THE SILESIAN SUB-SYSTEM IN WARWICKSHIRE, SOME ASPECTS OF ITS PALYNOLOGY, SEDIMENTOLOGY AND STRATIGRAPHY

VOL I

IAIN MACFIE FULTON
Doctor of Philosophy

THE UNIVERSITY OF ASTON IN BIRMINGHAM
March 1987

CONTAINS
PULLOUTS

This thesis is dedicated to my wife Linda,
without whose patience and support this
study would not have been possible.

....For knowledge should teach us above all that every fact is a matter of opinion.

Professor A.M. Low 1937

The University of Aston in Birmingham

The Silesian Sub-System in Warwickshire, some aspects of its palynology, sedimentology and stratigraphy.

Iain Macfie Fulton
Doctor of Philosophy
1987

SUMMARY

A detailed palaeogeography of the Warwickshire Coalfield for the Namurian, Westphalian A and B Stages has been constructed to demonstrate that during these times the Coalfield lay at the southern perimeter of the Pennine Basin.

Examination of large amounts of Westphalian A and B age borehole core has allowed the construction of a framework for the description and classification of rocks of these ages. The lithofacies recognised have been combined to form 10 associations and the depositional environments in which they accumulated have been interpreted. Five associations have been identified illustrating processes by which lakes were infilled, including proximal and distal overbank flooding, crevassing and progradation of distributary mouth bars. Four palaeosol associations have been interpreted on the basis of drainage, histosol accumulation and proximity to siliciclastic sedimentation. Channel fill and marine deposits have also been interpreted.

A study of the palynology of a Westphalian B example of the association 'Long-residence histosol/s', the Warwickshire Thick Coal, has enabled the identification and systematic description of 146 miospore species belonging to 58 genera, including 19 new forms.

Use of 5 miospore types characterised by 7 miospore species has allowed the leaves of the Thick Coal to be divided palynologically. A palaeoecological interpretation of the Thick Coal has been made using both this and sedimentological data. Miospore species likely to be useful in the correlation of the leaves of the Thick Coal have been identified.

Two depositional models have been constructed for periods of time when areas underwent either rapid or slow subsidence, and the mechanisms controlling the distribution of associations during these times have been discussed. Factors controlling subsidence and their effects have also been considered, on both a local scale with respect to the Thick Coal, and on a regional scale with respect to palaeogeography. Finally the environmental setting for the Coalfield was discussed and comparisons made with other Coalfields in the Pennine basin.

Keywords: Warwickshire, Silesian, lithofacies, miospores,
palaeogeography.

ACKNOWLEDGEMENTS

This thesis was completed part time at Aston University whilst the writer was working for the N.C.B. (now British Coal) in South Midlands Area as Mine Geologist for the Warwickshire Coalfield. Financial help from British Coal for fees, typing, and photography is gratefully acknowledged.

Supervision of the project was initially undertaken by Dr. Mavis Butterworth (Aston University) and I would like to thank her for the encouragement I received, and for the lively discussions about, and constructive criticism of the palynological aspects of this study. Dr. Peter Turner (Aston University) supervised the later stages of this project and I am very appreciative of his time spent in discussion and scrutiny of all other aspects of this study. I would also like to thank Professor D.D. Hawkes (Head of Department, Aston University) for use of the University facilities, and Eric Hartland (Head Technician Aston University) and members of his staff for their enthusiastic assistance.

I am indebted to Mr. S. Criddle (South Midlands Area Chief Scientist, retired) for granting me permission to use the facilities at British Coal's, South Midlands Area Laboratory, Nuneaton, and Mr. R. Blythman (Acting Area Chief Scientist) for his continued support. Acknowledgement is also made for the technical assistance received from Glenda Downes, Peter Abell and John Lewis (Water Laboratory) and Peter Neal (Coal Survey Laboratory).

Study of underground exposures was simplified by the co-operation given me by the Managers of collieries visited, especially Daw Mill (Mr. Dennis Childs) and Coventry Collieries (Mr. Cyril Smith) where the majority of the underground work was undertaken, and by members of

the Survey staff at each of the collieries. Invaluable aid has also been given me by colliery survey staff and Peter Bateman (British Coal geologist, seconded to South Midlands Area) in discussion and logging of underground exposures.

I am grateful to Graham Crawford (South Midlands Area Programmer) for writing the computer program enabling me to carry out Markov Chain analysis, and to Philip Richardson (South Midlands Area, Mine Geologist) and Bill Read (British Geological Survey, retired) for discussions on that subject. Data necessary for the compilation of the palynological tables Appendix 'C' and 'D' was fed into the computer and manipulated by Ivan Larter (British Coal, Daw Mill Colliery).

I with to acknowledge the help given by Paul Griffiths (Aston University, Technical Dept.) who developed the negatives for all the individual palynological photographs, and Michael Conibear (South Midlands Area Photographer) who took, developed and printed the pictures of underground exposures and produced the palynological plates.

Most of the graphic logs of boreholes were partly drafted by Tom Freeman (British Coal, Production Managers Centre, Warks.) and Heather Newbold (South Midlands Area, Geological Department, Tracer), and the typing of both these logs and many other figures and tables was carried out proficiently by Sheila Cadman (British Coal, Production Managers Secretary, Warks.). Susan Bourne (South Midlands Area, Planning Department, Tracer) also drafted a few of the figures.

The first draft of several of the chapters was typed by Margaret Gregory (South Midlands Area, Typing Services Supervisor) and her staff, but the final version of the thesis was typed rapidly and efficiently by Carole Humber (Havencrest Word Processing Services).

This thesis would not have been possible without the help and advice of many colleagues both within British Coal and at universities and the British Geological Survey. In particular I would like to thank Tim Ball, Peter Bateman, Bernard Besly, David Clay, Robert Elson, Christopher Fielding, Paul Guion, Philip Jones, Eddie McInairnie, John O'Dell, Robin Old, Philip Richardson, John Rippon, Harold Smith and Huw Williams for many stimulating discussions.

Special thanks go to Alyn Jones (South Midlands Area Geologist, retired) without whose assistance I would not have been able to start this study, and to Philip Jones (South Midlands Area Geologist) for his continued support during the course of this study.

Permission to carry out this thesis was originally given by Mr. R. Rawlinson (South Midlands Area Director, retired) and permission to use and publish British Coal geological data has been given by Mr. L. Harris (South Midlands Area Director).

The views expressed in this thesis are those of the writer and not necessarily those of British Coal.

LIST OF CONTENTS

VOLUME I

VOLUME II

LIST OF FIGURES

VOLUME II

LIST OF TABLES

VOLUME II

LIST OF PLATES

CHAPTER 1

INTRODUCTION

1.1 EXTENT OF THIS STUDY

This thesis is a combined palynological, sedimentological and stratigraphical study of the Silesian Sub-System of the Warwickshire Coalfield, an area within which sediments of Westphalian A and B age occur, and contain workable coal seams. It lies at the centre of England with the South Staffordshire Coalfield to the west, the South Derbyshire Coalfield to the north, the Leicestershire Coalfield to the north east and the Oxfordshire Coalfield to the south (Fig.1.1). When placed in the context of other coalfields occurring in the Pennine basin it can be seen that the Warwickshire Coalfield lies towards its southern perimeter.

The shape of the Warwickshire Coalfield is an elongate triangle nearly 60km long and 30km at its widest (Fig.1.2). In the extreme north-west the coalfield is bounded by faults with a NE-SW trend, whilst in the west it is limited by the north-south trending Western Boundary Fault. The Coalfield is bounded in the northeast by faults with a NNW-SSE trend, and to the southeast it is limited by both outcrop and incrop beneath sediments of Triassic age. In the southeast both Westphalian A and B sediments attenuate to zero, against the Brabant Barrier but in the southwest thin Westphalian A and B sediments continue into the Oxfordshire Coalfield. Westphalian A and B sediments outcrop in a narrow strip to the north of the Coalfield, but the majority of the Coalfield is concealed below red Upper Coal Measures and Triassic strata.

Serious exploitation of the Coalfield, using shallow shafts and drift mines along the surface outcrop may have begun as early as the

Fig. 1.1 Coalfields of Great Britain showing the position of the Warwickshire Coalfield within the Pennine basin

After Moses (1981)

Fig. 1.2 Boundaries of the Warwickshire Coalfield fourteenth century. The depth to which the shafts were sunk and the distance from the outcrop increased through the centuries; until the deepest shafts in Warwickshire were sunk at Coventry Colliery by 1918 to a depth of 662 m, and the shafts farthest from the outcrop were sunk at Daw Mill Colliery by 1969. The number of mines producing coal and forming the active Coalfield were five at the beginning of this study viz. Baddesley, Birch Coppice, Coventry, Daw Mill, and Newdigate, but Newdigate shut in 1982 and Birch Coppice will shut this year. Coventry and Daw Mill are the two remaining modern mines both with long term futures, and workings from them are proceeding south west and south respectively, away from the outcrop.

The palynological part of this study was concentrated on the leaves of the Thick Coal at Longmeadow Wood borehole. Sedimentological aspects of the study involved a detailed examination of many metres of mainly Westphalian A and B age borehole core. The stratigraphical part of the study entailed an examination of changes in thickness of Namurian and Westphalian A and B sediments across the Coalfield, and their relationship to the palaeogeography.

1.2 OBJECTIVES OF THE STUDY

The objectives were chosen in such a way that the author's employer the National Coal Board (now British Coal) would benefit directly from the research. Because borehole core plays an important part in the exploration of coalfields it was decided to make its use central to the study.

The principal objectives in the order in which they were dealt with are:

1) To review previous work carried on and to give a description of the geology of the Warwickshire Coalfield. Particular attention was

paid to the lithostratigraphy and sedimentology of the Pre-Permian sediments, together with Lower Silesian biostratigraphy and palaeontology. Details have also been given on the structure of the Coalfield, and a brief history of the possibilities of exploration within and beyond the Coalfield.

2) To summarise the global palaeogeography leading to the formation of the continent on which deposition in the Coalfield took place, and to review evidence for the lower Westphalian palaeoclimate. Some aspects of the relationship between palaeogeography, palaeoclimate and deposition have been given together with a detailed reconstruction of the palaeogeography of the southern part of the Pennine basin. Controls on the evolution of the Pennine basin have also been considered.

3) To provide a framework suitable for use by the N.C.B. for the description and classification of Westphalian A and B sediments. Although based mainly on borehole core, the system has now been devised so that it could be used at both surface and underground exposures. Over 70 lithofacies have been recognised, of which over 50 have been described in detail.

4) To combine the lithofacies into associations and interpret the depositional environments in which they formed. This has been carried out with the aid of computer analysis, and over 50 examples drawn from both borehole core and underground exposures have been presented.

5) To study the palynology of the four leaves of the Warwickshire Thick Coal at Longmeadow Wood borehole, together with the associated siliciclastic sediments, and to provide a type section of the Thick Coal for the N.C.B. 146 miospore species belonging to 58

genera have been systematically described, including 19 new species forms. Special emphasis has been placed on the description of <u>Densosporites</u> species found in this study.

6) To divide each leaf of the Thick Coal on a palynological basis, and using both this and sedimentological data make a palaeoecological interpretation of the Thick Coal. Five miospore types characterised by seven miospore species have been used to divide each leaf.

7) To identify species most likely to be useful in the correlation of the leaves of the Thick Coal.

8) To construct depositional models from the study of the vertical relationship of lithofacies associations and miospore types, and discuss the mechanisms controlling their distribution. Factors controlling subsidence have also been considered, together with the environmental setting within which deposition took place in the Warwickshire Coalfield during the lower Silesian.

CHAPTER 2

MATERIALS EXAMINED

The area within which this study was carried out, the Warwickshire Coalfield, was defined in the previous chapter. Written logs of cored boreholes, drilled by the N.C.B. in their search for coal within and around the Coalfield, form the database for most of this study. Over 80 surface boreholes have been drilled, the majority since 1975, with distances between them varying from a few hundred metres to several kilometres (Fig. 2.1). Core from boreholes drilled before 1975 was not examined by the author, but core from boreholes drilled subsequently has been investigated in detail. Within the active Coalfield many underground exposures have been visited by the author. Those used in this study are shown in Fig. 2.1. Sections of strata encountered during the sinking of mineshafts subsequently abandoned used in the construction of isopachyte maps in the chapter on Silesian palaeogeography are also shown in Fig. 2.1.

It was felt that the precise locations of boreholes specifically mentioned in the text should be supplied, and these are shown below using the National Grid Reference system.

1. Amington SK2205/7984
2. Birch Tree Farm SP3182/0188
3. Bockendon SP2875/0124
4. Bolehall SK2204/1702
5. Broadacres SP3084/1115
6. Blyth Bridge SP2189/1979
7. Catchems Corner SP2576/3334
8. Comberford Lane SK2006/1069
9. Crew Farm SP3172/3600
10. Gibralter SP4464/6165
11. Greenways SP2528/4775
12. Hazel Grove SP3083/1575
13. Little Chase SP2673/4605
14. Longmeadow Wood SP2774/1615
15. Middle Road SP3561/1255
16. Moat House Farm SP2785/8275
17. Muzzards Wood SP2983/8738
18. Newhall Green SP2685/4997

