The Sedimentology of the Marlstone Rock Bed and Dyrham Silt Formations (Pliensbachian, Lower Jurassic) of the Cotswold Hills.

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Abstract

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The formations were examined along the Cotswold scarp (160km), and subcrop data were also utilised. The spatial and temporal characteristics of the formations allow sedimentological patterns to be related to structures in the pre-Permian basement and in the overlying Middle Jurassic strata. Sedimentation was strongly controlled by an actively subsiding block faulted basement, which formed part of the North Atlantic Rift system. The generalised Pliensbachian-Bajocian model of Sellwood and Jenkyns (1975) is supported by evidence in the Cotswolds.

Both formations show cyclic sedimentation characterised by upward changes in grain size, mineralogy, thickness, sedimentary structures and fauna. Spatial patterns reflect the N-S structures of the basement. Primary controls on the cyclicity are shown to be tectonic rather than eustatic. Five facies are recognised in the Marlstone Rock Bed Formation.

The stratigraphic interpretation of the formations is refined. There was a break in sedimentation at the end of the Pliensbachian. The base of both formations is diachronous, and spread from the centre of the basin outwards to both E and W margins. Randomly-interstratified illite-smectite in these rocks is interpreted as a weathering product of illite, while smectite was produced by alteration of air-fall volcanic ash. Both were derived from adjacent land areas.

Ferruginous ooids probably formed through mechanical and/or algal accretion in temporary reducing conditions on the sea bed. The iron-rich sediments were formed at the boundary between siliciclastic and carbonate regimes. True ironstones are virtually absent as a result of rapidly changing patterns of sedimentation within the rift. Widespread 'wavy' bedding is shown to be mostly diagenetic pseudo-bedding, although some appears to have been produced by wave rippling or by compaction alone.

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CHAPTER 1

Introduction

1.0 Characteristics of the Marlstone Rock Bed and Dyrham Silt Formations

The Marlstone Rock Bed and Dyrham Silt Formations of the Cotswold Hills in the W of England, are largely confined to the Pliensbachian Stage of the Lower Jurassic Series. These diachronous sediments extend across a number of ammonite zones; the Dyrham Silt Formation (DSF) ranges from within the top subzone of the *Tragophylloceras ibex* zone to the top of the *Amaltheus margaritatus* zone, and the Marlstone Rock Bed Formation (MRBF) from within the *margaritatus* zone to the *Dactylioceras tenuicostatum* zone (Toarcian Stage).

The two formations display marked differences in thickness when compared with each other, and also variations within themselves. The DSF is up to 93 metres thick, but disappears altogether on the E flank of the hills, and the MRBF, although much thinner (maximum 6.1 metres), also displays considerable variation. As its name implies, the DSF is composed largely of silt-grade material. It is dominantly siliciclastic, and lithologies range from clays through to sandstone and pebble conglomerates, with subordinate thin carbonate grainstones and ferruginous oolites. The MRBF is made up of sand-grade, ferruginous siliciclastic and carbonate sediments.

2.0 Geographic extent of the study area

The Cotswold Hills (Fig. 1) form a NW facing escarpment with its crest generally lying between 200 and 330 metres. Altitudes decline gradually to the SE, down the dip slope, to about 100 metres in the area of the Thames headwater S of Cirencester. Down the scarp face, there is an abrupt drop to a height to about 15-30 metres in the Severn Vale. Outliers form several hills, separated from the main upland by erosion; these occur to the S of Bristol, in the Gloucester area, and to the N of Cheltenham. The S end of the Cotswolds is generally accepted to lie at Bath, although a similar topography continues beyond, to the S. The NE end is more clearly defined by the Vale of Moreton and the Evenlode Valley.

3.0 Geology of the study area

The geology of the area is outlined on Fig. 2. In contrast to the folded nature of the Palaeozoic rocks of the Welsh Borderland and Wales, the Mesozoic rocks of the Cotswolds and adjacent areas are relatively flat lying, with a very low regional dip to the SE. The Cotswolds are capped by limestones of Middle Jurassic age with the Lower Jurassic strata, or Lias, cropping out along the steep scarp face. Consequently the outcrop of the Pliensbachian strata (Lower to Middle Lias age) is narrow, and controlled by the trend of the escarpment front. The MRBF, which is more resistant to erosion than the overlying Upper Lias strata, characteristically forms a shelf along the scarp face which becomes well developed where

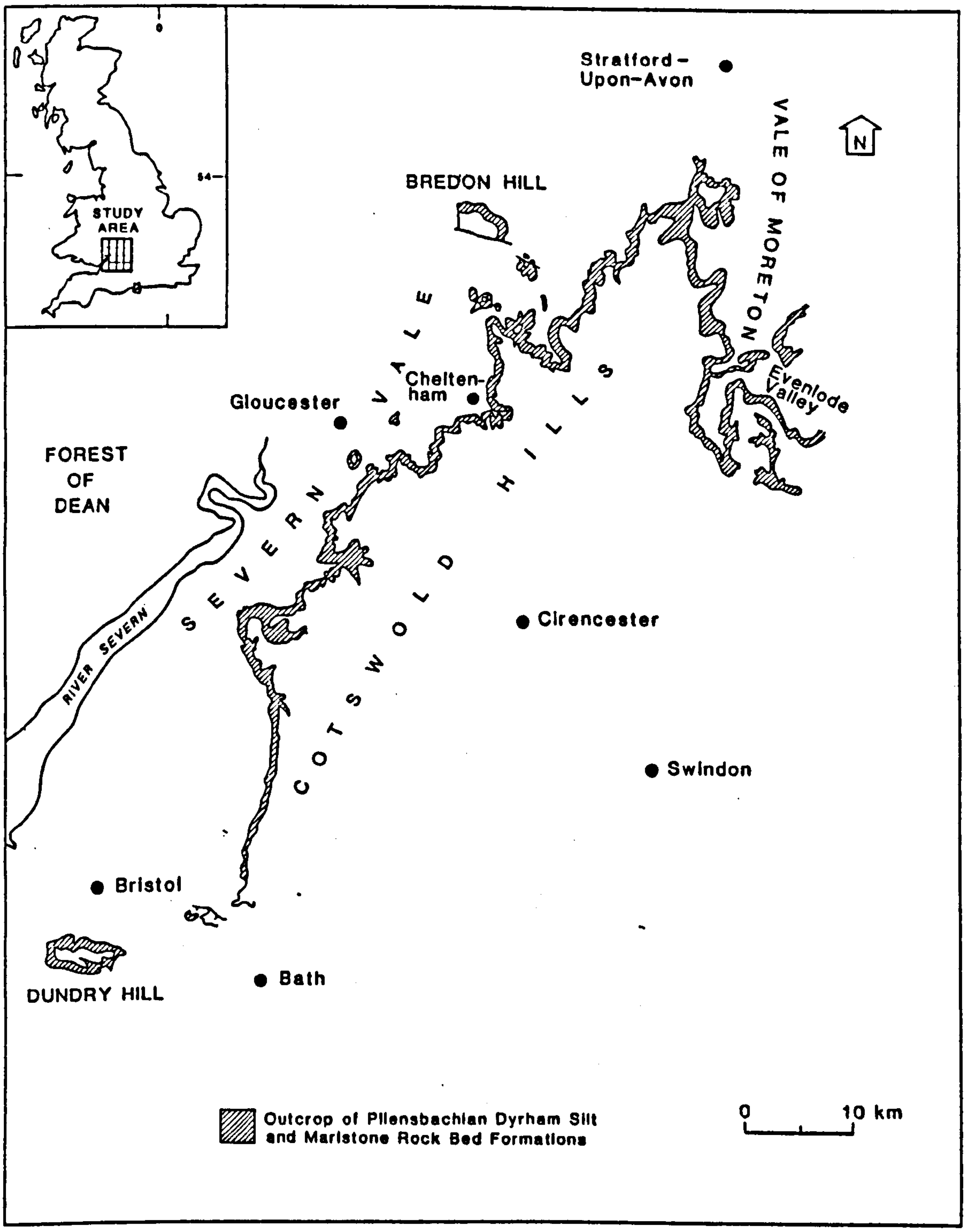


Fig. 1. Geographic extent of the study area and major topographic features.

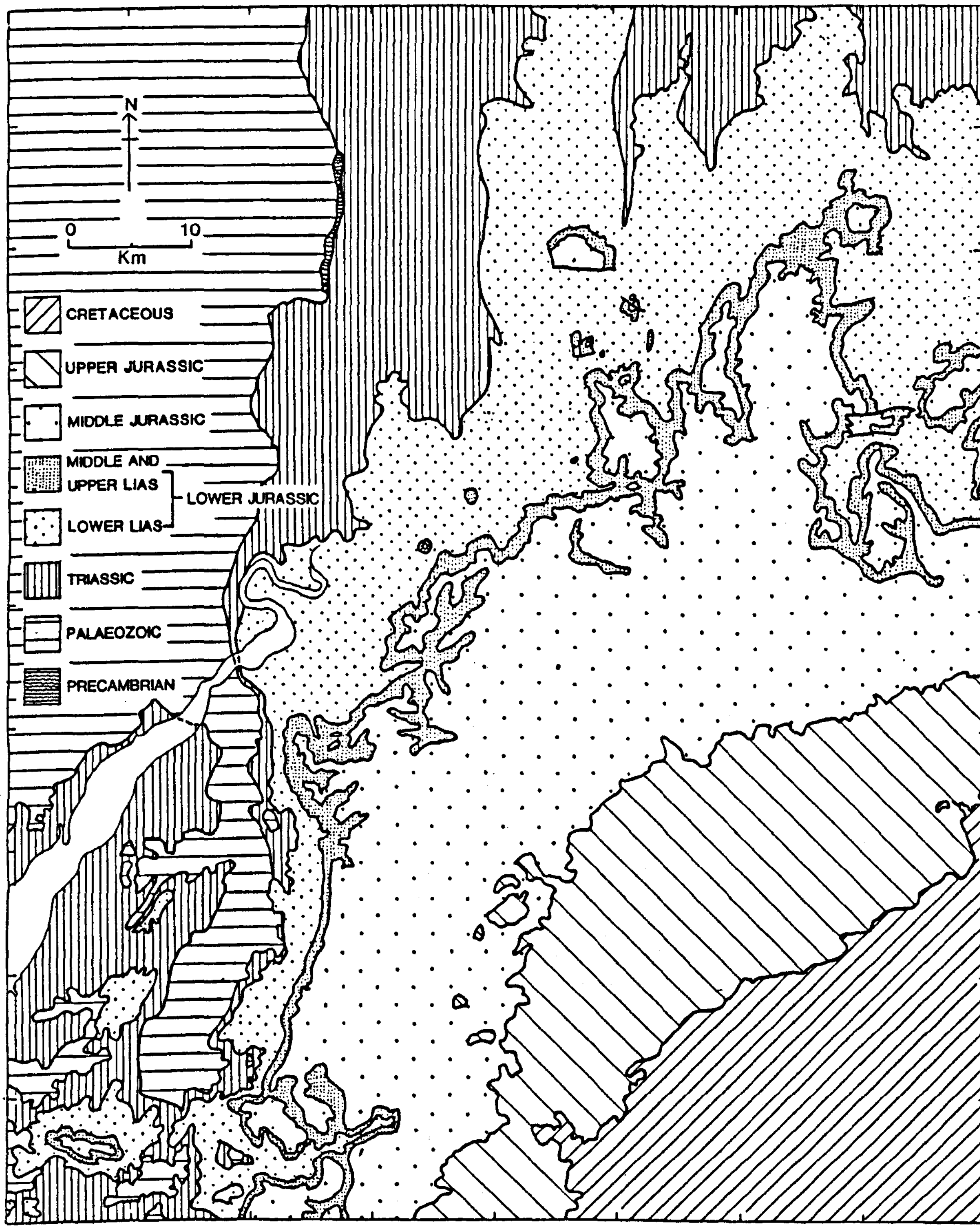


Fig. 2. Solid geology of the Cotswolds and adjacent areas (BGS 1:625 000 Geological Map of Great Britain 1979).

the formation is thick, and diminishes where it thins or disappears (Fig. 3).

4.0 Area of the present study

Fieldwork was concentrated on the Pliensbachian outcrop along the full length of the escarpment, from Dundry Hill in the SW, to the Vale of Moreton in the NE, a distance of some 160km. The outliers near Gloucester and Cheltenham were also included in the survey. Exposures are variable in quality, and most man-made sections in quarries, brickpits and railway cuttings have been abandoned for some time. Many of these exposures, however, are still well preserved and fresh sections, both temporary and permanent, have become available during the course of this study. In addition natural exposures, particularly landslip scars, are numerous and provide valuable information. Supplementary data from the subcrop has been fully utilised. This information has been drawn from British Geological Survey (BGS) boreholes, a variety of other boreholes and well data at the BGS National Geoscience Data Centre, Keyworth, Notts., and logs from various 'Wildcat' oil wells drilled in the area, available at the Department of Energy Library, Millbank, London.

5.0 Aim of the present study

Although the Cotswolds are widely recognised as an area of Jurassic rocks which have received some of the most concentrated attention in the world, much study is still required. Previous work, although detailed, concentrated

Fig. 3. Topographic expression of the MRBF. Top: view N near Hawkesbury, Avon. MRBF is thin or absent locally, with little expression on the scarp. It is well developed to the N, near Wotton-under-Edge, where a distinct shelf is seen. Below: Well developed MRBF and associated shelf, Robinswood Hill, near Gloucester. Note Tuffley Brickpit.

mostly on the Middle Jurassic sediments, and was published mainly in the two decades around the turn of the century, when these rocks were well exposed by quarrying operations and railway development. This classic work was orientated towards descriptive palaeontology and lithology. Modern sedimentological study, particularly that developed in the search for hydrocarbons, has highlighted the importance of basin analysis in the interpretation of the Jurassic.

A modern understanding of the structural evolution of the area began soon after the end of the Second World War as a result of work by Kent (1949), who used borehole and geophysical data aquired from onshore oil exploration and the Geological Survey. More work has been carried out in recent years (Chapter 5). Little detailed work has so far been published on the relationships between facies and structure in the post-Carboniferous formations of the area. The original concept of 'fold structures' in the Middle Jurassic rocks of the Cotswolds (Arkell 1933:87, 88) is here replaced by a different interpretation.

In the present study, the fundamental aim has been to establish the sedimentological characteristics of the two Pliensbachian formations in the Cotswolds. This has been based on new field and laboratory evidence, and incorporates previous research, reviewed from a modern standpoint. Emphasis has been laid on spatial and temporal patterns traced across the area, particularly as they affect changes of facies and thickness in the two formations. These are related to the underlying tectonic controls.

The nature of the Pliensbachian-Bajocian sediments of Britain was summarised and their origins modelled by Sellwood and Jenkyns (1975), using a selection of widely scattered localities across the country. The present study represents an attempt to test their model within a small geographical area.

6.0 Advanced studies undertaken

The advanced studies undertaken fell into four parts:-

6.1 A literature survey of the history of the opening of the North Atlantic.

6.2 A study of sedimentological techniques in the Sedimentology Laboratory, University of Bristol, under the direction of Dr. D. Hamilton.

6.3 Experience in surveying and sampling methodology as a member of the scientific party on Bristol University's research cruise CH7/8 to the Whittard Canyon and Deep Sea Fan, SW Approaches.

6.4 Presentation of two Science Faculty seminars at College.

CHAPTER 2

History of Research

1.0 Stratigraphic Terminology

The term 'Marlstone' was originally applied by William Smith in his earliest, unpublished stratigraphic table of 1799 to beds within the Rhaetic or Tea Green Marls at the Triassic/Jurassic boundary of the Bath area (Arkell 1933: 7). In Smith's improved table of 1815-16, it appeared between 'Sand' (Midford Sands, Upper Lias) and 'Blue Marl' (Lower Lias Clays). The beds understood as 'Middle Lias' today are very thin or absent around Bath, and this 'Marlstone' was suitably assigned to the argillaceous limestones of the basal Upper Lias (Woodward 1893:185). Phillips (1829), applying Smith's divisions to the succession in Yorkshire, recorded on his 'Tabular View of the Series of Yorkshire Strata' (p. 2-3)

		Feet Thick
Lias Formation	Upper Lias Shale	200
	Marlstone Series	150
	Lower Lias Shale	500

Smith's term 'Marlstone', therefore, was applied in a stratigraphic sense rather than directly to a particular rock type, and has remained a lithological misnomer to the present day.

At Boulby, Phillips (1829:73-74) described the whole of the

Lias in detail. His middle division was recorded as 'Ironstone and marlstone series', divided into (a) 'The ironstone bands (nodules of ironstone) 20'-40' thick' overlying (b) 'The marlstone series - alternations of shale and sandstones. Calcareous and shelly (40'-120' thick)'. Phillips (1829:137) noted that his three Lias divisions could be traced through midland England and Gloucestershire to Somerset, and that the Marlstone series was composed of 'sandy and irony layers of stone full of many organic remains' which maintained '...a general conformity of character...'.

Phillips' terms began to appear in publications on the Jurassic of the Cotswolds from the middle of the 19th century onwards. The term 'Marlstone' was used initially to indicate Phillips' 'marlstone series', but later was applied to a hard ferruginous rock type found at different levels within the series. Hull (1857) was the first to apply the term 'rock-bed' in the Cotswolds to the upper of two divisions he identified in the marlstone series. Further complications occurred at this time with the publication of Moore's (1867) paper in which he used 'Marlstone' to indicate the upper division, a limestone, only. In the Geological Survey's memoir on the British Lias by Woodward (1893), Moore's practice was continued. The memoir was influential, and subsequent publications continued to use 'Marlstone' in this way with few exceptions.

Biostratigraphic control on the Marlstone series followed the establishment by Oppel(1856-8) of his ammonite zonal scheme which, with certain modifications, continues to be used today. Oppel's '<u>Pliensbachgruppe</u>' included the zones <u>Ammonites jamesoni</u> to <u>A. spinatus</u>, equivalent to the 'Pliensbachian Stage' of current use (Dean <u>et al</u> 1961). This was for a while referred to as equivalent to 'Middle Lias' by English geologists, but the latter term was soon confined only to the top two zones, that of <u>A. margaritatus</u> and <u>A. spinatus</u>. This was preferred as it corresponded most closely to the lithological divisions of Phillips, and was adopted in Woodward's memoir. In the latter, 'Marlstone' was taken to correspond to the <u>A. spinatus</u> zone and the marlstone series to the <u>A. margaritatus</u> zone. This scheme continues in use to the present day, although it is understood that the marlstone series-type lithologies commenced deposition earlier than the base of the <u>margaritatus</u> zone in many areas, and that the lithological boundary with the Lower Lias Clay is gradational rather than sharp.

The term 'Marlstone Rock Bed' or 'Marlstone Rock-bed' appears to have been introduced in SW England by Kellaway and Welch (1948) and has been widely used since, being written in the latter style for a short time in the 1950's. In keeping with modern stratigraphic nomenclature (Holland <u>et al</u> 1978), Phelps (1982 Fig. A:1:1) recognised the Marlstone Rock Bed as a 'formation' and used the abbreviation 'Marlstone Formation'. In the present study, for the sake of continuity of established terms, and because of difficulties in devising a concise and meaningful alternative, 'Marlstone Rock Bed Formation' will be used. The gradual alienation of the term 'Marlstone' from Smith's original meaning, and its present application to a formation of totally different character, however, remains a problem.

Phillips' description of his 'marlstone series' in S England, or its approximation, was employed in the Cotswolds until more exacting observations were used by Kellaway and Welch (1948:54), recording 'micaceous and marly silts' in Gloucestershire. Subsequent publications to date have supported a dominantly silt lithology for these strata. The term 'Dyrham Silts' was first used by Stubblefield (1963:9 <u>in</u> Cave 1977:78) when describing the Middle Lias of the Elton Farm Borehole, and has since been applied to Phillips' division in the central and southern Cotswolds (BGS 1:63360 sheet 265 'Bath', Cave 1977:78, BGS 1:50 000 Sheet 234 'Gloucester'). The more generalised terms 'Middle Lias Clays' (Worssam and Bisson 1961), 'Middle Lias Silts' (Whittaker and Ivimey-Cook 1972) and 'Middle Lias Silts and Clays' (Williams and Whittaker 1974) have been used in the north Cotswold area. Phelps (1982: Fig. A:1:1) used 'Dyrham Silts' to include the same strata over the whole Cotswold area, and employed the term 'Dyrham Silt Formation'. It is considered here that the epithet 'Dyrham' is unsuitable, because at Dyrham (ST 738756) the formation is thinly developed and no exposure is known to have existed there. The best exposure currently available and where the formation is well developed, is at Tuffley Brickpit on Robinswood Hill near Gloucester, a locality considered the best inland exposure of the Lias in England by McKerrow _et al_ (1973:8). It would seem more appropriate to name the silt formation after this site. However, in order to avoid confusion, the term 'Dyrham Silt Formation', as used by Phelps, is adhered to here.

2.0 Details of DSF and MRBF studies in the Cotswolds

The most notable feature of research on the DSF and MRBF in the Cotswolds is the fragmentary, generalised nature of most of the work up to the present time. Although material has been published frequently from the first half of the 19th century, it is largely composed of simplified and non-interpretative field descriptions of lithologies, and their fossil contents.

2.1 Early Research:1845-1893

Murchison (1845) described the broad lithologies and listed fossil contents of the Marlstone (Phillips' 'Marlstone series') of the Cotswold escarpment, and quarries on the outlier hills (Churchdown, Dumbleton, Alderton, Bredon) of the Cheltenham district. His section on Churchdown Hill (p. 38), although using now obsolete terms, is invaluable as it provides the only published record of a continuous section in the DSF at this locality. Gavey (1853) described the 'Marlstone' of the Mickleton Tunnel and nearby cuttings in NE Gloucestershire, giving generalised descriptions of lithology, fossil remains and the stratal thicknesses. Hull's (1857) Geological Survey memoir of the N Cotswolds divided the 'Marlstone' into two distinct lithological units. The 'rock-bed' (MRBF) was described as a hard bluish limestone weathering brown, noted for its fossiliferous nature, and its higher ferruginous content on the E margin of the district. General descriptions of lithology and faunal lists were given, together with variations in the regional thickness of the 'Marlstone' and valuable descriptions of the succession at significant, now obscure sites. Hull also commented on the marked attenuation of the Jurassic strata in the Burford area, Oxon, compared with the much thicker succession to the W near Cheltenham.

Witchell's (1865) section at Stroud lists the local Jurassic succession, giving fossil contents, and is again important in view of the poor exposures at the present time. He used 'Marlstone' to indicate hard bands within the 'Marlstone series' (p. 12). Moore (1867), using 'Marlstone' sensu Hull's 'rock-bed', mentioned numerous localities in the Cotswolds. Investigations for workable iron ore noted the presence of beds with 22-30% iron, but too thin to be of economic value, in the Bath area (p. 128, 152). Shafts sunk for iron ore at Stinchcombe, Glos. below the Marlstone into the 'indurated marls' gave an unprofitable result, as did the analyses on the Marlstone at 'Newent' (Newnham) Quarry nearby (p. 147). Moore noted striking variations in the thickness of the Marlstone between Stinchcombe and Stroud, and provided the only published thickness of the Marlstone 'At Stanley' (Cups Hill Quarry, Gretton, Glos.) and at Dumbleton (p. 148, 149). Moore also recorded Marlstone lying unconformably upon the Upper Carboniferous coals at Mells Colliery in the E Mendips (p. 150).

Walford (1879) gave brief details of a section in the Middle-Upper Lias boundary beds at Alderton Hill Quarry. A sequence of papers by Smithe (1865, 1877, 1895) concentrated on the road metal quarries exposing the Middle and Upper Lias on Churchdown Hill. Smithe used the term 'Marlstone' to indicate the hard, dark ferruginous lithology found there near the top of the DSF rather than Hull's 'rock-bed'. Smithe's 1877 paper is unusually penetrating for its time, providing a simple graphic log, discussion and definition of the '<u>Spinatus</u> zone', detailed field descriptions, simple laboratory analyses, and palaeoenviromental interpretations. Palaeogeographic implications were considered for the British Isles as well as for the continent.

Witchell (1882) followed Oppel's definition of the Middle Lias, as had Moore. He described the succession at a brickpit adjacent to Dudbridge Mills, Stroud, giving details of lithology and zone allocations to beds. He reported a similar succession in a section nearby near Lightpill (p. 17). Witchell continued to use 'Marlstone' in the same sense as in his 1865 paper. Both Smithe and Witchell's work revealed a different lithology for the MRBF in the Stroud and Churchdown areas, where it was found to be a friable yellowish micaceous sandstone. Witchell was the first to notice a facies change in the MRBF across a part of the S Cotswolds, and compared the different lithologies of the same zone at Stroud and Stinchcombe.

A further paper on the roadstone quarries at Alderton and Ashton-under-Hill by Smithe and Lucy (1892) concentrated on the basal Upper Lias strata, and few Middle Lias details were given. The lithology of the spinatum zone at Gretton (Cups Hill Quarry) was referred to as 'coarse foxy marlstone' (p. 210). This paper noted the replacement at that time of the MRBF as a source of road metal by Clee Hill basalt and Carboniferous Limestone; subsequently many quarries were abandoned and remain today as exposures of variable quality, and the MRBF continued to be used, with increasing infrequency, as a building stone only.

2.2 Establishment of Regional Lithological Variations: 1893-1933

The important Geological Survey memoir by Woodward (1893) included the first attempt to collate published and unpublished data on the Middle Lias of the Cotswolds. The first clear definitions of the English Middle Lias lithologies were presented (p. 185), noting lateral facies variations in the MRBF from calcareous sandstones through earthy bluish or green grey ironshot (sometimes oolitic) limestones, into ironstones of economic importance. In section, the sandstones were noted to occur locally below the limestones and ironstones (p. 186). Woodward continued to refer to Phillips' 'marlstone series' division as dominantly 'sandy' in the Cotswolds, which may reflect the influence of the sequences seen in the costal sections of

Dorset and Yorkshire, over the poorer sections inland.

New data provided by Woodward included the Lower to Upper Lias sequence of the Bath area (p. 212) and details of sections at Wotton-under-Edge, at Nibley (p. 213), at Alderton (p. 267) and the first published details of the Middle Lias at the long established quarries at Ashton-under-Hill. Also mentioned in this publication were MRBF quarries on 'Burrell Hill' (now Burhill) near Buckland, and Chipping Campden (p. 217), but they were reported overgrown. Sections in the NE Cotswolds included only that at Ebrington (p. 217), and the lack of exposures and quarries in the Windrush valley was taken to imply a thinning of the MRBF. A clay facies was noted for the margaritatus zone in this area (p. 219, 221). Data were presented from a deep borehole at Mickleton Wood (p. 156) indicating very thick Middle Lias locally, and details of boreholes at Signet, near Burford and Kingham Hill, Chastleton (p. 221) showed the changing nature of the Middle Lias from the Cotswolds into Oxfordshire. The full succession of the Signet borehole was published later (Woodward 1894:303).

The presence of the 'Marlstone Rock' (containing Pleuroceras spinatum) on Dundry Hill S of Bristol was first described by Buckman and Wilson (1896), where it had previously been mapped as part of the Inferior Oolite by the Geological Survey, because of its local facies. Reynolds and Vaughan (1902) described the Middle Lias sequence from the Sodbury railway tunnel excavations on the escarpment near Yate (Avon). The Middle Lias was found to be extremely thin, with A. capricornus found within 10' (3.05m) of the basal Upper Lias. At the top of the Middle Lias a thin band of the dark bluish ferruginous limestone, referred to as 'Marlstone' was doubtfully assigned to the margaritatus zone (p. 731), suggesting an absence of the MRBF at this site.

In the first decade of the 20th century several publications including descriptions of the Middle Lias were produced by Richardson (1904a, 1904b, 1905, 1908, 1910a, 1910b). The 1904a publication included details from previous local works, but did note that 'Marlstone' (sensu Woodward 1893) contained fossils from the spinatum zone in its upper part and the margaritatus zone in its lower part. Also mentioned, for the first time, was a brickpit at Robinswood Hill exposing the capricornus zone (p. 47), and MRBF locations on Oxenton and Dixton Hills, at Prinknash (p. 50), and the Painswick area. The latter indicated the presence of the MRBF sandstone facies, known at Stroud and Churchdown, in this area. A log of the MRBF at a quarry on Bredon Hill was given. Two sections claimed to be in the MRBF at Ham and near Battledown, Cheltenham, have been proved to be erroneous in the present study. Probably also in error was the section at Stutfield Wood on Cleeve Hill (see Appendix 1). Two exposures in the MRBF were briefly mentioned on Broadway Hill and at Chipping Campden in the 1904b publication, and the Bredon Hill section log was republished in Richardson's 1905 paper (p. 66). He was first to mention road metal quarries (then abandoned) in the MRBF on Ebrington Hill in the extreme NE Cotswolds, in his publication of 1908.

The opening of new brickpits in Gloucestershire around the turn of the century led to descriptions of the Middle Lias by Richardson at Aston Magna (1910a), and at Robinswood Hill and Stonehouse (1910b:258, 254). Few details of the sequences were given, but the '<u>capricornus</u> Beds' were noticeably sandier in their higher levels. Richardson also mentioned the site of a then disused brickworks, probably in the '<u>capricornus</u> Beds', near Hackmill at Wotton-under-Edge (p. 248), and enlarged on details from the brickpit mentioned by Witchell (1882) at Lightpill. At the latter site he gave details of lithology and thickness of units, and noted pebble horizons and waterworn shells at the top of the 'Marlstones' (<u>sensu</u> Witchell), suggesting that they indicated pauses in deposition and penecontemporaneous erosion (p. 250).

Watts (1928) gave views on the palaeoecology of the fauna at the Tuffley Brickpit (Robinswood Hill) but did not include lithological descriptions. Whitaker and Edmunds (1925:55) published a log of a borehole, probable made for coal, at Lucknam, Wiltshire which indicated that the Middle Lias there is in a blue shale facies or (more likely) is absent. Richardson (1929, 1933) noted that the 'Sandy Beds' of the Middle Lias were poorly exposed in the areas under inspection, but listed numerous localities for the MRBF. Many of these were taken from previous publications but new ones included (1929:25-26) exposures at Blockley, Wood Stanway, abandoned quarries on Burhill, Buckland and quarries near Stow-on-the-Wold. Richardson (1933:9) mentioned an exposure of MRBF near Dodd's Mill, Windrush, but gave no further details.

2.3 Development of Modern Analysis: 1933-present

Arkell's (1933) classic analysis and literature review of the British Jurassic gave only brief attention to the Middle Lias of the Cotswolds, providing little new information. In Kellaway and Welch's (1948) work, attention was given to the true nature of the 'Sandy Beds' below the MRBF in the Cotswolds and they were described for the first time as 'micaceous and marly silts' (p. 54). Suggestions were also made that the coarser nature of these sediments above the Lower Lias Clays may indicate basin infilling as a result of greater sediment input over subsidence. They drew attention to the presence in the Cotswolds (presumably from Richardson's work) of both margaritatus and spinatum zone fossils in the MRBF, whereas in Somerset only the latter were present, suggesting that its deposition began earlier in the Cotswolds (p. 54). Kellaway and Welch were clearly influenced by Arkell's (1933) establishment of the effect of structural 'axes' in the pre-Mesozoic basement on Jurassic sedimentation patterns in Britain. They drew attention to the thickness changes in the MRBF in SW England and suggested they were due to contemporary movement of the axes during deposition.

A temporary trench on the Cotswold escarpment at

Dodington Ash, Avon, was described by Fry (1951) who compared the sequence exposed with that of Reynolds and Vaughan (1902). Fry gave thickness of probable Middle Lias/youngest Lower Lias strata and noted the absence of the MRBF at this site. McKerrow and Baden-Powell (1953: 89) gave a brief mention of the lithology and zonal position of the Middle Lias exposed in the brickpit at Aston Magna. Edmunds (1954:28) gave a summary log of a Geological Survey borehole drilled at Upton, Burford, Oxon in 1953 giving an overall thickness for the Middle Lias.

Ager (1956a) briefly mentioned the thickness, lithology and faunal aspects of the MRBF at Newnham Quarry, Stinchcombe, the MRBF and margaritatus zone at Jeffries' Brickpit near Stonehouse, and the MRBF and DSF down to the davoei zone exposed at Stonehouse Brickpit. Like Witchell (1882), Ager noticed the facies change in the MRBF between Stinchcombe and Stroud, and suggested that the sandstone facies probably indicated shallow inshore sediments. In this paper, Ager included the first log of the sequence exposed in the brickpit at Tuffley giving thicknesses of lithological units, their description, and estimated zonal ranges. Additionally, he established that the sandy MRBF facies at Stroud continued to Tuffley, and onto Churchdown Hill, citing Smithe's work in the 19th century. Ager (1956b:160) provided apparently the only published outline of the MRBF facies for the Cotswolds as a whole, although this was very brief.

The first highly detailed and precise descriptions of the Middle Lias in the Cotswolds were by Green and Melville (1956) from the Geological Survey borehole at Stowell Park. The logged sequence provided data on thickness, lithology, fauna, and ammonite zones. The first published details from thin sections on Middle Lias sediments in the Cotswolds were given on an 'oolitic ironstone' found near the top of the margaritatus zone. A well at Dundry, south of Bristol, was logged by Donovan (1958:132) who recorded a stratum containing Pleuroceras salebrosum (Hyatt), indicating the MRBF, but which he assigned the name "Margaritatus Bed". Clays were noted to underlie the MRBF, but the margaritatus zone was not proved; the first ammonites encountered belonged to the davoei zone 30' (9.14m) below the MRBF.

The onshore search for oil in Britain by the British Petroleum Company Limited (previously D'Arcy Exploration Co. Ltd.) from the 1930's onwards included the drilling in 1954 of a test well at Faringdon, Berks. (Falcon and Kent 1960:14, 15). Twenty feet (6.1m) of green oolitic MRBF was recorded, with the base of the Middle Lias taken 30' (9.1m) below this. Lithological details of the original well log have been supplied to the writer by the BGS (1986). Worssam and Bisson (1961) gave brief details on the lithologies and thickness of the Middle Lias cropping out in the Windrush valley, and adjacent areas near Burford. Details of the MRBF and 'Middle Lias Clays' from the Upton borehole (Edmunds 1954:28) were given (p. 77). Exposures in the area were supplied for both formations (p. 78), although the one at Dodd's Mill was incorrectly located (see Appendix 1).

Hallam (1967:409) in his study of major facies distributions, their associated fauna and environmental reconstructions of the Middle-Upper Lias boundary beds of Great Britain, gave brief petrological details of the MRBF sections at Chipping Campden, and Newnham Quarry, Stinchcombe, noting a similarity between the two lithologies. A simple facies map of the _spinatum_ zone (taken as equivalent of the MRBF) for Britain was given, but was not detailed enough to improve on Ager's (1956b) facies information in the Cotswolds.

Details of lithology and thickness for the Middle Lias in a Geological Survey borehole drilled at Apley Barn, Oxon in 1960-61, were given by Poole (1969). Fry (1970) recorded the lithology and thickness of the MRBF on Bitton Hill, Avon. Palmer (1971) produced detailed logs of the by then disused Stonehouse and Tuffley Brickpits, enlarging on Ager's (1956a) work. He noted that Jeffries Pit had become badly slumped. Palmer used the detailed ammonite zonal stratigraphy established by Dean _et al_ (1961), enabling subzones to be allocated for the first time to the Middle Lias of the Cotswolds. Close correlation was demonstrated between the sites, and comparisons made with the Middle Lias of the Stowell Park Borehole and the Dorset coast. Further details on the palaeontology of the Tuffley and Stonehouse pits were given in a paper by Palmer in 1973.

Whittaker and Ivimey-Cook (1972) described the MRBF and the 'Middle Lias Silts' from the Geological Survey's Bredon Hill No. 1 (Lalu Barn) Borehole, producing another highly detailed log comparable in quality to that of Stowell Park. Subzone stratigraphy was also attempted in this borehole, and correlations made with Stowell Park. Williams and Whittaker (1974) included descriptions of the MRBF and 'Middle Lias Silts and Clays' on Bredon Hill and the extreme NE Cotswolds. Thickness estimates of the two formations were given, together with lithological descriptions, although the latter for the MRBF are somewhat in error. Additionally, the mapped junction of the two formations along the W side of Ebrington Hill is disputed in the present study (see Appendix 5). Facies variations in the Middle Lias Silts and Clays were indicated across the area. Numerous exposures were listed, giving very detailed location positions, but many were of limited size. The sites of numerous old abandoned workings in the MRBF were noted, some being described for the first time.

The Geological Survey memoir for the Malmesbury Sheet by Cave (1977) provided an account of the Middle Lias in the S Cotswolds comparable in approach to Williams and Whittaker's work. He used Stubblefield's (1963) term 'Dyrham Silts' for the formation underlying the MRBF. The complex facies in the Dyrham Silts of the Dursley area were described, and the upward transition from sand to limestone in the MRBF was noted. Insufficient zonal proof was obtained to state whether the base of the MRBF was of *margaritatus* or *spinatum* zone age (p. 80), as it had been in the Midlands and Somerset. Full thicknesses of the MRBF were given or estimated for a number of localities, and it was shown that the MRBF becomes thinner and less calcareous NE of Dursley (p. 92).

Cave noted the gradual thinning of the DSF southwards along the escarpment, also the very thin, patchy nature of the MRBF S of Hawkesbury, which he assigned to the Junction Bed, more commonly seen S of the Mendips. Cave noted cyclic sedimentation patterns in the DSF, first recognised in the Cotswolds by Sellwood and Jenkyns (1975) in the Stowell Park Borehole. Cave recorded a clearly developed upward coarsening within individual cycles, accompanied by upward increases of shelly fauna and carbonate cement.

Ivimey-Cook (1978) gave a detailed account of the stratigraphy of the Elton Farm borehole drilled by the Geological Survey on Dundry Hill, Avon in 1962-63. Lithologies of the MRBF, similar to those noted by Buckman and Wilson (1896) and Donovan (1958) were described using thin section petrography. The underlying formation was referred to as 'Middle Lias Silts' rather than 'Dyrham Silts'.

Recent work includes that of Howarth (1980) who demonstrated a Toarcian (basal Upper Lias) age for the MRBF top over most of England, but could not prove this for the Cotswolds. Phelps (1982) produced logs of a temporary exposure and stream sections in the Middle and Lower Lias of the Dursley area, and reorganised Palmer's zonal divisions at the Stonehouse and Tuffley Brickpits. Simms (pers comm. 1983) has found the first known gibbosus subzone fossils (top of the margaritatus zone, Dean et al 1961) in the Cotswolds, and allocated margaritatus and spinatum subzones to the MRBF in the Cheltenham area. Most recently, Donovan and Kellaway (1984) have described the MRBF and DSF of the Bristol district, largely based on the work of previous authors. They considered Moore's (1867:50), 'Marlstone' at Mells Colliery in the Mendips, containing 'A. spinatus' (Pleuroceras) to be a misidentification; these strata were thought more likely to represent the Jamesoni Limestone of the Lower Lias (p. 50).

Additional information on the thicknesses and lithologies of the MRBF and DSF exists in borehole and well records currently available at the National Geoscience Data Centre, British Geological Survey, Keyworth, Notts. The data are collected from a variety of sources (BGS boreholes, civil engineering projects, privately drilled water wells) and are of variable age. Consequently the data vary from excellent to unreliable, but much are valuable and have been used in the present study. Most notably, an abundance of data was generated from the Oxfordshire border area following the Gas Council's search for hydrocarbons in the early 1960's.

The continued programme of the search for oil onshore Britain led to the drilling of a number of 'Wildcat' wells in the Cotswolds and adjacent areas in the 1970's. The log data are available at the Department of Energy library in London and those passing through the Middle Lias have been inspected in this study. These are of variable quality and use, and are listed in Appendix 30.

CHAPTER 3

Geological Framework

1.0 Stratigraphy

The stratigraphy of the MRBF and DSF in the Cotswolds according to Phelps (1982, Figs. A:1:1, A:2:5:1 and A:2:6:2), with modifications adopted in the present work, are shown in Fig, 4. The accepted ammonite zonal scheme of Dean et al (1961) is employed. This diagram shows that the two formations have diachronous boundaries, and are largely confined to the Pliensbachian Stage of the Lower Jurassic, or Lias.

Phelps' tables concluded that the MRBF corresponds to the whole of the Dactylioceras tenuicostatum zone of the Toarcian Stage overlying the Pliensbachian, the Pleuroceras spinatum zone, and with a diachronous base continuing in the south Cotswolds down to the base of the Amaltheus subnodosus subzone in the underlying Amaltheus margaritatus zone. The base of the DSF was drawn below the Oistoceras figulinum subzone, down to within the Aegoceras maculatum subzone, of the Prodactylioceras davoei zone. Below the DSF occurs the Blockley Clay Formation (BCF), corresponding to the Lower Lias Clays. The boundary between the MRBF and DSF is marked by an erosion surface and overlying thin pebble conglomerate at most well documented sites across the Cotswolds. This was considered to correspond to a major unconformity at the margaritatus/spinatum zone junction, and it has been recorded almost everywhere in

CHRONOSTRATIGRAPHY				LITHOSTRATIGRAPHY		
SERIES	STAGE	ZONE	SUBZONE	GROUP	FORMATION PHELPS(1982)	FORMATION (THIS THESIS)
	TOARCIAN (PARS)	DACTYLIOCERAS TENUICOSTATUM	D. SEMICELATUM		SW NE	SW UPPER NE LIAS CLAY (PARS)
			D. TENUICOSTATUM			
			D. CLEVELANDICUM		MARLSTONE	? HIATUS
			PROTOGRAMMOCERAS PALTUM			
	PLIENSBACHIAN (PARS)	PLEUROCERAS SPINATUM	P. HAWSKERENSE			
			P. APYRENUM			MARLSTONE ROCK BED (0-6.1m)
		AMALTHEUS MARGARITATUS	A. GIBBOSUS			
LOWER JURASSIC (PARS)			A. SUBNODOSUS	LIAS (PARS)		
			A. STOKESI		DYRHAM SILT	DYRHAM SILT (0-93.7m)
		PRODACTYLIOCERAS DAVOEI	OISTOCERAS FIGULINUM			
			AEGOCERAS CAPRICORNUS			
			AEGOCERAS MACULATUM			
		TRAGOPHYLLOCERAS IBEX	BEANICERAS LURIDUM			
			ACANTHOPLEUROCERAS VALDANI		BLOCKLEY CLAY (PARS)	BLOCKLEY CLAY (PARS)
			TROPIDOCERAS MASSEANUM			

Fig. 4. Stratigraphy of the DSF and MRBF in the Cotswolds.

Britain (Phelps 1982, in Hallam 1984a:212).

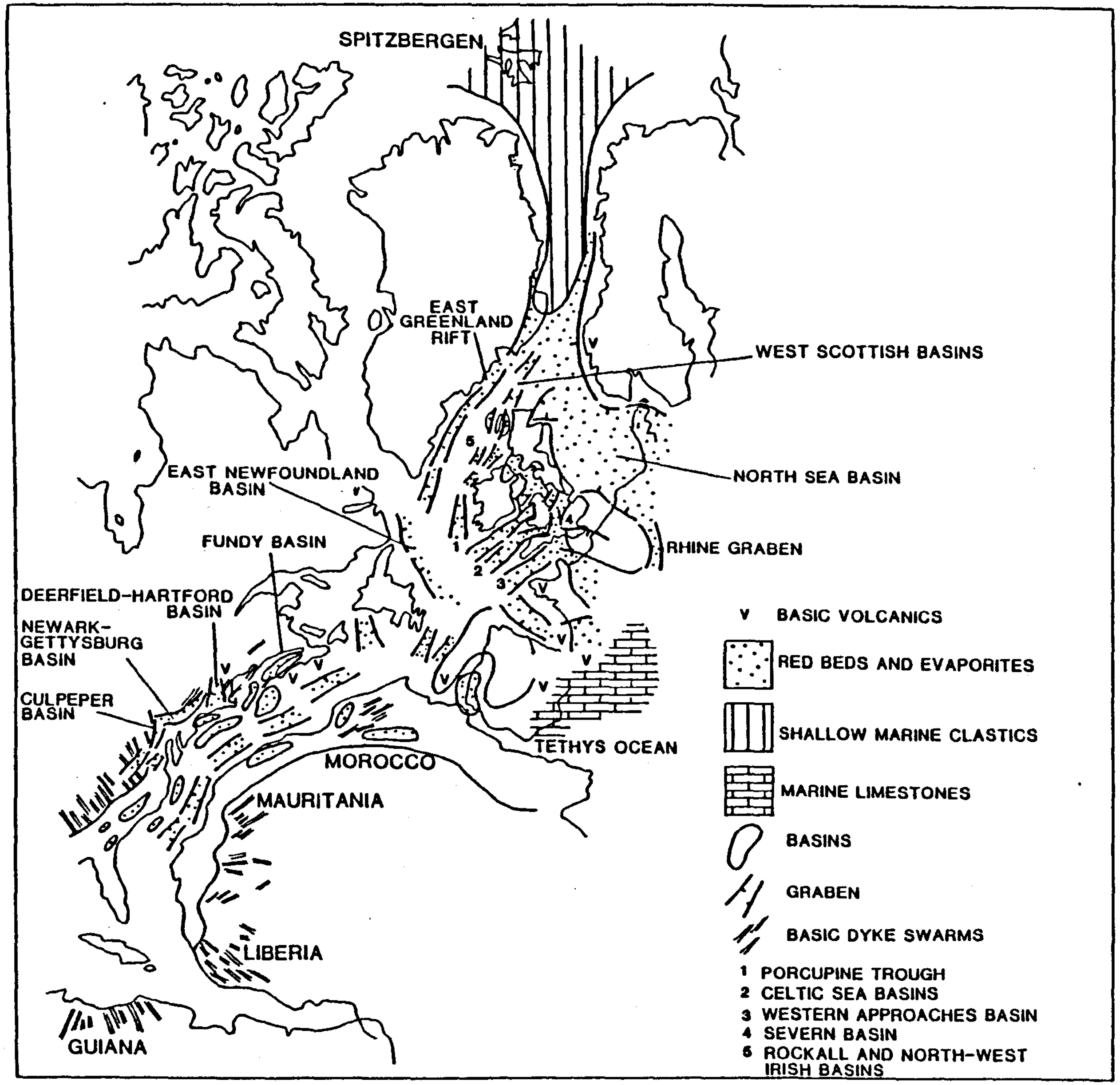
The appellation 'Middle Lias' to the DSF in recent literature (Whittaker and Ivimey-Cook 1972, Williams and Whittaker 1974, Ivimey-Cook 1978) was used as an expedient; as this term is taken in Britain to imply the spinatum and margaritatus zones only, its use required qualification by these authors in each case. Until recently, no evidence for the Amaltheus gibbosus subzone had been found, and Palmer (1971) suggested it may have been removed, leaving the erosion surface at the top of the DSF.

Modifications to Phelps' stratigraphy, as proposed in the present study, is based upon Donovan and Kellaway (1984) and recent ammonite identifications by M. Simms (pers. comm. 1986). The top of the MRBF is taken from the top of the Pleuroceras apyrenum subzone (spinatum zone) to the top of the tenuicostatum zone. The latter occurs only locally in the MRBF, on the E flank of the Cotswolds (Howarth 1980:641). In the present study, the Pleuroceras hawskerense subzone of the spinatum zone was not proved, and at some localities the apyrenum subzone was noted to extend up to within a few cms of the boundary with the Upper Lias Clay. However, Howarth (1980:641) stated that species belonging to the hawskerense subzone have been collected at some Cotswold localities in the past. The Protogrammoceras paltum and Dactylioceras clevelandicum subzones of the basal Toarcian have not been proved in the Cotswolds, and the MRBF/Upper Lias Clay boundary may mark the absence of three subzones in some areas. The base of the MRBF is diachronous between the bottom of the apyrenum subzone, and down to within the subnodosus subzone. The base of the DSF is taken to continue down in the Stowell Park Borehole (Green and Melville 1956) into the Beaniceras luridum subzone (Tragophylloceras ibex zone), where silts first begin to appear above the BCF. In the Elton Farm Borehole (Ivimey-Cook 1978) in the SW Cotswolds, however, silts occur only in the Margaritatus zone, and on the E side of the Cotswolds, the BCF continues up to the base of the MRBF (Worssam 1963, Worssam and Bisson 1961).

2.0 Structural and Tectonic Setting

The collision of the cratonic units of Gondwanaland, Laurasia and Siberia towards the end of the Palaeozoic era (Read and Watson 1975b), created the Pangaea super-continent. This configuration was short lived however; within the stabilized late Palaeozoic mobile belts bordering the present North Atlantic Ocean, crustal extension had already begun in late Carboniferous (Stephanian) times in N Europe (Anderton et al 1979:78). By late Triassic times, a linear complex of fault basins had developed from the Caribbean to the Arctic, forming the North Atlantic Rift (Fig. 5). This pattern of extension began to occur on a worldwide scale, and rift complexes spread through the Gondwanaland craton, followed by its incipient disintegration in the late Jurassic - early Cretaceous (Read and Watson 1975b, Ch. 8). Continued extension within the North Atlantic Rift during the

Fig. 5. The North Atlantic Rift in Late Triassic times (Hallam 1971, Hallam and Sellwood 1976, May 1971, Naylor and Shannon 1982, Smith and Noltimier 1979, Van Houten 1977, Ziegler 1981).

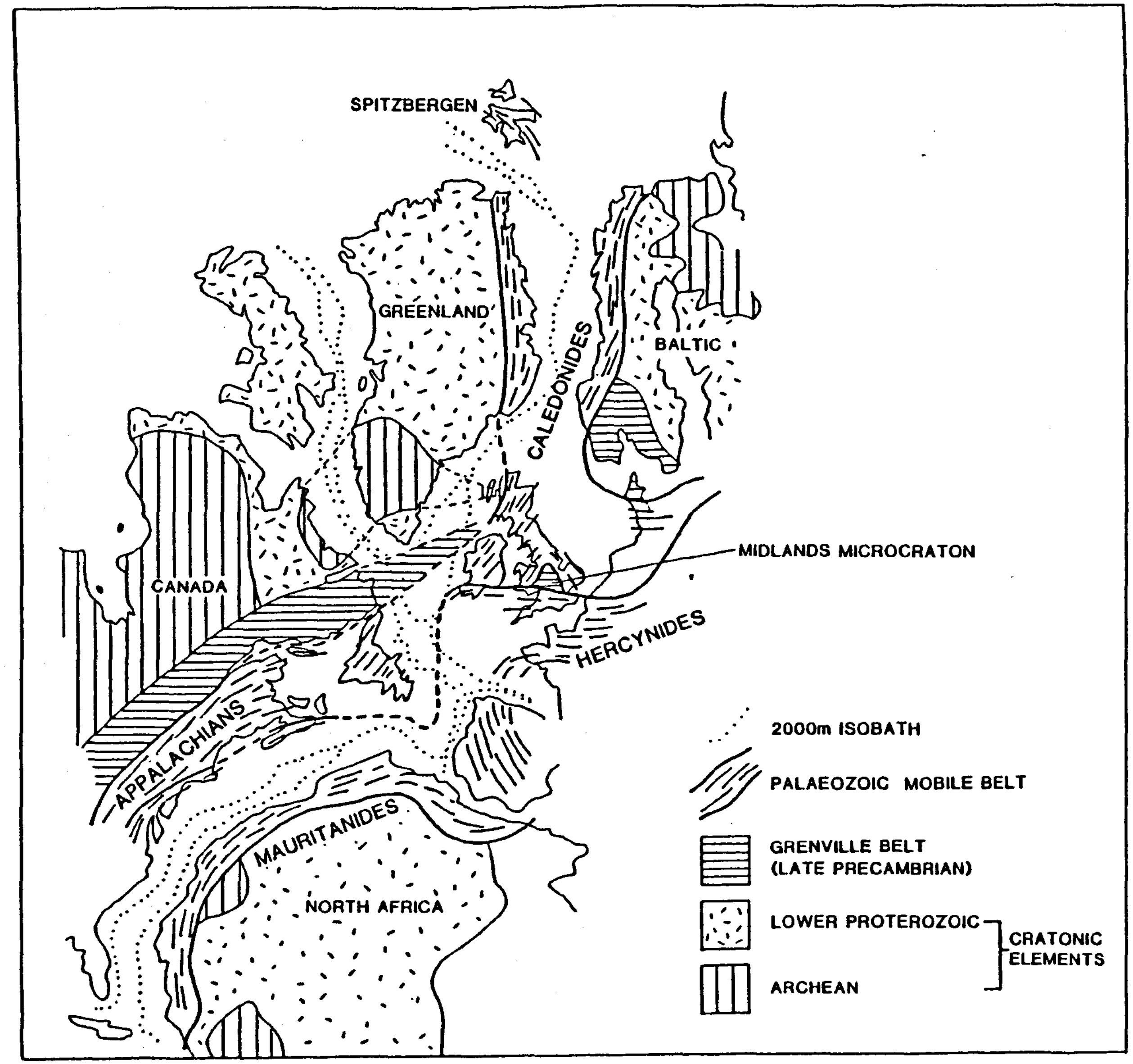


Mesozoic, Tertiary and Quaternary led to the development of the present North Atlantic Ocean basin, propagating from S to N. This process continues at the present time.

The fault patterns creating from the crustal stretching, rupturing and subsidence during the establishment of the North Atlantic Rift system, closely followed the structural grain of earlier mobile belts that lay within the area of extension. In NW Europe, this involved the Caledonides and the Hercynides which had largely stabilised at the end of the Lower and Upper Palaeozoic respectively. These belts bordered older Precambrian cratonic elements which were only slightly deformed during the Palaeozoic orogenic episodes. They included the major cratonic regions of the Baltic, Greenland and Canadian Shields (Read and Watson 1975a:41), and the much smaller 'Midlands Microcraton' (Whittaker 1985:9), underlying C England and E Wales.

Structural grains of the Palaeozoic mobile belts are shown in Fig. 6. The Caledonides comprise two branches, a NE-SW trend, part of which extends through N Britain, and the North German-Polish Caledonides trending NW-SE through the North Sea (Ziegler 1981:4 in Illing and Hobson Eds.). The Hercynides possess an E-W grain running through S Ireland, Britain and C Europe, and cut out the arms of the Caledonian belts where they intersect. On the Midlands Microcraton in Britain, a N-S 'Malvernoid' grain is present (Whittaker 1985:9 and Map 2). The influence of these structural grains on the trends of the Permo-

Fig. 6. Pre-drift structural continuities of the Palaeozoic mobile belts across the North Atlantic continents (Anderton et al 1979, Ziegler 1981).



Triassic graben can be seen by comparing Figs. 5 and 6. The history of the whole system is complex, and after their creation, the fault basins underwent variable episodes of subsidence, many of which were eventually abandoned before the course of the new ocean basin was finally established.

In the area of what is now the British Isles and the adjacent continental shelf, the newly-formed mosaic of horst blocks and graben gave rise to the major topographic units known today; the pre-Mesozoic upland massifs such as Cornubia and Wales were the horsts and the modern lowlands and shelf seas were mostly the sites of graben and sediment accumulation. Details of this tectonic phase directly affecting the Cotswold area are given in Chapter 5.

3.0 Palaeoenvironment

3.1 Distribution of land and sea

The position of the North Atlantic Rift within the interior of the Pangaea supercontinent left it isolated from the surrounding oceans during the early stages of its formation. With continued extension and subsidence, however, intermittent advances of seas into NW Europe occurred from the Tethys Ocean in the S during the Permo-Triassic, and a boreal sea in the N of the rift in the late Triassic (Fig. 5).

Marine conditions eventually became established in NW

Europe at the beginning of the Jurassic (200 Ma, Salvador 1985 Fig. 2), associated with a eustatic rise in sea level which continued into the Upper Jurassic. This expansion of the marine environment onto the continents is thought to be the result of displacement of oceanic waters by newly-created buoyant spreading ocean ridges associated with the break up of Pangaea (Hallam 1984a:224, 237). A shallow epicontinental or 'epeiric' sea thus advanced northwards from the Tethys Ocean at the beginning of Liassic times, flooding the extensional rift basins formed during the Permo-Triassic, which continued to remain active.

3.2 Palaeoclimate

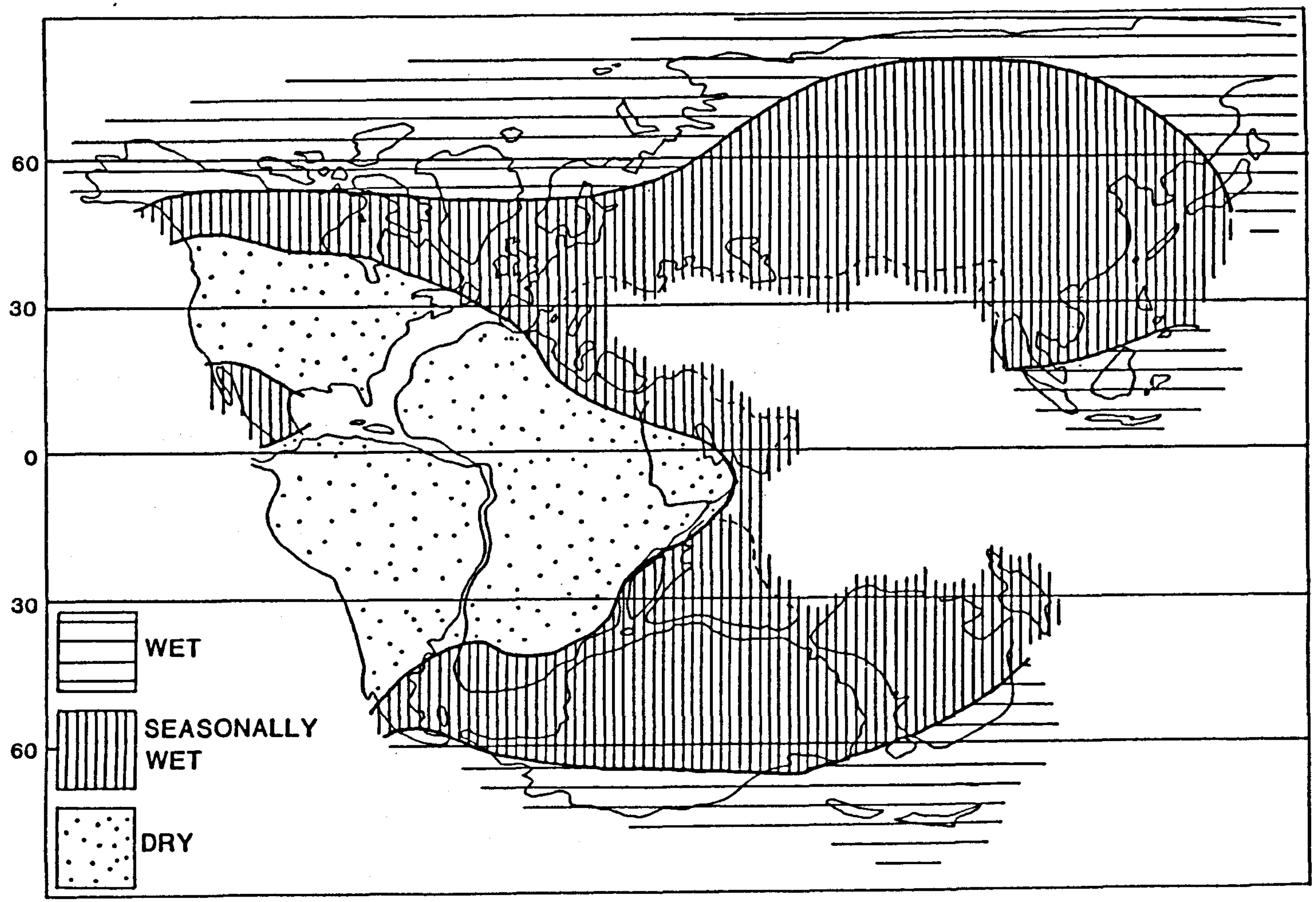
Palaeomagnetic reconstructions of Pangaea at the beginning of the Mesozoic (Smith et al 1981 Map 49) suggest that the North Atlantic Rift lay approximately between 10^{o}S and 50^{o}N. Hallam (1985) reviewed sedimentary and palaeontological evidence that showed the Mesozoic climate of the earth to be much more equable than at present, with broader zones and no polar ice caps. It was shown that in Triassic times, no equatorial humid belt was present around the earth. This was thought a result of the configuration of Pangaea controlling the route of the trade winds which, having crossed no large tracts of oceanic waters, would have remained dry. Hallam (1985, Fig. 5) showed that the arid climate belt would have occupied most of the North Atlantic Rift in early Triassic times.

