (Plate 3.24). The contact with the Upper Sandstone is, however, gradational, and the presence of similar mudrocks within the Upper Sandstone suggests a depositional affinity between these two units which is lacking between the mudstones and the Lower Sandstone.

This unit consists of soft grey/green, blue/green and dark grey silty mudstones interbedded with thin (mm/cm scale) laminated and lenticular bedded, buff-coloured siltstones and fine sandstones (see Plate 3.25). These coarser-grained lithologies become more prevalent and thicker towards the top. In addition two or three dark brown, highly carbonaceous mudstone bands, a few cms in thickness, are present.

The mudstones contain a sparse fauna, mostly bivalves such as Rhaetavicula contorta (Portlock), Chlamys valoniensis (Defrance), Protocardia rhaetica (Merian), Eotrapezium sp; fish remains including Gyrolepis and Saurichthys and the occasional gastropod. Comminuted plant material is abundant, especially in the brown lignitic horizons.

X-ray diffraction studies indicate the principal clay mineral present to be illite.

3.3.4 THE UPPER SANDSTONE

The Upper Sandstone consists of flaggy, buff-coloured fine-grained sandstones interbedded with which are green silty mudstones containing sand or silt lenticles, indistinguishable from the underlying mudstones (Plate 3.26). Cross-lamination is common with small to medium-scale sets, the small-scale cross lamination being wave-generated whilst the medium-sized sets are of probable current origin and locally display bidirectionality.

The fauna is similar to that of the mudstones beneath with perhaps a lesser contribution of fish remains, poorly preserved bivalves and gastropods being common at certain horizons - especially towards the top of the visible section at Stormy Down. The gastropods are species of 'Natica'. With regard to the bivalves, Rhaetavicula, Eotrapezium and Protocardia were seen at Stormy Down. In addition Lima praecursor (Quenstedt), Lyriomorphoria postera (Quenstedt), 'Gervillia' praecursor (Quenstedt) and ?Modiolus have been recorded from other exposures by Francis (1959). In common with the other components of the Bridgend Member, carbonised plant debris is also present.

Petrographically the upper sandstone is finer grained than the lower and at times contains sufficient clayey matrix (? illitic) in the form of grain coatings, to be termed a quartz wacke. A further contrast with the Lower Sandstone is the presence of numerous reddish-brown carbonaceous fragments (Plate 3.27). In general sutured grain contacts and quartz overgrowths are rare (their development probably inhibited by the clay matrix) and consequently the upper sandstones are poorly indurated.

The mudstones and the Upper Sandstone can be correlated, with reasonable certainty, with the upper part of the Westbury Member (Francis, 1959).

3.3.5 DISCUSSION AND INTERPRETATION

The Bridgend Member lies to the north and north west of a well documented island of Carboniferous limestone that was not completely submerged until the Sinemurian (George, 1970). The proximity to land is further indicated

by the abundance of terrestrial plant material. That the Bridgend Member represents deposition in a nearshore environment is therefore clearly established; however, the precise characterisation of the depositional environment is greatly hindered by limited exposure and hence the interpretations made here must be regarded as tentative.

The Lower Sandstone was deposited largely by offshore-orientated unidirectional currents and probably represents accumulation in an ebb-dominated tidal channel. Similar deposits have been described from the Lower Cretaceous of Colorado (Mackenzie, 1975) and from the Late Precambrian of North Norway (Johnson, 1975). The alignment of this sand body parallel to the palaeoshoreline indicates lateral migration of the channel. Comparison can be made with barrier inlet sequences which are a feature of submerging coasts and which may migrate rapidly in the direction of wave approach (Kumar and Sanders, 1974). The absence of bioturbation in the bulk of the lower sandstone suggests that sedimentation was sufficiently rapid to produce conditions hostile to organisms (Tankard and Hobday, 1977). Clearly the intense bioturbation at the top of the unit represents a cessation of sediment movement of sufficient duration to allow extensive colonisation by burrowers.

The marked break at the top of the Lower Sandstone is attributed here to transgression of the barrier; the pebble deposit resting on the upper surface is believed to represent a transgressive lag, comparable to the basal bone-bed of the Westbury Member, an unknown thickness of the Lower Sandstone having been removed. The transgressive nature of the mudstones and Upper Sandstones is indicated by their overlap of the Lower Sandstones to the east of Bridgend (Francis, 1959).

The mudstones are here interpreted, on the basis of their fine-grain size, restricted bivalve fauna and the abundance of plant debris, as lagoonal deposits. The thin, intercalated sandstones being the products of storm induced washovers, or fluvial runoff (Scott, Hoover and McGowen, 1969). Although no rooted plant material was seen, the highly carbonaceous layers within the mudstones may represent back barrier swamp material similar to that described from the Pleistocene of Natal by Hobday and Orme (1974).

The Upper Sandstone follows the mudstones gradationally and may represent a lagoon-margin, tidal-flat sequence. The argillaceous nature of the sandstones supports a back-barrier origin (Klein, 1967). The alternation of sandstones with flaser and lenticular bedded sandstones/mudstones suggests a position low on the tidal flat (sand and mixed flats of Reineck and Singh, 1973).

The overlying argillaceous rocks of the Cotham Member, from the descriptions of Richardson (1905b) and Francis (1959), are similar to the mudstones facies of the Bridgend Member and probably also of lagoonal origin.

3.4 THE GRIBUN MEMBER

3.4.1 INTRODUCTION

This name is proposed for the arenaceous facies of western Scotland which is considered to be equivalent to the Westbury Member elsewhere, on the basis of a bivalve fauna which includes: Rhaetavicula contorta (Portlock), Chlamys Valoniensis (DeFrance), 'Pleurophorus' elongatus, Moore,

Protocardia rhaetica (Merian and 'Gervillia' praecursor (Quenstedt) (Lee and Bailey, 1925; Lee and Pringle, 1931). This unequivocally 'Rhaetic' fauna has only been reported from the Gribun area of Western Mull; other sections of possible contemporaneity exist at Morvern, Ardnamurchan, on the islands of Rhum, Skye and Raasay and at Applecross (see Fig. 3.9). Of these, the Morvern and Rhum outcrops have yielded identifiable fossils, suggesting a 'Rhaetic' or Liassic age for the Morvern strata and a Keuper or 'Rhaetic' age for those on Rhum (Lee and Bailey, 1925; Scott, 1928; Bailey, 1944). At other localities contemporaneity has merely been suggested on lithological grounds (Lowe, 1965; Steel, 1971b). The dangers of this are obvious, especially as the lowermost zones of the Lias (liasicus and planorbis) have not been identified outside Mull and Arran (Oates, 1978). It is possible, in fact, that, at these localities, the Lias (and hence the 'Rhaetic') may extend some distance down into rocks of 'Triassic' aspect (Oates, 1976).

The Gribun Member is sandwiched between a continental New Red Sandstone (Permo-Trias) sequence and a shallow-marine succession of Early Jurassic age. The Permo-Trias has previously been described in detail by Lowe (1965), Steel (1971b) (1974a), (1974b)), Steel, Nicholson and Kalandar (1975) and Steel and Wilson (1975), and the Liassic by MacLennan (1954), Hallam (1959), Oates (1976, 1978) and Amiri-Garroussi (1978).

The Gribun Member is poorly exposed, even at the type locality, where the succession is incomplete and intruded by Tertiary doleritic sills. Streams and short cliff sections are the normal types of exposure, allowing vertical sequences to be examined but offering little opportunity to examine lateral variation.

3.4.2 WESTERN MULL

Four exposures of the Gribun Member were examined in Western Mull, the most extensive of which is the stream section in Allt na Teangaidh, near to Balmeanach Farm (see Fig. 3.10). The remaining outcrops (shown in Fig. 3.9) reveal a comparable lithological sequence (Fig. 3.11). Whilst the sharp change from the underlying Trias can be seen in two of the sections (Allt na Teangaidh and Coireachan Gorma) the junction with the overlying strata of the planorbis zone is never revealed. Following Lowe (1965) the grey-green sandstone exposed at Sloc nam Ban is interpreted as a post-Cretaceous deposit, because of the presence of silicified chalk clasts. Lee and Bailey's (1925) 'Rhaetic' interpretation is clearly erroneous.

The Gribun Member consists basically of grey sandstones (weathering buff) interlayered with which are varying amounts of dark grey siltstone flasers and partings. The complete range is from pure, pale grey fine sandstones to dark grey silty sandstones with a preponderance of siltstone laminae. The bivalve fauna described earlier has been found in all lithologies. Plant remains and occasional fish teeth and scales were also seen. The sandstones are commonly ripple-drift cross-laminated, more rarely wavy bedded or bioturbated. The interlayered silty sandstones are frequently bioturbated, usually by Skolithos and Teichichnus burrows (plate 3.28). The general sequence: ripple-cross bedded sandstone - finely laminated and bioturbated silty sandstone is repeated a number of times up the succession.

Cementation of the quartz arenites and silty quartz arenites of the Gribun Member is almost invariably by poikilotopic (Scholle, 1979) ferroan calcite. The calcite for these large, optically continuous areas of cement is probably derived from dissolution of shell material, at points of grain contact, during compaction. This contention is supported by the increased volume of cement in samples rich in bivalves. Rocks previously described as sandy limestones (e.g. Lee and Bailey, 1925) are in fact highly calcareous sandstones in which the sparry carbonate cement may be of greater volumetric importance than the siliciclastic grains.

In addition to quartz, the rocks of the Gribun Member contain grains of white mica, feldspar (plagioclase, microcline and orthoclase), glauconite, carbonaceous matter, and occasional lithic fragments. The darker silty rocks may also have an appreciable matrix of clay minerals. Whilst the plagioclases are relatively fresh, the alkali feldspars are often extensively sericitised.

Rounding of grains is usually moderately good: grains being normally subangular or subrounded. The degree of roundness has, however, been influenced by the post-depositional development of quartz overgrowths (fairly rare) and grain corrosion by the carbonate cement (rather common). Sorting, in the sandstones, is moderately good and they may thus be described as "mature" in the terminology of Folk (1974). In contrast the underlying Triassic sandstones are typically poorly sorted and the grains subangular. They differ also in the increased content of lithic fragments (usually quartzitic) which removes them from the quartz arenites into the sublitharenites and litharenite pigeonholes.

3.4.3 MORVERN

Two separate exposures in Morvern (see Fig. 3.9) have been tentatively assigned to the 'Rhaetic' by previous authors. A thin (30-35 cm) band of black shale occurring between New Red Sandstone and Broadford Beds (Liassic) at Larachbeg was described by Scott (1928) and Lowe (1965). This yielded plant fragments and a fauna of freshwater bivalves believed by Clark (1969) to be of Rhaeto-Liassic age. The other exposure, described by Lee and Bailey (1925), occurs on the east side of Loch Aline in and above the raised beach scarp. Red conglomerates and conglstones exposed on the fore-shore are overlain in a small stream by about 3 metres of cross bedded, pale grey sandstones and pebbly sandstones, which in turn are overlain by almost white sandy limestones rich in bivalves and plant debris. The lithology and the bivalve fauna are quite distinct from those of western Mull. Lima sp and Ostrea sp, recorded from these beds by Lee and Bailey (1925), and Pleuromya sp found by the present writer, are unknown in the Lower "Rhaetic" and a correlation with the Gribun sections does not therefore seem justified. The fauna is more suggestive of a Lower Liassic age. The lithology of the underlying pebbly sandstones is reminiscent of the upper-most pre-"Rhaetic" beds at Gribun. The evidence currently available, in the present author's opinion, points to the complete (or near complete) absence of the "Rhaetic" from Morvern.

3.4.4 ARDNAMURCHAN

A 1.8 m thick, pale grey sandstone lying between red beds and obvious Liassic limestones and shales was tentatively assigned to the "Rhaetic" by Lowe (1965), having previously been grouped with the Lias by the Survey

(Richey and Thomas, 1930). This outcrop occurs at Rudha a' Mhile (see Fig. 3.9), the section being illustrated in Fig. 3.12. The sandstone described by Lowe is divisible into two portions, the lower of which is a 70 cm thick erosively-based conglomeratic sandstone grading upward into medium grained sandstone, whilst the upper is a grey sandstone, 1.1 m thick, with numerous dark grey silty laminations. This upper portion contains rare indeterminate bivalve fragments and is identical lithologically with the silty sandstones of the Gribun exposures. The lower portion is more akin to the topmost, pre-Rhaetic Trias of Gribun: a correlation supported by the absence of bivalves and the presence of small chalcedonic concretions similar to those occurring in underlying cornstones.

The upper silty sandstone is assigned here to the Gribun Member. This interpretation is, however, made very cautiously, as specimens of Pleuromya sp discovered in the immediately overlying strata were believed to be similar to examples from the bucklandi zone (Richey and Thomas, 1930).

3.4.5 RHUM

Triassic rocks rest unconformably on Torridonian in a small area (about 1 km²) in the north west corner of the island (Fig. 3.9). This small outcrop was originally interpreted (Harker, 1903) as a thrust-transported, allochthonous mass of Durness limestone, "crush-conglomerate" and mylonite. The mistake was rectified by Bailey (1944) who recognised Harker's thrust plane and brecciated Durness limestone as an unconformity on which is developed a Triassic cornstone. The crush-conglomerate and mylonite being

a normal sequence of conglomerates and sandstones with no evidence of shearing.

Access to this part of Rhum is restricted because of a deer research project, and only a cursory examination of these rocks was possible. The Triassic red bed sequence is overlain by a series of pale grey sandstones, grey and grey/green siltstones and dark grey sandy limestones. The sandstones are often coarse and occur as large-scale planar cross-stratified channel fills, especially towards the base. Higher in the succession ripple-drift cross-laminated sandstones, flaser-bedded sandstones and siltstones become more common. Carbonised plant material occurs frequently and the siltstones and silty sandstones are often bioturbated. The overall sequence shows a tendency to fine upwards from erosively-based conglomeratic sandstones → siltstones. The various lithologies are illustrated in Plates 3.29 to 3.31. A close lithological similarity to the Gribun exposures is readily apparent. The fauna of Euestheria minuta, darwinulid ostracods and fish remains is either of Keuper or "Rhaetic" age (Bailey, 1944). Whilst the ornament of the Euestheria suggests a Keuper age, the sediments so closely resemble those of the Western Mull exposures that a "Rhaetic" age seems more plausible (a conclusion also reached by Lowe, 1965; and Steel, 1971b).

3.4.6 SKYE

Possible representatives of passage beds (? Rhaetic) were examined in the Strath district near Heast and Broadford (see Fig. 3.9). In Ob Lusa, Broadford Beds of probable angulata zone age overlie Triassic sandstones

on the west side of the bay. There is no marked non-sequence between the two suggesting that if "Rhaetic" sediments are present they are of New Red Sandstone type.

In the sections at Heast pale grey conglomerates and coarse sandstones (no more than 2 m thick) occur between red beds and liassic limestones and shales. The lithologies resemble basal ?"Rhaetic" strata on Rhum. The few bivalves identified by the Survey (Clough et al, 1910) include 'Ostrea' (now Liostrea) indicating an upper "Rhaetic" or Liassic age. This suggests that the transitional beds between the New Red and Liassic strata (Broadford Beds) generally become younger northwards.

A sequence of conglomerates and sandstones, containing abundant wood fragments, at An Leac (Sound of Soay) was tentatively assigned to the "Rhaetic" by Lowe (1965) and Steel (1971) on the basis of lithological comparison with the sequences of Mull and Rhum.

3.4.7 RAASAY AND APPLECROSS

Strata at Applecross and Raasay (Eyre) were described as ?Rhaetic by Lowe (1965) and Steel (1971) respectively. However, Lee (1920) believed that "the fuller knowledge we have at present of the Liassic basement-beds in this region favours the view that neither at Applecross nor in Raasay is there any recognisable development of the 'Rhaetic'". It therefore appears very doubtful that any representative of the Penarth Group occurs in this area, unless part of the New Red sequence is of this age.

3.4.8 DISCUSSION AND INTERPRETATION

The Gribun Member follows a New Red succession of continental sediments. The various facies of this red bed sequence have been attributed to sedimentation on alluvial fans (mudflows, streamfloods and braided streams), floodplains (high and low sinuosity channels) and in playa lakes. Deposition occurred in fault-bounded basins and showed a general time trend from alluvial fan → floodplain environments. Repetition of this trend being produced by rejuvenation of the fault blocks (Steel, 1971b, 1974 a)). The Gribun Member usually overlies floodplain sediments (Mull and Rhum). However, in central Skye it succeeds alluvial fan deposits (An Leac) and possibly interfingers with braided stream deposits (Heast).

The presence of cornstones (interpreted by Steel, 1974 b) as fossil caliche) and, to a lesser extent, the red colouration of the rocks, strongly supports a semi-arid climatic interpretation for the New Red Sandstone.

The Gribun Member marks the first Mesozoic marine transgression in North West Scotland. Its stratigraphical position, between well documented continental and shallow-marine deposits, indicates a nearshore depositional environment. This contention is supported by the abundance of plant remains. The preservation of land plant fragments at this time, and the change from red to grey colouration, has been taken by Steel (1971b, 1974 a)) as evidence for a change towards a more humid climate. Further credence is lent to this idea, by the upward decrease in the importance of cornstones (Steel, 1971b, 1974 a)).

The sediments of the Gribun Member compare closely to recent lower intertidal flat and shallow subtidal channel deposits of the North Sea. This applies especially to the sequence on Rhum which shows a general upward fining from channel filling cross-bedded sandstones, to sheet-like ripple-drift cross-laminated sandstones and finally interbedded sandstone and siltstone. This is closely analogous to the vertical sequence described by Van Straaten (1954) from the tidal flats of the Wadden Sea in Holland. The cross-bedded channel sandstones being equivalent to subtidal channel deposits which pass upwards into the sands and silty sands of the lower tidal flats; the overall vertical sequence being built up in response to rising sea level. Looking at the more detailed tidal - flat subdivisions of, for example, Evans (1965, 1975) and Reineck (1967, 1975) the ripple-drift cross-laminated sandstones can be closely compared to sediments of the sand flats of the Jade (Reineck, 1967) or the lower sand flats of the Wash (Evans, 1975) whilst the bioturbated, finely interlaminated silty sandstones are practically identical to Evans' lower mud flats or more especially to the Misch (mixed sand-mud) flats described by Reineck. Increased burrowing activity in the more silty lithologies is in keeping with organic activity in recent tidal flats where the finer grained sediments are more extensively bioturbated (Van Straaten, 1954; Reineck and Singh, 1973).

This model would predict that, should the topmost strata of the Gribun Member be exposed (this not being the case at present) they would probably be predominantly argillaceous rocks deposited in mud-flat and possibly supratidal marsh environments.

The possible intertonguing of braided stream and tidal flat deposits in Central Skye (Steel, 1971b) suggests that the marine Gribun Member may be contemporaneous to continental fluviatile sedimentation in the more northerly portion of the area studied.

The overall picture presented here is of a transition from the continental New Red sequence to the more established shallow-marine conditions of the Lower Lias represented by a thin sequence of shallow subtidal and lower intertidal flat deposits. The Liassic Broadford beds were deposited in more stable environments of a more fully marine nature. However, the presence of oolites and corals indicates that shallow-water conditions prevailed (Hallam, 1959; Amiri-Garroussi, 1978).

3.5 THE HAPSFORD MEMBER

3.5.1 DESCRIPTION

This name is proposed for the conglomeratic facies of the Penarth Group exposed on the flanks of the Mendips near Frome, Butcombe and Shepton Mallet (see Fig. 3.13). The type section is at Hapsford Bridge, where a thin, gently dipping conglomeratic "Rhaetic" sequence unconformably overlies steeply inclined Carboniferous limestone (Plate 3.32). The complete succession here contains elements correlatable with the Westbury, Cotham and Langport Members and represents the 'feather-edge' of the Penarth Group thinning rapidly southwards to be overlapped by Inferior Oolite (Moore, 1867; Richardson, 1911; Savage, 1977). Since the Langport Member occurs in its typical pale grey calcilutitic facies the term,

Hapsford Member, is restricted to the conglomerates, which, on petrographical examination can be subdivided into equivalents of the Westbury and Cotham Members. This section deals specifically with the thin sequence equivalent to the Westbury Member.

The exposure at Hapsford Mills (Fig. 3.13, 3.14) consists of conglomerates (e.g. plate 3.32) containing well-rounded and commonly bored pebbles of Carboniferous limestone (Plate 3.34) interbedded with thin bluish-grey clays, resting on a bored and oyster-encrusted surface of Carboniferous limestone. The matrix of the conglomerates is usually calcilutite, now recrystallised to sparry calcite and contains occasional bivalve fragments and fish remains. From the presence of Rhaetavicula contorta (Portlock) and Atreta intusstriata (Emmrich) the lower part of the sequence can be equated with the Westbury Member. The fish fauna includes teeth and scales, of Acrodus and Gyrolepis (Moore, 1867; Richardson, 1911) whilst the thin clays are rich in plant remains.

Similarly well rounded Carboniferous limestone pebbles occur at Butcombe (see Figs. 3.13, 3.14). The Butcombe conglomerates differ in the general scarcity of matrix and in the presence of interbedded calcarenites rather than clays. The pore space between the clasts at Butcombe is usually occupied by sparry calcite (see Plate 3.35). Correlation of at least part of the Butcombe conglomerate with the rocks exposed at Hapsford Mills is indicated by Richardson's finds of Chlamys Valoniensis (Defrance) and Eotrapezium. Higher parts of the Butcombe sequence are lithologically comparable to parts of the Cotham and Langport Members. The main exposed mass of conglomerate at Butcombe displays large-scale cross-bedding

produced by roughly easterly flowing currents. The interbedded calcarenites (biosparrites) are cross-stratified on a small scale.

The lower 1.3 m of the Hapsford Member at Hapsford may be equated with the Westbury Member, whilst over 2.3 m of the Butcombe sequence may be similarly correlated. Clasts in the conglomerates are almost wholly of Carboniferous limestone, are generally well rounded and sorted, and exceed 8 cm in diameter. Graded beds are not uncommon.

A thin (30 cm thick) conglomerate at Shepton Mallet may also be correlated with the Westbury Member (Moore, 1867; Richardson, 1911) whilst fissure-fillings of "Rhaetic" age were identified in the quarry at Bowlish (Richardson, 1911).

3.5.2 DISCUSSION AND INTERPRETATION

The Hapsford Member clearly represents a nearshore equivalent of the Westbury Member. This is demonstrated by the rapid lateral thinning (to zero thickness), the coarse nature of the detritus and especially by the abundance of plant debris in the clays. Further support lies in the fissure fills of the Mendips, which contain some of the earliest mammal remains known. The terrestrial elements of the fissure faunas in the Mendips and south Wales are evidence for the existence of a chain of Carboniferous limestone islands in Late Triassic and early Jurassic times. This is the Mendip Archipelago of Richardson (1903e) or, to use a term which includes the islands of South Wales, the St. David's Archipelago (Ager, 1974).

The mammalian teeth of Haramiya (formerly 'Microlestes') were first discovered by Charles Moore (1867, 1881) from Holwell Quarry near Frome (see Fig. 3.13). The fissure fills at this locality are believed to be submarine "neptunian dykes" containing Rhaetian fossils redeposited in Bajocian times (Robinson, 1957). Other fissures are of Rhaeto-Liassic age (precise dating is virtually impossible) and are also interpreted as submarine infills by Robinson (1957). The same author considers the late Triassic (pre-Rhaetian) deposits to be the fills of terrestrial cave systems. In addition to the mammal teeth and jaws the fissures have also yielded fish, reptile and coniferal plant remains, the latter described by Harris (1957). Because of the difficulty of dating the fissure fills they have not considered in detail here. The interested reader is referred to Kuhne, 1946, 1949; Robinson, 1957; Savage and Waldman, 1966 and Kermack et al, 1973.

The grain size and rounding of the Hapford Member and the large-scale cross-stratification at Butcombe reveal the great extent of reworking undergone by those sediments. The lack of matrix in the Butcombe conglomerates suggests that all fines were winnowed away. The matrix at Hapsford Mills is so much finer grained than the clasts as to suggest that it is the product of a later phase of sedimentation during, considerably less energetic hydrodynamic conditions.

A possible analogy may be drawn with recent beach deposits of the Bay of Fundy (Klein, 1963; Knight and Dalrymple, 1975). Marginal gravels develop here at the high-water mark where they form a thin veneer on wave-cut benches. Composition of the gravels is controlled by the bedrock (hence

at Hapsford Carboniferous Limestone' bedrock is consistent with conglomerates composed of Carboniferous limestone clasts). Wave action winnows away fine sediment, but at high slack-water mud settles from suspension to form a mud matrix in the gravel framework, or a thin veneer over the gravel. This mechanism would explain both the fine grained matrix and the thin interbedded mudstones at Hapsford Mills. However, the thicker mudstones with plant remains are more probably the result of surface runoff. The gravel beaches of the Bay of Fundy are crossed by braided drainage channels generating cross-stratified gravels which may be comparable to the structures observed at Butcombe.

3.6 THE LONDON PLATFORM MARGINS (TWYFORD BEDS)

For completeness, mention is made of an arenaceous/rudaceous facies probably equivalent to all or part of the 'Rhaetic' occurring along the northern and western flanks of the London Platform. This marginal development has recently been mentioned by Donovan et al (1979) and Poole (1979). It has been termed the Twyford Beds and is due to be described in a forthcoming publication (Horton et al, in prepn). Previous mention of sandstones of possible 'Rhaetic' age was made by Kent (1968), the rocks having been drilled through in the Glington (Kent, 1962), Twyford (Kent, 1968) and Noke Hill (Falcon and Kent, 1960) boreholes. The distribution of the Twyford Beds is shown in Fig. 3.15.

A similar sandy facies is also known from the southern North Sea (Kent 1968) which may well represent an offshore extension of the Twyford Beds.

3.7 TRANSITION BETWEEN BASINAL AND MARGINAL FACIES

In a few instances it is possible to examine exposures which reveal the nature of the transition between the marginal facies (Bridgend Member, Twyford Beds, Hapsford Member) and the basinal Westbury Member.

3.7.1 SOUTH WALES

The section in the lane at Treguff near Cowbridge, south Glamorgan (Fig. 3.16) lies, geographically, between the marginal Bridgend Member and exposures of the Westbury Member in the Penarth district, and is litho-logically transitional. This transitionality is expressed in a marked increase in the ratio of arenaceous/argillaceous strata when compared with that of the Westbury Member. The coarser-grained rocks are especially prevalent in the basal part of the sequence.

Previous mention of this exposure has been made by Richardson (1905) and Willey (1966). Supplementing their information with that gleaned by the present author correlation can be made with the Westbury Member of the Penarth district (Fig. 3.16). From this it can readily be seen that the enhanced proportion of sandstone occurs in beds equivalent to the Lower Unit of the Westbury Member. The counterparts of the Upper Unit are reasonably comparable to those elsewhere.

The basal 40 cm of the section consists of carbonaceous grey-green calcareous siltstones and mudstones similar to the inter-sand mudstones of the Bridgend Member and likewise interpreted as lagoonal deposits. These

argillites are overlain by a thin sequence of sandstone passing upwards into lenticular and flaser bedded sandstones and mudstones and capped by a ?channel-filling conglomerate, which may represent tidal-flat deposits (Van Straatan, 1954; Evans, 1965, 1975) in this case belonging to the inshore zone of the barrier, with the conglomerate being a tidal-channel fill. This sequence is interpreted here to have been produced as the barrier migrated shorewards during transgression. The ensuing deposition of lenticular and flaser bedded sandstones and mudstones passing upwards into a more mud-dominated succession is also related to transgression. These beds are comparable to recent transition-zone and shelf-mud facies (Reineck and Singh, 1973; Reineck, 1975) and reflect the drowning of the barrier during the later stages of marine incursion.