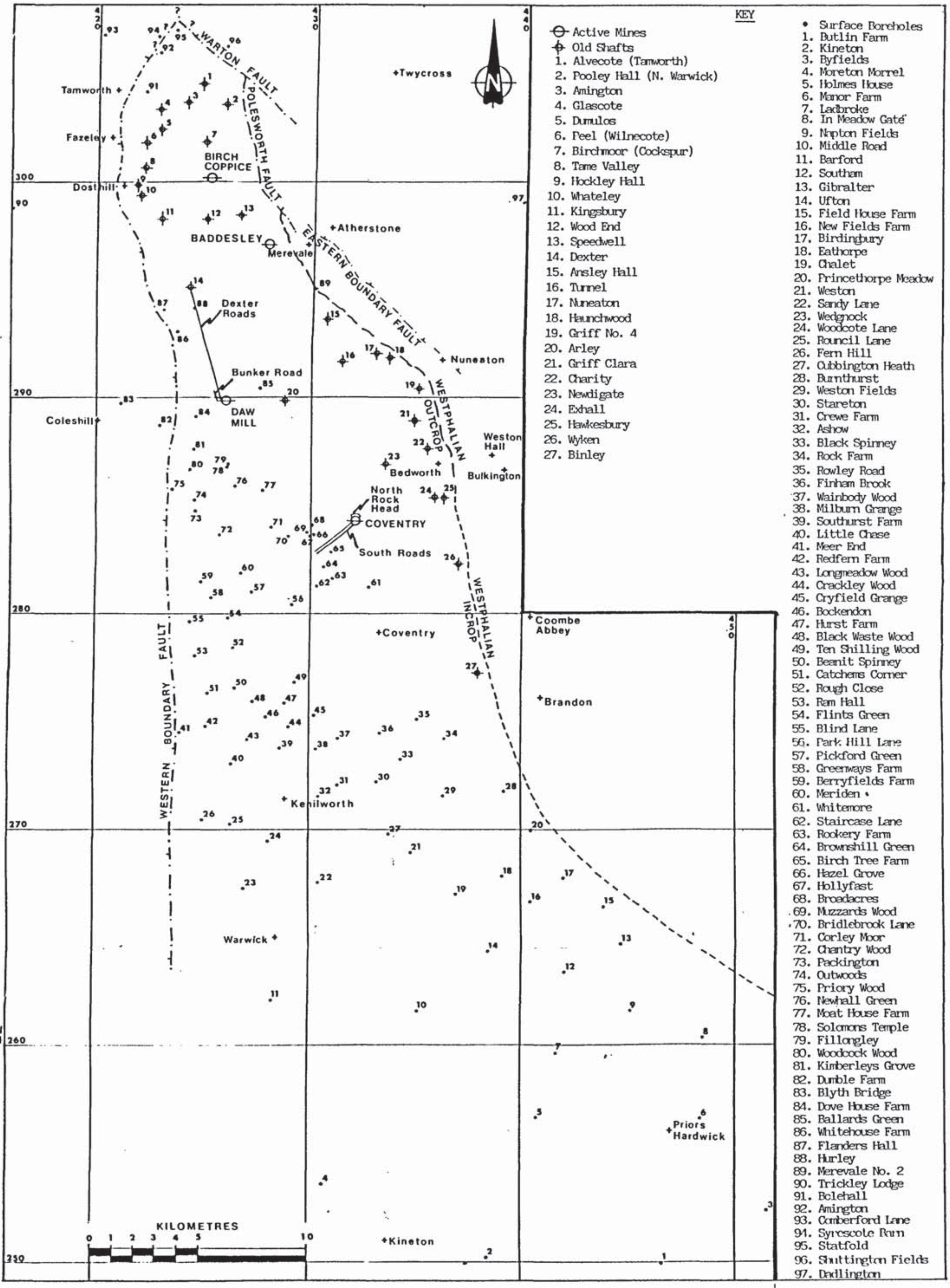


Fig.2.1 The Warwickshire Coalfield, location of data points used in this study

19. Outwoods SP2485/6328

20. Rookery Farm SP3181/0661

21. Solomons Temple SP2686/1089

22. Stareton SP3372/2118

23. Statfold SK2306/4799

24. Syrescote SK2206/6665

25. Trickley Lodge SP1698/0484

26. Ufton SP3864/4425

27. Whitehouse Farm SP2393/8603

Outcrop of strata of Westphalian A-B age is confined to a narrow strip at the northern end of the Coalfield, and is poorly exposed. The discontinuous nature of the exposures makes exact stratigraphical location difficult. The number of exposures are few and overgrown, and this together with the considerable amount of weathering limits the amount of information obtainable from them, and therefore makes them unsuitable for the purposes of this study.

Graphical sections of the boreholes used in the chapter on the Warwickshire Coalfield have been drawn at 1:500 scale (subsequently reduced) and are included in that chapter.

Those portions of the surface boreholes used to illustrate lithofacies associations can be found in the appropriate places in section 5.4. They were originally drawn at 1:20 scale and subsequently reduced.

Although the chapter on palynology is based on data from the Thick Coal at Longmeadow Wood borehole, the palynology of leaves of coal at other localities has also been studied. This includes the leaves of the Thick Coal at Moat House Farm borehole and Westphalian A and B age leaves of coal at Solomons Temple borehole. Some of the photographs of miospore species in Appendix 'D' have been taken from specimens found in these leaves.

CHAPTER 3

THE WARWICKSHIRE COALFIELD

This chapter is a review of previous research on the Warwickshire Coalfield, with special reference to the Silesian Sub-System. It also includes unpublished geological data, derived following recent exploration by the N.C.B. The term Silesian was first proposed as a Series name for the Upper Carboniferous by van Leckwijck (1960) but has now been changed to a Sub-System, divided into three Series, viz. the Namurian, Westphalian and Stephanian (George and Wagner 1972). Its base has been defined as the earliest occurrence of Cravenoceras leion and its top has been defined following Smith et al. (1974) at the base of the overlying Permian. Each of the Series has been subdivided into Stages using a variety of zonal schemes.

The history of the identification of lithostratigraphic 'units' (Beds, Series, Group, Formations) found in the Coalfield is examined in chronological order, and a brief description of each unit is given. Only Silesian units and those lying below the Silesian are analysed in detail, the latter because of possible interaction with the former. However, both those units above the Silesian and those analysed in detail are shown in Table 3.1. Although the terms Lower and Middle Coal Measures are not strictly Formations (Table 3.1) in the sense of Harland et al. (1972), they are used lithostragraphically to define Westphalian A, and Westphalian B plus the grey sediments of Westphalian C age respectively within the Warwickshire Coalfield. Where it is thought necessary the modern equivalents of older stratigraphical units are shown in square [ ] brackets. Previous sedimentological research on the Coalfield is also reviewed.

Four biostratigraphical methods applied to the correlation of Silesian sediments in the Coalfield are discussed. Marine bands are

TABLE 3.1 AN HISTORICAL STRATIGRAPHICAL CORRELATION OF THE ROCKS IN THE WARWICKSHIRE COALFIELD

Latest Stratigraphical Terms															
System	Sub-System	Series	Stage	Group	Formation	Member/ Goniatite Marker	Smith 1815	Howell 1859	Vernon 1912	Barrow et al. 1919	Eastwood et al. 1923	Shotton 1927, 1929	Stubblefield & Trotter 1957 Taylor & Rushton 1971	Geological Society Permian 1974 Silesian 1978 Triassic 1980	R. Old I.G.S. pers. comm. 1980
Jurassic		Lower Lias					Jurassic	Lias	not studied	Not studied	Lower Lias				
Triassic						Pre-Planorbis Beds Watchet Beds						Not studied	not studied	TRIASSIC Penarth Group	not studied
				Penarth	Lilstock Westbury										
				Mercia Mudstone	Blue Anchor	Arden Sandstone	Triassic	Keuper Marl	Keuper Marl	Keuper Marl	Keuper Marl	Keuper Marl		Mercia Mudstone Group	
				Sherwood Sandstone	Bromsgrove Sandstone Polesworth			Keuper Sandstone	Keuper Sandstone	Keuper Sandstone	Keuper Sandstone	Keuper Sandstone		Sherwood Sandstone Group	
								Bunter	Bunter	Bunter	Not studied	Not studied			
Permian		Lower		Enville	Ashow			Permian	Permian Kenilworth Sandstones	Not studied	Not studied	Upper Coal Measures Ashow Group		PERMIAN Ashow Group	Permian Ashow Fm.
					Kenilworth Sandstone	Kenilworth Breccias Gibbet Hill Con.						Kenilworth Breccia Group Gibbet Hill Group		Kenilworth Breccia Group	Kenilworth Sandstone Fm.
Carboniferous	Silesian	Stephanian ?			Tile Hill Mudstone	Beechwood Con.					Permian ? U. Coal M.? Tile Hill Beds	Tile Hill Group	Stubblefield and Trotter 1957 Upper Coal Measures	A. tenuis Gibbet Hill Con. Beechwood Con.	Westphalian 'D' Tile Hill Mudstone Fm.
		Westphalian	D		Coventry Sandstone	Allesley Con. Corley Con. Arley/Exhall Con.			Corley Conglomerate		Allesley Con. Corley Con. Arley/Exhall Con. Envillle Group	Allesley Con. Corley Con. Arley/Exhall Con. Envillle Series		Allesley Con. Corley Con. Arley/Exhall Con. Enville Fm. T. obscuris	Coventry Sandstone Fm. Envillle Group
					Keele				Barren C.M. Keele Beds	Upper C.M. Keele Beds	Upper C.M. Keele Group	Not studied		Keele Fm.	Keele Fm.
					Halesowen Sandstone		Coal Measures	Coal Measures	Haunchwood Sandstone	Halesowen Sandstone Lapworth (1898)	Halesowen Sandstone Group			'D' Halesowen Sandstone Fm. 'D'	Halesowen Sandstone Fm.
			C		Etruria Marl	Aegiranum M.B.			Nuneaton Clay	Etruria Marl	Etruria Marl Group			'C' A. Cambriense 'C' Aegiranum	
			B		(Middle Coal Measures)	Vanderbeckei M.B.			Productive C.M.	Middle C.M.	Middle C.M.		Middle Coal Measures	'B' Vanderbeckei	
			A		(Lower Coal Measures)	Subcrenatum M.B.							Lower Coal Measures	'A' Subcrenatum	
		Namurian	Yeadonian Marsdenian K'scoutian										Taylor and Rushton 1971 Millstone Grit	not studied	not studied
	Dinantian	Visean	Brigantian D_2										Carboniferous Limestone		
Devonian		Upper Devonian											Upper Old Red Sandstone		
Cambrian				Merevale Shales					Cambrian Stockingford Shales Harrison (1882) Lapworth (1882)	Stockingford Shales	Cambrian Merevale Shales Illing (1913) (1916)		FORMATIONS Merevale Shales Monks Park Shales Moor Wood Flags Outwood Shales Mancetter Grits Abbey Shales Purley Shales Hartshill Qzite		
				Oldbury Shales							Oldbury Shales				
				Purley Shales							Purley Shales				
				Hartshill Quartzite			Millstone Grit	Millstone Grit	Hartshill Quartzite		Hartshill Quartzite				
Pre - Cambrian		Caldecote Volcanics						Greenstones	Caldecote Volcanic Series, Lapworth(1898)	Not studied			Not studied		

Con. = Conglomerate

Interdigitation

Unconformity

easily recognisable but those of very wide geographical extent occur infrequently and so are useful in broadly dividing the stratigraphic column into a number of stages. Non-marine bivalves allow smaller units of time to be defined, but their sporadic occurrence may not permit the collection of the large numbers necessary for identification. Zonation based on plant macrofossils requires many species to be collected because of the relatively slow rate of evolutionary change. Once again only broad divisions of the stratigraphic column can be defined. Plant miospores are abundant in coal and common in siliciclastic sediment but again are subject to slow evolutionary change. Those in siliciclastic sediments may be reworked, but those in coal seams may provide a means of local correlation. In this study the informal terms lower Silesian are used for sediments of Namurian, and Westphalian A and B age and lower Westphalian for sediments of Westphalian A and B age. The latest stratigraphical terms applied to sediments in the Warwickshire Coalfield are shown on the left of Table 3.1. Previous research into palaeontology in the Coalfield is discussed.

Information concerning the structure of the Coalfield is presented and a discussion on exploration and possible extensions to the Coalfield is given.

3.1 LITHOSTRATIGRAPHY AND SEDIMENTOLOGY OF THE PRE-PERMIAN SEDIMENTS

The first geological map showing the Warwickshire Coalfield was produced by William Smith (1815). It showed the oldest rocks in the area as Millstone Grit [Hartshill Quartzite] overlain by red and green Coal Measures (Stockingford Shales) and grey Coal Measures [Lower and Middle Coal Measures, Etruria Marl Formation and Halesowen Sandstone Formation], superceded by red Triassic strata of Bunter and Keuper rocks [Keele Formation, Coventry Sandstone Formation, Tile Hill Mudstone Formation, Kenilworth Sandstone Formation, Ashow Formation, and the Sherwood Sandstone and Mercian Mudstone and Penarth Groups] and grey Liassic Strata (Table 3.1).

Lloyd (1849) found in "Bunter Sandstone" [? Kenilworth Sandstone Formation], a skull of a Labyrinthodont, which was later renamed Dasyceps bucklandi, and shown to have Stephanian affinities (von Heune 1910). But because of the close lithological similarity of the red beds below the Keuper in Warwickshire to the Permian of South Staffordshire, Ramsay (1855) referred these beds to the Permian.

The first detailed map and account of the Warwickshire Coalfield was published by Howell (1859). His stratigraphy closely followed that of Smith (1815) except that the red beds were subdivided into those of Permian and Triassic age (Table 2.1). In a description of the Coal Measures, particulars were given of the coal seams being worked viz. Four Feet, Thick Coal, Seven Feet and Bench seams. An attempt was made to correlate the seams of the Thick Coal (Two Yard/Rider, Bare, Ell and Slate seams, but this correlation has since been shown to be erroneous. In the upper part of the Coal Measures [Halesowen Sandstone Formation], Howell mapped a Spirorbis Limestone which he stated to be about 15m below the base of the Permian [Keele Formation]. Howell believed that the overlying Permian strata [Keele to Ashow Formations] was mostly conformable upon the Coal Measures. However, he recognised a marked unconformity between the Permian and Triassic strata which were divided into the basal Bunter Pebble Beds, recognised east of Polesworth, and the overlying Keuper Sandstone and Marl [Sherwood Sandstone and Mercian Mudstone Groups]. Triassic strata was shown beyond the Coalfield to the east and west, but only in the south and south east was a clear unconformity shown to exist with Permian strata below.

Lapworth (1882) discovered brachiopods and trilobites in the red and green rocks previously referred to as Coal Measures and assigned a Cambrian age to them. The name Stockingford Shales was adopted following Harrison (1882). A description of the Caldecote Volcanic Series was given by Lapworth (1898), which it was realised was Pre-Cambrian in age.

Thus at the end of the nineteenth century it was believed that the Old Red Sandstone, Carboniferous Limestone and Millstone Grit were not present in the Warwickshire Coalfield, and that the majority of red beds were Permian in age.

3.1.1 Cambrian sediments

Illing (1913, 1916) divided the Stockingford Shales into three units and recognised four subdivisions of the Oldbury Shales and three of the Purley Shales. The Hartshill quartzite was also divided into three units.

Later, Taylor and Rushton (1971) following the mapping of the northern part of the Warwickshire Coalfield, produced a detailed stratigraphical study of Cambrian strata encountered at both outcrop and following the drilling of surface boreholes at Merevale. The

Stockingford Shales were divided into seven Formations, and information concerning their thickness, sedimentology and palaeontology were given.

3.1.2 Devonian sediments

Rocks previously mapped as basal Coal Measures (Strahan 1886) in the Merevale area, have recently been proved to be Upper Old Red Sandstone (Taylor and Rushton 1971). In Merevale No. 2 borehole 152m of greyish green conglomerates, sandstone, siltstones and reddish brown mudstones were cored which resembled Devonian strata east of the Coalfield. The fauna found in this borehole and in surface exposures has indicated an Upper Devonian age. Fossils diagnostic of an Upper Devonian age include the fish Bothriolepis and Holoptychius and a bivalve Prothyris stubblefieldi. The sediments were believed to represent fluvial deposition on a sub-aerial delta plain, with rare marine incursions.

3.1.3 Dinantian sediments

Three boreholes drilled by the N.C.B. in the north of the Warwickshire Coalfield (Statfold, Amington Hall and Bolehall) encountered dark grey limestones, and mudstones with red and grey siltstones and sandstones (Taylor and Rushton 1971). They were originally described by Grieg in an unpublished report to the N.C.B. The maximum thickness penetrated was 26.3m and the fauna which included the corals Lithostrotion junceum, L. pauaradiale, Diphyphyllum latesptatum as well as brachiopods and bivalves enabled the sediments to be assigned an Upper Visèan (D_2) age. The increase in proportion of sandstones southwards was attributed to the presence of the Wales-Brabant Island.