The drift northwards of Pangaea, and probably the establishment of the epeiric sea in the early Jurassic, brought NW Europe out of the arid zone and into a seasonally humid climate regime (Hallam 1985:443). By Pliensbachian times (190-185 Ma, Salvador 1985 Fig. 2), Britain lay approximately 35-45°N (Smith et al 1981 Map 41), with the arid zone lying to the S, and annually wet conditions at the N end of the rift and beyond (Fig. 7). Hallam (1985 Fig. 2) showed that Krassilov's (1981) boundary between warm and temperate palaeoflora ecotones for the Lias was drawn approximately across N central Europe. Duke (1985) drew attention to the modern latitudinal range (10-45°) of violent tropical cyclones (hurricanes and typhoons), and argued that the zone was wider in the equable Mesozoic. It is likely, therefore, that NW Europe was seasonally subjected to these powerful storms, which would have had important implications for contemporary sedimentation (Chapter 5).

3.3 Sedimentation

During the Permo-Triassic, the arid hot equatorial climate and continental environment gave rise to red bed and evaporite sedimentation in the North Atlantic Rift. The detrital deposits were initially coarse grained as a result of erosion from the newly-formed mountains within the stabilized Upper Palaeozoic mobile belt. Associated with the crustal tension, basic volcanics were extruded at this time, and basic dyke swarms and sills were intruded into the new sediments and older country rock. This process continued into Liassic times in E North America (Fig. 5).

Fig. 7. Global Pliensbachian palaeogeography and palaeo-climate (Hallam 1985, Smith _et al_ 1981).



With the establishment of the early Jurassic epeiric sea in NW Europe, the red beds gave way to open marine deposits. Hallam (1984b Fig. 2), drawing attention to the distribution of climatically sensitive sediments showed that in the Lias of Europe, ironstones were forming in the NW, coals in the E, and minor evaporites in the S. The coal deposits indicate an abundant flora and the ironstones, more fully discussed in Chapter 6, suggest iron derivation from lateritic weathering on well vegetated lands in a humid tropical climate.

Johnson and Baldwin (1986) showed that humid tropical environments generate sediments with high mud, noticeably high clay contents, and these are abundant in the Jurassic of NW Europe. Most of the terrigenous input into the epeiric sea appears to have been rarely coarse grained, suggesting the mountains present during the Permo-Triassic had been worn down and the horst blocks forming the Jurassic land areas possessed no great relief. Where terrigenous inputs were low, the warm clear shallow sea was ideal for the formation of carbonates, and were associated with ironstone deposition.

During the early Jurassic in Britain, terrigenous inputs were high and siliciclastic mudrock facies dominated sedimentation (Anderton et al 1979:Ch14). Cyclic patterns are known from the Lias throughout Britain (Sellwood 1972, Sellwood and Jenkyns 1975), showing upwards coarsening (clay to sand grade) and upwards replacement of thick siliciclastic sediments by stratigraphically condensed carbonates and ironstones. Often individual cycles may be capped by a thin pebble conglomerate. Upward coarsening may be accompanied by a change from flat-lying to cross-lamination, suggesting an increase in current activity, and the cycles are thought to indicate shallowing upward conditions (Sellwood and Jenkyns 1975:376). Sellwood and Jenkyns (1975) interpreted the cycles throughout Britain as basin infillings following periodic fault-controlled subsidence in the shelf sea environment. In the Cleveland Basin of Yorkshire, however, alternative explanations have since been favoured such as climatic variation, periodic uplift of sediment sourcelands and coastal sedimentary processes, associated with more broader crustal subsidence (Rawson et al 1983, Howard 1984). A further possible cause, by eustatic control, was discounted by Hallam (1984b :212) who considered the cyclicity to be more a result of local and/or regional epeirogenic crustal movements. This subject is fully discussed in Chapter 6.

CHAPTER 4

Field and Laboratory Work

1.0 Fieldwork

1.1 Fieldwork Objectives

The primary objectives of the fieldwork were to log and sample the MRBF and DSF at as many localities as possible in order to produce a clear indication of spatial and temporal facies, as well as variations in thicknesses of the two formations. In so doing, the field and analytical results were to be used in conjunction with published data to build up a knowledge of patterns on a basin-wide scale as a test of the Sellwood and Jenkyns (1975) model.

1.2 Methods

A thorough examination of the literature for localities of exposures was undertaken, and all were visited with the exception of those too small to be of value to the main fieldwork aims, or where better exposures existed in close proximity. This work was then supported with information from other exposures not so far described in the literature, in order to obtain an even coverage across the study area. Details on the locations of some of these sites were obtained through personal contacts, and through examination of temporary exposures such as waterpipe trenches and building sites. Location of possible sites was determined by examination of BGS 1:50 000 and 1:63360 series sheets covering the Cotswolds, as well as the relevant BGS memoirs. Some of these sites included old quarries or pits marked on OS 1:25 000 maps, but most were found in deeply incised streams on steep slopes, railway cuttings, and small wooded areas marking possible landslip scars.

The position of the MRBF, on maps where it was not differentiated from the DSF, could often be located by the position of a flattish topographic shelf on the escarpment. Exposures created by landslips proved a valuable source of many of the sections for both the MRBF and DSF. The shear planes were particularly useful, although rotationally slipped and cambered blocks and slabs of the MRBF were also valuable. Often these blocks, which had moved only a short distance from their original position, were usually rotated between 30° and 60° without disruption of their sedimentary sequence. They were, therefore, used in graphic logging.

1.3 Problems in obtaining an even distribution of localities

Whilst nearly all literature sites were utilised in the present study and were supplemented with numerous new localities, an even spread of sites could not be obtained in all areas. The weakly-cemented nature of much of the DSF, which causes sections to degrade quickly, has meant that fewer sites were available for study than in the MRBF. Landslips, while a valuable source of sections for both the MRBF and DSF, also created a mantle of slumped material over the formations in places. Where landslips are combined with low angled slopes such as in parts of the Evenlode, Dikler and Windrush valleys along the NE flank of the Cotswolds, study was impossible. At some localities slumped material appears to have been quarried, and old workings in the Vale of Winchcombe, which coincidentally lie along the mapped Middle-Upper Lias boundary, have exposed rotated blocks of Inferior Oolite. (Appendix 3 lists areas that were examined, but where no MRBF sections or samples from soil brash could be obtained).

The BGS Sheet 234 'Gloucester' 1:50 000 has much of the Lias on the escarpment north of Stroud marked as indeterminate 'Landslip'. Field observations in the present study, however, suggest that the MRBF platforms in a number of areas appear to be free of disruption and of any landslip mantle, and sampling was possible. In the area covered by the BGS Sheet 217 'Moreton-in-Marsh' 1:50 000, however, landslips are widespread and have had an important influence on the local geology. They have, however, been virtually omitted from the map as it was not considered important (Green 1981) at the time.

1.4 Recognition of the DSF and MRBF boundary in the field.

Because of the existing problems of establishing precise biostratigraphic zonation at the junction of the MRBF and DSF in the Cotswolds (Chapter 3), this boundary is defined here on lithostratigraphy alone. Present fieldwork and published data show that both formations can be distinguished across most of the area, although problems do exist in the NE Cotswolds were similar facies appear to occur in both formations. Resolution of this difficulty has been hampered by disagreement over the definition of the MRBF in the literature, as well as the poor quality of present exposures.

Two sedimentological criteria useful in distinguishing the MRBF and DSF are (i) grain size and (ii) sedimentary structures. The MRBF is nearly always a sand grade deposit and usually lacks primary sedimentary structures; the DSF is dominantly silt grade, usually possessing well developed flat laminations. The boundary between the two formations is often marked by a thin pebble conglomerate and has been noted at well-documented sites across the whole of the Cotswolds. These factors were used on numerous occasions to distinguish the MRBF and DSF where other evidence was lacking.

1.5 Field logging and collecting techniques

At all sites with good vertical sections, graphic logging was carried out. This includes collection of data on thicknesses of units, lithological types, sedimentary structures, fossil content and preservation, and grain size. Where extensive vertical exposures were present, units were accurately measured using an Abney level. Corrections were made for dip where the strata were affected by rotational shearing. The logging style is based on the approach used by Tucker (1982 Figs. 2.1, 2.3). Four logs are provided at each site illustrating the above information, so as to avoid the problems of overcrowding or selective use of data on more condensed graphic logs.

During the logging, appropriate material was collected for laboratory investigation. More emphasis was laid on lateral collecting in the MRBF than vertically, corresponding to the dominant facies changes. At localities where no sections were available, soil brash was collected. Vertical collecting in the MRBF was only undertaken where distinct variations in lithology were noted, and/or the formation was thickly developed or well exposed. Collecting was carried out along the full length of the Cotswold escarpment, a distance of some 160km. Most of the DSF collecting was carried out at locality 9 (Tuffley Brickpit), the most vertically continuous exposure, and was taken as a case study of vertical sedimentological patterns. Interesting lithologies such as ferruginous oolites, however, were collected at other sites, wherever seen. At Tuffley samples were collected from most lithological divisions present.

Sampling schemes which provide random selection (e.g. Krumbein and Graybill 1965, Griffiths 1967) often proved impractical in the field, and have not been used in this study. A pilot scheme of collection showed that 600 grams of material was appropriate for laboratory purposes. The collecting programme was governed by several constraints, including the geographical limit of the study area, the narrow width of the outcrop along the escarpment, and the variable quality of the exposure. The possibility of extending the sampling into the subcrop using cores from

BGS boreholes and released oil company wells was investigated, but discontinued. This was because of the very small size of samples available for analysis in view of national archive restrictions at the BGS core repositories. In total 197 field samples were collected, 150 from the MRBF, and 47 from the DSF.

1.6 Marlstone Rock Bed Formation

Seventy nine sites mentioned in the literature are listed in Appendix 1, and of these 66 were visited; the present state of these exposures is also listed. A further 39 sites were located during the present field investigations (Appendix 2). Areas of the escarpment where no exposures were found are listed in Appendix 3. The number of sites where exposures were seen or soil brash could be found amounted to 76. Of these, 23 sites were vertically continuous and could be logged; 10 of these logged sites are new and are not listed in the literature. The total number of sites used in the present fieldwork sampling programme are shown in Appendix 4 and listed in geographical order from SW to NE. Their geographical distribution is shown on Fig. 8.

1.7 Dyrham Silt Formation

A total of 27 sites were visited in the present study. Of these, 12 have been described in the literature (Appendix 5), and the remainder were found during this study (Appendix 6). Seventeen sites were logged, of which 11 were new. The localities are listed in Appendix 7, in SW

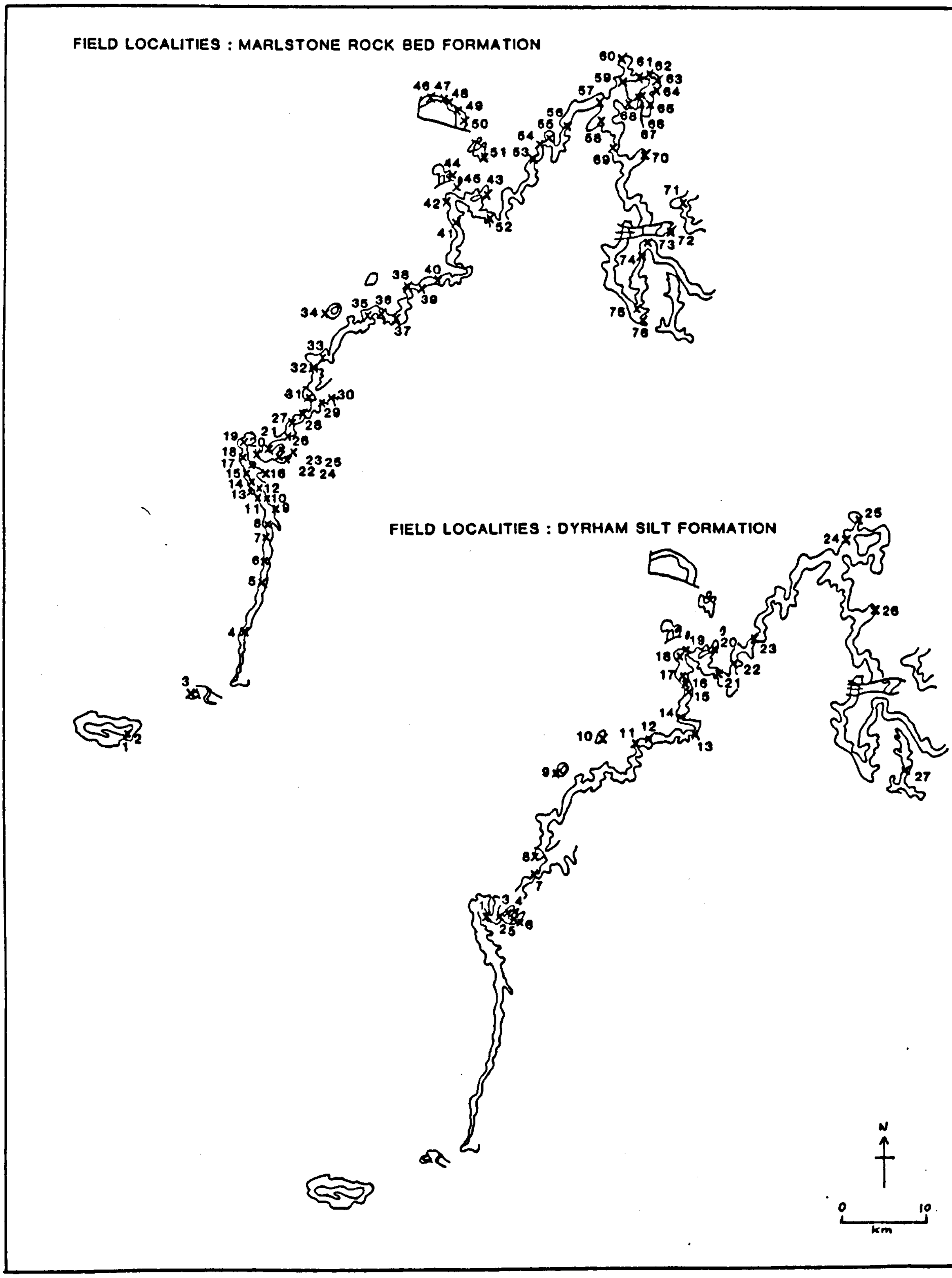


Fig. 8. Geographical distribution of field localities along the Cotswold escarpment.

to NE order as for the MRBF. Abbreviations correspond to those used in Appendix 4. Site localities are shown in Fig. 8.

2.0 Laboratory Work

2.1 Methods

Four 'wet' laboratory techniques and 3 'dry' laboratory techniques were employed. The former are described first.

2.1.1 $CaCO_3$ content (weight %)

This technique was particularly directed at samples which were not examined in thin section. Flugel (1982:417) noted that $CaCO_3$ evaluation can sometimes reveal cyclic patterns not evident in thin sections. The $CaCO_3$ values were also used for simple geochemical investigations into the possible causes for the development of iron-rich sediments in the sequence studied (Chapter 6). Sixty one samples were analysed from the MRBF, and 23 from the DSF. The method used for obtaining $CaCO_3$ values is described in Appendix 8.

2.1.2 Non-carbonate Particle Size Analysis (PSA)

A significant component of siliciclastic and ferruginous material was found in both formations. After digestion with acid, the residue was then subjected to PSA. Hallam (1981:3) outlined a number of reasons for the current disenchantment with PSA in facies analysis, including diagenetic corrosion, cement overgrowths, earlier-aquired grain surface textures, and bioturbation. While these reservations may be true for many sediments in the geological record, they are believed to be largely inapplicable to the MRBF and DSF siliciclastics. Diagenetic corrosion was seen in thin sections but was nowhere significant; cement overgrowths, which are calcitic, were easily removed by acid digestion. Surface textures of grains have not been studied. Bioturbation is not prolific in the DSF, in which most of the primary sedimentary structures remain intact. In contrast, the MRBF is thoroughly bioturbated, but areas of undisturbed sediments have been found (Figs. 9 and 31, 34, 35, 38) in which grain sizes are very similar to those in the bioturbated levels. Non-carbonate sand, silt and clay percentages were determined for most MRBF samples under 2mm in grain size. Their correlation with Fe contents were tested as part of the investigation into the origin of the iron-rich sediments (Chapter 6). Sixty-one samples were analysed from the MRBF, and 22 from the DSF. The method used for PSA is given in Appendix 9.

2.1.3 X-Ray Diffraction (XRD) studies of the clay minerals

This was carried out on 25 samples from the MRBF and 17 from the DSF. The former were spread across the whole study area in order to obtain maximum geographical coverage although some vertical analysis was also carried out. The DSF samples were almost exclusively selected from those at DSF locality 9 (Tuffley Brickpit) to assess vertical changes in the clay mineralogy at this key exposure.

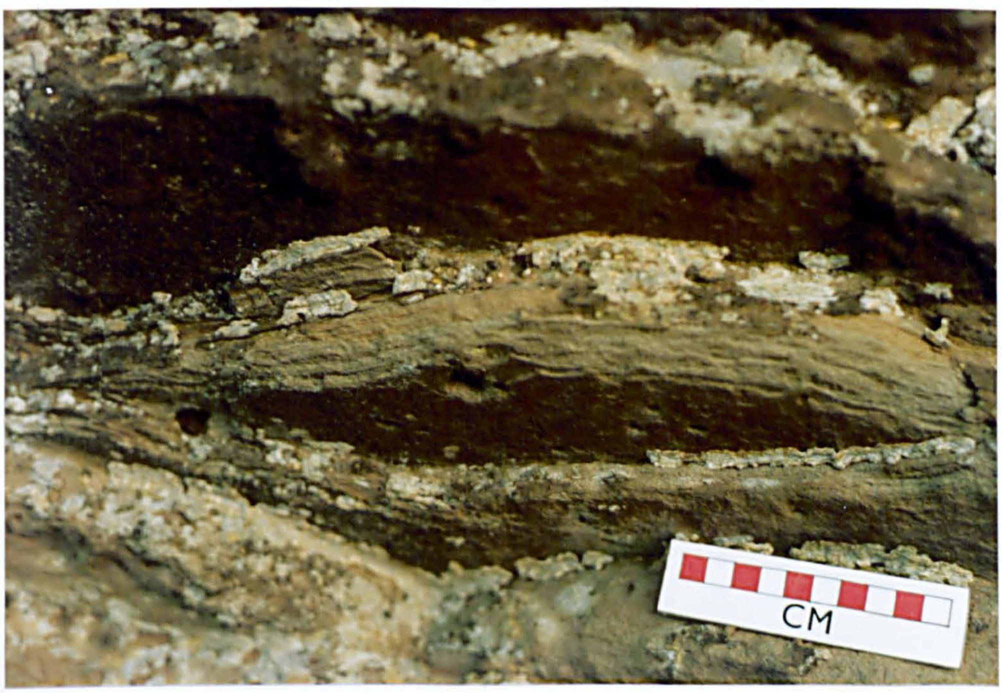


Fig. 9. Undisturbed sediment in the MRBF. Top: Cross-laminations, Tuffley Brickpit. Below: Flat laminations, Laverton.

The main purpose of the clay investigations was to detect any evidence for the palaeoclimatic regime (Chapter 3) and to investigate the possibility of smectite being present at this stratigraphical level in the Cotswolds. Corbin (1980) noted smectitic clays in the Pliensbachian of Dorset and discussed their possible origins as air-fall ash from contemporary volcanic activity (Chapter 6). The X-ray analysis in the present study was essentially qualitative in view of limited attention to the subject, and the questionable value of quantitative and semi-quantitative analysis (D. Robinson pers. comm.) The method used to prepare samples is described in Appendix 10.

2.1.4 Atomic Absorbtion Spectrophotometry : Fe_2O_3 content (Weight %)

The content of Total Iron Oxides (weight %), expressed as Fe_2O_3, was carried out to assess areas where 'Ironstones' may have formed (for definition see Chapter 6). Sixty samples from the more ferruginous MRBF were analysed, and 10 from the DSF. The DSF samples were of various lithologies, including some suspected ironstones. The method used to obtain Fe_2O_3 values and their conversion to Fe content is shown in Appendix 11.

2.1.5 Hand specimen description

All MRBF and DSF samples collected were subjected to detailed hand specimen examination in the laboratory. This was particularly useful where only soil brash was available as evidence of lateral continuation of logged sequences. Samples were sawn in order to reveal trace fossil evidence which were often otherwise invisible in the field. Data were separated into 'Lithology And Sedimentary Structures' on the one hand, and 'Fauna And Flora' on the other.

2.1.6 X-Ray Radiography of rock slabs

This method was employed to reveal sedimentary structures in the MRBF sediments which appeared massive in the field (Fig. 10), or even following sawing. Ten samples were analysed. The method used follows that of Hamblin (1965).

2.1.7 Thin section Petrography

Detailed petrography was carried out mainly on samples from the MRBF, in view of its coarser grain size compared with the DSF. Some DSF ferruginous oolites were sectioned for photomicrographs. The purpose of this work was to enhance information on lithologies, sedimentary structures, flora and fauna noted in the field and in hand specimens. From this information, facies groups were defined, and their textural divisions determined using the scheme proposed by Dunham (1962). Seventy-eight MRBF samples were analysed and 7 from the DSF. The methods used in preparation of the samples for thin sectioning are shown in Appendix 12. Reference was made to Adams et al (1984) for identification of components. Area percentage values for components were obtained from thin sections based on visual estimations using charts devised by Terry and Chillingar (1955). The use of these type of charts

Fig. 10. Massive sediment in the MRBF. Left: Tuffley Brickpit. Right: Stonehouse Brickpit.

was discussed by Flugel (1982:259) who showed that results could be obtained which are favourably comparable with the more time-consuming point-counting method.

Well established mineralogical classification schemes were applied to the samples analysed in thin section, including those for limestone (Folk 1959, 1962), for sandstones (Pettijohn et al 1973) and for ironstone (Taylor 1949). In the siliciclastic-rich facies of the MRBF and the DSF lithologies, Picard's triangular classification was employed (Tucker 1982 Fig. 3·2), using PSA data. Seven thin sections were also made of the boundaries of 'wavy' bedding encountered at many of the MRBF and DSF sites, to ascertain whether it has a primary or diagenetic origin.

2.2 Analytical Results

2.2.1 $CaCO_3$ content (weight %)

Results for $CaCO_3$ determinations for the MRBF are listed in Appendix 13, and for the DSF in Appendix 14.

2.2.2 Non-carbonate Particle Size Analysis (PSA)

Results for the MRBF samples analysed are listed in Appendix 15, and for the DSF in Appendix 16.

2.2.3 X-Ray Diffraction (XRD) studies of the clay minerals

After Brown (1980), Brown and Brindley (1980).

Kaolinite

The peak at 7·1Å on the air dried trace is unaffected by glycol, is much reduced at 390°c and disappears altogether at 550°c. The peaks at 3·56Å and 2·38Å behave in the same way. These three peaks therefore represent 001, 002 and 003 reflections from Kaolinite and since there is no residual on heating, there is therefore no chlorite.

Illite

The peak at 9·9Å is unaffected by glycolation, and is increased in intensity by heat treatment. This response to heating is characteristic of 001 illite, as hydroscopic water is lost. Illite reflections at 002, 003, 004 are also well represented, although the 003 reflection is intensified by the 101 reflection of Quartz.

Smectite

The peak at 16·8Å on the glycolated trace corresponds with a peak at 14·0Å on the air dried trace. This shift on glycolation is characteristic of smectite. Since all X-ray smears had received prior treatment by the dithionite-citrate method for the removal of iron, the nature of the original smectite is uncertain, but in view of the nature of the sediments, was almost certainly a calcium montmorillonite. The 16·8Å peak disappears on heating; it appears to collapse and is obscured by the 001 illite reflections.

Randomly Interstratified Illite-Smectite

There are several subsidiary peaks which form a shoulder on the air dried trace between smectite 001 and illite 001. This shoulder also displays enhanced d-spacing on the glycolated trace, and represents random interstratification of illite-smectite. This random rather than ordered arrangement is indicated by the sloping nature of the shoulder on the glycolated trace rather than having a definite peak (Reynolds 1980, Bailey 1980).

<u>Non Clay Minerals</u>

<u>Quartz</u>

This was identified by reflections at 4·26Å (100), and 3·34Å (101); the latter reflection is largely obscured by illite (003).

<u>Siderite</u>

A peak at 2·8Å (104) was present.

<u>Aragonite</u> (?)

Peaks at 2·7Å (012) and 3.4Å (100) possibly indicate the presence of aragonite.

<u>Feldspars</u> (?)

A peak at 3·198Å is suspected to indicate the presence of feldspars.

Results for the X-ray analysis of samples from the MRBF are shown in Appendix 17 and for the DSF, in Appendix 18. Diffractograms, mostly of samples containing smectite, are shown for the MRBF on Fig. 11 and for the DSF on Fig. 12. The bulge in the background between 2θ 20° and 35° is probably the result of noise generated by the glass slide

Fig. 11. X-Ray Diffractograms of MRBF samples containing smectite (NC 115 without smectite shown for contrast).

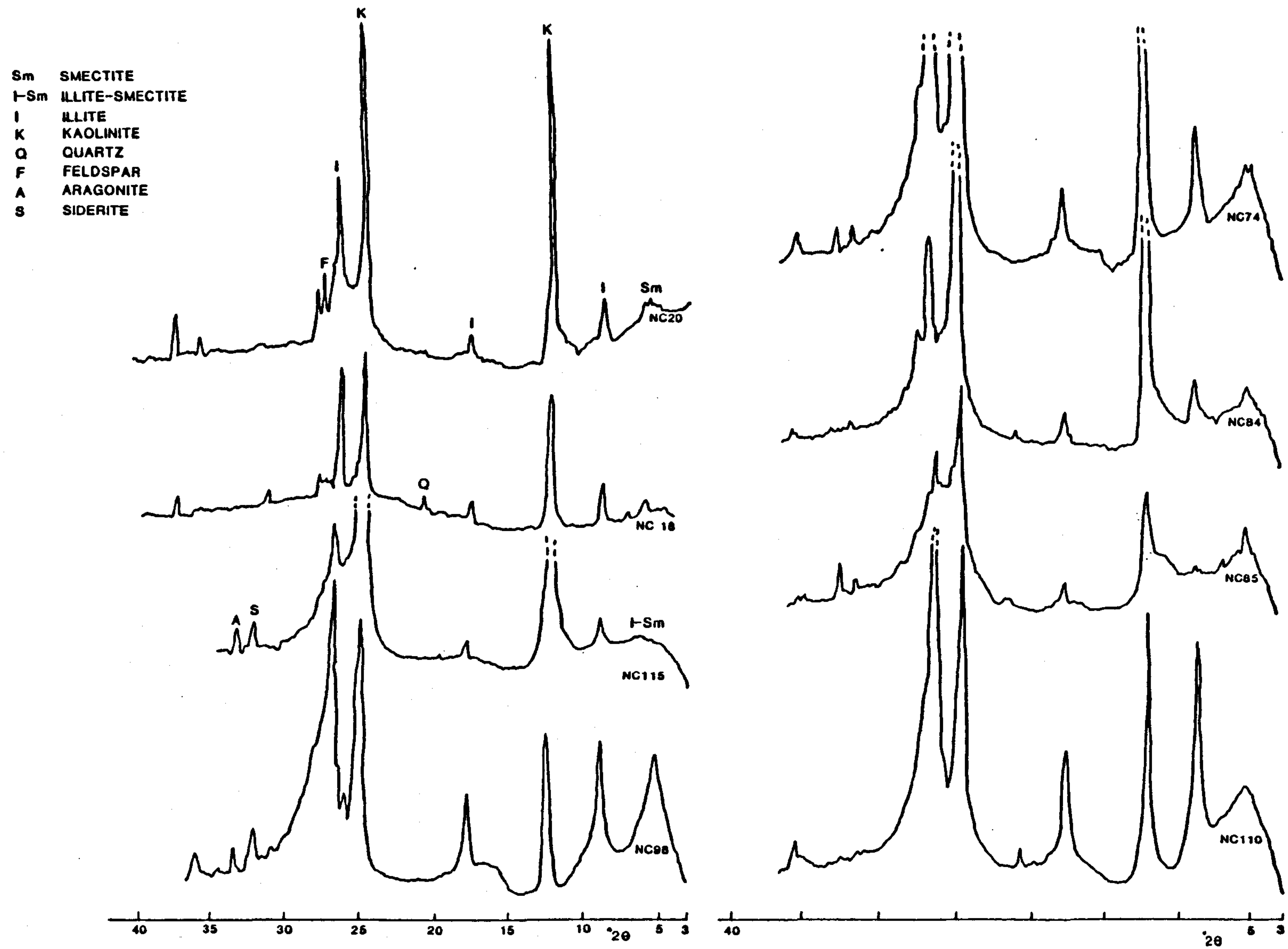
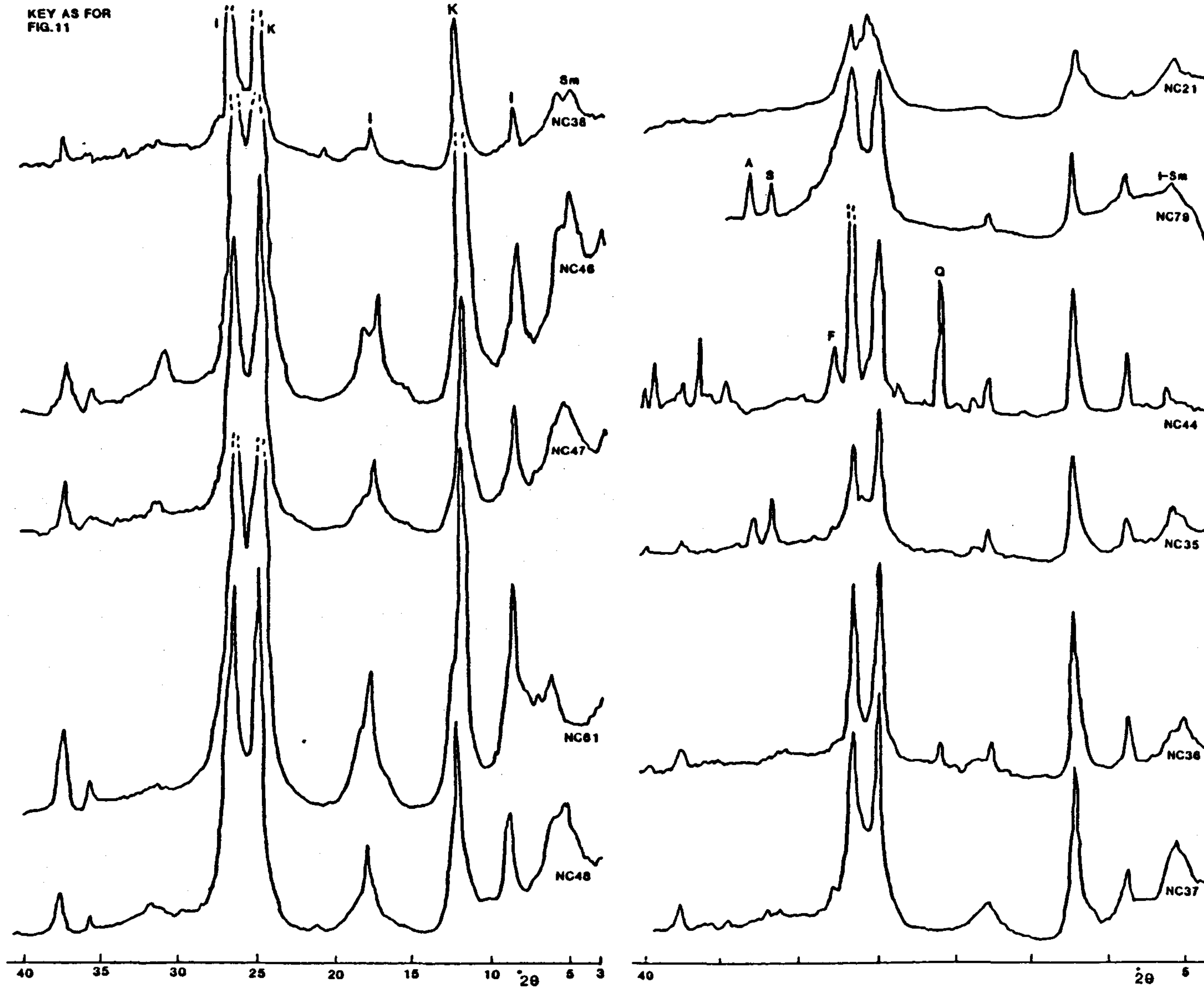


Fig. 12. X-Ray Diffractograms of DSF samples containing smectite (NC 79 without smectite shown for contrast).



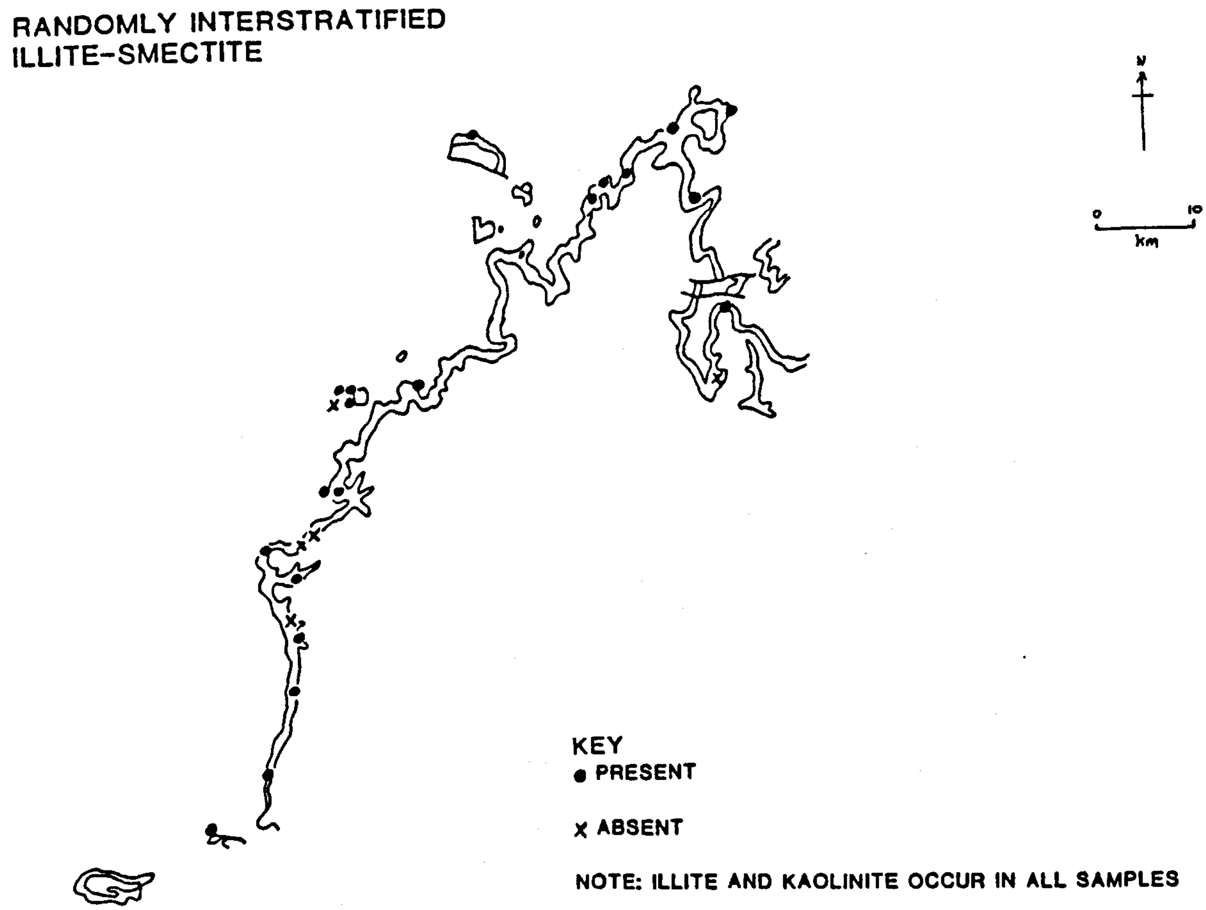
(J.R. Harpum, pers. comm.). The distribution of smectite and interstratified clays in the MRBF samples across the Cotswolds are shown in Fig. 13.

2.2.4 Atomic Absorption Spectrophotometry: Fe_2O_3 content (weight %)

Appendix 19 lists the results for the MRBF, and Appendix 20 results for the DSF.

2.2.5 Hand specimen descriptions

In Appendix 21, characteristics of Lithology and Sedimentary Structures are listed for the MRBF samples, and those for the DSF are shown in Appendix 22. Characteristics of Fauna and Flora in the MRBF samples are shown in Appendix 23, and for the DSF, Appendix 24. The MRBF samples show that 5 clear divisions exist, with associated conglomerates. These divisions are classified using field terms. They correspond to facies types, which are classified more precisely using a petrographic and PSA scheme in subsection 2.2.7. Similarly, hand specimen classifications for the DSF samples, particularly the mudrocks (under 63 micron grain size) can also be shown to be inaccurate when compared with more precise methods, such as PSA as used here (Appendix 25). Attention should also be drawn to DSF 'Oolitic Ironstones', to which a different classification is required following petrographic examination (Fig. 29). These precise definitions are, however, substituted for the more generalised term 'ferruginous oolite' in the following text. These



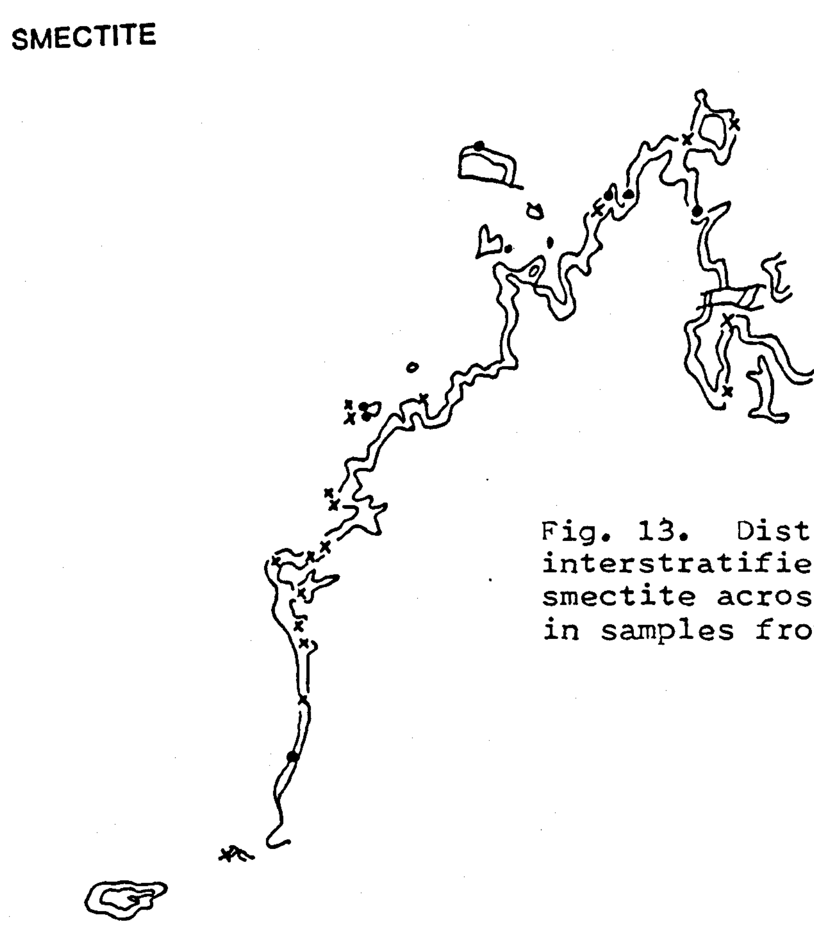


Fig. 13. Distribution of interstratified clays and smectite across the Cotswolds in samples from the MRBF.

comparisons serve to illustrate the limited value of field classifications in these sediments.

2.2.6 X-Ray Radiography of rock slabs

Positives of radiographs of NC174 and NC179 are illustrated on Figs. 14 and 15 respectively.

2.2.7 Thin Section Petrography

The hybrid nature of the MRBF facies did not accord with the well established mineralogical classification schemes listed in subsection 2.1.7. The scheme used here, and adopted throughout the following text, is shown in Appendix 26. This scheme employs a combination of terms derived from hand specimen observations, particle size analysis and petrographic work in order to emphasise important features in each facies. Grain size classification of the MRBF Facies I and the DSF siliciclastics may be seen on Fig. 16. Dunham's (1962) textural classification for limestone was found to be applicable to most of the facies, regardless of mineralogy. This is shown in Appendix 27. This classification does not strictly apply to Facies V, as its 'matrix' is largely a pseudospar with little micrite. This cement, however, is believed to be a diagenetic alteration of a micritic matrix, and the scheme has been applied.

The thin section petrography indicates that 3 major components are present in the MRBF of the Cotswolds:-

(i) CALCIUM CARBONATE ($CaCO_3$) in the form of skeletal and

Fig. 14. Radiograph positive of NC 174, MRBF, Ilmington. Note well developed vertical burrows and pseudo-bed boundary (Chapter 5).

Fig. 15. Radiograph positive of NC 179, MRBF, Tuffley Brickpit. Thoroughly bioturbated sediment.

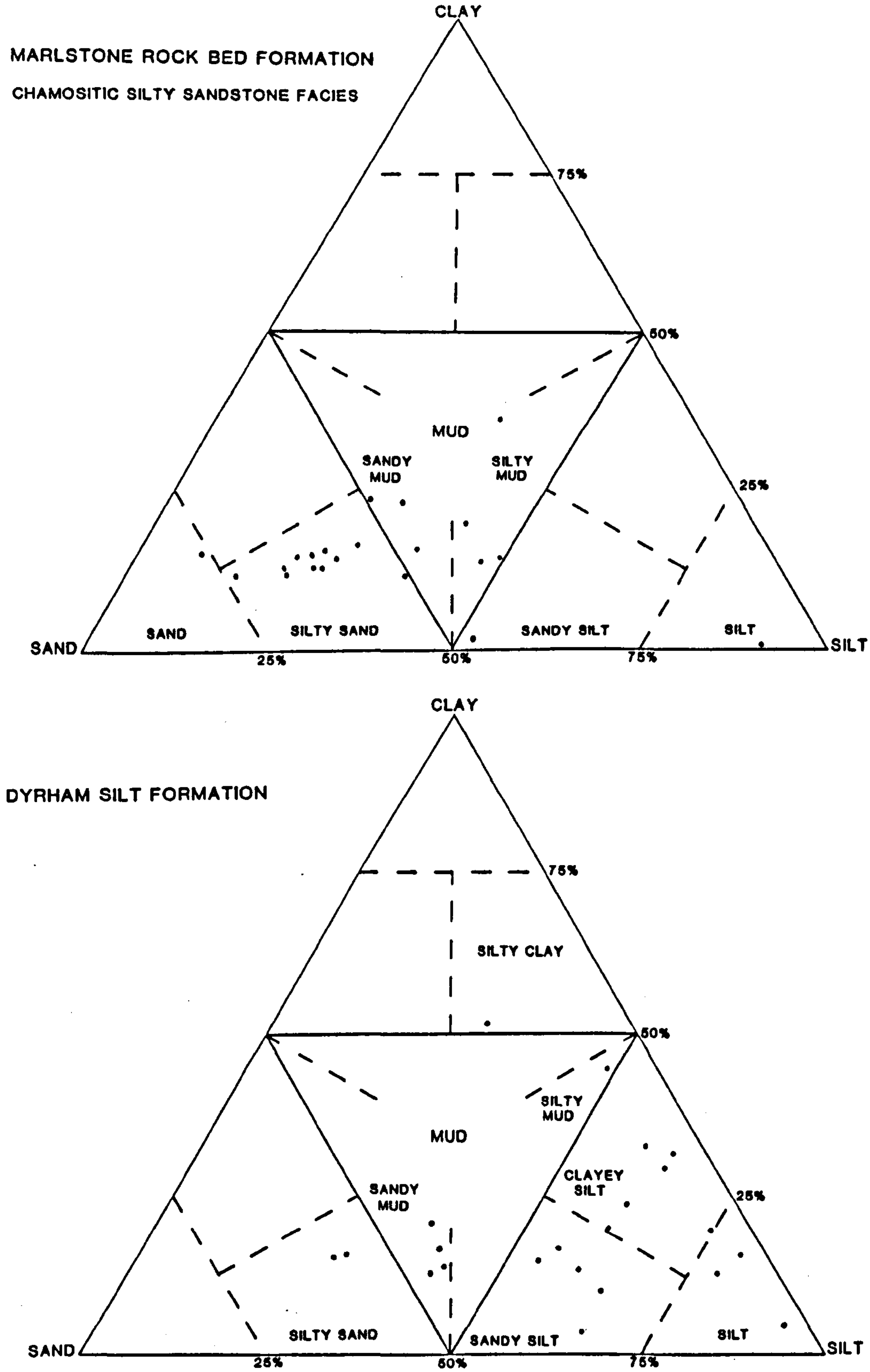


Fig. 16. Classification of siliciclastic sediments (Picard in Tucker 1982).

non-skeletal grains, micrite matrix, and sparite neomorphic pseudospar and patchy poikilotopic cements.

(ii) IRON MINERALS : CHAMOSITE ($Fe_2Al_2Si_2O_{10}.3H_2O$) in the form of grains and mud matrix, often in variable stages of oxidisation to LIMONITE ($FeO.OH.nH_2O$). Limonite is here taken to include GOETHITE α - FeO.OH. SIDERITE (Mg,Fe) CO_3 also may be present as a cement, altered to Limonite. The material was assumed to be siderite, a common associate of chamosite in bedded ironstones. The possibility that it may be ANKERITE was ruled out because of the lack of evidence of any hydrothermal activity in these rocks.

(iii) SILICICLASTICS composed of variable detrital silicate minerals and mud matrix. Magnetite (Fe_3O_4) is also present as part of the detrital component.

Photographs of representative hand specimens and photomicrographs of each facies are shown on Figs. 17-21. Some DSF ferruginous oolitic rocks are illustrated in Fig. 22. The variety of ferruginous grain types from the MRBF facies are illustrated in Figs. 23-25. Field photographs of 'wavy' bedding are shown in Fig. 26, and photomicrographs in Figs. 27 and 28.

2.3 Synthesis of field and laboratory data

A combination of data from both field and laboratory work has been used to construct the graphic logs for the MRBF and DSF. The key to these logs is shown on Fig. 29. Figures 30 to 38 include all sections logged in the present study of the MRBF of the Cotswolds. Dotted lines on these logs indicate estimated true thickness of the formation of any one site, based on isopachyte data discussed in Chapter 5. Many good sections were noted in the Dursley - Wotton-under-Edge area and it was decided that all these should be logged to provide a record of their sequence before they ultimately become degraded.

Figures 33-42 include all the logged DSF localities. Dotted lines on these DSF logs indicate discontinuous exposures. Colours of rock types are given where samples were not collected. For DSF Locality 9 (Tuffley Brickpit), selected for special attention because of its extensive vertical exposure, a log has been constructed with adjacent presentation of values for $CaCO_3$ content, non-carbonate PSA, and clay mineralogy to provide indications of temporal changes.

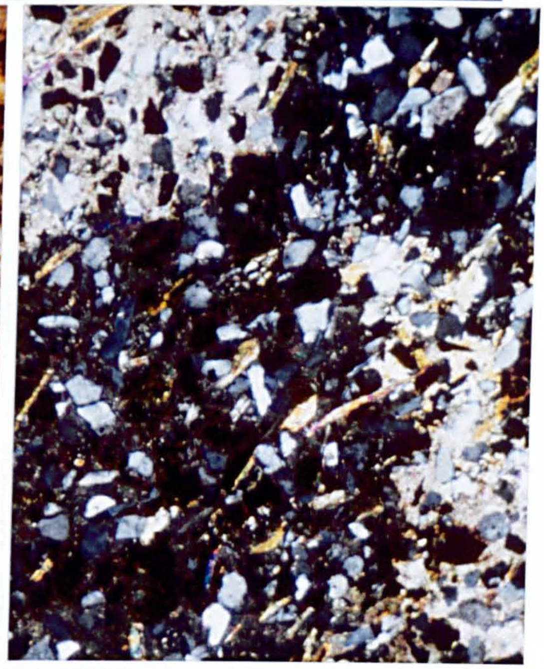
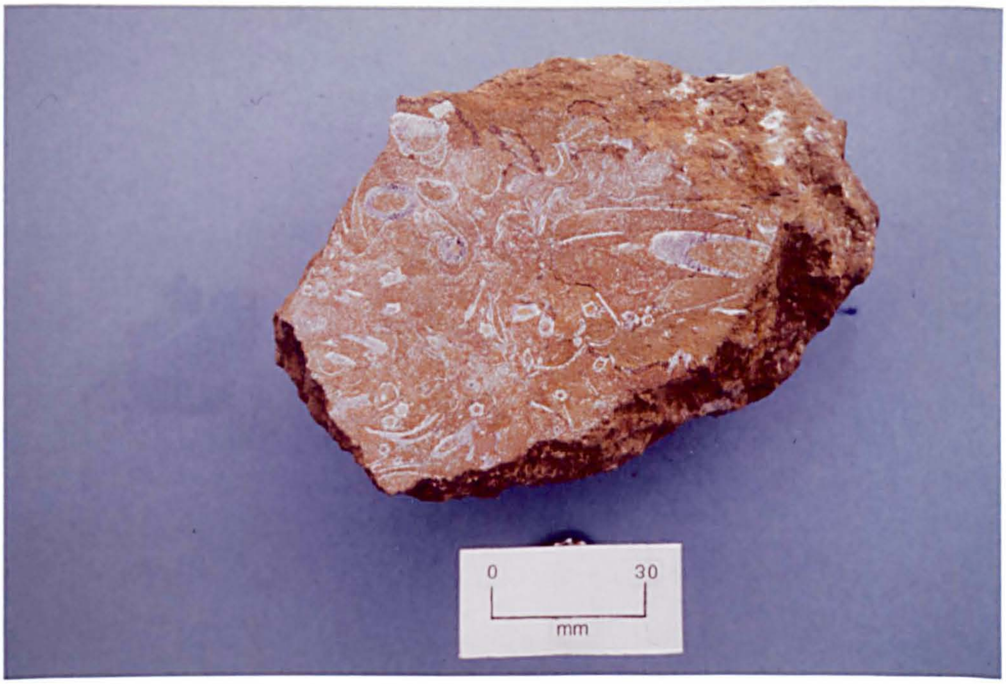


Fig. 17. MRBF Facies I. Top: friable (left) and cemented (right) units. Middle: friable unit, PPLX20 (left). Patchy poikilotopic cement cross nicols X4 (right). Below: Friable unit in cross nicols X4.



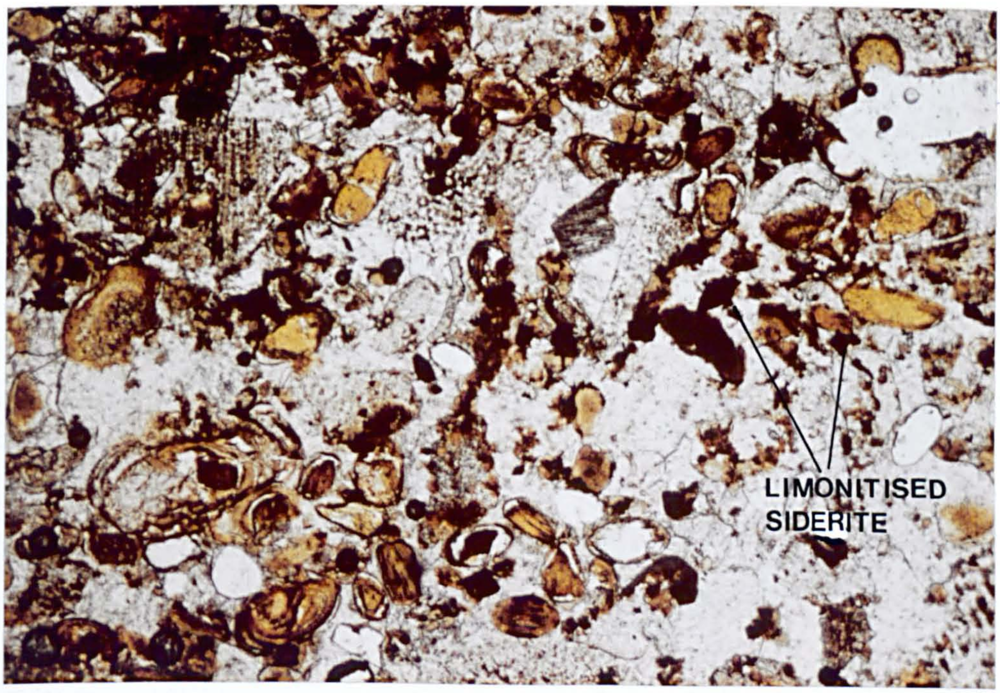
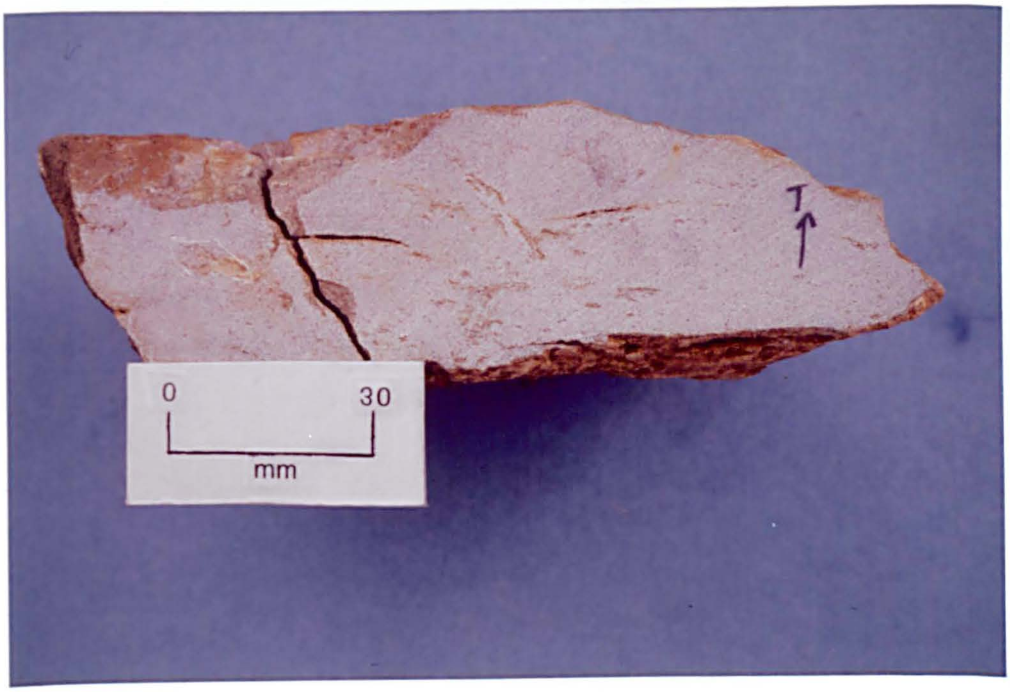


Fig. 18. MRBF Facies II. Top: Hand specimen showing abundant shelly material. Below: PPLX4.



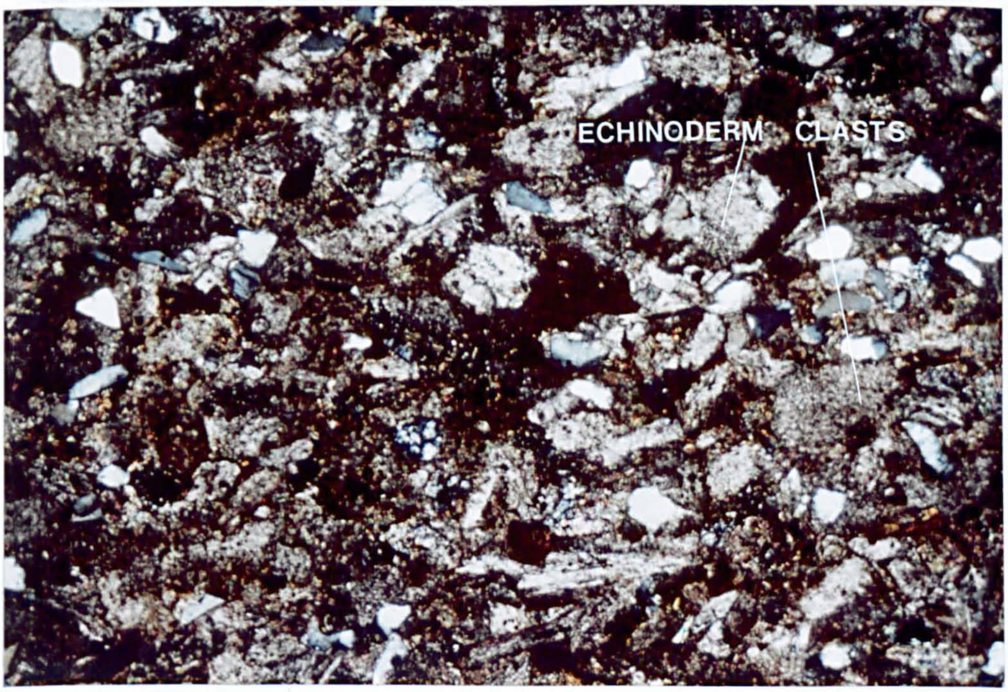


Fig. 19. MRBF Facies III. Top: Hand specimen showing lack of shelly material, and low Fe content. Below: cross nicols X4.