The sandstones at Treguff show some interesting cementation features, which appear to be dependent on the quantity of skeletal carbonate present. Where the sandstones are almost devoid of bivalve shells they have tightly packed and sutured grains and are cemented by a combination of quartz and feldspar overgrowths (Plate 3.36). When bivalve material is present, however, the development of overgrowths is of much lesser importance, the rock being cemented by a single generation of sparry ferroan calcite (Plate 3.37). This implies that production of a sparry calcite cement, in this instance, largely predates the development of syntaxial quartz overgrowths.

3.7.2 LONDON PLATFORM MARGINS

Kent (1968) gives borehole information relating to the change from argillaceous to arenaceous sediments on the north and west margins of the

London Platform. The available evidence suggests that the increase in sand content takes place first in the lower "Rhaetic" (Westbury Member equivalents) and as the basin edge is approached, extends to include the whole of the Penarth Group. Thus in the Glington borehole near Peterborough probable Cotham Member is underlain by medium to coarse sandstones with thin dark grey shale intercalations whilst in the Twyford borehole, Buckinghamshire, the entire Penarth Group is probably represented by sandstones (Kent, 1962, 1968).

3.8 SUMMARY

The broad palaeogeography of the Westbury Member and penecontemporaneous lithofacies is shown in Fig. 3.17. The Westbury Member can be divided lithologically and faunally into two units. The lower of these, characterised by a low diversity, vertebrate-dominated fauna and by marked lateral discontinuity, represents deposition in a series of semi-isolated brackish-water basins. The Upper Unit has far greater faunal diversity and more uniform sedimentological characteristics, and is interpreted here as a deeper water and only slightly hyposaline marine deposit, formed largely below normal wave-base. Deposition of the Westbury Member followed the transgression of intertidal sediments and hypersaline lake deposits, in a progressively deepening subtidal environment, subjected to an interplay of storm and fair-weather processes. The basal bone-bearing horizon is believed to have been a transgressive strand-line deposit - a relict of shorezone sediments mostly removed by ravinement that accompanied the marine incursion.

Lateral equivalents to the Westbury Member exist in South Wales (Bridgend Member), the Mendips (Hapsford Member), flanking the northern and western margins of the London Platform (Twyford Beds) and in western Scotland (Gribun Member). These beds represent a variety of nearshore counterparts to the Westbury Member.

The Bridgend Member is interpreted here as a barrier-lagoon complex with preserved tidal-inlet, lagoon-pond and back-barrier tidal-flat sediments. The Hapsford Member formed as a thin veneer of gravel beach sediments covering wave-cut benches of Carboniferous Limestone fringing an archipelago of small islands in the Bristol Channel area. These islands were cloaked in conifers, and supported a fauna of small reptiles and some of the earliest known mammals.

The Twyford Beds are poorly described, and have not been examined by the present author, but they probably represent a nearshore facies comparable to the Bridgend, Hapsford and Gribun Members.

In western Scotland continental sedimentation of Permo-Triassic age was followed by deposition in the subtidal channels and intertidal sand and mixed tidal-flat environments of the Gribun Member. In the more northerly area (Skye, Raasay and Applecross) contemporaneous continental "New Red" facies may have persisted into the Jurassic; precise correlation is hampered by non-diagnostic faunal assemblages.

CHAPTER FOUR

LILSTOCK FORMATION: COTHAM MEMBER

4.1 INTRODUCTION

The term Cotham Member is used as a lithostratigraphic replacement for the earlier Cotham beds, as explained in the general introduction. Cotham being the district of Bristol noted for its "landscape stone" (Cotham Marble) a highly distinctive bed which occurs towards the top of the Cotham Member. The Member can be defined as the series of mainly calcareous siltstones and mudstones located above the dark grey argillites of the Westbury Member and below the off-white, micritic limestones of the Langport Member (or where this Member is absent, the limestones and mudstones of the Lower Lias). Both the lithology and the paucity of fauna aid in making a clear distinction from the over- and underlying strata.

The Cotham Member is a virtually ubiquitous component of the Penarth Group being absent only in western Scotland, in parts of the Mendips and in certain areas on the northern and western periphery of the London Platform. No equivalent beds are known from the Hebridean area, but counterparts exist in the Mendips and, probably, on the fringes of the London Platform. In these latter instances, the probable lithostratigraphic equivalents are portions of the Hapsford Member and the Twyford Beds.

From examination of oil and gas exploration boreholes from the Southern North Sea it would appear, from the available data, that the Cotham Member is also represented there.

4.2 SEDIMENTOLOGY AND MINERALOGY

The Cotham Member comprises a series of calcareous siltstones and mudstones interbedded with siltstones, fine- to medium-grained sandstones and limestones. Representative graphic logs are shown in Fig. 4.1.

The base of the Cotham Member is clearly defined in south west England and south Wales, but further north it grades imperceptibly downwards into the darker, non-calcareous mudstones of the Westbury Member. In these transitional areas the base has normally been taken, by previous workers, at an arbitrary lithological position or has been placed above the highest occurrence of a bivalve fauna typical of the Westbury Member. From an environmental viewpoint the latter course is undesirable as there is a suggestion of faunal reworking (Poole, 1977). In this account the base is defined at the centre of the gradational sequence; that is, at the midpoint of beds of unequivocal association.

The calcareous siltstones and mudstones which form the bulk of Cotham Member are normally grey, pale grey or grey-green in colour, but an extensive development of pale brown, chocolate brown and reddish brown hues occurs in a belt stretching from Oxfordshire through to Yorkshire, and extending eastwards into the North Sea (Poole, 1969; 1978; Kent, 1970 and unpublished IGS and oil company well-logs). The distribution of this brown colouration, which is always confined to the central portion of the member, is shown in Fig. 4.2.

Interlayered with the siltstones and mudstones are thin siltstones and sandstones, ranging from layers no more than a few grains thick, through lenticles, into small-scale cross-laminated units several centimetres in thickness. This fine interbedding imparts a striped appearance to the rocks, which survives because of the general lack of bioturbation (Plate 4.1). The subordinate siltstones and sandstones are frequently rippled, the ripples invariably being symmetrical, oscillation ripples (Plate 4.2). The development of interference patterns is also common and flat-crested ripples, produced by planation during falling stage, immediately prior to emergence (e.g. Tanner, 1960) have been noted on a few occasions (Plate 4.3). Trails are sporadically preserved on the upper and lower surfaces of these beds showing that biogenic activity was not totally absent (Plate 4.2). Small trails and burrows have also been noted near the top of the Cotham Member in the IGS Burton Row, Apley Barn, Withycombe Farm, Thorpe-by-Water and Blyborough boreholes (Poole, 1969, 1978 and unpublished IGS borehole logs).

Calcarenites and sandstones occur most commonly in the Somerset coast (St. Audrie's, Lillstock and Blue Anchor) and the South Wales (St. Mary's, Lavernock and Penarth) sections and are rare elsewhere. The crest trends for oscillation ripples from these localities are shown in Fig. 4.3. These display a wide range of orientations, indicating a great variety of wave approach directions, however, two dominant azimuths do emerge: one aligned north east-south west, the other north west-south east, corresponding to north west-south east and north east-south west directed oscillatory systems respectively. These are comparable with directions recorded from the Westbury Member.

The mudstones of the Cotham Member are usually only slightly calcareous: the presence of both calcite and dolomite being typical. The bulk of the mudstones consist of clay minerals (described in Chapter 7), quartz and feldspars. The interbedded siltstones usually have an enhanced calcite content and display an increase in quartz and feldspars relative to clay minerals (see Fig. 4.4). The increase in carbonate content with grain size can be directly related to the presence of pore-filling sparry calcite and is thus a diagenetic feature governed by porosity and not due to the original deposition of carbonate. X-ray diffraction studies in which the brown mudstones were compared with grey-green argillites at the same localities, and elsewhere, failed to reveal any mineralogical contrast (Fig. 4.5). This colour variation is therefore not linked to any gross mineralogical difference.

A feature commonly seen towards the top of the Cotham Member in south west England and south Wales is the presence of sandy oolitic limestones and oolitic and peloidal limestones. These occur as ripple-marked beds, and, in Somerset and south Wales as the infills of extremely deep (over 1 m) polygonal desiccation cracks (Plates 4.4-4.6). The beds are themselves often penetrated by a network of smaller desiccation polygons (Plate 4.7). The ooids are usually only incipiently developed (superficial ooids) and may be incomplete, suggesting that they formed in low to moderately energetic conditions (cf. Scholle, 1978). The nuclei are usually bivalve shell fragments, peloids or occasionally quartz grains. The presence of bivalve nuclei is interesting as bivalves are extremely rare in the Cotham Member at these localities which implies that the ooids were formed elsewhere and subsequently transported. The only true oolitic limestone (i.e. formed principally from ooids) known to the author occurs near the top of the

member at Culverhole Point, Devon. The nuclei here are mostly bivalve shell fragments, the aragonite of which has been replaced by sparry calcite (Plate 4.8). The morphology of the nuclei is such that most of the ooids are elliptical, although on occasions a secondary ellipticity has resulted from compaction following dissolution of nuclear aragonite.

Two algal limestone horizons occur near the top of the Cotham Member in south west England and south Wales and extend as far north as Gloucestershire. The lower is the "Estheria Bed" of Richardson (1903c) and the higher the well-known Cotham Marble. There are close similarities between the two but they can be clearly demonstrated to occupy different horizons because of the presence of both in such sections as Aust and Sedbury Cliffs.

The distribution of the Cotham Marble is shown in Fig. 4.6. The origin of this limestone has been the subject of great debate; the various processes previously invoked are reviewed by Hamilton (1961). The algal origin proposed by this author is now generally accepted.

The Cotham Marble displays a vertical sequence of zones referred to as "hedge", "tree", "canopy" and "atmosphere" by Hamilton (Plate 4.9). Thin sections reveal a variety of structures (Plate 4.10) which Hamilton compared to structures of algal origin.

Using the discrimination of Rezak (1957) between fossil algae and algal stromatolites, the hedge represents a fossil algal structure whilst the canopy is clearly an algal stromatolite. This variety of structure is entirely consistent with modern algal mats, which may contain a large

number of algal species (e.g. Ginsburg et al, 1954). A common feature of the "canopy" is the development of a basal zone of discrete, vertically-stacked domes (S. H. in the nomenclature of Logan, Rezak and Ginsburg, 1964) overlain by laterally linked hemispheroids (LLH) illustrated in Plate 14. The latter morphology is normally found on protected intertidal mud flats at the present day (Logan et al, 1964; Logan, Hoffman and Gebelein, 1974) whilst the former is produced on more exposed intertidal headlands. This suggests conditions of fluctuating turbulence during the formation of the Cotham Marble. However, overall conditions were probably rather sheltered, as recent algal mats are normally restricted to beaches protected from severe wave action and tidal currents (Kendall and Skipwith, 1968). Remarkably similar, arborescent stromatolites have been described and figured by Hoffman (1975) from the Lower Proterozoic of North-West Territories, Canada.

Associated with the stromatolitic Cotham Marble is a channel-filling, edgewise-breccia known as "Crazy" Cotham Marble (Plate 4.11). The controversy surrounding the origin of Cotham Marble has never extended to "Crazy" Cotham Marble, for which a mechanical mode of formation, by desiccation of exposed sediment, has been accepted since its proposal by Short (1903). The flakes of "Crazy" Cotham Marble frequently show angular terminations suggesting that at least partial induration had occurred prior to their removal. The flakes may also display a weakly-developed algal encrustation.

Richardson's "Estheria Bed", at Westbury Garden Cliff and Wainlode Cliff, displays arborescent algal growths very similar to those of Cotham Marble (Plate 4.12) except that the "canopy" is not usually present. These growths are commonly associated with brecciated and algally-encrusted mud flakes reminiscent of "Crazy" Cotham Marble. The development of this algal limestone at an horizon of localised disturbance has resulted, in places, in the intense deformation of the bed.

Contorted lamination is a common feature throughout the Cotham Member, and is particularly prominent at a number of horizons. This is best illustrated by reference to a number of sections through the thicker developments of the Cotham Member from a number of boreholes in the Midlands (Fig. 4.7). In these sections, widespread deformation occurs near the base and top of the Member. The upper horizon of contorted bedding appears to be extremely persistent geographically, being developed in the majority of sections between Pinhay Bay, near Lyme Regis (Devon) and Blue Hill, Owthorpe (Nottinghamshire), a distance of some 275 km (Fig. 4.8). (The Blue Hill occurrence has been described by Kent, 1970). In the coastal exposures of Devon, Somerset and South Wales it is possible to examine this contorted horizon in detail. The folds are asymmetrical with the axes being consistently aligned in a NE-SW direction. When traced vertically and laterally the folds die out, passing into completely undeformed strata (Plates 4.13-4.15). The upper surface of the contorted horizon is often eroded and the bed is penetrated by extremely deep desiccation cracks which indicate that the deformation took place prior to lithification. In Nottinghamshire outcrops the deformation is preserved within early diagenetic limestone nodules (Plates 4.16 and 4.17).

Sedimentary deformation can result from a number of mechanisms:-

1. True slumping, produced by down-slope gravitational movement.
2. The action of gravity on strata showing a reverse density gradient i.e. denser sediment overlying less dense material, producing, for example, load structures.
3. Shear stress acting on recently deposited water-saturated sediment as a consequence of flow moving over the bed.
4. Liquefaction of sediment, which may be caused by:-
 - a) Water expulsion
 - b) Overloading
 - c) An increase in hydrostatic pressure or a movement of pore water
 - d) Temperature change
 - e) Sudden shock e.g. seismic shock

from: Blatt, Middleton and Murray, 1972; Reineck and Singh, 1973; Williams, 1960; Sanders, 1965; Anketell, Cegla and Dzulynski, 1970.

The deformation in the Cotham Member shows no evidence of any significant lateral movement and therefore cannot be ascribed to slumping, *sensu stricto*.

The style of folding is not consistent with that normally produced by loading and the presence of desiccation cracks only later filled with oolitic material from the overlying bed suggests that deformation preceded burial.

It could be argued that overlying sediment had been eroded prior to the production of mud cracks, but in places a normal (i.e. non-erosional) contact can be seen with the superincumbent sandy oolitic material suggesting that deformation took place below the sediment/water interface, and was not

produced by intra-stratal flow (Williams, 1960). Folding clearly took place, after the deposition of the entire bed and is therefore not the result of deformation concomitant with deposition (e.g. Sanders, 1960).

Having rejected the above mechanisms only deformation as a result of liquefaction remains. Of the several causes of liquefaction, most can be ruled out on the grounds that they would be extremely unlikely to produce contortion penecontemporaneously over such a wide area. The only viable method for producing such widespread deformation would appear to be seismic shock, probably resulting from fault movement or halokinetic activity. Indeed, an earthquake mechanism has been invoked to explain the contorted horizons encountered in IGS boreholes (Poole, 1969; 1977, 1978; Poole and Whiteman, 1966). This interpretation is supported by the knowledge that early Cimmerian movements (of Rhaetian age) are well known, especially from hydrocarbon exploration in the southern North Sea (see e.g. Kent, 1975a), b); W. Ziegler, 1975; P. Ziegler, 1975). These fault movements resulted from the tensional stress regime which was responsible for the horst-graben system that controlled Triassic sedimentation (Audley-Charles, 1970a), b); Steel, 1971a), b); Steel and Wilson, 1975; McQuillin and Binns, 1973), and continued to exert an influence throughout the Jurassic (Sellwood and Jenkyns, 1975; Whittaker, 1975). This extensional tectonic regime may be related to the opening of the North Atlantic (Hallam, 1971; Hallam and Sellwood, 1976) and is known to be associated with the development of salt diapirs (Kent, 1975).

The consistent orientation of the synsedimentary fold axes throughout south west England and south Wales (Fig. 49) is problematical. It may be related to the propagation direction of the seismic impulse or to slight

gravitational movement down the palaeoslope at the moment of liquefaction. The latter hypothesis seems implausible as it would require a remarkably uniform palaeoslope. Alternatively the directionality may have been produced by the propagation of a water wave (seiche), that formed as a result of seismic activity (see for example: Gutenberg and Richter, 1954; Richter, 1958; Bullen, 1963; Bath, 1973) or may merely reflect the direction of water movement at the moment of liquefaction.

The widespread occurrence of contorted horizons could have important repercussions on regional correlation. If the well-developed horizon stretching from Devon to Nottinghamshire was, in fact, produced by a single seismic impulse and was thus contemporaneous, it would imply that deposition of the Cotham Member as a whole was penecontemporaneous, over a distance of at least 275 km.

4.3 FAUNA AND FLORA

The Cotham Member has a particularly sparse fauna when compared to under and overlying units. The bivalve assemblage of the Upper Westbury Member continues to occur in transitional beds between the Westbury and Cotham Members but is usually absent at higher levels unless derived from below (Poole, 1977).

The typical Cotham Member fauna consists of the conchostracan branchiopod Euestheria minuta with ostracods, and fish teeth and scales. Anderson (1964) identified the following ostracods:-

Darwinula liassica Jones, D. major Jones, Hungarella moorei (Jones), H. bristolensis Anderson, Cytherella plattensis Anderson, Pontocypris grandis Anderson, P. richardsoni Anderson, Eocythereis vertebrale Anderson, Allocythereis combrookensis Anderson, Klinglerrella sp. and Metacytheropteron sp. Palaeoecologically the Darwinulids are important as they are believed to be restricted to brackish and freshwater habitats. The other ostracods noted above belong to cosmopolitan groups and therefore cannot be used as environmental indicators (Benson et al, 1961).

Euestheria is normally considered to have inhabited brackish or freshwater environments (e.g. Lomas, 1905; Kobayashi, 1954; Thompson, 1966; Heckel, 1972). However, the eggs of conchostracans can withstand lengthy periods (3 to 5 years) of desiccation (Tasch, 1969; Kobayashi, 1954); modern examples commonly live in small, temporary pools of neutral or mildly alkaline pH (Tasch, 1969; Tasch and Zimmerman, 1961). Therefore although conchostracans live in fresh or brackish waters they can survive major fluctuations of wetting and salinity.

Fish remains in the Cotham Member include representatives of Lower "Rhaetic" genera such as Gyrolepis and Saurichthys; but more usually occur as unidentifiable fragments (e.g. Richardson, 1905; Wilson, 1891; Short, 1904; Wickes, 1900; Kellaway, 1937).

The Cotham Member is well known for the presence of liverwort Naiadita lanceolata which occurs in the "Naiadita-bed". This extends for some 144 kilometres (90 miles) of outcrop, from Somerset to south Worcestershire and Warwickshire (Harris, 1938). Harris considers Naiadita to have been

an aquatic plant living in the waters of fresh or brackish lakes. Interestingly, adjacent strata in the Bristol area contain fish remains, darwinulids and brachiopods associated with a number of marine molluscs such as Eotrapezium, Protocardia, Atreta and Chlamys (Wilson, 1891; Short, 1904; Kellaway and Oakley, 1933) suggesting an interplay of marine and brackish conditions. Harris also notes the presence of the thalloid liverwort Hepaticites and the algae Botryococcus and Stenixys in the "Naiadita" bed.

The majority of the above biota suggests brackish or freshwater conditions. However, palynological studies reveal, in addition to terrestrial miospores, and plant tissues, the presence of a marine microplankton assemblage consisting of dinoflagellate cysts (e.g. Rhaetogonyaulax rhaetica (Sarjeant), Dapcodinium priscum Evitt and Suessia swabiana Morbey), acritarchs, tasmanitids and the tectinous test-linings of foraminifera (Chaloner, 1962, 1969; Fisher, 1972 a, b; Geiger and Hopping, 1968; Morbey, 1975; Orbell, 1971, 1973; Warrington, 1974 b, 1977 a, b, 1978 a; Warrington and Harland, 1975). The microplanktonic component is analagous to that of the Westbury Formation and has led Warrington (1977 a, b, 1978 a) to point out that there was at least a marine influence in the Cotham Member in contrast to earlier interpretations (e.g. Kent, 1970) which favoured a lacustrine origin.

4.4 DISCUSSION

The bulk of the fauna and flora contained within the Cotham Member is considered to have inhabited a fresh- or brackish-water habitat. This has

led to a general tendency to interpret the Cotham Member as a lacustrine accumulation (e.g. Kent, 1970). However, the presence of a marine microplankton assemblage and of sporadic finds of marine bivalves necessitates a modification of this viewpoint. The mixture of marine, and brackish or freshwater forms leads logically to the conclusion that the environment was, in the broadest sense, lagoonal. The fact that all the ripples observed by the author from the Cotham Member are symmetrical suggests that tidal-current influence was small. The overall sparsity of the fauna indicates salinities markedly above or below those of the open sea: the fauna and flora suggest that hyposaline conditions were prevalent. This is further supported by the absence of evaporites which would be expected to occur in conjunction with desiccation features (well known in the Cotham Member) were the waters hypersaline.

The marine connection to this lagoonal complex is believed to have lain to the south or south west. This conclusion is based on the occasional reports of marine bivalves in the Bristol area (e.g. Short, 1904; Tutchter, 1908; Kellaway and Oakley, 1933), and on the occurrence of ooids nucleated on bivalve fragments, which occur around the Bristol Channel. These ooids may well have been derived from further south, in the east Devon area, where thin oolitic limestones are developed. Although an isolated piece of evidence, this does suggest that the sea lay somewhere in the direction of the English Channel or Western Approaches, an interpretation consistent with the lack of any marine forms (other than microplankton) further to the north. Conditions in more northerly areas (north Midlands, Lincolnshire, Humberside, Yorkshire, Cleveland and Cheshire) may have been more lacustrine than lagoonal.

An emergent area in the south is demonstrated by the presence of desiccation features (shrinkage cracks, capped-off wave ripples, edgewise breccias). This area is illustrated in Fig. 4.10. Prolonged exposure is indicated in the western periphery of this region by the occurrence of very deep desiccation cracks. These desiccation features occur at more or less the same horizon and suggest that if the marine area did in fact lie to the south or south west, then it would seem probable that the more northerly area was almost completely cut off from the sea at this time.

The alternation of siltstone or fine sandstone with mudstone, which is typical of the Cotham Member, is attributed to an interplay of quiet and turbulent conditions. Water depth must have been sufficiently low to allow frequent agitation of the bottom waters by waves. In modern lagoons laminated sediments are preserved when salinities are such that organisms are sparse, or in areas near river mouths where the sedimentation rate is sufficiently high to prevent extensive bioturbation (Rusnak, 1960; Shephard and Moore, 1960). Oolites are most highly developed on the tidal deltas of recent lagoons, which occur adjacent to open marine waters (Evans and Bush, 1969; Wagner and Van der Togt, 1973; Purser and Evans, 1973; Loreau and Purser, 1973). Their presence in the Cotham Member of south west England and south Wales therefore lends further support for a marine connection in this direction. Glauconite also occurs occasionally in the south west and, like oolites, is normally found adjacent to inlets in recent lagoons (Shephard and Moore, 1960).

The Cotham Member exhibits a tendency for conditions to revert towards those of the Keuper. It is clearly the product of a regression which gradually brought about a changeover from marine to brackish lagoonal environments. Occasional incursions of the sea are indicated in the south west of Britain but conditions further north were of a more continental nature.

The development of a zone of brown colouration in that direction suggests oxidising pore-water conditions (Walker, 1967) which implies a low rate of organic input or high bacterial degradation of organic matter. Oolites and marine bivalves towards the top of the Member in the south, and more extensive bioturbation at this level further north, suggests that a return to marine conditions was beginning by the close of Cotham Member deposition.

4.5 LATERALLY EQUIVALENT FACIES

Lateral counterparts to the Cotham Member are known only from the Mendips and the margins of the London Platform.

4.5.1 THE MENDIPS

In the Mendips at Hapsford Bridge and Butcombe, part of the Hapsford Member can be correlated with the Cotham Member (see Fig. 3.14). This portion consists of thin representatives of typical Cotham Member silty micrites, interbedded with greater thicknesses of calcarenites and calcirudites. The whole attains a maximum thickness of 2.6 m. The

rudites are composed of rounded Carboniferous limestone clasts, usually not exceeding 5 cm in diameter, set in a calcarenitic matrix. Various types of Carboniferous limestone are present, for example, oosparrite, bivalve/foraminiferal biosparrite and crinoidal biosparrite (see plates 4.18, 4.19). The matrix contains ooids, micrite-enveloped grains, bivalve fragments, ostracods, quartz silt and occasionally small grains of Carboniferous limestone (plates 4.20, 4.21). Cementation has mostly been achieved by sparry ferroan calcite, sometimes as large, zoned crystals with usually no more than an incipiently---developed earlier rim cement (Plate 4.22). Iron-rich and iron-poor zones in optically continuous cement crystals implies that sudden changes in pore-fluid chemistry took place during cementation.

Limestones consisting of sand-sized material are developed as thin, ripple cross-laminated beds of oo-biomicrite incorporating ooids, fish fragments, bivalve fragments, quartz-silt grains and elongate allochems with a thin micritic rim and sparry calcite core. These are probably bivalve fragments from which the aragonite has been leached and replaced by calcite. The micrite rims may be incipient oolitic coatings or micrite envelopes. The development of micrite rims around polycrystalline quartz grains suggests an ooidal origin. The preservation of bivalve fragments as sparry calcite casts implies that dissolution of aragonite and infill with sparry cement preceded significant compaction.

A typical vertical sequence from rudites with an oobiosparrite matrix through oobiomicrites to micrites was observed. This is interpreted as representing a gradual decrease in turbulence with a concomitant increase in the deposition of carbonate mud. This fining-upward sequence is repeated several times.

The occurrence of coarse lithic fragments of Carboniferous limestone, with ooids and skeletal debris are indicative of turbulent, shallow-water conditions. Modern oolite shoals in the Persian Gulf and Great Bahama Bank occur in extremely shallow agitated water (see e.g. Evans and Bush, 1969; Loreau and Purser, 1973; Newall et al, 1960; Bathurst, 1975). The optimum depth appears to be less than 2 m. Support for a nearshore depositional environment is also given by locally abundant terrestrial plant debris (Richardson, 1911) and by the wedging out of the 'Rhaetic' deposits against Carboniferous limestone, with overstep by the Inferior Oolite.

4.5.2 THE LONDON PLATFORM MARGIN

A number of boreholes drilled on the north and west flanks of the London Platform have penetrated a series of sandstones, conglomerate and breccia deposits of equivocal age. The evidence from these wells indicates that the whole or part of the Penarth Group is probably represented (Kent, 1968; Falcon and Kent, 1960; Donovan et al, 1979; Poole, 1979). This coarse-grained facies, termed the Twyford Beds (Poole, 1979; Horton et al, in prep) can probably be correlated in part with the Cotham Member. From its position and relatively large grain size this facies is probably a near-shore or fluviatile counterpart of the Cotham Member.

4.6 SUMMARY

The Cotham Member represents a broadly regressional phase following the transgressive events responsible for the deposition of the Westbury Member. Open marine environments were gradually replaced by depositional environments which are interpreted here as a lagoonal complex. All the available evidence points to a sole marine connection lying somewhere in the English Channel or Western Approaches area. In south western Britain the regressive pattern was interrupted a number of times by brief marine incursions, whilst further to the north continental influences on sedimentation became more dominant.

The point of maximum regression is marked by the extensive occurrence of desiccation features, normally found just below the top of the unit, indicating the emergence of a large area. The conclusion of Cotham Member deposition shows widespread signs of returning marine influences heralding the onset of true marine conditions in the Langport Member and Lower Lias.

The Cotham Member is therefore taken to represent predominantly distal lagoonal facies, nearshore equivalents of which exist in the Mendips and (probably) on the periphery of the London Platform (see Fig. 4.11).

The widespread development of contorted lamination in the Cotham Member is believed to have been produced by seismic shock - probably related to early Cimmerian fault movements and halokinetic activity and suggests that deposition of the Cotham Member throughout much of Britain was penecontemporaneous.

CHAPTER 5

LILSTOCK FORMATION: LANGPORT AND WATCHET MEMBERS

5.1 INTRODUCTION

The Upper 'Rhaetic', Lilstock Formation can be subdivided into three Members: Cotham, Langport and Watchet. The former was described and interpreted in the previous chapter, the Langport and Watchet Members will be dealt with here.