3.1.4 Namurian sediments

The three boreholes mentioned above plus Syerscote Barn and Comberford Lane boreholes in the NW and Merevale No. 2 borehole in the NE all encountered pale grey sandstone and 'grits', purple, red and grey siltstones and mudstones, rare coals, and dark grey mudstones containing marine fauna (Taylor and Rushton 1971). The maximum thickness of Millstone Grit recorded by Taylor and Rushton (1971) was 77m in Amington borehole. However, using dark mudstones containing fish remains and bivalves, together with seatearth horizons as correlatable markers it is believed that Taylor and Rushton (1971) placed the top of the Namurian strata 20m too high in this borehole. Therefore the maximum thickness present in the Warwickshire Coalfield is 57m (Fig.3.1). Taylor and Rushton (1971) also discovered Millstone Grit in the NW of the Coalfield which had previously been mapped as Keuper sandstone, and in the Merevale area which had previously been mapped as Coal Measures. Examination of shaft sections within the Warwickshire Coalfield revealed the probable occurrence of Namurian sediments at Wilnecote (Peele) Wood End, Baddesley, Griff No. 4 and Charity. In the south they consist of pebbly sandstones, but at Wood End and Baddesley reddened seatearths and possible marine bands are present.

3.1.5 Westphalian A and B sediments

In Warwickshire Vernon (1912) divided the Coal Measures into two units. The lower grey unit contained all the coal seams and was termed 'Middle' or 'Productive Coal Measures' [Lower and Middle Coal Measures]. Later Stubblefield and Trotter (1957) applied the names 'Lower', 'Middle' and 'Upper Coal Measures' in a chronostratigraphic sense for sediments defined using marine bands. One of the greatest

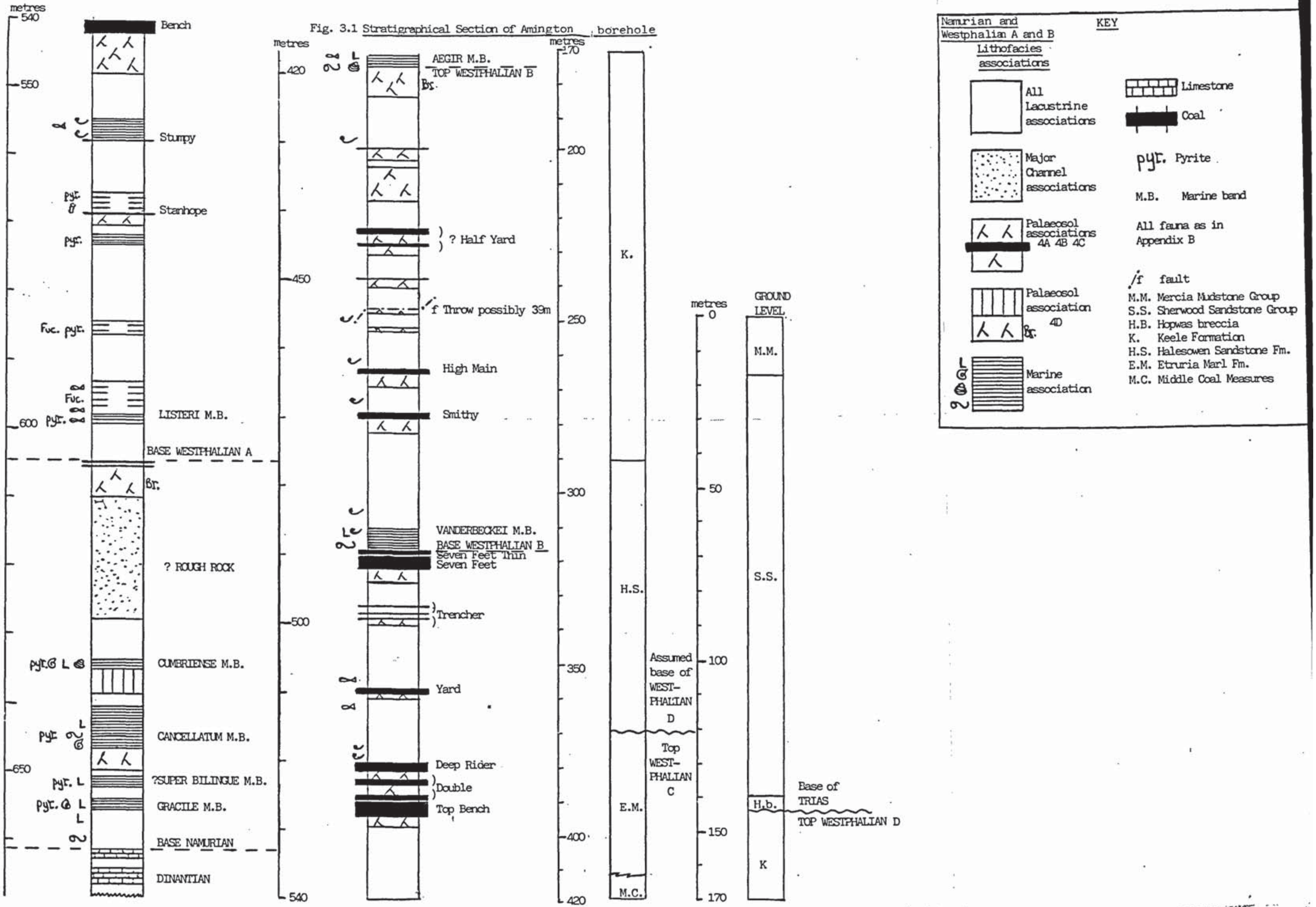


Fig. 3.1 Stratigraphical Section of Amington borehole

problems in the study of Coal Measures is the correlation of coal seams. Many authors including those who undertook the mapping of the Warwickshire Coalfield for the Geological Survey during the early part of the Twentieth century paid particular attention to this subject.

Fox-Strangways (1900) in the 'Atherstone Memoir' for the NE part of the Coalfield doubted that many of the seams called by the same name for commercial reasons were in fact the same seam, and in particular the Slate coal at Polesworth shaft was probably the Seven Feet of other collieries. Browne (1907) gave a detailed section of the Thick Coal at Newdigate Colliery. Vernon (1912) believed that the only seam which was correlated reasonably accurately across the Coalfield was the Seven Feet seam. In the NW of the Coalfield Barrow et al. (1919) reviewed the Middle Coal Measures for the 'Lichfield Memoir'. Seam information from 15 colliery shaft sections was given with the following seams being worked at the time viz. Rider, Smithy, Seven Feet, Double and Bench. Correlation of seams remained poor with only the Seven Feet and Smithy seams being correlated across this part of the Coalfield. Eastwood et al. (1923) in the 'Coventry Memoir' increased details concerning the number of seams mined in this part of the Warwickshire Coalfield and produced a section showing the correlation of the Four Feet, Two Yard/Rider, Bare, Slate, Smithy and Seven seams. An attempt was made to correlate the seams of the Thick Coal at 8 collieries (Eastwood et al. 1923, Plate VI). The most comprehensive correlation of coal seams occurring within the Coalfield was made by Mitchell et al. (1942). A total of 31 shaft sections were shown and nineteen named seams were correlated and isopachyte plans between several of the seams were constructed. Again correlation of seams of the Thick Coal at several collieries was made. The basis for seam correlation was thickness and the presence of 'mussels' and marine bands. Later Mitchell (1944) proposed the adoption of standard names for the main coal seams and marine bands in Warwickshire, and with the exception of the Slate Coal which is now called the Nine Feet seam and the omission of the Stumpy seam, these names prevail today (Figs. 3.1, 3.2, 3.3, 3.4).

The most detailed published correlation of the Thick Coal was made by Cope and Jones (1970). Although eight seams were included by them within the Thick Coal viz. Thin Rider, Two Yard, Bare, Ryder, Ell, Nine Feet, High Main and Smithy the latter seam is excluded in this study (section 5.4.7.3). Only nine seams were named by Ramsbottom _et al_. (1978) in their graphic section of the Warwickshire Coalfield.

Details of interseam lithologies found in the Warwickshire Coalfield have been very generalised and in early publications are often referred to as 'measures'. Recognition of lithologies is mostly restricted to the use of a variety of mining terms for mudstone, seatearth (fireclay) and sandstones (Vernon 1912), Barrow _et al_. 1919, Eastwood _et al_. 1923). Ironstones have been given names (section 5.2.7.2) because of their commercial potential. Vernon (1912) recognised the association of sphaerosiderite and seatearths. He also mentioned the presence of washouts of the Two Yard at Kingsbury and Arley collieries and of the Thick Coal at Exhall colliery, and interpreted them as the products of penecontemporaneous erosion. Mitchell _et al_. (1942, fig.11) plotted the courses of the principal washouts in the Seven Feet, Nine Feet and Two Yard seams and noted that the latter washout was at its widest in the NW and split into several thin belts in the SE. At Kingsbury he believed that it extended 15.5m into the Ell seam below. Verbal descriptions of the