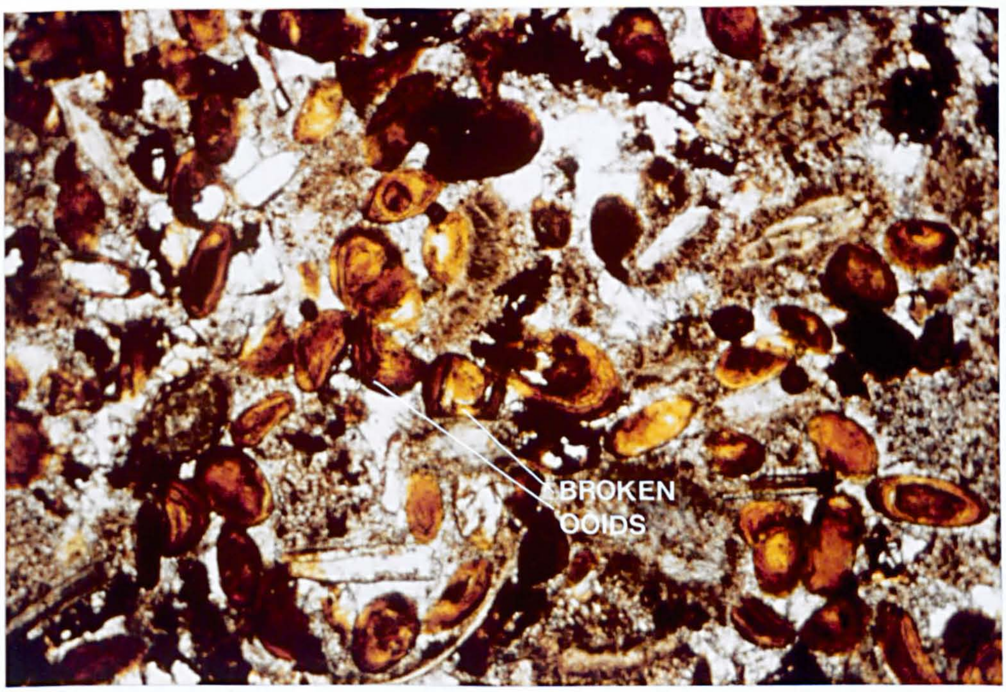
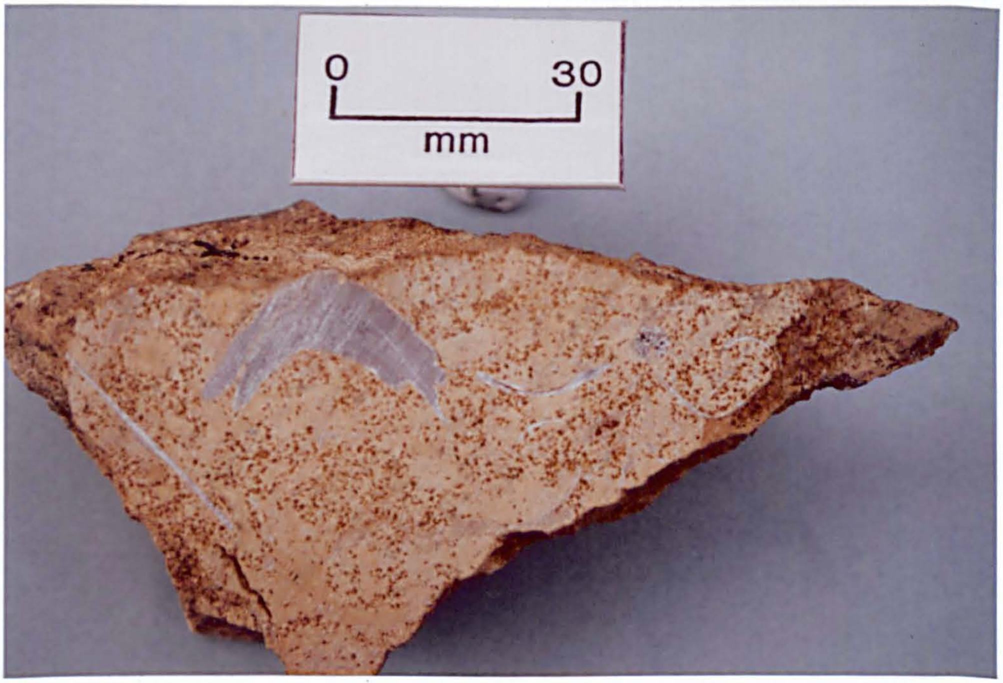


Fig. 20. MRBF Facies IV. Top: Hand specimen showing characteristically high Fe content. Below: PPLX4 showing various ferruginous grains, some broken.



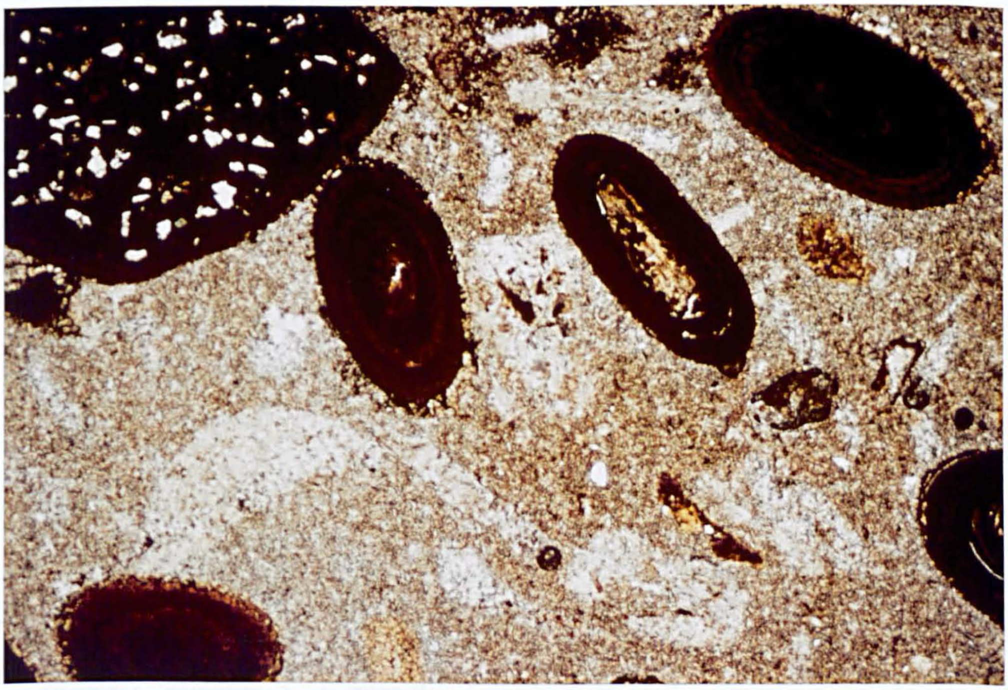


Fig. 21. MRBF Facies V. Top: Hand specimen showing iron-shot appearance and thick shelled bivalve. Below: PPLX4, showing large limonitised ooids, silt clast and neo-morphic pseudospar cement.

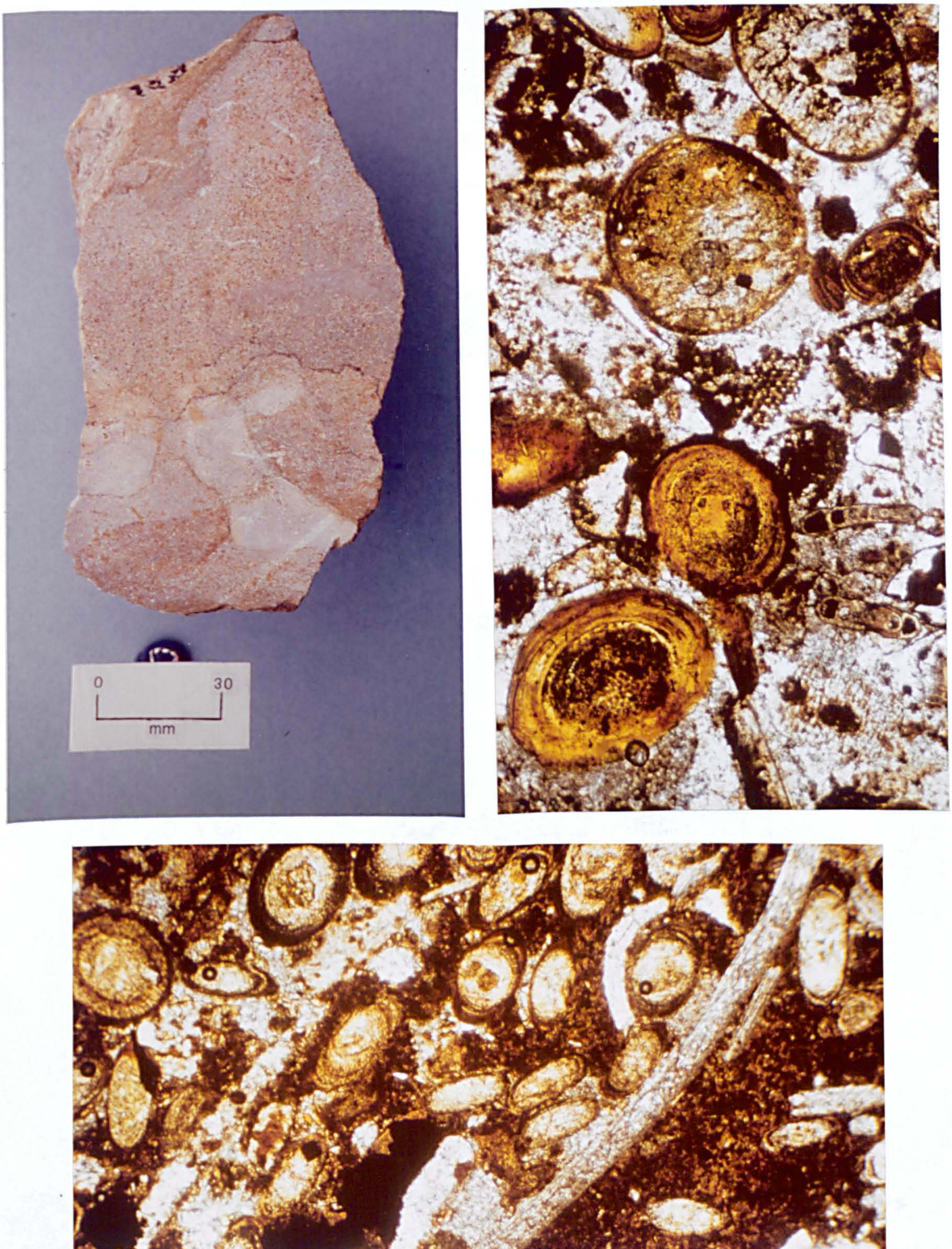


Fig. 22. Ferruginous oolites, DSF. Left: hand specimen showing iron-shot appearance and bioturbation. Right: Chamosite ooids PPLX4 (top). Chamosite ooids largely replaced by calcite. Chamosite mud matrix PPLX4 (below).

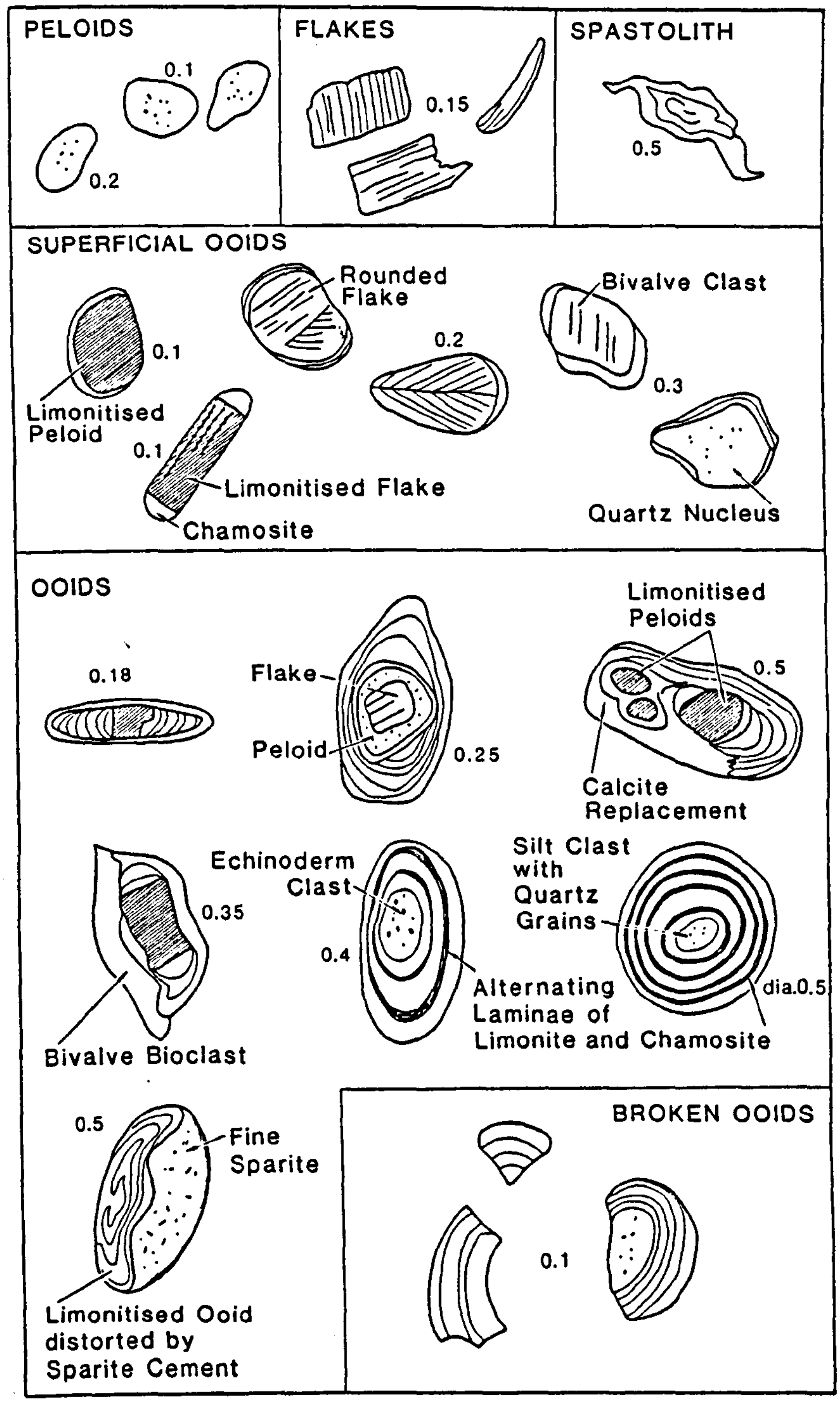


Fig. 23. Ferruginous grain types present in MRBF Facies II. Size (mm) refers to long axis of grains. All chamositic unless stated otherwise or shaded (= limonite).

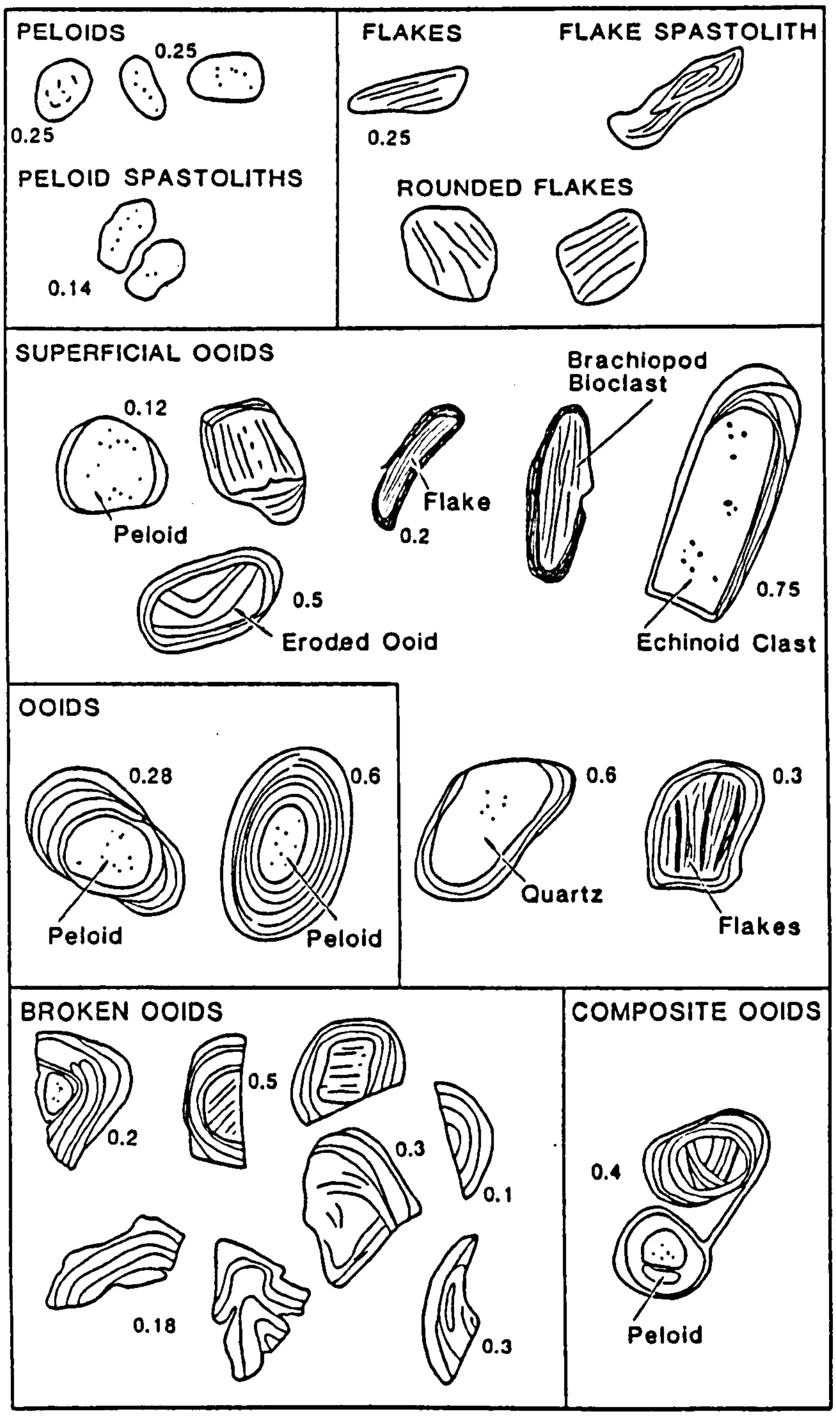


Fig. 24. Ferruginous grain types present in MRBF Facies IV. Explanation as given on Fig. 23.

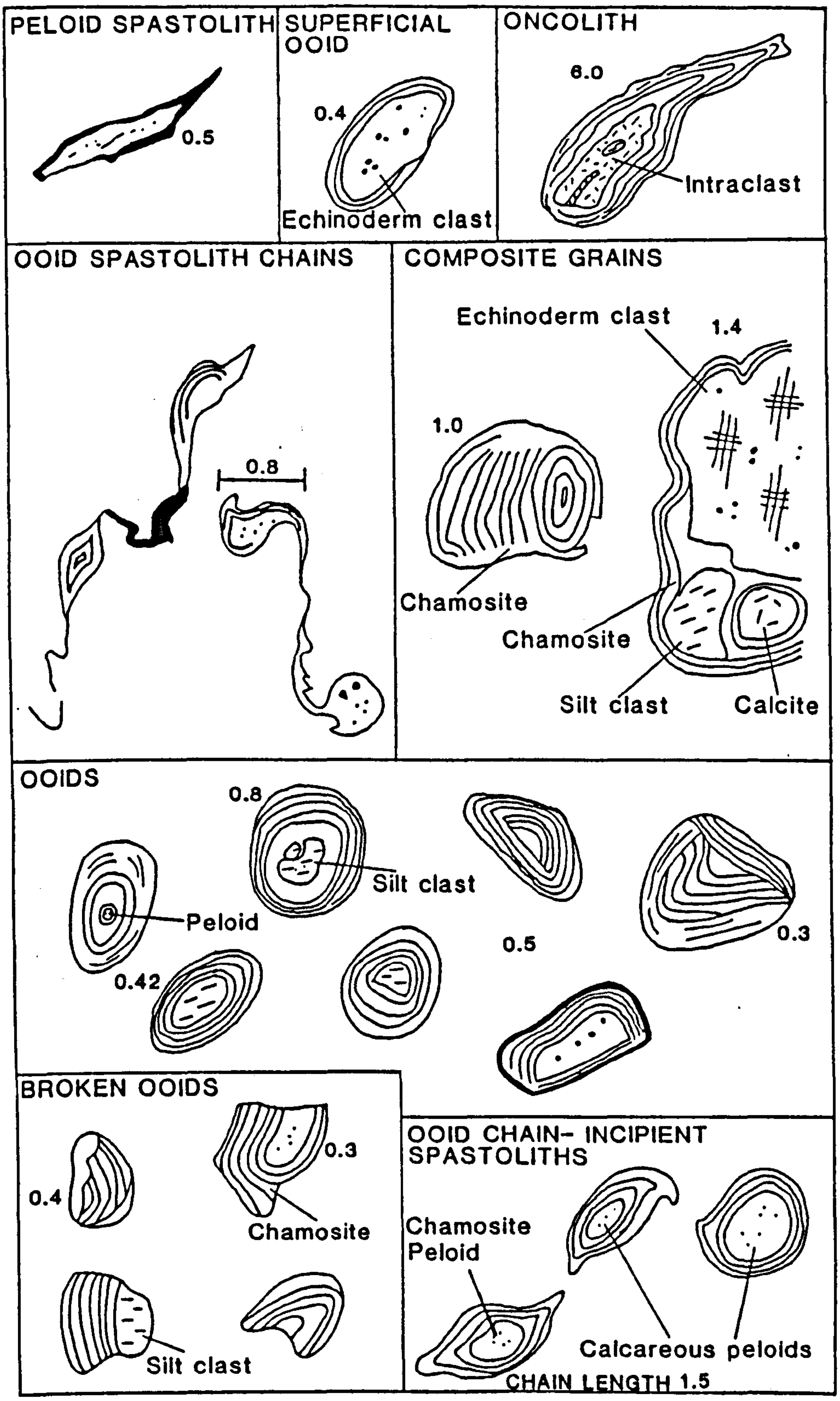


Fig. 25. Ferruginous grain types present in MRBF Facies V. Explanation given on Fig. 23.

Fig. 26. 'Wavy' Bedding (pseudo-bedding). Top: MRBF, Newnham Quarry. Below: DSF, Prescott. Note interlocking 'mound' and 'depression' relief.

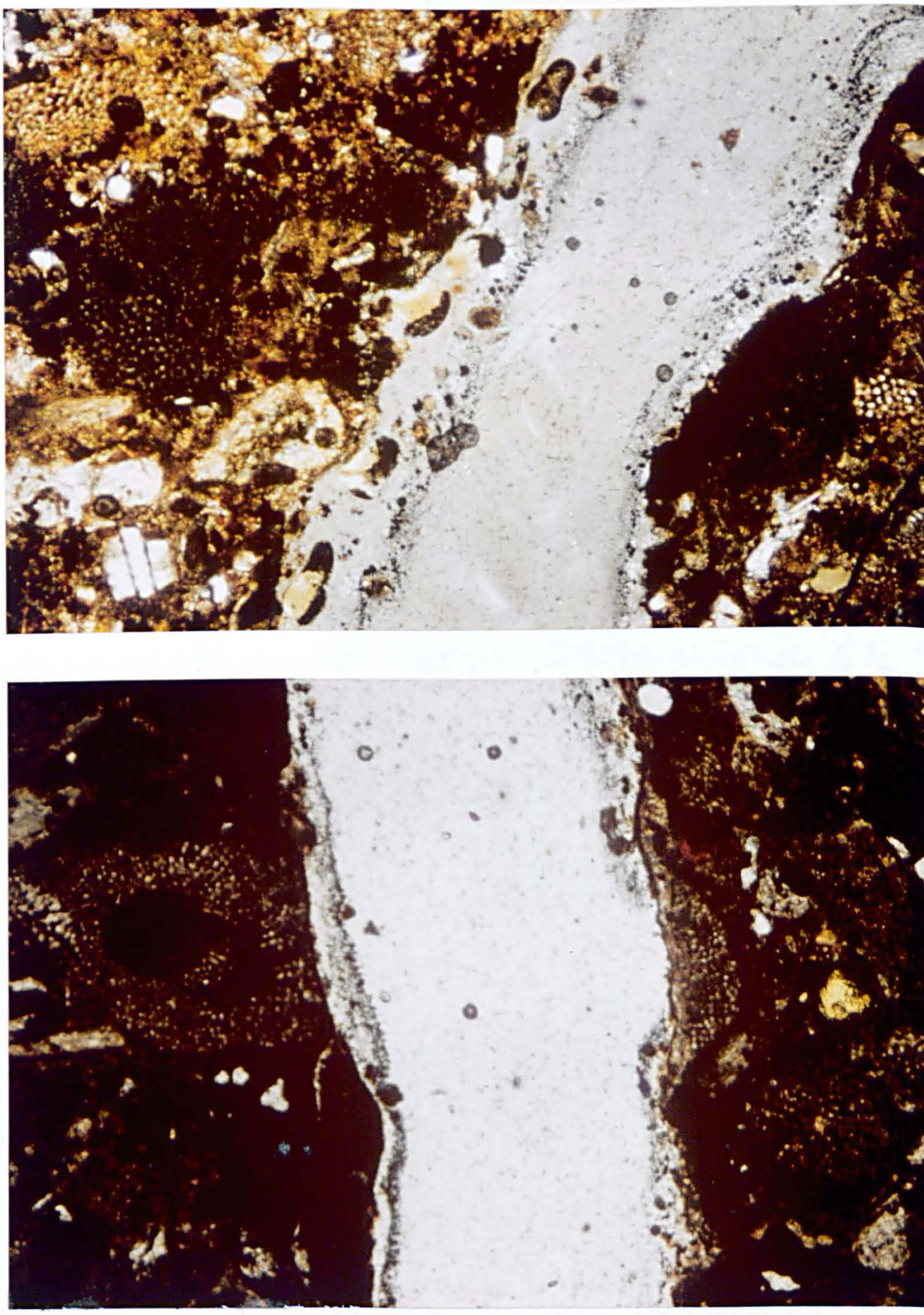


Fig. 27. Pseudo-bed boundaries. Diagenetic origin shown by dissection of echinoderm grains. Note lack of micro-stylolites, interpenetrant grains, and insoluble residues. Top: X10, Below: X4.

Fig. 28. Pseudo-bed boundaries. Dissection of echinoderm clast (length 5mm).

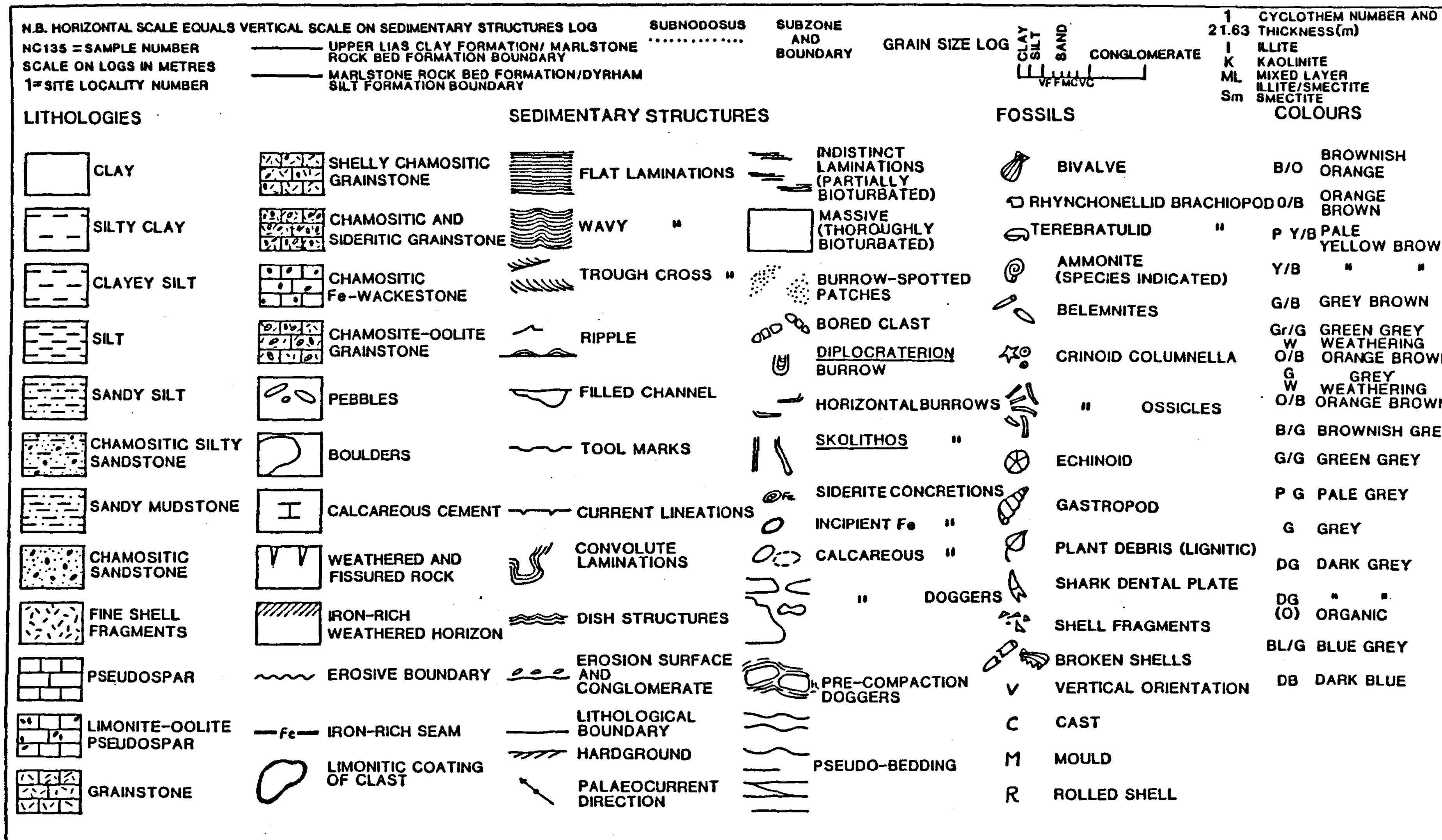


Fig. 29. Key to Figs 30-42, and Fig. 56.

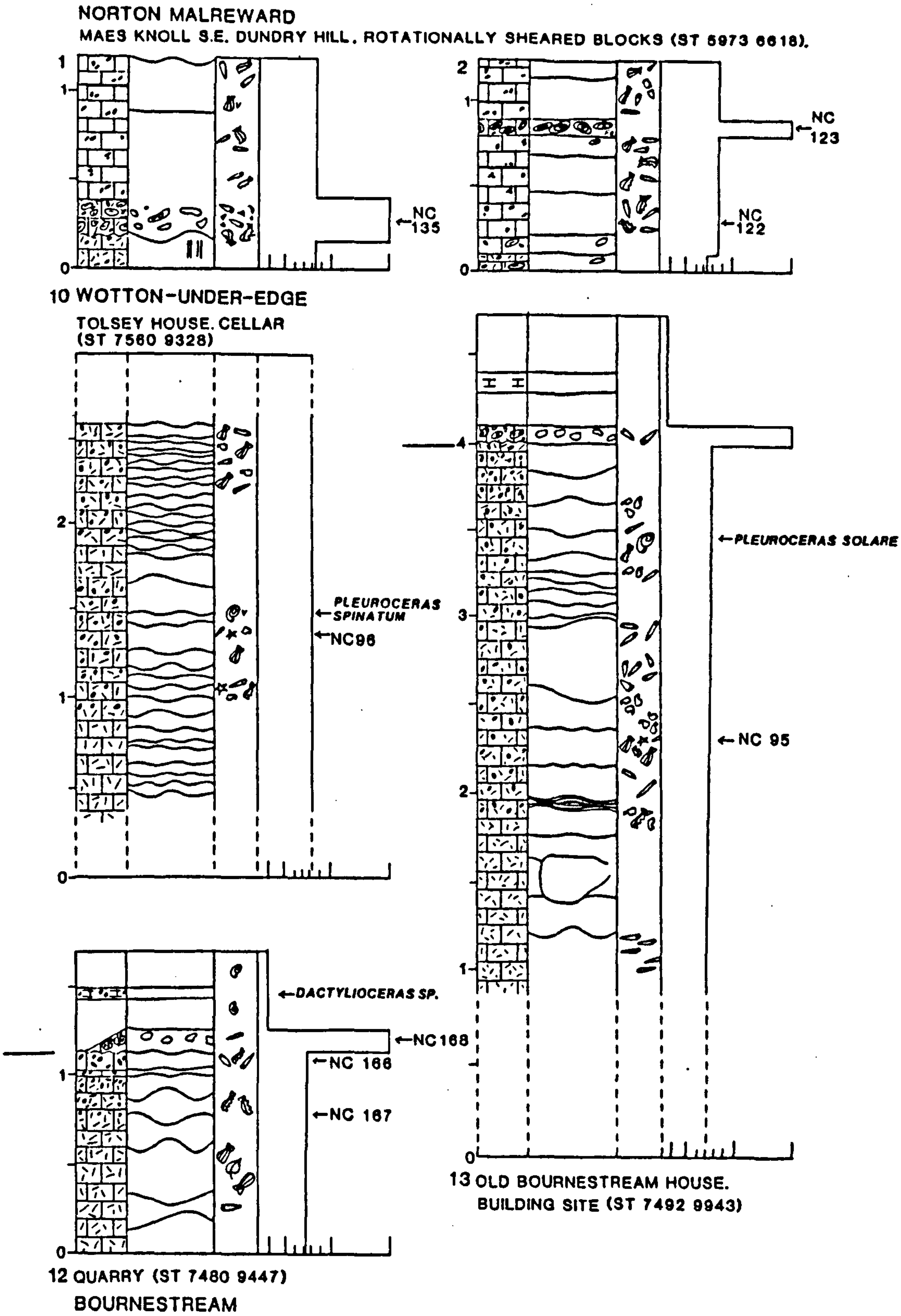


Fig. 30. MRBF logged sections. Site localities 1, 2, 10, 12, 13.

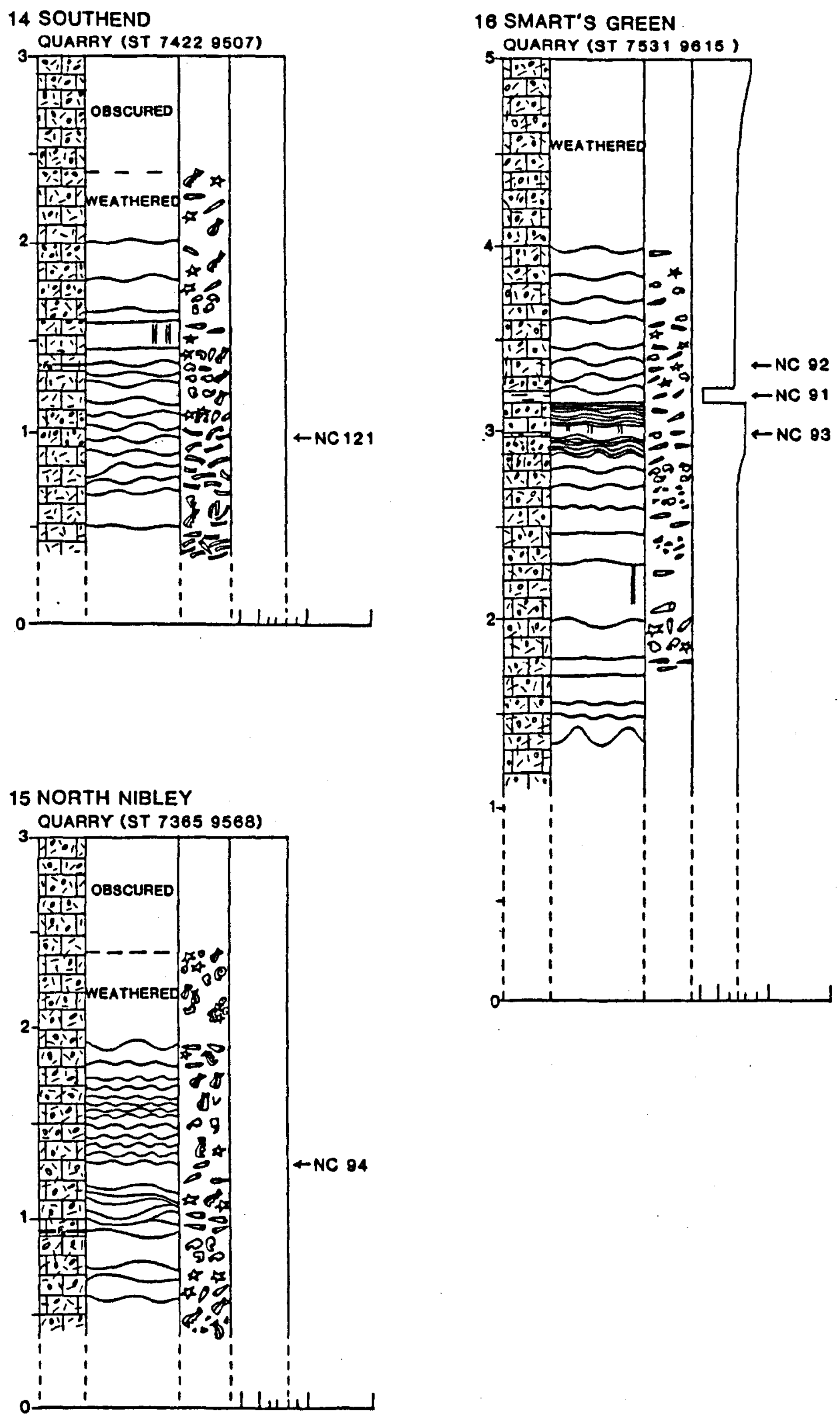


Fig. 31. MRBF logged sections. Site localities 14, 15, 16.

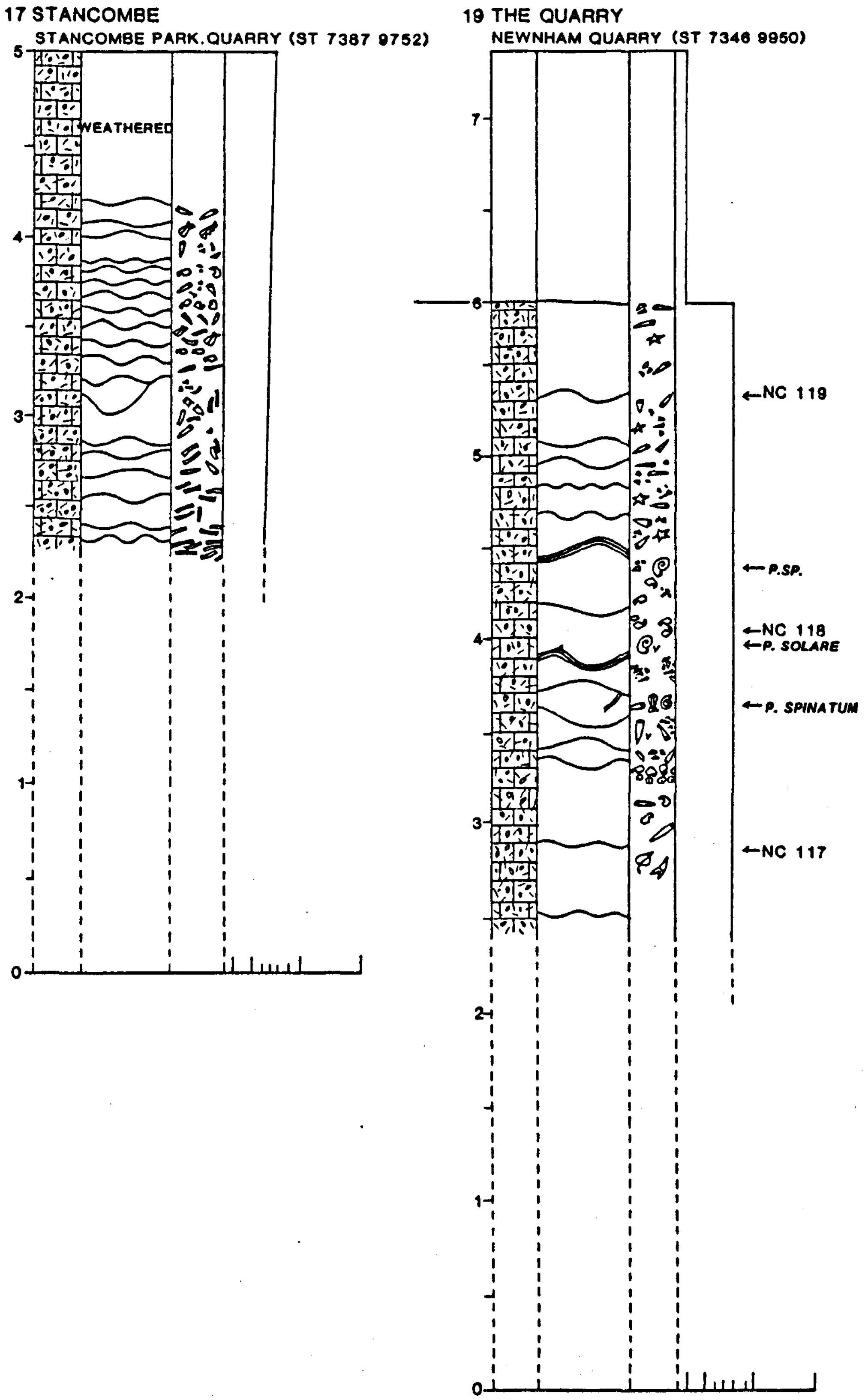


Fig. 32. MRBF logged sections. Site localities 17, 19.

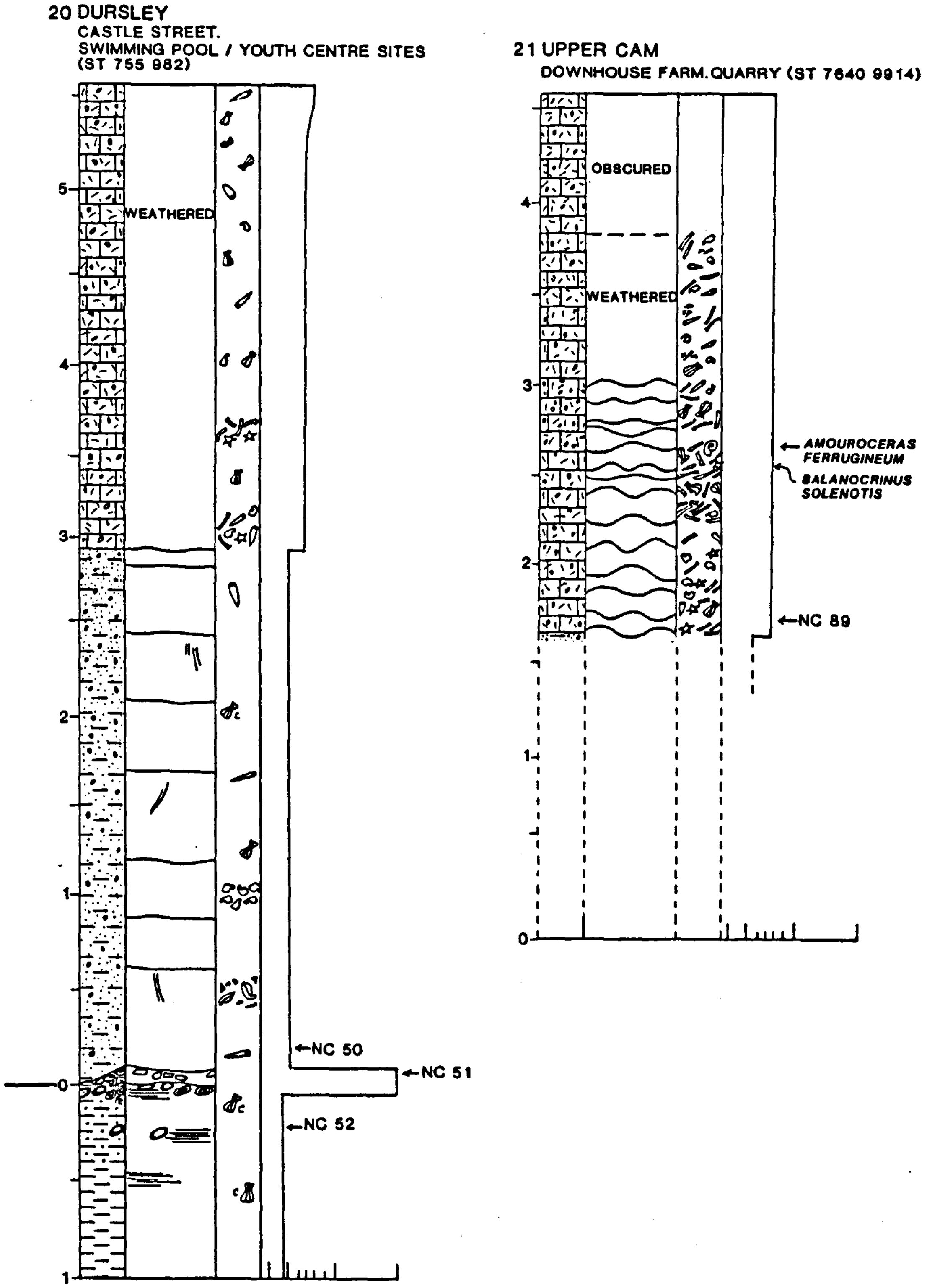


Fig. 33. MRBF logged sections. Site localities 20, 21 and DSF locality 1.

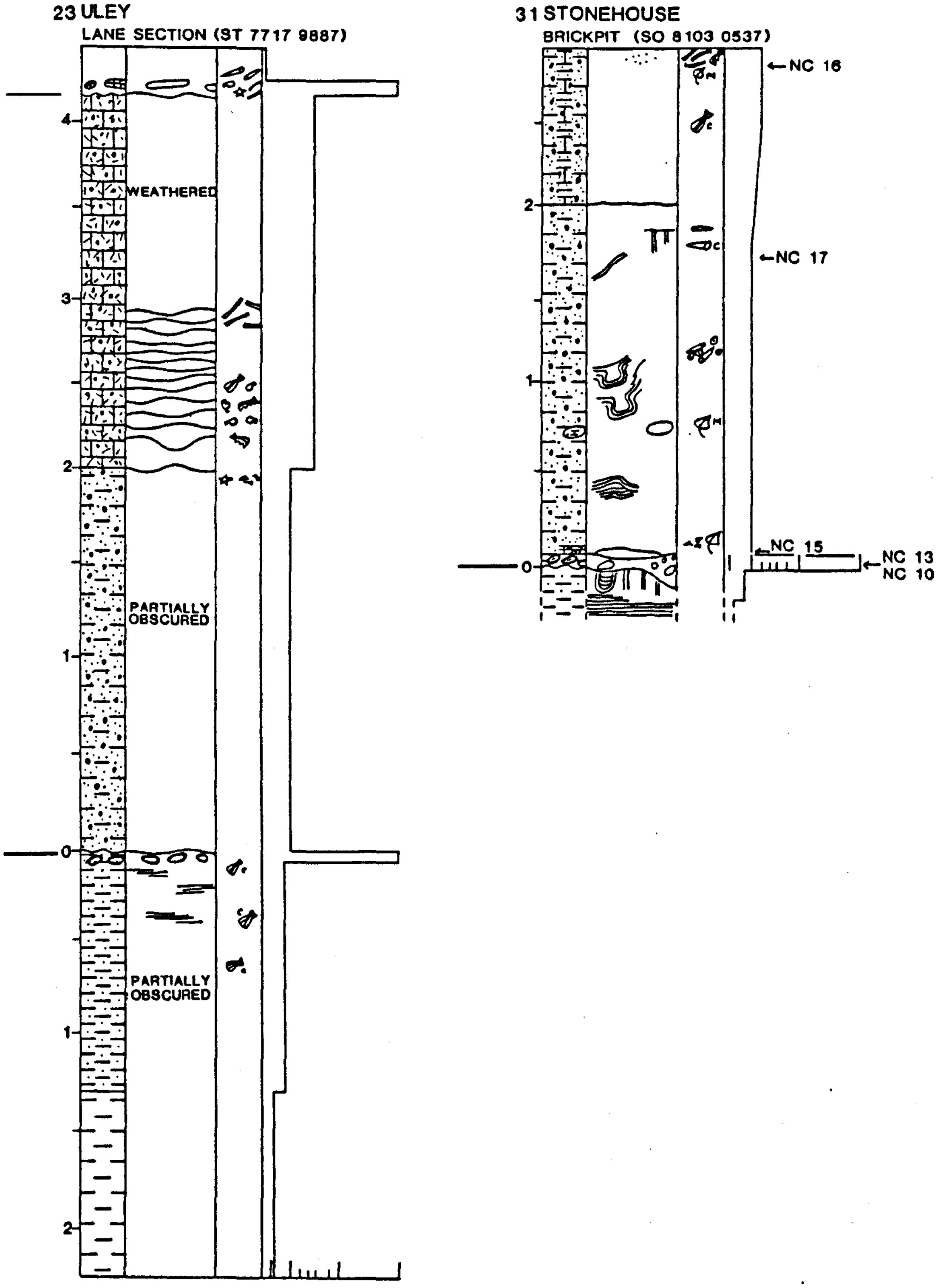


Fig. 34. MRBF logged sections. Site localities 23, 31 and DSF localities 4, 8.

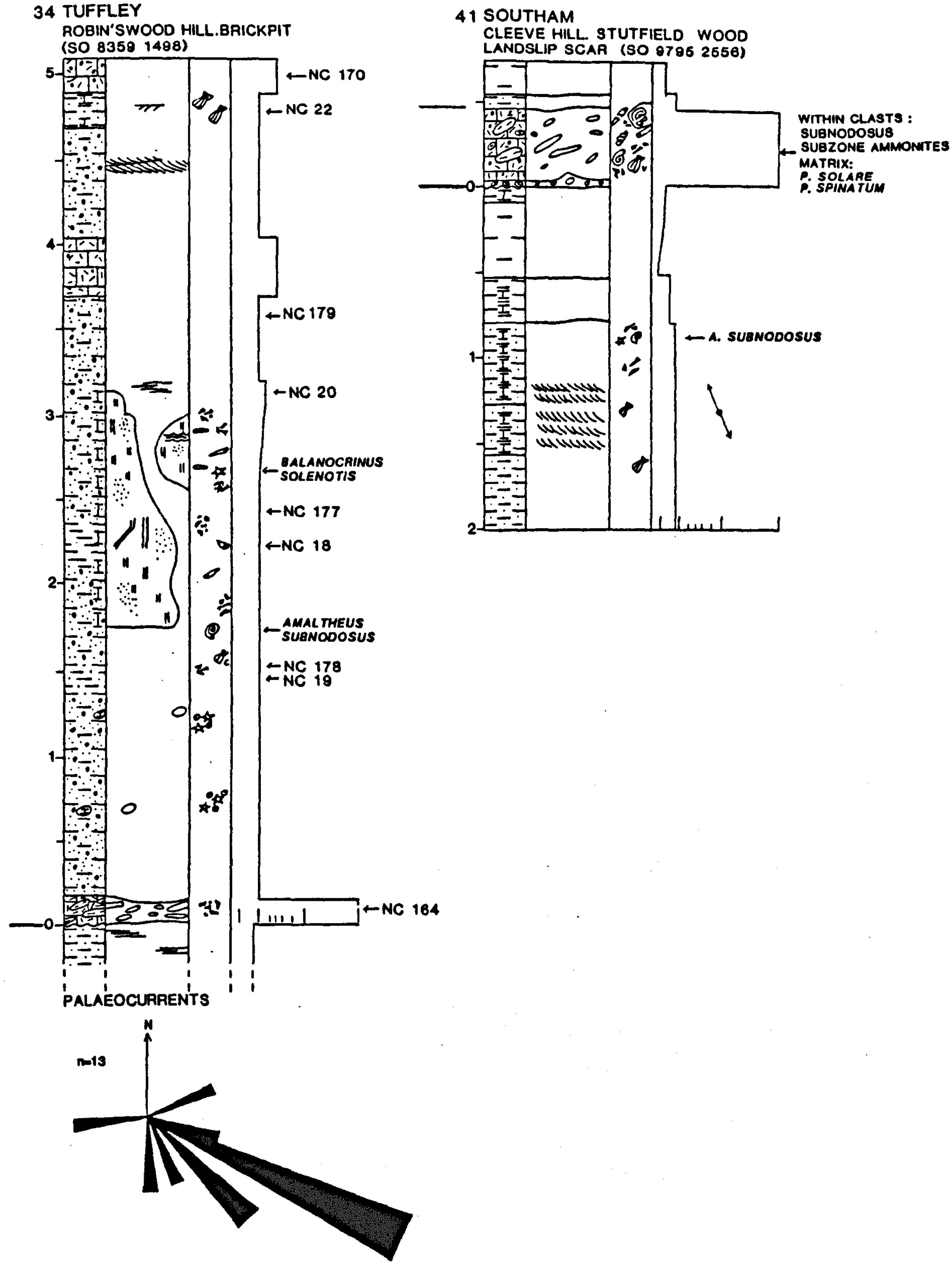


Fig. 35. MRBF logged sections. Site localities 34, 41 and DSF localities 9, 16.

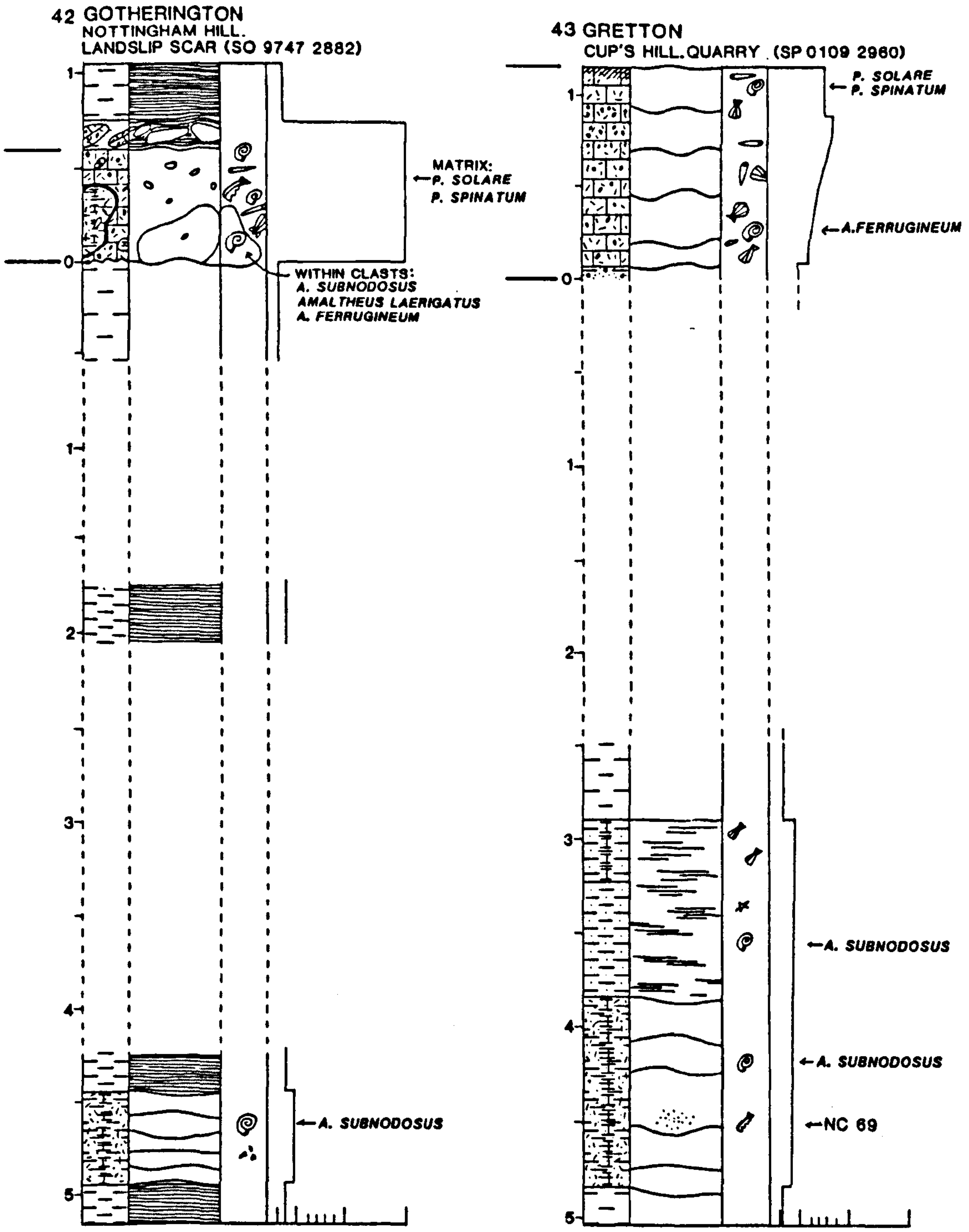


Fig. 36. MRBF logged sections. Site localities 42, 43 and DSF localities 18, 20.

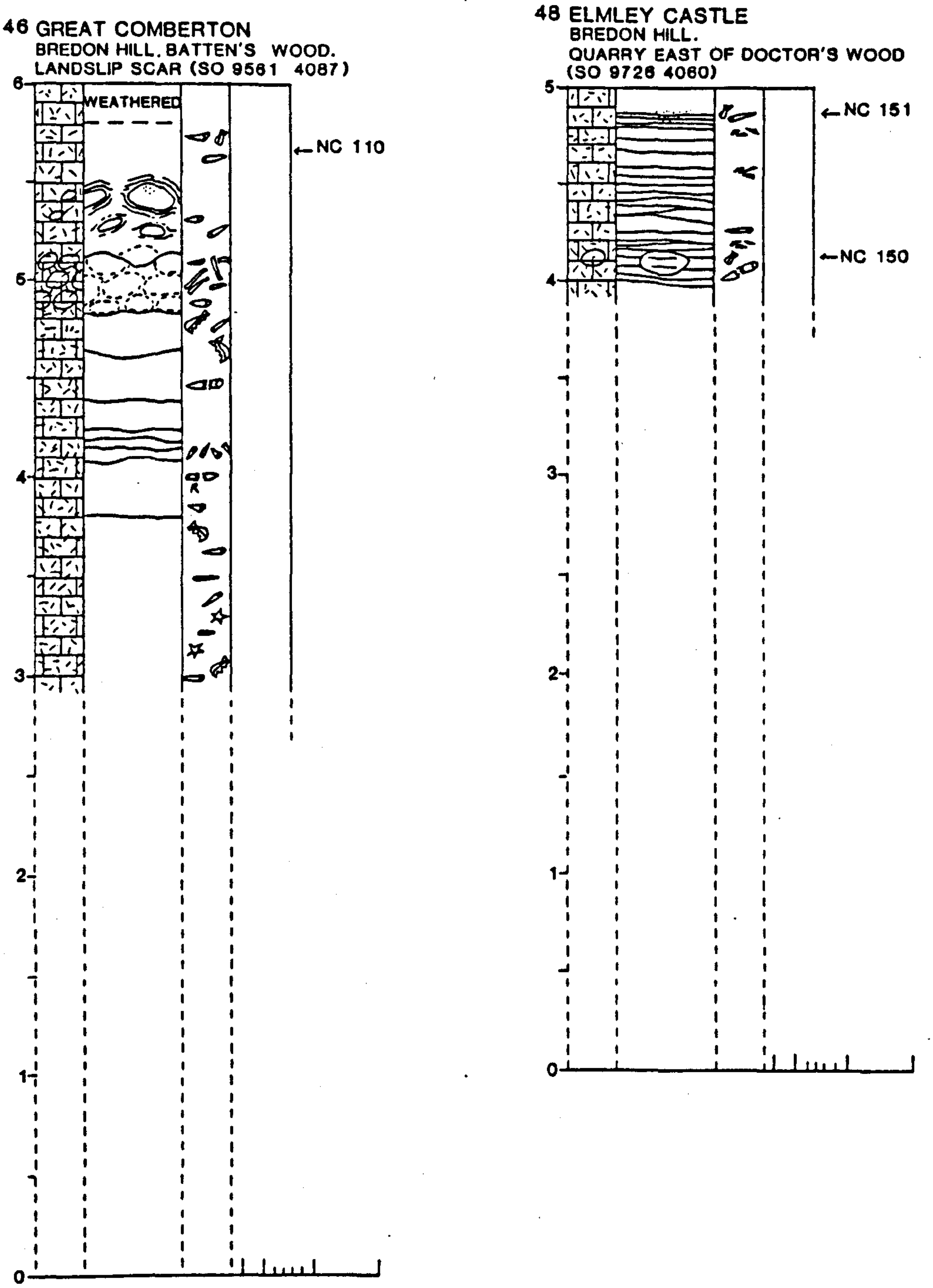


Fig. 37. MRBF logged sections. Site localities 46, 48.