These two members correspond in name to Richardson's (1911) Langport Beds (or White Lias) and Watchet Beds, but the modified definition of the Watchet Beds of Whittaker (1978) is followed here.

The Langport Member occurs in a belt stretching from south and south west England to the north west flank of the London Platform in the manner depicted in Fig. 5.1. The Watchet Member has an extremely limited geographical extent (Fig. 5.2), occurring above a thin development of White Lias in north Somerset and South Wales, and is interpreted here as the counterpart of the Upper Langport Member of the thicker sequences to the east and south. It is, however, conceivable that the present spatial restriction is the result of post-Rhaetian erosion, as the White Lias is frequently capped by an erosional discontinuity (observations of the present author, and Poole, 1969, 1977, 1978,) Green and Welch, 1965, plus unpublished IGS borehole logs).

It has recently been suggested (Poole, 1979) that the Langport and Watchet Members can be correlated with part of the Pre-planorbis beds of northerly exposures (Nottinghamshire, Lincolnshire, Yorkshire, Cheshire). The evidence is, however, rather equivocal; it is discussed in greater depth in the chapter nine.

The Langport Member has sharply-defined upper and lower boundaries, being a highly distinctive lithological unit contrasting strongly with the Cotham Member below and Watchet Member or Lower Lias above. The upper limit, as stated earlier, is often delineated by an erosion surface, especially in areas marginal to the London Platform, where the lowermost zones of the Lias are missing, with the result that beds of the angulata-zone rest directly on White Lias (Donovan et al, 1979; Poole, 1969; 1977; 1978). The calcareous silts and mudstones of the Watchet Member are readily distinguished from the superincumbent Liassic 'paper shales' by their lack of lamination and fissility. The removal of typically fissile Liassic shales from the Watchet Beds (sensu Richardson 1911) of the north Somerset coast, by Whittaker (1978) has led to the ironic situation whereby only a maximum of 0.2-0.3 m of Watchet Member occurs at Richardson's type locality, whilst a directly comparable sequence attaining 2.15 m is developed in South Wales. Most of the original Watchet Beds are now assigned to the Aldergrove Beds of C.P. Palmer (1972).

5.2 LANGPORT MEMBER (WHITE LIAS)

5.2.1 SEDIMENTOLOGY AND MINERALOGY

The Langport Member is a highly distinctive limestone unit (Plate 5.1) consisting mainly of a series of very pale grey, cream-weathering calcilutites, interbedded with which are bioclastic calcarenites, calcirudites and thin beds and partings of darker grey calcareous siltstone and mudstone (Fig. 5.3).

White Lias limestones are typically very pure non-ferroan calcite rocks; Hallam (1960a) quotes acid-insoluble residues of only 2-4% from Pinhay Bay, Devon. Terrigenous clastic input in the Langport Member, which comprises quartz, feldspars and white mica, is only an important contributor to the sediment in the South Wales/north Somerset area, where it forms a significant proportion of the arenaceous fraction.

On weathered surfaces the calcilutites frequently display a fine lamination, on occasion they show small-scale cross stratification. The interbedded calcarenites occur either as continuous thin beds, attaining a maximum thickness of about 10 cm (Plate 5.2) or as discrete lenses of bioclastic material. They commonly fine upwards from an irregular, locally erosive base grading from bioclastic calcarenites → micrite reflecting a progressive decline in depositional turbulence.

When examined microscopically the calcilutites are seen to consist of an interlocking mosaic of carbonate, which staining with alizarin red-S reveals to be non-ferroan calcite. The individual calcite crystals have a diameter averaging 5μ . This microspar fabric (Bathurst, 1975, p 566) illustrated in Plate 5.3, is probably the result of a neomorphic alteration of an original micrite. The calcarenites are biosparrites and biomicrites containing fragments of bivalves, echinoderms, gastropods, ostracods, foraminifera, with peloids and rarely, ooids. In the fining upwards units described earlier the matrix grades from spar microspar. Bivalve fragments are normally preserved as infilled moulds presumably after leaching of original aragonite. In some instances the shell structure is preserved intact, probably because the original material was calcitic, (the majority of calcite shells probably belong to the oyster Liostrea hisingeri). The filling of bivalve moulds shows an interesting variety; in some cases the void has a fringing isopachous calcite cement (non-ferroan) with the remaining space being occupied by microspar (Plate 5.4) or sparry ferroan calcite. Alternatively the rim cement is pyrite with a later spar-fill (Plate 5.5) or the rim cement is absent and the cast consists of blocky ferroan calcite with or without the later addition of replacive pyrite (Plate 5.6).

A further diagenetic feature is the development of syntaxial calcite overgrowths on allochems. These overgrowths consist of clear, relatively inclusion-free, non-ferroan calcite and are frequently developed on echinoderm fragments (Plate 5.7) and more rarely on bivalve material (Plate 5.8). Their textural relationship to ferroan spar (Plate 5.9) demonstrates that they predate this cement and are therefore a comparatively

early diagenetic feature. Later ferroan spar commonly continued to develop in optical continuity with the non-ferroan overgrowths (Plate 5.9). The following diagenetic sequence, applicable to the Langport Member of South Wales, was ascertained:-

1. Dissolution of aragonite producing voids
2. Peripheries of voids fringed by carbonate/pyrite cement approximately synchronous with overgrowths on echinoid and bivalve fragments.
3. Remaining voids infilled with blocky ferroan calcite.

Liostrea shells, which were originally calcitic are preserved virtually intact with detailed internal shell-structure still readily discernible.

Close comparisons may be drawn between this diagenetic sequence and that suggested for Oxford Clay ammonites by Hudson and Palframan (1969, fig. 2, p 406).

The presence of ooids in the Langport Member of South Wales is not uncommon. They are typically nucleated on darkened micritic grains (Plate 5.10) and occur in thin (centimetre-scale) calcarenite beds, interbedded with the more prevalent micrites. The relative scarcity of ooids in this Member suggests that they may have been derived from the underlying Cotham Member, in which they are relatively common (see previous chapter).

Rubbly beds form an important part of the White Lias succession in the east Devon coastal exposures. They consist of small, mostly subangular calcilutite 'pebbles' (1-5 cm in diameter) sitting in a calcilutitic matrix (see Plate 5.1). Hallam (1960a) describes thin beds of rubbly rock

in which pebbles are spread out as layers, in addition to a c. 1 metre thick bed with scattered pebbles. He terms both types "intraformational conglomerates". It is, however, the present author's contention that within this grouping are two types of rubbly bed whose structure has originated by two quite distinct processes. One group, including the thick bed mentioned above, are true intraformational conglomerates whose texture results from the erosion of semi-lithified sediment and its subsequent redeposition. This type of bed is comparatively rare in the Langport Member as a whole. Outside the Devon coastal exposures the author has only observed undoubtedly genuine, depositional calcirudites at 179.15 m depth in the IGS Withycombe Farm borehole. The great majority of rubbly beds are here interpreted as having resulted largely from the effects of pressure solution. They bear a striking resemblance to the flaser structure and solution seams described by Garrison and Kennedy (1977) from the English Chalk and attributed by those authors to late diagenetic mechanical compaction and pressure dissolution of calcium carbonate. The resultant structures appear to be fairly closely controlled by the original lithology, and in particular by the amount of terrigenous argillaceous material. A gradation from marly limestone → pure limestone produces a sequence from scattered small bodies of limestone surrounded by composite clay seams → numerous small elliptical limestone bodies with fairly simply clay seams → large limestone bodies with widely-spread solution seams (Plate 5.11). The purest limestones seem to lack these sub-horizontal solution seams, but are commonly traversed by intricately-fretted vertical, or steeply-inclined stylolites. Garrison and Kennedy concluded that solution seams in the Chalk resulted from a more diffuse solution than that occurring in true stylolites. They attributed this to the relatively unconsolidated nature of the sediment, true stylolites only

occurring in completely lithified limestone. On this basis the stylolites can be inferred to post-date solution seams (except where they are developed in early-lithified sediment).

Returning to the depositional calcirudites of the Devon coastal exposures, the beds comprising clasts supported by a micritic matrix are most interesting. They are interpreted here, on account of their matrix support and wavy internal bedding (see Plate 5.1), as carbonate debris flows.

Contorted bedding is a prominent sedimentary structure in the White Lias on the Devon coast. In contrast, however, to the underlying Cotham Member the convolutions are not geographically widespread but are restricted to the Culverhole, Charton and Pinhay Bay exposures. The most striking example of disturbed bedding occurs in a 1.4 m thick bed at Pinhay Bay and was described by Hallam (1960a). This horizon is intensely deformed both by folding and plastic fracturing with a conglomeratic basal unit, 15 cm thick, separating it from undeformed strata beneath (see Plate 5.12). It appears to be a true slump bed that overrode a relatively well-lithified sediment which behaved in a brittle manner. Hallam attributed it to earthquake-activated slumping down a gently-inclined slope (possibly no greater than 1°). The nature of the deformation implies that the sediment was partially indurated. The intriguing question posed by this phenomenon, and one not considered by Hallam because of the restricted area of his study, is that, when viewed in a regional context, why is this disturbance so localised? This is especially difficult since deformation on a smaller scale in the Cotham Member can be traced laterally over at least 275 km. A possible explanation may be that the east Devon area lay near the edge of the shelf on which the Langport Member was

deposited and that slumping occurred only in this platform-margin position and not in the more central portions (see for example the various models in Wilson, 1975). Support for an unstable setting in this area is afforded by the presence of the calcirudite beds earlier interpreted as carbonate debris flows. A test for this hypothesis would be the examination of similarly-aged material from further south in the English Channel. The only possible source of information in this crucial area lies in a British Gas/BP exploration well (98/22-2) details of which are at present unavailable, due to their highly confidential nature.

Hallam (1960a) describes desiccation cracks from the topmost "Sun Bed" of the White Lias at Pinhay Bay, Devon. However, a lengthy search of the foreshore by the present author failed to locate these features; it may be that reddened, vertical joint surfaces were mistakenly identified by Hallam. The present author has, however, recognised mudcracks from the White Lias at Lillstock, Somerset (Plate 5.13).

5.2.2 BIOGENIC STRUCTURES AND EARLY LITHIFICATION

Bioturbation is a common feature in the Langport Member ranging from general biogenic mottling of the sediment to distinguishable burrows and borings, the latter indicate that lithification, in some instances, was very early. A hardground is most frequently associated with the top surface of the White Lias, especially where the overlying strata are disconformable. Early lithification has never previously been described from the White Lias, except in passing (e.g. Green and Welch, 1965) and

whilst Richardson (1906b) mentions "borings" and encrusting oysters, the term "hardground" has never been used in connection with these beds. The earlier literature is also somewhat misleading in that "boring" and "burrow" are used synonymously; the distinction between structures excavated in soft sediment and consolidated rock is not brought out. In this account the term "boring" is only used in the context of a tube drilled in lithified material.

Burrow-mottling is a practically ubiquitous structure in the Langport Member (see e.g. Plate 5.14) seemingly occurring whenever the sedimentation rate was low, and frequently reworking of beds, interpreted as having been rapidly deposited, has taken place. Identifiable soft-sediment excavations include representatives of the ichnogenera Diplocraterion, Thalassinoides, Spongeliomorpha and Chondrites (Plates 5.15-5.17) (Häntzschel, 1975).

Another burrow type encountered (Plate 5.18), for which the present author can find no previous description, consists of steeply inclined (about 50° to the horizontal) circular tubes 1-1.5 cm in diameter penetrating to a maximum observed depth of 8 cm, with the tube gradually narrowing and attaining the horizontal. In detail the sides of the burrows show fine striations parallel to the walls, which may be crustacean scratch-marks (T. J. Palmer, pers. comm. 1979). The infill of these burrows is highly variable, being sometimes a soft, grey, marly material (removed from the example illustrated in Plate 5.18) but in other cases is well lithified, pale-grey calcilutite identical to the surrounding matrix, which makes the burrows difficult to discern.

The most spectacular bioturbation occurs in the topmost "Sun Bed" of the Langport Member at Chanton Bay and Pinhay Bay (see Plates 5.15 and 5.19). This particular stratum has been extensively bioturbated by Diplocraterion burrows, always exhibiting protrusive Spreite indicating a continual deepening of the burrow due to constant sediment removal (Goldring, 1971). The burrows penetrate to depths of up to 12 cm and are surrounded by a prominent bleached halo, contrasting strongly with the orange colour of the remainder of the rock. Hallam (1960a) suggested this colouration could be due to penecontemporaneous weathering, however it is far more extensively developed on the foreshore than in the cliff and is especially prominent along cracks and joint planes, commonly forming a superficial skin a few centimetres deep, all features which are more consistent with recent weathering. The bleached zone around burrows can be explained in terms of a local reducing environment caused by an enhanced content of organic matter - in other words modern weathering is tending to bring out an original inhomogeneity associated with bioturbation. In addition to the two localities examined by the present author, U-shaped burrows (probably Diplocraterion) have been described from the top of the White Lias elsewhere. Specifically, these occurrences are in the IGS Charmouth No. 16A borehole (IGS unpublished borehole log) and north of the Mendips at Chelwood (Green and Welch, 1965). Some of the burrows examined have been truncated by pre-Liassic erosion, indicating at least two distinct phases of bioturbation.

Evidence for early lithification of Langport Member sediment, with the production of hardgrounds, occurs at several widely-spaced locations (Fig. 5.4). Hardgrounds are probably much more widespread than this

record suggests, but the evidence for lithification elsewhere is not conclusive, being hampered by the necessarily limited amount of material available in a borehole core, and by the difficulties associated with distinguishing recent and White Lias borings on foreshore "reef" exposures.

Early lithification is inferred from the presence of borings, sediment wrapping around surface irregularities or on underlying bed and by the occurrence of encrusting oysters. Following Bromley (1972) most of the borings may be referred to the ichnogenus: Trypanites Magdefrau, and include structures probably produced by bivalves (T. clavatus (Leymerie)) or worms/wormlike organisms (siphunculids, phoronids or annelids) e.g. T. Weisei Magdefrau (Plates 5.17, 5.18, 5.20). Borings penetrate burrows (Plate 5.18) indicating two phases of biogenic activity, one excavating soft sediment, the other lithified sediment. Horizontal or sub-horizontal burrows are commonly compacted but in other instances they have avoided flattening, implying that, in the latter case, protection was afforded by the hardground, whilst the compacted burrows form part of an earlier suite significantly predating lithification.

Encrusted hardgrounds are comparatively rare in the Langport Member, the only place where the author knows of extensive encrustation by oysters is at the top of the White Lias at Culverhole Point, Devon. At this locality, the Langport Member is overlain disconformably by Gault Clay (Woodward and Ussher, 1899, 1911; Sellwood et al, 1970). Comparison with the Charton Bay and Pinhay Bay sections indicates the probability that several metres of Langport Member has been eroded at Culverhole. It seems extremely likely, in view of the total absence of Jurassic and most of Lower Cretaceous strata, that development of this hardground took place in post-White Lias times.

The hardground displays, amongst other features, multiple-phase bivalve borings and has clearly had a complex and interesting history. A post-Langport Member date is, however, certain, at least for the encrusting oyster fauna, which consists of specimens of Exogyra sp (J. Brannan, pers. comm. 1979) a genus of mid-Jurassic to Upper Cretaceous age (Stenzel, 1971).

Compaction effects in Liassic sediment overlying an irregular indurated upper surface of White Lias are known from two localities. Green and Welch (1965) describe the eroded and hardened topmost Langport Member at Harris's Quarry near Chelwood, some 13 km (c. 8 miles) SSE of Bristol (Grid Ref: ST 655 616), the surface of which consists of rounded, sub-parallel ridges, 19 cm wide, 7 cm high and with a wavelength of 0.6 m, which are mirrored by contortions in the overlying Blue Lias which extend upwards for 0.3-0.6 m. This quarry has now, unfortunately, been filled in, but in a stream exposure about 200 m to the south-east the present author observed Trypanites borings in the Uppermost White Lias which provide confirmation for early lithification. Similar, but less spectacular, compaction effects have been seen by the present writer from the top of the Langport Member in cores from the IGS Thorpe-by-Water borehole. In this instance disturbance to the overlying sediment is restricted to a zone only 1.5 cm thick. The White Lias below this discontinuity is penetrated by vertical and steeply inclined burrows, 0.2-1.0 cm wide, to a depth of several centimetres. Burrows are, in fact, a common feature at the top of the White Lias in boreholes and surface exposures on the flanks of the London Platform (Edmonds, Poole and Wilson, 1965; and the current author's personal observations). Many of them may be associated with hardgrounds, but conclusive evidence is lacking. Examples from the IGS Upton, Stockton Locks and Withycombe Farm boreholes are illustrated in Fig. 5.5.

5.2.3 STRONTIUM GEOCHEMISTRY

Hallam (1960a) quoted the results of strontium analyses performed on three White Lias samples from Devon. The values for the ratio 1000 Sr/Ca were 10.0, 10.0 and 2.0 respectively (= 4,000, 4,000 and 800 ppm). The present author has analysed a further ten samples, from Devon, Somerset and South Wales, by X-ray fluorescence spectrometry. The strontium contents of these limestones ranged from 150-320 ppm with a mean of 288 ppm (see Figs. 5.6 & Table 5.1). The values for two micritic limestones from Pinhay Bay, Devon were significantly higher than the others at 398 and 817 ppm; in fact the remaining eight limestones have an average strontium content of only 208 ppm, and contrast petrographically with the micrites, being biosparrites and biomicrites composed primarily of bivalve shell material. The data thus suggests a division into two groups of limestones, one whose strontium content is somewhat greater than the "average" for ancient limestones of 500 ppm (Kulp, Turekian and Boyd, 1952; Wolf, Chilingar and Beales, 1967; Stehli and Hower, 1961; Kahle, 1965; Veizer and Demovic, 1974; Bausch, 1968; Bathurst, 1975; also see Fig. 5.7) consisting of micrites and the other, composed of bioclastic limestones, with below-average strontium concentrations. This subdivision clearly requires a much greater volume of data to be statistically valid, but it is contended here that a genuine contrast does exist between the two groupings.

This variation in strontium content must be the result of either an original difference of strontium concentration in the sediments, variations in the efficiency of strontium removal during diagenesis, or a combination of the two. Veizer, Demovic and Turan (1971) attributed high strontium values in limestones to an initial sediment comprised of inorganic

TABLE 5.1 STRONTIUM ANALYSES OF LANGPORT MEMBER LIMESTONES

(Determined by X-ray fluorescence spectrometry)

<u>LOCATION</u>	<u>LITHOLOGY</u>	<u>STRONTIUM CONTENT (ppm)</u>
PINHAY BAY	MICRITE	817
PINHAY BAY	MICRITE	398
BLUE ANCHOR POINT	BIOMICRITE	220
LILSTOCK	BIOMICRITE	181
LILSTOCK	BIOSPARRITE	213
ST. AUDRIES BAY	BIOMICRITE	255
ST. AUDRIES BAY	BIOSPARRITE	226
LAVERNOCK POINT	BIOMICRITE	152
ST. MARY'S WELL BAY	BIOSPARRITE	246
ST. MARY'S WELL BAY	BIOSPARRITE	184

aragonite. Kinsman (1969b) suggested, on the other hand, that the principal factor determining the amount of Sr^{2+} in limestones was the quantity of calcium carbonate dissolved and reprecipitated per unit volume of pore solution. The nature of Langport Member sediments suggests that both initial strontium content, and subsequent differential diagenetic strontium removal, were responsible for the present levels. The micritic sediments of the Devon coastal exposures now display completely recrystallised fabrics, generally lacking any evidence of skeletal material; there seems little doubt that they were originally deposited as carbonate muds, and hence, by analogy with recent sediments, were probably mostly aragonite. They presumably originally contained $\sim 2,800\text{--}9,400$ ppm strontium (Stehli and Hower, 1961; Kinsman, 1969b; Bathurst, 1975; see Fig. 5.7). The bioclastic limestones, being mostly composed of bivalve shells, would, by comparison with recent examples, have lower levels of strontium, probably ranging from 800–4,000 ppm (Lowenstam, 1963; Friedman, 1968; Bathurst, 1975; and Fig. 5.7). During diagenesis the coarser bioclastic limestones would permit the passage of much greater volumes of pore fluid than the micrites and consequently strontium would be preferentially removed (Kinsman, 1969b).

The 4,000 ppm values quoted by Hallam (1960a) are anomalously high, the reason for this is unknown. The large strontium content of these rocks is consistent with the present author's determinations, but to maintain a level of 4,000 ppm strontium would imply an almost closed diagenetic system (Kinsman, 1969b) which seems very likely to have been the case. Much emphasis has been placed on the loss of strontium due to the movement of freshwater in a subaerial environment (e.g. Flugel and Wedepohl, 1967;

Matthews, 1968; Harris and Matthews, 1968). However, in basin-margin positions with gently offshore-dipping strata, freshwater may penetrate over 100 km offshore (Manheim, 1967). The experimental work of Katz, Sass, Strannsky and Holland (1972) has also demonstrated that low levels of strontium (< 500 ppm) in ancient limestones can be produced by aragonite $\rightarrow$ calcite transformation in a system open only to sea water. There is therefore no need to invoke subaerial diagenesis to explain the strontium levels in the White Lias.

5.2.4 FAUNA AND FLORA

The transition from the Cotham to Langport Member is marked by the return of a marine, predominantly molluscan fauna, which whilst not particularly diverse at any one locality or horizon, yields overall a fairly varied assemblage. The fauna tends to be concentrated at certain horizons, between which the strata are usually poorly fossiliferous. Bivalves are the dominant components with Modiolus hillanus (J. Sowerby), Atreta intusstriata (Emmrich), Liostrea hisingeri (Nilsson), and species of Plagiostoma and Lima being the most important representatives (see e.g. Richardson, 1929; Hallam, 1960a; Ivimey-Cook, 1974). Several other bivalves have been noted, amongst which are: Meleagrinella decussata (Münster), M. fallax (Pflucker), Gervillia praecursor (Quenstedt), Lima valoniensis (Defrance), Dentalina pseudocommunis d'Orbigny, Lingulina lanceolata (Haenster), Chlamys valoniensis (Defrance), Pteromya aff. crowcombeia (Moore), P. tatei, Placunopsis c.f. numismalis (Quenstedt), Astarte sp, Cardinia sp, Pholadomya?, Protocardia sp and Placunopsis sp (e.g. Edmonds, Poole and Wilson, 1965; Cave, 1977; Poole, 1977, 1978). The other molluscan representatives are gastropods, generally too poorly-preserved to identify even at generic level, which have been referred to as ?neridomids (Poole, 1977) or as "turreted gastropods" (Edmonds, Poole

Ostracods are sometimes a significant faunal contributor the species Hungarella bristolensis Anderson, H. moorei Anderson, Darwinula liassica Jones, Pontocypris richardsoni Anderson, Cytherella plattensis Anderson and Cytherelloidea cf. pulchella Apostolescu, having been identified (see e.g. Anderson, 1964; Ivimey-Cook, 1974).

None of the fauna so far mentioned are particularly significant as indicators of palaeosalinity, as they are generally euryhaline forms, with the exception of Darwinula liassica which is believed to be a brackish or fresh water species (Benson et al, 1961). Information is, however, given by the presence of comparatively stenohaline faunal elements which include the corals Montlivaltia rhaetica Tomes and Thecosmilia (Richardson, 1911; Ivimey-Cook, 1974) and echinoid spines and plates, normally referred to the genus Diademopsis.

Lagenid and polymorphinid foraminifera e.g. Eoguttina liassica (Strickland), occasional coprolites and fish fragments, complete the faunal list.

The palynomorph assemblage for the Langport Member shows a reduction in the importance of dinoflagellate cysts, the presence of only acanthomorph acritarchs and an increase in the numbers of foraminiferal test-linings, when compared to the Westbury and Cotham Members. These changes may possibly be related to a shallower, more turbulent environment of deposition (Warrington, 1978 a). The same author also notes a reduced diversity of miospores at the base of the White Lias - a feature which persists into the Lower Lias, in conformable sequences. The remaining flora is restricted to rare occurrences of indeterminate plant material.

5.2.5 DISCUSSION

There can be little doubt that the Langport Member represents deposition in a shallow shelf environment, following transgression of the Cotham Member lagoonal complex. The abrupt nature of the change between these rock units suggests that the marine invasion was rapid. Influx of terrigenous material onto this shelf was virtually non-existent except in the North Somerset/South Wales area where it forms a significant part of the coarser fraction.

Workers on modern shallow-water carbonates recognise two types of shelf: protected shelf-lagoons, and open shelves (Logan et al, 1969; Ginsburg and James, 1974; Sellwood, 1978). It is only on the former type of platform that large quantities of carbonate mud accumulate which suggests that the Langport Member was formed in a similarly protected setting. Restriction of circulation by the barrier and the frictional dampening of tidal currents, which takes place rapidly as one moves towards the platform centre, are of paramount importance in preventing the removal of fine sediment.

Hallam (1960a) compared the White Lias to Recent Bahamian *drewite* deposits and, despite subsequent studies in other areas, this comparison is still valid; equally, analogies may be made with other barred shelf-lagoons, for example those developed off British Honduras (see e.g. Matthews, 1966).

The genesis of lime muds has been the subject of some controversy, reviewed in Bathurst (1975). From this discussion it would appear that a multiple origin is likely. Lime muds from British Honduras have been demonstrated to consist of fragmented skeletal material and coccoliths (Matthews, 1966; Scholle and Kling, 1972). At the other extreme most of the aragonite needle muds of the Persian Gulf are probably an inorganic precipitate (Wells and Illing, 1964; Kinsman, 1966; Kinsman and Holland, 1969) although the precipitation may be controlled physiologically (Kendall and Skipwith, 1969). The breakdown of algae could provide all the recent aragonite mud in Florida Bay (Stockman et al, 1967) whilst on the Bahamas Bank it appears that skeletal and inorganic components are both likely to be of importance (Bathurst, 1975). This dual contribution may well have been the case in the Langport Member, but is now impossible to assess because of the totally recrystallised fabric.

The White Lias fauna is also comparable to that of modern shelf lagoons being of a semi-restricted nature (Kraft, 1971). Some stenohaline forms such as echinoids and corals are present but others, for example, brachiopods, are absent. This type of assemblage is analagous to that of Persian Gulf lagoons (e.g. Hughes Clarke and Keij, 1973) and the shelf lagoons of British Honduras (Matthews, 1966) and the Great Bahama Bank (Newell et al, 1959). Echinoid species are found in the Persian Gulf wherever the salinity of the water does not exceed 48‰ (Hughes Clarke and Keij, 1973) suggesting a possible upper salinity limit for the White Lias. Further information is given by the presence of hermatypic corals (although not actually forming reefs in this instance). These provide a

fairly close control on depth (probably < 50 m), temperature (probably in the 25-29°C range) and salinity (27-40‰). They rarely survive in muddy conditions (like the White Lias) except where sedimentation is slow, and require an adequate supply of nutrients (J. W. Wells, 1956). The abundance of lime mud implies a tropical or subtropical setting and probable depths of around 10-15 m (Wilson, 1975).

The thin interbeds of coarse, bivalve calcarenite, especially those which fine upwards are here interpreted as the product of deposition under waning high-energy conditions and represent the influx of material into normally quiet areas during storms. Similar graded sand units were deposited in Florida Bay by Hurricane Donna (Ball, Shinn and Stockman, 1967), and a sand bed in a predominantly fine-grained core, also from Florida Bay, was likewise interpreted in terms of a catastrophic event (Müller and Müller, 1967).

The high percentage of calcarenites, containing terrigenous clastic material, in north Somerset and South Wales, and the presence of desiccation cracks at one locality (Lilstock) in this area is taken as indication of deposition on sand-shoals in a shallow, occasionally emergent, nearshore position.