Fig.3.2 Stratigraphical section of Whitehouse Farm borehole

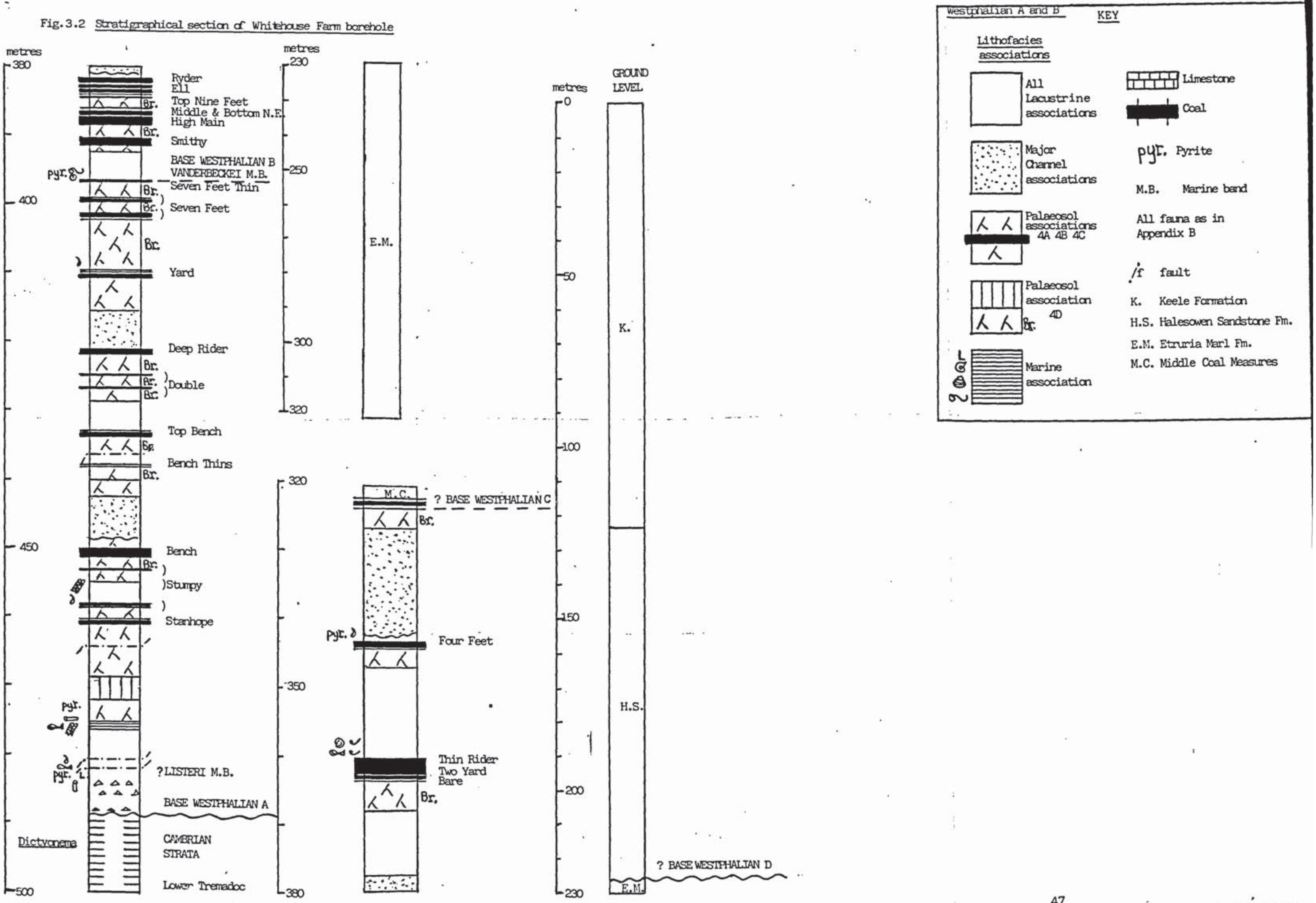


Fig. 3.3 Stratigraphical section of Birch Tree Farm borehole

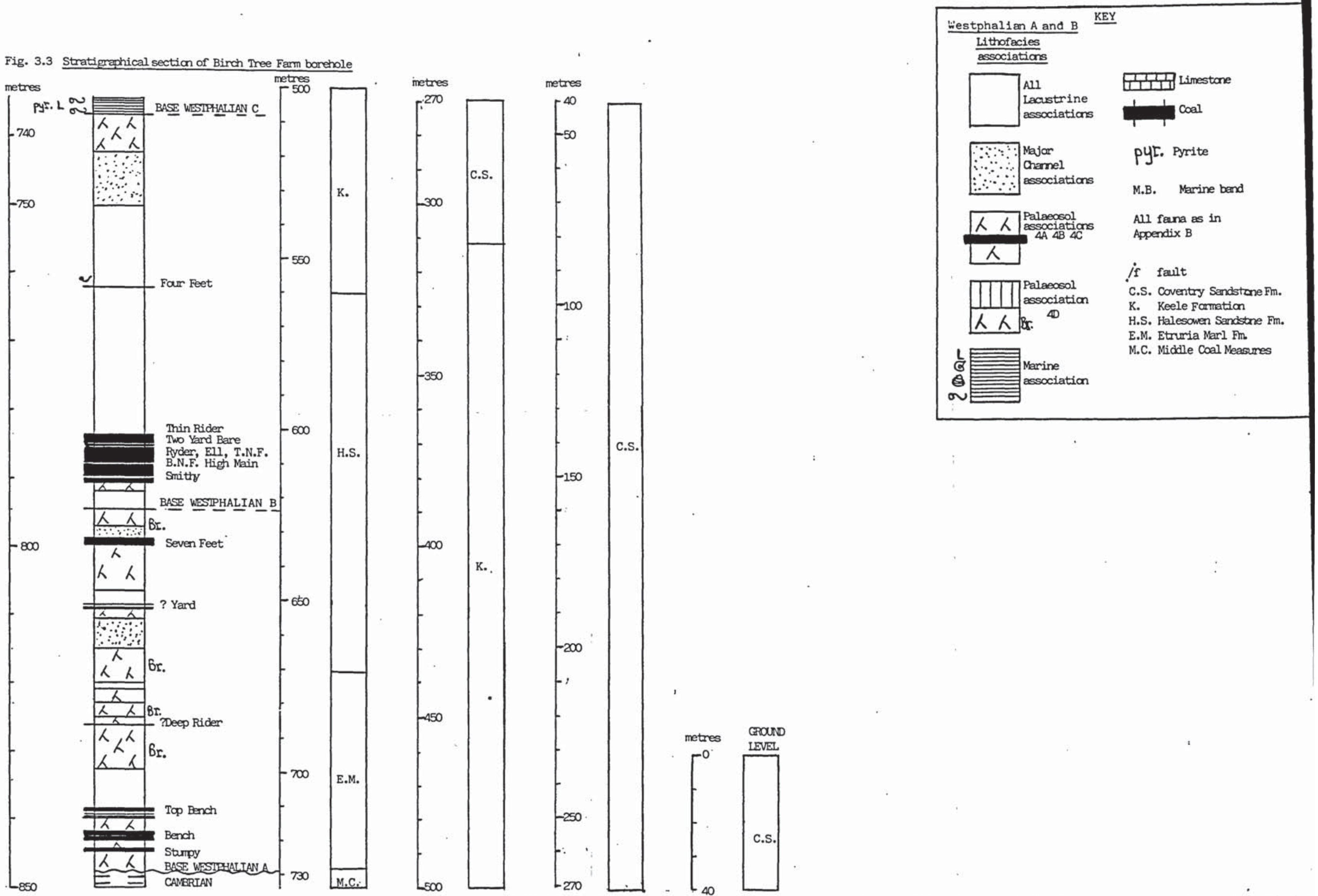
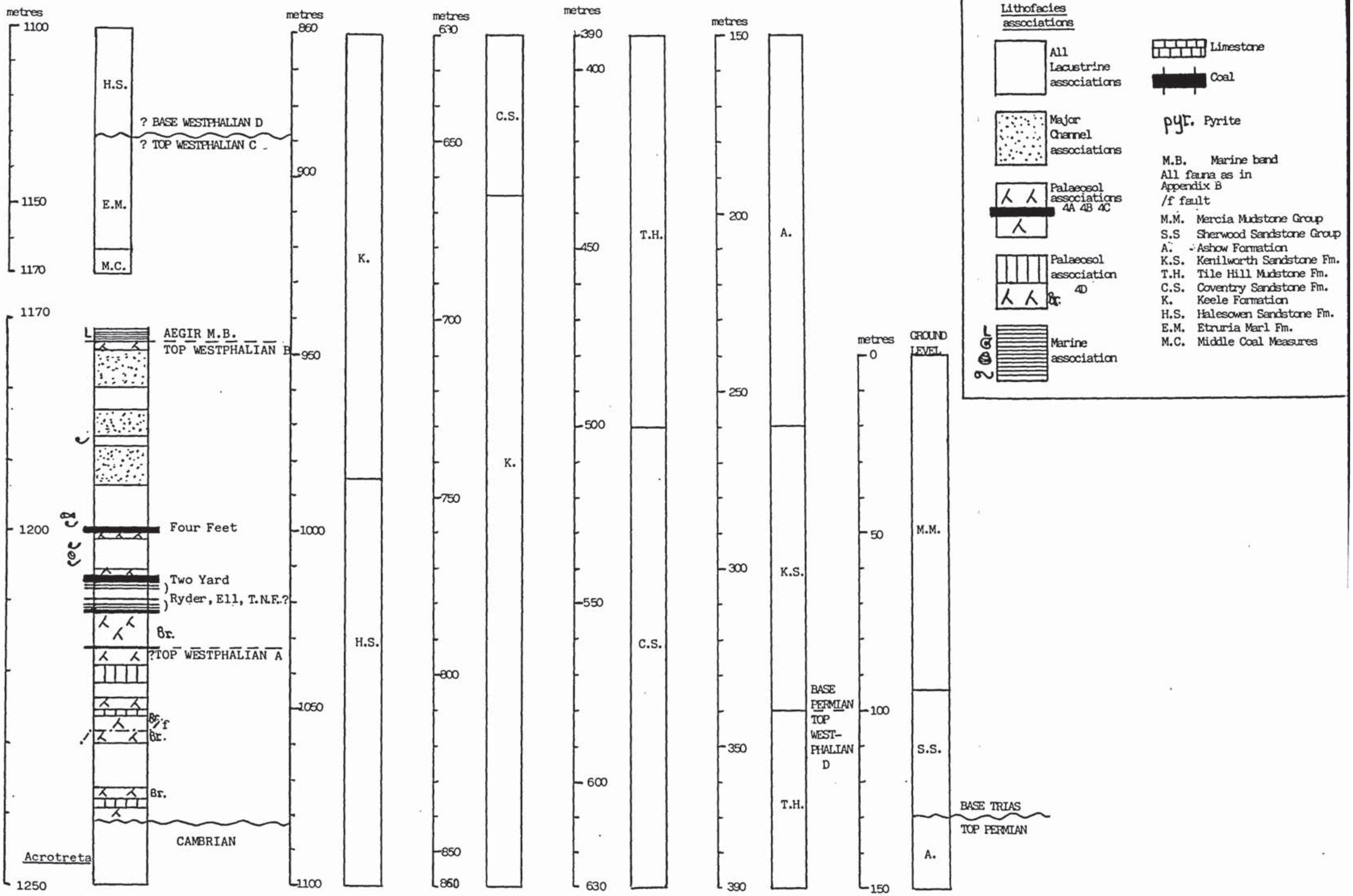


Fig. 3.4 Stratigraphical section of Middle Road borehole



lithologies forming the washout were given to Mitchell et al. (1942) and from these it appears that the majority of the fill was of sandstone with ironstone pebbles at its base at Newdigate. Sedimentary structures included slumping and wavy bedding, and both faulting and overfolding of the Two Yard seam were associated with it.

Mitchell et al. (1942) also realised that the thickness of Lower and Middle Coal Measures decreased from north to the centre of the Coalfield. This has recently been shown to continue to the south in Lower Coal Measures and to the south west in Middle Coal Measures and is demonstrated in Figs. 3.1 - 3.4 (also section on palaeogeography).

3.1.6 Westphalian C and D sediments

Vernon (1912) placed the lower boundary of the Upper Coal Measures at the occurrence of the first red bed forming the Nuneaton Clay [Etruria Marl Formation]. This sub-group was described as a series of red and purple mottled marls, containing a thin *Spirorbis* limestone, beds of gritty sandstone Espley rock and breccias of red and green sandstones averaging 33m in thickness. The Nuneaton Clays were believed to pass gradually into the next sub-group of the Upper Coal Measures which Vernon (1912) termed the Haunchwood Sandstones [Halesowen Sandstone Formation]. The base of the Haunchwood Sandstones was taken at the top of the highest 'Espley' bed, and they were seen to consist of pale grey, cross bedded sandstones, shales and marls with thin coal seams and *Spirorbis* limestones. Above the Haunchwood Sandstones were calcareous red and purple sandstones, alternating with red marls containing three beds of *Spirorbis* limestone, and calcareous marly breccia which together form the Keele Beds. The lowest of the three *Spirorbis* limestones form the base of the Keele Beds which Vernon (1912) estimated to range in thickness from 200-500m.

The presence of extraformational pebbles in the overlying Corley Conglomerate was the basis for Vernon (1912) assigning a Permian age to these beds together with what was considered to be an unconformity, although they are now believed to be Westphalian in age. They consist of red sandstones and marls alternating with beds of conglomerate containing pebbles ranging in age from Silurian to Dinantian. Directly above the Corley Conglomerate Vernon (1912) described a sequence of calcareous red sandstones and marls belonging to the Kenilworth Sandstones. The lower part of this sequence is now believed to be Westphalian in age.

Barrow _et al_. (1919) correlated the Nuneaton Clays with the Etruria Marls of Staffordshire and described them as variegated marl containing lenticular Espleys (iron cemented mudstones and sandstones) passing laterally into sphaerosiderite. Shale-chip beds composed of discs of Cambrian mudstone in a comminuted Cambrian mudstone matrix were recognised, which were supposed to have come from a Cambrian landmass upstanding in Etruria Marl times. Barrow _et al_. (1919) also correlated the Haunchwood Sandstones with the Halesowen Sandstones of the Birmingham district, a name applied by Lapworth (1898) to the lower unit of a group of sandstones overlain by a _Spirorbis_ limestone group. Both these groups were amalgamated to from the Halesown Sandstone by Barrow _et al_. (1919) which they believed ranged from 107-146m thick. The lowest limestone named the Index Limestone, was used as a marker bed lying approximately 46m below the base of the Keele Group. A description was given of the Keele Group with its base at a white calcareous sandstone overlain by red marls seen in Wood End shaft. The fault which marked the northern termination of the Coalfield on Howell's map is not the end of the Coalfield, as rocks to the north of it mapped originally as Keuper Sandstone were later recognised as Keele Beds. Barrow <u>et al</u>. (1919) believed that another fault to the north of this Keele outcrop marked the northern limit of the Coalfield.

Eastwood <u>et al</u>. (1923) followed Barrow <u>et al</u>. (1919) in using the same names for the lowest three units of the Upper Coal Measures although the term 'Group' was applied to each. Above these the Kenilworth Sandstone of Vernon (1912) were renamed the Enville Group [Coventry Sandstone to Ashow Formations] by Arber (1922) and the unconformity between them and preceding rocks eliminated by the realisation that Vernon has miscorrelated conglomerates at Arley and Corley. However, Eastwood <u>et al</u>. (1923) were uncertain how much of the Enville Beds if any were Permian or, if in fact they were Stephanian in age. He divided them using 3 conglomeratic units - Arley/Exhall, Corley and Allesley, separated by sandstones and marls and topped by the marls of the Tile Hill Beds.

Shotton (1927) produced a paper on conglomerates in the Enville "Series", which he later expanded (Shotton 1929) with an account of the geology of the country around Kenilworth. In the latter he subdivided the Enville "Series" into a number of Groups based in lithological characteristics. The base of the Enville "Series" was defined as the Arley Exhall conglomerate, which was up to 18m thick and believed to be derived from the Lickey area. This was succeeded by 198m of marls and sandstones containing the Astley Court limestone to which Shotton did not attach a Group name.

Later, Shotton (1933) supplemented his investigation of the Enville "Series" by an examination of 3 boreholes drilled in the Mount Nod area of Coventry. Firstly he found an horizon 15-30m above the

Corley Conglomerate where pebble composition showed that the Nuneaton anticline was still supplying part of the sediment to the basin of deposition. Secondly, a breccia in the middle of the Allesley conglomerate of similar composition and so similar formation to the Kenilworth and Clent Breccias, was interpreted as an early example of flood type deposition that was to characterise the later Kenilworth Breccias. Shotton (1933) emphasised the continuity of deposition from the Keele to the Ashow Group, although no palaeontological evidence was available to decide whether the boundary between Carboniferous and Permian lay above or below the Kenilworth Breccia Group.

The top of the Silesian and therefore the base of the Permian in Warwickshire was defined by Smith et al. (1974) at the base of the Kenilworth Breccia Group above the Gibbet Hill conglomerate. The basis for this was the discovery of two Permian fossils and the similarity of the breccias with others in Worcestershire and south Staffordshire below which is an unconformity. Recently, following mapping of the Warwick sheet R. Old pers. comm. (1980) confirmed the use of the term Formation for all subdivisions of the Upper Coal Measures, and the name Coventry Sandstone Formation for those sediments lying between the Tile Hill Mudstone and Keele Formations. The Ashow, Kenilworth Sandstone, Tile Hill Mudstone and Coventry Sandstone Formations were all included in the Enville Group. However, the base of the Permian has been placed below the Gibbet Hill conglomerate at the boundary between the Kenilworth Sandstone and Tile Hill Mudstone Formations.

Besly (1983) studied the Etruria Formation within the coalfields of the Midlands including the Warwickshire Coalfield. Three facies associations characterising the Formation were defined dependant on drainage and proximity to alluvial fans. Within them six types of palaeosol were described. It was shown that the occurrence of red coloured palaeosols was associated with improved drainage and that grey and red beds were interdigitated. In Warwickshire the Etruria (Marl) Formation was shown to be diachronous varying in age from upper Westphalian B to Westphalian C age, becoming older towards the Western Boundary Fault. Also, he believed that a 5km wide belt of sediment rich in Cambrian pebbles associated with alluvial fans existed on the eastern side of the Western Boundary Fault, and that in the remainder of the Coalfield these were absent. (Boreholes drilled since then have proved that this is an oversimplification). On the basis of the preceding data Besly (1983) believed that during the upper Westphalian B to Westphalian C times the area to the west of the Western Boundary Fault was elevated to form a source for the pebbles in the Etruria (Marl) Formation.

3.2 SILESIAN BIOSTRATIGRAPHY AND PALAEONTOLOGY

3.2.1 Namurian

A full discussion of the origin of the biostratigraphy of the Namurian is given in Ramsbottom *et al.* (1978). Originally Bisat (1928) proposed a set of Stages for the Namurian using goniatite marker bands, and these have been revised and developed until Ramsbottom (1969) advanced the use of seven Stages based on goniatite chronozones. As the only biostratigraphical correlation of the Namurian in Warwickshire was undertaken later than this (Ramsbottom in Taylor and Rushton 1971) the current Namurian Stages were used. Four marine bands were recognised in boreholes to the N and NE of the Coalfield viz. Gracile, Superbilinque, Cancellatum and Cumbriense. On this basis it appears that sediments from the Kinderscoutian, Marsdenian and Yeadonian Stages are present within the Coalfield. Ramsbottom (in Taylor and Rushton 1971) also mapped the facies changes taking place within the fauna of the marine bands (section 5.4.1).

The Namurian has also been biostratigraphically zoned using miospores, and Smith and Butterworth (1967) examined coal seams in Amington borehole which they assigned to zone V which ranges from upper Namurian to lowest Westphalian A in age. Since then Owens *et al.* (1977) have revised the Namurian and lowest Westphalian A palynological biostragraphic zones of Smith and Butterworth (1967) so that the base of their upper zone corresponds to the base of the Westphalian.

3.2.2 Westphalian

The rarity of marine fossils within a non-marine sequence was used by Phillips (1832) to correlate parts of the Westphalian. In the Warwickshire Coalfield marine strata above the Seven Feet seam was recognised by Vernon (1912) and named the Seven Feet Marine Band (M.B.), although the marine strata actually occurred above the Seven Feet Thin seam. A list of fauna identified at 7 collieries was given, and later in Mitchell et al. (1942) both the list of fauna and the localities at which it could be found were expanded. Since then this M.B. has been discovered in many surface boreholes drilled by the N.C.B. in Warwickshire and its areal extent plotted (section 5.4.1).

The presence of another M.B. was discovered by the Geological Survey at Stanleys Brickpit Nuneaton and named the Nuneaton Marine band. It was included by Dix (1941) in her generalised sequence for the Coalfield. A list of fauna associated with it was given by Mitchell et al. (1942). Since then the M.B has been discovered in most of the surface boreholes drilled by the N.C.B. in Warwickshire and its areal extent plotted (section 5.4.1).

Two more Westphalian M.B's, the Subcrenatum and Listeri, have tentatively been identified in boreholes previously mentioned in the section on the Namurian in the north of the Warwickshire Coalfield (Taylor and Rushton 1971). The latter has since been recognised in another borehole in Warwickshire (section 5.4.1).

A few Lingula have been discovered in a dark grey mudstone above the Four Feet Coal and this has tentatively been correlated with the Maltby M.B.

Calver (1968) plotted the distribution of fauna within M.B's across the Pennine basin (including the Warwickshire Coalfield) and recognised faunal facies belts. The base of certain M.B's were related to the base of Westphalian Stages and subsequently adopted by Ramsbottom et al. (1978).