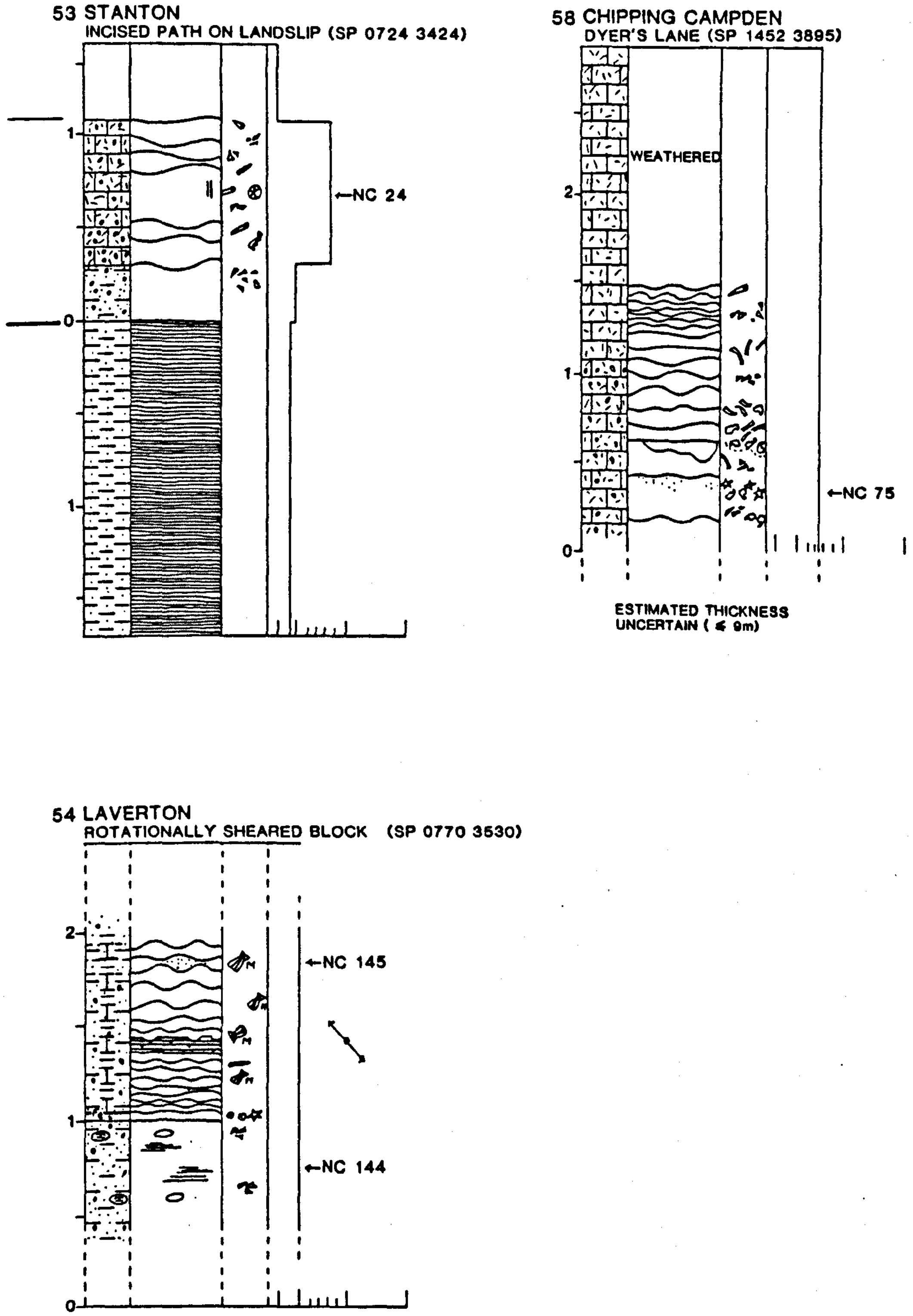


Fig. 38. MRBF logged sections. Site localities 53, 54, 58.

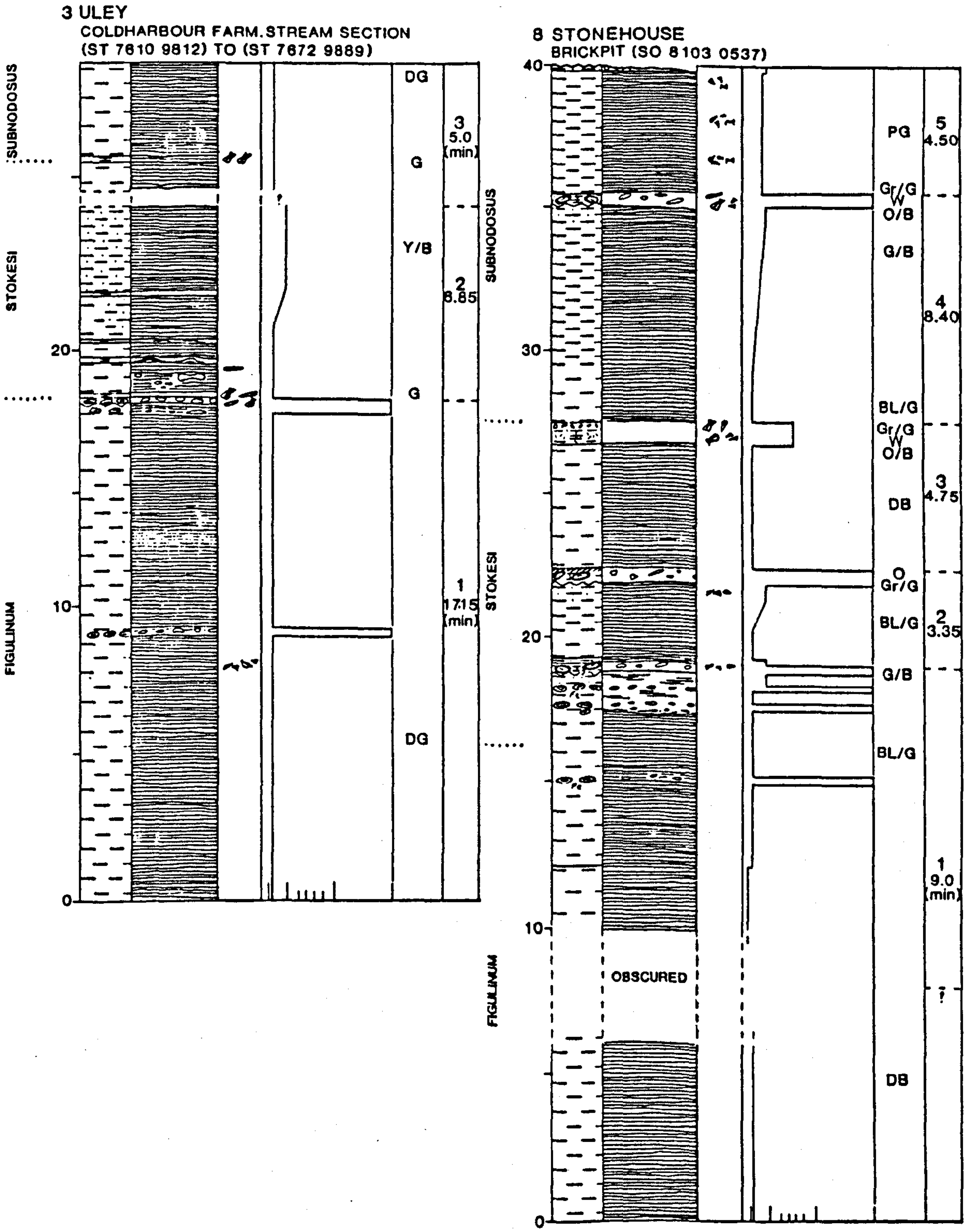


Fig. 39. DSF logged sections. Site localities 3, 8.

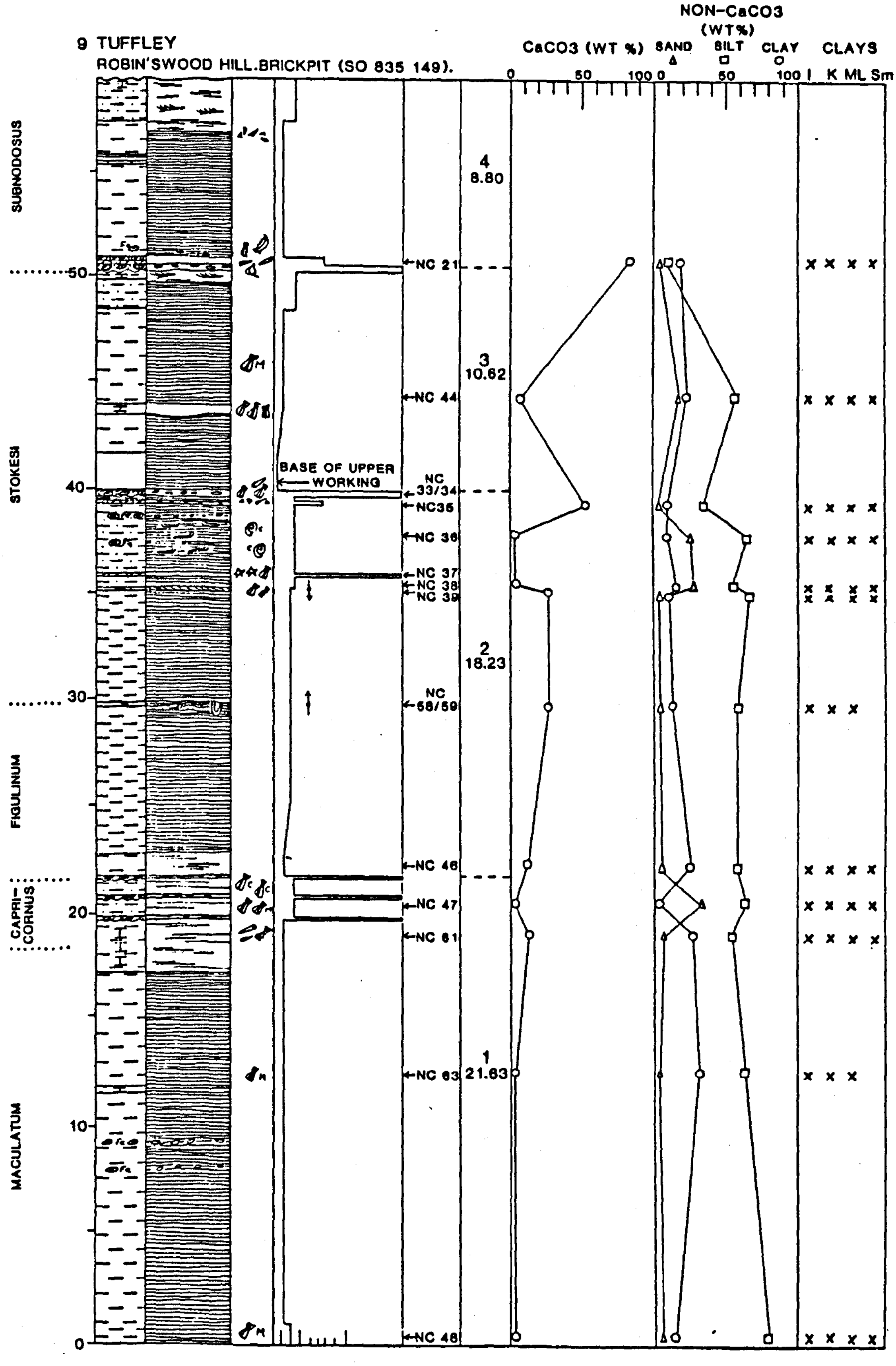


Fig. 40 DSF logged sections. Site locality 9.

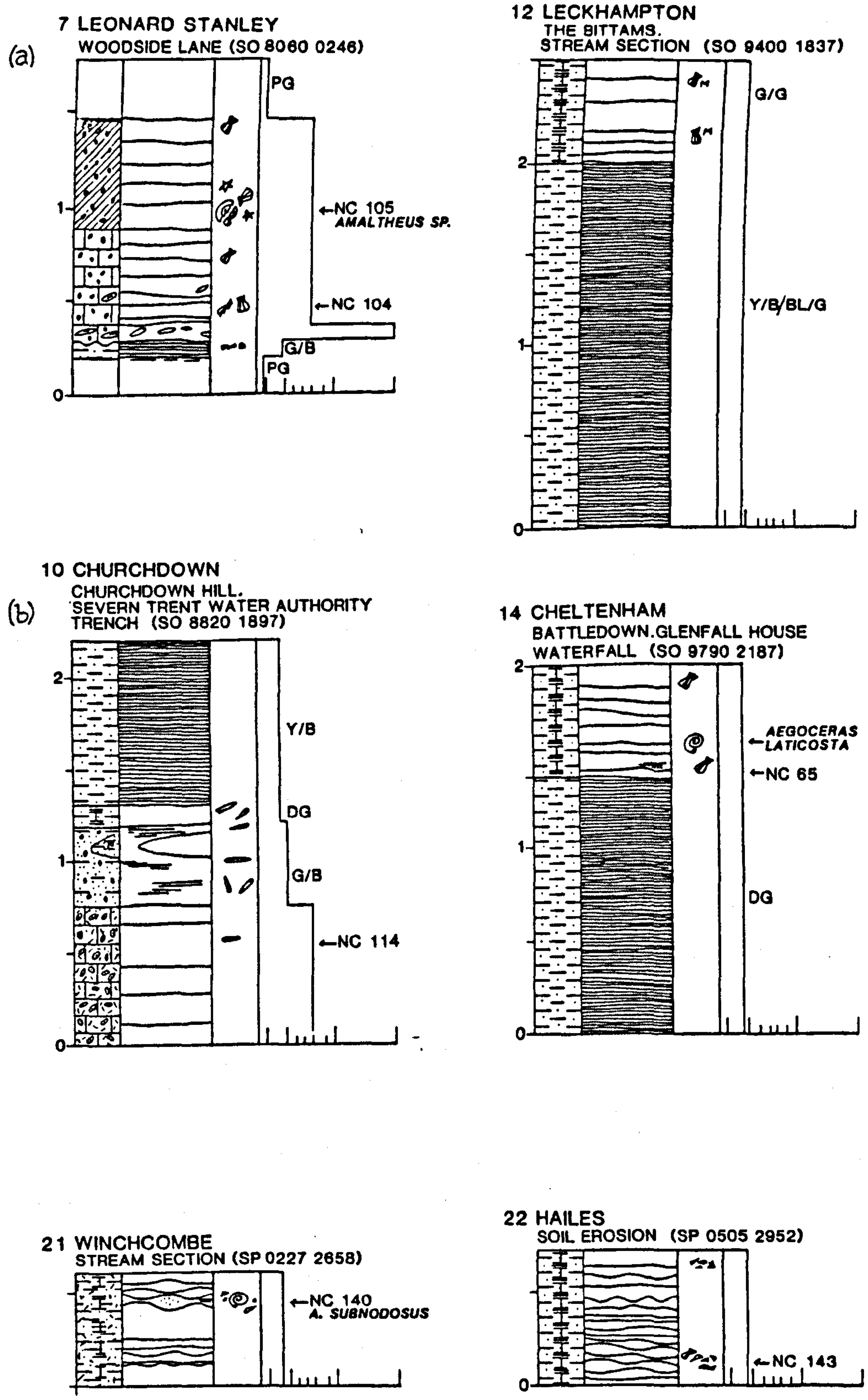


Fig. 41. DSF logged sections. Site localities 7, 10, 12, 14, 21, 22.

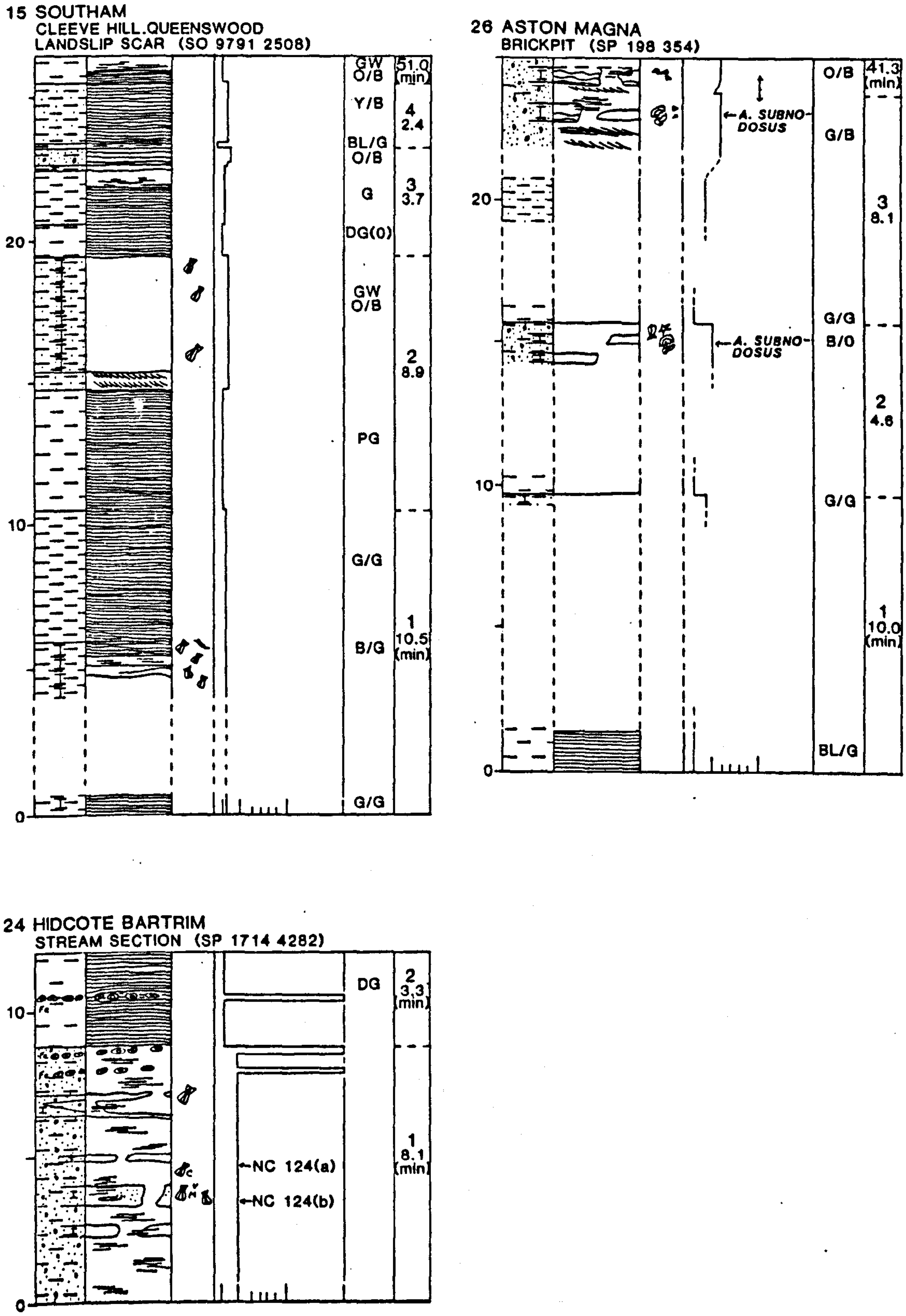


Fig. 42. DSF logged sections. Site localities 15, 24, 26.

CHAPTER 5

Description and Interpretation

1.0 Introduction

This chapter is directed at two fundamental aspects: temporal and spatial variations in sedimentary patterns. This analysis is supplemented with data from the literature and details from BGS borehole and well files, as well as from oil well logs available for the study area.

2.0 Field and laboratory work : temporal patterns

The most fundamental temporal feature of the DSF and MRBF, is a clear and repeated cyclicity. The term 'cycle' in its precise sense implies a symmetrical sedimentary sequence e.g. ABCDCBA. This is distinct from 'rhythm' which is ABCDABCD. While some authors retain this definition (e.g. House 1983), the two terms have become synonymous (Bates and Jackson 1980). Essentially, the 'cycles' in the British Pliensbachian are rhythms, but the former term has become firmly established in the literature. For this reason, 'cycle' will be used in the following sections. The DSF and MRBF cyclicity exhibits a number of features:-

(i) Upward coarsening of grain size (clays to boulder conglomerates),

(ii) Upward transition from siliciclastic to carbonate and ferruginous sediments,

(iii) progressive upward contraction of successive cycles, with minor variations,

(iv) Upward change in primary sedimentary structures from flat to cross-laminations,

(v) Upward increase in bioturbation.

(vi) Upward increase in diversity, size and destruction of shelly fauna.

These cyclic units vary in thickness from tens of metres down to under two metres. These can be considered to be first order cycles or 'Cyclothems' (Holland 1978:15). Another larger scale of cyclicity referred to by Holland as a 'Mesothem' can also be recognised in the two formations combined. All the above characteristics apart from (iii) and (iv) can be demonstrated on this larger scale. The upward increase in grain size is indicated by the replacement of the dominantly silt grade DSF by the sand grade MRBF. Upward change from siliciclastics to carbonates and ferruginous sediments is clearly shown by the change from the siliciclastic DSF to the MRBF limestones and ferruginous sediments. The upward transition from flat- to cross-laminations is difficult to assess because of bioturbation; this is only weakly developed in the DSF as a whole, and contrasts greatly with the MRBF which is thoroughly bioturbated, producing a massive appearance with only traces of the primary structures remaining. Upward increase in diversity, size and destruction of shelly fauna is clearly seen between the DSF and MRBF. This destruction affects not only the most commonly-occurring DSF fauna of thin shelled bivalves, but also the more robust bioclasts such as belemnites, brachiopods and echinoids. The intense bioturbation has affected these shells so that they typically show rotation and disarticulation which results in a scattered, jumbled appearance. Sometimes bioclasts such as ammonites or bivalves may be seen in vertical or inverted positions.

2.1 Temporal patterns : Dyrham Silt Formation

2.1.1 Upward coarsening of grain size

The following grain size scales refer to the divisions of Udden and Wentworth (Tucker 1981 Table 2.1) and are also used in descriptions of the MRBF.

Cyclothems within the DSF can show an upward progressive increase in grain size from clay to sandy silt, usually with boundaries that are gradational over a metre or so. At DSF localities 24 (Hidcote Bartrim) and 26 (Aston Magna) silty sandstones and true sandstones occur towards the top of the cyclothems. At Tuffley Brickpit a thin carbonate grainstone is present at the base of the uppermost cyclothem which has occasional limonite ooids in its top few centimetres. A similar horizon occurs at Stonehouse at the same stratigraphic level.

At DSF locality 9 (Tuffley Brickpit), where three cyclothems were analysed for grain size variations (Fig. 40), there is an overall decline in the silt content up through the formation, while clay and sand values show variations on the scale of a cyclothem only; the sand shows sharp increases near their tops, and clay shows a gradual decline. Clay-grade quartz and feldspar begin to appear towards the top of the formation, while the overall content of siliciclastics decreases.

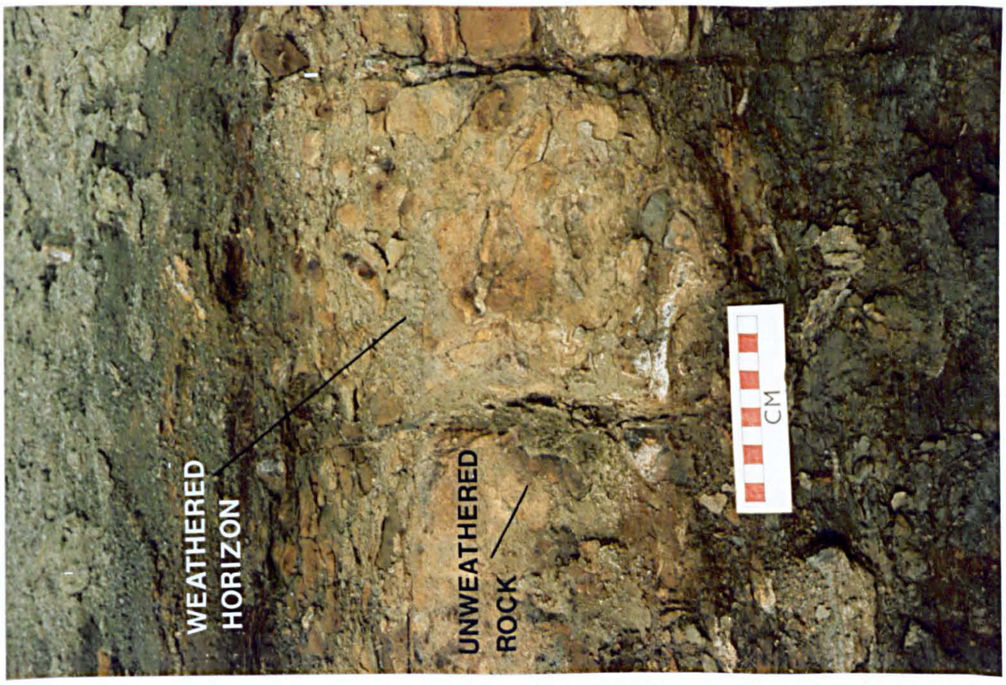
The top of the DSF cyclothems in the Cotswolds are often marked by a flattish erosion surface which may truncate underlying sedimentary structures, and is in turn overlain by a thin pebble conglomerate. The pebbles are discoidal and ellipsoidal in shape and may be subhorizontal to imbricate in orientation. The matrix is usually bioclastic sand accompanied by mud. The conglomerate is usually succeeded by an abrupt return to clays at the base of the next cyclothem. At some localities, however, a brief waning may occur instead (Fig. 41 a,b.)

2.1.2 <u>Upward transition from siliciclastic to carbonate and ferruginous sediments</u>

At Tuffley Brickpit, there appears to be an exponential upward increase in $CaCO_3$ throughout the DSF, accompanied by a gradual decrease in the silt content. Changes in $CaCO_3$ content are also noticeable in the cyclothems at this site, where it is greatly reduced towards their tops during increased input of quartz sand. The overall pattern shows that limestones (over 50% $CaCO_3$, Bates and Jackson 1980) only occur in the upper part of this sequence. The hard bands below are mostly the result of $CaCO_3$ cementation. Characteristically, dogger horizons may also be present in these horizons of lower lime content.

Calcium carbonate contents towards the tops of cyclothems at other DSF localities show variations, but all are above 30%. The sandy mudstones (Fig. 16) and silty sandstones (NC 79) have $CaCO_3$ contents between 30% and 54%, and the ferruginous oolites between 55% and 83%. In those cyclothems not studied in the laboratory, the upward increase in $CaCO_3$ content could be determined in the field. Thus dogger horizons appear towards the top of the sandy cyclothems at Hidcote Bartrim and Aston Magna, and continuous calcarous cements were noted in the more silty sequences.

There was also an increase in Fe content towards the tops of the cyclothems. This was accompanied by an upward change in colour in the field. The sandy mudstones had Fe contents of 2% to 6%, and the ferruginous oolites approximately 4% and 13%. The low Fe content of 4% is attributed to replacement by calcite. Colour changes, enhanced by weathering, show an upward trend from dark blue-grey and pale greys through green and blue-grey weathering yellow-brown, to green greys weathering orange-brown to reddish-orange. Clearly at the base little or no iron is present, but upwards, the appearance of chamosite with siderite gave rise to the reddish-orange weathering colour. The conglomerate at the top of the second cyclothems at Tuffley and Stonehouse brickpits, and the chamositic Fe-wackestone at DSF Locality 7 (Leonard Stanley) are reddish-orange and leached of $CaCO_3$ (Fig. 43) as a result of deep weathering which has left a soft friable residue. Siderite concretions appear towards the top of some cyclothems.



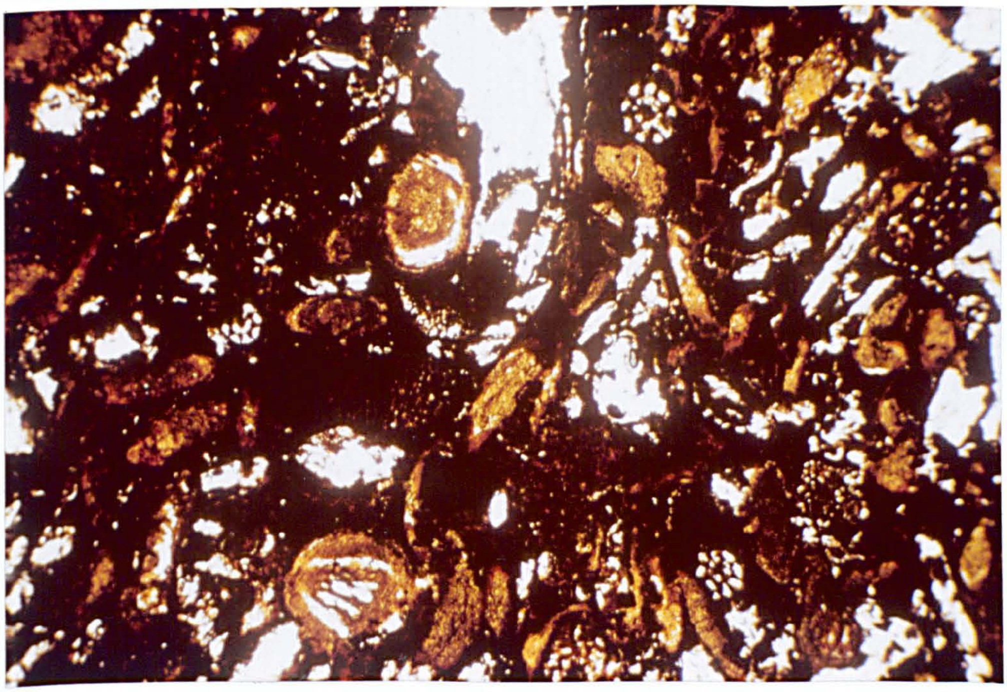


Fig. 43. Weathered horizons, DSF. Top: conglomerate, Tuffley Brickpit. Below: PPLX4 oxidised and calcite-leached ferruginous oolite, Leonard Stanley.

2.1.3 Progressive upward contraction of cycles

This was clearly seen at a number of DSF sites, but variations occurred. Thicknesses of cyclothems are shown in Fig. 44. No correlation is implied between cyclothems at different localities.

2.1.4 Upward change from flat to cross-laminations

This was noticeable at several sites although on numerous occasions it does not occur and flat laminations may persist to the top of the cyclothems. In some cases, it was not possible to ascertain the nature of the primary structures because of intensive bioturbation near the top of the cyclothems. A typical feature of these levels, where $CaCO_3$ contents in the sediments begins to exceed 30%, is 'wavy' bedding. This diagenetic feature is widespread in the MRBF and is discussed fully in sub-section 2.2.

2.1.5 Upward increase in bioturbation

This occurs towards the tops of many cyclothems, and may be so intense that it obliterates all previous primary structures. Towards the top of cyclothem 2 at Tuffley, horizontal burrows were noted. Burrow spotting in massive horizons was noted from sawn DSF samples, occasionally accompanied by horizontal burrows. Rare *Diplocraterion* traces were noted at Tuffley and Stonehouse, and at the latter, were accompanied by vertical *Skolithos* burrows. Rotation and scattering of the shelly fauna is typical in the well-bioturbated units of the DSF; in the

Fig. 44 Variation in cyclothem thicknesses at Five Dyrham Silt Formation Sites

DSF Locality	Cyclothems (metres)				
	Lowest				Highest
4 Coldharbour Farm Stream	17.15*		6.85		5.0*
8 Stonehouse Brickpit	9.0	3.35	4.75	8.40	4.50
9 Tuffley Brickpit	21.63*	18.23		10.62	8.80
15 Queenswood	10.5*	8.90	3.70	2.40	1.0*
26 Aston Magna	10.0*	4.61		8.1	1.3*

* Minimum thickness

unaffected flat-laminated sediment below, shells lie flat and undisturbed.

2.1.6 Upward increase in diversity, size and destruction of shelly fauna

The benthic shelly fauna of the DSF consists of low numbers of small thin-ribbed to large thick-ribbed bivalves, occasional crinoid stems with pentagonal cross-sections, and brachiopods. A free-swimming fauna is represented by occasional belemnites and ammonites. The upward increase in $CaCO_3$ clearly correlates with the increased presence of shells. In the weakly cemented, laminated silt horizons, the few shells present are often thin-shelled, small and often only preserved as moulds or casts, following dissolution of the $CaCO_3$ during diagenesis. In the well-bioturbated, $CaCO_3$-rich horizons above, shells are much more common and diverse, and the thin-shelled bivalves present are often fragmented. In the horizons of pebble conglomerates and ferruginous oolites, large thick-shelled bivalves are present. At Tuffley, a thin limestone is present full of flat lying crinoids which have undergone little disarticulation. This unit lies within the flat-laminated, poorly-cemented silt lithology which supports a sparser shelly fauna. Floral remains are virtually absent in the DSF; only a small fragment of fossil wood was found in NC33 in the penultimate pebble conglomerate at Tuffley Brickpit.

2.2 Temporal patterns: Marlstone Rock Bed Formation

The present fieldwork on the MRBF and supplementary data from boreholes and the literature show that the 5 MRBF facies have the relationship shown on Fig. 45. It is emphasised that this complete pattern does not necessarily occur at any one locality, and that absence of an individual facies in any particular area is not uncommon.

2.2.1 Upward coarsening of grain size

The base of the MRBF is marked at many localities by a thin conglomerate with discoidal to ellipsoidal pebbles and cobbles. These are composed of massive siltstone and closely resemble the cemented units in the DSF below. Sometimes only a layer of ferruginous concretions may be present (Fig. 51). Typically, the matrix of the conglomerate is composed of the overlying MRBF facies at any particular site. At some localities where the MRBF is very thin, the formation itself becomes largely conglomeratic. At these sites, similar siltstone pebbles are scattered through the matrix, and accompanied by boulders (up to 0.3m) of cemented material from the DSF below.

Particle Size Analysis indicates that Facies I has a mean modal peak of 3.6 phi, corresponding to 'very fine sand'. This was less accurately assessed in thin section ('fine sand' range) and least accurately in hand specimens (up to 'medium sand', although 'muddy'). In all the other facies, which have coarser grain sizes, measurements from thin sections and hand specimens were in good accordance. Particle Size Analysis for these facies, however, was less

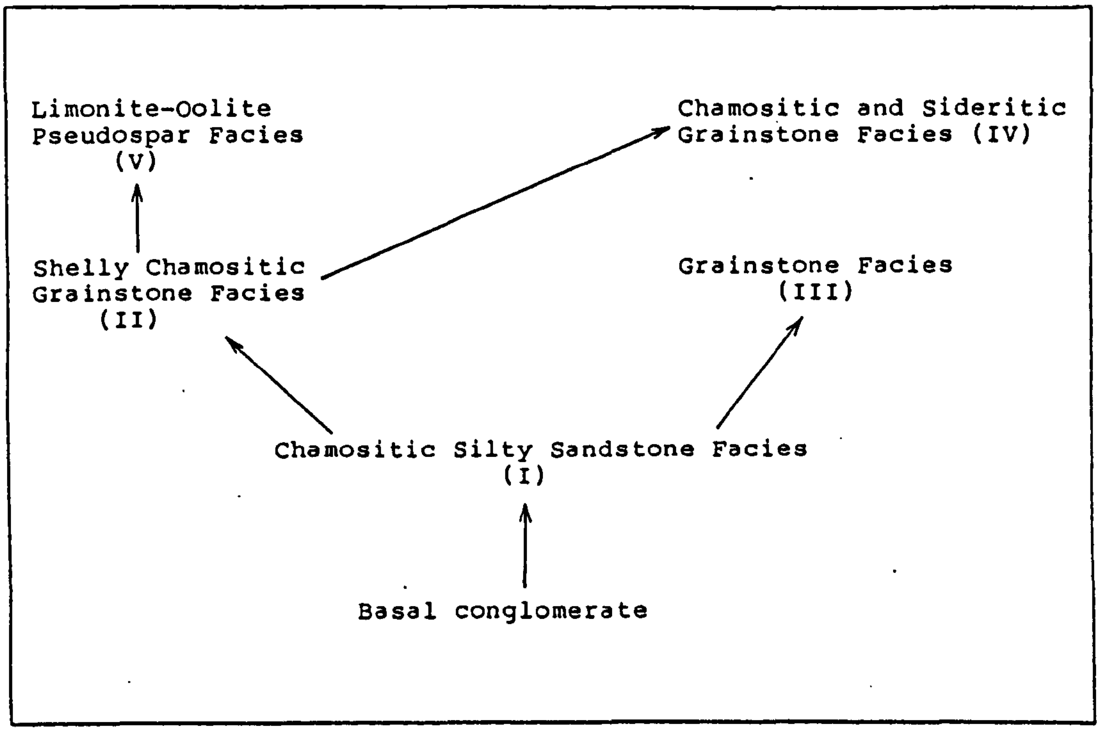


Fig. 45. MRBF facies succession.

useful because it considered only the non-carbonate fraction.

Facies II and III have grain sizes of fine to medium sand range, and in facies IV grain sizes range from fine up to the medium-coarse sand boundary. Facies V contains grains within the coarse sand range. These upward-coarsening patterns correspond to the carbonate and ferruginous grains, the former noticeable both in thin sections and in the size of shells in the field. The siliciclastic component shows little change upwards, except in the size of the lithic silt clasts. Upward coarsening in the ferruginous grains show particularly interesting patterns. Peloids dominate most facies, but there is a distinct upwards change. Peloids and flakes in Facies I and III are also present in Facies II, with the addition of superficial ooids and some true ooids; true ooids (often broken) increase in Facies IV, and true ooids (also often broken) finally become dominant in Facies V. Spastoliths, or distorted ferruginous grains, occur in most facies and can be of most grain types.

The ferruginous grains also show upward changes in their degree of limonitisation, and types of nuclei. Limonitised grains are subordinate to unaltered ones, in all facies with the exception of Facies V. Some ooids may have alternating limonite and chamosite laminae (Figs. 23-25). Facies II has some limonitised ooid nuclei while the laminae are unaltered. Nuclei are dominated mostly by chamosite peloids and flakes in all the facies except for

Facies V, where echinoderm fragments, echinoid spines and siltstone clasts are important. The siltstone nuclei increase in abundance up through the facies succession.

The top of the MRBF can only be observed at a few sites, but is locally marked by a pebble conglomerate of material eroded from the unit below (Fig. 46). This may lie within a matrix of grey or brown clay which becomes the dominant lithology above; this conglomerate marks the base of the Upper Lias Clay.

Grain characteristics in all facies show consistently 'well' to 'very well' sorting, (except the lithic silt clasts) and increase from 'subrounded' to 'very well rounded' grains up through the facies succession (although the siliciclastic component remains consistently 'subangular' to 'angular'). Grain shape nearly always shows low sphericity for the carbonate and ferruginous grains, and variable low to high sphericity for the siliciclastic grains in all facies. Upward changes in matrix content show a rapid decline in the siliciclastic matrix above Facies I; the chamosite matrix is low (1% to 3·5%) and remains more or less constant, while carbonate matrix appears in Facies II and becomes the major component of the overlying Facies V.

2.2.2 Upward transition of the siliciclastic to carbonate and ferruginous sediments

Facies I This is the oldest type in the MRBF, is siliciclastic-dominated, and above more carbonate and

Fig. 46. MRBF/Upper Lias Clay Formation boundary, Old Bournestream House. Note basal conglomerate of Upper Lias Clay.

ferruginous-rich facies occur. In Facies I, $CaCO_3$ contents are variable, corresponding to the friable and cemented dogger horizons. In the friable units, $CaCO_3$ contents lie close to 5%, but are 25%-30% in the doggers. The logs and hand specimens show that the few shells present in the friable units are usually dissolved out to leave moulds or casts. Shelly material remains unaltered in the cemented dogger units, which vary in size from 0·08m long to the huge examples up to 1·5m thick by 3·0m in length at Tuffley Brickpit. In these doggers, calcareous cements (41%) include sparite and patchy poikilotopic varieties. Fe content in this facies include a mean of 8% ferruginous grains and 3% siderite. The siderite, disseminated through the facies, occurs as very fine rhombic crystals altered to limonite. These form the weak cement in the friable units. This appearance of siderite is repeated in all the remaining facies, although the rhombs do become noticeably larger in samples with the highest Fe content . In the field Facies I is greenish-grey when unweathered, but limonitisation of the ferruginous grains and siderite cement causes a change to buffs and red-browns.

<u>Facies II</u> In this facies, $CaCO_3$ content lies between 50% and 82%, and is therefore, much higher than those in Facies I. This is indicated in the field by an abundance of bioclasts ranging from sand grade material up to whole shells which are ubiquitous, and the well-cemented nature of the rock. Thin sections show a mean of over 44% carbonate grains, with 32% sparite cement. Fe contents

are variable, and show a wider range than those in Facies I, with values from 1% to 11%. In thin section ferruginous grains show a mean of about 9%, which is slightly higher than those in Facies I. Siderite contents are also slightly higher, at 3.5%. In the field Facies II is green-grey, sometimes blue-grey in colour in which the iron minerals weather to give a uniform yellow-brown.

Facies III Facies III has high $CaCO_3$ contents, between 70% and 81%. It is well cemented but has fewer shelly fauna than Facies II. In thin section, 56% of the rock is bioclastic material, and 29% sparite cement. Fe contents are low, ranging from 2% to 6%, and thin sections show 2·5% siderite and 0·7% ferruginous grains. The low iron content means that little alteration to colour occurs on weathering, so that the facies is generally pale grey in the field. Locally, iron staining may give it a superficial red brown colour.

Facies IV This facies has a $CaCO_3$ content of 48% to 72%. Examination in the field shows it to be less shelly than Facies II. Thin sections show that Facies IV has a mean of 47% carbonate grains, and sparite content is about half of Facies I, II, and III. In contrast ferruginous grains (18%) and siderite cement (6%) are twice that of these facies. Fe values range from 7% to almost 14%, and weathering causes the originally greenish-grey sediment to take on a distinctive rich reddish-brown colour.

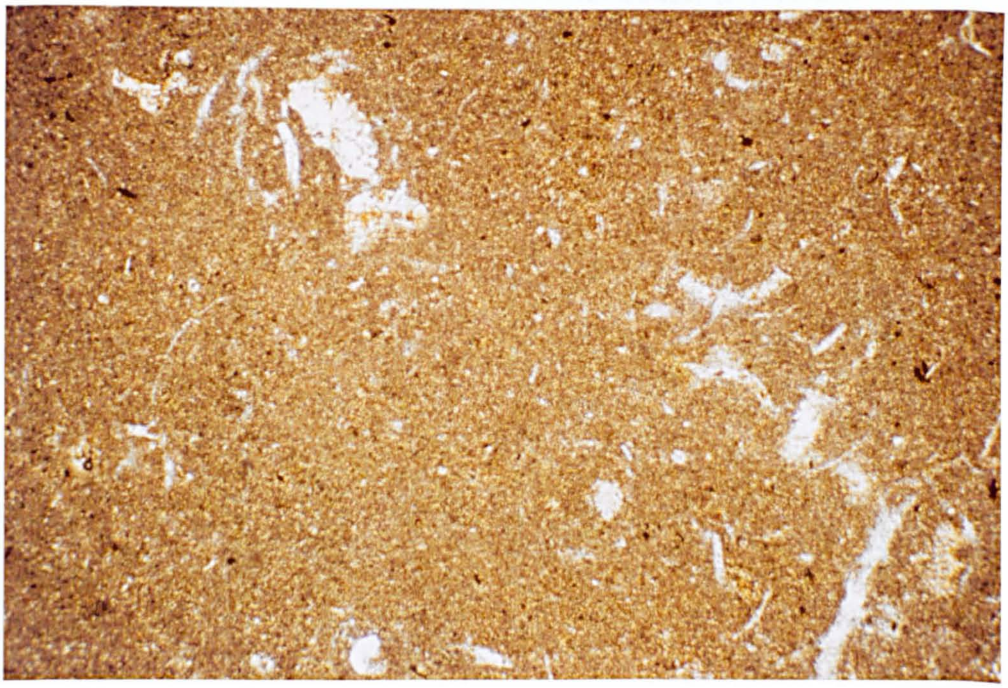
Facies V Facies V has the highest $CaCO_3$ contents ranging from 61% to 85%. The facies is not highly shelly, and the $CaCO_3$ values are attributed to high contents of micrite and neomorphic pseudospar (68%), with subordinate carbonate grains (12%) and sparite (9%). Siderite cement and ferruginous grains are low in quantity (below 1% and 6·3% respectively). Fe values lie between 1% and 7%. The facies has a distinct ironshot appearance, caused by limonitisation of the scattered ferruginous ooids, with a buff matrix. In some areas the ooids are absent (Fig. 47).

2.2.3 Progressive upward contraction of cycles

The MRBF at most localities consists of only one cyclothem, but where two are present, at MRBF locality 16 (Smart's Green), and locality 34 (Tuffley Brickpit), the upper cyclothem (1·8m) is thinner than the lower one (3·2m). The cyclothem boundary at Smart's Green is shown in Fig. 48.

2.2.4 Upward change in primary sedimentary structures

Little evidence is available in the MRBF to show this because of widespread and extreme bioturbation. Of the few structures remaining, most are present in Facies I, and include suggestions of indistinct bedding (but this may be a compressional feature enhanced by the rotation of platy mica minerals), convolute laminations, dish structures (Fig. 49), flat laminations with tool marks and current lineations, and rare sets of trough cross-laminations (sets about 0·05m thick). In the other



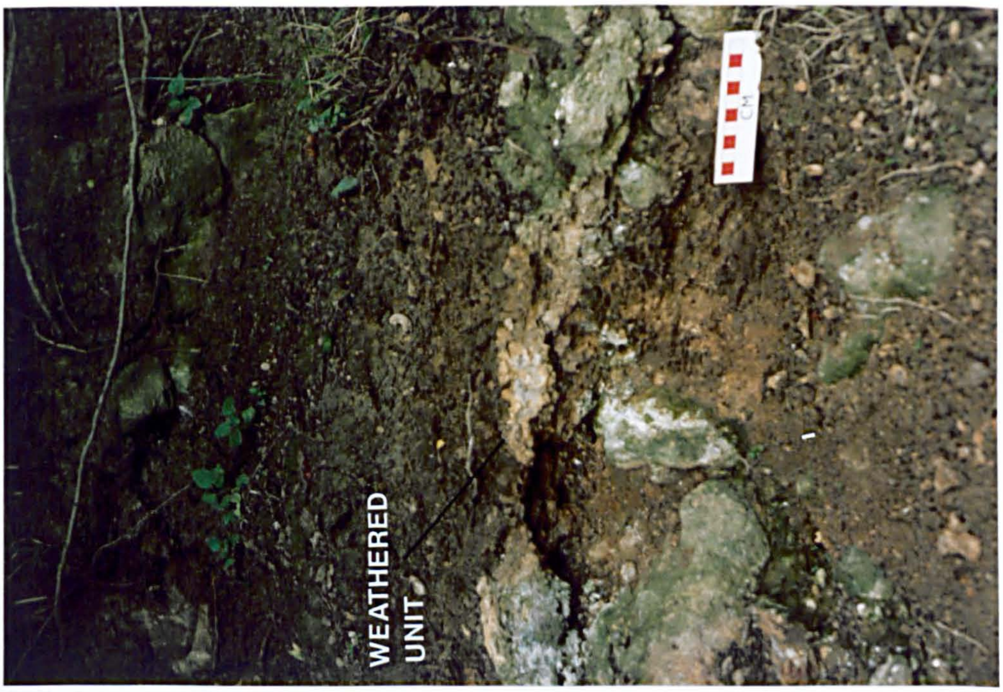


Fig. 47. Weathered top to MRBF. Bournestream Quarry (left). PPLX4 of weathered unit, Facies V, ooids absent (right).

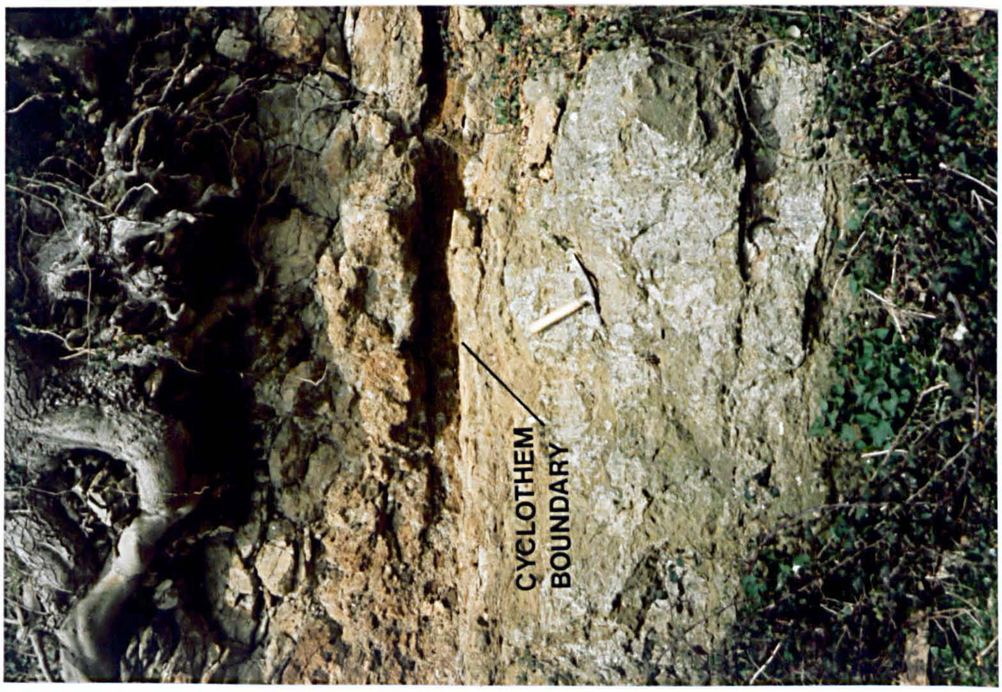


Fig. 48. Cyclothem boundary, MRBF, Smart's Green.

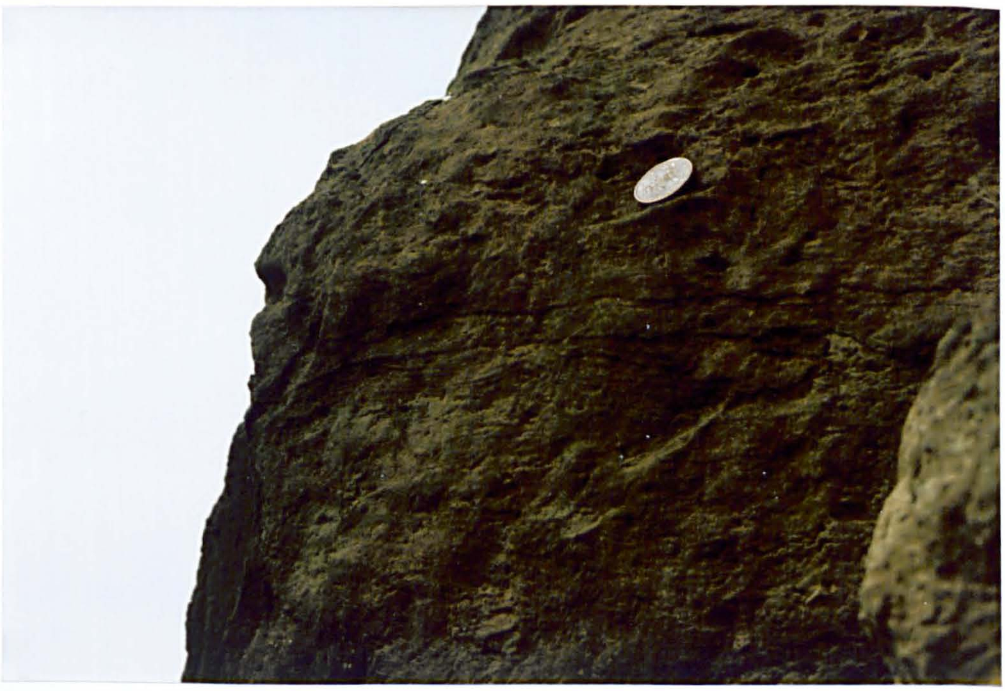


Fig. 49. Soft sediment deformation, MRBF Facies I. Top: convolute laminations, Stonehouse Brickpit. Below: dish structures, Tuffley Brickpit.

facies, few of these features were observed, although flat laminations were noted in Facies V at Smart's Green. A shallow filled channel was also noted at MRBF locality 58 (Chipping Campden).

'Wavy' bedding is ubiquitous in the four limestone facies and occurs in some localities in Facies I. It has the following general characteristics:-

Cross section	Wavelength approximately 0.3m Amplitude 0·05m to 0·08m 'Waves' are often out of phase Bed thicknessess are thin to medium range (0·03m to 0·3m) * Bed thickness is often proportional to the thickness of the formation
Plan view	Interlocking, elongate 'mounds' and 'depressions' with smooth surfaces.

* Thickness divisions from Tucker (1982 Table 5.2).

Photomicrographs and field photographs of these structures are shown on Figs. 26, 27 and 28. The X-Ray radiograph positive of a slab containing the bedding in Fig. 14 is also relevant. The dissection of bioclasts and burrows by these surfaces clearly indicate they have a diagenetic origin. They are consequently referred to as 'pseudo-beds' (Simpson 1985:495). The presence of interpenetrant grains, microstylolites and insoluble residues from pressure-dissolution as described from similar bedding planes elsewhere (Simpson 1985, R.G.C. Bathurst pers. comm. 1986) have not been observed in the laboratory. As the MRBF logs show, some of the surfaces are marked by Fe seams and these are likely to be insoluble residues from pressure-dissolution. These Fe seams however, are not commonly found along the pseudo-bedding. The cause of the marked rarity or absence of evidence for diagenetic condensation seems unclear. Possibly, only incipient pressure-dissolution has occurred. It is significant to note, however, that some of the 'wavy' bedding does mark the boundaries between different lithologies at MRBF localities 12 (Bournestream) and Smart's Green. They are therefore not always independent of primary lithological variation and may be due to rippling by currents, or compaction. In addition to pseudo-bedding, widespread but crudely-developed stylolites also occur in the four limestone facies (Fig. 50).

2.2.5 Upward increase in bioturbation

Although bioturbation is present to an advanced degree in all the MRBF facies, the oldest Facies I, has more primary structures remaining in it and this indicates that an upward increase does occur. In the logged sequences much of the limestone facies appear massive between the pseudo-bedding, suggesting extremely thorough bioturbation, leaving only occasional vertical Skolithos and inclined burrows. The scattering and rotational effect of the bioturbation on the shelly clasts has already been

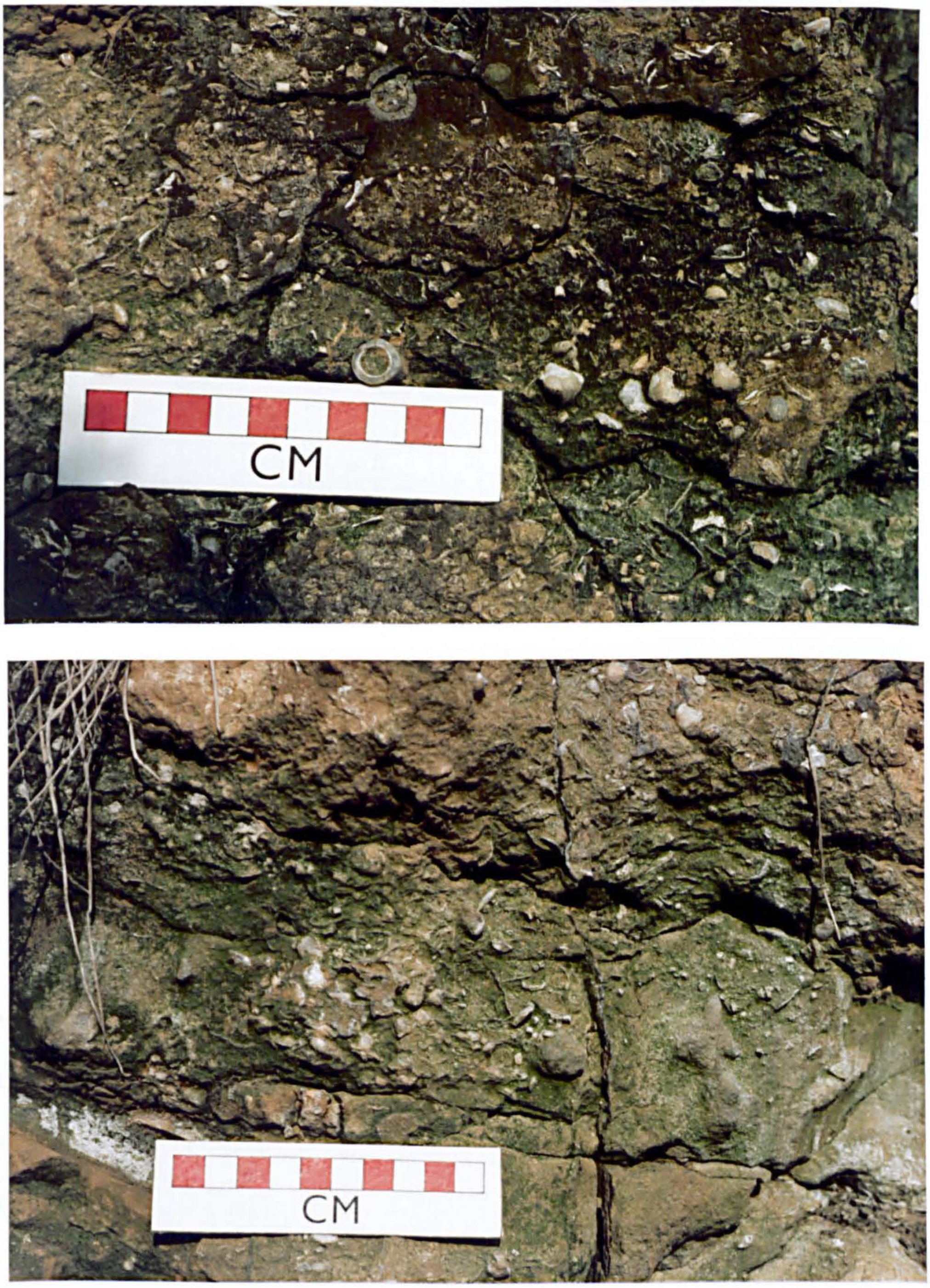


Fig. 50. Crude stylolites, MRBF, Upper Cam.

referred to. Sawn blocks and hand specimens show that this massive appearance is, in many cases, a result of weathering. Well developed, abundant vertical Skolithos burrows were noted from Facies IV (Fig. 14).

It was thought that the use of the X-Ray radiograph technique (Chapter 4) might have revealed structures in some of the sawn blocks which still appeared to be massive, but they gave no additional information (Fig. 15). This shows that for the MRBF, sawing of blocks is sufficient to indicate all internal structures, and radiographs are not necessary. In the field and in hand specimens, burrow-spotted areas were most clearly seen in Facies I (Fig. 51), and vertical and inclined burrows in that facies and in Facies II.

Rare Rhizocorallium and Thalassinoides traces were found within Facies IV and II respectively, and a horizontal trail was seen in Facies III. Hardgrounds are indicated in the limestones towards the top of the MRBF at Tuffley Brickpit where Liostrea were found attached to the rock. The basal pebble conglomerates of the MRBF were bored in some cases (Fig. 52). These are thought to indicate hardground conditions, and not reworked hardgrounds from the DSF below, where they have not been observed. In thin section, micritisation of grains by algal borings was notably absent in Facies I, but locally common in all the overlying facies, with some grains completely micritised. The 'variable' texture noted occasionally in most facies (Appendix 27) is thought to indicate the presence of

Fig. 51. Burrow-spotted horizon, MRBF, Tuffley Brickpit (left) and MRBF/DSF boundary, Dursley (note concretions).

Fig. 52. Basal conglomerate, MRBF, Dundry Hill (left) and Dursley (right). Note borings in pebble in Dursley sample.

numerous mud-filled burrows.