The nature of the barrier to the proposed shelf lagoon is problematical. Most modern shelf lagoons are fringed by either islands or reef complexes. There is evidence for islands which could have afforded at least partial protection, but no sign of any reefs. This may, however, be simply because

most of the crucial area where one would expect the barrier to occur, that is somewhere south of England in the direction of the presumed marine connection, is now beneath the waters of the English Channel. No information on this part of the succession is as yet available from this area, although some may soon be provided by the current interests in oil exploration.

5.3 WATCHET MEMBER

5.3.1 SEDIMENTOLOGY AND MINERALOGY

The Watchet Member consists of grey and blue-grey calcareous siltstones and mudstones with thin, intercalated siltstones which separate the pale grey limestones of the Langport Member from the dark, fissile, bituminous "paper shales" of the Lower Lias. This unit is very thin in North Somerset, and only attains significant thickness (of over 2 m) in the coastal exposures of the Penarth area, South Wales (see Fig. 5.3 and plate 5.21).

Mineralogically the rocks are composed of quartz, feldspars, clay minerals and calcite, with the coarser-grained siltstones being predominantly quartz with a calcite cement. These interbedded siltstones are usually lenticular, taking the form of "starved" oscillation ripples, which are especially prevalent towards the base of the member, becoming less important upwards.

5.3.2 FAUNA AND FLORA

The Watchet Member has a very sparse macrofauna of two bivalve species, Liostrea hisingeri (Nilsson) and Modiolus hillanus (J. Sowerby) which tend to occur in small shell-rich pockets (plate 5.22) which are probably the result of wave or current concentration.

A diverse microfauna comparable to that of the Langport Member occurs near the base, but is absent from higher levels (Ivimey-Cook, 1974). This microfauna includes the ostracods; ?Pontacypris grandis Anderson, Cytherella plattensis Anderson, Cytherelloidea cf. pulchella Apostolescu and Coronocypris coronula Anderson (Anderson, 1964).

The microflora appears to be comparable to the Langport Member in the reduced diversity of the miospore assemblage (Warrington, 1974 b).

5.3.3 DISCUSSION

As stated in the introduction to this chapter, the Watchet Member is probably a counterpart of the Upper Langport Member in other sections. It differs in the great increase of the terrigenous component and in having a more restricted fauna. Both these features are here related to fluvially-derived clastic input; this explains the dilution of carbonate by fine-grained terrigenous detritus, and the reduction in faunal diversity can be accounted for in terms of the lowering of salinity accompanying fresh-water influx. The Watchet Member is therefore considered to have been deposited in a nearshore portion of the shelf-lagoon adjacent to a river mouth which introduced a sediment-laden stream of freshwater (see Fig.5.10). Similar

areas of mixed clastic/carbonate deposition are known from modern shelf lagoons e.g. British Honduras (Matthews, 1966). The terrigenous mud input is known to severely limit carbonate production as it reduces light penetration, provides an unsuitable substrata for most benthos, dilutes the indigenous carbonate and is usually associated with freshwater that causes a salinity reduction (Ginsburg and James, 1974).

5.4 SUMMARY

The Langport Member and Watchet Members represent deposition in a shallow, tropical or subtropical shelf-lagoon. Lime muds accumulated in this protected environment, probably as a result of both skeletal breakdown and inorganic precipitation. These muds were originally predominantly aragonite with an initially high strontium content, and became extensively bioturbated by members of the rather restricted fauna. The peace of this quiet setting was occasionally broken by the passage of storms, leading to the erosion of the upper part of the mud substrate and the deposition of graded calcarenites. A nearshore environment of sand shoals pertained in the South Wales/north Somerset area, which was subaerially exposed in places. Later, fine terrigenous material debouching from a nearby river, probably draining the South Wales area, led to the formation, in this area, of the Watchet Member. The influx of freshwater caused a salinity reduction and was responsible for a restriction of the fauna.

Diagenetic changes brought about the complete recrystallisation of most Langport Member sediments as calcitic microspar. Accompanying this change was the loss of much of the Sr^{2+} content from the sediments. However, the

higher initial Sr^{2+} content of the micritic sediments and their lower permeability permitted the retention of a higher level of strontium in these rocks than in the calcarenites.

The palaeoenvironmental interpretation made here is summarised in Fig. 5.8.

CHAPTER 6

THE LOWER LIAS

6.1 INTRODUCTION

The main aim in the inclusion of this chapter, is to provide a sedimentological framework in which the deposition of the Penarth Group can be discussed. This account will be primarily concerned with 'Blue Lias' sedimentation, prior to the incoming of the first ammonite; that is to say the emphasis will be on the Pre-planorbis Beds, the lower part of which have been examined by the author. In the broader aspects of Early Liassic deposition this chapter leans heavily on the literature, and especially on works published in the 1960s on the classic coastal exposures of Dorset and Glamorgan (e.g. Hallam, 1960b, 1964; Wobber, 1966, 1968a, b).

British Hettangian sediments can be readily divided into two distinct categories based on proximity to the palaeoshoreline - those of the near-shore and those of the offshore zones. Nearshore sediments are known from the South Wales, Mendip and Hebridean areas where they commonly rest unconformably on Palaeozoic basement (often Carboniferous Limestone). Offshore-zone deposition was much more widespread, being represented by the limestone-shale rhythms of the Blue Lias which occur everywhere from the Dorset coast to the southern part of the Hebridean area in Scotland.

6.2 THE NEARSHORE FACIES

Nearshore facies of Hettangian and probable Hettangian age are known from the Mendips, south Wales and from Ardnamurchan, Skye, Raasay and Applecross in north west Scotland, and include the Downside Stone (Richardson, 1911), Sutton Stone (e.g. Trueman, 1922), part of the Southerndown Beds, and the Broadford Beds (e.g. Hallam, 1959; Amiri-Garroussi, 1978; Oates, 1978).

These nearshore units commonly overlap 'Rhaetic' strata to lie unconformably on Palaeozoic and pre-Palaeozoic basement indicating a general expansion of the depositional basin accompanying the Liassic transgression.

6.2.1 THE MENDIP AREA

Dealing first with the Mendips; Downside Stone has been used to describe coarse bioclastic limestones with some conglomerates, (especially towards the base) both north and south of the Mendips. These have been named after two entirely separate hamlets called Downside and are only fortuitously of the same age and facies (Savage, 1977). The Downside Stone generally consists of pale grey, coarse-grained, shelly, bioclastic calcarenites with subordinate pebbly limestones and conglomerates. Clasts are mostly chert and limestone derived from the Carboniferous, with occasional quartz pebbles probably of Old Red Sandstone affinity (Green and Welch, 1965). The thickest development of the Downside Stone is in the Shepton Mallet area, where it locally exceeds 30 m, and ranges in age from the planorbis to the bucklandi zone. To the south of the Mendips the Downside Stone passes laterally into Blue Lias facies in a matter of only a few kilometres, whilst to the north the transition takes place gradually over some tens of kilometres, Downside Stone passing into shelly limestones with thin clay partings in the

"Radstock Shelf" area (Kellaway and Welch, 1948) and thence into more normal Blue Lias rhythms with a higher proportion of mudrocks. Towards the Mendips, the Downside Stone thins against Carboniferous limestone. Fissures in this latter rock have yielded terrestrial reptiles of probable Liassic age (e.g. Robinson, 1957), indicating emergent islands of limestone against which the Downside Stone was banked. The Downside Stone is thus interpreted as the product of nearshore sedimentation, probably mostly representing deposition on shallow shoals or banks (Savage, 1977).

6.2.2 SOUTH WALES

Two nearshore facies are recognised in South Wales: the Sutton Stone and Southerndown Beds (Trueman, 1922; Hallam, 1960b; Wobber, 1966). As in the Mendips, the nearshore sediments overlap 'Rhaetic' beds and abut against Carboniferous limestone. The precise age of the strata is difficult to determine and is hindered by their diachroneity, but the Sutton Stone appears to range from the planorbis to the angulata-zone, whilst the Southerndown Beds are somewhat younger, probably extending into the bucklandi-zone (Trueman, 1922; Cope, 1971).

The Sutton Stone consists of creamy white to pale grey polymictic conglomerates and gravelly calcarenites, 10-13.5 m thick. Conglomerates are most important in the massive lower portion of this unit, and become less significant upwards, in the more thinly bedded calcarenitic lithologies (Hallam, 1960b). The fauna of the Sutton Stone is mostly molluscan

but does locally include corals near the base. Bivalves dominate the fauna, especially Chlamys and Terquemia, with Lima, Pseudolima Cardinia and patellid gastropods also being present. The ammonite Psiloceras (caloceras) johnstoni (indicating the johnstoni-subzone) occurs 6 m above the base (Hallam, 1960b). Clasts in the conglomerates are principally limestones and chert, derived from the Carboniferous limestone.

The Southerndown Beds consist of conglomerates of light to dark grey colour, typically with a higher clay mineral content. Clasts are usually limestone and chert, but occasionally include sandstone and dolomite (Wobber, 1966). The Southerndown Beds also include calcilutites, calcareous mudstones and skeletal and oolitic limestones. The Southerndown Beds' fauna is closely comparable to that of the offshore facies (see Section 6.3) and in fact the Southerndown Beds are seen to grade vertically and laterally into it.

The Sutton Stone and Southerndown Beds, like the Downside Stone, have been interpreted as nearshore deposits. Wobber (1966) emphasised the strong prevailing currents and waves and recognised representatives of the beach and sublittoral zone, the latter including probable density current and subaqueous slide deposits. The Sutton Stone is better washed than the Southerndown Beds, a fact which led Wobber to conclude that the focus of sedimentation must have shifted northwards, leading to a decrease in the efficiency of winnowing of fines with time. A similar situation to the Mendips, with shoals of coarse sediment adjacent to emergent areas of Carboniferous limestones, has also been envisaged for South Wales.

6.2.3 WESTERN SCOTLAND

The Broadford Beds, which occupy the northerly part of the western Scottish Jurassic outcrop on the islands of Skye, Pabay and Raasay and on the mainland at Ardnamurchan and Applecross, comprises a series of limestones and coarse terrigenous clastic sediments (Hallam, 1959; Amiri-Garroussi, 1978; Oates, 1978). The Broadford Beds are characterised, particularly in their lower half, by rapid lateral change which has led to the above authors' inference of a complex depositional environment. Within this multiplicity of facies the presence of coralline limestones, oolitic limestones and the abundance of coarse bioclastic and terrigenous clastic material are all indicative of a shallow-water setting at no great distance from the shoreline.

6.3 THE OFFSHORE FACIES

6.3.1 DESCRIPTION

Over most of Britain the Lower Lias occurs as the Blue Lias offshore facies, which is known from Morvern, Mull and Arran on the west coast of Scotland (Oates, 1976, 1978) from beneath the Tertiary basalt plateau of Northern Ireland (e.g. Wilson and Manning, 1978) and throughout most of the English and South Welsh outcrop and subcrop. The thickest known development of this facies was cored in the Llanbedr (Mochras Farm) borehole, near Harlech in North Wales (Woodland (Ed), 1971).

At first sight this facies appears to comprise a monotonous repetition of grey-blue/grey limestones and mudstones (see plates 6.1 and 6.2). When examined in more detail a greater variety of lithologies can be detected, including shales and mudstones (sometimes laminated and bituminous), marls and limestones (see Fig. 6.1). The latter may be laminated or massive and range from micrites to biomicrites. The proportions of these different lithologies are variable, both vertically at any given locality, and laterally at any particular biostratigraphic horizon.

A number of rhythmical units can be discerned, for example a limestone-marl-bituminous shale-marl-limestone cycle occurs frequently in Dorset (Hallam, 1960b). Junctions between the various components of the cycle appear sharp in weathered outcrop, but when examined in fresh borehole cores the boundaries between limestones and marls are diffuse and only become easily visible after exposure to the atmosphere (Taitt and Kent, 1958, p 31; C. P. Palmer, 1972).

Boundaries between beds may be planar to highly irregular. In the lowermost planorbis and Pre-planorbis Beds the author has noted mostly planar bed junctions, a fact confirmed by reference to Hallam (1960b). In these basal strata there is also a tendency for many of the argillaceous bands to be finely laminated and bituminous (see Fig. 6.1, plate 6.3). The lamination is caused by alternation of organic-rich and quartz-silt-rich layers, the latter commonly cemented by sparry calcite (plate 6.4). The limestones in this part of the succession are mostly micrites (plate 6.5) or biomicrites containing fragments of bivalves, echinoderms, ostracods, foraminifera and ostracods (plate 6.6). Hallam (1960b) showed that the

fauna in the bituminous shales was dwarfed and impoverished relative to the other lithologies. The biota of the limestones and marls (with the exception of finely laminated limestones) is closely comparable, being dominated by bivalves, which in the planorbis-zone include Chlamys, Modiolus, Pseudolimnea and Liostrea. These, however, show no signs of stunting.

Examination of sections in the Pre-planorbis Beds and planorbis Beds on a regional scale reveals interesting lateral variation, specifically involving changes in the importance of limestones. In south-west England and the Midlands the succession is typically one of limestone-mudstone/shale alternations on a tens of centimetres scale. Further north, however, in the Cheshire Basin (Poole and Whiteman, 1966), Northern Ireland (Manning and Wilson, 1975; Ivimey-Cook, 1975) and in south Lincolnshire and Yorkshire (e.g. Fox-Strangways, 1892; Brunstrom, 1962; IGS unpublished borehole logs and the author's personal observations) the sequence is almost wholly composed of dark grey silty, calcareous mudstones. The rhythmic limestone-shale facies reappears in western Scotland (Mull and Morvern), being described and compared to the Blue Lias of southern England by Oates (1978).

The northern flank of the London Platform appears to have had a somewhat different Early Liassic history from other areas: because of uplift of the platform at this time the early beds of the Lias are regressive in relation to Langport Member sediments (Donovan, Horton and Ivimey-Cook, 1979) in complete contrast to other basin-margin settings where the uppermost Penarth Group elements are overlapped by Lower Liassic strata. The

situation on the northern margin of the London Platform is such that the eroded top of the White Lias may be overlain by Liassic strata from as high as the turneri-zone (as, for example in the Steeple Aston borehole, Poole, 1977).

6.3.2 DISCUSSION

The offshore facies can be divided into two broad zones, one of alternating limestones and argillites, the other dominated by calcareous mudrocks with few limestones. The position of these zones relative to emergent basement areas and to non-depositional areas indicates that the limestone-mudstone facies is comparatively nearshore, a contention supported by its lateral gradation into the coarser-grained limestone and rudite-dominated nearshore facies, whilst the mudstone facies was deposited in deeper water at greater distance from land. Support for this interpretation comes from Donovan et al's (1979) study of Liassic sediments on the northern flank of the London Platform; in this area transgressive phases of pronounced onlap are dominated by mudstones whilst periods of regression or standstill are marked by an increase in the importance of limestones.

The origin of Blue Lias rhythms requires some comment at this stage, having been a subject of some controversy. Early workers considered that the rhythms were either entirely secondary (Day, 1865; Lang, 1914) or primary (depositional) and partly secondary (diagenetic) (Woodward, 1893; Trueman, 1922) but in neither instance presented much corroborative evidence. Later, various lines of evidence were used in favour of an entirely diagenetic model (Richardson, W. A., 1923; Kent, 1936, 1957; Shukri, 1942) or a completely primary depositional model (Hallam, 1957;

Simpson, 1957). The evidence on both sides was summarised by Hallam (1964) and the compromise solution he proposed of a part-primary and part-secondary mechanism has largely been accepted by later workers (e.g. Wobber, 1966; Amiri-Garroussi, 1978). Features supporting each process are listed below (after Hallam, 1964):-

a) Features favouring primary deposition:-

1. Burrow mottling by Chondrites, Diplocraterion etc. in which light rock penetrates dark and vice-versa.
2. The presence of laminated bituminous shales.

b) Features favouring diagenetic segregation:-

1. Bands of ellipsoidal nodules.
2. Highly irregular bed junctions.
3. Fossils fractured by expansion accompanying calcite crystallisation.
4. Trace fossil infillings displaying migration of CaCO_3 towards limestones.

With regard to the irregular nature of bedding surfaces, Wobber (1967) has suggested that these may be produced by loading and intrastratal sliding as well as by concretionary accumulation of calcite during diagenesis.

The mechanism for producing primary limestone-shale alternations is somewhat problematical, various solutions having been proposed. Hallam (1960b) favoured eustatic rises and falls in sea level, Sellwood (1970) advocated eustasy linked to local tectonic instability, whilst Donovan et al (1979) prefer a complex process perhaps involving the development and destruction

of thermoclines. The present author prefers Sellwood's model, which best explains variations of turbulence, but also suggests that a crude upward fining of skeletal material in some pre-planorbis limestones may reflect transport of skeletal debris from the nearshore zone into more offshore areas by storm-surge ebb, rather than a relative shallowing of water depth. The occurrence of limestone-shale rhythms at moderate depths between near-shore lime-dominated and offshore mud-dominated facies supports relative oscillations of sea-level, shifting the emphasis in this intermediate zone, between limestone and mudstone deposition. A further suggestion is seasonal terrigenous clastic influx alternating with coccolith productivity, producing lime-rich and clay-rich beds, the former emphasised by selective cementation (Anderton et al, 1979).

Laminated bituminous shales with an impoverished fauna and no evidence of disturbance of sedimentary structures by bioturbation, are interpreted here, as by most previous authors, as deposits forming as a result of anoxic or near anoxic conditions at the sediment/water interface. Bituminous shales are, in general, rare in the Blue Lias, but are frequently encountered in the basal cycles where their alternation with biomicritic limestones, which are sometimes burrowed, indicates interplay between anoxic and oxic conditions. Hallam and Bradshaw (1979) relate this enhanced basal development of bituminous shales to the Lower Hettangian transgression, with anoxic conditions existing in localised topographic depressions with oxic environments (associated with non-bituminous clays) on the intervening highs (Fig. 6.2).

6.4 SUMMARY

The Hettangian was, in general, a period of marine transgression in north west Europe. This transgression can, however, be only documented in a few other localities elsewhere in the world, suggesting it was the result of local tectonism rather than a eustatic rise in sea-level (Donovan et al, 1979). Also we have seen (in Section 6.3) that locally, for example on the northern edge of the London Platform, tectonic uplift produced regression.

Regional variations in Hettangian sediments can be related to position relative to the basin-margin and hence, broadly, to water depth. The nearshore zone is represented, in England and Wales, by the Sutton Stone, Southerndown Beds and Downside Stone conglomerates and calcarenites which were deposited in a shallow-water littoral and sub-littoral setting adjacent to islands of Carboniferous Limestone. Whilst a similar shallow, sub-littoral environment is envisaged for the deposition of the Broadford Beds in north west Scotland.

The offshore zone can be subdivided into an intermediate, proximal area typified by limestone/shale interbeds, which grades laterally into sediments of the near-shore zone, and a more distal area dominated by mudstones with relatively few limestone interbeds (the distribution of these environments is illustrated in Fig. 6.3). Limestone-shale rhythms in the intermediate zone probably represent a complex interplay between eustatic rise and fall of sea-level, local tectonism, terrigenous clay input and primary carbonate productivity, coupled with diagenetic segregation tending to enhance originally carbonate-rich layers. Bituminous shale beds in the offshore zones reflect anoxic or poorly oxygenated conditions at the sediment-water

interface which seem to be best developed during transgressive phases, and whose distribution appears to be related to oxygen-deficient bottom waters associated with local topographic lows (Hallam and Bradshaw, 1979).

Lower Liassic palaeogeography can be seen in Fig. 6.3. The occurrence of a thick sequence of offshore-type sediments in the Mochras borehole (Woodland, 1971) suggests much, if not all, of Wales, with the exception of small islands in the extreme south, was covered by the sea during the Liassic period.

CHAPTER 7

CLAY MINERALOGY

7.1 INTRODUCTION

From the preceding chapters the preponderance of argillites in the Penarth Group will have become apparent. With the exception of the Langport Member, this part of the stratigraphical column is dominated by a series of calcareous and non-calcareous siltstones, shales and mudstones, the bulk of which are composed of clay minerals. Information on British "Rhaetic" clay mineralogy is extremely sparse (Perrin, 1971). This fact, coupled with the volumetric importance of the fine fraction, has prompted this study.

Both outcrop and borehole samples have been examined in order to give as wide a geographical distribution of sample points as possible. Several samples have been processed within each lithostratigraphical unit such that both vertical and lateral variations in clay mineralogy have been studied; the aim being to provide a regional synthesis of Penarth Group clay mineralogy which may be interpreted in the palaeoenvironmental framework provided by the preceding chapters, and which may also shed further light on the sedimentary processes operating within that framework.

7.2 ANALYTICAL METHODS

Samples were collected with particular attention being paid to obtain "fresh" material. At outcrop this has at times necessitated the removal of a thick (up to 50 cm) weathered zone prior to sample collection. With borehole samples any obvious surface contamination was removed.

In the laboratory, disaggregation of the specimens was achieved by gentle crushing followed by ultrasonic treatment. Where necessary, deflocculation was effected by the addition of a few drops of sodium hexametaphosphate. The $< 4 \mu$ (equivalent spherical diameter) fraction was then separated by centrifuging. This size fraction was used in place of the more conventional $< 2 \mu$ fraction because of the known occurrence of certain clay minerals, such as kaolinite (Grim, 1953) and chlorite (Towe, 1974) as grains $> 2 \mu$ in diameter. There also exists the possibility that clay minerals may occur as $> 2 \mu$ aggregates which survive disaggregation (Dumbleton and West, 1966).

The clay fraction, after separation, was mounted on ceramic discs using the suction method of Shaw (1972). This procedure avoids the segregation of clay minerals on the mount (Gibbs, 1965, 1968; Stokke and Carson, 1973).

Analysis was performed with a Phillips X-ray diffractometer using nickel-filtered $\text{CuK}\alpha$ radiation at 36kV/30mA. Mineral identification followed the standard four stage procedure (air dried, glycerated, heated at 400° and 550°C) with the occasional addition of treatment with warm 10% HCl, in the manner depicted in table 7.1.

TABLE 7.1 CLAY MINERAL IDENTIFICATION USING X-RAY DIFFRACTION.

(After Grim, 1953; Brown, 1961; Weaver, 1967; Carroll, 1970; Thorez, 1976).

CLAY MINERAL.	TREATMENT.				
	AIR DRIED	GLYCERATED	400°C	550°C	ACID (HCl)
	(d- spacing of peak in Angstroms).				
ILLITE	10	10	10	10	10
SMECTITE	12-15	18	10	10	
CHLORITE (Iron-rich)	14,7	14,7	14,7	14 enhanced 7 reduced.	Peaks disappear.
KAOLINITE	7	7	7	Peak disappears	7
SEPIOLITE	12	12	12	disappears or reduced	
CORRENSITE	14	16	12	12	
ILLITE-SMECTITE	10-14	10-18	10	10	

Quantification of the results was not carried out because of the many inherent difficulties. Towe (1974) has clearly demonstrated the bias that may be induced during the separation of the clay fraction. Numerous quantification schemes exist (e.g. Johns et al, 1954; Schultz, 1964; Griffin and Goldberg, 1963; Biscaye, 1965; Bradshaw, 1975). These have been shown to give widely divergent results using the same initial data (Pierce and Segal, 1969). Whilst any one scheme will provide internally-consistent, semi-quantitative data, it was found, in this study, that significant changes in clay mineralogy could be readily detected without recourse to such calculations.

7.3 RESULTS

7.3.1 MERCIA MUDSTONE GROUP

7.3.1.1 RED MARLS

There is a large volume of literature on the clay mineralogy of the Red Marls, stemming from their economic importance as a raw material for brick-making, from the extraction of evaporites and from the need to study their engineering properties in relation to road construction (Honeyborne, 1951; Steven and MacEwan, 1950, 1951; Keeling, 1956; Freeman, 1964; Lees, 1965; Dumbleton, 1966; Dumbleton and West, 1966; Sherwood and Hollis, 1966; Davis, 1966). More recently a comprehensive study has been undertaken by Jeans (1978).

Jeans (1978) subdivides the clay minerals of the Mercia Mudstone Group into two assemblages. He recognises a ubiquitous detrital assemblage of illite

and chlorite superimposed on which may be members of an "exotic" suite including sepiolite, palygorskite, smectite, corrensite and irregular mixed layers of illite-smectite and smectite-chlorite. If the term "swelling chlorite" is restricted strictly to the definition of Lucas (1962) (i.e. a chlorite-type mineral with incomplete octahedral layers that permit swelling, but remain stable on heating) then this mineral appears to be absent (Jeans, 1978). Small amounts of kaolinite are recorded in Perrin (1971) but were not listed by Jeans. This suggests a different approach between these authors in the X-ray identification of kaolinite and chlorite.

7.3.1.2 TEA GREEN AND GREY MARLS

In the area studied by Jeans (1978) that author recognised only members of his detrital assemblage, namely illite and chlorite. The present author has, however, identified members of Jeans' exotic suite at a number of locations. Corrensite occurs in the Tea Green Marls at Harrogate House, North Yorkshire and in the Grey Marls at Blue Anchor, Somerset (the latter observation is confirmed by its presence in these rocks at the nearby St. Audries exposure reported by Mayall, 1979). Sepiolite and smectite were identified from the Tea Green Marls of the Upton borehole, Oxfordshire and minor amounts of smectite have been found in the Tea Green Marls of the Blyborough, Cockle Pits and Scalla Moor boreholes in Northern England. These results are summarised in Figs. 7.1 and 7.2. Illite and chlorite are, as shown by Jeans, ubiquitous and, on the basis of the sharpness of their basal reflections, occur in a well-crystallised form (Thorez, 1976).

7.3.2 WESTBURY FORMATION

A marked change in the clay mineral assemblage occurs across the Mercia Mudstone Group/Penarth Group boundary. The complexity and variety of clay mineralogy in the Mercia Mudstone Group is replaced by a relatively simple pattern in the younger sediments (Figs. 7.3 and 7.4). This consists of two major clay mineral assemblages: in the Bristol Channel area, Cheshire Basin, North Yorkshire, Cleveland and in the Winterborne Kingston borehole, illite, chlorite and illite-smectite are present whereas in Devon, central southern England, the Midlands and Yorkshire (as far north as the Scalla Moor borehole) smectite occurs in addition to illite, chlorite and illite-smectite. Between these two areas a transition is demonstrated by the increase in the proportion of illite-smectite (as for example in the Stowell Park borehole).

In addition to the lack of, for example, sepiolite, palygorskite and corrensite, which occur in the Mercia Mudstone Group, a further noteworthy contrast with these beds lies in the greatly enhanced importance of illite-smectite. Minor quantities of vermiculite are also reported from south western England by Mayall (1979).

7.3.3 LILSTOCK FORMATION: COTHAM MEMBER

The same two clay mineral assemblages which typified the Westbury Member also occur in this unit, but their geographical distribution is rather different; the illite, smectite, chlorite and illite-smectite suite is now confined to Devon and to an area to the north and east of Nottingham,

whilst the remainder of the study area has a clay mineralogy consisting of illite, chlorite and illite-smectite (Fig. 7.5).

In central southern England the picture is rather transitional with an abundance of illite-smectite.

Mayall (1979) reports kaolinite from the upper Cotham Member of Devon.

7.3.4 LILSTOCK FORMATION: LANGPORT AND WATCHET MEMBERS

Smectite is greatly reduced in importance in these strata only being encountered in samples from the Upton Borehole. Illite, chlorite and illite-smectite are the important contributors to the fine fraction and kaolinite continues to occur in the Devon area (confirmation of this comes from Cosgrove and Salter, 1966 and Mayall, 1979). Results for these units are summarised in Fig. 7.6.

7.3.5 LOWER LIAS

The clay mineralogy of the Lower Lias is presented in Figs. 7.7 and 7.8. The striking feature is the greatly increased importance of kaolinite, which occurs in all samples with the exception of those from St. Mary's Well Bay near Cardiff. Smectite is restricted to the argillite-dominated borehole specimens from northern England. Illite, chlorite and illite-smectite remain ubiquitous.