The first detailed study of Westphalian fauna within the non-marine strata of the Warwickshire Coalfield was undertaken by

Vernon (1912) and a variety of fish and anthropod remains and non-marine bivalves listed. Mitchell et al. (1942) tabulated 54 species of non-marine bivalves as well as gastropods, annelids and ostrocods. The non-marine bivalves were examined by Trueman and by use of the non-marine bivalve zones erected in the North (Davies and Trueman 1927) and South (Trueman 1940) Staffordshire Coalfields the presence of the Ovalis, Modiolaris and Similis-Pulchra zones were recognised. Later Trueman and Weir (1946-1958) modified these so that the Westphalian was divided into 8 chronozones. These (except the Prolifera zone, abandoned on account of the erratic occurrence of A. prolifera) have been used by Ramsbottom et al. (1978) to zone the Westphalian of Warwickshire, demonstrating the presence of all 8 zones. A refinement on non-marine bivalve zones is the use of non-marine bivalve faunal belts (Calver 1956, Eagar 1956) and these also have been applied to the Warwickshire Coalfield by Ramsbottom et al. (1978).

Plant macrofossils were first used for correlation by Kidston (1905). The first list of flora found in the Warwickshire Coalfield was published by Horwood (1912) who studied the plants associated with the seams of the Thick Coal. Later the same year Vernon (1912) published a detailed list of all flora recognised in the Warwickshire Coalfield and constructed 3 tables to show the distribution of plants associated with (a) the lowest coals (b) the upper beds of the Productive Coal Measures and (c) the Upper Coal Measures. From this evidence he concluded that no Lower Coal Measures existed in Warwickshire. Dix (1934) established a floral zonal sequence formed of 10 zones and later (Dix 1935) studied the Keele Beds and Enville Series in Warwickshire and referred them to the Permian and Stephanian respectively. Crookall (1931, 1955-76) revised the zonal scheme of Kidston (1905) so that 4 zones were recognised. This revised scheme was used by Mitchell et al. (1942) to zone the Westphalian in Warwickshire. They believed that the lowest recorded floras were of Yorkian age and these extended at least as high as the Four Feet seam. Further, they believed the Halesowen Sandstone to be of Staffordian age but were unable to decide if the Keele Beds were of Westphalian, Stephanian or Permian age. Recently Cleal (1984) has used plant macrofossils to establish the base of the Westphalian D stage in Britain.

The study of palynology began fairly early in the Warwickshire Coalfield. Paget (1936) following the work of Raistrick and Simpson (1933) and Raistrick (1934) identified over 200 miospores and drew 26 of them which he believed had limited vertical ranges. He attempted to correlate the seams of the Warwickshire Coalfield using the six miospore groups previously identified by Raistrick (1934). Although some similarities in miospore content between the same seam at different localities were observed because of the crudity of spore identification many of the seams had similar miospore contents and so could not easily be correlated. Paget (1936) also believed that the miospores identified in seams in the Warwickshire Coalfield could be matched with plants found in stratigraphically similar seams in S. Wales. On this basis he believed it was possible to relate miospores to the plants that produced them. By comparison of the growing conditions of similar modern plants Paget (1936) postulated changes from wet to dry conditions which he associated with changes in climate. The number of seams examined in the Warwickshire Coalfield was later extended by Paget (1937) and comparison made between those in seams in the South Derbyshire Coalfield.

Butterworth (1956) examined the miospore content of seams from Baddesley, Coventry and Dexter collieries and Amington and Bolehall boreholes in a sequence extending from the top of the Namurian to the lower part of Westphalian C. The miospore content of the seams was found to be comparable with those observed in other coalfield of the Pennine basin.

The distribution of the miospore *Densosporites sphaerotriangularis* was investigated by Butterworth (1964) in the Thick Coal at 3 Warwickshire Collieries. She concluded that the Thick Coal occured in stable areas undergoing low rates of subsidence and that the proximity of the Wales-Brabant Island might account for the drier conditions believed to be associated with durain and the occurrence of *D. sphaerotriangularis*.

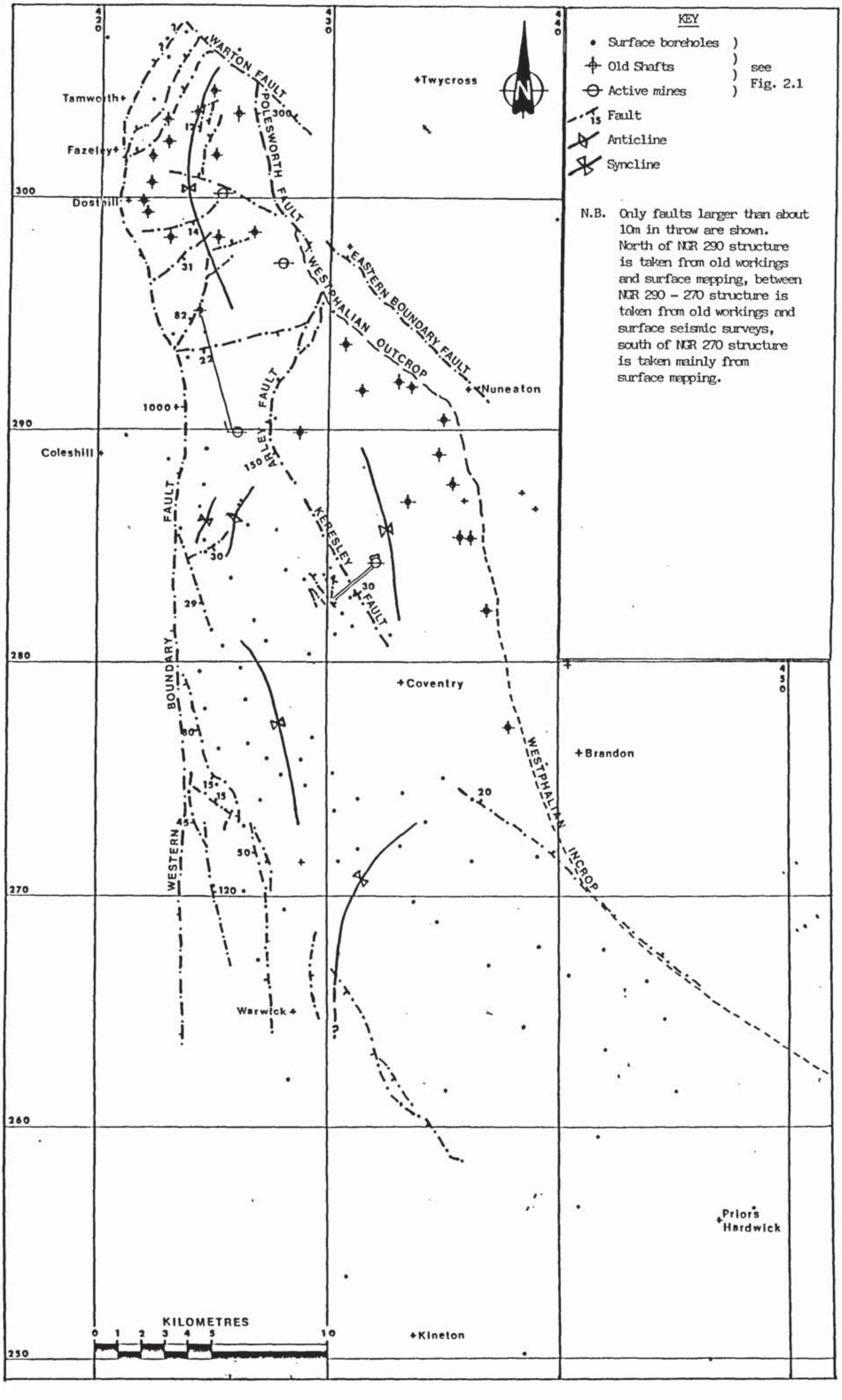
In a detailed survey undertaken by Smith and Butterworth (1967) the miospore content of coal seams in all the British coalfields was investigated and 11 miospore assemblage zones for stages from the Visèan to Westphalian D were erected. Seams at a total of 14 locations in the Warwickshire Coalfield were examined and all 6 of the Westphalian miospore assemblage zones identified. Relative frequencies of 10 miospore species were shown from the seams investigated in the Coalfield and the distribution of stratigraphically important species mentioned in the discussion of each of the miospore zones.

Most recently Clayton *et al.* 1977 produced a composite miospore zonal scheme for Western Europe which extends from the Upper Devonian to the lower Permian. Miospore epiboles, biozones and assemblages were used to define the zones, five of which replace the six Westphalian zones defined by Smith and Butterworth (1967). Although miospores from the Warwickshire Coalfield were not examined for this investigation it is believed that the zonal scheme should be applicable to Warwickshire.

3.3 STRUCTURE

The key elements which form the structure of the Warwickshire Coalfield were shown on the map produced by Howell (1859). Delimiting the west of the Coalfield Howell (1859) outlined the N-S trending Western Boundary Fault (W.B.F.) which was off-set at Berkswell. In the north near Tamworth the course of this fault was lost under river alluvium. Just south of this near Fazeley, a number of NE-SW trending faults (Fig.3.5) were plotted from surface mapping and through the activities of mining, and one of these faults limits the north-west of the Coalfield. The north eastern side of the Coalfield was shown to be fault bounded by three faults which join together. The most northern of these the Warton Fault has a NW-SE trend, the middle Polesworth Fault has a NNW-SSE trend and the most southern Eastern Boundary Fault has a NW-SE trend. From the easterly downthrow of the faults on the eastern flank of the Coalfield and the westerly downthrow of the W.B.F. the Coalfield can be described as a horst. The surface traces of two more major faults apparently joined together were outlined by Howell (1859) in the centre of the northern part of the Coalfield. In the north the sinuous trace of the Arley Fault trending approximately NNE-SSW was joined to the NE-SW trending Fillongley Fault. Dips plotted from outcrops in the northern half of the Coalfield indicated that structurally the Coalfield was a syncline which closed to the north and pitched to the south.

In the early part of this century, following mapping of the Coalfield by the Geological Survey (Fox-Strangways 1900, Barrow *et al.* 1919, Eastwood *et al.* 1923, Eastwood *et al.* 1925) the surface traces of many more faults of relatively small throw were plotted. During this time coal mining had extended along the eastern side of



N.B. Only faults larger than about 10m in throw are shown. North of NGR 290 structure is taken from old workings and surface mapping, between NGR 290 – 270 structure is taken from old workings and surface seismic surveys, south of NGR 270 structure is taken mainly from surface mapping.

Fig. 3.5 The Warwickshire Coalfield, structure map showing major faults and folds the northern third of the Coalfield and more relatively small faults were located by this method. In most cases they appeared to be parallel to the three previously mentioned trends (N-S; NE-SW; and between NNW-SSE and NW-SE).

Both Barrow et al. (1919) and Eastwood et al. (1923) discussed the size of throw of the W.B.F. and the faults which split from it in the north west of the Coalfield. The estimates for these throws are partly conjectural because of lack of knowledge concerning the stratigraphic positions at the surface within the Upper Coal Measures. However, estimates of fault throw size for these major faults ranged from about 40-335m in the Coal Measures. In the Trias the throw of these faults was found to be considerably smaller than in the Coal Measures which they believed indicated two periods of movement. The total throw of the W.B.F. could not be determined because of the presence of a thick cover of Triassic strata on the downthrown side. A similar situation existed in the case of the Warton Fault. The Polesworth Fault was believed to have a throw of about 300m in the Coal Measures.

The Arley and Devitts Green Faults were believed by Eastwood et al. (1923) to have a combined throw of 250m. Subsequent coal mine workings have shown that the Devitts Green Fault does not exist at depth and surface seismic surveying has shown that the throw of the Arley Fault is about 150m and that it is further west than originally believed north of Arley Colliery. Two other faults, the Dove House Farm fault and Coundon fault were plotted by Eastwood et al. 1923 and in the case of the former mine workings have proved that it does not exist at depth, and in the case of the latter surface trenching has indicated that it does not exist at the surface.

Apart from the Coalfield wide syncline, small anticlinal folds were shown north of Merevale, and between Bedworth and Nuneaton. Eastwood et al. (1923) also constructed a Seven Feet contour plan, which again showed the Coalfield wide pitching syncline, as well as monoclinal folding on the eastern flank of the Coalfield near Binley Colliery.

This map was extended southwards by Mitchell et al. (1942) to reveal more of the monoclinal fold near Binley colliery. Mitchell et al. (1942) also commented on the possibility of faulting affecting deposition during formation of the Etruria Marl near Dosthill, where Cambrian pellets were found within the Etruria Marl Formation.

Taylor and Rushton (1971) published details of faulting in the Merevale area with particular emphasis on the Arley Fault. At its northern end they believed this fault had a 270m sinstral shift and that several phases of movement were associated with it. Lack of Devonian sediments on the northern side of this fault and 140m on the southern side suggested that it either controlled deposition during this time, or subjected the northern side to uplift and erosion prior to the deposition of the Millstone Grit. These latter sediments are also lithologically different on either side of the fault. Taylor and Rushton (1971) believed that the Arley Fault was also active during deposition of the Productive Coal Measures because washouts developed in several seams as they approached the Arley Fault in Monks Park opencast site. Mapping of the boundary between Triassic and Cambrian strata in the Merevale area has revealed that in many places the contact is sedimentary and not the Eastern Boundary Fault as was originally believed (Taylor and Rushton 1971). However if this is the case another fault associated with the steep dips flanking this part of the Coalfield may lie farther east.

Since the Geological Survey mapping at the start of this century, a considerable amount of underground coal mining has taken place increasing our knowledge about the structure of the worked seams. Surface seismic surveys and boreholes have been carried out by the N.C.B. across the southern two thirds of the Coalfield (Fulton 1978b), and it is believed that all faults in excess of 15m throw at the Thick Coal level have been located within the surveyed areas.

Examination of Fig. 3.5 reveals that many of the minor faults have trends similar to the three major fault trends discovered by Howell (1859) viz. N-S, NE-SW, and NNW-SSE to NE-SE. There appears to be a concentration of faults above 15m throw in the northern third of the Coalfield. From underground observation and surface seismic sections all faults appear to have normal hades varying from 15-35°, except the Keresley Fault which is vertical. The southern two thirds of the Coalfield is dominated by faults with a NNW-SSE to NW-SE structural grain. These faults have a similar trend to those found in the area of Pre-Cambrian exposure in Charnwood Forest and so this trend is referred to as 'Charnoid'. In the northern third of the Coalfield faults of both Charnoid trend and NE-SW trend occur, and the faulting at the confluence of these fault patterns is thereby intensified. The NE-SW trend is very similar to that seen at Church Stretton to the west. It is possible that older faults with a Church Stretton or Charnoid trend have become reactivated following deposition of the Coal Measures.

Exploration has also proved that the pitching syncline in the north of the Coalfield continues and broadens to the south.

3.4 COAL EXPLORATION AND EXTENSIONS TO THE COALFIELD

Barrow *et al.* (1919) postulated the existance of "deep seated coal seams" at depth between the boundary faults of the South Staffordshire and Warwickshire Coalfields. Recently boring by the N.C.B. to the north east of the Coalfield at Comberford Lane proved the presence of faulted Lower Coal Measures beneath a cover of Triassic sediments and Keele and Halesowen Formations, and this together with Whittington Heath borehole further north indicates the probability of a link between the Coalfields in this area. To the south at Trickley Lane borehole Triassic strata lay directly on top of Cambrian strata, and still further south opposite Daw Mill Colliery Blyth Bridge borehole penetrated over 1000m of Triassic sediments and Upper Coal Measures before drilling was stopped. This indicates that if Lower and Middle Coal Measures are present in this area they are at great depth.