2.2.6 Upward increase in diversity, size and destruction of shelly fauna

This feature is intimately related to the upward increase in $CaCO_3$ content which has been described above. The fauna is dominated by a limited number of phyla:benthic groups (mostly suspension feeders) include brachiopods (mostly rhynchonellids), crinoids, thin shelled bivalves and rare echinoids, gastropods and serpulid worms. Free-swimming varieties include abundant belemnites and occasional (locally common) ammonites. A dental plate from a shark was found in Facies II at MRBF Locality 19 (Newnham Quarry).

In Facies 1, thin shelled bivalves are most common, often broken. In the succeeding Facies II, all the common groups are present. The thin shelled bivalves are again often broken and may be accompanied occasionally by broken more robust shells such as belemnites and brachiopods. Crinoid stems and ossicles are broken and fragments are rarely more than a few centimetres in length. Some horizons are charged with masses of crinoid ossicle debris.

In Facies III, few broken shells were noted. Like the first two facies, Facies IV has a preponderance of broken thin shelled bivalves, but has belemnites and brachiopods present. Facies V contains broken bivalves and belemnites. Strips or fragments of lignitised wood or their moulds have been found occasionally (Fig. 53) in all but Facies

Fig. 53. Wood fragments in the MRBF. Top: Uley (locality 25). Below: Bournestream quarry.

IV and V. Thin sections show that the macrofauna are accompanied by small numbers of planispiral and uniserial foraminifera, the former occurring most frequently in Facies IV and V. Foraminifera area % increases upwards through the facies from 0·3% to 0·6%. Very occasionally, fragments of the skeletal algae group Dasvcladaceae were noted in Facies III.

3.0 Field and laboratory work: spatial patterns

3.1 Dyrham Silt Formations

It was noted that units of ferruginous oolite were present at DSF Localities 7 (Leonard Stanley) 10 (Churchdown) and 11 (Shurdington). These were absent at all other sites, although ferruginous oolite-rich horizons a few centimetres thick were noted at DSF Localities 9 (Tuffley Brickpit) and 8 (Stonehouse Brickpit). The predominantly silty nature of the DSF in the sites examined over the W and C Cotswolds gives way on the eastern margin of the hills to coarser silty sands and sands at DSF Localities 24 (Hidcote Bartrim) and 26 (Aston Magna).

3.2 Marlstone Rock Bed Formation

The closely spaced sampling and logging programme carried out in the field provided a detailed control on facies distribution for the MRBF. The 5 facies and their geographical distribution across the Cotswolds is shown in Fig. 54. In order to produce as accurate a map as possible, some localities have been taken from other

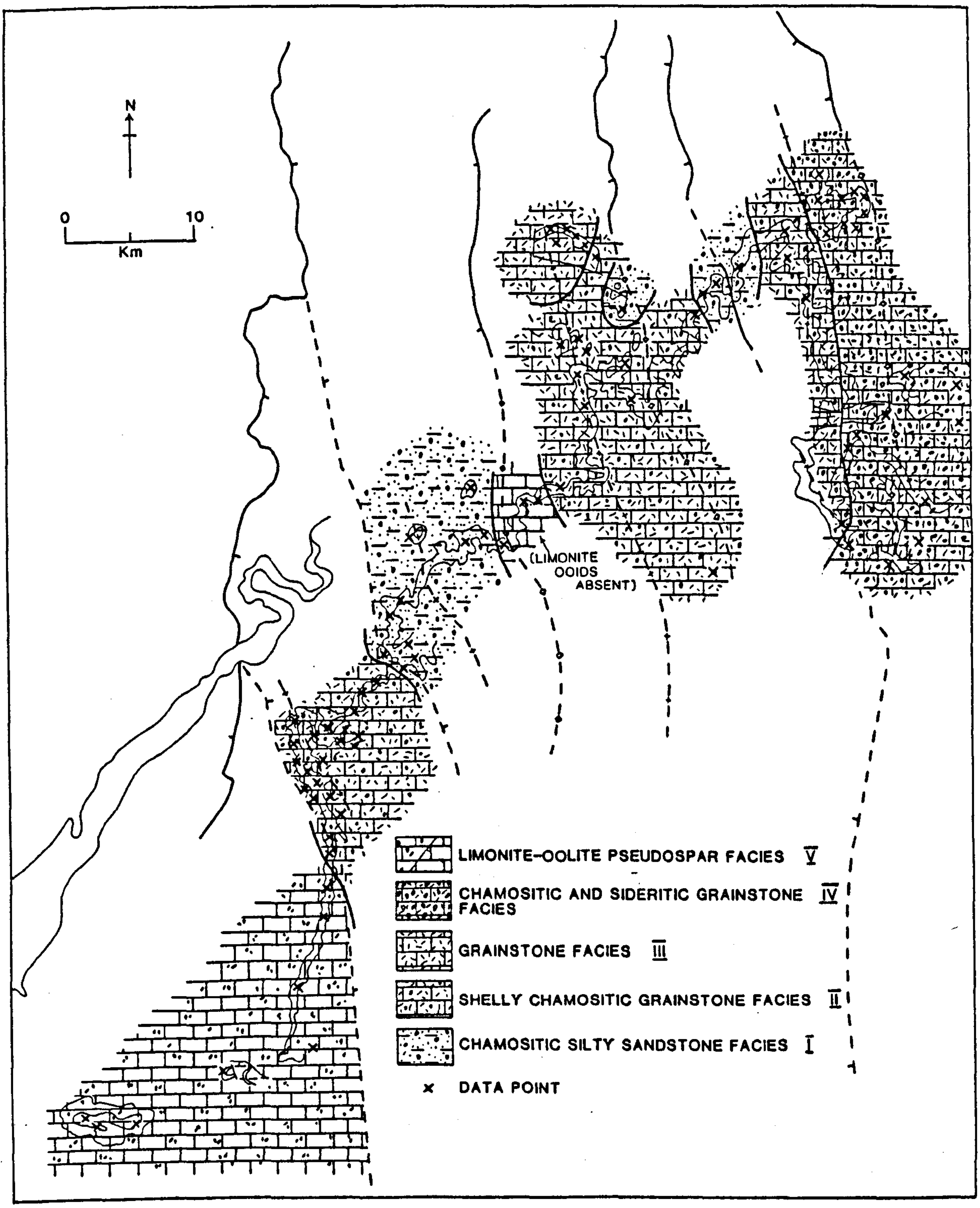


Fig. 54. MRBF facies map.

records (mostly borehole and well data from the BGS) and these are indicated in Appendix 28. It is emphasised that this map illustrates the dominant facies type in any one area; it should be noted that a certain amount of facies diachronism occurs.

The MRBF facies map suggests a well-defined N-S elongation of facies belts, with rapid E-W change. Most facies appear in more than one area.

4.0 Field and laboratory work: Interpretation

4.1 Dyrham Silt Formation

4.1.1 Water Depths

The few trace fossils noted towards the tops of the DSF cyclothems including dominantly burrow spotting, horizontal burrows and rare *Diplocraterion* and *Skolithos* traces, suggest an emphasis on sediment feeding. Collinson and Thompson (1982 Fig. 9·41) indicate that a dominance of sediment feeders is associated with waters below the tidal zone of continental shelves. Towards the tops of the cyclothems, where the *Diplocraterion* and *Skolithos* burrows are found, the appearance of shelly fauna dominated by suspension feeders closely resembles Collinson and Thompson's '*Skolithos* and *Glossifungites*' Association. This corresponds to their intertidal and subtidal range and is equivalent of the 'Foreshore', 'Shoreface' and 'Upper Offshore' of Howard *et al* (1972). It is suggested that the cyclicity indicates a transition from the deeper waters of Collinson and Thompson's

Cruziana Association, lying just below the tidal zone, to the shallower waters of the *Skolithos* and *Glossifungites* Association. On the grounds that there is a lack of intertidal sediments such as herringbone cross-stratification, tidal flat planar beds, channelling and algal mat development, a shallow subtidal environment is favoured for the cyclothem tops.

Some indication of possible emergence is present, however. The deeply leached, red-weathered horizons at Tuffley, Stonehouse and Leonard Stanley (subsection 2.1.2) lie on top of, or adjacent to, cyclothem-top pebble conglomerates. These could merely be a result of oxidation and leaching associated with post-depositional ground-water movements, connected with the impermeable clayey units which overlie each weathered horizon. Alternatively, they could represent emergence and palaeosol development with intensive oxidation and leaching associated with humid tropical climates, for which there is much evidence in the DSF and MRBF. The search for evidence such as rootlet beds has not been successful, but as Wright (1986:XI) states, they are not necessary proof. It is of interest to note for the present that the weathered profiles at Tuffley and Stonehouse can be correlated on biostratigraphical evidence (Phelps 1982 Fig. A:2:6:2), across a distance of 9.5km.

4.1.2 Palaeoclimate

Evidence in support for the humid tropical climatic regime outlined in Chapter 3, is present in the DSF. The

Presence of chamosite and siderite, both weathering to limonite, has been indicated earlier in this chapter, with the chamosite forming oolitic units at the top of or immediately above cyclothems at some localities. The notably high mud, high clay content of weathering products associated with humid tropical climates described by Johnson and Baldwin (1986), is clearly evident in the DSF, a mudrock sequence with clay contents up to 30% in some samples. The clay mineral assemblages at Tuffley Brickpit (Figs. 12 and 40) show that kaolinite is present at all levels, and is indicative of extreme weathering associated with tropical laterites (Hallam 1984:197). Illite, also very common, is not particularly useful for palaeoclimatic indications (Hallam 1981:4). The origin of the other two clay minerals noted in the sequence at Tuffley, namely randomly interstratified illite/smectite and smectite, are discussed in Chapter 6.

4.1.3 Sedimentation

The upward coarsening pattern of the cyclothems and the concomitant change from flat to cross-laminations in the DSF indicate an upward increase in hydrodynamic energy. Harms et al (1975) showed that for mean sediment grain sizes of 0·04mm (coarse silts), cross laminations will begin to form between approximately 20-30 cm/sec mean flow velocity and will continue up to over 60 cm/sec, beyond which 'Upper Flat Bed' forms will occur. Below approximately 20 cm/sec, lower flow regime flat beds will form, and this also applies to finer grained sediments.

The flat laminations below the cross-laminated horizons in the DSF are likely to indicate individual depositional events from suspension of low density slow-moving clouds of fines (Tucker 1981:27) in continuously quiet conditions. These may indicate annual events, or varves.

Higher $CaCO_3$ content, reflected in the upward increase of types, abundance and size of the shelly fauna together with the appearance of bioturbation in the upper parts of the DSF cyclothems, indicates higher rates of biogenic production and activity. Simultaneously, the greater quantities of comminuted shells indicate higher energy conditions. These features suggest that more favourable conditions occurred for organisms later in the deposition of the cyclothems. Clayey silts, lying at the base of some cyclothems (Tuffley Brickpit cyclothems 2 and 4, DSF Locality 15 (Southam) cyclothem 3), are dark grey to dark blue-grey in colour and suggest higher organic matter contents than the overlying sediments. This indicates a reduced potential for matter decomposition in the sediments and overlying waters when they were deposited, indicating some degree of anoxic conditions.

Throughout much of the overlying parts of the cyclothems, shells and ichnogenera are still infrequent while other factors were also important in producing unsuitable conditions. Walker <u>et al</u> (1983:701) indicated that carbonate production will be undermined by influxes of siliciclastic sediment, as this will dilute the amount of nutrients in the water, discouraging biogenic activity.

This is well illustrated by the present laboratory analyses on the sequence at Tuffley Brickpit, which shows a negative correlation between $CaCO_3$ and silt contents.

The overall effect suggests that the water column became clearer and more oxygenated as sedimentation in the individual cyclothems progressed. This may have been sudden in some cases, possibly due to pauses or cessation of sedimentary input, which allowed the substrate to be colonised. In such circumstances, bioturbation would become extreme so that homogenised units lie immediately above undisturbed laminated sediments. Sharp increases of siliciclastic sand at the top of some cyclothems, however, occasionally caused a reduction in carbonate content; examples of this occur at Tuffley Brickpit.

The upward increase in iron minerals in the DSF resulted in the production of thin (0·75m^{+}, 1·2m) units of ferruginous oolite at some localities. These units are well bioturbated so that all primary sedimentary structures have been destroyed and only diagenetic pseudo-bedding is present. Flow regimes cannot therefore be directly inferred for these sediments, but grain sizes (medium-coarse sand), occasional pebbles and a fauna of large thick-ribbed bivalves indicate deposition under greater energy conditions than the finer grained units. The two oolites examined in the present study lie at the top of a cyclothem as DSF locality 10 (Churchdown), and immediately above a cyclothem at Leonard Stanley. At the latter locality the oolite is succeeded by a clay indicating a rapid fall off in energy conditions.

At the top of a number of DSF cyclothems the presence of the flattish erosion surface with thin overlying flat pebble conglomerate indicates an abrupt, short lived erosion event or combination of events. The composition of the pebbles (massive siltstones) suggests that they were derived from the bioturbated, cemented horizons immediately below, or a short distance down into the underlying cyclothem. The shape of the pebbles suggests some form of gouging action by very high energy currents, probably induced by violent storms. These produced flattish or more equidimensional fragments from the substrate, which were then smoothed by abrasion into discoidal and ellipsoidal clasts. Sometimes these pebbles may have limonitic coatings, which may suggest weathering on the sea floor.

In considering the climatic regime indicated for the DSF, the erosion surfaces and pebble conglomerates are believed to indicate the effect of severe tropical storms, particularly cyclones (c.f. Duke 1985). Clearly, the substrate lay within the reach of storm waves when the pebble conglomerates were formed. Four cyclothems are present in the DSF at Tuffley Brickpit, where most of the full thickness of the formation is exposed. Biostratigraphic work by Phelps (1982) shows that 3 complete ammonite subzones are present, and parts of two others. Torrens (1980) indicated that the mean duration of an ammonite subzone was about 400,000 years. While sedimentation during the time span of any given subzone is likely to have been discontinuous, the thickness, finely-laminated and grain size nature of the DSF could mean deposition over long periods of time. It seems unlikely therefore, that the DSF by virtue of its sedimentary record, could have formed in a time scale of less than hundreds of thousands of years. During this time, sedimentation would have been sporadic, and interrupted on at least 4 occasions by tropical cyclonic events. Only 4 such interruptions can be identified with any certainty, which suggests that fluctuation of the sea floor occurred. Such fluctuations are necessary to account for such a small number of interruptions during such a long period of time. The cyclothems are therefore interpreted as shallowing-upward cycles.

Some of the cyclothems do not possess the pebble bed which indicates that it was either removed by subsequent erosion, or that wave base was never reached. The pebble horizons, wherever they occur, are overlain by finer grained sediments. There is usually an abrupt return to clays and fine silts, indicating a rapid deepening of water. There may be, as indicated by the ferruginous oolite at Leonard Stanley, and other cyclothems, a less rapid change in grain size suggesting slower, perhaps pulsed deepening.

4.2 Marlstone Rock Bed Formation

4.2.1 Water depths

The abundance of vertical and subvertical *Skolithos* burrows, burrow spotting and rare _Rhizocorallium_ and _Thalassinoides_ burrows in the MRBF facies suggest intertidal to subtidal conditions, similar to Collinson and Thompson's '_Skolithos_ and _Glossifungites_' Association. Positive Eh and normal salinity (30-40 PPT) are indicated from the limonitised layers within the chamosite grains, and abundant diverse fauna. As with the DSF, there is no evidence in the sedimentary structures for intertidal sedimentation, suggesting a shallow subtidal environment. However, a weathered top to the MRBF was noted at MRBF Locality 12 (Bournestream) (Fig. 47). This is a thin, weathered and cavernous fractured carbonate mudstone, represented by NC168. A reddish top to the MRBF occurs at Locality 43 (Gretton). As for the DSF weathered horizons, no root beds could be found at these sites, and proof of their exact origin remains unknown. Other weathered horizons were recorded by Simms (pers. comm. 1983) at a now obscure section on Oxenton Hill near Cheltenham, and by Howarth (1980) in the Midlands.

4.2.2 Palaeoclimate

A continuation of the tropical humid climatic regime suggested for the DSF is indicated. This is particularly clear from the abundant chamosite and subordinate siderite within the MRBF, and the ubiquitous kaolinite in the clays, which is widely distributed across the Cotswolds. The presence of plant material locally further supports the suggestion of well vegetated lands, probably at no great distance, on which the kaolinite and iron minerals were concentrated through lateritic weathering.

4.2.3 Sedimentation

Grain sizes are coarser (sand grade) for the MRBF than the DSF, and the clean-washed grainstone texture with good sorting and rounded grains indicates an environment of greater hydrodynamic energy. This is supported by the sedimentry structures. Trough cross-lamination sets are thicker than in the DSF, and tool marks and current lineations indicate strong currents. The latter are associated with flat laminations and are likely to indicate upper flow regime flat beds (60 cm/sec mean flow velocity).

Because bioturbation is so extreme in the MRBF, it is not possible to assess an upward increase in energy through the formation using sedimentary structures as it was for the DSF. However, an upward coarsening of grain size is clearly evident in the MRBF cyclothems, indicating stronger currents towards the top. Further evidence comes from the filled channel at MRBF Locality 58 (Chipping Campden), and the broken shells scattered through the facies, sometimes forming lags from substrate communities (Hallam 1967:410). Primary sedimentary structures in Facies I, such as convolute laminations and dish structures indicate water-escape features which in turn suggest liquified sediment within softground conditions.

The upward coarsening trend in the facies succession is reversed in Facies V. While it contains abundant ooids which are the largest in the facies succession, the wackestone texture suggests quiet conditions. The ooids are, however, sometimes broken, and interclasts are present, indicating strong currents. This is supported by the broken nature of much of the macrofauna. Possibly, the matrix (now mostly altered to neomorphic pseudospar) was produced by the trapping of calcareous fines by algal mucilage and sea grasses; this would be possible even in high energy conditions (Sellwood and Jenkyns 1975:380). Algal activity is supported by the presence of an oncolith found in NC109 (Fig. 25).

A possible source of the fines would have been from the disintegration of skeletal material including calcareous green algae, although inorganic precipitation cannot be ruled out (Tucker 1981:117, 118). It is not thought that the ooids in this facies were derived from another adjacent facies belt during storms, as their nuclei and form are different to the ooids in these areas. All factors support an equally high, if not higher energy environment for Facies V compared with the underlying facies.

The increasing upward frequency in the MRBF of ferruginous coated grains from superficial ooids, to ooids and broken ooids, together with all other factors suggest an upward increase in energy. Modern calcareous ooids form in waters of less than 5m depth (Sellwood 1986:285). However, there are no modern analogues for chamosite ooids, and their discoidal shape contrasts with the spherical shape of calcareous ooids suggesting a different mechanism for their formation. Their origin is discussed in Chapter 6.

As shown for the DSF, the upward increase of shelly material, lime mud and cement is associated with a decrease in siliciclastic content. In Facies I, the shelly fauna is sparse in number and the thin shelled bivalves, mostly broken up, indicate quiet conditions alternating with storms. These factors inhibited widespread colonisation by shelly invertebrates, and the slow settling of fines from suspension, diluting nutrient concentrations, would have occurred between episodes of more vigorous activity.

With the significant reduction in siliciclastic input, clearer waters above Facies I enabled widespread colonisation of the substrate by the benthonic fauna found in Facies II and III. Periods of quiescence, indicated by the ubiquitous thin shelled bivalves, were punctuated by periods of higher energy causing their break up. This also affected the crinoid material, and occasionally the belemnites and brachiopods. Similar conditions, but with more intense disruption by storms, continued with Facies IV and V, which contain greater quantities of broken ooids and broken shelly macrofauna. At MRBF Locality 1 (Norton Malreward), the lower part of the formation closely resembles the proximal tempestites described by Aigner (1982 Fig. 6A:188).

The upward increase of bioturbation becomes extreme in the carbonate facies above Facies I, suggesting slower sedimentation rates, during which many burrows became filled with chamosite mud. Accompanying this was the appearance of limited micritisation of calcareous grains by algae. Evidence for hardgrounding towards the top of the formation at Tuffley Brickpit further suggests longer periods of little or no sedimentation. Hardground conditions are also indicated by occasional borings in the basal conglomerate of the MRBF.

The contents of ferruginous grains and siderite cement have similar mean values in Facies I and II, but locally, higher contents were found in the latter. The upper part of the MRBF along the E flank of the Cotswolds is made up of the most ferruginous facies, Facies IV. The whole of the MRBF is composed of this facies to the E into Oxfordshire, as the Banbury Ironstone Field is approached. The boundary with the Upper Lias Clay has only been noticed on the E side of the Cotswolds at MRBF Locality 64 (Ilmington), and here Facies IV lies against the Upper Lias Clay. In the S Cotswolds, Facies II is succeeded at some localities by Facies V, very thinly developed, and here the pattern of upward increase in Fe content is sharply reversed.

The pebble conglomerate at the base of the MRBF is thought to have formed under similar circumstances to those in the DSF cyclothems. At Localities 41 (Southam) and 42 (Gotherington) rounded boulders of subnodosus subzone material were noted in the MRBF within a matrix containing spinatum zone fauna (M. Simms pers. comm. 1986). This suggests extremely high energy conditions to cause such erosion, and as the clasts in both this and the basal conglomerate are larger than those of the DSF conglomerates, very shallow water, well within storm wave base is visualised. Clasts in both the pebble/cobble and boulder units have thin, limonitised outer layers. It is unlikely that this was caused by recent weathering as the rest of the rock is still fresh; oxidisation of the outer layer of these clasts on the sea bed is therefore suggested.

At the top of the MRBF, the locally-seen thin pebble conglomerate marking the base of the Upper Lias is suceeded by clays. The evidence given above indicates that the MRBF is composed of a single, or locally two, upward coarsening cyclothems. At the sites where two cyclothems are found (Smart's Green Quarry and Tuffley Brickpit), the top of the cyclothems are typically marked by coarser grain size and higher $CaCO_3$ content, followed by finer, less calcareous sediment. This is clear at Smart's Green, but the grain size variations at the top of the lower cyclothem at Tuffley, marked by the top of the dogger horizon, is only detectable with PSA. The upward shallowing environment, indicated for the MRBF, continues the pattern of DSF deposition. Waters were generally shallower for longer periods in the MRBF than the DSF, however. Some emergence may have occurred.

5.0 Data from literature, British Geological Survey and Department of Energy

The field and laboratory work of the present study was supplemented with information provided at the National Geoscience Data Centre, BGS, and released oil well data from the Department of Energy Library (Appendices 29, 30, 31, 32).

5.1 Biostratigraphic control

This is of primary importance in assessing temporal changes in basinwide patterns of sedimentation. The available data provide information on the thicknesses of the davoei, margaritatus and spinatum zones, with subordinate information on the subzones. While it is generally accepted that the spinatum zone is thought to be equivalent to the MRBF, ammonite evidence as shown in this study indicates this is not the case for parts of the formation in the Cotswolds. At Tuffley Brickpit, and MRBF Locality 21 (Upper Cam) ammonites of the subnodosus/gibbosus subzones, of the margaritatus zone, were recorded (M. Simms pers. comm. 1986). These finds correspond to the lower cyclothem at Tuffley, where A. subnodosus was recorded together with Balanocrinus solenotis, a crinoid of subnodosus to gibbosus age. At Upper Cam, where only one cyclothem can be distinguished, Amouroceras ferrugineum and B. Solenotis were found in the lower part, indicating the presence of the gibbosus subzone at this horizon. In view of the Tuffley finds, the lower cyclothem at Smart's Green may occur in this subzone, but no ammonites were found to support this supposition.

In the Cheltenham area, where the MRBF is very thin, the <u>spinatum</u> zone occupies all the formation at MRBF Locality 41 (Southam), 42 (Gotherington) and at Oxenton Hill. At MRBF Locality 43 (Gretton), however, the basal 0·32m falls in the <u>gibbosus</u> subzone (M. Simms pers. comm. 1986). In the Cotswolds E of Cleeve Hill, ammonites were either not found in the present MRBF survey, or data from boreholes provided no details of the age of the MRBF. At DSF Locality 26 (Aston Magna), <u>A. subnodosus</u> was found in the sandy deposits towards the top of the brickpit, but without more information it is not possible to say if this belongs to the MRBF or the DSF.

It is interesting to note that only <u>apyrenum</u> subzone ammonites were found in the present survey; they occupy most of the formation where it is thin, and only the upper part where it is thicker. The overlying <u>hawskerense</u> subzone has not been proved. At a number of sites, the overlying Upper Lias Clay has, close to the boundary of the MRBF, yielded <u>Dactylioceras sp.</u> and ammonites from the <u>tenuicostatum</u> and <u>falcifer</u> zones, and the <u>commune</u> subzone (Cave 1977:91, Woodward 1893:215, Smithe 1895:250, Whittaker and Ivimey-Cook 1972). In the Elton Farm Borehole on Dundry Hill (Ivimey-Cook 1978), a facies similar to Facies V of the MRBF was found to occur immediately above, in the overlying Upper Lias. Its age, however, indicates the presence of a major hiatus as the Lower Toarcian is absent. Also, on the Oxfordshire/

Gloucestershire border, a facies corresponding to Facies IV continues up into the lower part of the Upper Lias, with 0·15m in the Upton Borehole (Worssam 1963:127), and 0·15m in the Maugersbury-Oddington lane (Hull 1857:20).

The accuracy of the literature and borehole data, therefore, needs to be considered with some caution when assessing the true thicknesses of the margaritatus and spinatum zones. However, even when possible variations in the thickness of these zones is considered, overall patterns are not affected greatly, because of the extreme overall variation in thickness between the two zones. The maps in Fig. 55 have utilised all the available information on zone and formation thicknesses across the Cotswolds. The oil well boreholes (Appendix 30) unfortunately were logged without detailed reference to litho-and bio-stratigraphy in all but the Highworth well, and so were unsuitable for the present work.

5.2 Facies and Thicknessess: Dyrham Silt Formation

Thicknesses of the davoei and margaritatus zones within DSF, thicknesses of the DSF alone, and DSF facies and their distribution across the Cotswolds are shown in Fig. 55. Sources of data are listed in Appendix 29. These maps show contrasting thickness and facies variations in the area, which may be locally very marked. Thicknesses for the davoei and margaritatus zones are consistently thin or absent in the extreme S Cotswolds, to the E of the Vale of Moreton, and in the Stroud area. They are thicker at Dundry Hill and around Dursley, and

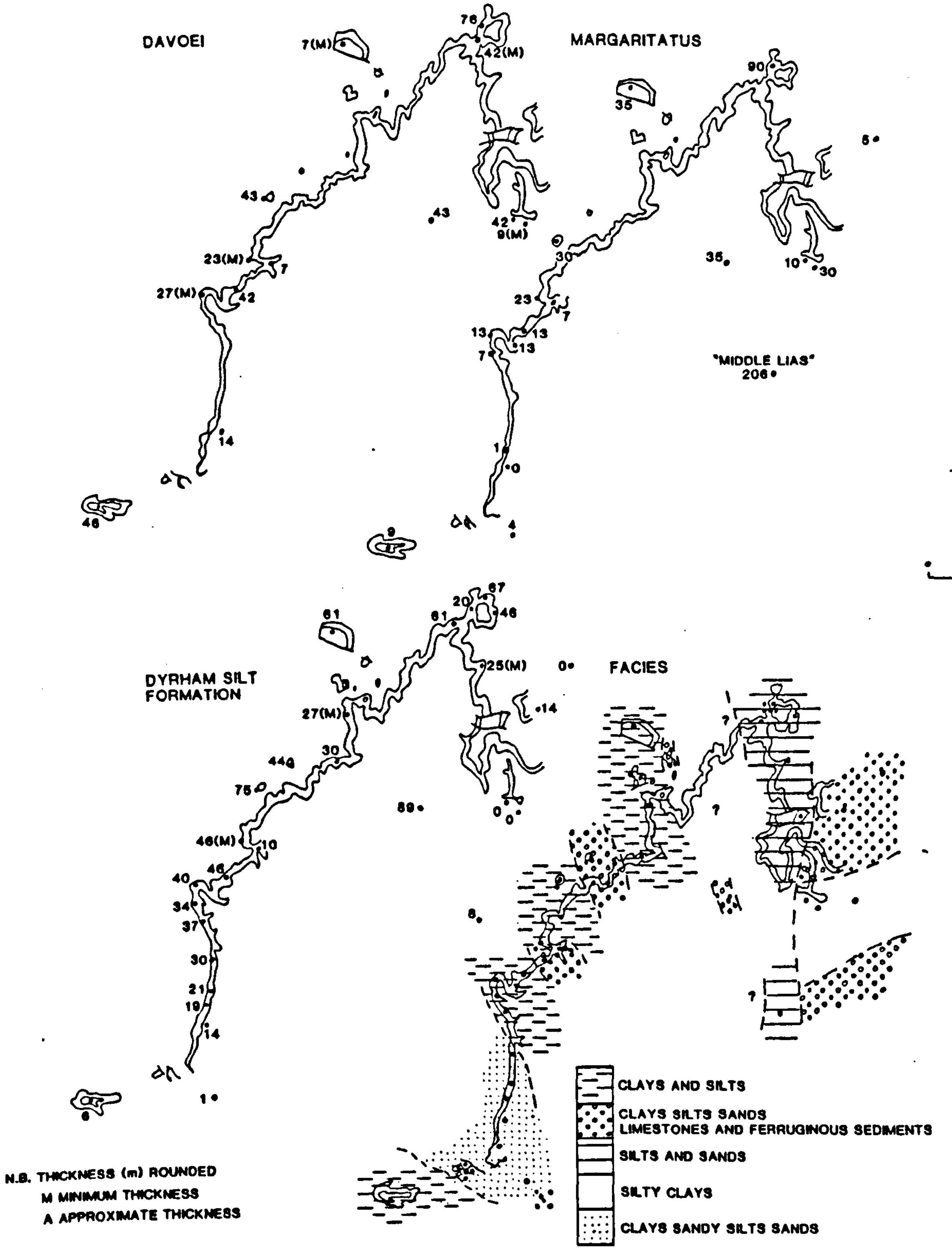


Fig. 55. DSF: ammonite zone thicknesses, formation thicknesses and facies.

become progressively thicker towards the Vale of Moreton. The _margaritatus_ zone is noticeably thinner than the underlying _davoei_ zone. The DSF thicknesses tend to decrease from the centre of the Cotswolds towards its E and W margins; it is consequently weakly developed at Dundry, and absent on the Oxfordshire border, where the mudstone and clay facies of the Lower Lias persisted into the Middle Lias.

The facies map clearly shows a N-S elongation of facies belts with rapid E-W change, closely resembling the patterns in the MRBF. There is good correlation between facies and thickness changes, so that the sandy facies in the S Cotswolds, the Oxfordshire clay facies and the ferruginous facies tend to correspond largely to the thinner deposits. The silt and clay facies and the sands and silts facies correspond to significantly thicker units. The sequence in the Stowell Park Borehole tends to be anomalous in that it is thick, but has a facies that elsewhere corresponds to lower subsidence.

5.3 Isopachyte Map of the Marlstone Rock Bed Formation

An isopachyte map of the MRBF, largely using data from the literature and boreholes, is shown in Fig. 56. Data sources are indicated in Appendix 31. Good correlation can be seen between this map and the MRBF facies map. Rapid thickness changes along narrow, elongated lineations are noticeable in the Oxfordshire border and in the Hillesley/Dursley area in the S Cotswolds. E and W of these areas respectively, the MRBF is very thin or absent.

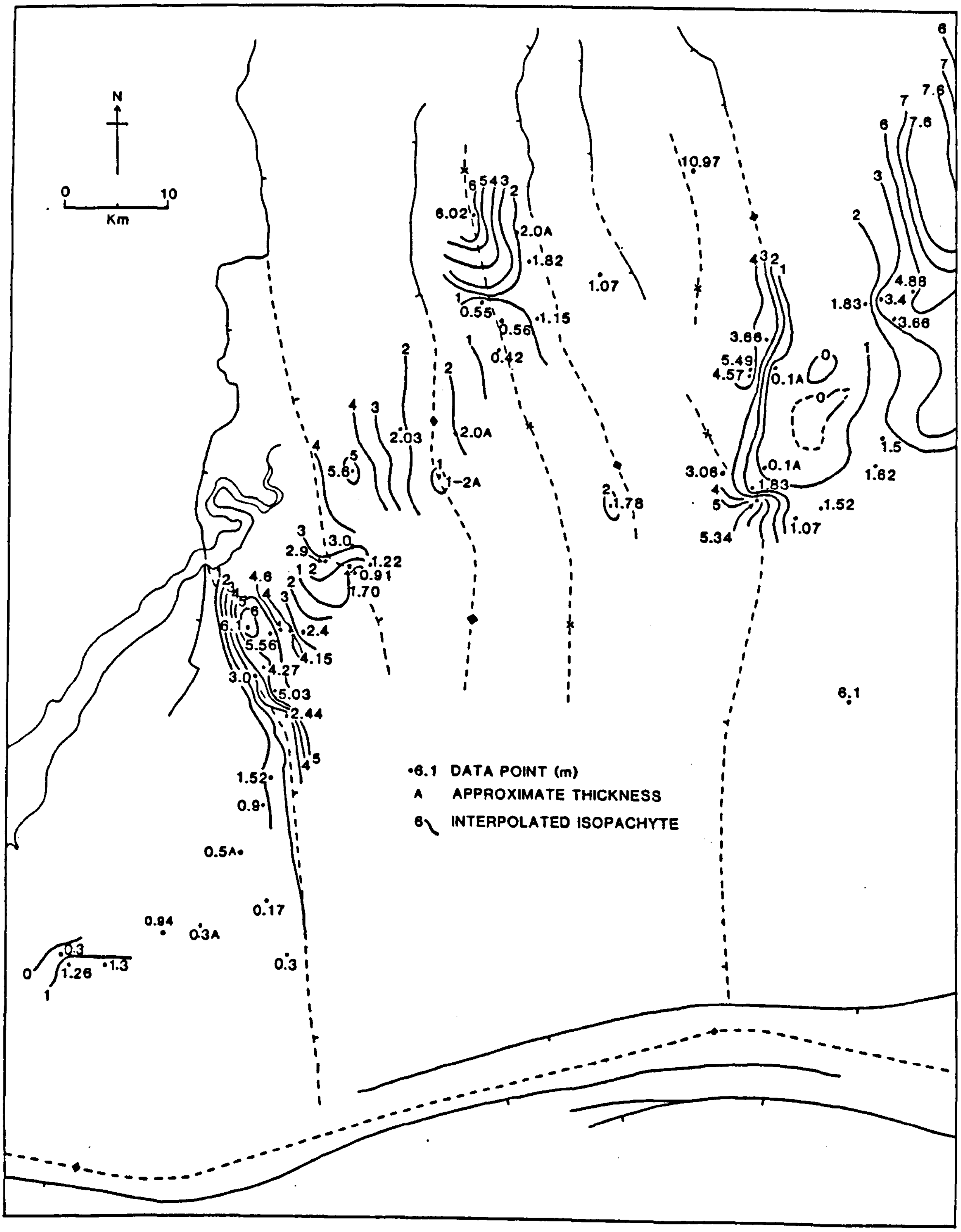


Fig. 56. MRBF isopachyte map.

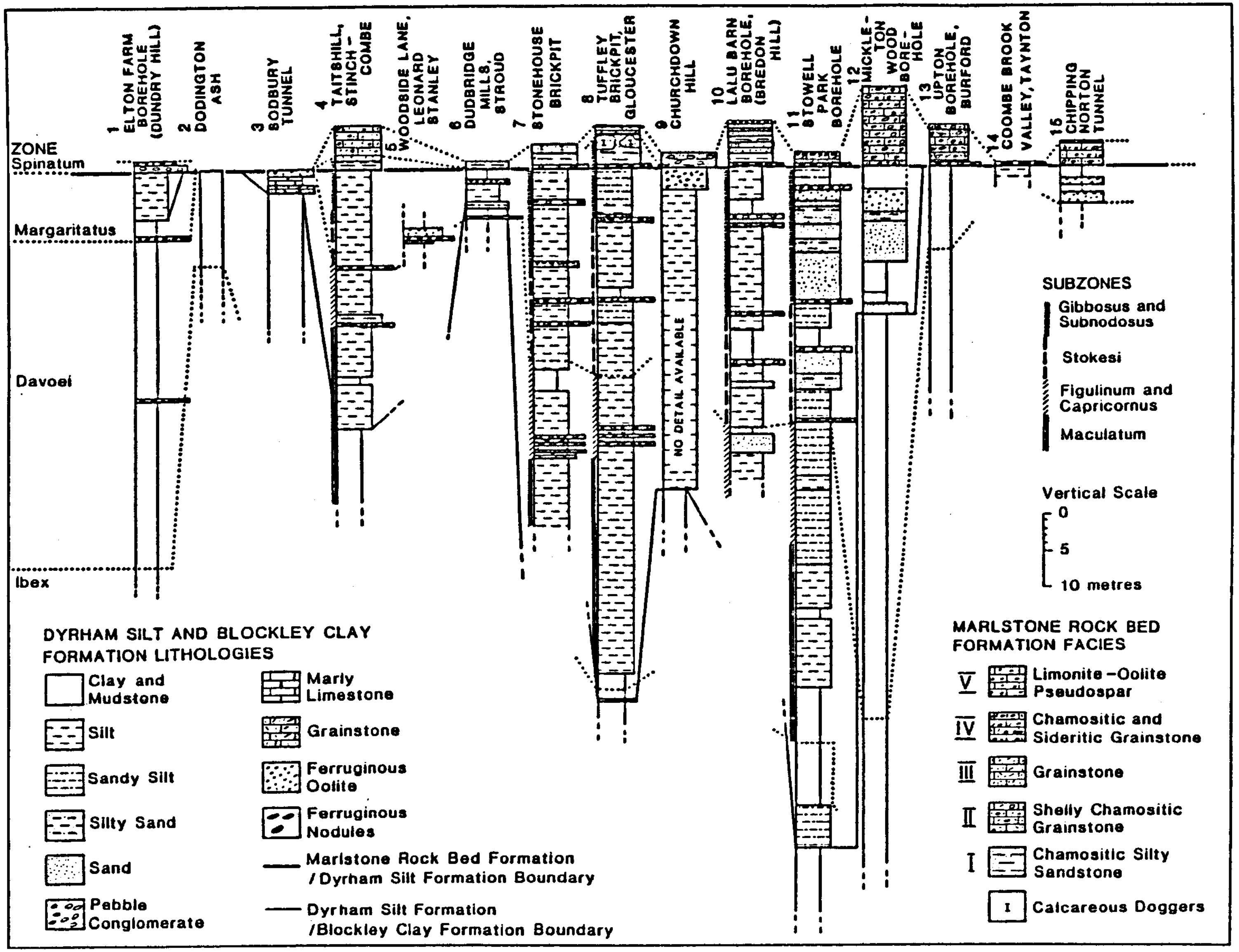
In between, the formation is characterised by a regular thickening and thinning pattern which corresponds closely to the facies belts. These patterns are in turn concordant with those observed in the DSF. This map also shows that the spinatum zone is much thinner than the margaritatus zone, so that throughout the deposition of the DSF and MRBF, rates of subsidence were decreasing.

6·0 Basinwide correlation

Stratigraphical interpretation of the MRBF and DSF are shown in Fig. 57. The sections are arranged serially from SW to NE (c.f. Fig. 59). Attention is drawn to the Mickleton Wood Borehole log which was considered unreliable by Williams and Whittaker (1974:42). However, the exceptional increases in zone thickness compared with adjacent sites is supported by information from the Highworth well, and has therefore, been included. This figure demonstrates the regular pattern of thickness changes in the formations and the rapid, localised changes in the ammonite zones. Similar temporal patterns to those discussed from the present fieldwork are also noticeable.

Available biostratigraphical evidence shows that subzone correlation can be made between 5 widely-spaced sites in the Cotswolds on Fig. 57, at localities 4, 7, 8, 10, 11. This shows that 4 pebble conglomerates, or cyclothem tops, may be closely traced between localities 8, 10 and 11 on biostratigraphical evidence. The two higher conglomerates overlie cyclothems within the subnodosus and gibbosus subzones, and the lower two cyclothems to the stokesi

Fig. 57. Stratigraphic correlation across the Cotswolds (Dreghorn 1967, Fry 1951, Green and Melville 1956, Ivimey-Cook 1978, Palmer 1971, Phelps 1982, Reynolds and Vaughan 1902, Smithe 1877, Whittaker and Ivimey-Cook 1972, Witchell 1882, Woodward 1893, Worssam 1963, Worssam and Bisson 1961).



subzone, all of which comprise the margaritatus zone. At Locality 7 on this figure, the top of the stokesi subzone corresponds to a grainstone and not to the conglomerate below, suggesting differential subsidence.

Despite the fact that the actual zonal position of the base of the MRBF remains to be determined, if evidence is present, in many parts of the Cotswolds, it is significant that both the margaritatus and spinatum zones collectively show a regular thickening and thinning pattern across the Cotswolds on an E-W axis (Fig. 57).

7.0 Tectonic structures in the Cotswolds

7.1 Development of ideas

Hull (1855, 1857) noted N-S trending anticlinal structures in the Vale of Winchcombe and Moreton, and associated stratigraphical thinning. Buckman (1901) recorded other regularly-spaced NW-SE trending anticlines and synclines across the mid Cotswolds and, following Godwin-Austen (1856), suggested that they were caused by orogenic activity, possibly as a result of posthumous movement of folds in the underlying Palaeozoic rocks. Cox and Trueman (1920) recognised another synclinal structure running N-S through Chipping Campden. These 'anticlines' and 'synclines', which are supratenuous (drape) folds, have a very low amplitude in the order of tens of metres, and are perhaps more appropriately thought of as gentle upwarps and downwarps.

Arkell (1933) noted similar structures in other areas of the English Jurassic, which he associated with stratigraphical thinning and facies boundaries. He demonstrated that some of these folds correlated with older Palaeozoic folds (e.g. the Mendip periclines) and supported the ideas of earlier geologists, adopting the term 'Axes of Uplift'. Arkell (1933:68), taking another axis he had identified along the line of the Malvern Hills which was parallel to the Vale of Moreton 'Axis', suggested that it probably continued southwards to account for the N-S trend of the Cotswold escarpment, and the absence or thinning of Jurassic strata E of Bristol. He considered that the escarpment in that area was a result of uplift along the axis. Between his Malvern and Vale of Moreton Axes, Arkell noted a marked thickening of the Jurassic strata and referred to this as the 'Cotswold Basin' (1933:65).

Kellaway and Welch (1948:9, 59, Fig. 20) supported the idea of a N-S trending axis along the W side of the Cotswolds, to account for rapid E-W changes of localised facies and thickness in the Upper Lias of that area. They referred to this as the 'Bath Axis' which was visualised as a linear area of shallows on which sands accumulated; clays and silts were deposited in the adjacent quieter deeper waters.

Modern ideas on the structural evolution of the area began with the publication of a Structural Contour Map of the pre-Permian basement below England and Wales by Kent (1949). This was based on data recently acquired from the onshore search for oil in the 1930's and 1940's. The map established the configuration of a discrete N-S trending post-Carboniferous sedimentary basin lying between the Gloucestershire-Oxfordshire border in the E, and the Malvern Hills and Forest of Dean in the W. Its N limit lay in the Kidderminster-Birmingham area and its S limit in the area around Swindon. To the SW of the basin a small shield-shaped area of low subsidence was noted (referred to in the present study as the Avon Platform), and to the E, a larger structure which Kent called the London Platform. This latter platform had already been described by Arkell (1933) as the Palaeozoic Platform, with the Oxford Shallows (Arkell 1947) on its W flank. To this newly-defined sedimentary trap, Kent applied the name Severn Basin.

Kent identified rapid changes in thickness on the W margin of the basin adjacent to the Malvern Hills, and suggested that they could be accounted for by a deep fault. He observed that the post-Carboniferous basins of England and Wales did not generally have a close relationship with Palaeozoic synclines, and concluded they were not a result of posthumous movement of basement folds, but rather of vertical movements along other structural lines (Kent 1949:101).

Wills (1956) studied the Permo-Triassic strata cropping out in the N part of the Severn Basin, and used available boreholes and geophysical data to indicate the presence of rapid changes in thickness and facies across N-S lineaments. These he attributed to active syn-sedimentary faulting, initiated in Permian times, for which he proposed the name Worcester Graben for the N end of Kent's basin. Wills (1956:87, 100, Fig. 14) suggested that an upland horst occupied the area of the basin prior to the tensional phase, supplying sediment to adjacent areas. With the onset of crustal tension, and subsidence, the marginal faults were reversed and a rift basin was created by Early Triassic times, when the Lower Bunter Sandstone was deposited.

Hallam (1958) described the platform areas as defined by Kent 'Swells', on which low subsidence had taken place forming submarine shallows or land, undergoing occasional epeirogenic movements. Between them, 'Basins' were present, where greater quantities of sediment accumulated. Hallam (1958:448) suggested that faulting in the basement was likely to have been the cause of fold development in the overlying sediments of the basins, ('supratenuous' or 'drape' folds). This was considered to have been either reverse faulting caused by crustal compression, or normal faulting, as a result of crustal extension.

Further work by Wills (1973, 1978) indicated, from more borehole and geophysical data, that the Severn Basin as a whole was likely to be fault controlled. Whittaker (1972) recognised another N-S trending synclinal structure running through Mickleton. Cope (1984:376) referred to the area of Jurassic sediments in the Severn Basin as the 'Vale of Gloucester Basin'. Chadwick (1985) and particularly Whittaker (1985) provided major advances in elucidating the faulted nature of the basin using seismic reflection profiles, and established a Precambrian and Lower Palaeozoic age for the strata forming much of its floor (Fig. 58). This indicates that the N-S faults that controlled the rift basin were strongly influenced by the underlying 'Malvernoid' trend. It is worth drawing attention to the fact that the dominant fracture pattern shown on BGS 1:50 000 and 1:63360 sheets covering the Cotswolds is essentially an E-W one, which contrasts with the N-S tectonics discussed here. The only evidence for E-W synsedimentary faulting in the Pliensbachian occurs in the area of outlier hills N of Cheltenham, where N-S changes in facies and thicknesses of units occur (Figs. 54 and 56, M. Simms pers. comm. 1986). It would appear that the E-W fault pattern has been superimposed at a much later date (Bevan 1984, Chidlaw 1987a:26). Both Chadwick and Whittaker referred to the Severn Basin as the Worcester Basin.

Deep N-S trending normal faults with downthrows towards the W in the Severn Basin were recorded at the surface in its N part (Williams and Whittaker 1974). These displaced the Permo-Triassic and Lower Lias sediments. To the S, these faults disappear below the surface as the younger Jurassic strata are met, but their trend continues in these sediments along the axes of the anticlines described by the earlier workers, with synclines lying between. Two other synclinal structures at the W and E margins of the basin are suggested from the present study, from

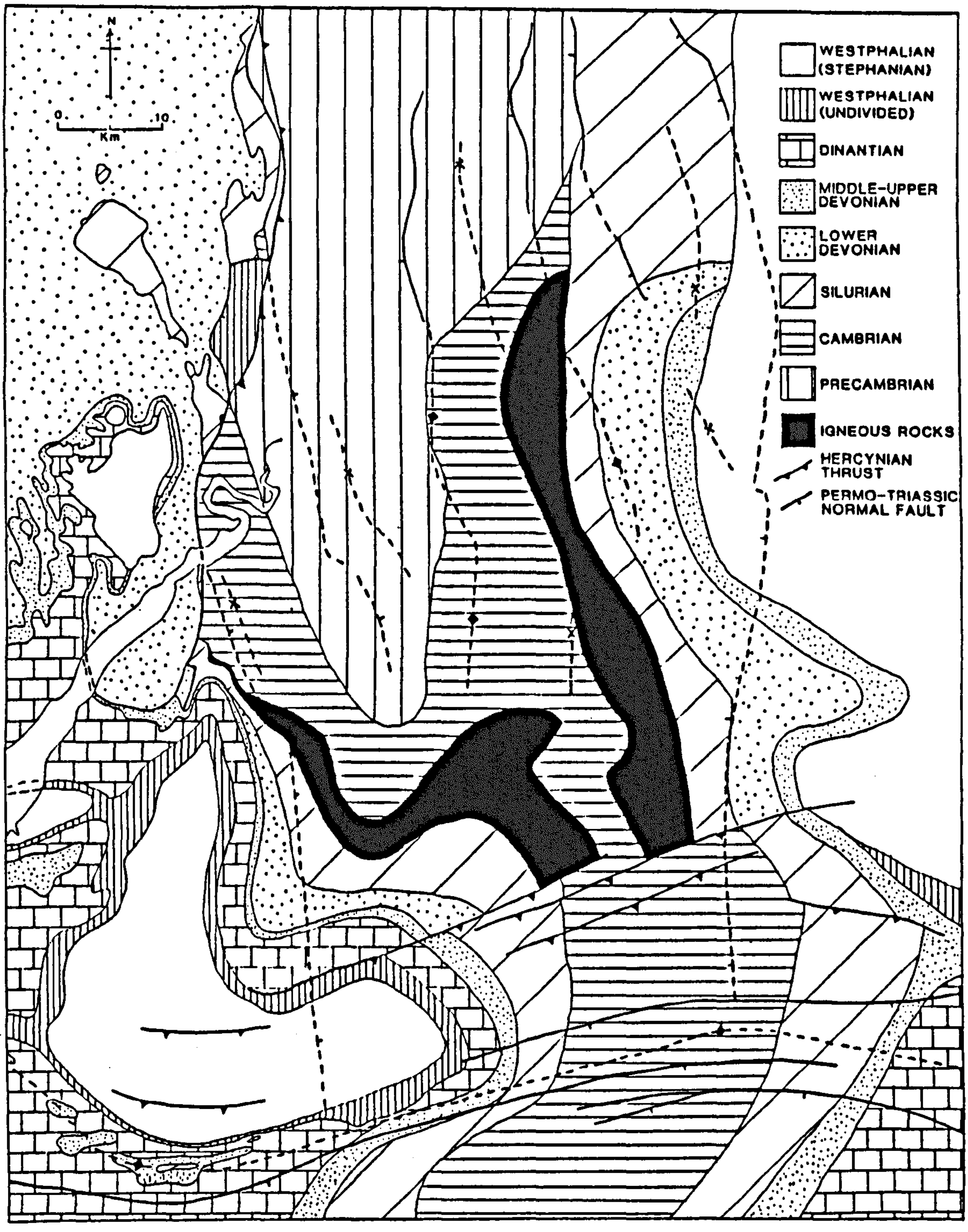


Fig. 58. Pre-Permian geology of the Cotswolds and adjacent areas (Whittaker 1985, BGS 1:625 000 Geological Map of Great Britain, 1979). Fold axes correspond to Fig. 59.

examination of local BGS 1:63360 and 1:50 000 sheets, OS 1:25 000 maps and calculations or estimations of dip in the MRBF. These are termed the 'Stinchcombe' and 'Windrush' Synclines, and are shown with other basin folds and faults on Fig. 59).

8.0 Tectonics and Sedimentological Model

It is clear, therefore, that the trend of upfolds and axes of uplift associated with the Severn Basin indicate the position of normal faults in the pre-Permian basement. Rapid changes in facies and thickness in post-Carboniferous stratigraphic units across the structures were first recorded by Arkell (1933). Wills (1956) and Audley-Charles (1970) noted a similar influence in the Permo-Triassic sediments; Kellaway and Welch (1948 Fig. 20) recorded similar patterns in the Upper Lias, as did Mudge (1978) and Baker (1981) in the Inferior Oolite. By the time the Cornbrash Limestone Formation (Bathonian-Callovian) was deposited in the Cotswold area, this tectonic control of deposition had more or less ceased (Chidlaw and Campbell in press). The present study indicates a similar structural control was occurring during the deposition of the Pliensbachian; the fold structures are believed to be supratenuous warpings created by synsedimentary extensional faulting in the pre-Permian basement.

Changes in temporal patterns, facies and thickness changes of stratigraphic units observed in the DSF and MRBF of the Severn Basin may be explained by the presence of a block-

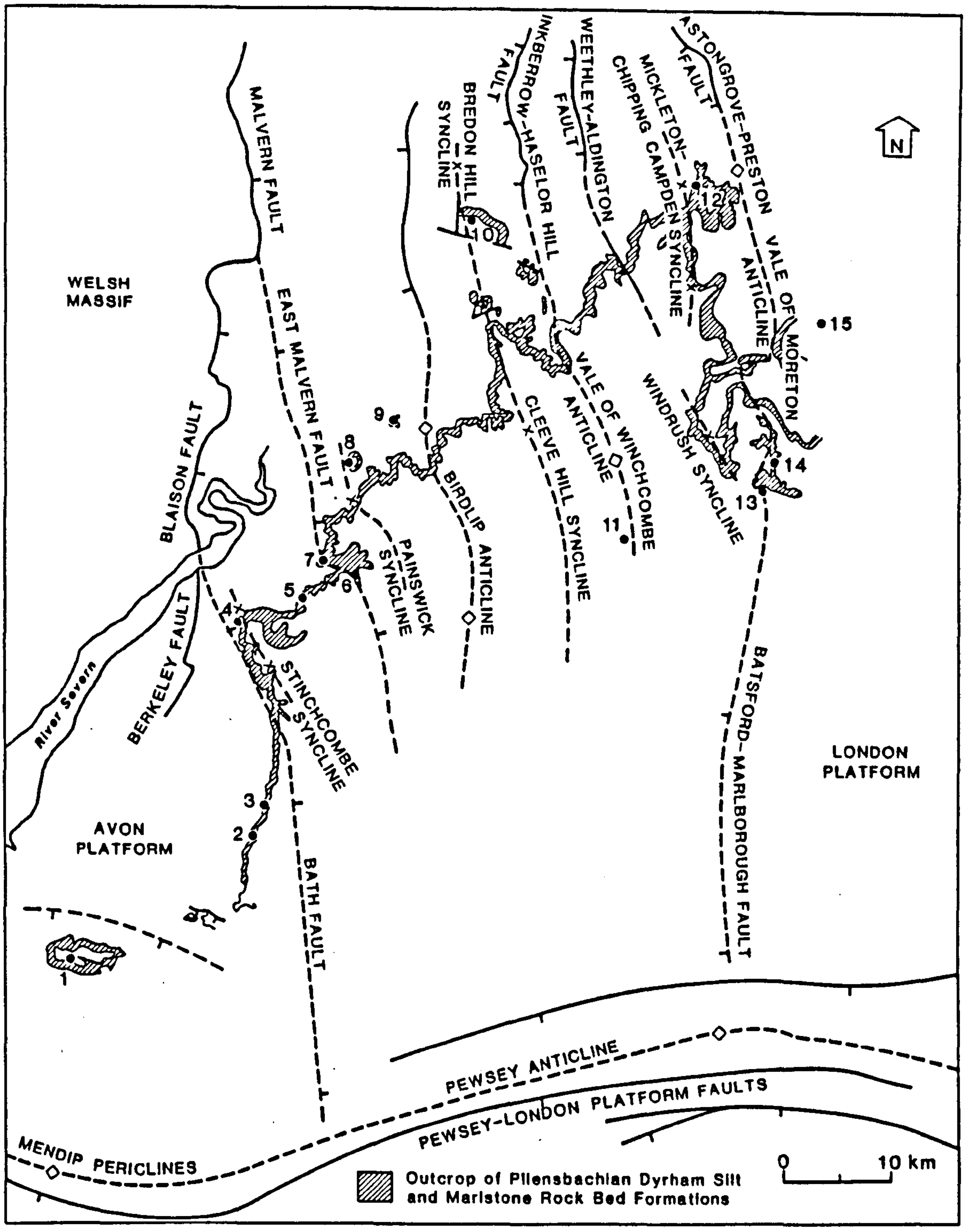


Fig. 59. Structural controls in the Cotswolds (Arkell 1933, Buckman 1901, Cox and Trueman 1920, Kent 1949, Whittaker 1972, 1985, Williams and Whittaker 1974, Wills 1973, 1978, BGS sheets 1:50 000 234 1972, 1:50 000 251, 1970).

faulted basement. The structure of the basement proposed here is shown on Fig. 60. The Buckland Half Graben is hypothetical, but may explain the noticeable promontory of Burhill near Buckland; this is capped by the MRBF which suggests rapid local thickening as has been shown for similar platforms in other parts of the basin. The fact that Burhill occurs on the downthrow side of a major fault which runs along the Broadway valley (Fig. 59), provides more supporting evidence for the structure; this may be a reactivated basement fault. Sedimentation over the unstable basement was strongly controlled by the horst and graben structures, which developed their own facies and thicknesses of stratigraphic units. Movement along the basement faults caused periodic rapid, or sometimes pulsed subsidence of the graben floors. This led to the development of the upward coarsening/shallowing cyclothems during periods of temporary crustal stability.

As Whittaker's (1985) Map 3 indicates, and the model here suggests, the Severn Basin was not a simple graben structure. Rather it was a broad zone of horsts and graben forming a rift complex as part of the evolving, and much larger, North Atlantic Rift. The structural terminology in this section is shown in Fig. 60 and Fig. 61. The latter shows the detailed development of ideas from a simple basin structure to the present interpretation of a rift complex.

9.0 History of Deposition

The tectonic setting in which the DSF and MRBF were

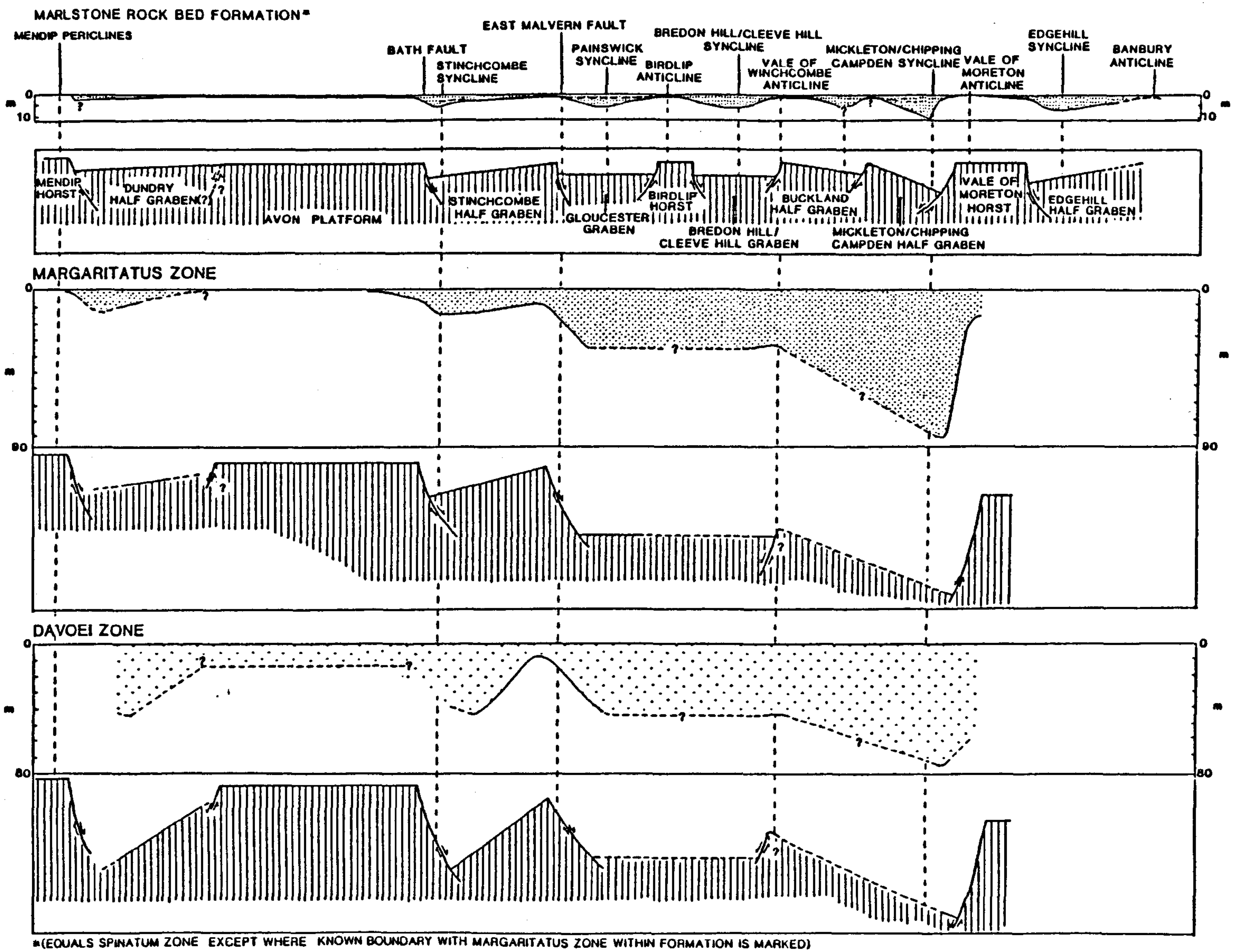


Fig. 60. Basement structures in the Cotswolds and adjacent areas.