7.4 DISCUSSION

The distribution of clay minerals in the Mercia Mudstone Group has been explained by Jeans (1978) in terms of the interaction between two chemically contrasting water masses (Fig. 7.9). To a detrital assemblage of illite and chlorite are added a neoformed suite of high magnesium clays (including sepiolite, corrensite, chlorite, smectite-chlorite and illite-smectite) believed by Jeans to have formed at the interface between a lower, dense hypersaline water mass and an overriding, lighter water mass of normal marine salinity. Variations in the neoformed suite result from the continuous reaction between the two water masses and from local differences within the hypersaline water body. A broad regional association exists between the neoformed clay minerals and the lateral zonation of evaporites (Fig. 7.9); the distribution of the latter being controlled by the salinity gradient of the hypersaline water mass (Jeans, 1978).

Results from the present study are broadly in line with Jeans' model. The occurrence of corrensite in the Grey Marls of North Somerset and the Tea Green Marls of northern North Yorkshire (Fig. 7.1) is in accordance with the basin-margin position envisaged for these areas and with their association with gypsum, anhydrite and halite. Likewise the coexistence of sepiolite, in the Tea Green Marls of the Upton borehole, with dolomitic mudstones which lack sodium and calcium salts is consistent with a position nearer to the basin centre. A similar argument may be used to explain the minor amounts of smectite in the Tea Green Marls of the Scalla Moor, Cockle Fitts and Blyborough boreholes. However, in these instances, the smectite is associated with greatly enhanced proportions of illite and

chlorite, relative to the overlying Westbury Member, suggesting that neoformation of much of the smectite to illite and chlorite has occurred (see Fig. 7.10).

The boundary between the Mercia Mudstone Group and the Penarth Group represents a major environmental change; the hypersaline lake and sabkha environments of the Tea Green and Grey Marls (see Chapter 1) being replaced by shallow marine environments (see Chapters 2 and 3). This profound change is mirrored by changes in the clay mineralogy: corrensite, sepiolite and palygorskite are absent from the Penarth Group where smectite and illite-smectite become more important components. Illite and chlorite are ubiquitous throughout.

Smectite may form by the transformation of volcanic glass in an aqueous alkaline environment under reducing conditions, as occur at the present day in the South Pacific (e.g. Griffin and Goldberg, 1963). It may also form by the in situ alteration of volcanic ash under terrestrial or subaqueous conditions (Brindley, 1957; Slaughter and Early, 1965; Biscaye, 1965; Hallam and Sellwood, 1968; Keller, 1970; Millot, 1970; Bradshaw, 1975). Alteration of volcanic glass is best evidenced by the association of smectite with glass shards, an association not observed in the Penarth Group. In the case of smectite derived from the alteration of volcanic ash, the vertical distribution is normally irregular being characterised by thin, smectite-rich bands alternating with smectite-poor layers, the smectite being associated with other alteration products such as zeolites and cristobalite (Keller, 1970; Bradshaw, 1975). Such alteration products have not been observed in the Penarth Group and the widespread vertical distribution of smectite likewise precludes a volcanic origin.

Smectite can also develop in soils of the hydromorphic, calcimorphic variety which exists under warm climatic conditions, where drainage is slight and cations, especially Ca^{2+} and Mg^{2+} , remain in the soil profile (Millot, 1970). The smectite in the Penarth Group, in the absence of evidence for a volcanic origin, was probably formed in this manner.

Illite-smectite may form as a product of rock breakdown in soil profiles (Millot, 1970) or from smectite during burial diagenesis (Pollard, 1971), both processes may be equally invoked for the present case.

In recent marine sediments, illite and chlorite are normally considered to be mechanically-derived detrital clays. K-Ar dating of illites supports their detrital nature and lack of crystallochemical alteration. The greater stability of muscovite over biotite, coupled with the dioctahedral nature of recent marine illites, indicates that the dominant precursors are muscovite-type micas (Griffin, Windom and Goldberg, 1968).

The geographical distribution of clay minerals in the Westbury Formation and Cotham Member (Figs. 7.2, 7.3) is best described in relation to palaeoenvironmental setting. In this way conclusions can be drawn without the need to imply a chronostratigraphical correlation between lithostratigraphical units. Three broad environments may be delineated:

1. The nearshore zone, occurring in South Wales, North Somerset and Cheshire, typified by an illite, chlorite, illite-smectite assemblage.

2. An intermediate zone occupying the south Midlands and central southern England, with an illite, smectite, chlorite, illite-smectite assemblage throughout the Westbury Formation being replaced in the Cotham Member by an illite, chlorite and illite-smectite suite.
3. An offshore zone, lying to the north and east of the intermediate zone with an illite, smectite, chlorite and illite-smectite clay assemblage throughout the Westbury Formation and Cotham Member.

The large volume of data on the clay mineralogy of Recent, marine sediments indicates that they most often reflect the mineralogy of the source area from which they are derived (e.g. Pinsak and Murray, 1960; Taggart and Kaiser, 1960; Griffin, 1962; Griffin and Goldberg, 1963; Griffin, Windom and Goldberg, 1968; Biscaye, 1965; Gorbunova, 1966; Oinuma and Kobayashi 1966; Neiheisel and Weaver, 1967; Morton, 1972 and Venkatarathnam and Biscaye, 1973).

Lateral changes in clay mineralogy with distance from the palaeoshoreline may be assigned to:-

1. Chemical transformations
2. Differential flocculation
3. Size segregation

Grim et al (1949), Grim and Johns (1954), Powers (1957) and Millot et al (1963) believed clays entering the sea to be out of equilibrium with marine waters and thus to be transformed, by reaction with sea-water, into more

stable phases; detrital smectite being altered to illite and chlorite by this process. This model thus predicts a seaward decline in smectite content - the exact opposite to the pattern observed here. Also, doubt is cast on the data interpretation of Grim and Johns (1954) by the more recent study of Morton (1972) and on the basic premise implicit to the transformation model, that estuarine clays are largely derived via the fluvial system draining into that estuary, by the observation (of e.g. Meade, 1969 and Hathaway, 1972) that much of estuarine clay input enters from the seaward end.

Differential flocculation has been invoked in explanation of lateral clay mineral variations by Porrenga (1966), Van Andel and Postma (1954) and Birch (1978). The basis for this conclusion is the experimental flocculation study of Whitehouse et al (1960) who found that at 26°C, in water of oceanic salinity, illite, kaolinite and smectite had settling velocities of 15.8, 11.8 and 1.3 metres per day respectively. These results, however, apply to pure standard clay samples in an essentially non-turbulent system and therefore should not be extrapolated to the natural environment (Gibbs, 1977). Laboratory flocculation studies of natural clays from the Niger Delta by Porrenga (1966) showed slight variations in the speed of flocculation of illite, kaolinite and smectite, in accordance with the experimental results of Whitehouse et al (1960); these could be related to the distribution of clays in Recent sediments around the mouth of the Niger. Experimentation with natural clays from the Amazon by Gibbs (1977) demonstrated that whilst flocculation does occur it does not lead to any compositional variation of bottom sediment with time. This is believed to be due to turbulence and organic or metallic coatings on clay grains tending to blanket the different electrostatic properties of the various

minerals (Gibbs, 1977). Gibbs demonstrated a strong probability that lateral clay variations off the mouth of the Amazon are the result of the size distribution of the clay minerals: illite, kaolinite and chlorite occur over a wide range of grain sizes and hence are deposited over the entire shelf. Smectite, however, has a narrow grain-size range, at the fine end of the spectrum, and thus tends to be carried some distance from the river mouth, being enriched in the bottom sediments (relative to the other clay minerals) as distance from the river mouth increases. The distribution of clays in the Westbury Formation and Cotham Member may be readily accounted for in terms of this size-segregation mechanism, with the possible assistance of differential flocculation. By analogy with Recent Amazonian sediments smectite would be expected to have been finer grained than illite, chlorite and illite-smectite and would therefore be concentrated in offshore sediments. This contention is supported by the low proportion of arenaceous interbeds in the smectite-bearing argillites of the Penarth Group. The fact that smectite occurs in both the intermediate and offshore zones of the Westbury Formation, but only in the offshore zone of the Cotham Member may be related to the regressional nature of the latter unit (see Chapter 4). This is illustrated in Fig. 7.5 by the abundance of desiccation features which occur and which are virtually mutually exclusive of smectite - an observation consistent with the smectite being transported some distance from the shoreline.

Some minor anomalies do upset the simplicity of the clay mineral distribution scheme postulated above (see Figs. 7.3 and 7.5) the most notable of which occur in Devon and Dorset. Smectite occurs in a relatively nearshore position at Culverhole, Devon whilst it is absent in a more offshore setting in the Winterborne Kingston borehole in Dorset. Smectite in Devon was

perhaps derived from a rich local source, possibly the weathering of basic igneous rocks (Millot, 1970) in the Cornubian area. The lack of smectite at Winterborne Kingston cannot readily be related to the diagenetic conversion of smectite to illite and chlorite as this occurs at temperatures exceeding 100°C and depths greater than 2 km (Velde, 1977). Temperatures within the 'Rhaetic' sediments at this locality probably only reached c. 80°C (J. Bloomer, pers. comm., 1979) even allowing for erosion of Upper Cretaceous and Tertiary strata. Smectite at this locality may have been winnowed away by the rather turbulent conditions which are implied by the relatively high percentage of siltstones, sandstones and bioclastic limestones present.

The importance of smectite declines in the latter part of the Penarth Group (Langport and Watchet Members) and the Early Liassic in concert with the appearance of kaolinite. Kaolinite first appears in Devon in the Upper Cotham Member (Mayall, 1979) continuing there in the Langport Member (Fig. 7.4) and appearing throughout the study area in the Lower Lias. This early appearance of kaolinite in Devon may perhaps be related to the unroofing of the Cornubian granites in the manner suggested by Cosgrove and Salter (1966). The later widespread occurrence of kaolinite is interpreted here as the result of a more humid climate leading to intense leaching in soil profiles, a process known to operate in tropical latitudes (Millot, 1970). Leaching leads to cation removal and allows insoluble silica and alumina to combine producing kaolinite. Britain was in the Tropics at this time (Smith & Brigden, 1977, 1974). Supportive evidence for increasing humidity comes from the upward decline of calcretes in Triassic fluvial sequences in north west Scotland (Steel, 1971^b; 1974 a, b). The existence of kaolinite at the expense of smectite is entirely

consistent with their mode of formation in soil profiles, kaolinite forming when cations are leached from the profile and smectite when cations are retained in the profile (Millot, 1970). Smectite is still a significant component in the Lower Lias of the Blyborough, Cockle Pits and Scalla Moor boreholes (Fig. 7.5) suggesting that significant quantities were still being produced and carried to offshore areas.

The apparently rapid widespread appearance of kaolinite is probably enhanced by the problems of detecting small amounts of kaolinite, rather than implying a major depositional break at the Penarth Group/Lias boundary, although such an hiatus is well known in the area flanking the London Platform (Donovan, Horton and Ivimey-Cook, 1979).

7.5 SUMMARY

The Mercia Mudstone Group contains clay minerals believed to be partly detrital and partly neoformational in origin. Detrital illite and chlorite occur in conjunction with members of a sepiolite, palygorskite, corrensite, chlorite, illite-smectite and smectite-chlorite suite thought to have formed at the interface of two chemically contrasting water masses during periods of transgression (Jeans, 1978). The zonation of this neoformed suite is broadly associated with zonation of evaporite minerals.

A marked change occurs at the Mercia Mudstone Group/Penarth Group boundary with the disappearance of neoformed clays, to be replaced by clay minerals thought to be of entirely detrital origin. These clays exhibit a simple zonation with illite, chlorite and illite-smectite occurring in nearshore areas whilst smectite appears in addition in more offshore zones. This zonation is interpreted here as being the result of differential sedimentation related principally to size-segregation.

The changing spatial distribution of these zones from the Westbury Formation to the Cotham Member may be attributed to the regressional nature of the latter unit. Smectite is progressively replaced with time by the increasing abundance of kaolinite, here interpreted as resulting from the gradual onset of a more humid climate associated with which is greatly increased leaching in weathering profiles. By the time the Lower Lias was deposited kaolinite was a ubiquitous component whilst smectite became removed to the most offshore areas of the basin of deposition. This model of clay mineral distribution is summarised in Fig. 7.11.

CHAPTER 8

THE DISTRIBUTION OF ORGANIC MATTER IN THE WESTBURY MEMBER

8.1 INTRODUCTION

The Westbury Member, which forms the bulk of the lower portion of the Penarth Group, consists largely of dark grey argillites whose appearance has been connected in the past with a high concentration of organic matter (Moore, in discussion of Elliot, 1952; Hallam, 1967; Hallam and Bradshaw, 1979). A dark colour is now, however, more generally believed to be connected with the distribution of fine-grained iron sulphides than of organic matter (McCave, 1979; Hallam, 1980; Curtis, 1980) although the two are often closely associated.

Palynological studies (e.g. Chaloner, 1962, 1969; Fisher, 1972a, b; Morbey, 1975; Orbell, 1973; Warrington, 1974b, 1977a), b), 1978a, b; Warrington and Harland, 1975) have identified both terrestrial and marine organic components, the spores and pollen of land plants being found intermingled with dinoflagellate cysts, acritarchs and tasmanitids. They do not, however, reveal the bulk concentration and distribution of organic matter. This chapter aims to display the results of the first steps towards achieving that end, and to attempt to explain the results so far obtained.

The initial stage of the investigation was the despatch of five samples, from widely-spaced locations, for analysis of total organic carbon content. The results of these analyses (0.43-3.16% organic carbon) gave

an indication of the general spread of values to be anticipated by more detailed sampling. To date three sections (at Lavernock Point, Glamorgan, Patchway, Avon and Barnstone, Nottinghamshire: see Fig. 8.1) have been examined in detail for their organic carbon content. Subsequent to the gross organic carbon work the detailed organic geochemistry of samples from Patchway has been examined by members of Bristol University's Organic Geochemistry Unit. Allied to these investigations, preliminary studies of trace element concentrations have been made using X-ray fluorescence techniques. The following sections summarise the methods used (full details are to be found in Appendix 2), present the results obtained and discuss these results in the sedimentary framework provided by Chapter 3.

(N.B. throughout this account the term "organic carbon" refers to the non-carbonate carbon fraction)

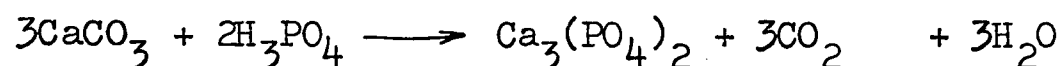
8.2 ANALYTICAL METHODS

8.2.1 ORGANIC CARBON

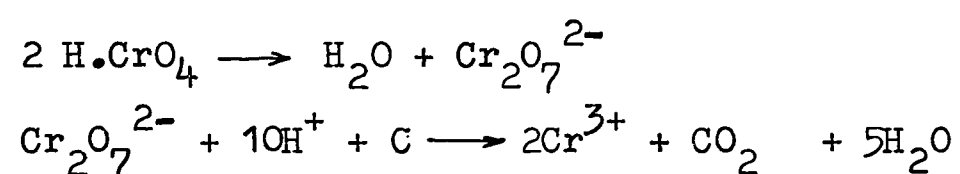
A wet oxidation method was employed for the determination of organic carbon. An early system, modified after Bush (1970) proved unwieldy in operation, was time-consuming, and yielded results of low precision, which were substantially lower than check analyses performed using a high temperature dry oxidation technique (Hewlett-Packard C, H and N analyser).

The present system is considerably more rapid and has provided results of good precision (generally duplicate analyses agreed to better than $\pm 3\%$ of

the mean) which closely match results obtained using high temperature dry oxidation. Carbonate carbon is removed by reaction with hot, syrupy orthophosphoric acid:



The organic carbon is then oxidised using hot chromic acid (10% CrO_3 in H_3PO_4):



The carbon dioxide evolved in this reaction is trapped by freezing in a liquid nitrogen cold trap, then liberated for measurement by gas chromatography.

8.2.2 DETAILED ORGANIC GEOCHEMISTRY

Two samples from Patchway, one of high organic content, the other of average-low organic content have been examined in depth at Bristol University's Organic Geochemistry Department. Study has been made there of the bitumen fraction (i.e. the fraction extractable with organic solvents). This has involved the examination of the hydrocarbons in both samples using combined gas chromatography - mass spectrometry, whilst the other fractions have been examined by gas chromatography alone. The reader interested in the details of the analytical methods is referred to: Mr. Paul Comet, Bristol University, Organic Geochemistry Unit, Cantock's Close, Bristol.

8.2.3 TRACE ELEMENT GEOCHEMISTRY

Examination of a number of trace elements (Chromium, Cobalt, Vanadium, Titanium) was made using X-ray fluorescence spectrometry on pressed powder pellets

8.3 RESULTS

At the three sections examined in detail samples were taken (depending on circumstances) at 10-25 cm spacings. All samples were analysed for organic carbon and subsequent organic geochemical and trace element geochemical investigations were geared to bringing out differences between samples with markedly different organic carbon contents. In addition "control" samples, from other parts of the lithostratigraphy, were looked at for comparison.

The results of the organic carbon analyses are summarised in Fig. 8.2. The principal feature in each case is a single prominent organic carbon peak with values several times the general background figure. At Patchway the maximum value is 9.51% organic carbon, at Lavernock/St. Mary's, 4.52% and at Barnstone 5.51%. Organic carbon levels in the adjacent Mercia Mudstone Group and Cotham Member did not exceed 0.5%. When examined in relation to the litho- and biostratigraphy the maximum of organic carbon content is seen to occur, at all three locations, in the lowermost part of the Upper Unit of the Westbury Member (as defined in Chapter 3). A high level of organic carbon (10.29%) has also been detected at a similar stratigraphical level in one of a small number of samples analysed from Westbury Garden Cliff (Fig. 8.1).

The organic geochemistry of extractable organic matter has been examined at Bristol using two Patchway samples, one from the organic carbon maximum (9.51% organic carbon) the other from adjacent, underlying mudstones with an organic carbon content of only 0.76%. Lipid distribution patterns in these two samples were very different. The low carbon sample contained a hydrocarbon fraction dominated by n-alkanes with some cyclic isoprenoids. Distribution of the n-alkanes was unimodal, with a maximum in the high carbon number region ($n\text{C}_{20}$ - $n\text{C}_{35}$). The overall hydrocarbon distribution is essentially that of plant waxes suggesting a "terrestrial" lipid distribution. The sample containing 9.51% organic carbon had a very different hydrocarbon pattern. Aliphatic components in this sample were considerably reduced in comparison to cyclic components and were maximised in the low carbon region ($n\text{C}_{16}$ - $n\text{C}_{18}$). Pristane and phytane were important contributors, implying a fairly high photosynthetic input. This evidence, pointing to a high productivity environment, was corroborated by the large steroidal component. Basically, this sample showed an algal distribution pattern with a significant contribution from bacterial lipids.

The pattern of alcohol and ketone distributions for the two samples tended to reinforce the differences outlined above, but the n-acids gave contradictory data in that the low organic carbon sample showed an exclusively algal pattern, whilst the sample rich in organic matter exhibited an appreciable terrestrial component.

Overall the results of this work point to low organic content (in a sample from the Lower Unit of the Westbury Member) being principally composed of terrestrial plant material, whilst, in contrast, a high level of organic carbon (in a sample from the Upper Unit of the Westbury Member) is associated with higher productivity and the dominance of algal- and bacterially-derived organic compounds.

On a smaller scale there are minor fluctuations in organic carbon content throughout the sections studied for which no obvious pattern or relationship to other sediment characteristics can be detected.

Trace element concentrations have been examined in relation to organic carbon content (Figs. 8.3-8.6). Nickel and vanadium appear to increase, in general, with increasing organic carbon content. Variation in chromium and copper concentration with changing organic carbon levels are only slight and show no significant correlation. Titanium content varies by several thousands of parts per million but its distribution in relation to organic carbon appears to be random. Of the five trace elements investigated nickel shows the most consistent correlation with organic carbon level. Any conclusions based on these results must, however, be regarded merely as tentative in the light of the small volume of data.

8.4 DISCUSSION

High levels of organic carbon in sediments are often equated with anoxic bottom water conditions. Available evidence suggests, however, that preservation of organic matter need not necessarily be related to anoxia (e.g. Richards, 1970; Stumm and Morgan, 1970). Sedimentological features of the Westbury Member provide evidence both for and against low oxygen concentrations in the bottom waters. Undisturbed millimetre-scale silt laminae occur in parts of the sequence, suggesting a lack of biogenic overturn of the sediments, perhaps due to oxygen deficiency. Elsewhere thin, wave-rippled sandstones are sometimes bioturbated, and frequently display casts of fine tracks and trails on both their upper and lower surfaces, indicating the presence of an active benthos. The abundant shelly fauna in the Upper Unit of the Westbury Member, whose components do not display dwarfing, and which includes a benthonic element (Ivimey-Cook, 1962) is likewise indicative of oxygenated conditions (Byers, 1977; Rhoads and Morse, 1971). Furthermore, the mudrocks of the Westbury Member do not possess a very fine fissility on weathering ("papery" in the terminology of McKee and Weir, 1953) but rather display a "platey" splitting habit, suggesting that lamination of the sediments may be on a rather coarse scale, in contrast to the fine (millimetre-scale) lamination often associated with anoxic conditions (Byers, 1974; Curtis, 1980; Curtis et al, 1980). The evidence from the sediments and their fauna therefore implies a mainly oxygenated regime with possibly short periods when bottom waters were oxygen-depleted. Undisturbed silt laminations occur both at Patchway and Barnstone at the stratigraphical

level of maximum organic carbon content suggesting that the high organic carbon pulse may be associated, at these localities, with anoxia. High levels of nickel, connected to these high organic carbon concentrations also point to anoxic conditions (Price, 1976).

The stratigraphical position of the organic carbon maximum, near the base of the Upper Unit of the Westbury Member, is most interesting. The Upper Unit is interpreted, in this account, as representing a transgressive phase when the semi-isolated, brackish basins of the Lower Unit were replaced by a more widespread, deeper, and only slightly hyposaline sea (see Chapter 3). Several authors have equated carbon-rich sediments with transgressive events (e.g. Schlanger and Jenkyns, 1976; Hallam and Bradshaw, 1979; Jenkyns, 1980; Leggett, 1980). The causative mechanism for this common correlation is thought to be two-fold; firstly, large areas of coastal plain and delta are drowned, transporting much plant debris seawards and secondly primary phytoplankton productivity is enhanced (Jenkyns, 1980). Studies show that modern organic productivity is concentrated in marginal and shelf seas (Koblenz-Mishke et al, 1970; Tissot, 1978). Therefore an expansion of the volume of epeiric seas by a transgressive event is liable to be accompanied by an increase in primary productivity. In the changeover postulated here, from partially-linked basins to a more continuously-linked epeiric sea both these mechanisms would be expected to operate. The high organic carbon pulse reported here may readily be explained in terms of enhanced productivity associated with expansion of a shelf-sea. Evidence from the detailed organic geochemistry supports a high-productivity environment and is, in general, corroborated by a bulge in the dinoflagellate population which occurs in the upper

part of the Westbury Member (Orbell, 1973). The duration of the high organic carbon pulse vertically, through some tens of centimetres of rock (Fig. 8.2), may be related to the progressive nature of the transgression, and must be related intimately to the supply of nutrients - a vital factor in phytoplankton productivity (Sverdrup et al, 1942; Tissot and Welte, 1978). For a finite period after transgression the nutrient supply would be greatly enhanced by the large contribution derived from drowning of coastal areas. Also, at this early stage in the transgression, the shallow water depth would allow effective nutrient recycling by waves and currents. In these conditions nutrient supply and hence phytoplankton activity will therefore be optimised. As the transgression proceeds, however, and water depth increases, any given site will become more distant from terrestrial nutrient sources and, because of the greater water depth, the ability of waves and currents to recycle nutrients from bottom sediments (despite their enhanced operation due to increased fetch) will moderate. Phytoplankton activity will thus tend to equilibrate with decreasing nutrient availability, and the level of organic carbon input to the sediments will drop off in concert. A further factor causing moderation of primary productivity may occur on stabilisation of sea-level following transgression. The development of stable relative sea-level may be accompanied by thermal or salinity stratification of the water column, the effect of which is to bring the rate of nutrient replenishment down to very low levels (Tissot and Welte, 1978). The development of a stratified water column would, given a continual rain of organic matter, lead, through bacterial oxidation of this organic matter, to a depletion in oxygen which would manifest itself in sediments in the deeper areas of the

basin (c.f. the position in the Black Sea, e.g. Degens and Ross, 1974; Degens and Stoffers, 1980). Reference to Figures 8.1 and 8.2 clearly shows, that the most widespread development of undisturbed lamination (implying oxygen deficiency) occurs in the most offshore (and presumably deepest) setting, at Barnstone and thus lends credence to the development of water stratification.

Running contrary to the ideas so far expressed, some studies have indicated a close relationship between the content of organic matter in the sediment and the sedimentation rate (Trask, 1939; Heath et al, 1977; Müller and Suess, 1979). Heath and his collaborators believe that accumulation of organic carbon is most strongly influenced by bulk sedimentation rate, the effect of biological productivity being less important. This model can be crudely tested in the present case by a comparison of organic carbon content to the sedimentation rate, as demonstrated by the overall thickness of the Westbury Member. Examination of this relationship (Fig. 8.7) shows an inverse correlation between average and maximum organic carbon content and total thickness of the Westbury Member. The implication of this is that net organic carbon input and dilution by other sediment appear to be more important factors here, in the preservation of high levels of organic matter, than is the bulk sedimentation rate.

Small scale fluctuations in the level of organic carbon may be related to short term variations in the input of organic material and of the gross sedimentation rate. These influxes could be either of terrestrial or planktonic nature - corroboration would be required from a detailed palynological study, linked to overall organic contents. They may be

connected to seasonal changes in terrestrial surface run-off or to seasonal phytoplankton blooms. In the latter case seasonal dinoflagellate blooms, similar to those believed to have occurred in the Kimmeridge Clay (Gallois, 1976) could perhaps be the controlling mechanism.

8.5 CONCLUSIONS

The analysis of organic carbon content through the Westbury Member at three separate locations has yielded profiles showing a strong peak which occurs a short distance above a transgressive pulse. Above and below this level organic carbon content falls off and there are only minor variations.

The following model has been proposed to explain this distribution, taking into account detailed organic geochemical results and sedimentological, faunal and trace element characteristics (Fig. 8.8).

1. The Lower Unit of the Westbury Member is deposited in a series of semi-isolated brackish basins. Organic matter at this stage is mostly of terrestrial origin.
2. A relative sea-level rise occurs altering the depositional environment, in the Upper Unit of the Westbury Member, to a broad, only slightly restricted epeiric sea. At an early (shallow) stage in the development of this sea conditions for phytoplankton productivity are optimised (plentiful supply and rapid replenishment of nutrients). This leads to sediments enriched in organic carbon.

3. Bacterial oxidation of organic matter depletes the oxygen supply of bottom waters, and as the transgression proceeds further, waves and currents are no longer as effective in replacing this oxygen or in recycling nutrients. Coupled with this effect a pycnocline develops further contributing to the lack of ventilation. This effect is most marked in the deeper parts of the basin (Barnstone) where laminated sediments develop. In the shallower parts of the basin (Lavemock/St. Mary's and Patchway) waters remain oxygenated as a result of wave and current action. Over the basin as a whole the reduced inefficiency in nutrient regeneration causes a lowering of primary productivity and hence of organic carbon production. Levels of organic carbon in the sediments therefore fall to a new equilibrium level.

Minor fluctuations in organic carbon level are attributed here to seasonal variations in terrestrial organic input and/or to phytoplankton blooms.

This model has an important bearing on stratigraphical correlation in the Penarth Group, since it implies that the organic carbon maximum marks a near-synchronous event of basin-wide significance; an interpretation which suggests that this geochemical feature may have widespread application as a stratigraphical marker horizon.