The close proximity of the South Derbyshire and Leicestershire Coalfields to the Warwickshire Coalfield suggested to many authors e.g. Eastwood *et al.* (1923) the possibility of Lower and Middle Coal Measures existing beneath the Trias between the Coalfields. Recent boreholes drilled by the N.C.B. near Twycross have determined that Triassic sediments lay directly on top of Cambrian strata.

Further south Boulton (1926) reviewed boreholes drilled to the east of the exposed Coalfield between Marston Jabbett and Brandon. He believed that Lower and Middle Coal Measures could be expected on the eastern limb of the southern extension of the Nuneaton anticline. This was proved at Bulkington borehole and may also be the case at Weston Hall and Coombe Abbey where Upper Coal Measures were found below Triassic sediments.

Shotton (1928) investigated the possibility of a southerly extension to the Coalfield, and addressed himself specifically to the problem of the southerly continuation of the Thick Coal and the depth at which it would occur. An isopachyte map of the total thickness of the seams of the Thick Coal was produced together with Thick Coal sections taken from shafts in a north south line along the eastern edge of the Coalfield. They showed that if any Thick Coal was present to the west of Coventry it would be undivided but to the south and west it would be split into its constituent seams. A contour map for the Two Yard seam was drawn, based on the thickness of Upper Coal Measure Formations relative to their boundaries mapped on the surface. The map showed a continuation of the southward pitching syncline towards Kenilworth, with the 4000ft (1200m) contour about 4km north of Kenilworth and 1km NE of Stoneleigh. Among answers to a number of questions concerning his paper Shotton was able to state categorically that a diviner had not been used to determine the presence or depth of coal.

Mention has already been made in the previous section of boreholes drilled by the N.C.B. in the Warwickshire Coalfield and the location of these together with other boreholes drilled in the Coalfield is shown on Fig.2.1. These boreholes have shown that the Thick Coal does exist in the southern part of the Warwickshire Coalfield and that it splits to the south and the south west as suggested by Shotton (1928).

CHAPTER 4

SILESIAN PALAEOGEOGRAPHY AND PALAEOCLIMATE

It is believed that to enable a more complete understanding of the environmental setting of the lower Silesian in the Warwickshire Coalfield it is necessary to study palaeogeography and palaeoclimate. Details are presented in this chapter concerning the movement of Britain within an evolving global palaeogeography, together with an examination of lower Westphalian palaeoclimate. Some of the effects of both of these on deposition are considered. Finally the palaeogeography of the Pennine basin and its bearing on deposition in the Warwickshire Coalfield is discussed, together with the controls of the evolution of the Pennine basin.

4.1 GLOBAL PALAEOGEOGRAPHY

Speculation about the shape and disposition of continents through time (including the position of Britain during the Carboniferous) has long had a place in the study of geology. In 1855 Snider drew a global palaeogeography for the Carboniferous, using the method of best fit of continental edges. Later Wegener (1924) grouped the continents together in a similar way.

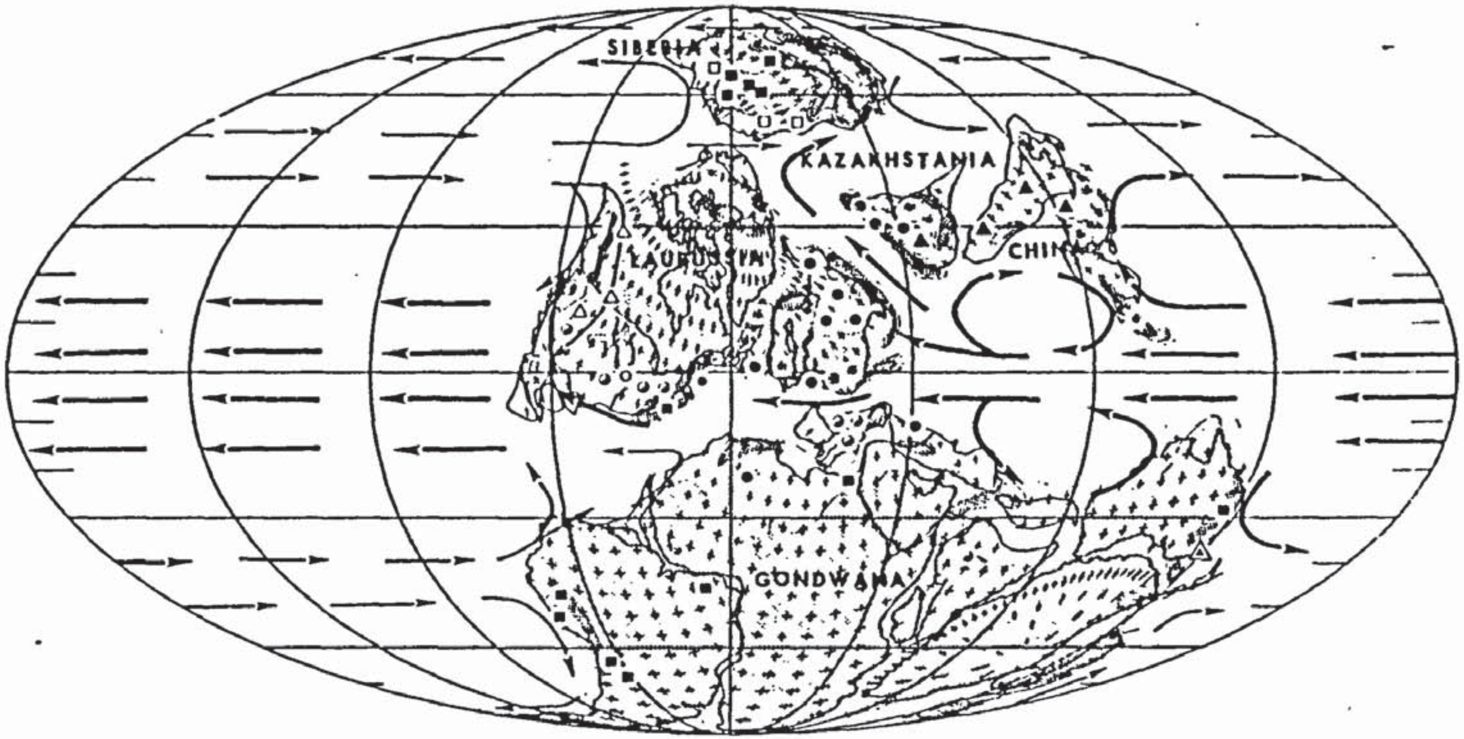
Palaeomagnetic data forms the basis for the most modern investigations into the global position of Britain during the Silesian. Collection was begun in earnest during the 1950's (Blackett 1961) and has continued to the present day. The reason for its importance is that the palaeomagnetic inclination fixes the palaeolatitude of a sampled locality, whilst the declination and inclination fix the position of the palaeomagnetic pole (north or south) from that locality. By comparison of palaeomagnetic poles continents can be positioned relative to one another to provide the basis for palaeogeographical maps for a given period of time.

The most recently discovered mechanisms for continental movement have been grouped together under the term plate tectonics (McKenzie and Parker 1967) and this theory has allowed the recognition of ancient continental boundaries (Mitchell and Reading 1969). Based on the information given above many authors during the 1970's drew generalised maps showing the position of the continents throughout the Palaeozoic (Smith et al. 1973, Turner and Tarling 1975, Scotese et al. 1979). Later Ziegler et al. (1981) modified the maps of Scotese et al. (1979) and in Fig. 4.1. the situation in Wenlock times can be seen prior to the collison of Laurentia and Baltica. By Viséan times (Fig. 4.2) these continental masses had merged to form Laurussia, a large continental area which included the Caledonian mountains in northern Britain. By Westphalian C/D times the combined southern hemisphere continents (Gondwanaland) had drifted northwards and were joined with Laurussia to form the 'supercontinent' of Pangea (Fig.4.3). A chain of 'Hercynian' highlands was built west of Britain towards the eastern edge of the new supercontinent. From the previous three figures Britain can be seen to have moved from a position just south to a position just north of the equator, and this drift continued into the Permian (Fig.4.4). Recent palaeomagnetic evidence derived from rocks of Westphalian C age in the Warwickshire Coalfield has shown that this area lay within a few degrees of the equator (Turner et al. 1985).

The relative position of continents during the Palaeozoic can be determined using apparent polar wander paths and an independant relative assessment can also be made by studying the distribution of marine faunas and terrestial flora and fauna.

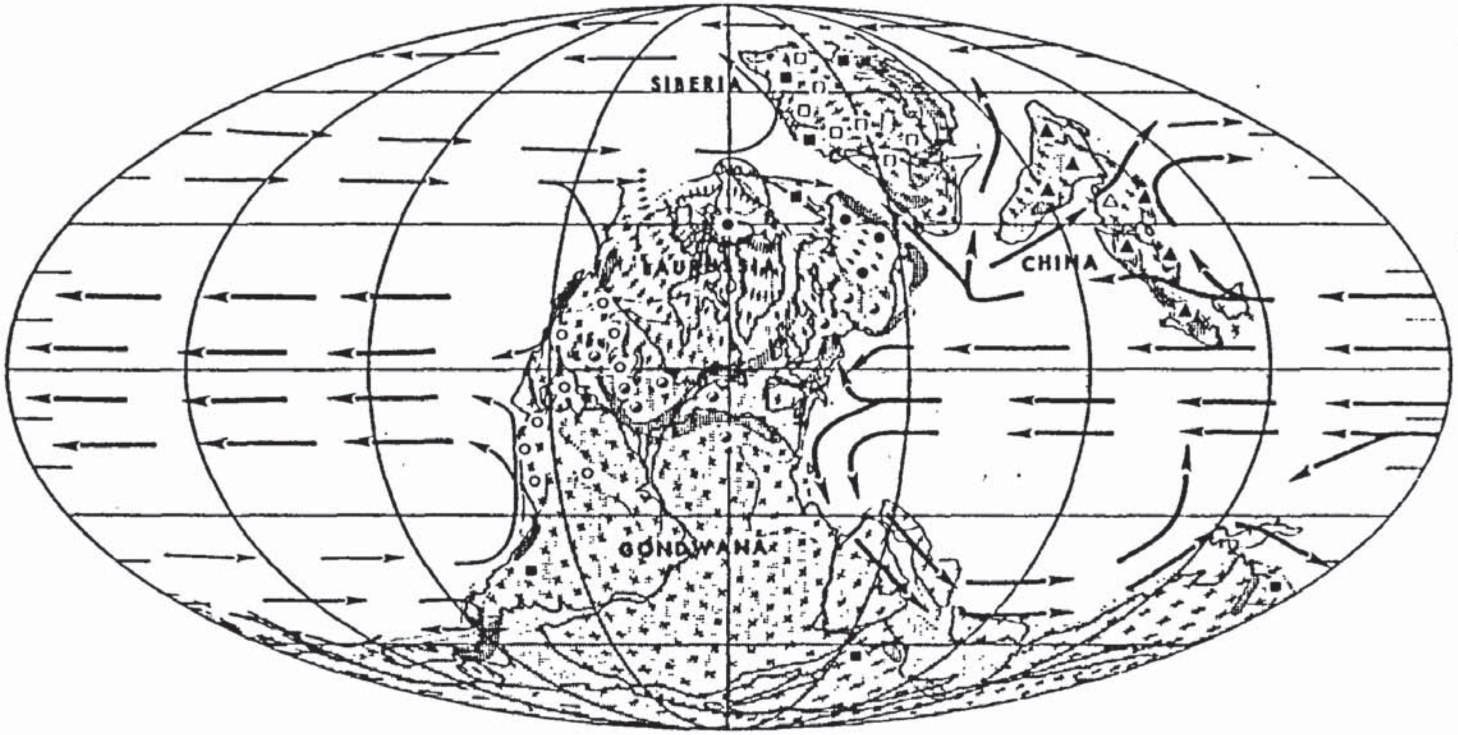
Fig. 4.1 Middle Silurian (Wenlock) global biogeography (from Ziegler et al. 1981)

Fig. 4.2 Late early Carboniferous (Viséan) global biogeography (after Ziegler et al. 1981)



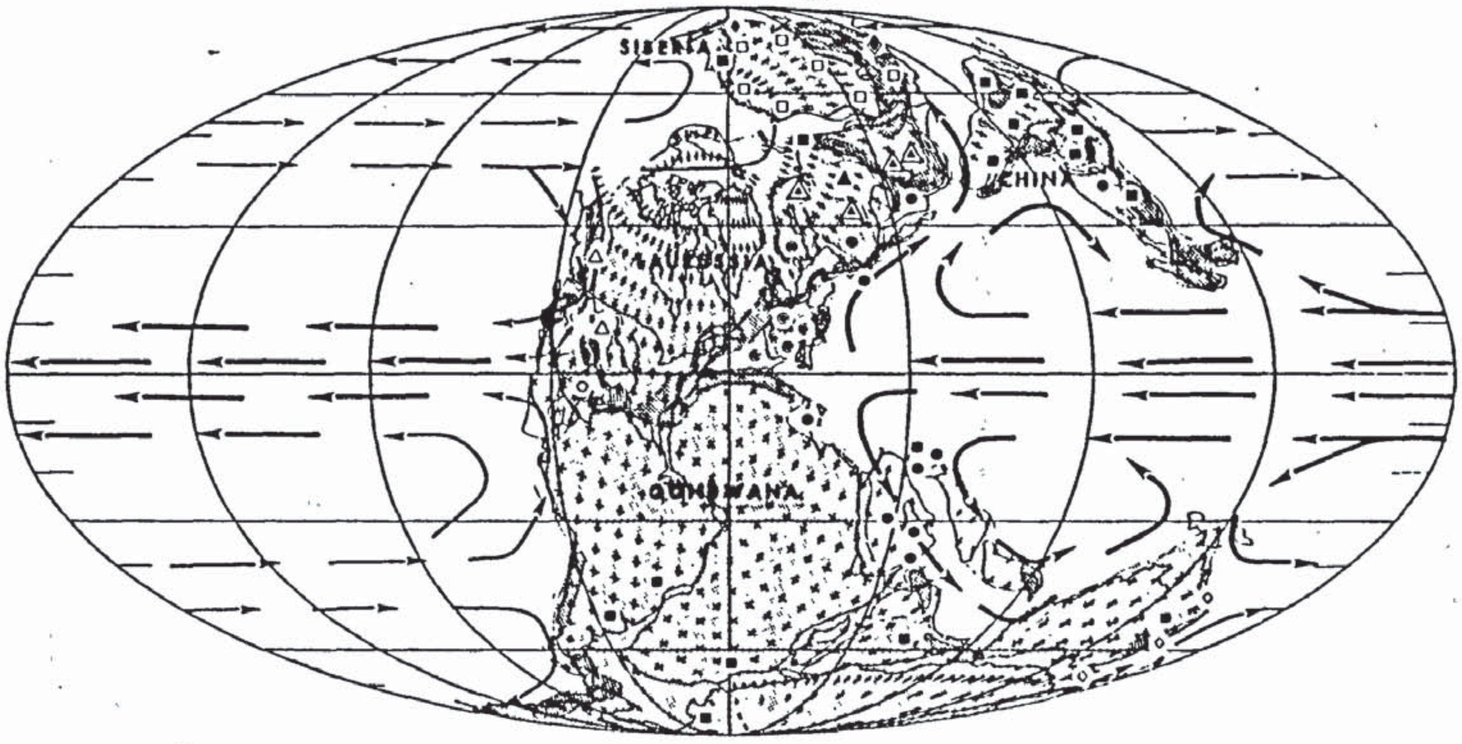
Symbols for marine biogeographical units are as follows: □ = Siberian, △ = Western Interior, ▲ = Chinese, ○ = Southeastern, ● = European, △ = Australian. Symbols for terrestrial biogeographical units are as follows: ◙ = Angaran, ⊙ = Northern Circum-Tethys, ◑ = Southern Circum-Tethys, ■ = Gondwanan. Symbol shape code for climatic assignments is as follows: ○ = tropical, △ = subtropical, □ = temperate. Arrows indicate inferred surface ocean currents: thick = warm, thin = cold. Topography is as follows: dark shading = mountains, intermediate shading = shallow shelves, white = ocean basins.