Fig. 61 Development of recognition of structures and their terminology, in the Severn Basin

(A) Basin Terminology

Arkell (1933)	Kent (1949)	Wills (1956,1973,1978)	Cope (1984)	Chadwick (1985)	Whittaker (1985)	This Thesis
Cotswold Basin	Severn Basin	Worcester Graben (N end of Severn Basin)	Vale of Gloucester Basin (Jurassic of Severn Basin)	Worcester Basin	Worcester Basin	Severn Basin

Fig. 61 (B)

Structures Adjacent to Basin

Arkell (1933)	Arkell (1947)	Kellaway (1948)	Kent (1949)	Hallam (1958)	Whittaker (1985)	This Thesis
					Welsh Massif	Welsh Massif
		Radstock Shelf	**Welsh** Highland	**Welsh Massif** Swell		Avon Platform
						Dundry Half Graben
		Mendip Axis	Mendips	Mendip Swell	Mendip High	Mendip Horst
Palaeozoic Platform	Oxford Shallows (W Flank of Platform)		London Platform	London Platform Swell	London Platform	London Platform

Fig. 61 (C)

<u>Basin Structures</u>

Hull (1855, 1857)	Buckman (1901)	Cox and Trueman (1920)	Arkell (1933)	Kellaway and Welch (1948)	Whittaker (1972)	Wills (1973)	Williams and Whittaker (1974)	Wills (1978)	This Thesis	
									Folds	Underlying Structures
Anticline in Vale of Winchcombe			Winchcombe Axis		Vale of Winchcombe Anticline		Haselor Hill Fault		Vale of Winchcombe Anticline	Haselor Hill Fault (Continuation)
Anticline in Vale of Moreton	Anticline in Vale of Moreton		Vale of Moreton Axis	Moreton Anticline	Vale of Moreton Anticline	Stratford-Batsford Fault	Aston Grove Preston Fault and V. of M. Anticline	Batsford Marlborough Fault	Vale of Moreton Anticline	Vale of Moreton Horst
	Anticline in Birdlip area		Birdlip Axis	Birdlip Anticline					Birdlip Anticline	Birdlip Horst
	Syncline in Painswick Area		Painswick Syncline	Painswick Syncline					Painswick Syncline	Gloucester Graben
	Syncline in Cleeve Hill Area		Cleeve Hill Syncline	Cleeve Hill Syncline					Cleeve Hill Syncline	Bredon Hill/ Cleeve Hill Graben
			Bredon Hill Syncline		Bredon Hill Syncline		Bredon Hill Syncline		Bredon Hill Syncline	
			Malvern Axis			Malvern Fault		Malvern Fault		
				Bath Axis		Bath Fault		Bath Fault	Stinchcombe Syncline	Bath Fault
						Malvern-Nailsworth Ridge		East Malvern Fault		East Malvern Fault
						Inkberrow Fault	Inkberrow Fault	Inkberrow Fault		
							Weethley-Aldington Fault			Buckland Half Graben
		Chipping Campden Syncline							Chipping Campden Syncline	Hickleton Half Graben
		Banbury Anticline							Banbury Anticline	?
		Edge Hill Syncline							Edge Hill Syncline	Edge Hill Half Graben
									Windrush Syncline	Weethley Aldington Fault (Continuation)
					Hickleton Syncline				Hickleton Syncline	Hickleton Half Graben

deposited was within, and on the margins of, a small (70 x 40km) N-S trending active rift basin. This lay within the broad zone of extension of the European part of the North Atlantic Rift. The rift basin occupied a shelf sea, with waters lying within the range of below storm wave base, to very shallow, possibly sometimes emergent. The sea was part of the shallow epicontinental or 'epeiric' sea covering much of Europe at this time. Land areas lay at no great distance, were low lying, and well vegetated. These most likely correspond to the platforms of the Welsh Massif, Avon and London. The horsts of the Vale of Moreton and the Mendips may have been land areas occasionally. Land probably existed N of the rift, but to the S other basins were evolving within the Variscan Terranes (Whittaker 1985), and marine conditions are indicated. Climatically, humid tropical conditions prevailed, punctuated by severe storms such as cyclones.

Within the rift basin, bathymetry varied between shallow and deeper N-S trending belts, in a regularly spaced (10km) pattern. These were controlled by the positions of horsts and graben in the pre-Permian basement. The clay and mudstone lithologies of the Lower Lias were gradually replaced by dominantly silts in the central parts of the rift, which spread E and W with time to its margins. In these marginal areas, more sandy sediments were also deposited. There is little evidence available to suggest the provenance of these coarser silty and sandy sediments. Clearly, they were derived from an area N or S of the rift, but evidence from diachronism is lacking, and the few palaeocurrent indications suggest flow from both N and S. Across a broader geographical area, data suggest that limestone-clay lithologies were widespread,but locally, easterly prograding sands and silts were derived from islands within the epeiric sea (Fig. 62). The silts and subordinate sands in the rift could therefore have been the distal sediments from the sands introduced into the Wessex basin, to the S. Alternatively, they may have been derived from a land area, such as in the Midlands or Pennines, to the N. (Well and borehole data sources for Fig. 62 are shown in Appendix 32).

Periodically, the sea floor of the rift was rapidly deepened in the rift graben in response to extensional movements along the basement faults. At these times, only fine grained sediment could reach the substrate which lay well below storm wave base; poorly oxygenated conditions, with few life forms, sometimes occurred. Stabilisation of the floors of the graben for a time allowed gradual infilling to occur. At these times, progressively coarser material was deposited, waters became clearer and more oxygenated with conditions which were suitable for colonisation by burrowers and shelly fauna. Ferruginous minerals also became more abundant as the dominantly silty input waned, and higher energy currents caused a transition from flat to cross-laminations to occur. Infillings eventually reached the zone of storm influence in some areas, and severe storms, possibly cyclones, eroded the substrate to form flat-pebble conglomerates.

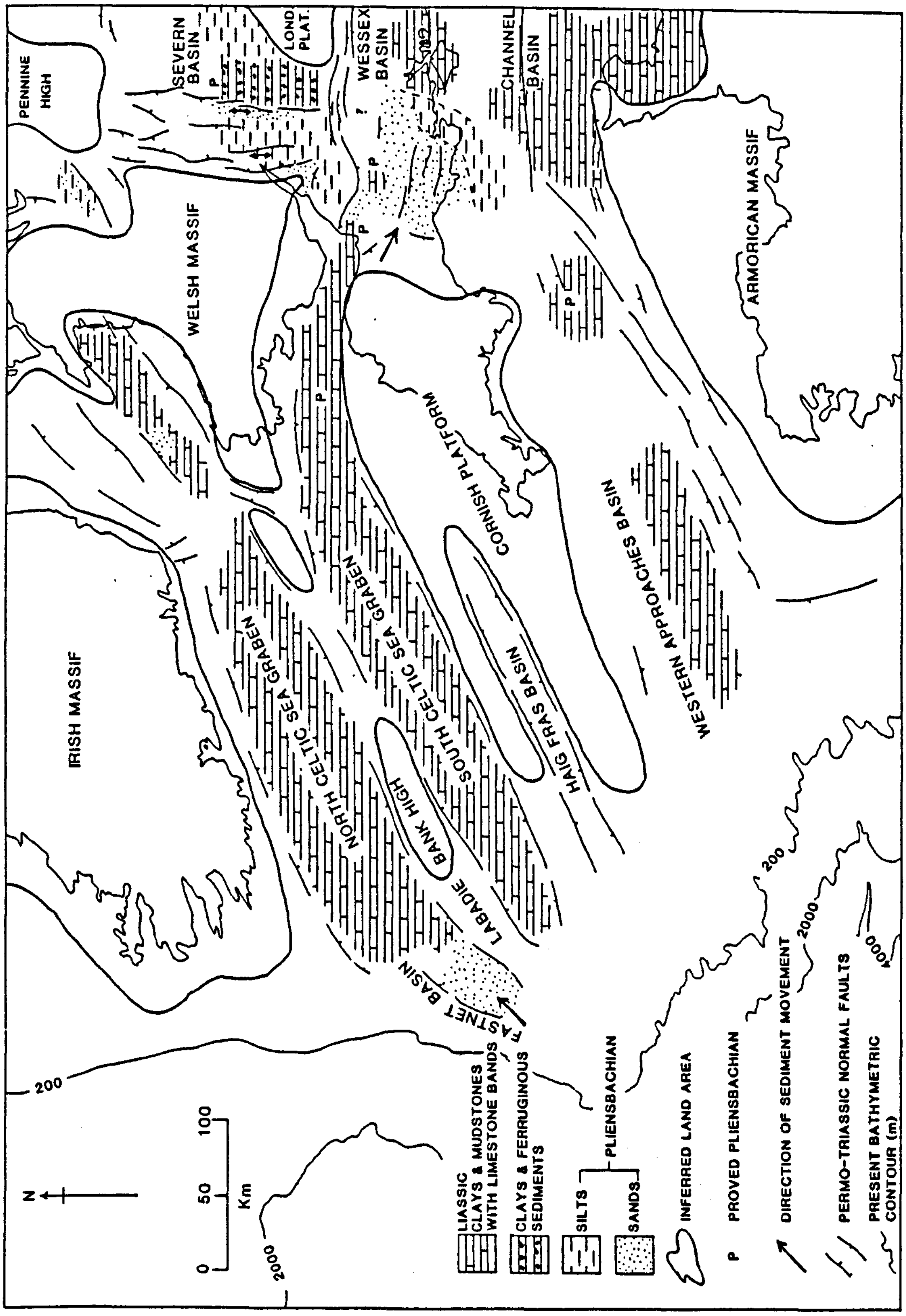


Fig. 62. Liassic facies distributions and palaeogeography, SW Britain and continental shelf (Naylor and Shannon 1982, Wilson et al 1958, Woodward 1893).

Emmergence and lateritic weathering may have taken place in some areas at this time. Renewal of movement on the basement faults caused the sea floor once again to subside, and a new episode of infilling was indicated.

Within the rift and on its margins, areas of low subsidence occurred occupied by shallower waters. Here, coarser sediments were deposited, including thin units of ferruginous oolite. One of these areas, the Avon Platform, was possibly also the site of erosion prior to the deposition of the MRBF (Fig. 57). Noticeably, these areas attracted less siliciclastic material. The cyclic patterns of sedimentation developing in the graben areas however, also occurred on these areas of net lower subsidence. This suggests that deeper water conditions also occurred in these areas on occasion. Many of the pebble conglomerates at the tops of cyclothems can be correlated across the rift complex, so that synchronised basinwide cyclicity must have occurred. An overall slowing down of subsidence is indicated during the deposition of the DSF. This is reflected in the upward contraction of zonal thicknesses and cyclothems at many sites.

During the deposition of the last cyclothem associated with the margaritatus zone, a return to deeper waters did not occur within the Stinchcombe Half Graben and Gloucester Graben (Fig. 60), and instead siliciclastic silty sandstones containing chamosite peloids and flakes (MRBF Facies I) were deposited. These are similar to sediments deposited earlier on the E flank of the rift in the DSF, and which continued to be deposited there. Shallow subtidal, well-aerated conditions prevailed, and much of the sediment was extensively burrowed, although suspension of fines discouraged extensive colonisation by a shelly fauna. Those present were subjected to frequent comminution by storms, with the production of shelly lags.

While the sandy lithology continued to be deposited in the Gloucester Graben throughout this cyclothem, in the Stinchcombe Half Graben it was replaced by clearwater conditions where crinoids and brachiopods became abundant, and plant debris, belemnites, ammonites and shark were present. Frequent abrasion of shelly material produced carbonate sands, which were deposited with chamosite peloids and flakes and subordinate siliciclastic sand (MRBF Facies II). Some of the chamosite grains developed laminated coatings, forming superficial and true ooids. The laminae may be alternatively oxidised and unaltered. Thorough bioturbation occurred, so that virtually all primary sedimentary structures were destroyed; subsidence was low or negligible.

These shallow waters were, as in the sandy conditions, frequently disturbed by storms causing periodic destruction and fragmentation of the shelly fauna. Sometimes these were deposited in winnowed masses and lags. The top of this cyclothem has provisionally been identified at MRBF Locality 16 (Smart's Green) in the Stinchcombe Half Graben. Here, it is overlain by a thin layer of carbonate mudstone (MRBF Facies V) with large scattered and broken limonite ooids deposited in still shallower waters. Above this cyclothem, a return to deeper waters is indicated at this site, and the last, and thinnest cyclothem of the Pliensbachian was deposited. This cyclothem corresponded to the *spinatum* zone, and indicated a time of least subsidence and shallowest waters.

The base of the same cyclothem is marked by a thin pebble conglomerate on the Avon Platform, Dundry Half Graben and in the Bredon Hill/Cleeve Hill Graben, but it appears to be absent in remaining areas. The siliciclastic sandy facies was at this time deposited on or adjacent to the structural highs near Stroud and the Birdlip Horst, indicating diachronism from S to N. Where it was deposited in the Gloucester Graben, palaeocurrents indicate a N derivation. These sands show little change in grain size or mineralogy throughout the MRBF, while other grains were affected by shallowing. This indicates a continued supply of similar material, and the quartz-dominated mineralogy suggests at least second-cycle sources. Possibly, these sands were derived from Carboniferous, and/or Permo-Triassic sediments in the Midlands or Pennines.

Over much of the rift during the *spinatum* zone times, the shelly and chamositic carbonate sand (MRBF Facies II) was deposited, and in the Bredon Hill Graben the siliciclastic sand lithology was replaced by carbonate sands with fewer shells and fewer chamositic grains (MRBF

Facies III). Across the Cleeve Hill Graben subsidence was greatly reduced at this time, and the MRBF is thin and conglomeratic. Severe storms affecting the very shallow waters caused erosion of the substrate and deposition of clasts from pebbles to boulders in size in the S, to finer more pebbly deposits in the N. This fining of conglomeratic clast size is accompanied by rapid northernward thickening of the MRBF into the Bredon Hill Graben, which suggests that E-W faulting also occured.

On the Avon Platform, and Dundry Half Graben, the very thin carbonate mudstone with limonite ooids (Facies V) was deposited in very shallow waters, frequently affected by storms, causing the break up of shells and ooids. Here, lime muds accumulated, probably under the binding influence of sea grasses and algae. The presence of silt clasts in this facies indicates that nearby the DSF was undergoing erosion, either on land or current-scoured shoals. Towards the end of MRBF deposition, this facies advanced into the W margin of the rift as basin infilling neared completion.

On the E side of the complex, the shelly chamositic carbonate sands (Facies II) were replaced from the E by a more iron-rich facies (Facies IV) advancing into the basin for a short distance. This facies continued to be deposited throughout the rest of the deposition of the MRBF in this area. This facies contains an abundance of broken ooids, and suggests stronger currents and shallower waters than for the facies below.

The completion of MRBF sedimentation was marked by deposition of limestones and iron-rich sediments over most of the rift complex, indicating that influxes of siliciclastics had become progressively fewer with time. The weathered profiles at some localities may indicate subaerial exposure at the time, when water depths would have been at their shallowest. A storm event or events at the top of the MRBF locally produced another pebble conglomerate from the material lying immediately below, and was subsequently followed by basinwide deepening associated with the deposition of the Upper Lias Clays.

CHAPTER 6

Discussion and Conclusions

1.0 The origin of the randomly interstratified and smectite clays

Several origins for these clays are possible:-

Randomly interstratified clays

(a) Pressure and temperature alteration of smectite through burial.

(b) Neoformation through alteration of smectite in the depositional environment.

(c) Weathering of illite on land and transportation of the interstratified clay into the depositional environment.

Smectite

(a) Weathering in climates with pronounced dry seasons.

(b) Weathering of igneous rock outcrops.

(c) Suba queous alteration of volcanic air-fall ash.

1.1 Randomly interstratified clays

Corbin (1980) showed that these clays could be produced by heat and pressure alteration of smectites, so that above 60°C, random illite interlayers began to form which became increasingly dominant to produce illite alone at approximately 200°C. Randomly interstratified clays may occur down to a burial depth of 1km (Eberl 1984), below which ordered interstratification occurs.

The limited thickness of overburden which was once present above the Pliensbachian of the Severn Basin precludes any possible origin of these clays by heat and pressure alteration. The isopachyte maps of Whittaker (1985) suggest that, at the most, about 1km of Jurassic and Cretaceous sediment covered the area. Further, 4km of overburden is required to allow temperatures to rise to $60^{\circ}C$ (Hoffman and Hower 1979).

Neoformation of smectite within the depositional environment occurs through oxidation of the smectite in well-aerated waters. This is less likely to occur in more anoxic conditions where the smectite would be preserved and the interstratification inhibited. There is a marked abundance of randomly interstratified clays and a concomitant rarity of smectite in the MRBF; this formation was deposited in well oxygenated conditions. The DSF formed in waters with a lower Eh and both randomly interstratified and smectite clays are preserved. This alteration process is accompanied by a release of silica. This silica, however, does not seem to correspond with the presence of clay-sized quartz found in the samples analysed and does not relate to the absence of smectite. This quartz is more closely associated with siliciclastic-rich sediments and is therefore thought to be of detrital origin.

The possibility of alteration of illite on land through weathering is thought to be the most likely cause for the presence of the randomly-interstratified clays. This is produced through a weakening of the illite structure allowing water and associated cations to become adsorbed to form the smectite interlayers. The requirement of an abundance of weathered illite on land areas adjacent to the Severn Basin presents no difficulties; illite is the most prolific and ubiquitous group of clay minerals found in the Jurassic sediments of Britain (Hallam 1975).

1·2 Smectite

Smectite clays form in soils in areas with pronounced dry seasons (Singer 1984). The palaeoclimatic evidence for the Pliensbachian of NW Europe suggests a humid tropical environment, and is clearly incompatible with such an origin for smectite. Weathering of mafic igneous and metamorphic rocks is another source of smectite, and such a possibility cannot be entirely ruled out. Nearby igneous centres are unknown at present (Woodhall and Knox, 1979 Table 3, Moreton (1980) Fig. 3), but they may have been missed in boreholes and geophysical surveys of the shelf basins around Britain.

The alteration of volcanic air-fall ash seems to provide the most promising source of smectite in the Severn Basin. Corroborative evidence such as glass shards, pumice, hypo-crystalline rock fragments or euhedral biotite and apatite are known from the Coombe Hay Bentonite (Bathonian) near Bath, Avon (Hallam and Sellwood 1968, Sellwood and Hallam 1974, Jeans et al 1977) and Callovian bentonites on Skye (Knox 1977, Woodhall and Knox 1979), but have not been identified in the present study. Corbin (1980) could find no evidence of this nature in smectite clays in the Toarcian-Aalenian boundary beds of Skye and Dorset, and in the davoei-spinatum zones of the Dorset coast. Corbin (1980:179, 180) concluded that while a volcanic origin could not be proved for the smectites he described, such a source was the most probable. It is significant that Corbin's Dorset coast smectites are of similar age to those described in this thesis.

Corbin (1980 Fig. 7·5) listed the geographical distribution of Jurassic smectite and proven bentonites in Britain and showed that with the exception of those described by Bradshaw (1975) in the Middle Jurassic of E England, all were located in the W. These occur d on Skye, in Avon, and in Dorset. He also reported smectite in the levesqui zone (Toarcian) from the Stowell Park Borehole (Table 7·3), but none from samples taken in the davoei and margaritatus zones below. In view of the interrupted appearance of smectite at Tuffley Brickpit, and that Corbin analysed one sample alone from the two zones, it is understandable that it was missed.

The distribution of British smectites and bentonites suggest a volcanic source area to the W during the Jurassic, and this correlates well with the early opening of the North Atlantic. Some of the oldest ocean floor basalts in the North Atlantic, formed at 160Ma, have been recorded off the continental margin of the E USA (Perry et al 1981). Magmatism was widespread on both sides of the central North Atlantic Rift in the Liassic (Smith and

Noltimer, Fig. 7 1979). The most likely source for the British smectites is therefore from the W, but as stated above, no igneous centres are yet known. Exploration of the W basins and the continental margin is only just begining and further work could reveal such centres with time.

In conclusion, it seems that the smectite in the MRBF and DSF of the Severn Basin was of volcanic origin, derived from the W in igneous centres within the North Atlantic Rift. It is noticeable that in Figs. 12 and 40 the DSF smectite is too continuous and too diluted to suggest the direct input of air-fall ash into the basin. Additionally, in the MRBF it is again diluted (Figs. 11 and 13) and its presence is sporadic across the basin in the samples analysed. These factors suggest that the ash most likely fell on adjacent land areas and was brought into the basin by the processes of erosion and transportation.

2.0 The regional context of the DSF and MRBF cyclicity

In Chapter 5 it was shown that at four sites in the Severn Basin, where detailed lithostratigraphic and biostratigraphic work had been carried out, correlation could be established between five cyclothems in the *margaritatus* zone. The overlying *spinatum* zone was shown to correspond to a single, thin cyclothem and it was noticeable that a pattern of regularly-spaced thickening and thinning of the two zones occurred in the basin. This evidence strongly supports the proposed tectonic and sedimentological model.

Though much condensed, evidence of cyclicity was also found on the basin highs and platform area (localities 6 and 15, Fig. 57), and basinwide subsidence may have occurred occasionally across all the local tectonic structures.

If the DSF and MRBF stratigraphy of the Severn Basin is compared with contemporary sequences in other parts of Britain, striking contrasts are noticeable. On the Dorset coast ('Dorset Basin', Whittaker 1985), the spinatum and margaritatus zones are assigned a maximum of 135m of sediment (Howarth 1957), compared with 41m in the Lalu Barn Borehole and 85m in the Mickleton Wood Borehole of the Severn Basin. In the Midlands, and on the 'Eastern England Shelf' (Whittaker 1985:7), the Liassic sequence is thin, and non-sequences make estimations of original thicknesses difficult. North of the Market Weighton 'swell', however, the Cleveland Basin contains a thick well developed Pliensbachian sequence. Here, the spinatum and margaritatus zones comprise a maximum of 45m of sediments (Howard 1985).

Accompanying this regional contrast in zonal thickness, are notable variations in the number of cyclothems present within the sequences. Up to 6 have been recorded in the Cleveland Basin in the spinatum zone (Howard 1985), compared with only 1 in the Severn Basin and in Dorset. Five cyclothems in the subnodosus and gibbosus subzones in Cleveland compare with only 2 in the south, and while the stokesi subzone has 2-3 cyclothems in Dorset and the Severn Basin, none are present in Yorkshire.

If larger scales of cyclicity are considered, it is noticeable that the Liassic sequence of the Severn Basin is essentially composed of 2 large cyclic units, which correspond to the Lower/Middle Lias, and the Upper Lias respectively. These repeat the characteristics of the cyclothems in the DSF and MRBF but on a much larger scale. There is, for example, a marked tendency for a progressive decrease in thickness; the combined Lower and Middle Lias is some 383m thick, and the Upper Lias 168m (Kellaway and Welch 1948:46). It is considered that the Lias as a whole, an essentially siliciclastic sequence, is a still larger cyclic unit within the Severn Basin. The Liassic cycle is, also, considerably thicker than the carbonate-dominated Middle Jurassic (140m:Whittaker 1985 Maps 12 and 14). The dominantly siliciclastic material of the Upper Jurassic is absent over much of the Cotswolds, and any previous cover is likely to have been thinner than the Middle Jurassic. The pattern of upward decrease in thickness of cycles therefore also occurs on this mega-cycle scale.

If lateral variations in the Middle Lias of Britain are considered, in the Middle Lias of Britain as a whole, upward coarsening is noticeable from the Dorset to North Yorkshire coasts (Whittaker 1985:37). A similar pattern, although with less lithological variations, was recorded on the Isle of Raasay in W Scotland (Sellwood and Jenkyns 1975 Fig. 1). The difficulty in interpreting this regional temporal pattern was expressed by Holloway (in Whittaker 1985:37-38), who suggested that the coarsening upwards and basin infilling could have occurred during sea level rise, fall or stillstand, depending on sedimentation rates.

On a secular scale, eustatic curves within Phanerozoic times have been constructed by Vail et al (1977, with modifications for the Jurassic by Vail and Todd 1981), and Hallam (1978, 1984a). These curves show that at the beginning of the Jurassic, the extent of shelf seas covering the continents was similar to the present day, but was followed by a gradual transgression, reaching its maximum towards the end of the Cretaceous. Hallam (1978) indicated that short-lived minor regressions occurred at the begining, middle and end of the Pliensbachian. The British onshore cycles contrast with the secular eustatic pattern, indicating that an upward shoaling took place in the area, whilst on a global scale deepening occurred.

Hallam (1984a:212 Fig. 3) illustrated the secular deepening pattern from sequences in SE France and W Germany, and suggested that the progressive nature of the British deposits reflected localised tectonic instability and erosion. Similar shallow water deposits occur in Normandy and western Iberia; these distributions indicate sourcelands to the W, and accord with the trend of the North Atlantic Rift. This suggestion is further supported by the westerly-derived Pliensbachian sands present in the Fastnet and Wessex Basins (Fig. 62).

It may be concluded, therefore, that the Pliensbachian cyclicity of Britain was produced by localised tectonic uplift along the axis of the North Atlantic Rift, resulting in the erosion of sourcelands, (probably horsts) and infilling of adjacent subsiding basins within the system. This setting contrasted to patterns of sea level change and sedimentation elsewhere in the world, including areas peripheral to the rift, such as central Europe. Within the upward-coarsening pattern of sedimentation occurring across the whole of Britain, individual basins possessed their own rates of subsidence and basin infill. This led to local variations in ammonite zone thicknesses and the numbers of cyclothems present.

3.0 Nature and origins of the ferruginous grains

3.1 Temporal variations

In the description of the temporal changes in the facies succession of the MRBF in Chapter 5, it was shown that with the progressive upwards coarsening of the formation, notable changes occurred in the ferruginous grains. This involved a transition from chamositic peloids and flakes in the oldest facies, through the appearance of superficial ooids and true ooids in the facies above, to a dominance of true ooids in the youngest facies. This transition was accompanied by an increase in the size of the ferruginous grains, although erosion also increased and the whole grains became increasingly accompanied by comminuted grains. Spastoliths, of most grain types, were shown to be present in most facies. All other sedimentological evidence indicated that upward shallowing occurred during the deposition of the formation.

Limonitisation of the chamosite grains occurred in a number of ways. The nuclei of the ooids alone may be affected, alternating laminae may be changed, or the whole grain might be altered. Nuclei are predominantly chamositic peloids and flakes except in Facies V, where they are replaced by bioclasts and siltstone. The ferruginous grains are very well sorted and show an upward change from subrounded to very well rounded. They always exhibit low sphericity, and it is of interest to note that the accompanying bioclastic sand grains in the sediment also possess this form. Examples of the changes in the ferruginous grains corresponding to the facies succession are shown in Figs. 23-25. Partial replacement of grains by calcite is a common feature but is only occasionally shown.

These figures illustrate a number of points. The spastoliths clearly show that the chamosite grains were sometimes soft upon burial, and were distorted on compaction to accomodate more rigid grains, such as bioclasts and quartz. Others are not distorted, however, and must have been hard and resistant. The occurrence of limonitised nuclei in many grains indicate oxidisation before the laminae of chamosite were deposited. Many of the ooids reflect the shapes of their nuclei, although with progressive addition of more laminae, all ooids became ellipsoidal. Abrasion of flakes giving smoothed outlines and truncated laminae at their margins, as well as broken ooids with angular and rounded outlines, indicate active currents. It is concluded that with progressive shallowing and the increase in current activity, chamosite peloids and flakes together with other nuclei, developed laminae to become progressively larger grains forming firstly superficial ooids, and finally true ooids.

3.2 Formation of chamosite and modern occurrences

The origin of chamosite and its formation into grains remains a subject of controversy and debate to the present day. 'Chamosite' is here referred to as a collective term for a group of clay minerals including berthierine, a 7 Å trioctahedral serpentine, and chamosite, a 14 Å trioctahedral chlorite (Van Houten and Purucker 1984:214, 215). Berthierine is common in post-Palaeozoic ironstones. The chamosite group is only stable in conditions of negative Eh, and will alter to limonite if ambient conditions adjust to a positive Eh. In these former conditions, siderite will also form, often as an early diagenetic rhombic cement replacing various grains and formed from Fe^{2+} and CO_2 in the sediment porewaters.

Most types of ferruginous grains have been recorded in modern sediments. Although chamosite flakes have not been found, peloids, thought to be of faecal origin, are known from the marginal offshore waters of the Niger, Ogooué and Orinoco deltas, with rare goethite superficial ooids found near the coast (Porrenga 1967, Giresse 1969). Further occurrences of superficial or 'proto' ooids have been recorded off the Mahakam delta, Kalimantan (Borneo), by Allen et al (1979), and in Loch Etive, Scotland by Rohrlich et al (1969). Limonite ooids and pisoliths have been recorded by Siehl and Thien (1987) in lateritic soils formed as microconcretions during groundwater movements and leaching. These were also found in adjacent fluvial deposits derived from erosion of the soils.

The pre-concentration of iron required to form Phanerozoic 'minette' ironstones is widely believed to have occurred during tropical weathering in lateritic soils. Subsequently, the iron was transported by rivers (and possibly sometimes groundwater), in a soluble ferrous form, or in the ferric form either in organic colloids or adsorbed on clay micelles. Precipitation or flocculation occurred on entering the sea. These waters were well oxygenated, but chamosite formation would have been possible in the poorly-oxygenated zone a metre or so below the sea bed (Hallam 1975). In this environment, chamosite mud and flakes may have formed, and peloids accumulated. It has been suggested that the chamosite may have formed by Fe combining with kaolinite (Howard 1984:226). It is also possible that the chamosite in the peloids formed in a reducing micro environment within the guts of marine invertebrates (Howard 1984:225).

3.3 The origin of the ferruginous ooids

The origin of the superficial and true ooids remains a subject of much debate. Although some ferruginous ooids are similar in form to calcareous ooids, with their concentric laminae and spherical structure, many possess laminae which thicken on their 'equatorial' zone and pinch out over their 'poles', producing the characteristic discoidal appearance. Examination of the laminae (Wright 1977, Corbin 1980) shows that they are mostly composed of tangentially-arranged crystals. The equatorial bulge of the laminae is thought to be caused by preferential accretion there of the crystals. Van Houten and Purucker (1984) believe this to be a result of mechanical accretion of gelatinous crystals on the sea floor. Corbin (1980), however, suggested that the nuclei may not be in motion, but rather that crystals could have adhered to their equatorial zones by horizontally moving currents. Since in this oxygenating environment the chamosite would be unstable, it is difficult to see how such a mechanism could take place. Possibly, the seawater, at least close to the seabed, occasionally became anoxic such as if a large input of decaying organic material was introduced off the land.

Siehl and Thien (1987) suggested that some oolitic iron-stones could have been produced by winnowing and selective transportation of lateritic ooids which were subsequently carried into the marine environment. The possibility of alteration of originally calcareous ooids, suggested by Kimberley (1974, 1979, 1980, 1983) is now no longer supported by that author (D. Bhattacharyya, pers. comm. 1987). Champetier <u>et al</u> (1987) have suggested that some discoidal chamositic ooids are the altered tests of Nubecularid foraminifera, although the evidence for this is not convincing (M. Hart, pers. comm. 1987).

A role for algae in the formation of ferruginous ooids is at present unknown, but blue-green algae were shown by Shterenberg et al (1968) to have been present during the formation of chamositic micro concretions in Lake Punnis-Harvi. In the Ordovician ironstones of North Wales, Trythall (1987) recorded chamositic oncolites. This chamosite could be primary, but it may be a replacement of calcareous oncolites; similar alteration has been recorded for bioclasts such as gastropods by A. Kearsley (pers. comm. 1987). The ooids described by Champetier et al (1987) have been likened to the much larger limonite concretions or 'snuff-boxes' of the Middle Jurassic in Dorset and Somerset (M. Hart pers. comm. 1987). The snuff-boxes were thought to have formed, at least in part, by algae (Gatrall et al 1972).

3.4 Conclusions

If the MRBF and DSF ferruginous grains are considered in the light of the above discussion, a number of conclusions can be drawn:-

(a) The chamosite mud and flakes are likely to have formed in a reducing environment by the combination of ferrous iron and/or ferric particles with kaolinite clay a short distance below the sediment/water interface.

(b) The mud (and sometimes flakes) were absorbed by sediment-feeding invertebrates and converted to faecal pellets. Some of the chamosite pellets could have formed by direct intake of clay and iron by filter feeders which produced the chamosite in reducing micro environments within their guts.

(c) The grains were initially soft and some were distorted by compaction.

(d) Thorough bioturbation carried some of the grains up into the oxidising zone where they were converted to limonite. Further bioturbation returned some into the reducing environment.

(e) In the MRBF, as progressive shallowing occurred, and higher energy conditions became more dominant, chamosite laminae were deposited with increasing frequency around various nuclei. Oxidation and abrasion of the grains also increased.

(f) The chamosite laminae may have formed by mechanical accretion on the sea floor during temporary periods of anoxicity produced by influxes of decaying organic material off the land. Alternatively, they may have been produced by algal accretion. This suggestion is perhaps more applicable to certain grains seen in the MRBF, e.g. the composite grains on Fig. 25; one of these appears more akin to the oncolith shown above, and the other seems unlikely to have formed by mechanical accretion during rolling.

4.0 The origin of the iron-rich sediments

This section is based on Chidlaw (1987b).

In the Jurassic strata of Britain, ironstones have a wide distribution, occurring largely in the Liassic strata of the Midlands and NE England. Important ironstone ores (Zitzmann 1978) are present in the Lower Lias at Frodingham, and in the Middle Lias at Banbury, Grantham and the Cleveland Hills; in the Middle and Upper Jurassic they are fewer in number, occurring at Northampton and at

Westbury, Wiltshire, respectively. Elsewhere, notably in the Cotswolds and in Wessex, ironstones are virtually absent. The term 'ironstone' is generally applied to rocks with 15% or over Fe content. In the present study, no values of over 14% were recorded and the range 5%-15% is referred to as 'iron-rich'. Some analyses of these sediments in the Bath area (Moore 1867:128), however, indicate that Fe contents of up to 30% may be present locally.

4.1 Ironstone models

A characteristic of most ironstones is their marked lack of coarse siliciclastics, and the 'clastic trap' hypothesis of Huber and Garrels (1953) has often been used to explain this feature. An assumption was made that large quantities of coarse as well as fine siliciclastic material would be transported simultaneously with the iron from its source area, so that some mechanism was in operation which concentrated the iron, separating it from the other material. A subsiding basin between the source area and the basin of accummulation was invoked, in which clastics were deposited while fines and iron were carried into the next basin.

Brookfield (1971) suggested that oolitic ironstones could have been concentrated by mechanical separation of the ooids and siliciclastic sand, without recourse to a clastic trap. Ironstones are often associated with marine regressions, and lie at the top of siliciclastic coarsening/shallowing upwards (shales to sandstone) cycles

(Hallam and Bradshaw 1979). This shallowing would have been accompanied by increased hydrodynamic energy leading to the formation of sand bars, which would allow areas free of siliciclastics, in which oolitic ironstones could form.

4.2 Problems with ironstone models

Some ironstones are stratigraphically condensed in relation to their lateral siliciclastic equivalents (Hallam and Bradshaw 1979:161); this supports Huber and Garrels' 'clastic trap' hypothesis. However, Brookfield (1971:138) pointed out that the inshore sandy sediments are often thinner than the ironstones themselves. Additionally, the Banbury and Northampton Sand Ironstones are thicker than their lateral sandy equivalents (Hallam and Bradshaw 1979: 161). Knox (1971:544) showed that a clastic trap may not be necessary in areas of low relief, because transgressions would cause the extensive flooding of land areas leading to a marked reduction in the input of siliciclastics required to allow ironstones to form. Brookfields' mechanical separation model was shown to be inapplicable by Knox (1971). Hallam and Bradshaw's (1979) coarsening upwards association does not apply to the Frodingham and Raasay (Toarcian, W Scotland) ironstones, which are underlain by mudrocks.

In the Pliensbachian of the Cotswolds, the clastic trap hypothesis is applicable to the DSF, at a time when the various graben acted as siliciclastic sinks allowing the fines and the iron to accumulate on the horsts and platforms as ferruginous oolites. In the MRBF, however, this does not apply, as the iron rich sediments are as thick as the adjacent siliciclastics. The eustatic regression at the Pliensbachian/Toarcian boundary (Hallam 1978) is well represented in the Cotswolds, where it is a good example of Hallam and Bradshaw's (1979) upward coarsening/regression association. Within the cyclothems of the DSF and MRBF, the upward increase in iron minerals also conforms to this model. However, the ferruginous oolites at locality 15 on Fig. 57 do not show this association. Clearly, therefore, existing models are inadequate to explain the presence of ironstones generally in Britain, and the presence of iron-rich sediments in the Pliensbachian of the Cotswolds.

4·3 A model for the iron-rich sediments

Figures 63 and 64 show values for $CaCO_3$, Fe, and non-carbonate sand, silt and clay. The facies of the MRBF and the lithologies of the DSF are ranked according to their siliciclastic and carbonate contents. These figures show a clear relationship between the iron-rich, siliciclastic and carbonate sediments. In the MRBF, the highest Fe contents occur in Facies IV, where $CaCO_3$ contents lie at about 58%. As $CaCO_3$ contents decrease in Facies I and increase in Facies II, Fe contents decline. The lowest Fe contents occur in Facies III and V, and correspond to the highest $CaCO_3$ values. In relation to sand, Fe contents are low where sand contents are highest in Facies I, and highest where sand is about 20% in Facies IV. Both Fe and sand contents decline in the remaining facies. A similar

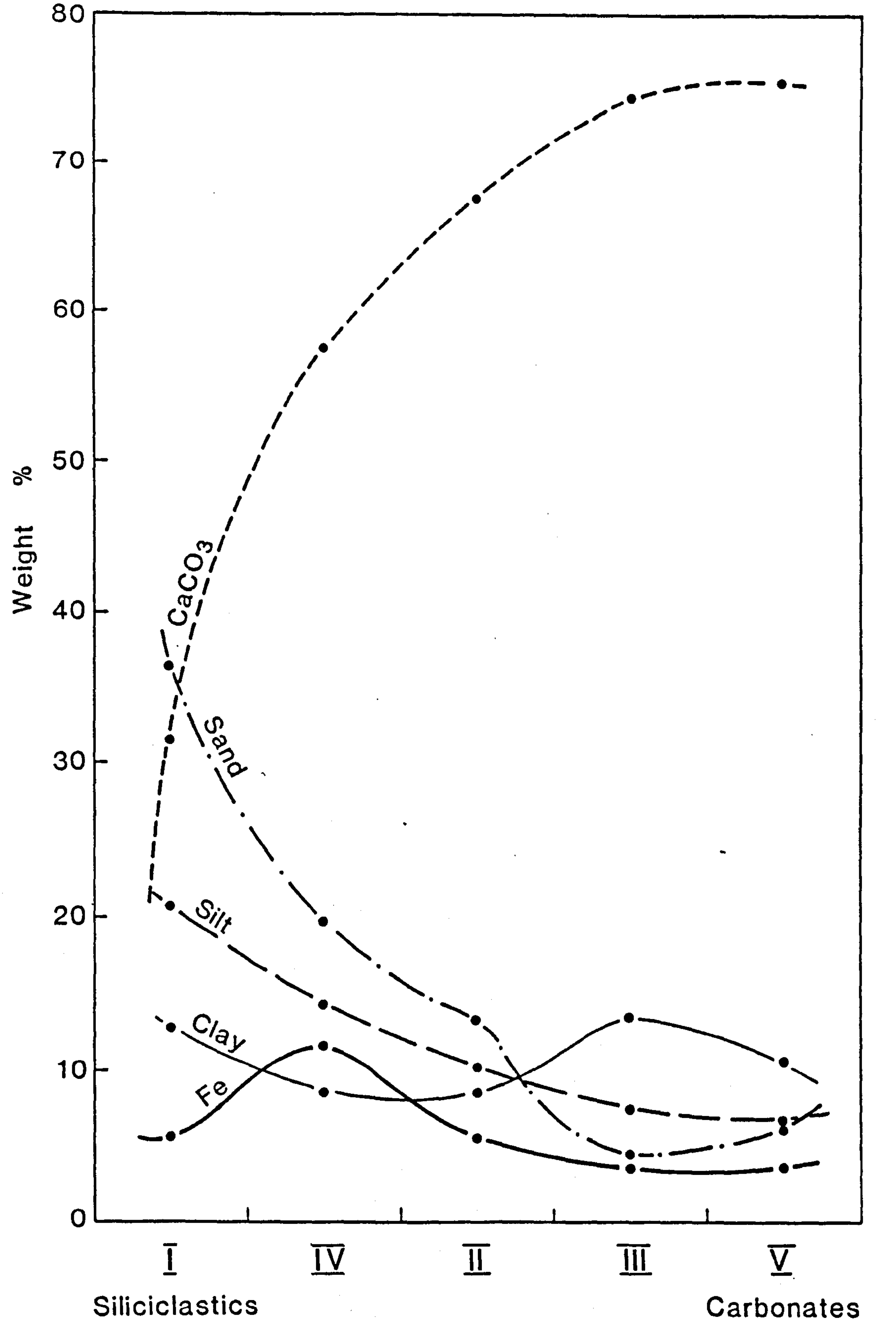
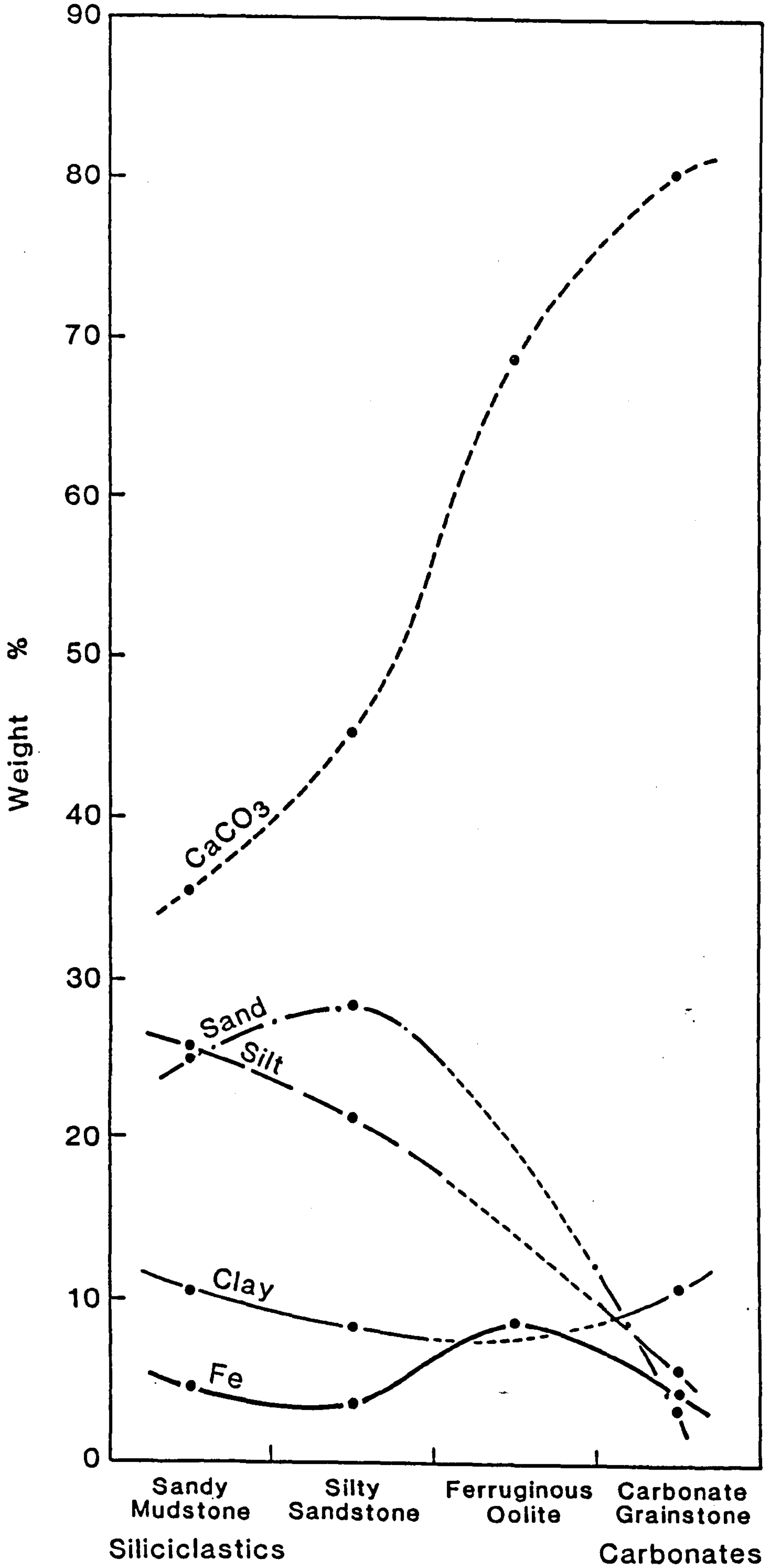


Fig. 63. Mean values for various characteristics in the MRBF facies.

Fig. 64. Mean values for various characteristics in the Lithologies of the DSF.



relationship is noticeable between Fe and silt. There is a clear inverse relationship between Fe and clay content. Similar overall patterns are noticeable in the DSF lithologies of Fig. 64.

The curves on Figures 63 and 64 show that the most ferruginous sediments in the MRBF and DSF occur where carbonate and siliciclastic sediments were being deposited in roughly equal proportions. This process is illustrated on Fig. 65. A siliciclastic-free marine shelf environment is envisaged, where carbonate was produced without restriction (Fig. 65a). Siliciclastic sediment, carrying iron, was introduced, blocking and replacing the carbonate production. At this point, siliciclastics only were deposited (Fig. 65b). At the leading edge of siliciclastic dispersal in the basin, however, iron accumulated as only fines were being deposited. Some of the iron combined with kaolinite to form chamosite, causing the depletion of clay shown on Fig. 63. Also at this point, the waning of the siliciclastic input allowed an increase in carbonate production allowing the iron to form siderite. Further away from the leading edge of the siliciclastics, carbonate production increased, iron became progressively less concentrated, and clay contents correspondingly recovered as less was taken up to form chamosite. The area of iron-rich sedimentation therefore passed into one of limestone formation (Fig. 65c). This model may be applied to any of the iron-rich sediments examined in the present study, whether found on the horsts, in the graben or on the platforms, and whether associated with coarsening upwards

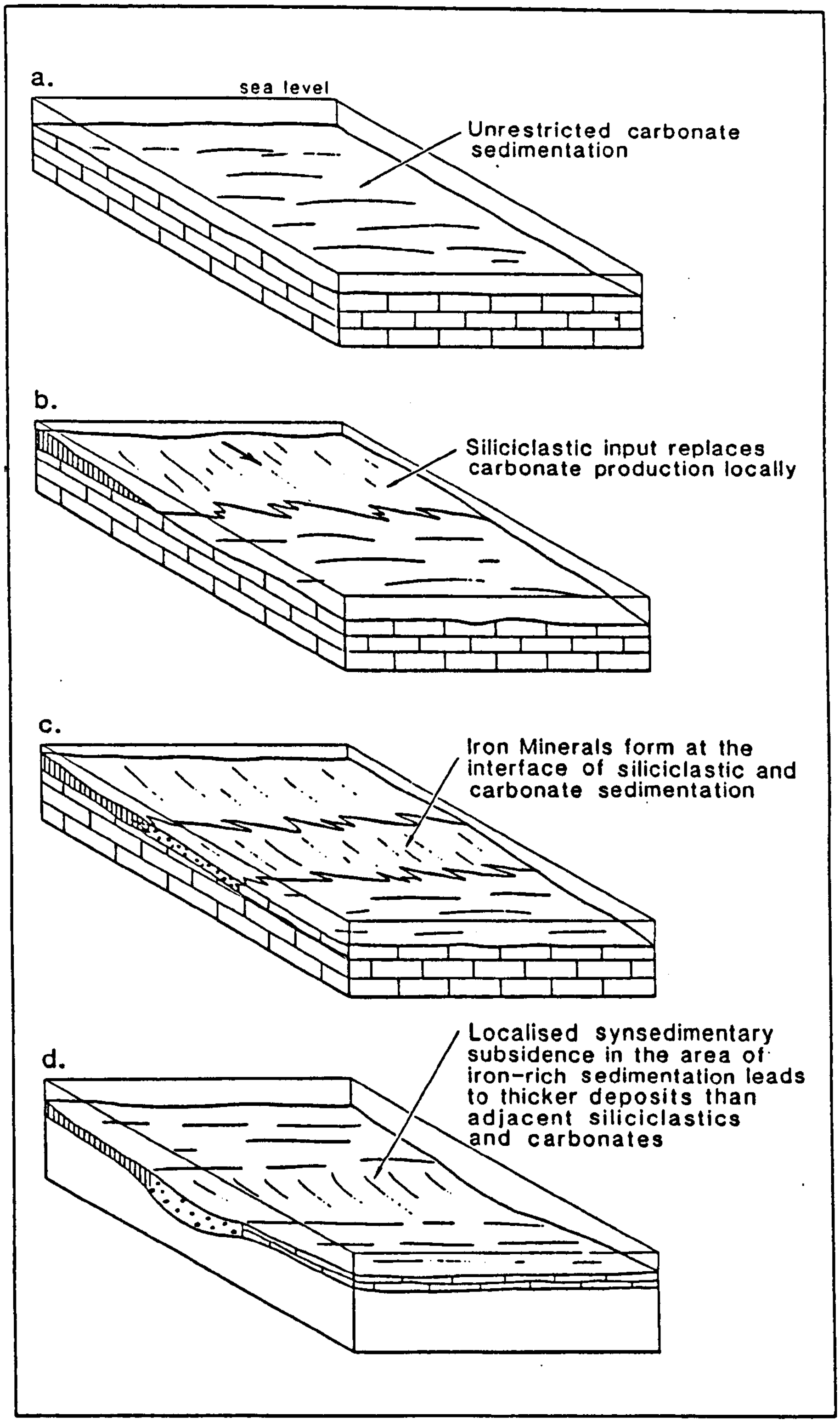


Fig. 65. Model proposed for the origin of iron-rich sediments in the Pliensbachian of the Cotswold Hills.

cyclothems or mudrocks only. Provided that the siliciclastic/iron and carbonate sedimentation boundary is maintained, localised subsidence could conceivably produce thicker units of iron-rich sediment than adjacent siliciclastics or carbonates (Fig. 65d).

4.4 The scarcity of true ironstones

An important difference between ironstones and the iron-rich sediments examined in the present study, is the higher content of siliciclastic sand and silt in the latter. This higher content of siliciclastics diluted the concentrations of iron and clay and restricted carbonate production, all of which are necessary for the concentrated production of iron minerals. Additionally, the deposition of the MRBF was characterised by rapid changes from siliciclastic-rich to carbonate-rich sedimentation, reducing the opportunity for the maintainance of the facies interface. Post depositional replacement of chamosite by calcite is frequently noticeable in the ferruginous oolites of the DSF, and has caused mean $CaCO_3$ values to be higher and mean Fe values to be lower on Fig. 64 than they would originally have been.

On the London Platform, where the Banbury and Grantham Ironstones of similar age to the MRBF of the Cotswolds were deposited, coarser siliciclastics accumulated only locally. This suggests that large parts of the platform, considered to have been land during much of the Jurassic (Hallam and Sellwood 1976) had low relief and iron was probably concentrated in laterites and carried into adjacent marine areas along with only small quantities of fine detritus. There is therefore no need for recourse to nearshore clastic traps. Conditions were therefore suitable for the concentration of iron minerals and with the continuation of this regime, substantial deposits were formed.

The Cotswold area, which lay within an active rift basin, was one of rapid sedimentological change, and did not match the more stable conditions required for the formation of ironstones. This may account for the lack of ironstones in the rift basins to the S of the Variscan front, which were active at this time.

5.0 Discussion of the tectonic and sedimentary model for the Pliensbachian of the Cotswolds.

5.1 Sellwood and Jenkyns' (1975) model

Sellwood and Jenkyns' (1975) model was proposed to explain the cyclic nature of the Pliensbachian-Bajocian sequence of Great Britain, in the context of Hallam's (1958) concept of Jurassic 'Basins and Swells'. The essentials of this model included the recognition of a repeated sequence of clays, sandstones, limestones and ironstones; the clays and sandstones were seen to be stratigraphically expanded and the limestones and ironstones stratigraphically condensed. The upward change in lithologies was also accompanied by an upward increase in more diverse forms of infaunal and epifaunal suspension feeders, and the appearance of wave-induced cross-lamination in the sandstones and ironstones. The faunal assemblage was taken to indicate a shallow neritic environment. The sequence was interpreted as an indication of upward shallowing, by analogy with the relationships between grain size of sediments and bathymetry in the modern Celtic and Tyrrhenian seas.

Hallam's (1958) concept of basins and swells was formulated to explain stratigraphically expanded and condensed sequences of the British Jurassic. Sellwood and Jenkyns critically examined this interpretation, and it was shown that the cyclic pattern occurred in both the expanded and condensed sequences. The lack of slumping and turbidites at all localities examined in the model (except in the Mochras Borehole, W Wales), was considered to indicate that the transition of swells to basins involved only slight topographic variation. Localised intermittent stabilisation of the subsiding basement (the pre-Permian floor), and subsequent sediment infilling, was invoked to produce the coarsening upwards cycles. This localised stabilisation was taken to indicate synsedimentary movement along basement faults. Less frequently, widespread uniform subsidence was believed to have occurred. On the temporarily-stabilised areas, erosion surfaces and hardgrounds were formed and ironstones deposited, as sedimentation built up into the zone where erosion checked further deposition.

The model was based on an analysis of a number of widespread, isolated localities across Britain; basin areas were exemplified by sequences such as on the Dorset coast and in the Stowell Park borehole, and swells by sections in the Mendip and Market Weighton areas. Block faulting, suggested as the major control on Triassic sedimentation of Britain by Audley-Charles (1970), was considered to have continued into the Jurassic. Supporting evidence was given from steep gravity gradients on the N and S sides of the Mendips, and the presence there of Liassic neptunian dykes. It was stated, however, that the Peak Fault on the Yorkshire coast was the only fracture zone in the onshore area of Britain which could be directly shown to have moved in Early Jurassic times.

The zone of crustal extension was continuous across other parts of Europe, as determined from oil exploration work in the North Sea, and studies in the Baltic and the Alps. The possibility that eustatic controls had been influential in the formation of the cyclicity was regarded as slight; there was then 'no convincing evidence for major synchronous phases of shallowing or deepening that can be recognised on a world scale' (Sellwood and Jenkyns 1975: 384).

5.2 Criticism of Sellwood and Jenkyns' model

The model was criticised by Hudson (1976) on the grounds that there was little evidence for the faulting required to mark the boundaries of basins and swells in S England. Hudson did consider, nevertheless, that it was the most likely explanation for the sedimentological and statigraphic patterns, particularly in the light of evidence from the North Sea. A major drawback of the model was the employment of the few isolated and scattered sequences, from which the authors attempted to invoke a spatial image of fault-controlled basins and swells. Supporting evidence such as isopachyte and facies maps of stratigraphical units, preferably concentrated on individual basins, would have provided a much firmer ground for their argument. By producing such maps as far as is possible with available data, and establishing detailed correlation on a local basis, the model can be rigorously tested.

5.3 Testing of Sellwood and Jenkyns' model

Like all good models, this one is amenable to rigorous testing. The present study has attempted this in two ways. The temporal basis was examined for two formations deposited during the stratigraphical range discussed in their model. Secondly, a spatial approach was adopted by taking a discrete, well-studied sedimentary basin in which known basement structures could be examined for synsedimentary activity. Clearly the evidence given in the present work, and summarised below, is strongly supportive of the Sellwood and Jenkyns model.

Hudson's (1976) criticism has now been largely met by more recent research, but even at that time evidence was available for intra-Liassic faulting, at least in the Severn Basin, in the Stroud area and along the Vale of Moreton Anticline. Sellwood and Jenkyns' suggestion that eustatic changes had had little effect on the deposition of the Pliensbachian cycles, however, is supported by the evidence given in this chapter section 2.0. Their suggestion that basement faulting was the major controlling factor behind the cyclicity of the Pliensbachian-Bajocian sequence in Britain as a whole, however, is not supported by existing evidence from elsewhere. In the Cleveland Basin, for example, the lack of significant lateral changes in thickness in the Pliensbachian zones and cycles (Howard 1985) over tens of kilometres, suggests a broader crustal downwarping. Furthermore, Rawson et al. (1983) suggested that these cycles may not just reflect tectonically-controlled subsidence, and uplift of sourcelands, but also climatic variations. This could influence the rate of run-off on nearby land areas. Climatic influences could also be applied to the Pliensbachian cycles in other parts of Britain, including the Cotswolds, but the evidence, as shown in the present study, suggests a dominantly tectonic control.

Ultimately, the best suggestions for all instances in the Pliensbachian of Britain, will be obtained only through detailed regional investigations of the sort provided in the present study.

6.0 Summary of the tectonic and sedimentary model for the Pliensbachian of the Cotswolds.

6.1 Anticlinal structures in the Severn Basin indicate the position of N-S trending normal faults and horst blocks in the pre-Permian basement.

6.2 Synclinal structures indicate N-S trending graben and half graben blocks in this basement.

6.3 The fold structures are 'supratenuous' or 'drape' folds produced by differential subsidence in the block-faulted basement.

6.4 The MRBF and DSF characteristically thin over the anticlines and thicken in the synclines, features that are a result of differential subsidence. Changes in thickness may be sudden across the basement faults. These patterns are supported by the bio-stratigraphical evidence.

6.5 Changes in facies show a clear correlation with changes in thickness of lithostratigraphic and bio-stratigraphic units.

6.6 Periodic movement along the basement faults during the Pliensbachian caused rapid or sometimes subdued pulsed subsidence of the graben floors. During intervening episodes of temporary crustal stability, sedimentary infillings led to the development of coarsening upward cyclothems. These cyclothems characteristically show upward changes from siliciclastic to carbonate and ferruginous sedimentation, accompanied by flat to cross-laminations, increased bioturbation and increases in diversity, size and destruction of shelly fauna. These patterns also occur on the larger 'Mesothem' scale of the two formations combined.

6.7 The cyclothems show a progressive upward thinning, indicating that subsidence slowed down towards the end of the Pliensbachian. This is supported by the bio-stratigraphical evidence.