CHAPTER 9

GENERAL DISCUSSION AND SYNTHESIS

9.1 INTRODUCTION.

The objectives of this Chapter are discussion, synthesis and summary; the aim being to discuss the topics dealt with in the preceding chapters in a broader frame of reference, to attempt to synthesise the individual parts into a coherent palaeogeographical picture and finally to summarise the content of the Thesis.

9.2 DISCUSSION

9.2.1 CORRELATION

In the preceding chapters the sedimentology of the Penarth Group has been described and interpreted in terms of a number of lithostratigraphical subdivisions. The integration of these interpretations into palaeogeography can only be achieved in temporal relationships between the lithostratigraphical units can be established on a regional basis.

Taken as a whole, the Penarth Group has long been known to contain Rhaetian biotas, and thus to be broadly contemporaneous, but the upper and lower boundaries of the stage have yet to be identified in Britain (Warrington et al, 1980) and cannot therefore be used as datums for correlation. Such a correlation is reliant on biostratigraphy coupled with the incidence of stratigraphical events of assumed basin-wide significance.

In the course of his extensive examination of "Rhaetic" exposures from Devon to Leicestershire Richardson (1903 a, b, c, d; 1904; 1905 a, b, c; 1906 a, b; 1909; 1911; 1912) attempted a combined lithostratigraphical and biostratigraphical approach to correlation. This approach was based on the occurrence of beds of distinctive lithological and faunal character at different localities. Recognising that "... sufficiently distinctive, permanent and successive developmental characters have not been made out as yet in any group of Rhaetic mollusca in the beds of this country" he (Richardson, 1906 b) turned, for correlative purposes, to thin hard bands in the predominant argillites. With these he believed that beds could be correlated within certain areas (e.g. he compares strata at Culverhole, Devon with those in the Penarth district of south Wales). The present author's interpretation of these hard bands as storm-deposits (Chapter 3) supports their use as marker horizons. Whilst this approach is useful for fairly localised correlation it cannot readily be extended on a regional scale. It has been suggested that one particular bed in the Westbury Formation (the Ceratodus Bone Bed) may be a reliable datum of widespread application (Richardson, 1906 a; Kellaway and Oakley, 1933; Kent, 1968, 1970). The use of the dental plates of a continental lungfish occurring in shallow marine sediments as a biostratigraphical tool does not, however, seem desirable to the present writer.

Realising the unsuitability of macrofaunas for detailed correlation within the Penarth Group, workers in the last 20 years have focussed their attention on the use of microfossils.

The distribution of ostracods in the Penarth Group was described by Anderson (1964) who proposed a tentative zonal scheme. These zones descend relative to the lithostratigraphy as one progresses northwards from south Wales towards Nottinghamshire and Cheshire, and led Anderson to suggest a transgression of marine "Rhaetic" which moved north from the continent. This suggestion should be treated with caution, however, on several counts; namely, the overall paucity of ostracod faunas, the general lack of stratigraphically sound work on British Triassic ostracods and problems related to taxonomy and the degree of facies control. Whilst ostracods occur in all facies of the Penarth Group their distribution vertically is restricted to a small number of ostracod-rich horizons. The range of individual species is only moderately well known and a number of Anderson's species were established upon very little material (Lord, 1978). Whilst Bate (1978, p 179) asserts that "... it is difficult to suggest that facies has exerted any control at all", Tressler (1957) and Lord (1974, 1978) both recognise the benthonic habit of most ostracods and conclude that the type of substrate is an important limiting factor on their distribution. Ostracods therefore appear to be very poor chronostratigraphical tools whose local stratigraphical range may be controlled by time or ecological factors (Cope et al, 1980, p 9).

The study of palynomorphs is potentially much more rewarding, for correlative purposes, than that of ostracods. The microflora of the Penarth Group has been examined by Chaloner (1962 a, b; 1969), Fisher (1972 a, b); Geiger and Hopping (1968), Morbey (1975), Orbell (1971, 1973), Warrington (1974 b, 1977 a, b, 1978 a, b) and Warrington and Harland (1975). In contrast to the distribution of ostracods, palynological preparations

from the Penarth Group are invariably productive. Orbell (1973) recognised two pollen/spore zones based on the association and acmes of certain taxa; an older Rhaetipollis Zone and a younger Heliosporites Zone (Heliosporites is now considered a junior synonym of Kraeuselisporites, Morbey, 1975). The boundary of these zones climbs from the Cotham Member/Westbury Member junction at Lavernock (south Wales) to a position midway up the Cotham Member in Nottinghamshire (Orbell, 1973) suggesting a southward younging of the Cotham Member. A similar lithostratigraphical position midway up the Cotham Member can be inferred, for the zonal boundary in the Steeple Aston and Withycombe Farm boreholes of Oxfordshire, from the results of Warrington (1977 b, 1978 a). In the latter paper, however, Warrington suggests that major variations, in the miospore succession of the Penarth Group, probably reside " mainly in geographical and ecological changes associated with successive stages in the progress of the Rhaeto-Liassic transgression rather than, within the short time involved, in evolutionary developments" (p 27). This contention is based on marked changes in the miospore assemblage which occur near the top of the Cotham Member and at the base of the Langport Member. Whilst no clear-cut relationship to lithological boundaries is shown by the taxa whose association and abundances define the boundary between Orbell's zones, suggesting a possible evolutionary control in their case, it is difficult to rule out environmental factors of a more subtle nature and hence too much reliance should not, at present, be placed on microfloral biostratigraphy in the erection of a chronostratigraphy. On the other hand, evidence outlined in Chapter 4 (on the distribution of marine macrofauna, ooids and glauconite) suggests a fully marine area lay to the south or south west of Britain during deposition of the Cotham Member. This

observation implies that the effects of a regression (as documented in the Cotham Member) would first be felt in northerly areas, remote from the open sea, and is thus compatible with the southward younging of the Cotham Member suggested by Orbell's zonal scheme. Further detailed palynological work is clearly highly desirable as it may enable the extent of evolutionary and ecological controls on the microflora to be established. Also, the palynology of English sections to the north of Nottingham has yet to be documented.

To the limited and equivocal biostratigraphical data can be added information provided by "event stratigraphy" (Ager, 1973, p 63). The organic carbon maximum recorded near the base of the Upper Unit of the Westbury Member in south Wales, Avon and Nottinghamshire (see Chapter 8) is interpreted as a penecontemporaneous, productivity event thereby suggesting its employment as a datum for correlation. Similar use may be made of a widespread horizon of soft-sediment deformation occurring towards the top of the Cotham Member from Devon to Nottinghamshire, which is considered (see Chapter 4) to be the product of synchronous seismic activity. Whilst certain assumptions are implicit in the use of these events for correlation their application is felt to be justified by the absence of reliable evidence from evolving fossil lineages. A further datum on which to "hang" Penarth Group sequences is the base of the planorbis Subzone of the Hettangian. This horizon, defined by the appearance of ammonites belonging to the genus, Psiloceras, is now considered to mark a virtually synchronous event which is taken as the base of the Jurassic system in Britain (Whittaker, 1976; Cope et al, 1980; Ivimey-Cook et al, 1980).

To summarise, the available evidence suggests that correlation of the Penarth Group may be based on three time-stratigraphical datum levels. The base of the Upper Unit of the Westbury Member is probably penecontemporaneous, at least from Nottingham to south Wales, pointing to a rapid transgression - an inference supported by the probability that the relief of Britain was extremely subdued at this time (Kent, 1970; Audley-Charles, 1970 b). Another datum of comparably widespread application occurs near the top of the Cotham Member. The available biostratigraphical evidence points to a diachronous junction between the Cotham and Westbury Members which youngs southwards. A third datum is provided by the incoming of ammonites marking the base of the Hettangian. Correlation of the units between the upper part of the Cotham Member and the base of the planorbis Subzone is difficult. Limited biostratigraphical information, from the macrofauna and microflora, indicates a possible correlation of the Langport Member with the basal Pre-planorbis Beds of areas where that unit is absent (Kent, 1970; Fisher, 1972 a; Warrington and Harland, 1975). This implies that the White Lias was a shallow-water equivalent of the lower part of the Pre-planorbis Beds of areas where that unit is absent - as suggested by Poole (1979).

The available correlative evidence is summarised in Fig. 9.1.

9.2.2 TECTONISM

It is well established that Triassic deposition (prior to the Penarth Group) was strongly influenced by faulting. Sedimentation occurred in a number of fault-bounded basins and graben structures known to exist in both

onshore (Audley-Charles, 1970 a, b; Steel, 1971 a, b, 1974 a, 1977; Steel and Wilson, 1975; Whittaker, 1973, 1975) and offshore areas (e.g. Binns, McQuillan and Kenolty, 1974; McQuillan and Binns, 1973; Brennand, 1975; Dobson and Evans, 1974). This extensional style of tectonic control, believed to be related to normal faulting linked to structures in the pre-Mesozoic basement, continued throughout the Jurassic (e.g. Chester and Bacon, 1975; Kent, 1975 a, b; Sellwood and Jenkyns, 1975; Ziegler, P. A. 1975; Ziegler, W. H. 1975 and Jenkyns and Senior, 1977), being associated with the early stages in the opening of the North Atlantic (Hallam, 1971; Hallam and Sellwood, 1976; Pitman and Talwani, 1972; Dalrymple, Grommé and White, 1975).

From an examination of "Rhaetic" isopachs, Audley-Charles (1970 b) concluded that their diffuse pattern, compared to isopachs for earlier divisions of the Trias, indicated that the influence of faulting on sedimentation, which became greatly reduced during the deposition of the Mercia Mudstone Group, ceased to be effective during the deposition of the Penarth Group. Whilst in a general way this conclusion is probably correct, there is a body of evidence which suggests that fault movements were still manifesting themselves in these sediments, implying a less tranquil tectonic regime than that envisaged by Audley-Charles.

When local thickness variations are studied they often show a general thickening over basement lows and an attenuation over Palaeozoic structural highs. This association was noted by Kent (1953, 1970) in the east Midlands and can also be displayed elsewhere, for example in the

Central Somerset Basin (of Whittaker, 1973, 1975) where the Penarth Group thins from 10-20 m in the basin-axis to about 4 m at the margins. Other evidence of synsedimentary faulting comes from slumping and contorted bedding. An extensive horizon of intra-stratal deformation occurs near the top of the Cotham Member (see Chapter 4) and is attributed here to earthquake-induced liquefaction. Slump structures and carbonate debris flows, documented from the Langport Member of east Devon coastal exposures, testify to a localised zone of tectonic instability. The general nature and disposition of this unit is, however, suggestive of deposition on a stable platform (Chapter 5).

The varying nature of the Cotham Member/Westbury Member boundary may perhaps be attributed to local tectonic movement. This junction can be transitional (as in the Midlands) suggesting a gradual change of environment or abrupt (as in the south west) implying, in the absence of evidence of an erosive contact, a more dramatic change in depositional setting, possibly linked to sudden uplift. The existence of desiccation cracks over a metre deep in the Cotham Member of this area provides corroborative evidence for such movement.

The general picture of the uppermost Triassic of onshore Britain as a period of tectonic stability is not, therefore, borne out by detailed study, which indicates localised earth movements and occasional, short periods of widespread tectonism. Work in the North Sea (Kent, 1975 a, b; Ziegler, P. A. 1975, 1978; Ziegler, W. H. 1975) extends this evidence by revealing that early-Cimmerian normal faulting and associated halokinetic activity commenced in the Rhaetian.

9.2.3 PALAEOCLIMATE

Throughout most of the Triassic, Britain was in the grip of a harsh arid or semi-arid climate (see e.g. Audley-Charles 1970 a), b)). This aridity is witnessed by the occurrence of sabkha-type evaporites (e.g. Warrington, 1974 a; Whittaker, 1972; Tucker, 1978), by a sparse, desert fauna and by the presence of fossil caliche soils which require seasonal aridity for their development (Steel, 1971 b, 1974 a, b; Tucker, 1977). These climatic conditions are consistent with Britain's tropical palaeolatitude at this time (Smith and Briden, 1977).

Sedimentation time-trends from the Scottish sequence testify to the onset of more humid conditions towards the close of the Triassic. Low-sinuosity streams are gradually replaced, in time, by high-sinuosity streams, and fossil caliche soils ("cornstones") disappear towards the top of the succession. Both factors imply higher and less strongly seasonal rainfall patterns (Steel, 1971 b), 1974 a), b)). Corroborative evidence for an increasingly humid climate is provided by the present study.

In both the Westbury and Cotham Members (Chapters 3 and 4) conditions are generally considered here to have been slightly hyposaline, indicating that loss of water by evaporation was more than balanced by freshwater input from rivers and rainfall. Thus conditions of lengthy emersion, recorded by deep desiccation cracks in the Cotham Member of Glamorgan and Somerset, are unaccompanied by the development of evaporites. By analogy with recent sediment patterns (e.g. Hayes, 1967 b); McManus, 1970)

the preponderance of mudstones in the Westbury and Cotham Members is consistent with deposition on a shelf area adjacent to humid tropical landmasses. The large volume of fine detritus derived from these land areas is believed to result from intense chemical weathering in source areas coupled with transport in the extensive river systems permitted by a non-arid climatic regime.

The sediments of the Langport Member are similar to those of modern tropical and subtropical shelf areas (Chapter 5) which, while reinforcing Britain's latitudinal location, reveals little about the amount and annual distribution of its rainfall. Confirmation of increased rainfall comes, however, from the relative importance of kaolinite and smectite with time. In progressively higher levels of the succession smectite becomes gradually replaced by kaolinite (see Chapter 7) suggesting that leaching of cations in soil profiles becomes increasingly more important.

The overall picture of climatic conditions around the Triassic/Jurassic boundary in Britain is therefore one of a gradual change from a hot, dry regime of seasonal aridity to a more humid tropical or sub-tropical climate with an increased and more evenly distributed rainfall.

9.2.4 PALAEOCEANOGRAPHY

The Mercia Mudstone Group is believed to have been deposited in a hypersaline lake of fluctuating water level, whose margins periodically became emergent, permitting the development of sabkha-type evaporites (see Chapter 1). Sedimentation in this lake was halted by its inundation

as a result of the "Rhaetic" transgression. What can we deduce concerning the nature, hydrodynamics and chemistry of the waters in which the Penarth Group was deposited?

Whilst it is very difficult to provide accurate information of the conditions pertaining in ancient seas, in some instances, it is possible to provide limiting evidence.

The Westbury Member represents the earliest widespread marine invasion of the Penarth Group. Faunal evidence (outlined in Chapter 3) suggests that an early restricted, brackish phase of sedimentation was later replaced by more fully marine conditions with average salinities perhaps in the 20-30‰ range. The extent of tidal influence can be assessed from basin-margin exposures (the Bridgend and Gribun Members) which are respectively interpreted as barrier-inlet/lagoon and prograding tidal flat sequences. The inferred presence of barrier-inlet and lagoonal sediments in the Bridgend Member suggests, by comparison with the relationship between tidal range and coastal morphology in the Recent, that micro- or mesotidal conditions (0-4 m tidal range) were operative (Hayes, 1976). Application of the palaeotidal range model of Klein (1971) to the Gribun Member of western Scotland is difficult because of the fragmented nature of the exposures, but in general indicates tidal ranges of 1-2 m. These small tidal ranges are consistent with the predominance of wave-generated structures throughout the bulk of the Westbury Member; a situation which persists into the Cotham Member (see Chapter 4). Whilst absolute water depths are extremely difficult to

assess from the sediments of the Westbury Member, it is clearly a shallow-water deposit on the basis of its bracketing by units containing evidence of emergence (e.g. desiccation cracks and edgewise breccias), on the recognition of its lateral passage into shoreline sediments and on its ichnofauna. This ichnofauna comprises Diplocraterion, Skolithos, Teichichnus and Thalassinoides all members of the Skolithos ichnofacies believed to indicate littoral or sublittoral conditions (Frey and Seilacher, 1980). Kent (1970) considered water depths, during the deposition of the Westbury Member, to have been unlikely to have exceeded a few metres. In the light of probable tidal ranges of this order, and of the extent of the basin of deposition away from inferred shore-zone sediments, depths of several tens of metres would appear to be more appropriate.

Clearly, the regressive nature of the Cotham Member (see Chapter 4) implies shallower water depths. These must have ranged from the maximum envisaged for the Westbury Member to zero (as evidenced by the indicators of emergence mentioned earlier). Very shallow waters are also demonstrated by the occurrence of ooids, whose Recent production appears to be restricted to depths < 5 m (e.g. Newell, Purdy and Imbrie, 1960; Bathurst, 1975). The biota of these shallow waters, and the lack of evaporites suggest generally hyposaline conditions.

The overlying Langport Member can be compared to modern tropical or subtropical shelf-lagoons (Chapter 5). The importance of lime-muds in this unit suggests probable depths around 10-15 m (e.g. Wilson, 1975) with local evidence for shallower and occasionally emergent shoal areas. Depths of this order are confirmed by the fauna which also indicates

warm ($\sim 25-29^{\circ}\text{C}$) waters of average to slightly hypersaline (27-40‰) nature.

The generally transgressive Lower Liassic strata represent deeper-water deposits than those of the Langport Member. Hallam (1960 b) suggests limiting depths of 150 m for the near normal salinity waters of the Lower Liassic sea.

9.3 PALAEOGEOGRAPHY: SYNTHESIS AND SUMMARY

This section has a two-fold purpose: to summarise the interpretations of palaeoenvironment made in earlier chapters and to integrate them into palaeogeography using the correlative evidence discussed in Section 9.1 and outlined in Fig. 9.1. The land areas depicted in the palaeogeographical maps (Figs. 9.2-9.7) are based on the work of Audley-Charles (1970 b).

The Mercia Mudstone Group largely comprises the deposits of a hypersaline lake in an arid or semi-arid setting. In basinal positions, sedimentary structures attributal to deposition above and below normal wave-base can be distinguished (Klein, 1962). Near the basin-margins are shore-zone sediments which indicate periodic submergence and emergence. Larger-scale fluctuations of lake water level are evidenced by the extensive development of sabkha-type evaporites in sediments of the offshore zone (Tucker, 1977, 1978). In South Wales, shore-zone deposits pass laterally, at the basin-margins, into non-lacustrine sediments. Similar sediments

also form the complete infill of basins of deposition in north west Scotland. They include the deposits of alluvial fans (mudflows, streamfloods and braided streams), talus slopes, floodplains (low- and high-sinuosity streams) and playa lakes (Tucker, 1977; Steel, 1971 b), 1974 a); Steel, Nicholson and Kalander, 1975). The red colour of much of the group is attributed here to the slow, diagenetic production of haematite by the alteration of hydrated iron oxides and/or iron-bearing silicate minerals. The Tea Green Marls at the top of the unit probably owe their grey-green colour partly to higher initial contents of organic matter and partly to reducing pore-water conditions induced by the overlying, organic-rich Westbury Member.

The Grey Marls of south western Britain reflect an interplay of subaqueous lacustrine deposition producing laminated sediments, and subaerial conditions leading to the development of evaporitic and mudcracked sabkha deposits with disrupted lamination. The presence of former evaporites is frequently witnessed by calcitic or dolomitic pseudomorphs bearing gypsum or anhydrite relicts.

The clay mineralogy of the Mercia Mudstone Group reflects a probable combination of detrital illite and chlorite with neoformed minerals including sepiolite, palygorskite and corrensite which are believed to have resulted from the interaction between dense, hypersaline waters and lighter, overriding marine waters during periods of transgression. A lateral zonation of these neoformed clay minerals can be broadly related to the areal distribution of evaporite minerals (Jeans, 1978).

The palaeogeography of this period is summarised in Fig. 9.2.

The earliest signs of the "Rhaetic" marine transgression are recorded in south west England and south Wales in the form of the Sully Member, which contrasts with the underlying Grey Marls by containing a fairly diverse marine macrofauna, microflora and ichnofauna, and by lacking evaporites (except in the form of vein infills derived from below). This lithofacies is believed to have been deposited in a shallow sublittoral environment.

The Westbury Member represents the first widespread manifestation of marine conditions in the Penarth Group. Its base is frequently marked by an erosion surface overlain by a vertebrate-bearing rudaceous deposit (bone-bed) believed to represent a beach remnant which survived the passage of the transgression. The lower beds of the Westbury Member vary greatly in thickness and individual beds cannot be traced laterally for more than a few kilometres. Coupled with the restricted fauna, dominated by vertebrate remains and a few molluscan species, this suggests that the early phase of the transgression resulted in the establishment of a number of semi-isolated basins of deposition. The low diversity of, and certain elements within, the fauna (e.g. darwinulids) suggests that the waters of these basins were brackish. The position of these basins was probably governed by pre-existing topography.

The progression of marine inundation is witnessed in the Upper Unit of the Westbury Member by a markedly more diverse fauna, now dominated by molluscan elements, and by a great increase in the lateral persistence of individual beds, indicating a much wider uniformity of environment than

hitherto. The sediments are believed to represent subtidal shelf muds with intercalated arenaceous beds representing a variety of storm deposits. A marked peak of organic carbon content occurs near the base of the Upper Unit in at least three localities. It is contended here, that this maximum results from a phytoplankton productivity event which occurred across the basin at a time when nutrient supply and replenishment were optimised. Subsequent progress of the transgression led to the development of a basin-centre pycnocline, which reduced vertical circulation and thus nutrient recycling, causing a fall-off in organic carbon levels. The fauna of the Upper Unit indicates salinities approaching those of "normal" marine waters. The lack of ammonites and most brachiopods (which occur in coeval Tethyan rocks) suggests a physical or chemical barrier to their migration. This might, for instance, have been a slight degree of hyposalinity, salinity fluctuations or a depth restriction.

A regional study of clay mineralogy reveals a zonation in the Westbury Member between an illite + chlorite + illite-smectite, nearshore assemblage and an illite + chlorite + smectite + illite-smectite offshore assemblage. This is attributed to differential sedimentation of detrital clays in which a size-segregation mechanism, comparable to that invoked by Gibbs (1977) to explain variations in Recent clays off the mouth of the Amazon, was probably the dominant factor.

When traced laterally towards the basin margins, the Westbury Member passes into arenaceous and rudaceous deposits which are here accorded local member status. These coarse-grained sediments are interpreted as nearshore equivalents of the Westbury Member, deposited in a variety of

environments. The Bridgend Member of south Wales is believed to contain barrier-inlet, lagoon and tidal-flat elements. Subtidal and intertidal-flat environments are envisaged for the Gribun Member in north west Scotland and an intertidal gravel-beach setting for the Hapsford Member, which occurs on the northern margin of the Mendips. Similar milieux may have existed on the northern and western fringes of the London Platform, during the deposition of the Twyford Beds. The nature of these nearshore facies suggests a tidal range of between 0 and 4 m.

The palaeogeography of the Westbury Member is outlined in Fig. 9.3.

Deposition of the Westbury Member was terminated by a regression which led to the accumulation of the Cotham Member. The effects of this regression appear to have been experienced earliest in northerly areas, remote from the open sea and spread to the south and south west (Fig. 9.4).

The Cotham Member is interpreted here as a lagoonal deposit. A number of elements of the biota, namely darwinulid ostracods, Euestheria and the liverwort Naiadita, coupled with the absence of evaporites in emergent strata, point to predominantly fresh to brackish water conditions. On the other hand the ubiquitous occurrence of marine microplankton indicates connection with the open sea. Intermittent submersion and emersion is demonstrated by mud-cracked ripple marks and by the co-existence of algal stromatolites (Cotham Marble and Estheria Bed) with edgewise breccias.

Extremely deep desiccation cracks, developed near the top of the unit in the south west, point to an extended period of emergence, signifying the maximum stage of the regression. Strata above this level herald returning marine conditions.

A two-fold zonation of clay minerals, identical to that of the Westbury Member, persists into the Cotham Member, but with the main smectitic zone displaced northwards. Smectite is however almost completely absent in emergent areas, suggesting it was still being transported to more offshore regions in the manner envisaged for the Westbury Member. The lateral displacement of the zones can therefore be assigned to the regressive nature of the Cotham Member, whose palaeogeography is depicted in Fig. 9.5.

The Cotham Member is followed abruptly by marine sequences testifying to rapid, renewed transgression. Three essentially coeval facies are probably represented by the Langport Member, the Watchet Member and the lower part of the Pre-planorbis Beds (where the former units are absent).

The Langport Member is dominated by pure micritic limestones with subordinate bioclastic calcarenites and calcirudites. The calcarenites and some of the calcirudites are interpreted as storm deposits. Matrix-supported calcirudites, common in the east Devon coastal sections, are believed to reflect deposition from subaqueous density flows. These strata testify to a local zone of tectonic instability which is further evidenced by the occurrence of slump-beds. Other rubbly beds are probably the product of diagenesis as they possess strikingly similar features to inferred pressure solution seams and flasers described by Garrison and Kennedy (1977) from the English Chalk. The Langport Member is commonly bioturbated;

the ichnogenera Diplocraterion, Thalassinoides, Spongeliomorpha and Chondrites being recognised. Evidence for early lithification, at several horizons and locations, is provided by Trypanites borings, encrusting oysters and the wrapping of sediment around underlying irregularities. The White Lias is closely comparable to sediments accumulating in the shallow waters of modern tropical and subtropical shelf-lagoons, which in the absence of clastic influx are largely floored with carbonate muds. An increase in calcarenites to calcilutites occurs on the Somerset coast and in south Wales in association with infrequent mudcracks, and is taken to represent a shallow shoal environment. The localised appearance of kaolinite in the Langport Member of the Devon area is believed to be related to the unroofing of Cornubian granites as envisaged by Cosgrove and Salter (1966).

The Watchet Member is probably a local equivalent to the upper part of the Langport Member in which the increased terrigenous clastic content and the low diversity fauna are believed to reflect proximity to a river mouth. The introduction of clastics is known to reduce carbonate production by limiting sunlight penetration and by providing a substrate unsuitable for benthos (e.g. Ginsburg and James, 1974) and the input of fresh-water would be expected to lead to a reduction of faunal diversity.

The White Lias appears to pass northwards into the impure limestone-mudstone sequence of the basal Lias in the north Midlands and northern England. The transition between the two facies seems to be gradual with, for example, a very thin remnant of Langport Member occurring in south Nottinghamshire (Kent, 1970). This facies interrelationship suggests

that the northern boundary of the Langport Member shelf-lagoon was not a sharp break of slope with fringing reefs or islands (as in most modern shelf-lagoons) but a more subdued feature with the deposition of pure carbonates being gradually prevented by increasing water depth and an increased influx of terrigenous material, presumably from a northerly source. The Langport Member is therefore probably a shallow-water equivalent of deeper-water limestones and mudstones in more northerly areas. The palaeogeography as deduced from the spatial arrangement of the three facies discussed above is shown in Fig. 9.6.

The spread of Lower Liassic Pre-planorbis Beds facies over the Langport and Watchet Members demonstrates the continuance of marine transgression with the replacement of shallow-water deposits by sediments believed to have been deposited in waters up to 150 m deep (Hallam, 1960 b)). Shallow-water conditions are known, however, to have still pertained into the basal Jurassic (*sensu* Cope et al, 1980) in south Wales, the Mendips and in parts of north west Scotland. In south Wales, the Sutton Stone and Southerndown Beds comprise conglomerates and calcarenites with subordinate calcilutites, representing beach and shallow sublittoral deposition (Wobber, 1965). A similar nearshore setting, adjacent to islands of Carboniferous limestone, is envisaged for the calcarenites and calcirudites of the Downside Stone which outcrop both north and south of the Mendips (Savage, 1977). The Broadford Beds of Skye, Pabay, Raasay and Ardnamurchan include a variety of limestones and coarse siliciclastic sediments in which the presence of coralline and colitic limestones clearly indicate nearshore depositional environments. These nearshore sediments grade over a few kilometres into the more areally widespread, offshore "Blue Lias" facies.