Fig. 4.3 Middle late Carboniferous (Westphalian C/D) global biogeography (after Ziegler et al. 1981)



Symbols for marine biogeographical units are as follows: ⊡ = Siberian, △ = Chinese, ○ = Mid-Continent-Andean, ● = Eurasian-Arctic. Symbols for terrestrial biogeographical units are as follows: □ = Angaran, ▲ = Cathaysian, ◑ = Euramerian, ■ = Gondwanan. Symbol shape code for climatic assignments is as follows: ○ = tropical, △ = subtropical, □ = temperate. Arrows indicate inferred ocean currents: thick = warm, thin = cold. Topography is as follows. dark shading = mountains, intermediate shading = lowlands, light shading = shallow shelves, white = ocean basins.

Fig. 4.4 Early late Permian (Kazanian) global biogeography (after Ziegler et al. 1981)



Symbols for marine biogeographical units are as follows: ◆ = Transbaikalian, ⊡ = Taymyr-Kolyma, △ = Cordilleran, ▲ = Mordvinian, ○ = Grandean, ● = Tethyan, ◇ = Tasman. Symbols for terrestrial biogeographical units are as follows: ◈ = Far Eastern, □ = Angaran, ⊡ = Petchora, ● = Cathaysian, △ = Eastern European, ⊙ = Euramerian, ⊠ = Gondwanan. Symbol shape code for climatic assignments is as follows: ○ = tropical, △ = subtropical, □ = temperate, ◇ = polar. Arrows indicate surface ocean currents; thick = warm, thin = cold. Topography is as follows: dark shading = mountains, intermediate shading = lowlands, light shading = shallow shelves, white = ocean basins.

When in one time period similar habitats are separated by great distances then some of the species may be expected to be different in each of the habitats. If later, the remains of these plants and animals are brought closer together because of continental movement, it will be obvious that at one time they were further apart. Also if the remains of plant and animals which once lived in the same habitat are later found to be on two separate continents it may be surmised that originally the continents were much closer together. The areas inhabited by groups of plants or animals are known as faunal or floral provinces or realms, and these are limited by various barriers (not the least being the state of our knowledge) and defined by association often using statistical techniques. Ziegler et al. (1981) using data mainly from Chaloner and Meyen (1973) on compression flora assemblages and from Sullivan (1967) on miospore assemblages outlined 3 floral units (realms) for Viséan times viz. Angaran, Gondwanan and Circum Tethyan (Fig.4.2). Britain, represented only by data from Scotland, falls into the Circum-Tethyan unit. Using data from Read (1947) together with that from Chaloner and Meyen (1973) the number of realms was increased to four during Westphalian C/D times (Fig.4.3) by the recognition of the Cathaysian floral realm, and following the suturing of Laurussia and Gondwanaland the Circum-Tethyan unit is replaced by the Euramerican realm. Although not represented by a symbol on the map, it is clear the Britain falls into this latter realm. However, much of this analysis is speculative, often based on old data and as the authors point out forms only the basis for more detailed studies.

4.2 LOWER WESTPHALIAN PALAEOCLIMATE

The modern world can be used as a model to predict palaeoclimate. Due to heating and cooling of the earth's surface during rotation, latitudinally arranged zones of atmospheric circulation are created (Fig.4.5A). Moisture is moved from the oceanic areas to the continents by this circulation, but the pattern of circulation and the resulting pattern of precipitation are affected by the shape and distribution of continents and the location and orientation of highlands (Fig.4.6) within them (Robinson 1973, Ziegler *et al*. 1979). It has already been shown that during Westphalian C times Britain lay in equatorial latitudes (10°N to 10°S). Using the modern world as a guide this would indicate a tropical climate for Britain during this time. The modern tropical climate is defined (Tricard 1972) not by the presence of high temperatures, but by the absence of cool temperatures (the mean temperature of the coolest month being above 20°C). Also the annual temperature range is small (less than 10°C), there is a regularity of daily temperature (with important ecological consequences) and the daily temperature range is higher than the annual temperature range. Although the modern tropical zone is divided into two thermal regimes based on the presence or absence of torrid months, the best basis for division is on rainfall. This is produced by large convection currents moving humid air up to an elevation of 6-10,000m where it condenses forming rain. Convectional rainfall is greatly influenced by unequal relief of not just mountains but even hills, and being produced from cumulonimbus clouds is often accompanied by thunder and lightning. There is a high frequency of torrential rains, and in regions with a dry season the first downpours of the rainy season are often produced by violent electrical storms. Tricart (1972) lists 5 types of tropical climate based on the distribution of rain and the arrangement of seasons. If there are four seasons present in a year the climate is called

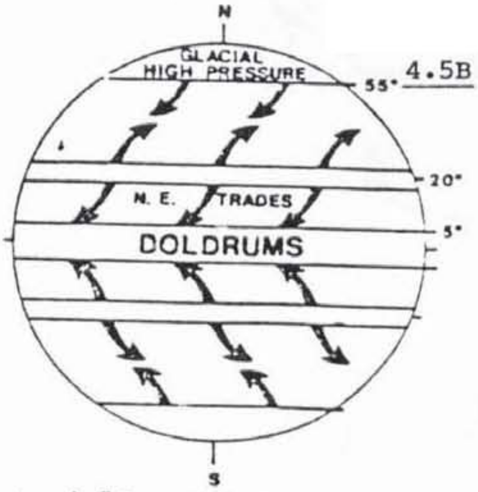
Fig. 4.5 Atmospheric circulation on a homogeneous earth showing the effect on the air pressure belts of an increase or decrease in the size of the polar ice caps.

4.5a Present atmospheric circulation (from Parrish 1982)

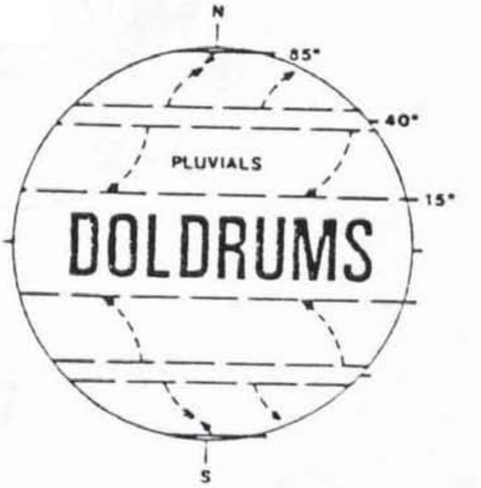
Illustration removed for copyright restrictions

4.5B-D (from Glennie 1981)

Illustration removed for copyright restrictions



4.5C GLACIALS



4.5D INTERGLACIALS

Fig. 4.6 The effects of highlands on continental precipitation patterns (based on Robinson 1973 from Ziegler et al. 1979) equatorial but if there is only an alternation of a wet season with a dry season the climate is termed (pure) tropical. The equatorial regime is divided into two types, pure equatorial - in which the 2 dry seasons still receive enough precipitation to sustain the plant life which grew in the preceeding wet seasons; and transitional equatorial - where the latter is not the case because one of the dry seasons is at least two months long. The (pure) tropical regimes are divided on the basis of the amounts of rainfall received throughout the year.

It is believed that the formation of the Hercynian highlands during the Silesian to the east of Britain may have affected precipitation in the manner shown in Fig.4.6c, so that Britain lay in a narrow equatorial wet zone. However, the effect of the remnants of the Caledonian highlands to the west of Britain may have complicated the situation producing a wider equatorial wet zone. Other variables which affect the intensity of atmospheric circulation are size of polar ice caps, the temperature at the sea surface and the equator-to-pole gradient which is affected by the former two. Glennie (1981) has shown that the effect of increased glaciation on atmospheric circulation is to decrease the size of the equatorial belt and increase the strength of the winds (Fig.4.5d). Although the climax of Gondwanaland glaciation occurred towards the end of the Westphalian it is possible that it began earlier, and underwent oscillations similar to the Pleistocene glaciation.

Periodic melting and freezing of the polar ice caps would also have resulted in a eustatic rise and fall of sea level. Because of this, areas of lowland may have become shelf seas during periods of transgression and reverted back to lowland during periods of regression. During the Silesian as the continents of Laurussia and

Gondwana moved closer together, it is believed that the ocean currents became restricted resulting in a marked contrast between the warm currents on the eastern side of Laurussia, and cold currents on the western side (Ziegler et al. 1981). Because of this and the distribution of the highlands there was probably a marked temperature asymmetry between eastern and western margins of the supercontinent.

Climate affects the structure and distribution of plants and animals and studies of them are useful in determining palaeoclimate. Various authors have argued for a variety of climatic regimes in the Westphalian coal forming basins of Europe and America. Ramsbottom (1984) believed the presence of the brachiopod Levipustula in Westphalian marine bands in N.W. Europe was indicative of a cold water climate during this time. Frederikson (1972) argued on the basis of a comparison between modern and ancient flora that the climate during the Westphalian in the 'swamp belt' was subtropical. This was based on the preference of ferns for a cooler environment than found in tropical lowlands, the small size of leaves, lack of drip-tips of swamp plants and the excellent preservation of plant structures within coal seams. Other factors which he put forward to support the subtropical climate included the exceptional occurrence of low ash coals which were believed mainly to have formed in areas with high precipitation (section 5.4.7.3) and the presence of fusain requiring periods of dryness in swamps. However, it is believed by the author that low ash coals occur frequently within the Westphalian A and B of both the Warwickshire Coalfield and others within the Pennine basin, and that fusain can be formed without prolonged periods of dryness within swamps (Section 5.3.8.5.7). DiMichele et al. (1979) showed that Carboniferous LYCOPHYTES were based on an herbaceous strategy, with only small amounts of wood and abundant living secondary cortex in the arborescent species. According to these authors this is indicative of rapid uninterrupted growth which only seems possible in a pure equatorial climate. Supporting this contention is the lack of growth rings which Chaloner and Creber (1973) correlated with a uniform 'seasonless' climate. For the reasons immediately above it is believed that the climate during the deposition of the Westphalian A and B in Warwickshire was tropical - pure equatorial.

4.3 DEPOSITION RELATED TO PALAEOGEOGRAPHY AND PALAEOCLIMATE

The topography of the earth's surface and the position of sea level are the two key factors in determining the environment of sedimentary deposition. A broad division can be made into marine and terrestial sedimentary depositional environments, according to the positions of the continents during the Late Westphalian. In Figs. 4.1-4.4 the marine environment has been further divided into ocean basin and shelf whilst the terrestial environment has been divided into mountains and lowlands. During the Silesian, deposition in the Pennine basin took place in lowland areas. These have been termed paralic indicating the proximity of marine environments to distinguish them from land-locked limnic areas. As Britain migrated northwards in time it is believed that the paralic areas moved southwards, so that they are recorded in sediments of Dinantian age in the north of England but in Westphalian sediments in central England. The production and preservation of peat is not believed to be climatically controlled as peat forming coal has been found in all latitudes from the equator to the polar regions (Habicht 1979).

4.4 THE PALAEOGEOGRAPHY OF THE PENNINE BASIN

The basement upon which Silesian sediments in the Warwickshire Coalfield were laid is variable and can be assigned to four different ages (Fig.4.7). In the SW of the Coalfield Wills (1978) postulated an area of Pre-Cambrian strata, based on the presence of a magnetic ridge towards the west of the Coalfield. Recent cored boreholes have established that the majority of the Coalfield is underlain by Cambrian strata. In the east of the Coalfield Devonian age sediments have been proved exposed in the north (Taylor and Rushton 1971) and in cored boreholes to the south. Following a period of continental deposition during which the Devonian sediments were laid down, a period of subsidence led to the deposition of Dinantian sediments in a series of 'blocks' and 'gulfs' within the Pennine basin (Kent 1966). Dinantian sediments have only been proved in boreholes in the extreme north of the Warwickshire Coalfield.

Originally it was believed that Namurian sediments did not exist in the Warwickshire Coalfield (Wills 1948). Later however, in the same boreholes mentioned above, the presence of Namurian sediments allowed Ramsbottom (1969) to draw a crude line showing that the Coalfield lay on the southern edge of the Pennine basin (Fig.4.8). Ramsbottom (1969) divided the British Namurian basin of deposition into 3 provinces. The 'Scottish province' is separated from the 'Northern province' by non-depositional 'highs' (stippled), whilst the latter province is separated from the 'Central province' on a faunal basis. These latter two provinces are jointly termed the 'Pennine basin'. Separating this basin from other basins to the south is another non-depositional high termed the Wales-Brabant Island. Since Ramsbottom (1969) Namurian strata has been found in exposures in the NE and NW of the Coalfield