6.8 The areas of least subsidence were most strongly affected by periods of erosion. These included the Avon and London Platforms marginal to the Severn Basin. However, synchronous erosional episodes occured at times across the whole of the basin and adjacent platforms. These are often marked by thin conglomerates of pebble to boulder size range, and ferruginous concretions. The conglomerate clasts were sometimes bored indicating hardground conditions. The most potent of these erosive episodes occurred at the Pliensbachian-Toarcian boundary, where several ammonite subzones have not been proved and are likely to have been removed and/or were never deposited. This indicates a considerable hiatus before the deposition of the Upper Lias commenced.

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APPENDIX 1

MRBF Localities in the Cotswolds from the Literature

Locality	Grid Reference	Present state of exposure and comments	Reference
Dundry, Avon			
Well containing 0·3m of MRBF.	None given. Well 300 yards SSW of church.		Donovan (1958:131)
East Dundry, Avon			
Exposure on slope below Watercress Farm.	From map (p.715) exposure approx. at (ST 5705 6612)	Not visited	Buckman and Wilson (1896:705)
East Dundry, Avon			
Spring Farm. Exposure in bank of rick-yard.	Farm is at (ST 5737 6620)	Not visited	Buckman and Wilson (1896:683)
Whitchurch, Avon			
Tumbled blocks on hill-side above Hill Farm. MRBF 0·43m thick.	From map (p.715) approx. at (ST 5925 6692), (ST 5908 6682). Isolated block also at (ST 5775 6718).	Not visited	Buckman and Wilson (1896:683)
Whitchurch, Avon			
Exposure above Hill Farm. 0·61m thick.	From map (p.715) approx. at (ST 5900 6673)	Not visited	Buckman and Wilson (1896:683)

Locality	Grid Reference	Present state of exposure and comments	Reference
Whitchurch, Avon			
Slightly shifted blocks above Hill Farm. MRBF 0·84m thick.	From map (p.715) approx. at (ST 5949 6687)	Not visited	Buckman and Wilson (1896:683)
Norton Malreward, Avon			
Immediately W of corner of spinney SW of Maes Knoll Tump. Also slipped blocks along S side of spinney. 0·86m exposed.	From map (p.715) approx. at (ST 5973 6618). Also isolated block at (ST 5955 6620)	Good exposure of rotated blocks. Lichen covered but rock fresh inside.	Buckman and Wilson (1896:705)
Norton Malreward, Avon			
Section on slopes of Maes Knoll, 70 yards E of spinney below the Tump. MRBF 0·84m thick, and *in situ.*	Approx. at (ST 6035 6617)	Not visited	Buckman and Wilson (1896:684)
Limpley Stoke, Avon			
"Opposite Dundas". Section in Middle and Upper Lias and Inferior Oolite. 0·30m of "Marlstone".	No details. Dundas Aquaduct is at (ST 785 625)	Woodward (1893:210) stated section obscured. Thought that "Marlstone" was basal Upper Lias age.	Moore (1867:153)
Upton Cheyney, Avon			
Section in Oaks Lane (?) MRBF 0·30m thick.	No details. Possibly at (ST 6902 6070)	Not visited	Moore (1867:152)

Locality	Grid Reference	Present state of exposure and comments	Reference
Bitton, Avon			
MRBF Fully exposed (0·94m) in base of sand pit in 1950-1952.	(ST 679 702)	Not visited	Fry (1970)
Horton, Avon			
Narrow plateau with MRBF field brash.	229m S of Upper Widdenhall Farm to 183m NNW of the farm.	Numerous fragments seen e.g. at (ST 7618 8417)	Cave (1977:90)
Hawkesbury, Avon			
Plateau with MRBF field brash.	366m SW of Hawkesbury church.	Some fragments found along hedge at (ST 7760 8672)	Cave (1977:90)
Hillesley, Avon			
0·9m exposed.	558m SE of Hillsley Mill.	Site approx. at (SP 773 901) but no exposures or brash found.	Cave (1977:90)
Wortley, Glos.			
Excavations 2·4m exposed.	(ST 7728 9146)	Cites Donovan's observations. Excavation probably for pumping station when built. No exposures now.	Cave (1977:90)

Locality	Grid Reference	Present state of exposure and comments	Reference
Wotton-under-Edge, Glos.			
Side of Nind Lane E of Leys Farm 0·9m seen.	No grid reference. 366m E of Leys Farm.	Approx. at (ST 761 922) Bank seen in laneside but no exposure or brash today.	Cave (1977:90)
Wotton-under-Edge, Glos.			
Potter's Pond area. Road cutting. 5·03m exposed. (Full thickness seen).	(ST 762 933)	Completely grassed over.	Cave (1977:90)
Southend, Glos.			
Road cutting in the MRBF Southend-Hawley Road.	Approx. (ST 742 948)	Erroneous. Road too low topographically to section the MRBF.	Anderson (1983: 264)
Southend, Glos.			
Old quarries, At least 3m exposed.	(ST 743 953)	No exposure or suggestion of previous quarry. Probably erroneous location.	Cave (1977:91)
North Nibley, Glos.			
Quarry near Northfield House. Up to 2·1m exposed. Rubbly and broken.	(ST 7392 9617)	No exposure or indication of a quarry here previously.	Cave (1977:91)

Locality	Grid Reference	Present state of exposure and comments	Reference
North Nibley, Glos.			
Hunt's Court Farm. Up to 2·1m exposed. Often rubbly and broken.	(ST 7415 9624)	Completely obscured. Slight uneven ground with brash. Farmer states covered up pre-1968.	Cave (1977:91)
Stancombe, Glos.			
Old quarry in Stancombe Park. 3m exposed.	(ST 7387 9752)	Very good exposure but deeply frost shattered. Rock still fresh 2·34m exposed.	Cave (1977:91)
Stinchcombe, Glos.			
Old quarry W of Street Farm. 3m exposed.	(ST 7317 9900)	Mostly overgrown. Small craggy exposures in a series of terraces.	Cave (1977:91)
The Quarry, Glos.			
Newnham Quarry. 6·1m (max) exposed.	(ST 7346 9950)	General area of quarrying now moderately exposed. Very good re-excavation in part of the quarry. (Nature Conservancy Council Nov. 1982). 4·47m max now exposed.	Moore (1867:146) Witchell (1882:18) Woodward (1893:215) Ager (1956a:358) Hallam (1967:409) Cave (1977:91,92)

Locality	Grid Reference	Present state of exposure and comments	Reference
Upper Cam, Glos.			
Small quarry at Downhouse Farm. 2·1m exposed.	(ST 7639 9916)	Good exposure, but weathered and crumbly. About 2·0m now exposed.	Cave (1977:92)
Uley, Glos.			
Old quarry near Coldharbour Farm. Up to 1·8m exposed.	(ST 7702 9844)	Very overgrown and weathered. About 1·0m now exposed.	Cave (1977:92)
Uley, Glos.			
Road cutting at Marsh Farm 2·4m exposed.	(ST 7850 9793)	Completely grassed over. Loose fragments in face collected at (ST 7853 9795).	Cave (1977:92)
Coaley, Glos.			
"Far Green Stream". Exposure in deeply incised stream.		Stream locally called 'The Delkin'. No section in the MRBF here, but much brash in stream bed at (ST 7814 9960)	Phelps 1982 (Fig. A:2:6:2)
Frocester, Glos.			
Hill side sections on Frocester Hill. MRBF 2' (0·61m) Full thickness.	No details	No exposures of MRBF seen. Some loose fragments collected at (SO 7925 0188)	Moore (1867:147)

Locality	Grid Reference	Present state of exposure and comments	Reference
Rodborough, Glos.			
Brickpit on Dudbridge-Lightpill Road. Also Lightpill see Richardson 1910(b):248.	No details	Old working at (SO 8391 0444) Very overgrown.	Witchell (1882:17) Richardson (1910b: 250) OS Sheet SO80 1:25 000
Rodborough, Glos.			
Brickpit at back of Dudbridge Mills. 3·3m exposed.	No details	Brick site extensive. Now occupied by variety of uses. Poor exposures and brash in rotationally sheared abandoned railway cutting at (SO 8400 0473). True MRBF thickness considered 0·91m.	Witchell (1882:16, 17) Richardson (1910b: 249)
Stonehouse, Glos.			
Samuel Jeffries' Brickpit. Badly slumped in Palmer's visit.	(SO 816 050)	Not visited	Richardson (1910b: 254) Ager (1956a:360) Palmer (1971:58)
Pitchcombe, Glos.			
Exposure at Rock Mill.	Mill is at (SO 8480 0680)	No exposure visible	Richardson (1904a: 51)

NB Other sections by Richardson in the Painswick area see 1904(a):51-52. Not visited in recent study.

Locality	Grid Reference	Present state of exposure and comments	Reference
Stonehouse, Glos.			
Stonehouse Brickpit. Full thickness of MRBF considered seen. (2·90m)	(SO 8103 0537)	Very good. No scree or vegetation.	Richardson (1910b) Ager (1956a) Palmer (1971) Phelps (1982)
Tuffley, Glos.			
Robinswood Hill. Tuffley Brickpit. Full thickness of MRBF seen (5·6m)	(SO 8359 1495)	Very good. Little scree or vegetation.	Richardson (1904a: 47) Richardson (1910b: 258) Watts (1928:139) Ager (1956a:364) Palmer (1971) Phelps (1982)
Prinknash, Glos.			
Deep road cutting.	None given	Not visited	Richardson (1904(a) :50)
Churchdown, Glos.			
Churchdown Hill. Quarries on flat summit of hill in boundary beds of Middle and Upper Lias.	None Given	Hilltop now reland-scaped with three large resevoirs. Two small mounds of MRBF left (BGS Sheet 234) But no brash or exposures found.	Murchison (1845:38) Smithe (1865, 1877, 1895) Dreghorn (1967ch.8) BGS Sheet 234 1:50 000

Locality	Grid Reference	Present state of exposure and comments	Reference
Charlton Kings, Glos.			
Lilley Brook Golf Club. Flat short platform at 160m OD immediately W of Lilley Grove.	(SO 9623 1908)	W side of Grove contains spoil heaps with large slab of MRBF and oolite rubble.	Dreghorn (1967 Fig. 63)
Charlton Kings, Glos.			
Timbercoombe. Sunken lane near Lilleybrook Hotel.	None given	Site approx. at (SO 9712 1932) Totally obscured.	Richardson (1929: 25)
Charlton Kings, Glos.			
Ham. Small exposure in the lane.	None given	No exposure found. Erroneous location (see Appendix 5)	Richardson (1929: 25)
Battledown, Cheltenham			
Glenfall House. Waterfall on MRBF.	None given	Waterfall is at (SO 9790 2187) Erroneous designation (see Appendix 5)	Richardson (1904a: 51)
Southam, Glos.			
NW corner of Stutfield Wood. MRBF exposed on a Knoll.	None given	DSF exposures approx. at (SO 9787 2518). Extensive rotational shear and camber in the area. Erroneous designation.	Richardson (1904a: 51)

Locality	Grid Reference	Present state of exposure and comments	Reference
Gretton, Glos.			
"Stanley Hill". Section in boundary beds of Middle and Upper Lias. MRBF 3'6" (1·07m) Full thickness.	No details	Cups Hill Quarry in present study. Extensive old workings now largely overgrown. Small MRBF section noted at (SP 0109 2960)	Moore (1867:148) Smithe and Lucy (1892:209) Richardson (1929: 25)
Wood Stanway, Glos.			
Knoll E of Wood Stanway. Exposures in road from village.	No details	No exposures visible but large slab of DSF found on trackside at (SP 0663 3018)	Richardson (1904a: 51)
Oxenton, Glos.			
Oxenton Hill. Small track-side exposures at Puckle-church Brake. 0·55m full thickness of the MRBF.	(SO 9634 3145)	Now obscured	M. Simms (pers. comm.)
Dixton, Glos.			
Oxenton Hill. "Indifferent exposure a little to the SW of Dixton Wood".	None given	No exposure found. Fragments collected from root of upturned tree at (SO 9787 3633)	Richardson (1904a: 48)

Locality	Grid Reference	Present state of exposure and comments	Reference
Dixton, Glos.			
Dixton Hill.	No details	Hill is at (SO 986 306). Cambered blocks at (SO 9860 3061) and (SO 9861 3070).	Richardson (1904a: 49)
Great Comberton, Worcs.			
Old workings on N side of Bredon Hill above Woollas Hall. Few inches exposed to Williams and Whittaker.	(SO 9518 4061)	Not visited	Richardson (1904a: 49) Richardson (1905: 66) Williams and Whittaker (1974:43)
Great Comberton, Worcs.			
N side of Bredon Hill at Batten's Wood. Several feet exposed in steep cliff-like section.	(SO 9561 4087)	Batten's Wood located on series of very large rotational shear planes. Very good exposure in MRBF on landslip scar at top of Wood. 2·83m seen.	Williams and Whittaker (1974:43)
Great Comberton, Worcs.			
N side of Bredon Hill at Even Hill. Brash on surface of MRBF platform.	(SO 9677 4109)	Not visited	Williams and Whittaker (1974:43)

Locality	Grid Reference	Present state of exposure and comments	Reference
Great Comberton, Worcs.			
Old quarry on Even Hill. Overgrown but MRBF can be revealed by digging.	(SO 9677 4109)	Not Visited	Williams and Whittaker (1974:43)
Elmley Castle, Worcs.			
Old quarry above village. 2·1m exposed.	(SO 9729 4062)	Fairly clear exposure 1·0m high. Deeply frost-shattered but rock is fresh.	Williams and Whittaker (1974:43)
Elmley Castle, Worcs.			
Old quarry above village. 2·1m exposed.	(SO 9726 4060)	As site above. Mostly obscured.	Williams and Whittaker (1974:43)
Elmley Castle, Worcs.			
Dip slope of MRBF spur SSW of the earthworks.	No details	Castle is at (SO 9795 4022). Not visited.	Williams and Whittaker (1974:43)
Kersoe, Worcs.			
Old quarry. 0·6-0·9m exposed.	(SO 9840 3960)	Series of long degraded terraces noted. Small scattered crags only, some 0·5m high. Rock deeply shattered but still fresh.	Williams and Whittaker (1974:43)

Locality	Grid Reference	Present state of exposure and comments	Reference
Ashton Under Hill, Worcs.			
Quarries on Holcomb Nap.	No details	Old workings marked on the OS Sheet. Overgrown bank 2m+ high seen today. Recent excavation showed rubbly and flaggy condition of MRBF, but rock still fresh.	Smithe and Lucy (1892:211) Woodward (1893:217) Richardson (1929: 27) OS Sheet SO93 1:25 000
Dumbleton, Glos.			
Quarries in MRBF and basal Upper Lias. MRBF 1·82m thick.	No details	No sign of any quarries today. MRBF brash noted at (SP 0156 3436)	Murchison (1845: 35,36) Moore (1867:149) Smithe and Lucy (1892) Woodward (1893:216) Richardson (1929: 26)
Buckland, Glos.			
Burhill. Abandoned quarries.	No details	Shallow overgrown workings at (SP 0880 3641) (SP 0876 3665) (SP 0852 3652) No exposures were seen. Much field brash, e.g. at (SP 0833 3632)	Richardson (1929: 25)

Locality	Grid Reference	Present state of exposure and comments	Reference
Aston-Sub-Edge, Glos.			
Old overgrown quarry on Aston Hill. Fragments can be found on quarry floor.	(SP 1462 4088)	No exposures now visible Fragments collected at (SP 1463 4087)	Williams and Whittaker (1974:44)
Chipping Campden, Glos.			
Ebrington roadside opposite St. James' Church 0·9m exposed.	(SP 1548 3949)	Very degraded. Now 0·45m visible.	Williams and Whittaker (1974:44)
Chipping Campden, Glos.			
Cutting in lane to Dover's Hill. Max 10' (3·05m) exposed originally.	(SP 1446 3897)	Much overgrown. Williams and Whittaker noted 2·4m at grid reference given. In present study 2·71m were noted at (SP 1452 3895)	Richardson (1904: 393) Richardson (1929: 25) Hallam (1967:409) Williams and Whittaker (1974:44)
Hidcote Bartrim, Glos.			
Stream section nearby. 3·0m exposed.	(SP 1713 4279)	Designation as MRBF disputed here. (See Appendix 5)	Williams and Whittaker (1974:44)
Quinton, Warks.			
Meon Hill. Field brash on hill top.	No details	Hill is at (SP 176 454). Brash collected at (SP 1755 4525)	Williams and Whittaker (1974:44)

Locality	Grid Reference	Present state of exposure and comments	Reference
Lark Stoke, Warks.			
Upper Lark Stoke. 2·4m exposed.	(SP 1935 4338)	Completely overgrown.	Williams and Whittaker (1974:44)
Ilmington, Warks.			
0·6m exposed on edge of spur.	(SP 2058 4312)	Completely overgrown.	Williams and Whittaker (1974:45)
Ilmington, Warks.			
Old quarries up to 1·2m exposed.	(SP 2083 4290)	Similar thickness seen today. But exposures are rubbly and decayed.	Williams and Whittaker (1974:45)
Ilmington, Warks.			
"Fairly extensive old workings".	(SP 2088 4300)	Almost completely degraded. Only fragments seen in soil.	Williams and Whittaker (1974:45)
Ilmington, Warks.			
Exposure 1·5m high with 0·6m of Upper Lias Clay above.	(SP 2096 4278)	Very degraded. Only small crags visible. Traces of the clay still visible.	Williams and Whittaker (1974:45)
Ilmington, Warks.			
1·1m exposure near Cathole.	(SP 2071 4182)	Mostly rubbly and collapsed. Some clear exposures show 0·6m of cambered MRBF.	Williams and Whittaker (1974:45)

Locality	Grid Reference	Present state of exposure and comments	Reference
Foxcote, Warks.			
Old quarries in the vicinity of Foxcote House.	No details	Old largely filled in quarry in MRBF at (1973 4171). No faces. Some MRBF brash on the quarry floor.	Richardson (1908: 130) Williams and Whittaker (1974:45)
Ebrington, Glos.			
0·9m exposed.	(SP 1841 4012)	Exposures not found at this referenced site, but two large blocks 1m thick noted in base of a wall at (SP 1840 4010)	Williams and Whittaker (1974:44)
Blockley, Glos.			
Exposures next to track near ruined Baths.	300 yds S by W from the church.	Very overgrown and slipped quarry seen near old Bath at (SP 1640 3470). Small exposures visible.	Richardson (1929: 25)
Aston Magna, Glos.			
Aston Magna Brickpit. MRBF may be present at top of section. (Sandstone Facies).	(SP 198 354)	Very overgrown but small scattered exposures present.	Richardson (1910a) McKerrow and Baden-Powell (1953)

Locality	Grid Reference	Present state of exposure and comments	Reference
Chastleton, Oxon.			
Extensive quarries in the MRBF near Chastleton House.	No details	Old overgrown workings with MRBF brash at (SP 2471 2881)	Hull (1857:20)
Daylesford, Glos.			
Quarry S of the village.	No details	No MRBF cropping out S of Daylesford, but Middle Lias exposed to SW towards Oddington church. Area examined but no quarry found.	Hull (1857:20) BGS Sheet 217 1:50 000 BGS Sheet 218 1:63360
Oddington, Glos.			
Section in Maugersbury-Oddington road.	No details	Richardson could not locate the site. No sections seen in present investigation.	Hull (1857:19) Richardson (1929: 26)
Maugersbury, Glos.			
Quarries W of Maugersbury Grove.	No details	No faces now visible - rough ground with trees. Much brash from burrowing animals seen at (SP 2020 2367)	Richardson (1929: 25)

Locality	Grid Reference	Present state of exposure and comments	Reference
Wyck Rissington, Glos.			
Quarry in MRBF.	Nine-tenths of a mile E by N of Wyck Rissington.	Area examined in vicinity of Wyck Hill Farm. No quarries present today, but lump of MRBF found in road ditch at (SP 1962 2292)	Richardson (1929: 25)
Windrush, Glos.			
Outcrops near Dodd's Mill.	No details	No exposure visible in immediate vicinity of mill site.	Richardson (1933:9)
Windrush, Glos.			
3'-4' (0·91-1·22m) of massive ironstone exposed on left bank of the river.	300 yards ESE of Dodd's Mill.	The site is approx. at (SP 1928 1520). Erroneous location. Actual location is at (SP 1915 1498) where 0·64m is now seen.	Worssam and Bisson (1961:78)
Windrush, Glos.			
Brash in valley N of Barrington Farm.	No details	Plentiful brash in soil visible at (SP 1960 1498)	Worssam and Bisson (1961:78)

Locality	Grid Reference	Present state of exposure and comments	Reference
Taynton, Oxon			
Coombe Brook Valley. Exposure of MRBF near small artificial waterfall.	¾ mile (1·2km) N of Taynton church.	Waterfall located on OS Sheet at (SP 2334 1473) No sign of MRBF now.	Worssam and Bisson (1961:78) OS Sheet SP 21 1:25 000
Milton-Under-Wychwood, Oxon			
Milton Down to Milton road section.	No details	Section probably in the area of Upper Milton (SP 259 171). Very overgrown when visited by Richardson. No section visible today.	Hull (1857:22,23, Fig. 2) Richardson (1946:13)

APPENDIX 2

MRBF Localities in the Cotswolds from personal Investigations

Locality	Grid Reference	Present state of exposure and comments	Reference
Bitton, Avon			
Outcrop of Junction Bed on Bitton Hill. Brash seen in bank.	(ST 6780 7037)	Low bank along hedge. Much brash of MRBF and basal Upper Lias.	BGS Sheet 265 1:63360
Hinton, Avon			
Small patches of Junction Bed on escarpment E of the village. MRBF and basal Upper Lias brash.	(ST 7378 7692) (ST 7400 7733)	Brash found in spring bed, ditches and loose fragments in fields.	BGS Sheet 265 1:63360
Hillesley, Avon			
Extensive platform of MRBF S of village and N of Lovattswood Farm. Occasional fragments along edge of platform.	(ST 7658 8888)	Fields on platform examined for brash but none found (only found on edge as stated).	BGS Sheet 251 1:63360
Hillesley, Avon			
Extensive platform of MRBF N of village. Brash noted on field boundary.	(ST 7691 9022)	Fresh and unweathered samples can be collected	BGS Sheet 251 1:63360
Wortley, Glos.			
Brash in stream bed near Pumping Station.	(ST 7733 9140)	Samples fresh and unweathered.	BGS Sheet 251 1:63360

Locality	Grid Reference	Present state of exposure and comment	Reference
Wotton-under-Edge, Glos.			
Long Street, Tolsey House cellar. 2·20m exposed.	(ST 7560 9328)	Moderate exposure. Unclad cellar wall.	BGS Sheet 251 1:63360 R.J. Chidlaw (pers. comm.)
Wotton-under-Edge, Glos.			
Dryleaze Court. Temporary trench next to old peoples' dwellings. 1·0m exposed.	(ST 7521 9330)	Top part of the MRBF seen. Upper 0·5m very rubbly and broken above the unweathered rock. Now obscured.	BGS Sheet 251 1:63360
Bournestream, Glos.			
Old quarry showing junction of MRBF and Upper Lias clay. 1·2m exposed.	(ST 7492 9443)	Moderate to poor exposure shows nature of top of MRBF rarely seen in present investigation.	BGS Sheet 251 1:63360
Bournestream, Glos.			
Old Bournestream House. 3·0m exposed in excavation for garage.	(ST 7480 9447)	Good exposure.recent (1979). Shows boundary with Upper Lias Clay.	BGS Sheet 251 1:63360
Southend, Glos.			
Old quarries in cambered MRBF in garden of cottages and in field to the west. 2·60m exposed.	(ST 7422 9507)	Good exposures in places. Long, low workings. Old, weathered and crumbling.	BGS Sheet 251 1:63360

Locality	Grid Reference	Present state of exposure and comments	Reference
North Nibley, Glos.			
Old quarry SW of village. 2·6m exposed.	(ST 7365 9568)	Good, long exposure. Very little vegetation and scree.	BGS Sheet 251 1:63360 OS Sheet 79 1:25 000
Smart's Green, Glos.			
Old quarry in MRBF 3·80m exposed.	(ST 7531 9615)	Good, large extensive exposure. Relatively little vegetation and scree.	BGS Sheet 251 1:63360
Stancombe, Glos.			
Old quarry at Stancombe Farm. 2·0m exposed.	(ST 7391 9760)	Moderate. Much vegetation but some continuous faces seen.	BGS Sheet 251 1:63360
Stinchcombe, Glos.			
Old quarry WSW of Drakestone Point. 1·5m exposed.	(ST 7318 9789)	Mostly overgrown. Long, narrow excavation. Some small crags showing top of MRBF still visible.	BGS Sheet 251 1:63360
Dursley, Glos.			
Castle Street. Site for Swimming Pool and Youth Centre Sites. 5·56m seen.	(ST 755 982)	Good exposures, but now obscured. MRBF exposed in series of stepped rotationally sheared blocks.	BGS Sheet 251 1:63360

Locality	Grid Reference	Present state of exposure and comment	Reference
Uley, Glos.			
Section in sunken lane.	(ST 7717 9887)	Variable exposure.	BGS Sheet 1:63360
Uley, Glos.			
Right bank of the River Ewelme. Bank with rotationally slipped and cambered MRBF. Small but good exposure noted.	(ST 7908 9818)	Rock is clear of soil and vegetation and unweathered.	BGS Sheet 251 1:63360
Leonard Stanley, Glos.			
Gypsy lane. Field adjacent to lane contains MRBF brash.	(SO 8036 0244)	Occasional lumps of MRBF noted along fence.	BGS Sheet 234 1:50 000
Selsley, Glos.			
Small natural crags ENE of Stanley Park church.	(SU 8267 0388)	Rubbly with small boulder-blocks of MRBF present. Fresh and largely unweathered.	BGS Sheet 234 1:50 000
Standish, Glos.			
Side of spur SE of Vinegar Hill. Small crags and brash in Crescentric landslip scar. 0·2m-0·3m exposed.	(SO 8183 0808)	Small exposures. Rock jointed and tilted but fresh.	BGS Sheet 234 1:50 000

Locality	Grid Reference	Present state of exposure and comments	Reference
Haresfield, Glos.			
Brash on MRBF outcrop in small valley on the escarpment SE of village.	(SO 8250 0955)	MRBf Brash in dry spring channel on S side of valley. Mixed with fragments of Upper Lias.	BGS Sheet 234 1:50 000
Upton St. Leonards, Glos.			
Well defined MRBF platform N of Prinknash Abbey. Much brash present.	(SO 8797 1402)	MRBF fragments mixed with Upper Lias limestones and Inferior Oolite.	BGS Sheet 234 1:50 000
Brockworth, Glos.			
Small shelf on the escarpment above Droy's Court with steep bank facing downslope. Small crags in bank and brash below. Brash also in adjacent copse.	(SO 8963 1508)	Area mapped on indeterminate landslip. Shelf is free of superficial deposits, however.	BGS Sheet 234 1:50 000
Great Witcombe, Glos.			
Ledge of MRBF in narrow side valley SE of the village at foot of the escarpment. Much brash and oolite rubble in incised stream bed.	(SO 9155 1418)	Area mapped on indeterminate landslip, but no superficial deposits here.	BGS Sheet 234 1:50 000

Locality	Grid Reference	Present state of exposure and comments	Reference
Leckhampton, Glos.			
The Bittams. Deeply incised stream. Extensive flat field to the SSW is at the local altitude of the MRBF. Soil brash found.	(SO 9409 1815)	All landslipped according to BGS Sheet, but field appears clear of slipped material. Fragments on edge of field above flank of stream.	BGS Sheet 234 1:50 000
Southam, Glos.			
Small landslip scar in Stutfield Wood.	(SO 9795 2556)	Good	M. Simms (pers. comm.)
Gotherington, Glos.			
Nottingham Hill. Landslip scar.	(SO 9747 2882)	Good	M. Simms (pers. comm.)
Winchcombe, Glos.			
Soil brash at top of incised stream in DSF.	(SP 0227 2658)	Poor	BGS Sheet 217 1:50 000 OS Sheet SP02 1:25 000
Stanton, Glos.			
Sunken track above the village. 1·07m full thickness of MRBF.	(SP 0724 3424)	MRBF much lichen-covered and dissected into blocks by severe rotational shearing and camber. Rock unweathered and is fresh.	BGS Sheet 217 1:50 000

Locality	Grid Reference	Present state of exposure and comments	Reference
Laverton, Glos.			
Landslip scars on the escarpment SE of the village. Small crags of MRBF vis ible. Large tilted block noted, exposing 1·34m.	(SP 0770 3530)	Block highly inclined but strata within are undisturbed. Rock is free of vegetation and fresh. Small poorer craggy exposures in copse immediately to the N.	BGS Sheet 217 1:50 000
Broadway, Worcs.			
Stream on escarpment E of Broadway. Loose fragments of MRBF in stream bed.	(SP 1125 3759)	Large lumps seen particularly at this point.	BGS Sheet 217 1:50 000
Hidcote Bartrim, Glos.			
Topographic platform on which Hidcote Bartrim is situated thought in this Thesis to be the outcrop of the MRBF. Fragments found in copse at site given.	(SP 1767 4303)	Fragments are small and weathered but closely resemble the local MRBF Facies.	BGS Sheet 200 1:50 000 and OS Sheet SP 04 1:25 000
Lark Stoke, Warks.			
Upper Lark Stoke. Exposure in bank up to 1·0m.	(SP 1935 4332)	Much weathered and overgrown exposure.	BGS Sheet 200 1:50 000

Locality	Grid Reference	Present state of exposure and comments	Reference
Ilmington, Warks.			
Natural exposure (?). Crag in cambered MRBF approx. 0·5m exposed.	(SP 2056 4309)	Very rubbly and jointed but clear of vegetation.	BGS Sheet 200 1:50 000
Ilmington, Warks.			
Small rubbly crags.	(SP 2177 4292)	As site above	As site above
Foxcote, Warks.			
MRBF platform SW of Foxcote House. Much brash in fields.	(SP 1960 4160)	Good specimen of *Rhizocorallium* found.	BGS Sheet 200 1:50 000
Oddington, Glos.			
Lower Oddington. Field brash near St. Nicholas' Church.	(SP 2359 2549)	Large loose blocks seen on edge of wood.	BGS Sheet 217 1:50 000
Windrush, Glos.			
Dodd's Mill. MRBF fragments on the left bank of the River Windrush.	(SP 1893 1537)	Fragments found protruding from soil S of small river cliff cut in alluvium. MRBF had weathered Fe rinds but was fresh inside.	BGS Sheet 235 1:63360

APPENDIX 3

Areas of MRBF outcrop in the Cotswolds where sampling could not be undertaken during personal investigations (Non-literature sites)

Locality	Grid Reference	Site Comments	References
Dodington, Avon			
Patches of Junction Bed mapped SSW of Dodington.	(ST 7476 7944)	Ledge of Junction Bed could be seen on the escarpment but no MRBF brash was found.	BGS Sheet 265 1:63360
Harescombe, Glos.			
Outcrop of MRBF mapped near Pike House NE of village on the escarpment.	(SO 842 108)	Middle Lias strata heavily slipped along shear planes. Some weathered calcareous bands from the DSF visible, but no MRBF seen.	BGS Sheet 234 1:50 000
Shurdington, Glos.			
Crippets. Flat field E of Crippets and below springs at the altitude of the local MRBF.	(SO 9361 1802)	Marked as landslip on the BGS map, but landslip tongues die out upslope. No MRBF fragments found, but samples previously collected in the area (in collection School of Geography and Geology, College of St. Paul and St. Mary, Cheltenham).	BGS Sheet 234 1:50 000

Locality	Grid Reference	Site Comments	Reference
Leckhampton, Glos.			
Escarpment at 150m OD due S of the village.	(SO 9489 1911) to (SO 9415 1861)	Examination of area at local level of MRBF mapped on BGS Sheet as landslip. MRBF shelf clearly seen in places but only fragments from strata above found.	BGS Sheet 234 1:50 000
Charlton Kings, Glos.			
Ham. Escarpment at 155m OD.	(SO 9796 2119)	Small platform on OS Sheet at local level of MRBF. No MRBF fragments found.	BGS Sheet 217 1:50 000 and OS Sheet SO 92 1:25 000
Greet, Glos.			
The Warren. Possibly MRBF is found on top of hill.		Hard cap on the Warren at (SP 023 315) lies at 134.72m OD. Too low to be MRBF .. all MRBF has been eroded.	BGS Sheet 217 1:50 000 OS Sheet SP 03 1:25 000
Winchcombe, Glos.			
Postlip. Old quarry on the mapped Middle-Upper Lias Junction at Corndean Farm.	(SP 0105 2676)	Mostly overgrown. Quarry was dug in slumped blocks of Inferior Oolite. No sign of MRBF.	OS Sheet SP 02 1:25 000 BGS Sheet 217 1:50 000

Locality	Grid Reference	Site Comments	Reference
<u>Sudeley, Glos.</u>			
Spoonley Quarry Plantation. Old quarry on the mapped Middle-Upper Lias boundary.	(SP 0490 2546)	Mostly overgrown. Quarry dug into slumped blocks of Inferior Oolite. No sign of MRBF.	BGS Sheet 217 1:50 000 OS Sheet SP 02 1:25 000
<u>Longborough, Glos.</u>			
Road into village N of Banks Fee House. Small recent cutting associated with new housing developments on mapped Middle/Upper Lias junction.	(SP 1771 2928)	Good exposure of slumped flaggy Oolite from upslope. No sign of the <u>in-situ</u> strata below.	BGS Sheet 217 1:50 000
<u>Longborough, Glos.</u>			
Banks Fee House. Old workings on OS Sheet along boundary of Middle/Upper Lias in the grounds of the house.	(SP 1783 2877)	Completely relandscaped and filled in.	BGS Sheet 217 1:50 000 OS Sheet SP 12 1:25 000
<u>Lower Slaughter, Glos.</u>			
Road junction near Springhill Barn. Old quarry on mapped junction of Middle and Upper Lias.	(SP 1613 2213)	Mostly overgrown. Some exposures showed only Inferior Oolite rubble.	BGS Sheet 217 1:50 000
<u>Bourton-on-the-Water, Glos.</u>			
Road up to Slaughter Farm from the Fosseway. Trenches on both sides of the road on the Middle Lias outcrop.	(SP 1600 2125)	Trenches revealed only land-slipped Oolite.	BGS Sheet 217 1:50 000

Locality	Grid Reference	Site Comments	Reference
Bourton-on-the-Water, Glos.			
Cutting along abandoned railway line. Crosses the Middle-Upper Lias boundary on the BGS Sheet.	(SP 1571 2114)	Cutting shallow and much degraded. Begins in the Cotswold Sands rather than the Middle Lias. No trace of MRBF or fragments.	BGS Sheet 217 1:50 000
Taynton, Oxon			
Coombe Brook Valley. Mapped boundary of the Middle-Upper Lias.	(SP 233 147)	Examined valley sides from Taynton village to Hazleford Bridge. Also in the Tangley Woods, but no MRBF exposures or brash was found.	BGS Sheet 235 1:63360 and OS Sheet SP 21 1:25 000

APPENDIX 4

Field Localities: Marlstone Rock Bed Formation

Site Number	Locality	Site Details (see key)	Sample Numbers
(1)	Norton Malreward. Maes knoll SE Dundry Hill. Rotationally sheared blocks (ST 5973 6618)	LS	NC 135
(2)	As above	LS	NC 122, 123
(3)	Bitton, Bitton Hill (ST 6780 7037)	B	NC 109
(4)	Hinton (ST 7408 7752)	B	NC 98
(5)	Horton (ST 7618 8417)	B	NC 99
(6)	Hawkesbury (ST 7660 8672)	B	NC 100
(7)	Hillesley (ST 7658 8888)	B	NC 147
(8)	Hillesley (ST 7691 9022)	B	NC 148
(9)	Wortley (ST 7733 9140)	B	NC 120
(10)	Wotton-under-Edge Tolsey House Cellar. (ST 7560 9328)	LS	NC 96
(11)	Wotton-under-Edge (ST 7521 9330)	TE/SE	NC 159
(12)	Bournestream Quarry (ST 7480 9447)	LS	NC 166, 167, 168

Site Number	Locality	Site Details (see key)	Sample Numbers
(13)	Bournestream. Old Bournestream House. Building site. (ST 7492 9943)	LS	NC 95
(14)	Southend. Quarry (ST 7422 9507)	LS	NC 121
(15)	North Nibley. Quarry (ST 7365 9568)	LS	NC 94
(16)	Smart's Green. Quarry (ST 7531 9615)	LS	NC 91, 92, 93
(17)	Stancombe. Stancombe Park. Quarry (ST 7387 9752)	LS	
(18)	Stinchcombe (ST 7318 9789)	SE	NC 90
(19)	The Quarry, Newnham Quarry (ST 7346 9950)	LS	NC 117, 118, NC 119, 175
(20)	Dursley. Castle St. Swimming Pool/Youth Centre Sites (ST 755 982)	LS/TE	NC 50, 51
(21)	Upper Cam. Downhouse Farm. Quarry (ST 7640 9914)	LS	NC 89, 169
(22)	Uley, Coldharbour Farm (ST 7702 9844)	SE	NC 88

Site Number	Locality	Site Details (see key)	Sample Numbers
(23)	Uley. Lane section (ST 7717 9887)	LS	
(24)	Uley (ST 7850 9793)	SE	NC 87
(25)	Uley (ST 7908 9818)	SE	NC 146
(26)	Coaley (ST 7814 9960)	B	NC 108
(27)	Frocester (SO 7925 0188)	B	NC 106, 107
(28)	Leonard Stanley (SO 8036 0244)	B	NC 136
(29)	Selsley (SO 8267 0388)	SE	NC 130
(30)	Rodborough (SO 8390 0470)	SE	NC 102, 103
(31)	Stonehouse. Stonehouse Brickpit (SO 8103 0537)	LS	NC 10, 13, 15, NC 16, 17,
(32)	Standish (SO 8183 0808)	SE	NC 112
(33)	Haresfield (SO 8250 0955)	B	NC 113
(34)	Tuffley. Robinswood Hill. Tuffley Brickpit (SO 8359 1495)	LS	NC 18, 19, 20, NC 22, 164, 170 NC 177, 178, NC 179
(35)	Upton St. Leonards (SO 8797 1402)	B	NC 125
(36)	Brockworth (SO 8963 1508)	SE	NC 127(C), 115
(37)	Great Witcombe (SO 9155 1418)	B	NC 128

Site Number	Locality	Site Details (see key)	Sample Numbers
(38)	Shurdington. Crippets approx. (SO 9361 1802)	B	NC 137
(39)	Leckhampton (SO 9409 1815)	B	NC 132
(40)	Charlton Kings (SO 9623 1908)	B	NC 129
(41)	Southam. Cleeve Hill Stutfield Wood, land-slip scar (SO 9795 2556)	LS	
(42)	Gotherington. Nottingham Hill. Land-slip scar (SO 9747 2882)	LS	
(43)	Gretton. Cup's Hill Quarry (SP 0109 2960)	LS	
(44)	Dixton. Oxenton Hill, Dixton Wood (SO 9787 3633)	B	NC 82
(45)	Dixton. Dixton Hill (SO 9860 3061)	B	NC 165
(46)	Great Comberton. Bredon Hill. Batten's Wood. Landslip scar (SO 9561 4087)	LS	NC 110

Site Number	Locality	Site Details (see key)	Sample Numbers
(47)	Elmley Castle. Bredon Hill. Quarry E of Doctor's Wood (SO 9720 4062)	SE	NC 149
(48)	As above (SO 9726 4060)	LS	NC 150, 151
(49)	Kersoe. Bredon Hill (SO 9840 3960)	SE	NC 111
(50)	Ashton-Under-Hill. Bredon Hill. Holcomb Nap (SO 9931 3868)	B	NC 152
(51)	Dumbleton. Alderton Hill (SP 0156 3436)	B	NC 134
(52)	Winchcombe (SP 0227 2658)	B	NC 141
(53)	Stanton. Incised path on landslip (SP 0724 3424)	LS	NC 24
(54)	Laverton. Rotationally sheared block (SP 0770 3530)	LS	NC 144, 145
(55)	Buckland (SP 0833 3632)	B	NC 85
(56)	Broadway (SP 1125 3759)	B	NC 84
(57)	Aston-Sub-Edge (SP 1463 4087)	B	NC 81
(58)	Chipping Campden. Dyer's Lane (SP 1452 3895)	LS	NC 75

Site Number	Locality	Site Details (see key)	Sample Numbers
(59)	Hidcote Bartrim (SP 1767 4303)	B	NC 80
(60)	Quinton. Meon Hill (SP 1755 4525)	B	NC 186
(61)	Larkstoke (SP 1935 4332)	SE	NC 78
(62)	Ilmington (SP 2056 4309)	SE	NC 158
(63)	" (SP 2080 4289)	SE	NC 157, 172, NC 173, 174
(64)	" (SP 2096 4278)	SE	NC 77
(65)	" (SP 2071 4182)	SE	NC 153, 154
(66)	Foxcote (SP 1973 4171)	B	NC 155
(67)	" (SP 1960 4160)	B	NC 156
(68)	Ebrington (SP 1840 4010)	SE	NC 76
(69)	Blockley (SP 1640 3470)	SE	NC 74
(70)	Aston Magna (?) Aston Magna Brickpit (SP 198 354)	LS	
(71)	Chastleton (SP 2471 2881)	B	NC 161
(72)	Oddington (SP 2359 2549)	B	NC 162
(73)	Maugersbury (SP 2020 2367)	B	NC 73
(74)	Wyck Rissington (SP 1962 2292)	B	NC 133
(75)	Windrush (SP 1893 1537)	B	NC 67

Site Number	Locality	Site Details (see key)	Sample Numbers
(76)	Windrush (SP 1915 1498)	SE	NC 160

Key

LS Logged section

SE Small exposure

TE Temporary exposure

B Brash

APPENDIX 5

Dyrham Silts Localities in the Cotswolds examined from the literature

Locality	Grid Reference	Present state of exposure and comments	Reference
Uley, Glos.			
Coldharbour Farm stream section. 29m patchily exposed.	(ST 7610 9812) - (ST 7672 9889)	Stream deeply incised. Low waterfalls, uprooted trees and meander scars give small but clear exposures.	Cave (1977:89,90) Phelps (1982 Fig.A: 2:6:2)
Stonehouse, Glos.			
Stonehouse Brickpit. At least 44m once exposed.	(SO 8103 0537)	Good exposure. Some parts obscured, particularly at the base.	Richardson (1910b) Ager (1956a) Palmer (1971) Phelps (1982)
Tuffley, Glos.			
Robinswood Hill. Tuffley Brickpit. 57m exposed. (Considered almost the full thickness of the DSF at this location).	(SO 8358 1490)	Good exposure. Faces still steep and clear in many places. Recent (1982) track cutting on the W side exposes the lower silts now obscured in the main pit.	Richardson (1904a: 47) Richardson (1910b: 258) Watts (1928) Ager (1956a:363, 364) Palmer (1971) Phelps (1982 Fig.A: 2:6:2)

Locality	Grid Reference	Present state of exposure and comments	Reference
Cheltenham, Glos.			
Battledown, Glenfall House. Waterfall on the Ham Brook. 2·1m exposed.	(SO 9790 2187)	Moderate exposure on right bank of brook below waterfall. Erroneously located by Richardson as MRBF.	Richardson (1929: 25)
Hidcote Bartrim, Glos.			
Nearby stream section 3·0m.	(SP 1713 4279)	Two adjacent deeply incised streams, with small waterfalls. Erroneously designated MRBF by Williams and Whittaker. Small section at (SP 1718 4290) showed 0·5m of DSF and good section at (SP 1714 4282) showed minimum of 11·4m of DSF.	Williams and Whittaker (1974:44)
Quinton, Warks.			
Meon Hill. Field brash on hill slopes.	None provided	Hill is at (SP 176 454). Large lumps found at (SP 1800 4513).	Williams and Whittaker (1974:44)
Aston Magna, Glos.			
Brickpit. Full section when fully exposed was about 25m.	None provided	Now virtually overgrown, but good, small isolated exposures still present.	Richardson (1910a) McKerrow and Baden-Powell (1953)

Locality	Grid Reference	Present state of exposure and comments	Reference
Taynton, Oxon			
Coombe Brook Valley. Section near small artificial waterfall.	¾ mile (1·2km) N of Taynton church.	Poor, small exposure of DSF at (SP 2334 1473)	Worssam and Bisson (1961:78)

APPENDIX 6

Dyrham Silts Localities in the Cotswolds examined through personal investigation

Locality	Grid Reference	Present state of exposure and comments	Reference
Dursley, Glos.			
Castle Street site for Swimming Pool and Youth Centre. 1·0m exposed.	(ST 755 982)	Good exposure but now obscured.	BGS Sheet 251 1:63360
Dursley, Glos.			
Ferney Hill. Temporary water (?) pipe excavation. 0·3m exposed.	(ST 7649 9798)	Now obscured.	BGS Sheet 251 1:63360
Uley, Glos.			
Lane section.	(ST 7717 9887)	Small patchy exposures.	BGS Sheet 251 1:63360
Uley, Glos.			
Wresden Farm. Temporary excavation for a garage. 1·2m exposed.	(ST 7716 9807)	Now obscured.	BGS Sheet 251 1:63360
Uley, Glos.			
Shadwell. Building excavation for a house. 1·22m exposed.	(ST 7838 9757)	Now obscured.	BGS Sheet 251 1:63360

Locality	Grid Reference	Present state of exposure and comments	Reference
Dowdeswell, Glos.			
Small cutting in abandoned railway line S of the Dowdeswell Reservoir dam. 0·6m seen in small exposure.	(SO 9870 1957)	Railway cutting is shallow and mostly overgrown.	BGS Sheet 217 1:50 000 OS Sheet SO 91 1:25 000
Southam, Glos.			
Large landslip scar in Queen's Wood on the escarpment SE of the village. 26·5m exposed.	(SO 9791 2508)	Good exposure. Shear faces in DSF at top. Lower slopes covered with uprooted trees and silt rubble.	Pers. Comm. M. Simms and J.P. Angseesing
Southam, Glos.			
Small landslip scars in Stutfield Wood.	(SO 9795 2556)	Good but small exposures.	Pers. comm. M. Simms
Gotherington, Glos.			
Nottingham Hill. Landslip scars.	(SO 9747 2882)	Good but small exposures	Pers. comm. M. Simms
Prescott, Glos.			
Well developed platform at 150m NW of Prescott House. Small crescentric landslip scars in hollow on W side.	(SO 9803 2943)	Cambered slab at this site is large but partially buried. Rock still fresh.	BGS Sheet 217 1:50 000

Locality	Grid Reference	Present state of exposure and comments	Reference
Leonard Stanley, Glos.			
Woodside Lane, Small exposures in sunken lane. 1·72m exposed.	(SO 8060 0246)	Good moderate exposure.	BGS Sheet 234 1:50 000 OS Sheet SO 80 1:25 000
Churchdown, Glos.			
Churchdown Hill. Temporary excavation for waterpipe from Severn Trent Water Authority Reservoirs. 2·20m exposed.	(SO 8820 1897)	Clear exposure but now obscured.	BGS Sheet 234 1:50 000 OS Sheet SO 81 1:25 000
Shurdington, Glos.			
Shurdington Grove. Large crescentic landslip on escarpment E of the village. Small exposures visible.	(SO 9284 1808)	Poor exposure, much earthy scree.	OS Sheet SO 91 1:25 000
Leckhampton, Glos.			
The Bittams. Deeply incised stream showing small but clear exposures in water-falls and crags. 2·60m seen at grid reference given.	(SO 9400 1837)	Clear exposure with little scree or vegetation.	BGS Sheet 234 1:50 000 OS Sheet SO 91 1:25 000

Locality	Grid Reference	Present state of exposure and comments	Reference
Winchcombe, Glos.			
Deeply incised stream SW of Sudeley Castle. Small 0·53m exposure.	(SP 0227 2658)	Exposure in dry part of stream above spring. DSF weathered but fresh inside.	BGS Sheet 217 1:50 000 and OS Sheet SP 02 1:25 000
Hailes, Glos.			
Hailes Fruit Farm. Small exposure created during planting of apple trees. 0·7m exposed.	(SP 0505 2952)	Good soil-free exposures of bedding planes due to gully erosion. Rock fresh and unweathered.	BGS Sheet 217 1:50 000 and OS Sheets SP 02, 03 1:25 000

APPENDIX 7

Field Localities: Dyrham Silt Formation

Site Number	Locality	Site Details	Sample Number
(1)	Dursley. Castle St. Swimming Pool/Youth Centre Sites. (ST 755 982)	TE/SE	NC 52
(2)	Dursley (ST 7649 9798)	TE/SE	NC 28
(3)	Uley. Coldharbour Farm. Stream Section (ST 7610 9812) to (ST 7672 9889)	LS	-
(4)	Uley. Lane Section. (ST 7717 9887)	LS	-
(5)	Uley (ST 7716 9807)	TE	NC 5
(6)	Uley (ST 7838 9757)	TE	NC 12
(7)	Leonard Stanley. Woodside Lane (SO 8060 0246)	LS	NC 104, 105
(8)	Stonehouse Brickpit (SO 8103 0537)	LS	-
(9)	Tuffley. Robinswood Hill Brickpit (SO 835 149)	LS	NC 48, 63, 61, 47, 46, 58, 59, 39, 38, 37, 36, 35, 44, 21, 30, 33, 34
(10)	Churchdown, Churchdown Hill. Severn-Trent Water Authority trench (SO 8820 1897)	LS/TE	NC 114

Site Number	Locality	Site Details	Sample Number
(11)	Shurdington (SO 9284 1808)	SE	NC 116
(12)	Leckhampton. The Bittams. Stream section (SO 9400 1837)	LS	NC 66
(13)	Dowdeswell (SO 9870 1957)	SE	NC 23
(14)	Cheltenham. Battle-down. Glenfall House waterfall (SO 9790 2187)	LS	NC 65
(15)	Southam. Cleeve Hill. Queenswood landslip scar (SO 9791 2508)	LS	-
(16)	Southam. Cleeve Hill. Stutfield Wood. Land-slip scar (SO 9795 2556)	LS	-
(17)	As above (SO 9787 2518); (SO 9783 2570)	SE	NC 72; 71
(18)	Gotherington. Nottingham Hill. Landslip scars (SO 9747 2882)	LS	-
(19)	Prescott (SO 9803 2943)	B	NC 138
(20)	Gretton. Cup's Hill Quarry (SP 0109 2960)	LS	NC 69

Site Number	Locality	Site Details	Sample Number
(21)	Winchcombe. Stream section (SP 0227 2658)	LS	NC 140, 142
(22)	Hailes. Soil erosion (SP 0505 2952)	LS/TE	NC 143
(23)	Wood Stanway (SP 0663 3018)	B	NC 86
(24)	Hidcote Bartrim. Stream section (SP 1714 4282)	LS	NC 124(A) NC 124(B)
(25)	Quinton Meon Hill (SP 1800 4513)	B	NC 79
(26)	Aston Magna. Aston Magna Brickpit (SP 198 354)	LS	-
(27)	Taynton (SP 2334 1473.)	SE	NC 68

APPENDIX 8

Calcium Carbonate Content Method

1.0 Break up unweathered air dried sample using iron pestle and mortar.

2.0 Sieve through a 0·5mm mesh nylon sieve.

3.0 Dissolve 40·00g of sample in 800ml of 1M acetic acid. (Acetic acid is preferred to HCl in order to avoid alteration of clay minerals for subsequent analysis).

4.0 Keep sample in suspension using a magnetic stirrer for several hours or until dissolution is complete.

5.0 Filter through preweighed Whatman's GP 91 Filter paper (15cm diameter) and wash through with hot (80^{oC}) water until filtrate has neutral pH. (Test with Universal Indicator).

6.0 Air dry sample and weigh.

7.0 Calculate weight loss = Calcium carbonate content.

8.0 Retain acid insolubles for Particle Size Analysis.

Experimental error $\pm$ 1·8%

APPENDIX 9

Non-Carbonate Particle Size Analysis Method

Acid insolubles are used from Calcium carbonate content (Appendix 8). **(After Mehra and Jackson 1959).**

1.0 Removal of iron oxide coatings from particles.
This ensures all particles are free of binding material. Additionally, the process prepares the sample for XRD analysis to reduce 'noise' on the X-ray diffractograms.

1.1 Remove dried samples from filter paper with a stiff brush, and weigh.

1.2 Place sample in a 800ml beaker. For every 4g of sample add 80ml of 0·3M sodium citrate solution and 10ml of 1M sodium bicarbonate solution.

1.3 Heat gently over a water bath to 75°-80°C.

1.4 For every 4g of sediment, add 2g of sodium dithionite powder using a plastic spoon (metal will be corroded). Stir strongly for 1 minute, then periodically for 15 minutes.

1.5 For every 4g of sediment, add 20ml of saturated sodium chloride solution. Stir thoroughly and allow to cool.

1.6 Pour off the clear liquid, and transfer sample to centrifuge. Centrifuge for 2 minutes at 2000 r.p.m., or until liquid is clear.

1.7 Remove sample using wash bottle and centrifuge twice again, to wash away any traces of sodium chloride.

1.8 Transfer sample to a beaker, and add 10ml of 10%

Calgon. Ensure the calgon is weighed <u>accurately</u> before making up the solution. Stir with magnetic stirrer for several minutes to ensure thorough dispersal of the sediment.

2.0 Particle Size Analysis (R.K. Lewis, Sedimentology Laboratory, University of Bristol)

2.1 Using a washbottle, wet sieve the sample through a 63 micron sieve into a bucket, to divide sand and mud portions. Use a minimum quantity of water. The passage of the mud through the sieve is assisted by gentle but firm tapping with the palm of the hand on the side of the sieve.

2.2 Transfer the sand to an evaporating bowl using a wash bottle. Pour off the excess water carefully and dry sand in an oven at 100°C. Allow to cool, and weigh.

2.3 Using a mechanical sieve shaker, sieve the sand for 15 minutes into ¼ phi intervals between -1.00 phi to 4.0 phi. The top sieve will contain any conglomerate material.

2.4 Remove material from each of the sieves by inverting each onto paper and applying brisk strokes with a soft brush across the back of the sieve. Rotate the sieve through 90° and repeat. Finally, tap the sieve firmly with the hand once. Do not attempt to remove material remaining in the mesh. Weigh each sieve contents to two decimal places. Calculate cumulative weight of total sand. Any material passing through the 4 phi sieve into the base pan must be weighed separately and incorporated into the final calculations.

2.5 Pour mud into a 1 litre stoppered measuring cylinder and top up to 1 litre with water. Place in water tank with constant temperature of 25°C and leave overnight.

2.6 For pipette analysis of the mud, a Gallenkamp or Griffin and George 20cm^3 Aadreasin pipette was used and preweighed porcelain evaporating dishes marked with phi numbers. A stop clock was used to obtain accurate pipette withdrawl times. These are as follows:-

Phi	Depth (below meniscus)	Time
4	20cm	20s
4·5	20cm	1m 41s
5	15cm	2m 30s
5·5	10cm	3m 22s
6	10cm	6m 45s
7	10cm	27m 1s
8	5cm	54m 2s

2.7 Mix sample in a cylinder thoroughly by repeatedly inverting and rotating the cylinder in ¼ turns for several minutes. Return to tank, start stop clock and begin withdrawls immediately.

2.8 Once all dishes contain suspended sediment, place in oven set at 100°C and leave until all water is evaporated. Remove and cool.

2.9 Weigh dishes and record weight. Subtract weight of each dish to obtain weight of sample.

2.10 Data from sieving and pipette were then analysed using a Particle Size Analysis programme written by R.K. Lewis. Printouts provide a wide range of data, including histogram, cumulative frequency curve, moment and percentile statistics, and percentages of gravel, sand and mud. For the present study, sand silt and clay weight percents and modal peaks only are reproduced (Appendices 15 and 16). These values given are recalculated as weight percents of the original untreated sample weight. This was obtained using the weight percent value of the non-carbonate residuum. Weight losses from iron oxide removed are included in these values.

Experimental error factor 2-3%.

APPENDIX 10

X-Ray Diffraction Method

1.0 Preparation of Clay Plates for X-Ray Diffraction

Centrifuge well-stirred muddy suspended sediment remaining from Particle Size Analysis (Appendix 9) for 3 minutes at 1000 r.p.m. Pour off the almost clear liquid from the tubes into a beaker.

1.1 Filter using a membrane filter attached to a vacuum flask.

1.2 Scrape off clay on the membrane filter and onto a labelled glass plate (25mm x 25mm), thoroughly cleaned with detergent. Mix well with a few drops of distilled water and spread over plate to obtain an even, thin layer. A thin layer is preferred to obtain a better scan. If flocculation occurs add some detergent solution. Allow to dry.

1.3 If heating of the plate is required, this was carried out using an electric furnace with the plate placed in a lead foil tray.

2.0 X-Ray Diffraction

This analysis was carried out using the Phillips PW 1730 X-Ray Generator at the Department of Geology, University of Bristol. The settings used were as follows:-

Speed 1° 2 θ (per minute)

Scan 3° - 40°

Chart Recorder set to X10 (1 centimetre per minute)

Range 2×10^3

40 kV

30 mA

Time constant set to 4

Attenuation set to 3

Copper radiation

2.1 Clay plates for each sample analysed were run using (i) air-dried plate, (ii) glycolated, (iii) heated to 390°C, (iv) heated to 550°C.

APPENDIX 11

Atomic Absorption Spectrophotometry Method

(A. Kemp, University of Bristol)

1.0 Crush unweathered air-dried sample to a fine powder using an iron pestle and mortar.

2.0 Place 0·2g of sample within a pressure decomposition vessel. Add 5mI of water, 2ml of aqua regia and 1ml of hydrofluoric acid 40%.

3.0 Heat to 160°C for 30 minutes.

4.0 Cool, open and add quickly 10ml of boric acid 4%.

5.0 Close and reheat to 160°C for 20 minutes.

6.0 Cool, transfer the solution to a 100ml volumetric flask.

7.0 Add 5ml of 10% caesium chloride solution as an ionisation buffer and dilute to volume.

8.0 The sample is now prepared for atomic absorption spectrophotometry. Standard procedure was followed using the Phillips PU9000 Atomic Absorption Spectrophotometer at the Department of Geology, University of Bristol. Total iron oxide contents were determined, expressed as Fe_2O_3 weight %.

Experimental error factor 0·1%.

2.0 Fe content was determined using atomic and molecular weights:-

Atomic weight Fe = 55·8470

O = 15·9994

Molecular weight ∴ = 55·847 x 2 + 15·9994 x 3

= 159·6922

Fe content (weight %) ∴ = $\frac{Fe_2O_3 \text{ content} \times 111{\cdot}694}{159{\cdot}6922}$

APPENDIX 12

Sample Impregnation Techniques For Thin Sections

Methods

All samples for thin sectioning were impregnated using one of the two techniques below, to avoid plucking of grains during the making of the thin sections.

1.0 Method 1 (M.E. Badcock, Cambridge)

1.1 Mix Araldite Resin MY753 and Araldite Hardener HY951 in parts by volume 10:1.

1.2 Add equal volume of acetone. Stir thoroughly.

1.3 Place sample in wax tray and pour on mixture. (Samples were prepared by sawing field samples into 10mm thick slabs perpendicular to bedding and trimmed to blocks 50mm x 25mm).

1.4 Place tray in a vacuum chamber and subject to a vacuum of 625mm of mercury for 30 minutes to draw air out of specimen.

1.5 Return to atmospheric pressure and leave for 3 days.

1.6 Remove the surplus Araldite which is now rubbery. Heat for 8 hours at 110°C to harden the Araldite internally.

1.7 Samples are then ground and polished using standard procedure.

2.0 Method 2 (P. Witts, College of St. Paul & St. Mary, Cheltenham)

2.1 Prepare field sample by sawing into blocks as described in 1.3 above. Grind one side of block down on an electric lap wheel using 400 size carborundum grit.