Alternations of limestone, mudstone/shale and marl typify this facies and are generally considered to result from a combination of primary depositional and diagenetic factors (e.g. Hallam, 1964; Wobber, 1965; Amiri-Garroussi, 1978). The preponderance of mudrocks in the north Midlands and northern England is attributed here to a distal offshore environment as compared to the more proximal offshore setting of the limestone-mudstone sequences of Mull and Morvern to the north and other areas of England and Wales to the south.

Whilst north west Europe in general experienced a Lower Liassic transgression, probably as a result of local tectonism rather than a eustatic sea-level rise, certain areas, for example, the northern flank of the London Platform, suffered a regression caused by tectonic uplift (Donovan, Horton and Ivimey-Cook, 1979).

Lower Liassic palaeogeography is illustrated in Fig. 9.7.

9.4 FURTHER RESEARCH

It is hoped that the present study has answered some of the questions posed by the Penarth Group. It has also, however, inevitably raised a whole series of new queries which provide the basis for future work:-

1. There is still considerable scope for palaeontological study.

Detailed faunal and palaeoecological work has only, to date, been carried out in south Wales (Ivimey-Cook, 1962). In particular, molluscan taxonomy in the Penarth Group is in need of revision. On

the micropalaeontological side an extension of palynological examinations to northern England is necessary, and a detailed investigation of the extent of evolutionary and environmental influences on the microflora is highly desirable from a regional correlation standpoint. Bone-beds in the Westbury Member justify a study in their own right. In particular the hydrodynamics of vertebrate debris is not understood and the extent of prefossilisation requires assessment.

2. Colour variations in the Mercia Mudstone Group clearly warrant intensive examination, especially from a chemical diagenetic angle. Which is the more important factor in Tea Green Marl pigmentation: original organic content or pore-water conditions induced by the overlying Westbury Member? A comparative study of the grey/green and brown facies of the Cotham Member could also prove rewarding.
3. It is hoped that the present thesis has provided the basis for a regional framework in which to examine aspects of Penarth Group sedimentation in detail over smaller areas. There is more to be learned from organic geochemical studies in the Westbury Member. How far can the organic carbon maximum be traced? Does further detailed organic geochemical analysis support its interpretation as a productivity event? How is organic carbon content related to palynomorph distribution?

Only a few of the possible avenues of future research are outlined here, there is clearly a great deal of room for further study of this thin, but extremely interesting sequence of rocks.

APPENDIX 1: EXPOSURES.

A map (Fig 0.3) showing the location of exposures with an accompanying list of grid references may be found in a pocket at the back of Volume 2. Graphic logs of major exposures, not given in full in illustration of the main text, are reproduced here (Figs. A1.1 - A1.10). A brief description of strata visible in the more important of the minor exposures visited by the author, is also included together with sources of further detail where appropriate.

1. Charton Bay, Devon.

Small areas of exposure on the west side of the bay enable the uppermost strata of the Mercia Mudstone Group to be examined. The top 3m of the Langport Member including the uppermost, *Diplocraterion* - burrowed, "Sun Bed" and the basal. Few metres of the Blue Lias are visible. (See also Hallam, 1960a, Orbell, 1973).

2. Charlton Mackrell railway cutting, Somerset.

This cutting is now mostly overgrown except for patchy exposure of the Langport Member and lowermost Lias. In massive beds near the base of the White Lias a fairly rich bivalve fauna including Modiolus, Liostrea and ? Mactromya was observed in association with numerous echinoid spine fragments. (Also see Richardson, 1911).

3. Shepton Mallet railway cutting, Somerset.

Amongst the undergrowth the dark grey shales of the Westbury Member can be seen overlying the Tea Green Marls. Near the top of the cutting the Langport Member is exposed. The pale grey/cream limestones of this unit contain bivalves (e.g. Modiolus and Liostrea) and poorly preserved corals. Thalassinoides burrows occur at two or more horizons and can be seen also on fallen blocks on the floor of the cutting. (Also Richardson, 1911).

4. Mudgley Hill, Wedmore.

In the stream section, described by Green and Welch (1965) Tea Green Marl containing dark shale bands is overlain by 30cm of dark grey shales (Westbury Member) on which rest a few metres of rust-coloured, cross-bedded sandstones. and often nodular, shelly limestones.

5. "Madwoman's Lane", Wedmore.

A short section of about 1.5 m. comprised of Tea Green Marls, succeeded by lenticular and cross-laminated sandstones and mudstones belonging to the Westbury Member. (Richardson, 1911; Green and Welch, 1965).

6. Harris' Quarry, near Chelwood, Avon.

The quarry, described by Green and Welch, 1965, is now filled in, but small exposures of the Langport Member occur in a stream

just north of the road.

7. Stormy Down, Bridgend.

In small disused quarries on the north side of the Down, some 2.5 m of ? the Lower Sandstone of the Bridgend Member are exposed, large scale tabular cross-bedding laid by west-north-westerly and north-westerly flowing currents are visible. Greenish clays were observed on spoil heaps. (See also, Francis, 1959).

Scattered about Stormy Down are also small outcrops of pebbly sandstone.

8. Laleston quarry.

Little can be added to the description of Francis, 1959 (p.165) The sandstones here are finer-grained than at Stormy Down, but small scale cross-lamination indicates westerly palaeoflows comparable to those at Stormy Down. The local council have plans to fill the quarry with refuse.

9. Cefn Cribwr.

Poor exposures seen in the banks of a small stream. About 1.5m of ? Upper Sandstone was observed. This appeared to be finer grained than that at Stormy Down and lacked obvious cross lamination. (See Francis, 1959).

10. Coity.

Only about 1 m of sandstone is now visible in the road cutting to the south of the village described by Francis (1959). This is horizontally laminated and contains leached bivalve moulds.

11. Quarella quarry, Bridgend (ss 903,808)

This disused quarry is now almost wholly overgrown, but a metre or so of sandstone and 1-2 metres of green calcareous mudstone are still visible (see also Richardson, 1905 b, Francis, 1959).

12. Sedbury Cliffs.

The main exposure is visible but inaccessible. Consituent beds can be examined on the shore-line and details of a section measured by Richardson (1903 b), but not located by the present author, are available. The section may be closely compared to that at Aust Cliff on the opposite bank of the Severn.

13. Wainlode Cliff.

This river cliff exposes the upper part of the Mercia Mudstone Group, the Penarth Group and lowermost Lias. With some rather precarious climbing and digging the section can be examined (part is shown in fig. 4.1). Distinctive limestone and sandstone horizons are best examined in fallen blocks at the base of the cliff (see also Richardson, 1903 c).

14. East Leake.

A preliminary account of the railway cutting to the S.S.W. of East Leake is given by Browne (1895). A little judicious excavation (aided by that of rabbits) reveals the general sequence from keuper - Lias. To the north of the road the Tea Green Marls and Westbury Member can be discerned whilst the remainder of the section can be gleaned wouth of the road. The mudrocks of the Cotham Member contain lenticular sandstones and nodular limestones - the latter a characteristic feature in the East Midlands.

15. Bunny.

The road cutting is now largely overgrown but can be sampled by digging. A section measured at the time of excavation is included in Kent (1953).

16. Stanton-on-the-Wolds.

Evidence of the Tea Green Marls and Westbury Member can be seen close to the northern end of the railway tunnel entrance. A description of the exposure and the contained fauna is given by Johnson (1950).

17. Blue Hill, Owthorpe.

In the old clay pit adjacent to the Grantham Canal, the upper metre of the Cotham Member and the basal limestone of the Lias can be excavated. Sedimentary structures can be seen preserved

in limestone nodules from the Cotham Member which litter the floor of the pit. (Further information in Kent, 1968, 1970).

18. Barnstone.

The section in the disused railway cutting was ascertained in some detail by Sykes, Cargill and Fryer (1970) following the cutting of a series of trenches by members of the East Midlands Geological Society. Examination is still possible with a little digging.

19. Beacon Hill, Newark.

Digging in the sides of the old gypsum pit revealed the upper 50 cm. of the Tea Green Marls and the basal 2 m or so of Westbury Member shales (see also e.g. Johnson, 1950)

20. Dibdale, Northallerton.

In the north bank of the stream in a small wood, about a metre of dark grey Westbury Member shale containing a single sandstone were visible (also see Fox-Strangways et al, 1886).

21. Allt nan Dris, Arran.

A small outcrop, about 100 metres long of "Rhaetic" sediments occurs mainly on the south bank of the stream. The dark grey mudrocks and thin, generally lenticular sandstones (Westbury

Member) have been baked and disturbed by minor faults during their incorporation into a Tertiary vent agglomerate, (see Peach, Gunn & Newton, 1901).