2.2 Mix Araldite Resin CY219, hardener HY951 and acetone in ratio 10:1:1.

2.3 Place sample ground side upwards with a sheet of aluminium foil below it, on a hot plate set to 90°C.

2.4 Gently pour the resin mixture onto the sample. Allow to cool overnight.

2.5 Regrind the impregnated surface of the sample and mount on a glass slide.

2.6 Grind and polish the sample in the normal way to complete the thin section.

APPENDIX 13

Marlstone Rock Bed Formation: $CaCO_3$ content (weight %)

Sample Number	$CaCO_3$ content	Acid insolubles (Non-Carbonate)
NC 122	70·30	29·70
NC 109	71·31	28·69
NC 98	81·88	18·12
NC 99	85·54	14·46
NC 100	79·64	20·36
NC 120	69·70	30·30
NC 96	78·13	21·87
NC 95	62·35	37·65
NC 121	78·07	21·93
NC 94	81·62	18·38
NC 91	26·42	73·58
NC 92	54·62	45·38
NC 93	61·08	38·92
NC 90	53·55	46·45
NC 117	50·06	40·94
NC 118	81·90	18·10
NC 119	76·15	23·85
NC 50	11·40	88·60
NC 89	57·55	42·45
NC 87	63·75	36·25
NC 108	52·80	47·20
NC 107	04·75	95·25
NC 136	42·20	57·80
NC 130	43·55	56·45
NC 102	37.57	62·43

Sample Number	$CaCO_3$ content	Acid insolubles (Non-Carbonate)
NC 103	35·20	64·80
NC 15	57·15	42·85
NC 16	26·69	73·31
NC 17	02·24	97·76
NC 112	34·90	65·10
NC 113	63·90	36·10
NC 18	26·12	73·88
NC 19	02·59	97·41
NC 20	04·20	95·80
NC 22	61·07	38·93
NC 125	71·08	28·92
NC 115	77·23	22·77
NC 127(C)	63·46	36·54
NC 128	79·58	20·42
NC 137	80·92	19·08
NC 132	70·92	29·08
NC 129	65·20	34·80
NC 82	80·65	19·35
NC 110	72·25	27·75
NC 111	74·95	25·05
NC 134	36·45	63·45
NC 24	78·57	21·43
NC 144	07·00	93·00
NC 145	38·99	61·01
NC 85	40·17	59·83
NC 84	45·78	54·22
NC 81	56·42	43·58
NC 80	32·38	67·62

Sample Number	$CaCO_3$ content	Acid insolubles (Non-Carbonate)
NC 78	71·68	28·32
NC 77	60·61	39·39
NC 76	47·22	52·78
NC 75	66·34	33·66
NC 74	76·60	23·40
NC 73	50·55	49·45
NC 133	48·07	51·93
NC 67	72·35	27·65

APPENDIX 14

Dyrham Silt Formation: $CaCO_3$ content (weight %)

Sample Number	$CaCO_3$ content	Acid insolubles (Non-Carbonate)
NC 104	55·29	44·71
NC 105	01·26	98·74
NC 21	80·48	19·52
NC 35	52·67	47·33
NC 36	02·23	97·77
NC 38	03·39	96·61
NC 39	26·70	73·30
NC 44	07·33	92·67
NC 46	12·02	87·98
NC 47	02·86	97·14
NC 48	02·93	97·07
NC 59	25·85	74·15
NC 61	13·49	86·51
NC 63	02·43	97·57
NC 114	82·56	17·44
NC 116	70·74	29·26
NC 72	53·17	46·83
NC 138	30·78	69·22
NC 69	41·70	58·30
NC 140	37·08	62·92
NC 143	30·53	69·47
NC 86	32·61	67·39
NC 79	51·33	48·67

APPENDIX 15

Marlstone Rock Bed Formation: Particle Size Analysis of Non-Carbonate (Weight %)

Sample Number	Sand	Silt	Clay	Phi Modal Peak
NC 122	6•56	-	-	-
NC 109	9•67	12•68	6.34	4•75
NC 98	12•74	3•46	1•92	2•00
NC 99	0•52	2•36	11•58	9•00
NC 100	2•3	4•28	13•78	6•50
NC 120	10•76	11•54	8•00	3•75
NC 96	5•43	5•64	10•80	3•50
NC 95	11•07	16•94	9•46	3•75
NC 121	8•93	7•45	5•55	3•50
NC 94	5•28	3•74	9•36	9•00
NC 91	1•32	16•41	55•85	9•00
NC 92	10•89	20•87	13•62	4•00
NC 93	5•49	11•99	21•44	5•50
NC 90	24•15	14•54	7•76	3•50
NC 117	24•52	8•72	7•70	3•50
NC 118	6•37	5•94	5•79	3•50
NC 119	3•72	10•83	9•30	6•00
NC 50	65•48	13•29	9•83	3•75
NC 89	17•15	11•12	14•18	3•50
NC 87	18•96	9•13	8•16	3•75
NC 108	20•44	15•20	11•56	3•50
NC 107	51•82	29•71	13•72	4•00
NC 136	35•43	15•43	6•94	3•75
NC 130	37•65	12•25	6•55	3•75

Sample Number	Sand	Silt	Clay	Phi Modal Peak
NC 102	38•39	16•17	7•87	3.50
NC 103	39•72	15•49	9•59	3•75
NC 15	10•80	16•54	15•51	4•00
NC 16	42•89	20•16	10•26	3•50
NC 17	57•78	25•32	14•66	4•00
NC 112	40•43	16•34	8•33	3•75
NC 113	16•14	9•25	10•21	3•50
NC 18	29•18	34•65	10•05	4•00
NC 19	44•03	31•07	22•31	4•00
NC 20	51•83	28•64	15•42	3•75
NC 22	18•06	20•36	0•51	4•00
NC 125	4•66	11•97	12•29	4•50
NC 115	4•03	7•95	10•79	8•00
NC 127(C)	14•10	14•07	8•37	4•00
NC 128	12•08	4•17	4•17	3•50
NC 137	8•85	5•17	5•06	3•25
NC 132	1•57	8•87	18•64	6•00
NC 129	9•50	16•70	8•60	5•50
NC 82	2•40	4•60	12•35	9•00
NC 110	9•27	8•55	9•93	3•50
NC 111	11•13	9•54	4•38	4•00
NC 134	31•66	17•19	14•59	3•75
NC 24	9•88	4•46	7•09	3•50
NC 144	46•78	35•43	10•79	4•00
NC 145	28•67	22•70	9•64	4•00
NC 85	39•91	12•62	7•30	3•75
NC 84	41•26	4•93	8•02	3•25
NC 81	25•23	9•50	8•85	3•50
NC 80	42•74	15•35	9•53	3•50

Sample Number	Sand	Silt	Clay	Phi Modal Peak
NC 78	9·91	12·12	6·29	3·50
NC 77	15·68	14·53	9·18	3·25
NC 76	19·26	26·13	7·39	4·00
NC 75	17·10	10·77	5·79	3·75
NC 74	15·63	2·85	4·92	3·25
NC 73	24·92	16·17	8·36	3·50
NC 133	28·25	13·66	10·02	3·50
NC 67	13·47	6·97	7·21	3·50

APPENDIX 16

Dyrham Silt Formation: Particle Size Analysis of Non-Carbonate (Weight %)

Sample Number	Sand	Silt	Clay	Phi Modal Peak
NC 28	27·2	59·7	13·1	4·50
NC 5	07·0	48·7	44·3	6·00
NC 12	14·9	61·3	23·8	4·50
NC 35	2·46	35·64	9·23	4·50
NC 36	25·81	62·48	9·48	6·00
NC 38	26·37	54·20	16·04	4·50
NC 39	2·86	67·44	3·01	4·50
NC 44	17·98	56·44	18·25	6·00
NC 46	6·16	56·31	25·51	6·00
NC 47	30·21	63·92	3·01	4·00
NC 48	7·86	77·27	11·94	6·00
NC 59	2·82	59·54	11·79	4·50
NC 61	6·66	51·47	28·38	5·00
NC 63	4·49	62·15	30·93	5·50
NC 21	3·85	5·58	10·09	9·00
NC 72	27·21	12·55	7·07	4·00
NC 138	32·26	28·17	8·79	4·00
NC 69	24·84	21·57	11·89	4·00
NC 140	27·37	25·04	10·51	4·00
NC 143	21·82	37·65	10·00	4·00
NC 86	29·72	28·30	9·37	4·00
NC 79	27·40	13·82	7·45	3·75

APPENDIX 17

Marlstone Rock Bed Formation: Clay Mineralogy

Sample Number	Clay minerals				Others			
	Illite	Kaolinite	Randomly Interstratified Illite-Smectite	Smectite	Qz	Sid	Arag	Feld
NC 109	P	P	P	A	A	P	P	A
NC 98	P	P	P	P	P	P	P	A
NC 100	P	P	P	A	A	P	P	A
NC 120	P	P	P	A	A	A	A	A
NC 96	P	P	A	A	A	P	P	A
NC 93	P	P	P	A	A	P	P	A
NC 117	P	P	P	A	A	P	P	A
NC 89	P	P	A	A	A	P	P	P
NC 108	P	P	A	A	P	P	P	P
NC 17	P	P	P	A	P	A	A	A
NC 16	P	P	P	A	A	A	A	A
NC 19	P	P	A	A	P	A	A	P
NC 18	P	P	P	P	P	A	A	P
NC 20	P	P	P	P	P	A	A	P

NC 22	P	P	P	A	P	P	P	P
NC 115	P	P	P	A	A	P	P	A
NC 110	P	P	P	P	P	A	A	A
NC 24	P	P	P	A	A	P	P	A
NC 85	P	P	P	P	A	P	P	P
NC 84	P	P	P	P	P	P	P	P
NC 81	P	P	P	A	A	A	A	A
NC 74	P	P	P	P	A	P	P	A
NC 77	P	P	P	A	A	A	A	A
NC 73	P	P	P	A	A	A	A	A
NC 67	P	P	A	A	A	A	A	A

Key

P = Present
A = Absent

Qz = Quartz Sid = Siderite Arag = Aragonite(?) Feld = Feldspar(?)

APPENDIX 18

Dyrham Silt Formation: Clay Mineralogy

Sample Number	Clay minerals				Others			
	Illite	Kaolinite	Randomly Interstratified Illite-Smectite	Smectite	Qz	Sid	Arag	Feld
NC 21	P	P	P	P	P	A	A	P
NC 44	P	P	P	P	P	A	A	P
NC 35	P	P	P	P	A	P	P	P
NC 36	P	P	P	P	P	A	A	P
NC 38	P	P	P	P	P	A	A	P
NC 39	P	P	P	P	A	A	A	A
NC 59	P	P	P	P	A	A	A	A
NC 46	P	P	P	P	A	A	A	A
NC 47	P	P	P	P	A	A	A	A
NC 61	P	P	P	P	A	A	A	A
NC 63	P	P	P	A	A	A	A	A
NC 48	P	P	P	P	A	A	A	A
NC 105	P	P	P	A	A	A	A	A
NC 114	P	P	P	A	A	A	A	A

NC 69	P	P	P	A	A	P	P	P
NC 72	P	P	P	A	A	P	P	A
NC 79	P	P	P	A	A	P	P	P

Key - as for Appendix 17

APPENDIX 19

Marlstone Rock Bed Formation: Iron Content (WT%)

Sample Number	Total Iron Oxide content (Fe_2O_3)	Fe content
NC 122	10·07	07·04
NC 109	08·68	06·07
NC 98	01·65	01·15
NC 99	01·35	00·94
NC 100	03·85	02·69
NC 120	06·16	04·31
NC 96	04·06	02·84
NC 95	14·48	10·13
NC 121	05·81	04·06
NC 94	05·15	03·60
NC 91	08·34	05·83
NC 92	14·92	10·44
NC 93	10·62	07·43
NC 90	09·99	06·99
NC 117	08·08	05·65
NC 118	03·65	02·55
NC 119	11·11	07·77
NC 50	13·18	09·22
NC 89	10·91	07·63
NC 87	06·18	04·32
NC 146	14·37	10·05
NC 108	15·50	10·84
NC 107	12·65	08·85
NC 136	08·77	06·13
NC 130	06·87	04·81
NC 102	13·26	09·27
NC 103	11·24	07·86
NC 15	13·07	09·14
NC 16	07·22	05·05
NC 17	04·28	02·99
NC 112	07·41	05·18
NC 113	06·73	04.71
NC 18	05·66	03·96
NC 19	05·08	03·55

Sample Number	Total Iron Oxide content (Fe_2O_3)	Fe content
NC 20	04·81	03·36
NC 22	04·05	02·83
NC 125	08·48	05·93
NC 127(c)	04·05	02·83
NC 128	00·52	00·36
NC 137	03·28	02·29
NC 132	07·95	05·56
NC 129	09·85	06·89
NC 82	05·55	03·88
NC 110	02·43	01·70
NC 134	06·51	04·55
NC 24	02·46	01·72
NC 144	04·01	02·80
NC 145	04·89	03·42
NC 85	10·25	07·17
NC 84	00·63	00·44
NC 81	16·60	11·61
NC 80	13·03	09·11
NC 78	10·39	07·27
NC 77	19·81	13·86
NC 76	05·11	03·57
NC 75	04·88	03·41
NC 74	01·75	01·22
NC 73	16·09	11·25
NC 133	19·55	13·67
NC 67	04·30	03·01

APPENDIX 20

Dyrham Silt Formation: Iron Content (WT%)

Sample Number	Total Iron Oxide content (Fe_2O_3)	Fe content
NC 104	18.55	12.97
NC 21	06.33	04.43
NC 114	05.39	03.77
NC 72	06.99	04.89
NC 138	03.31	02.32
NC 69	09.82	06.87
NC 140	07.69	05.38
NC 143	02.56	01.79
NC 86	07.05	04.93
NC 79	06.00	04.20

APPENDIX 21

Marlstone Rock Bed Formation: Hand specimen descriptions: Lithology and Sedimentary Structures

Lithology	Sample Number	Colour 1.	Grain size*	Sedimentary Fabric	Trace Fossils 2.
Ferruginous muddy fine micaceous sandstone. (cemented and friable)	NC 50	W Yellow brown	0·5	Massive	-
	NC 130	Green grey	M 0·25-1·0	Massive Compressed	BSP. V.I.
	NC 102	W Yellow brown	M 0·5	Massive	BSP. V.I.
(Facies I)	NC 103	Grey brown W orange	M 0·5	"	BSP. V.
	NC 15	Grey green W yellow brown	0 under 0·25	"	-
	NC 17(Friable)	W Orange buff	M 0·25-0·5	"	-
	NC 16	Blue grey W brown grey	M 0·25-0·5	"	-
	NC 112	Grey green W yellow-brown	M 0·5-0·75	"	-
	NC 19(Friable)	W Pale brownish buff	M 0·25-0·5	"	-
	NC 18	W Fawn orange	M 0·5-1·0	Massive Compressed	-
	NC 20(Friable)	W Yellow buff	M 0·5-1·0	"	-
	NC 22	W Pale brown grey	M 0·5	Massive	HG (<u>Liostrea</u>)

	NC 127(c)	Pale grey	M 0·25-0·5	Massive	-
	NC 165	Pale green grey W orange brown	M 1·0	"	-
	NC 134	Pale brown grey W yellow	M 0·25-0·5	"	-
	NC 144(Friable)	W Yellow buff	M 0·25	"	-
	NC 145	Green grey W reddish brown	M 0·25	"	BSP.
	NC 85	Green grey W Red/yellow/brown	M 0·25	"	BSP.
	NC 84	Pale green grey W red brown	M 0·5-1	"	BSP.
	NC 80	Pale green grey W orange brown	M 0·25	"	BSP.
	NC 76	Pale green grey	M 0·25	"	BSP.
	NC 106	W Yellow brown	M 0·5	"	-
	NC 107	W Fawn brown	2·5	"	-
Shelly ferruginous oolitic calcare-nite (Facies II)	NC 147	W Yellow brown	O 0·25-0·5	Massive	-
	NC 148	W Fawn brown	BS 0·5-1·0	"	-
	NC 120	Green grey W yellow brown	BS 0·25-0·5	"	-
	NC 96	W Brownish grey	O/BS 0.75-1·0	"	-
	NC 159	Green grey W reddish yellow brown	BS 0·5	"	-

	NC 167	Green grey W yellow brown	BS 0•25-0•5	Massive	-
	NC 95	W Yellow brown	BS 0•25-1•0	"	-
	NC 121	W Brownish grey	O/BS 0•5	"	-
	NC 94	W Yellow brown	BS 0•5	"	-
	NC 92	W Yellow brown	BS 0•5-1•0	"	-
	NC 90	Grey W yellow brown	BS 0•5	"	-
	NC 117	Greenish W yellow brown	BS 0•5-1•0	"	-
	NC 118	W Fawn brown	BS 0•5	"	-
	NC 119	W Fawn brown	BS 0•25-0•75	"	-
	NC 89	W Yellow brown	BS 0•25-0•5	"	-
	NC 88	Green grey W yellow brown	BS 0•5	"	-
	NC 87	Blue grey W yellow brown	BS 0•25-0•5	"	-
	NC 146	Grey green W yellow brown	BS 0•1	"	-
	NC 108	Grey green W rich yellow brown	BS 0•5-1	"	-
	NC 136	Blue grey W brown grey	BS 0•5	"	BSP. V.I.
	NC 113	W Greyish brown	BS 0•25	"	-
	NC 170	W Brownish grey	O/BS 0•5	"	-

	NC 125	Pale grey W yellow brown	BS 0·25–0·5	Massive	V.I.
	NC 129	Blue grey W yellow brown	O/BS 0·5–1·0	"	-
	NC 152	Pale green grey W buff orange	BS 0·25–0·5	"	-
	NC 141	W Yellow fawn	BS 1·0	"	-
	NC 24	W Pale fawn grey	BS 0·25–1·0	"	V
	NC 81	Green grey W yellow brown	O 0·25	"	-
	NC 75	Pale green grey W yellow brown	O/BS 0·5	"	V.
	NC 67	Pale green grey W yellow brown	BS 0·25–1·0	"	-
Calcarenaceous Limestone (Facies III)	NC 132	Pale grey	BS/O 0·5	Massive	-
	NC 82	Pale grey W orange brown	BS 0·5–1·0 M	Massive "Compressed"	-
	NC 110	Grey brown W yellow	BS 0·5	"	-
	NC 149	"	"	"	Horizontal Trall
	NC 150	Pale grey W buff	BS 0·25–0·5	Massive	-
	NC 151	Pale grey	BS 0·25–0·5	Massive "Compressed"	BSP.

	NC 111	Pale grey W red brown	BS 0·25-1·0	Massive	-
Oolitic Ironstone (Facies IV)	NC 186	W Pale fawn brown	O 0·25-1·0	Massive	-
	NC 78	Green grey W reddish yellow brown	O 0·25 BS 1.0	"	-
	NC 158	W Rich reddish yellow brown	O 0·5	"	-
	NC 157	W "	O 0·25 BS 0·5	"	-
	NC 77	W Rich orange-brown	O/BS 0·25	"	BSP.
	NC 153	W Rich reddish yellow brown	BS 0·5	"	-
	NC 154	W Reddish yellow brown	O/BS 0·5-1·0	"	-
	NC 155	W "	"	"	-
	NC 156				<u>Rhizocorallium</u>
	NC 161	W Rich orange-brown	"	"	-
	NC 162	W "	"	"	-
	NC 73	W Rich golden-brown	BS 0·5	"	Burrowed
	NC 133	W "	BS 0·25-0·5	"	-
	NC 160	Greenish grey W rich org.yel.brn	O 0·25 BS 0·5	"	-

Carbonate mudstone with scattered limonitised Oolids (Facies V)	NC 122	Buff with yellow brown spots	O 0•5-1•0 M	Mottled	-
	NC 123	Mottled red yellow brown buff	Concretions 3•4,5•0cm	Massive	-
	NC 99	Pale grey. yellow brown spots	O 0•25-0•75 M	"	-
	NC 100	Buff. yellow brown spots	O 0•5-1•0 M	"	-
	NC 93	Buff. yellow brown spots	O 0•25-0•5 M	"	V.
	NC 166	Buff. brown spots	O 0•5 M	"	-
	NC 128	Pale buff grey	BS 0•5-1•0 M	"	-
	NC 137	Pale grey	BS 0•5	"	-
Carbonate mudstone (weathered)	NC 168	Pale grey W buff	M	Massive	-
Pebble-cobble paraconglomerate (generally oligomictic) C = Clasts (massive) M = Matrix	NC 135	M Buff	BS 0•5-1•0	Massive	-
		C Pale grey & red brown siltstone	2•0cm-4•5cm	"	
	NC 109	M Buff	see NC 122	"	-
		C Grey siltstone with limonite rims	4•0-22•0	"	-

	NC 98	M Fawn	BS 1·0-2·0	Pebbles Horizontal	Borings on clasts
		C Grey siltstone	Discoidal 2·5cm-3·0cm		
	NC 51	M Fawn brown	BS 1·0-2·0	"	"
		C Grey siltstone	Rods & discs e.g. 9·2cm		
	NC 13/10	M Buff yellow	Mud grade	Massive	-
		C Greenish silt-stone	Ellipsoidal 30mm		-
	NC 164	M Yellow brown	BS 0·25-0·5	Pebbles Horizontal	-
		C Greenish grey siltstone	Discoidal 11cm	"	-
	NC 115	M Pale green grey	O/BS 0·25-0·5	Massive	Borings on clasts
		C Pale grey silt-stone	Ellipsoidal 10cm, 4·3cm		"
Soft "Marl"	NC 91	Grey green W fawn brown	mud grade	Massive	-

* O = Discoidal Ooids
BS = Bioclastic Sand
M = Mud Matrix

1. W = Weathered Colour

2. V = Vertical Burrows
I = Inclined Burrows
H = Horizontal Burrows
HG = Hardground
BSP = Burrow Spotted

APPENDIX 22

Dyrham Silt Formation: Hand specimen descriptions: Lithology and Sedimentary Structures

Lithology	Sample Number	Colour	Grain size (mm)	Sedimentary Fabric 1.	Trace Fossils
Coarse micaceous Silt	NC 52	Green grey W yellow brown	Mudgrade	FL 1·5	-
* = calcareous cement	NC 44	Pale green grey W yellow brown	"	FL 0·25	-
	NC 38	Green grey W yellow brown	"	FL 1·5 XL	-
	NC 12	Pale blue grey W yellow orange	"	FL 1·0	-
	NC 36	"	"	FL 0·5-1·0	H
	NC 65*	Pale blue grey W orange brown	0·5	FL 1·0-2·0	-
	NC 66*	"	0·25-0·5	FL 1·0	-
	NC 68*	"	Mudgrade	Massive	-
	NC 39*	Pale blue grey	"	FL 1·0 XL	-
	NC 61*	Pale grey W yellow brown	0·25-0·5	Massive	-
	NC 63*	"	M 0·25-0·5	"	-

	NC 35*	Blue grey W yellow brown	Mudgrade	Massive	-
Medium micaceous Silt	NC 48	Blue grey W yellow brown	Mudgrade	FL 1·0	-
	NC 47	"	"	Massive "Compressed"	-
	NC 23	"	"	FL 0·75-1·0	-
	NC 58/59	"	"	WL 1·0	BSP. H. Diplocraterion
Fine Silt	NC 46	Dark blue grey	Mudgrade	Massive "Compressed"	-
Clay	NC 5	Pale grey W yellow orange	Mudgrade	Massive	-
Shelly muddy micaceous sandstone	NC 72	Green grey W red brown	M 0·5	Massive	BSP.
	NC 138	"	"	"	"
	NC 69	"	"	"	"
	NC 140	"	"	"	" H.
	NC 143	"	"	"	-
	NC 86	"	"	"	BSP.

Friable micaceous silty sandstone * = Hard calcareous cement	NC 28	Green grey W yellow brown	0•25-0•5	Massive	-
	NC 124(a)	Light grey W yellow brown	0•25	Massive "Compressed"	-
	NC 124(b)*	Pale green grey W yellow orange	0•5-1•0	"	BSP. H.
	NC 79*	Green grey W golden brown	M 0•5	Mottled	-
Oligomictic pebble paraconglomerate pebbles = massive siltstone	NC 30	M Green grey	BS 0•5		-
		C Blue grey with limonite coatings	Discoidal 3•5cm	Imbricate	-
	NC 33 (weathered) with gypsum veins	M Grey green W reddish orange	BS 0•5	-	-
		C "	Ellipsoidal length 5.0cm	-	-
	NC 34	M Grey green	BS 0•5-3•0		-
		C Grey blue	Discoidal & Ellipsoidal lengths 3•3cm 2•7cm	Sub- horizontal	-
	NC 71	M Grey green	BS 0•5-3•0		-
		C Grey	Discoidal 6•0cm width	Sub- horizontal	-

Oolitic Ironstone	NC 104	Dark brown grey. Green white spots	O 0·25-0·5	Massive	-
	NC 105 (weathered)	Pale green grey W rich reddish orge.	O 0·25	"	-
	NC 114	Dark green brown with yellow grey spots W orange buff	O 0·25	"	-
	NC 116	Pale blue grey. Brown grey spots W yellow brown	BS 0·25 O 0·75	"	-
Calcarenite	NC 21	Light grey	BS 0·25-0·5	"	-
Crinoidal limestone	NC 37	Pale grey W orange brown	Stems length 2·8cm M	Stems horizontal	-

(N.B. Key as for Appendix 21)

1. FL = Flat laminations (thickness given mm)
   XL = Cross laminations
   WL = Wavy laminations

APPENDIX 23

Marlstone Rock Bed Formations: Hand specimen descriptions: Fauna and Flora

Lithology	Sample Number	Brachiopods Rhynchonellid(R) Terebratulid(T)	Crinoids Pentagonal Stems(P) Ossicles(O)	Thin Shelled Bivalves	Broken Thin Shelled Bivalves	Ammonites	Belemnites	Others*
Ferruginous muddy fine micaceous sandstone (Facies I)	NC 50	T	-	-	-	-	-	-
	NC 130	-	-	PR	-	-	-	-
	NC 102	-	-	-	-	-	-	-
	NC 103	-	-	PR C	-	-	-	-
	NC 15	R	P	-	PR	-	-	W
	NC 17	-	-	-	-	-	-	-
	NC 16	-	-	PR C	-	-	-	-
	NC 112	R	P	PR	-	-	-	G
	NC 19	-	-	-	PR C	-	-	-
	NC 18	-	-	-	PR M	-	-	-
	NC 20	-	-	-	-	-	-	-
	NC 22	-	-	PR	-	-	-	-
	NC 127(c)	-	-	-	PR	-	-	-
	NC 165	-	-	-	PR	-	-	-
	NC 134	-	-	PR M	-	-	PR	-
	NC 144	-	-	PR	PR M	-	-	-

C = Cast
M = Mould

*E = Echinoid
G = Gastropod
W = Wood fragments
SH = Shark dental plate
SP = Serpulid

PR = Present
- = Absent

Cont.

	NC 145	-	-	-	-	-	-	-
	NC 85	-	O	-	PR	-	-	-
	NC 84	-	-	-	-	-	-	-
	NC 80	-	-	-	PR	-	-	SP
	NC 76	-	-	-	-	-	-	-
	NC 106	R	-	-	PR	-	-	-
	NC 107	-	-	-	-	-	-	-
Shelly ferruginous oolitic calcarenite (Facies II)	NC 147	R	-	-	PR	-	PR	-
	NC 148	R	P	-	PR	-	PR	-
	NC 120	R	-	-	PR	-	PR	-
	NC 96	R	P	PR	PR	-	PR	-
	NC 159	R	O	-	PR	-	PR	-
	NC 167	-	-	-	PR	-	-	-
	NC 95	-	P	-	PR	-	PR	-
	NC 121	-	-	PR	-	-	-	-
	NC 94	T	P	PR	-	-	PR	-
	NC 92	-	-	-	PR	-	-	-
	NC 90	R	-	PR	PR	-	-	-
	NC 117	R	O	-	PR	-	PR	SH W
	NC 118	-	-	-	PR	-	PR	-
	NC 119	-	P	-	PR	-	PR (Broken in situ)	-

Cont.

	NC 89	R	O	PR	PR	-	PR	-
	NC 88	-	-	-	PR	PR <u>Pleuroceras sp</u>	PR	G
	NC 87	R	-	-	PR	-	-	-
	NC 146	R(Broken <u>in situ</u>)	-	PR	-	-	-	-
	NC 108	R	O	PR	PR	-	PR(Broken <u>in situ</u>)	-
	NC 136	-	-	-	PR	-	-	-
	NC 113	-	P	-	PR	-	-	-
	NC 170	-	-	-	-	-	-	-
	NC 125	-	-	-	PR	-	-	-
	NC 129	-	-	PR	PR	-	PR	-
	NC 152	-	-	PR	PR	-	PR	E(Broken <u>in situ</u>)
	NC 141	-	-	-	PR	-	PR (Broken <u>in situ</u>)	-
	NC 24	-	-	-	PR	-	PR	E
	NC 81	-	O.P.	PR	-	PR	-	G
	NC 75	-	-	-	PR	-	-	-
	NC 67	R	O.P.	-	PR	-	PR	-
Calcarenaceous Limestone	NC 132	R	-	PR	-	-	PR	-
	NC 82	-	O	-	PR	-	-	-
(Facies III)	NC 110	-	-	PR	-	-	PR	-

Cont.

	NC 149							W
	NC 150	-	-	PR	-	-	PR (Broken *in situ*)	-
	NC 151	-	-	PR	-	-	PR	-
	NC 111	T.R.	P	PR	-	-	PR	-
Oolitic Ironstone (Facies IV)	NC 186	-	-	-	PR	-	-	-
	NC 78	T	-	-	PR	-	PR	-
	NC 158	-	-	-	PR	-	-	-
	NC 157	-	O.P.	PR	-	-	-	-
	NC 77	-	-	-	PR	-	-	-
	NC 153	-	-	-	PR	-	-	-
	NC 154	-	-	-	PR	-	-	-
	NC 155	-	-	-	PR	-	-	-
	NC 156	-	-	-	-	-	-	-
	NC 161	-	-	-	PR	*Pleuroceras sp*	-	-
	NC 162	T	P	-	PR	-	PR	-
	NC 73	-	O	-	PR	-	PR (Broken *in situ*)	-
	NC 133	-	O	-	PR	-	-	-
	NC 160	-	-	-	PR	-	-	-

Cont.

Carbonate mudstone with scattered limonitised ooliths (Facies V)	NC 122	R	-	PR	-	-	-	-
	NC 123	R	-	PR	-	-	-	-
	NC 99	-	-	-	PR	-	-	-
	NC 100	-	-	-	-	-	-	-
	NC 93	-	-	-	-	-	PR	-
	NC 166	-	-	-	-	-	-	-
	NC 128	-	-	-	PR	-	-	-
	NC 137	-	-	PR	-	<u>Pleuroceras apyrenum</u>	-	-
Carbonate mudstone (weathered)	NC 168	-	-	-	-	-	PR	-
Pebble-cobble paraconglomerate	NC 135	T	-	-	PR	-	-	-
	NC 109	-	-	-	-	-	PR	-
	NC 98	R	-	-	-	-	-	-
	NC 51	-	O	-	PR	-	PR	-
	NC 13/10	-	-	PR	-	-	-	-
	NC 164	-	-	-	PR	-	-	-
	NC 115	-	P	-	PR	-	PR	-
Soft "Marl"	NC 91	-	-	-	-	-	PR	-

APPENDIX 24

Dyrham Silt Formation: Hand specimen descriptions: Fauna and Flora

Lithology	Sample Number	Bivalves			Belemnites	Crinoids Pentagonal Stems(P) Ossicles(O)	Ammonites	Others
		Small thin ribbed	Large thick ribbed	Broken thin shelled				
Coarse micaceous silt	NC 52	-	-	-	-	-	-	-
	NC 44	M	-	-	-	-	-	-
	NC 38	-	-	-	-	-	-	-
	NC 12	-	-	-	-	-	-	-
	NC 36	-	-	-	-	-	-	-
	NC 65	PR	-	-	-	-	<u>Aegoceras laticosta</u>	-
	NC 66	PR	-	-	-	-	-	-
	NC 68	PR	-	PR	-	-	-	-
	NC 39	PR	-	PR	-	-	-	-
	NC 61	-	-	PR	PR	-	-	-
	NC 63	M	-	-	-	-	-	-
	NC 35	-	-	PR	-	-	-	-

Cont.

Medium micaceous silt	NC 48	M	-	-	-	-	-	-
	NC 47	M	-	-	-	-	-	-
	NC 23	-	-	-	-	-	-	-
	NC 58/59	-	-	-	-	-	-	-
Fine silt	NC 46	-	-	-	-	-	-	-
Clay	NC 5	-	-	-	-	-	-	-
Shelly muddy micaceous sandstone	NC 72	-	-	PR		P	PR	Brachiopods(T)
	NC 138	-	-	PR	-	-	<u>Amaltheus sp</u>	-
	NC 69	-	-	PR	-	-	-	-
	NC 140	-	-	PR	-	-	<u>Amaltheus sp</u>	-
	NC 143	PR	-	PR	-	-	-	-
	NC 86	-	-	PR	-	-	-	-
Friable micaceous silty sandstone	NC 28	-	-	-	-	-	-	-
	NC 124(a)	-	-	C	-	-	-	-
	NC 124(b)	M	-	-	-	-	-	-
	NC 79	-	-	PR	-	-	-	-

Cont.

Oligomictic Pebble Paraconglomerate	NC 30	-	-	-	PR	-	-	-
	NC 33	-	PR	-	-	-	-	W
	NC 34	-	PR	PR	-	-	-	-
	NC 71	-	-	PR	PR	-	-	-
Oolitic limestone	NC 104	-	PR	PR	-	-	-	-
	NC 105	-	PR	-	-	P (M)	<u>Amaltheus sp</u>	-
	NC 114	-	-	-	-	-	-	-
	NC 116	-	PR	-	PR	-	-	-
Calcarenite	NC 21	-	-	PR	-	-	-	-
Crinoidal limestone	NC 37	PR	-	-	-	P	-	-

C = Cast
M = Mould

APPENDIX 25

Comparison between hand specimen Classification and Particle Size Analysis Classification (Picard) for Dyrham Silt Formation Mudrocks.

Sample Number	Classification: Hand Specimen	Classification: Particle Size Analysis
NC 52	Coarse micaceous silt	-
NC 44	"	Clayey silt
NC 38	"	Sandy silt
NC 12	"	Clayey silt
NC 36	"	Sandy silt
NC 65	"	-
NC 66	"	-
NC 68	"	-
NC 39	"	Silt
NC 61	"	Clayey silt
NC 63	"	"
NC 35	"	"
NC 48	Medium micaceous silt	Silt
NC 47	"	Sandy silt
NC 23	"	-
NC 58/59	"	Silt
NC 46	Fine silt	Clayey silt
NC 72	Shelly muddy micaceous sandstone	Silty sandstone
NC 138	"	Sandy mudstone
NC 69	"	"
NC 140	"	"
NC 143	"	Sandy siltstone
NC 86	"	Sandy mudstone
NC 28	Fine micaceous silty sandstone	Sandy siltstone
NC 124(a)	"	-
NC 124(b)	"	-
NC 79	"	Silty sandstone

NB - = not analysed

(A) APPENDIX 26

Marlstone Rock Bed Formation Facies. Thin Section Petrography: Mean values of components

Chamositic Silty Sandstone Facies (I) n = 24		Area %	Size (mm)	Sorting	Roundness	Shape
Carbonate Grains 3·64%	Echinoderm	2·6	0·33	Well	Subrounded	Variable
	Brachiopod (impunctate)	0·65	0·47	"	Rounded on ends	LS
	Foraminifera	0·33	0·1		Uniserial types	
	Bivalve	0·04	0·2		Occasional thin blades	
	Ostracod	0·02	0·25	Very well	Subrounded	Variable
Ferruginous Grains 8·09%	Peloid	2·9	0·16	"	"	"
	Peloid (spastoliths)	1·3	0·16	Well	Rounded	LS
	Flake	1·3	0·18	Very well	Subrounded on ends	LS
	Peloid (L)	0·8	0·2	Well	Subrounded	LS
	Superficial ooid (L)	0·6	0·3	Very well	"	HS
	Flake (L)	0·5	0·25	Well	Subrounded on ends	LS
	Flake (spastoliths)	0·5	0·2	Very well	"	LS
	Peloid (PL)	0·13	0·04	"	Rounded	HS

	Superficial ooid	0·06	0·12	Well	Rounded	LS
Silici-clastic Grains 31·75%	Quartz (MU)	20·9	0·12	Well	Subangular	LS
	Quartz (MUn)	3·9	0·11	"	"	LS
	Quartz (PY)	1·9	0·12	"	"	LS
	Lithic clasts:chert	1·52	0·12	"	"	LS
	Orthoclase	1·2	0·12	"	"	LS
	Muscovite	0·83	0·22	"	Angular blades	
	Plagioclase	0·63	0·13	"	Subangular	Low S
	Magnetite	0·5	0·1		Irregular grains	
	Biotite	0·19	0·28	Very well	Angular blades	
	Perthite	0·10	0·15	Well	Subangular	Low S
	Microcline	0·06	0·14	"	"	"
	Lithic clast:silt	0·02	0·5	"	Rounded	"

<u>Ferruginous superficial ooid nuclei</u>

(2 - 1 = increasing frequency)
(1) Chamosite peloids (not limonitised)
(2) Echinoderm fragments and Chamosite Flakes (not limonitised)

<u>Matrix</u>

(1) Siliciclastic 8·8%
(2) Chamosite 3·4%

<u>Cements</u>

(1) Sparite 34·24%
(2) Patchy poikilotopic sparite 7·03%
(3) Siderite 3·05%

(B)

Shelly Chamositic Grainstone Facies (II) n = 32		Area %	Size (mm)	Sorting	Roundness	Shape
Carbonate Grains 44•6%	Echinoderm (incl. ossicles & spines)	40•9	0•35	Very well	Subrounded	Variable
	Brachiopods (impunctate)	2•3	0•45	Well	Rounded edges	LS
	Bivalve	0•7	0•60	Well	Rounded	LS
	Foraminifera	0•5	0•1		Mostly uniserial types	
Ferruginous Grains 8•97%	Peloid	3•3	0•2	Very well	Rounded	LS
	Superficial ooid	1•3	0•2	"	"	LS
	Spastolith	1•1	(Consisting of distorted ooids, peloids and flakes)			
	Flake	0•78	0•2	Very well	Rounded on edges	LS
	Ooid (rarely broken)	0•64	0•3	Well	Well rounded	LS
	Superficial ooid (L)	0•55	0•2	Very well	Well	LS
	Peloid (L)	0•45	0•2	Well	Rounded	LS
	Superficial ooid (PL)	0•3	0•1	Very well	Subrounded-well rounded	LS
	Peloid (PL)	0•14	0•3	"	Well rounded	LS
	Ooid (PL)	0•1	0•2	"	Rounded	LS
	Flake (L)	0•01	0•2	Well	Rounded on edges	LS

Silici-clastic Grains 5·8%	Quartz (MU)	4·3	0·15	Very well	Subrounded-subangular	Variable
	Quartz (MUn)	0·42	0·12	"	"	LS
	Quartz (PY)	0·34	0·16	Well	Subangular	Variable
	Lithic clasts:chert	0·23	0·1	Very well	Subangular-subrounded	LS
	Lithic clasts:silt	0·18	6·25	Poor	Subrounded	HS
	Plagioclase	0·13	0·15	Very well	Subangular-subrounded	Variable
	Orthoclase	0·06	0·15	"	"	LS
	Microcline	0·03	0·1	"	"	LS
	Muscovite	0·05	0·1	"	Thin blades	
	Biotite	0·03	0·25	"	"	
	Magnetite	0·03	0·1	"	Irregular grains	

*PY = Polycrystalline (Over 3 crystals)

<u>Ferruginous ooid nuclei</u>

(6 - 1 = increasing frequency)
(1) Chamosite peloids
(2) Chamosite peloids (limonitised)
(3) Chamosite flakes (limonitised)
(4) Echinoid fragments
(5) Chamosite flakes
(6) Lithic clasts:silt, calcareous peloids

<u>Cement</u>

(1) Sparite 32·13%
(2) Siderite 3·5%

<u>Micritic Envelopes</u>

Occurs occasionally on carbonate grains. "Locally" very common in thin section. Mostly on echinoderm grains, lesser on brachiopods, least on peloids. Very occasionally clasts may be completely micritised.

<u>Matrix</u>

(1) Chamosite 3·3%
(2) Micrite (including neomorphic pseudospar) 1·5%
(3) Siliciclastic 0·2%

(C)

Grainstone Facies (III) n = 6		Area %	Size (mm)	Sorting	Roundness	Shape
Carbonate Grains 56·6%	Echinoderm	50·3	0·4	Very well	Subrounded	Variable
	Brachiopod (impunctate)	5·0	0·48	"	Subrounded on ends	Thin blades
	Foraminifera	0·4	0·18	Uniserial types		
	Algae	0·3	0·5	Fragments of <u>Dascyladaecae</u>		
	Bivalve	0·3	0·6	Well	Elongated fragments	
	Oolith	0·2	1·25	"	Rounded	HS
Ferruginous Grains 0·7%	Peloid	0·42	0·23	"	Subrounded	LS
	Spastolith (peloids)	0·17	0·25	"	Rounded	LS
Silici-clastic Grains 9·6%	Quartz (MU)	7·3	0·21	Very well	Subrounded-subangular	LS
	Lithic clasts:chert	1·6	0·18	"	Subangular	LS
	Orthoclase	0·25	0·1	"	"	LS
	Muscovite	0·08	0·1	"	"	LS
	Quartz (PY)	0·08	0·15	"	"	LS
	Perthite	0·08	0·25	"	"	HS
	Microcline	0·08	0·25	"	"	HS

	Plagioclase	0·08	0·15	Very well	Subrounded	LS

Micritic Envelopes

Occasional micritic envelopes on Echinoderm and Brachiopod clasts.

Matrix

(1) Chamosite 1·2%

Cement

(1) Sparite 29·4%
(2) Siderite 2·5%

(D)

Chamositic And Sideritic Grainstone Facies (IV) n = 11		Area %	Size (mm)	Sorting	Roundness	Shape
Carbonate Grains 47•7%	Echinoderm	43•4	0•32	Very well	Subrounded	LS
	Brachiopod (impunctate)	3•5	0•47	Well	Rounded edges	LS
	Foraminifera	0•45	0•3	Uniserial occasional planispiral		
	Bivalve	0•32	1•0	Well	Rounded edges	LS
Ferruginous Grains 18•91%	Peloid	6•27	0•12	Very well	Very well	LS
	Ooid broken (LP)	3•5	0•47	"	Angular	LS
	Flake	1•82	0•18	"	Rounded	LS
	Superficial ooid (L)	1•55	0•13	"	Very well	LS
	Superficial ooid	1•27	0•19	"	"	LS
	Superficial ooid (LP)	1•14	0•24	"	"	LS
	Flake (LP)	1•0	0•2	"	Rounded	LS
	Peloid (LP)	0•82	0•19	"	Very well	LS
	Ooid (LP)	0•18	0•5	"	"	LS

Silici-clastic Grains 6·61%	Quartz (MU)	3·27	0·12	Very well	Subangular	Variable
	Quartz (MUn)	2·77	0·15	"	"	HS
	Plagioclase	0·18	0·16	"	"	HS
	Quartz (PY)	0·14	0·25	"	"	HS
	Perthite	0·05	0·1	"	"	LS
	Orthoclase	0·05	0·1	"	"	HS
	Microcline	0·05	0·1	"	"	HS
	Lithic clasts:chert	0·05	0·25	"	"	HS
	Magnetite	0·05	0·06		Irregular grains	

<u>Ferruginous Ooid Nuclei</u>

(4 - 1 = increasing frequency)
(1) Chamosite peloids
(2) Chamosite flakes
(3) Echinoderm grains and quartz
(4) Brachiopod grains and calcareous grain intraclasts

<u>Micritised Grains</u>

Occasionally common "locally" in sections. Probably originally Echinoderm and Brachiopod clasts.

<u>Matrix</u>

(1) Chamosite 3·45%

<u>Cement</u>

(1) Sparite 16·73%
(2) Siderite 6·60%

(E)

Limonite-Oolite Pseudospar Facies (V) n = 9		Area %	Size (mm)	Sorting	Roundness	Shape*
Carbonate Grains 12·7%	Bivalve	5·1	0·7	Poor	Variable	Variable
	Echinoderm	3·7	0·6	Well	"	"
	Brachiopod (impunctate)	2·4	0·7	"	Rounded	LS
	Peloid	0·8	0·5	"	"	Variable
	Foraminifera	0·6	0·25	"	Planispiral and uniserial types	
	Intraclast	0·1	1·8	Poor	Angular	LS
Ferruginous Grains (1) 6·3%	Ooid (PL)	2·2	0·3-0·5	Very well	Well	HS
	Ooid (L)	2·1	0·7	"	"	Variable
	Ooid	1·1	0·3	"	Rounded	LS
	Peloid	0·3	0·2	"	Well	HS
	Superficial ooid (L)	0·2	0·1	"	"	HS
	Broken ooid (L)	0·1	-	"	Angular	LS
	Spastolith (L)	0·1	0·8	"	-	LS
	Spastolith	0·1	0·8	"	-	LS
	Peloid (L)	0·1	0·04	"	Subrounded	LS

Silici-clastic Grains (2) 0·6%	Quartz (MU)	0·6	0·1	Very well	Subangular	LS
	Lithic clasts:silt	0·2	3·0	Poor	Angular	LS
	Quartz (MUn)	0·1	0·2	Very well	Variable	HS

*LS = Low Sphericity
HS = High Sphericity

(1) L = Limonitised
PL = Partly Limonitised

(2) MU = Monocrystalline Unit
MUn = Monocrystalline undulose

<u>Ferruginous ooid nuclei</u>

(4-1 = increasing frequency)
(1) Echinoderm fragments and spines
(2) Siltstone clasts
(3) Eroded Fe ooids
(4) Calcareous peloids, Limonitised Chamosite flakes, Chamosite peloids.

<u>Matrix</u>

Micrite
(including Neomorphic Pseudospar) 68·7%
Chamosite 1·6%

<u>Cement</u>

Sparite = 9·4%
Siderite = 0·7%

APPENDIX 27

Marlstone Rock Bed Formation: Textural Divisions of Facies

Facies	Sample Number	Mudstone* (<10% Grains)	Wackestone (>10% Grains)	Packstone (Grains in contact & matrix)	Grainstone (no matrix)
Chamositic Silty Sandstone Facies (I)	NC 50		PR		
	NC 130				PR
	NC 102				PR
	NC 103				PR
	NC 15			—— Variable ——	
	NC 16			"	
	NC 17			PR	
	NC 112			—— Variable ——	
	NC 18			"	
	NC 19			PR	
	NC 20			PR	
	NC 22				PR
	NC 127(C)				PR
	NC 165				PR
	NC 134		PR		

	NC 145				PR
	NC 85				PR
	NC 84			Variable	
	NC 80			Variable	
	NC 76				PR
Shelly Chamositic Grainstone Facies (II)	NC 98				PR
	NC 147			Variable	
	NC 148				PR
	NC 120			Variable	
	NC 96				PR
	NC 159				PR
	NC 167				PR
	NC 95			Variable	
	NC 121				PR
	NC 94				PR
	NC 92			PR	
	NC 90			Variable	
	NC 117			"	
	NC 118				PR
	NC 119			Variable	
	NC 89			"	

	NC 88				PR
	NC 87				PR
	NC 146				PR
	NC 108				PR
	NC 136				PR
	NC 113			Variable	
	NC 170				PR
	NC 125				PR
	NC 129				PR
	NC 152				PR
	NC 141				PR
	NC 24			Variable	
	NC 81				PR
	NC 75				PR
	NC 74				PR
	NC 67				PR
Grainstone Facies (III)	NC 132				PR
	NC 82				PR
	NC 110				PR
	NC 150				PR
	NC 151				PR

	NC 111					PR
Chamositic & Sideritic Grainstone Facies (IV)	NC 78					PR
	NC 158					PR
	NC 157					PR
	NC 77					PR
	NC 153					PR
	NC 155					PR
	NC 161				Variable	
	NC 162					PR
	NC 73					PR
	NC 133				Variable	
	NC 160					PR
Limonite-Oolitic Pseudospar Facies (V)	NC 122		PR			
	NC 109		PR			
	NC 99			Variable*(1)		
	NC 100		PR			
	NC 166				PR	
	NC 168	PR				
	NC 93				PR	
	NC 128			Variable		

	NC 137		PR		

* Includes Neomorphic Pseudosparite

*(1) "Variable" = Sections containing irregular lenticular patches or streaks of matrix often parallel to the bedding (usually below 1·0mm in length). These are infillings of burrows. The rest of the rock is massive; both these features suggest intensive bioturbation.

APPENDIX 28

Sources of data for Fig. 50 (Marlstone Rock Bed Facies Map)

Donovan (1958)	p. 132	Dundry Hill
Hull (1857)	p. 22	Milton Down
Ivimey-Cook (1978)	p. 8	Elton Farm Borehole
Simms (pers. comm. 1983)		Oxenton Hill
Smithe (1877)	p. 355	Churchdown
Whittaker and Ivimey-Cook (1972)	p. 6	Lalu Barn Borehole
Witchell (1865)	p. 14	Stroud
Woodward (1893)	p. 156	Mickleton Wood Borehole
Worssam (1963)		Upton Borehole

BGS Borehole File

Swainswick No. 1 (ST 7422 7243)

Manor Farm, Burford (SP 2533 1379)

Stow-on-the-Wold No. 4 (SP 2933 2351)

Salford (SP 2885 2831)

APPENDIX 29

Sources of data for Fig. 51 (Dyrham Silt Formation - Thickness and Facies Maps)

Davoei Zone

Fry (1951)	p. 200	Dodington Ash	14
Gavey (1853)	p. 29	Mickleton Tunnel	42(M)
Green and Melville (1956)	p. 4	Stowell Park Borehole	43
Ivimey-Cook (1978)	p. 8	Elton Farm Borehole	46
Phelps (1982)	(Fig. A:2:6:2)	Taitshill	27(M)
		Far Green	42
		Stonehouse Brickpit	23(M)
		Tuffley Brickpit	43
Witchell (1885)	p. 17	Dudbridge	7
Whittaker and Ivimey-Cook (1972)	p. 40	Lalu Barn Borehole	7(M)
Woodward (1893)	p. 156	Mickleton Wood Borehole	76
(1894)	p. 303	Signet Borehole	9(M)
Worssam (1963)	p. 128	Upton Borehole	42

Margaritatus Zone

Consolidated Oil and Gas (UK) Ltd.		Highworth No. 1 'Middle Lias'	206
Fry (1951)	p. 200	Dodington Ash	0
Green and Melville (1956)	p. 40	Stowell Park Borehole	35
Ivimey-Cook (1978)	p. 8	Elton Farm Borehole	46
Phelps (1982)	(Fig. A:2:6:2)	North Nibley	7

Phelps (1982)	(Fig. A:2:6:2)	Taitshill	13
		Coldharbour Farm Stream	13
		Far Green Stream	13
		Stonehouse Brickpit	23
		Tuffley Brickpit	30
Reynolds and Vaughan (1902)	p. 731	Sodbury Tunnel	1
Whittaker and Ivimey-Cook (1972)	p. 38	Lalu Barn Borehole	35
Witchell (1882)	p. 17	Dudbridge	7
Woodward (1893)	p. 212	Batheaston Borehole	4
	p. 156	Mickleton Wood Borehole	90
	p. 221	Cheltenham-Banbury Railway Tunnel	5
(1894)	p. 303	Signet Borehole	30
Worssam (1963)	p. 127	Upton Borehole	10

Dyrham Silt Formation

Cave (1977)	p. 79	Sodbury	21
		Hawkesbury	30
		Wotton-under-Edge	37
		North Nibley	34
		Taitshill	40
		Coaley	46
Consolidated Oil and Gas (UK) Ltd.	(SU 1810 9155)	Highworth No. 1	8
Dreghorn (1967)	p. 72	Churchdown Hill	44
Fry (1951)	p. 200	Dodington Ash	14
Green and Melville (1956)	40,41	Stowell Park Borehole	89

Hull (1857)	p. 19	Leckhampton	30
Ivimey-Cook (1978)	p. 8	Elton Farm Borehole	6
Phelps (1982)	(Fig. A:2:6:2)	Stonehouse Brickpit	46(M)
		Tuffley Brickpit	75
Reynolds and Vaughan (1902)	p. 731	Sodbury Tunnel	19
Whittaker and Ivimey-Cook (1972)	38,39	Lalu Barn Borehole	61
Williams and Whittaker (1974)	p. 32	Weston Subedge	61
	p. 32	Lark Stoke	67
	p. 32	Ilmington	46
Witchell (1882)	p. 17	Dudbridge	10
Woodward (1893)	p. 156	Mickleton Wood Borehole	20
	p. 212	Batheaston	1
	p. 221	Kingham Hill Well	14
	p. 221	Cheltenham-Banbury Railway Tunnel	0
(1894)	p. 303	Signet Borehole	0
Worssam (1963)	p. 127	Upton Borehole	0
<u>Present Survey</u>	DSF Locality 17		27(M)
	26		25(M)

<u>Dyrham Silt Formation-Facies</u>

Cave (1977)	p. 79	Sodbury-Cam
Consolidated Oil and Gas (UK) Ltd.		(SU 1810 9155) Highworth No. 1
Falcon and Kent (1960)	p. 16	Faringdon No. 1
Fry (1951)	p. 200	Dodington Ash
Green and Melville (1956)	40,41	Stowell Park Borehole

Hull (1857)	p. 22	Milton Down
Ivimey-Cook (1978)	p. 8	Elton Farm Borehole
Moore (1867)	p. 128	Limpley Stoke
	p. 152	Upton Cheyney
Phelps (1982)	(Fig. A:2:6:2)	Taitshill
		Coldharbour Farm Stream
		Far Green Stream
Reynolds and Vaughan (1902)	p. 731	Sodbury Tunnel
Richardson (1929)	p. 26	Oddington
Simms (pers, comm. 1983)		Oxenton Hill
Smithe (1877)	p. 355	Churchdown Hill
Walford (1879)	p. 12	Dumbleton
Whittaker and Ivimey-Cook (1972)	38,39	Lalu Barn Borehole
Williams and Whittaker (1974)	p. 32	Ebrington Hill
Witchell (1865)	p. 14	Stroud
(1882)	p. 17	Dudbridge
Woodward (1893)	p. 212	Batheaston Borehole
	p. 221	Kingham Hill Well
	p. 221	Cheltenham-Banbury Railway Tunnel
(1894)	p. 303	Signet Borehole
Worssam (1963)	p. 127	Upton Borehole

<u>BGS Boreholes</u>

Swainswick No. 1 (ST 7422 7243)

Apley Barn Borehole (SP 3437 1066)

<u>Present Study</u> DSF Locality 7

8

Present Study	DSF Locality	9
		11
		12

APPENDIX 30

Wildcat oil well logs in the Cotswolds passing through the Pliensbachian (Department of Energy)

Shell UK Ltd. 1975 Sherbourne No. 1 (SP 13620 13930)

Shell UK Ltd. 1975 Cooles Farm No. 1 (SU 01641 92135)

Consolidated Oil and Gas (U.K.) Ltd. 1976 Highworth No. 1 (SU 1810 9155)

Bearcat Explorations (U.K.) Ltd. 1978 Guiting Power No. 1 (SP 2084 2450)

APPENDIX 31

Sources of data for Fig. 52 (Marlstone Rock Bed Isopachyte Map)

All thicknesses given are converted to metres.

Buckman and Wilson (1896)	p. 695	Dundry Hill (W)	0
Cave (1977)	p. 90	Hillesley	1.52
	p. 90	Hillesley	0.9
	p. 90	Alderley	2.44
	p. 91	Wotton-under-Edge	5.03
	p. 91	Southend	3.0
	p. 91	Millend	4.27
	p. 92	Uley	2.40
Donovan (1958)	p. 132	Dundry	0.30
Falcon and Kent (1960)	p. 16	Faringdon No. 1	6.1
Fry (1970)		Bitton	0.94
Green and Melville (1956)	p. 4	Stowell Park Borehole	1.78
Hull (1857)	p. 20	Chastleton	3.66
	p. 20	Daylesford	0.1A
Ivimey-Cook (1978)	p. 8	Elton Farm Borehole	1.26
Moore (1867)	p. 149	Dumbleton	1.82
Richardson (1929)	p. 26	Oddington	5.49
(1930)	p. 198	Callowell	3.0
Simms (pers. comm. 1983)		Oxenton Hill	0.55
Smithe (1877)	p. 355	Churchdown	2.03
Whitehead *et al* (1952)	p. 157	Fig. 20	
Witchell (1865)	p. 14	Stroud	1.22
(1882)	p. 17	Dudbridge	0.91
Whittaker and Ivimey-Cook (1972)	p. 6	Lalu Barn Borehole	6.02

Woodward (1893)	p. 156	Mickleton Wood Borehole	10.97
	p. 212	Batheaston Borehole	0.3
	p. 221	Cheltenham-Banbury Railway Tunnel	3.4
Worssam and Bisson (1961)	p. 77	Upton Borehole	5.34
	p. 78	Taynton	1.83
	p. 78	Taynton (Coombe Brook Valley)	0.1A
	p. 78	Windrush Valley	3.06

BGS Borehole File

Swainswick No. 1	(ST 7422 7243)	0.17
Ebley and Westrip No. 5	(SO 8281 0475)	1.70
Stow-on-the-Wold No. 2	(SP 20027 24524)	4.57
Burford Brewery	(SP 2500 1225)	1.52
Apley Barn Borehole	(SP 3437 1066)	1.62
Cornbury Park, Charlbury	(SP 34100 19770)	1.5
Great Rollright	(SP 32250 31900)	1.83
Hook Norton	(SP 37210 3351)	4.88
Chipping Norton	(SP 33815 29900)	3.66

BGS Maps 1:63360 Sheet 218 Chipping Norton

236 Witney

Present Survey

Locality	1	1.3
	3	0.3A
	4	0.5A
	20	5.56

Locality 21	4.6
23	4.15
31	2.9
34	5.6
37	1-2A
39	2.0A
41	0.42
42	0.56
43	1.15
50	2.0A
53	1.07

APPENDIX 32

Onshore oil well logs and BGS boreholes - Wessex Basin and Offshore areas

Ulster Petroleums (Canada) Ltd. 1972 Devizes No. 1 (ST 96026 56987)

Berkeley Petroleum UK Ltd. 1972 Nettlecombe No. 1 (SY 350530 095439)

British Petroleum Oil Development Ltd. 1972 Cranbourne No. 1 (SU 03408 09073)

British Gas Council 1973 Wytch Farm No. 1 (SY 9804 8526)

Berkeley Petroleum 1974 Seaborough No. 1 (ST 4348 0620)

British Gas Council 1975 Wytch Farm No. 2 (SY 9895 8555)

" " No. 3

" " No. 4

British Gas 1975 Arne No. 1 (SY 95750 87040)

" " 1977 Wareham No. 3 (SY 9059 8721)

" " 1977 Stoborough No. 1 (SY 9126 8659)

Shell UK Ltd. (pers. comm. 1983) Lockerley No. 1 (SU 3068 2591)

BGS Boreholes

Onshore Green and Whittaker (1980) Hill Lane, Brent Knoll (ST 3346 5156)

Holloway (1982) Bruton No. 1 (ST 6896 3284)

Rhys et al 1982 Winterbourne Kingston (SY 8470 9796)

Offshore Dingwall and Lott (1979) Whitethorn No. 74/40 50° 36.98' N 2° 54.15' W

Offshore Evans et al (1981) Zephyr No. 88/2-1

49° 51' 13.9" N 3° 47' 21.2" W

Fletcher, B.N. and Lott, G.K. (1973)

IGS Borehole 73/56 51° 26·75' N

4° 6·95' W