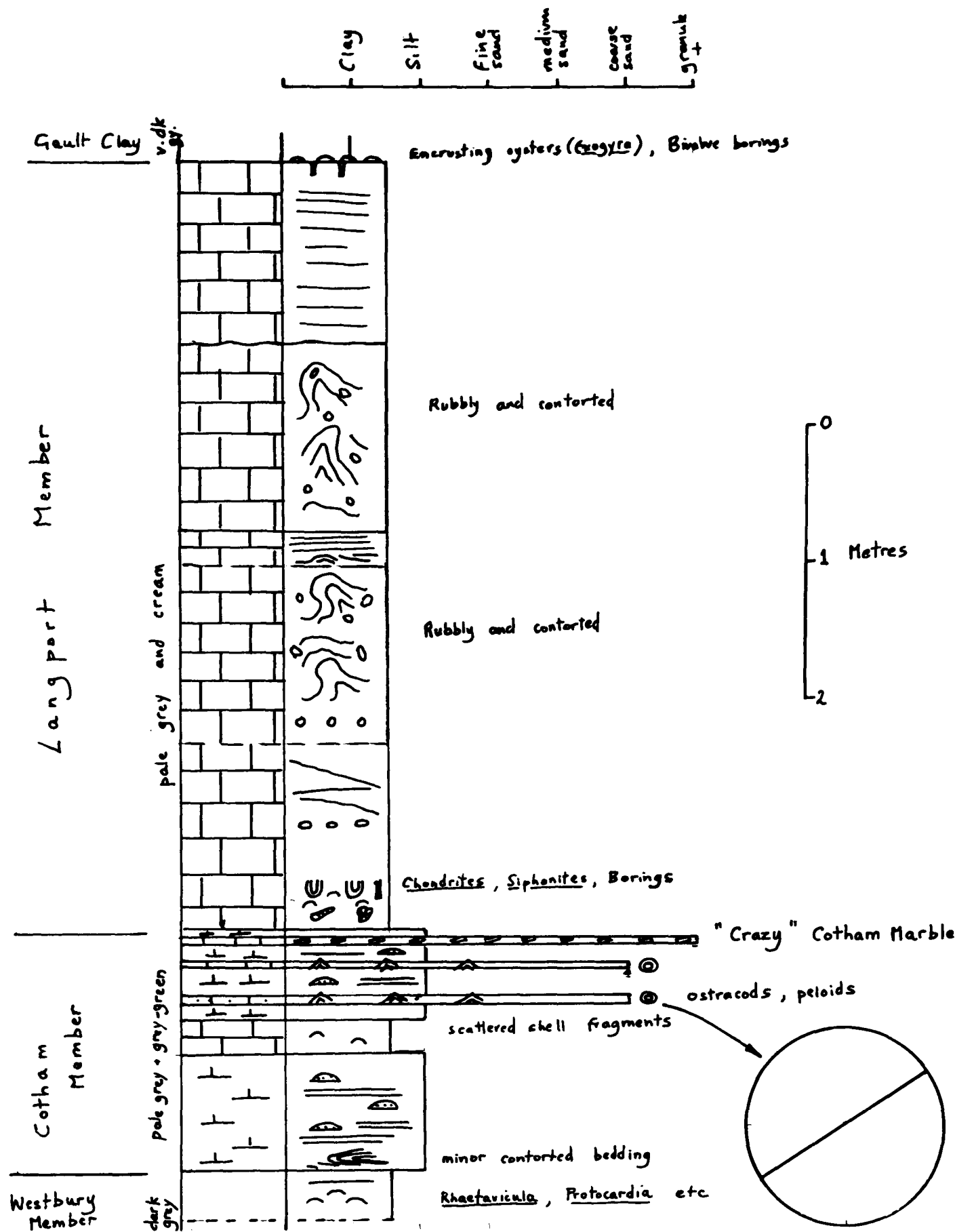


FIG. A 1.1: CULVERHOLE, DEVON

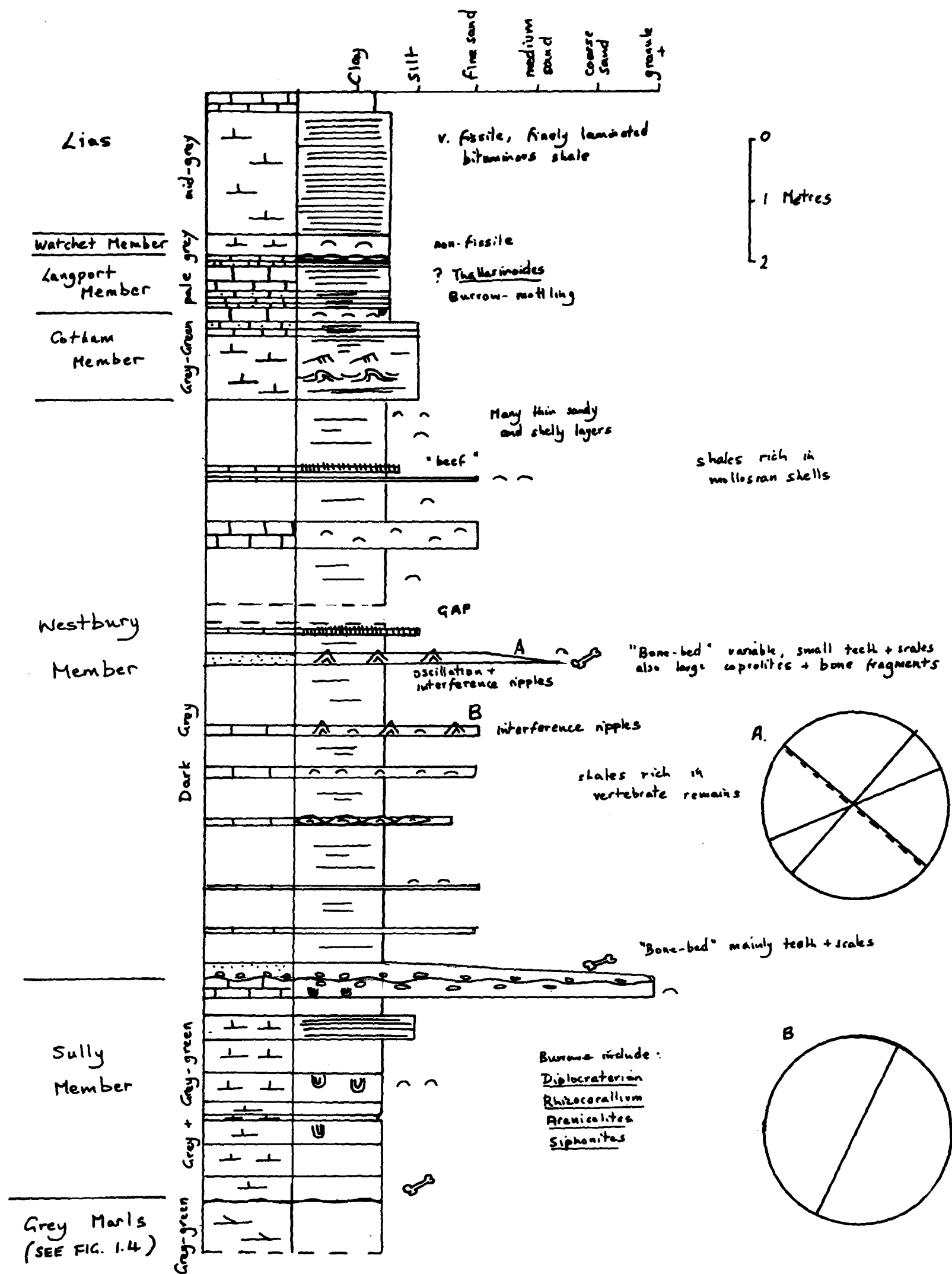


FIG.A1.2: BLUE ANCHOR POINT, SOMERSET

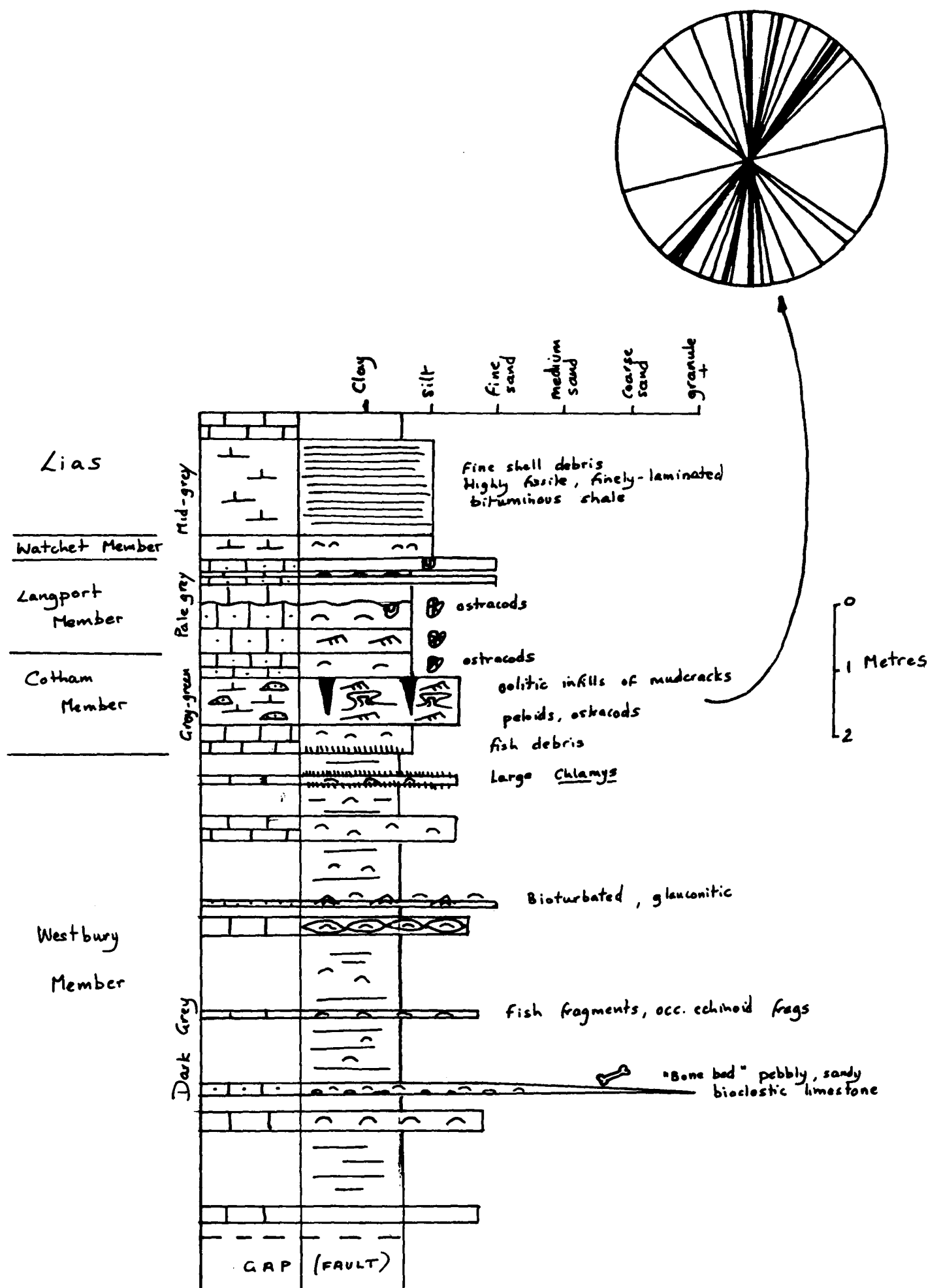


FIG. A1.3: ST. AUDRIE'S BAY, SOMERSET

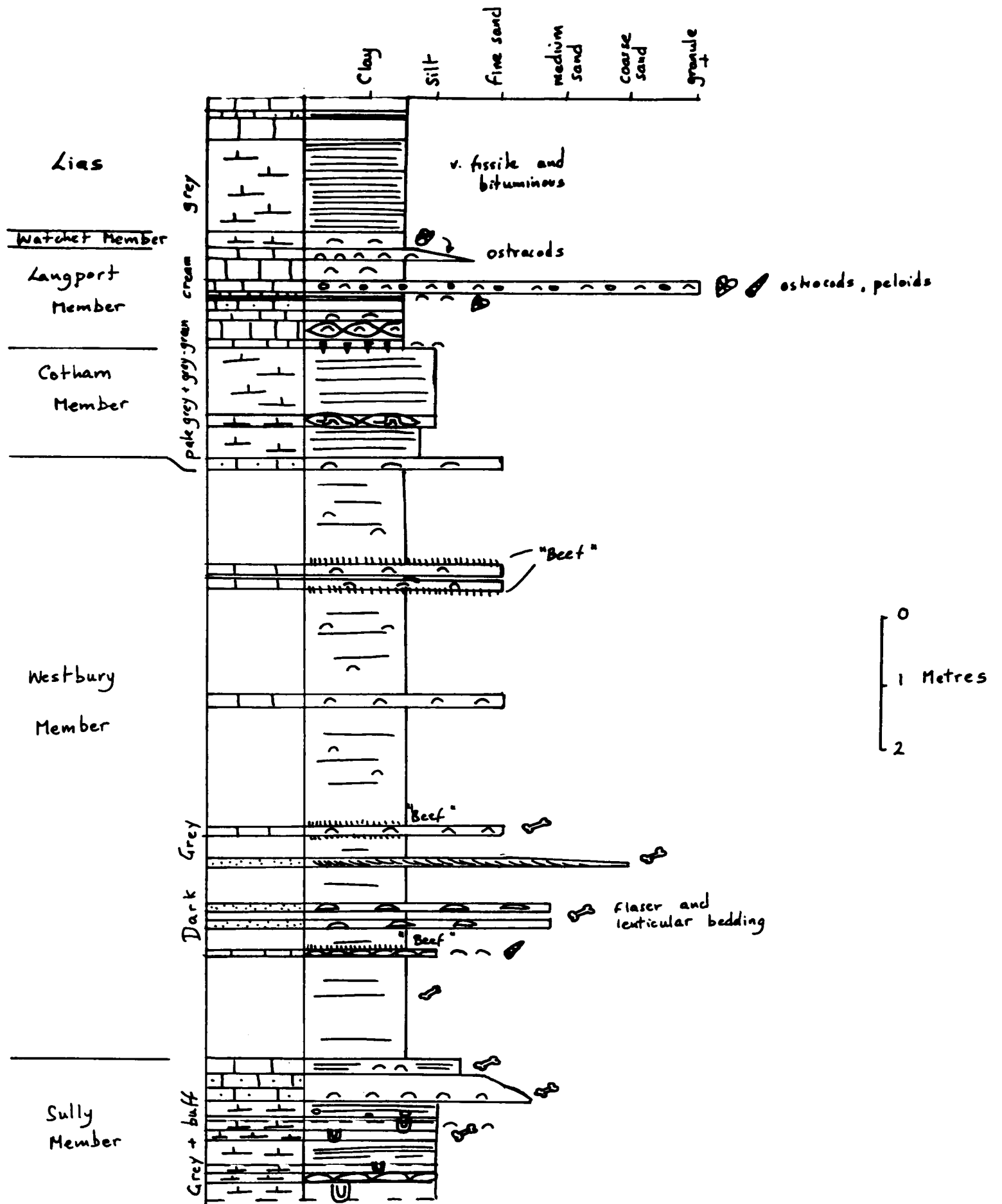


FIG. A1.4: LILSTOCK , SOMERSET

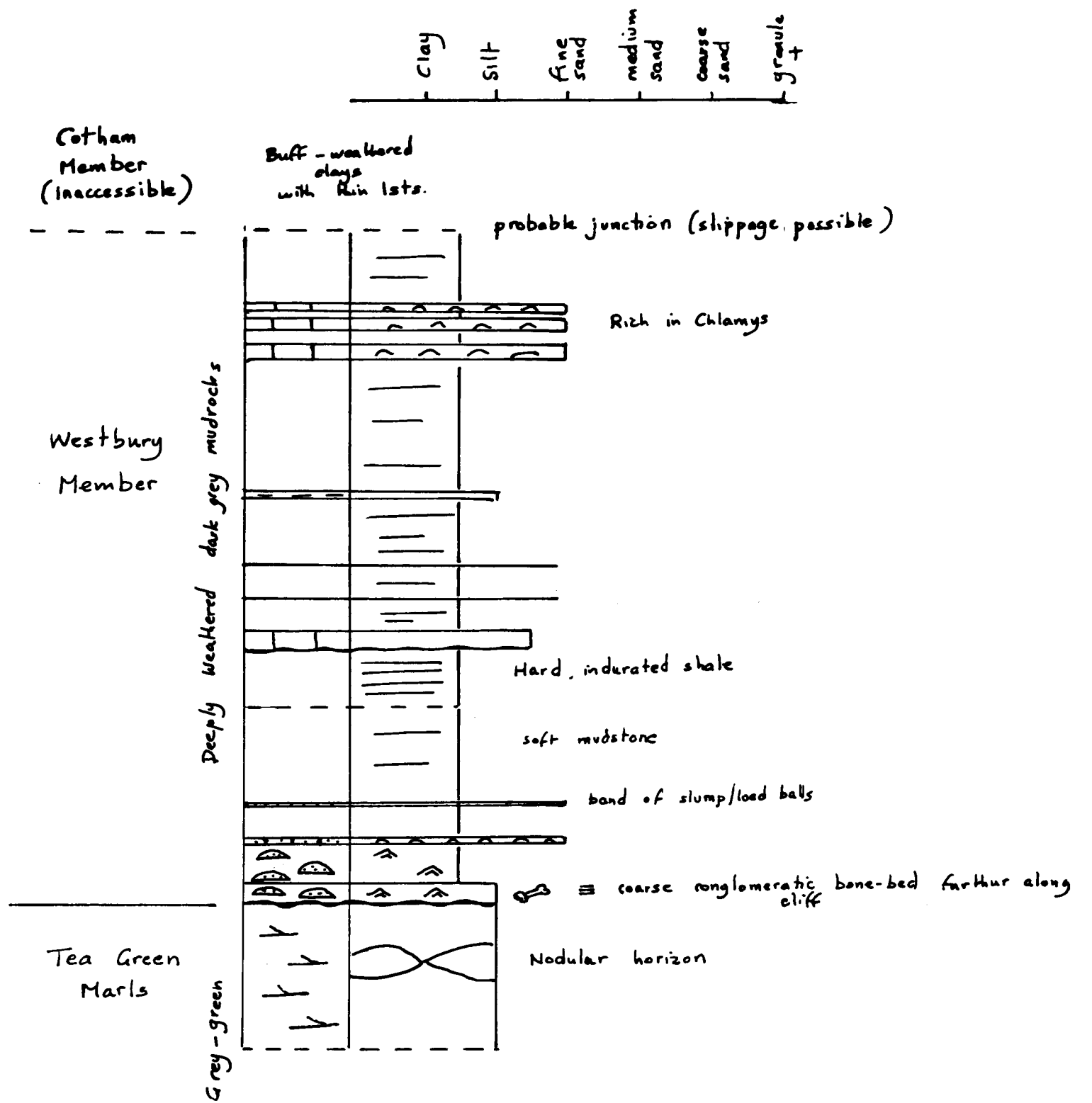


FIG. A 1.5: AUST CLIFF, AVON

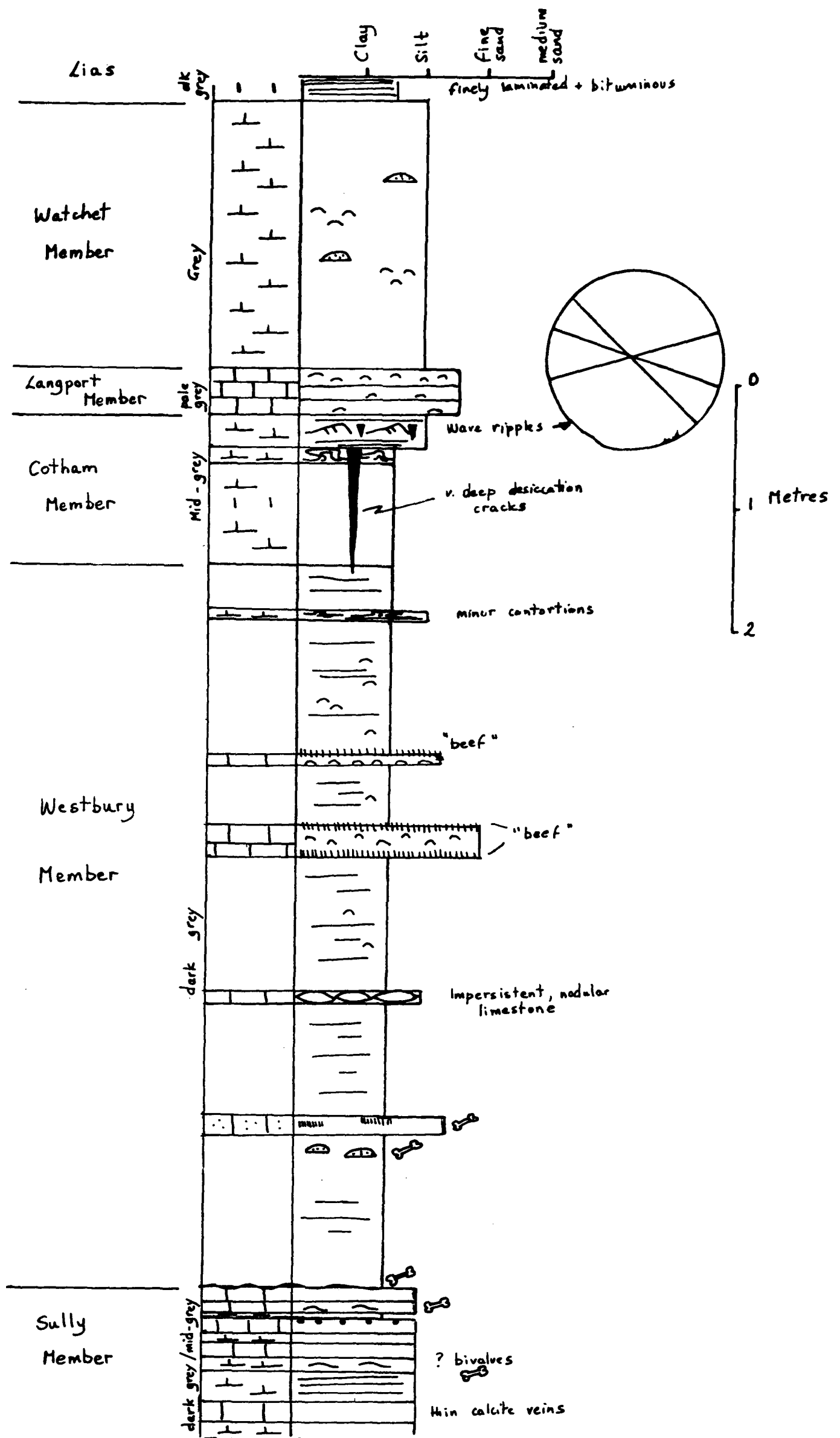


FIG. A1.6 : PENARTH CLIFF SOUTH GLAMORGAN

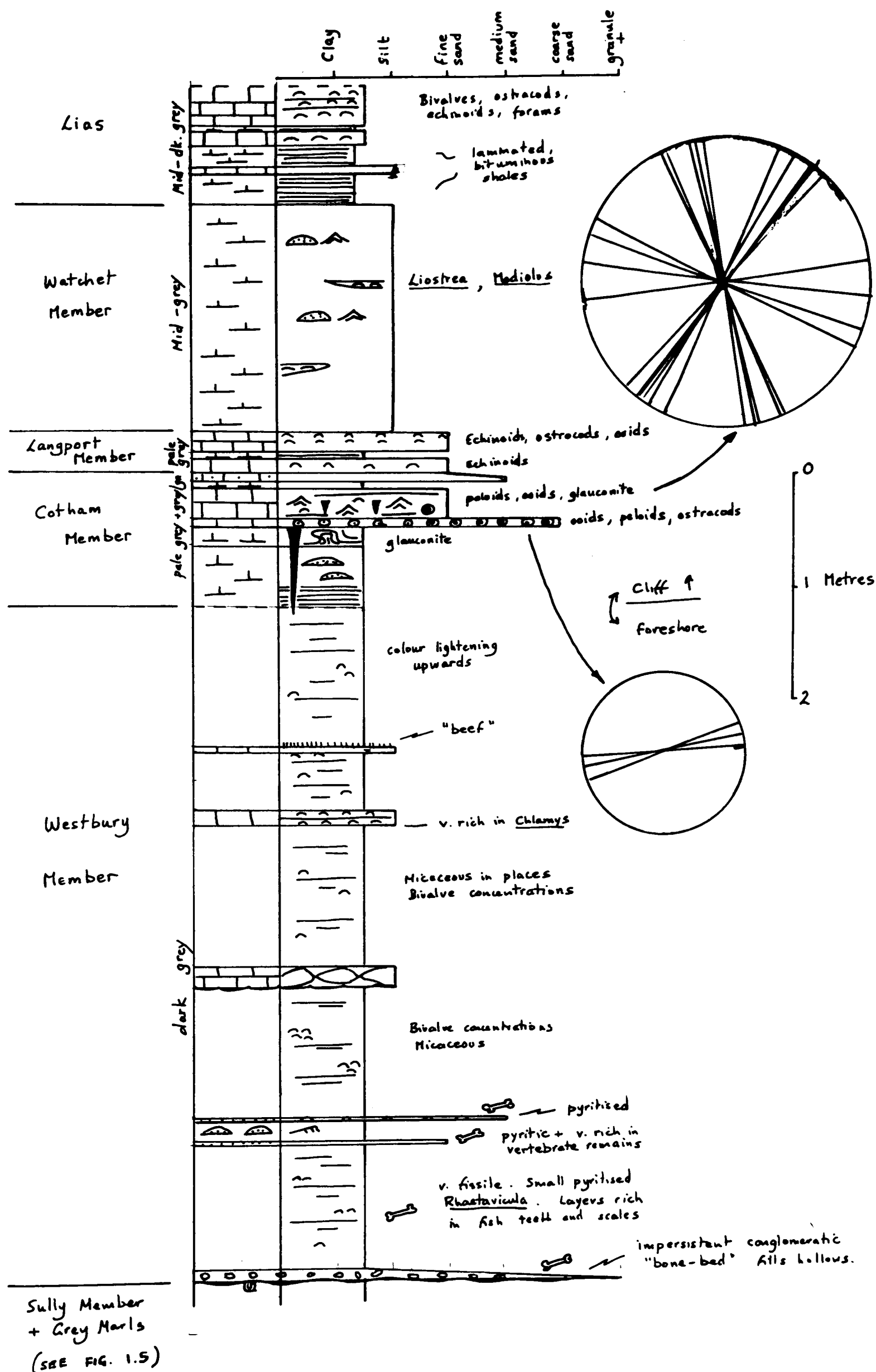


FIG. A1.7: LAVERNOCK POINT SOUTH GLAMORGAN

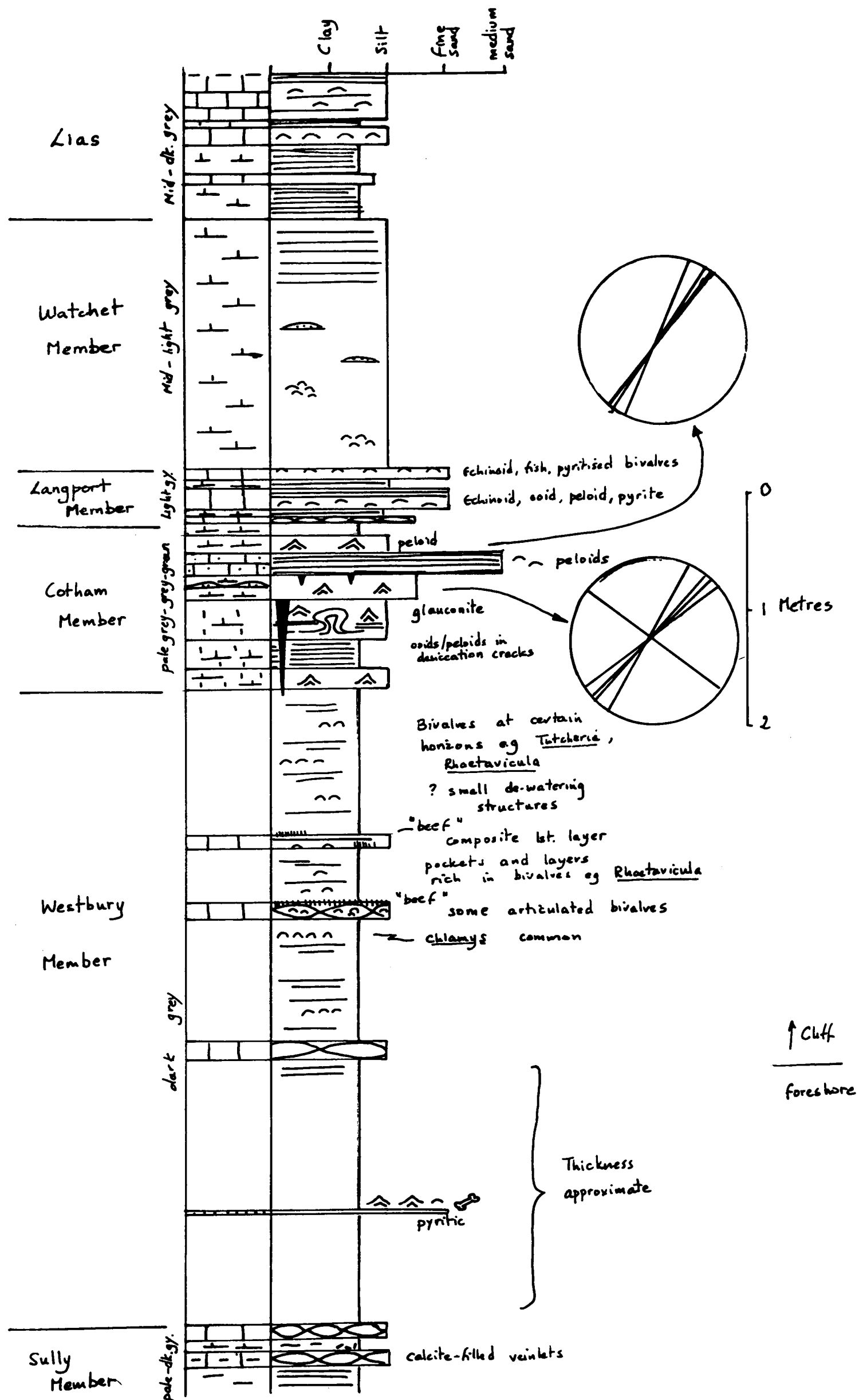


FIG. A1.8: ST. MARYS WELL BAY, SOUTH GLAMORGAN

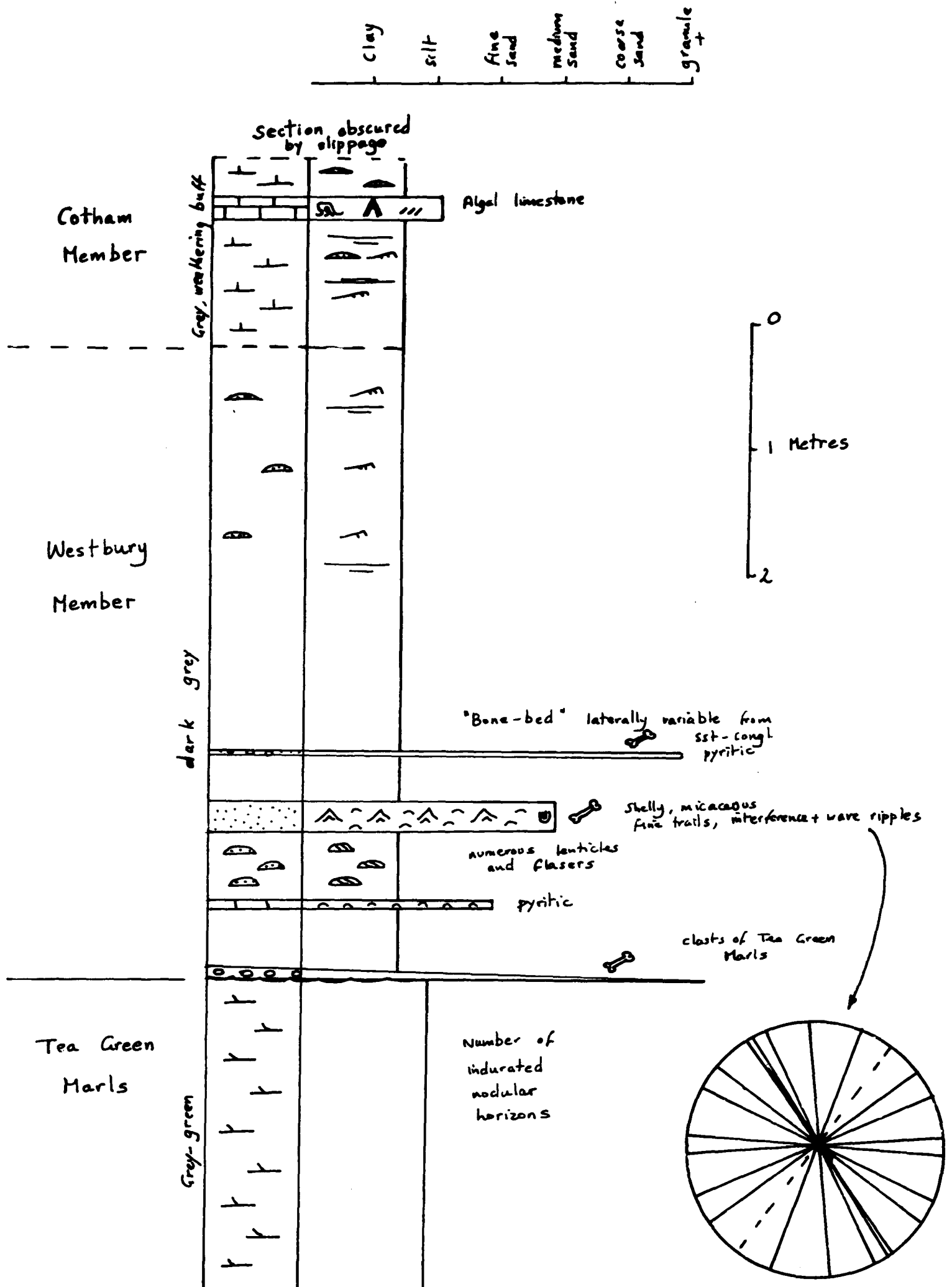


FIG. A1.9: WESTBURY GARDEN CLIFF, GLOUCESTER

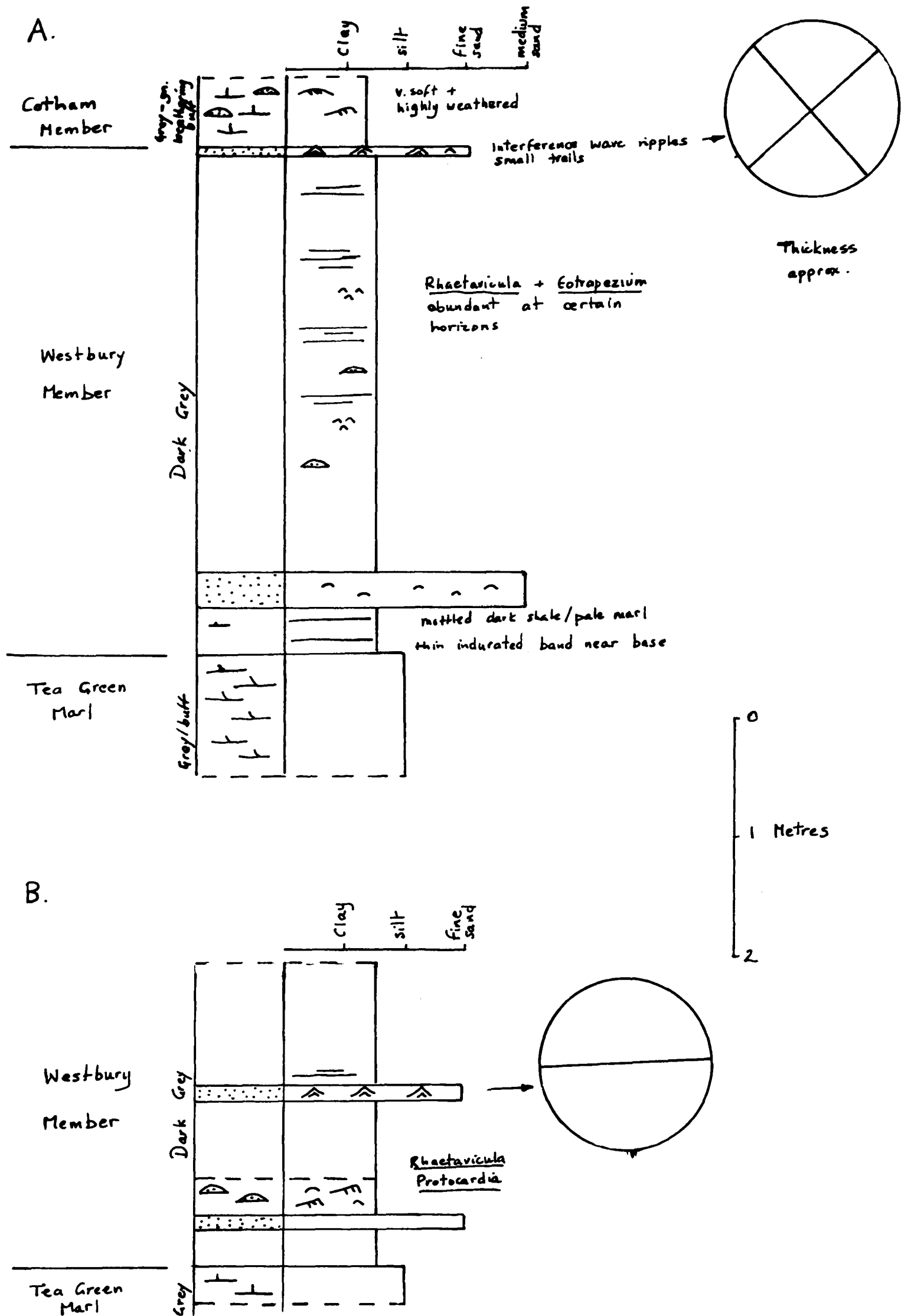


FIG. A1.10: A. HARROGATE HOUSE, B. CROSBY COURT,
NORTH YORKS.

APPENDIX 2.

DETERMINATION OF ORGANIC CARBON.

A 2.1 SAMPLE PREPARATION.

Unweathered samples were collected, washed in de-ionised water, dried and then ground to pass a 90 μ brass mesh (the use of nylon mesh should be avoided as a potential source of carbon contamination). Between 10-80 mg. of the resultant rock powder was weighed in an aluminium boat and transferred to the reaction flask.

A 2.2 APPARATUS.

The apparatus used is illustrated in fig. A 2.1. Helium was passed from a cylinder through a molecular sieve 4A clean up tube, the output of which passed:

- a) via a reduction valve into the reaction flask, monitored by the flow-tube connected to the outlet of Trap B and;
- b) via the Gas Chromatograph (G.C.) column, to a needle valve and flow-meter.

The G.C. used was a Shandon Southern UK 3 whose glass column (internal diameter = 0.5 cm, length 90 cm) was packed with Poropak R (100-120 mesh). The G.C., which employs a thermal

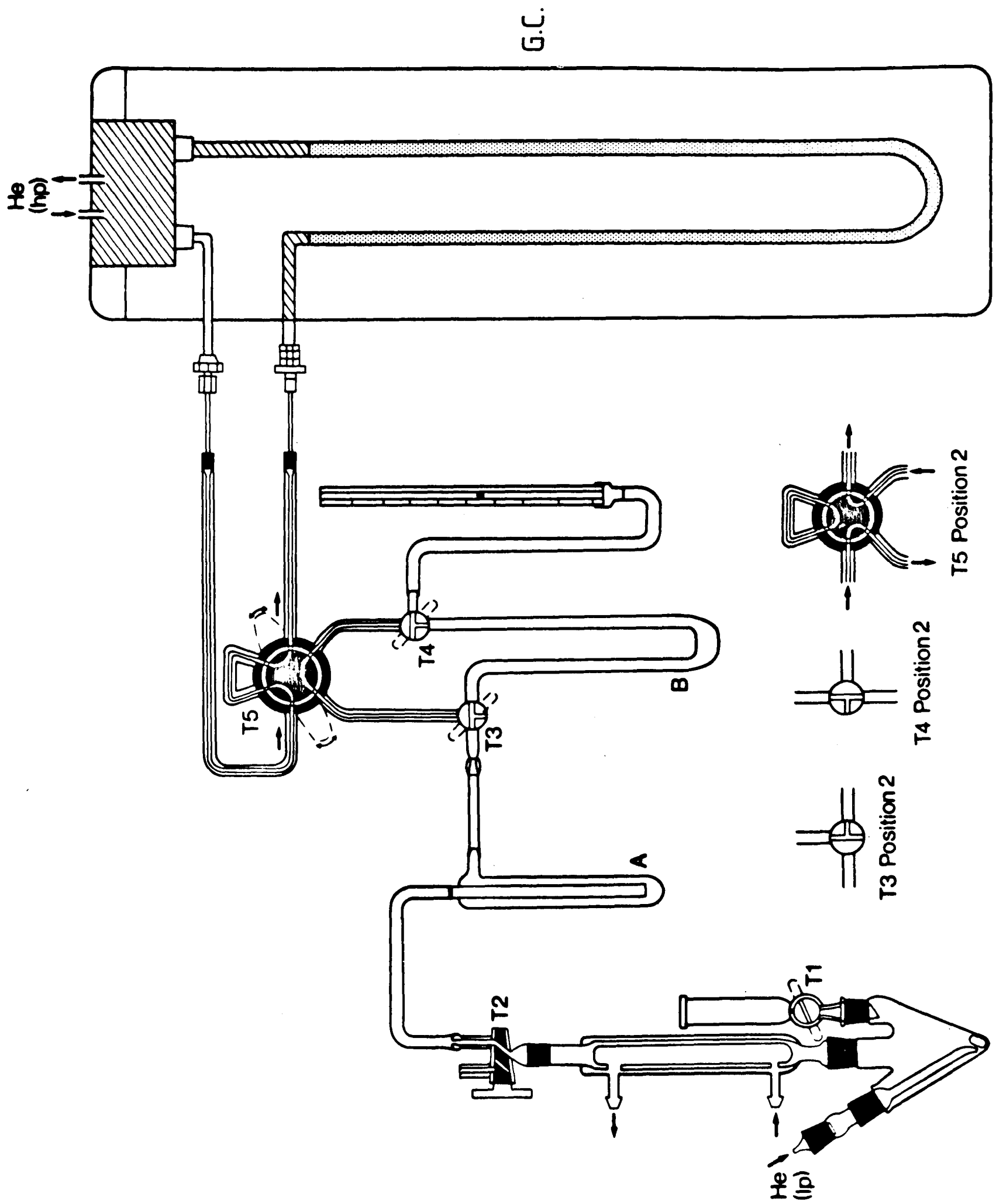


FIG. A. 2.1: APPARATUS FOR ORGANIC CARBON DETERMINATION

conductivity (katharometer) detector (current 300mA) was maintained at 110°C. The amplified signal from the detector was fed to a Servoscribe 1s potentiometric chart recorder (500 mv range and 30 mm/min chart speed were used). The carbon dioxide produced by oxidation of the organic carbon in the samples generated a symmetrical, gaussian shaped peak. The quantity; peak height x width at half height, was used as an expression of peak area. For this type of peak this parameter is equivalent to a constant 94% of total peak area and can hence be used for direct comparison (C. Simpson, 1970, p 83).

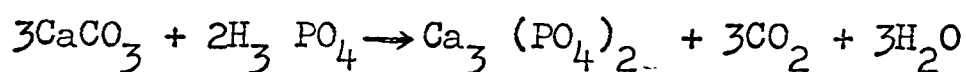
A 2.3 SYSTEM FLUSHING.

The reaction flask and sample were attached to the analytical system as depicted in fig A 2.1. The sample was wet with a few drops of deionised water to prevent sample loss during flushing and a teflon coated stirrer bar was placed in the flask to permit agitation during the reaction. Flushing was carried out by passing helium through the system at a flow rate of 25-30 cm³/minute for four minutes, with all taps in position 1. Air was cleared from the key of tap T1 by briefly closing T2, opening and closing T1, and re-opening T2 during the course of flushing.

A 2.4 REMOVAL OF CARBONATE CARBON.

After flushing, tap T4 was closed and T2 opened to atmosphere. A few mls of analar orthophosphonic acid were then run into the reaction flask via tap T1. The mixture in the flask was boiled

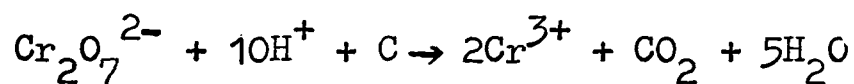
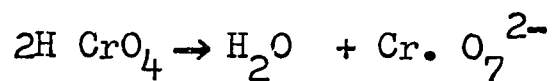
and the CO_2 produced by the reaction:



was purged to atmosphere for 2 minutes after reaction had ceased. The helium flow rate was maintained at 25-30 cm^3/min .

A 2.5 ORGANIC CARBON DETERMINATION.

Taps T2 and T4 were returned to their original positions and 10% wt./vol. $\text{Cr}_2\text{O}_3/\text{H}_3\text{PO}_4$ was run into the reaction flask. Heating of this sample-reagent mixture causes oxidation of the organic carbon:

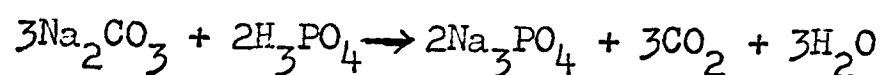


The bulk of the water vapour generated by this reaction was trapped out in the condenser and in the ice-water cooled trap, A. The remaining water and carbon dioxide were retained in the liquid nitrogen-cooled trap, B. To ensure collection of all the gas evolved, flushing was continued for four minutes after reaction was complete.

Taps T3 and T4 were now turned to position 2 and trap B was warmed for 25-30 seconds by substituting hot water for the liquid nitrogen. Tap T5 was then turned to position 2 and the carbon dioxide was swept onto the column using helium at a flow rate of 40 $\text{cm}^3/\text{minute}$.

A 2.6 CALIBRATION.

This was achieved by the use of a number of different volumes of 0.05M sodium carbonate solution, each aliquot of which yields 2.2 mg. CO_2/cm^3 of Na_2CO_3 on treatment with hot orthophosphoric acid:



A 2.7 SPEED AND PRECISION.

A single analysis can be performed in 20 minutes. All analyses were performed in duplicate, each single determination differing by, on average, 1.7% of the mean. If this deviation in any pair of samples exceeded 3% the analyses were repeated (this was necessary for less than 1 in 12 of the samples investigated).

Agreement between the results of the above method and those obtained independently using a high temperature, dry oxidation technique (Hewlett-Packard C,H and N analyses) at the Inorganic Chemistry Laboratories of the university, was found to be better, than the precision limits of the former method.

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