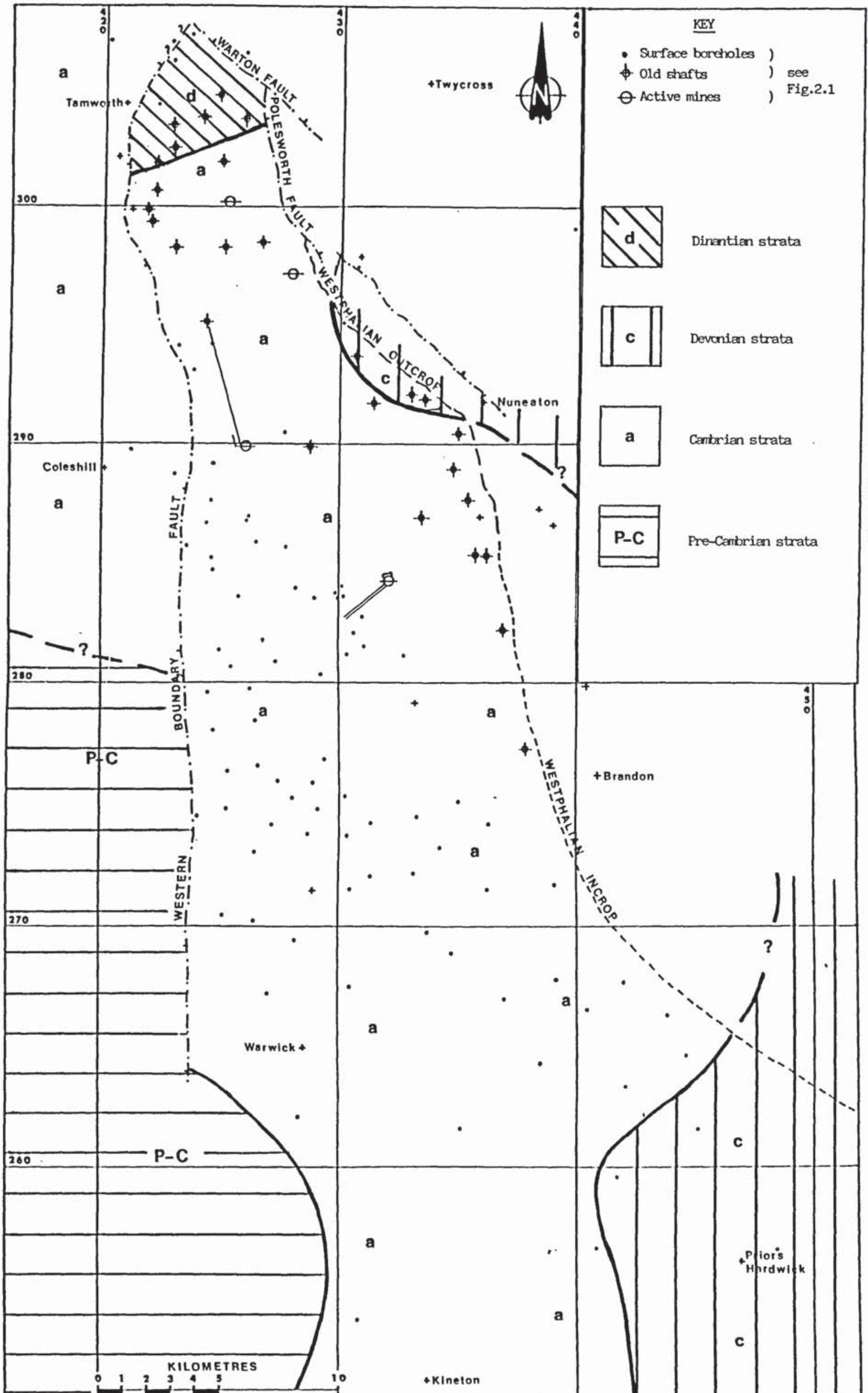


Fig. 4.7 Pre-Silesian basement of the Warwickshire Coalfield

(Taylor and Rushton 1971) and recent boreholes and examination of shaft sections has enabled a detailed Namurian isopachyte plan to be constructed (Fig.4.9). It shows that Namurian sediments extend from the north as a lobe approximately 20km into the Warwickshire Coalfield, and that the lobe is up to 15km wide.

The position of the Warwickshire Coalfield on the southern edge of the Pennine basin during the Lower Westphalian was recognised by Trueman (1947) and Wills (1948). Recently Guion _et al_. (In press) produced a palaeogeographic map of upper Westphalian A non-marine strata which showed a southerly directed embayment in the Wales-Brabant Island corresponding to the Warwickshire Coalfield. An isopachyte map for Westphalian A sediments (Fig.4.10) shows a maximum thickness of about 150m in the north, diminishing steadily southwards until in the central area of the Coalfield 50m of sediments exist. South of this a more gradual thinning takes place until in the extreme south the 10m isopachyte delimits a southward projecting lobe. It is believed that this lobe extends southwards into the Oxfordshire Coalfield. From a comparison of Namurian and Westphalian A isopachyte maps it is evident that the northern margin of the Wales-Brabant Island migrated at least 40km to the south during the Westphalian A Stage.

A separate isopachyte map has been drawn for sediments of Westphalian B age (Fig.4.11). The maximum thickness of Westphalian B sediments (150m) occurs in the north of the Coalfield and this thickness attenuates slowly towards the southeast. Difficulty in this area has been experienced in determining the position of the top of the Westphalian B because of the deterioration of the Aegir marine band (section 5.4.1) and the close vertical proximity of the

Fig. 4.8 Namurian palaeogeography of Britain (from Ramsbottom 1969)

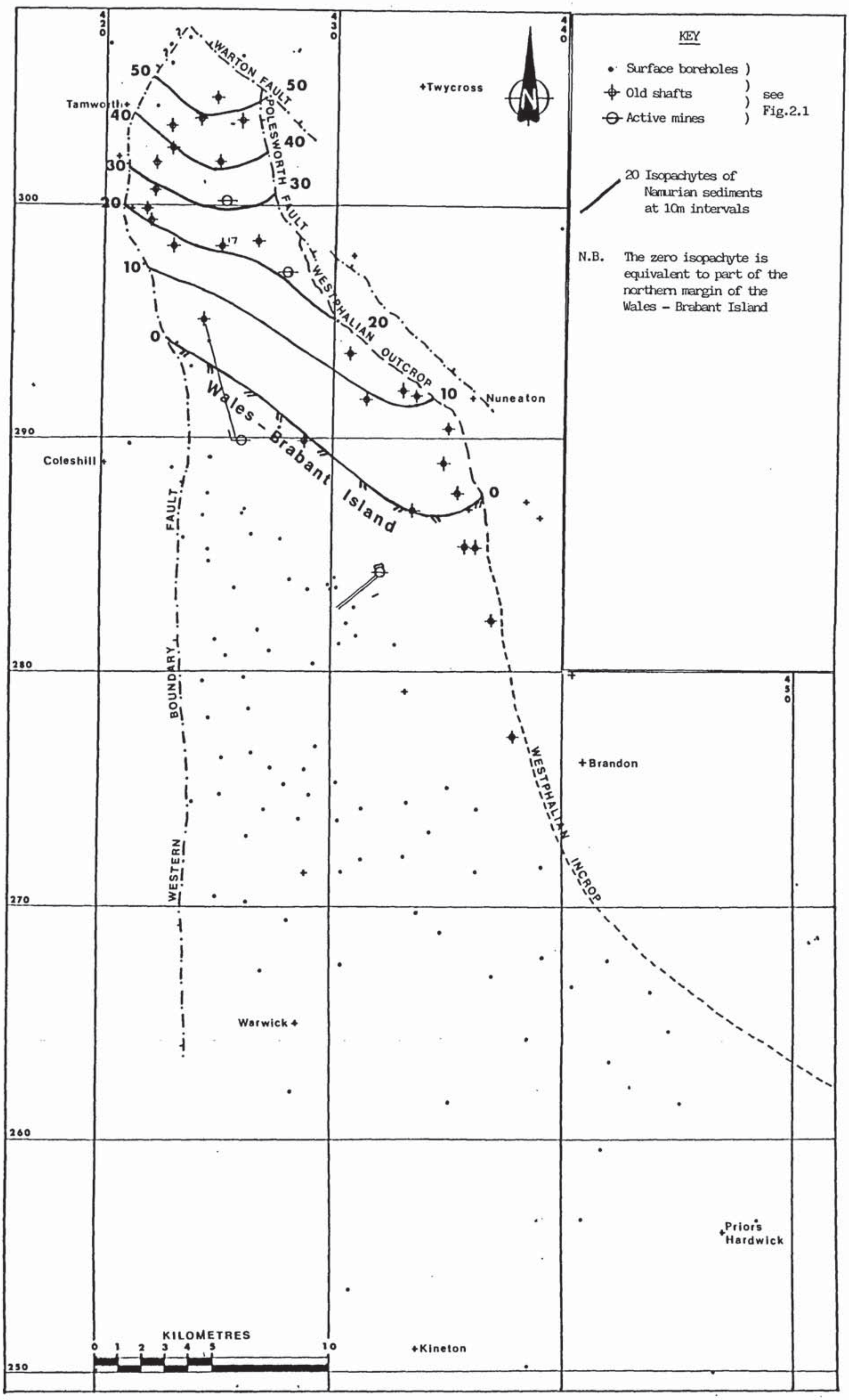


Fig.4.9 Palaeogeography of the Warwickshire Coalfield during the Namurian

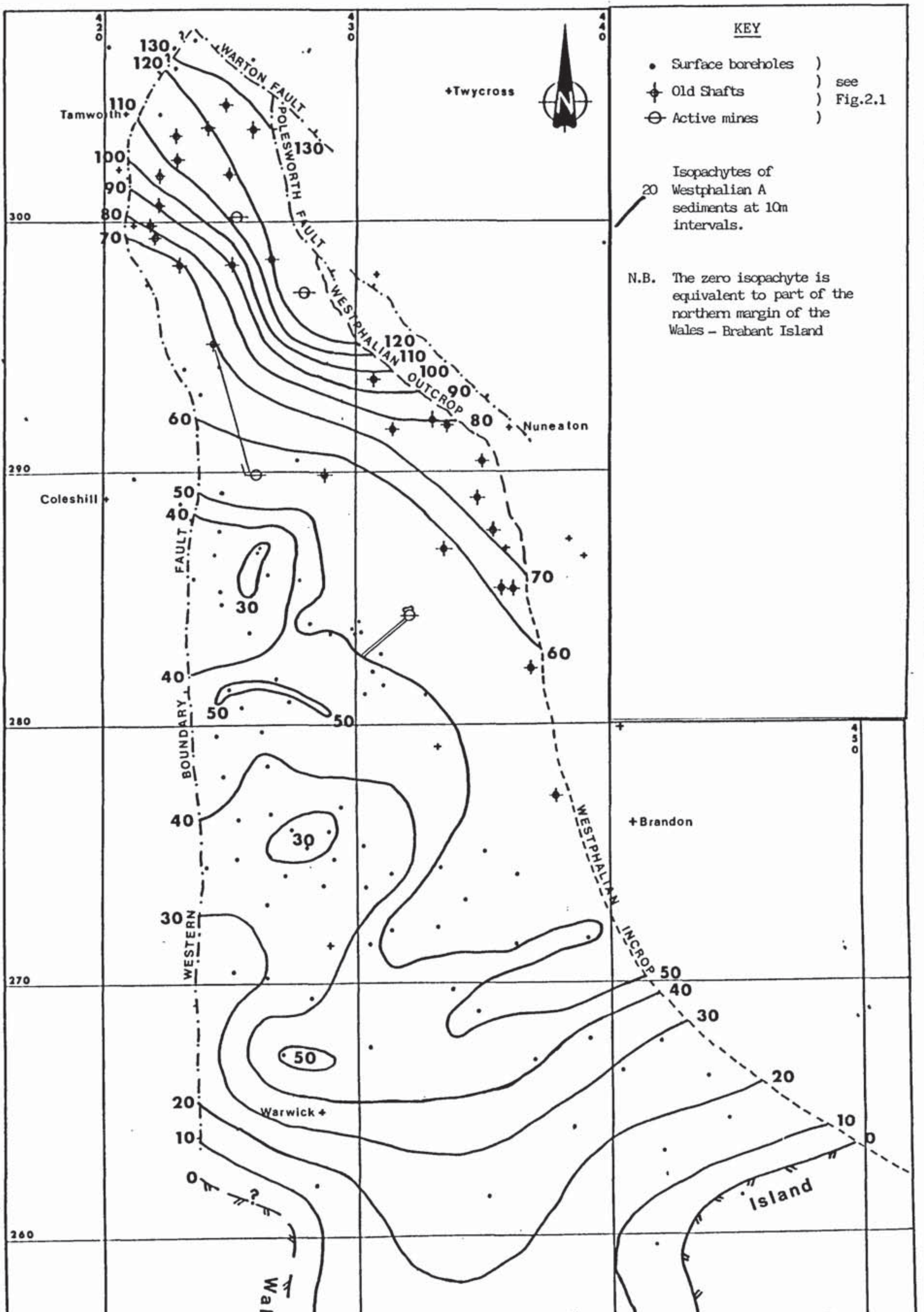


Fig. 4.10 Palaeogeography of the Warwickshire Coalfield during the Westphalian A

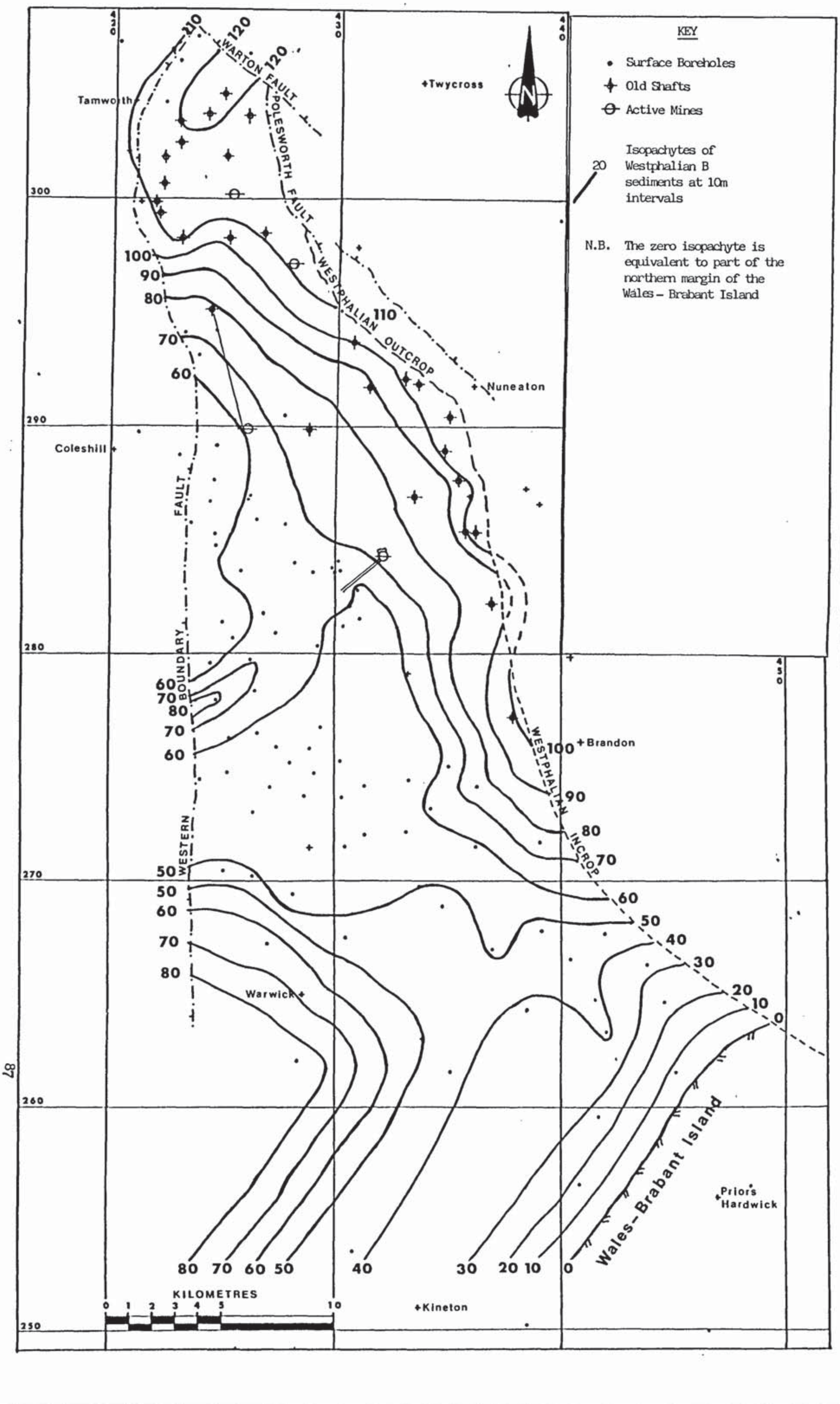
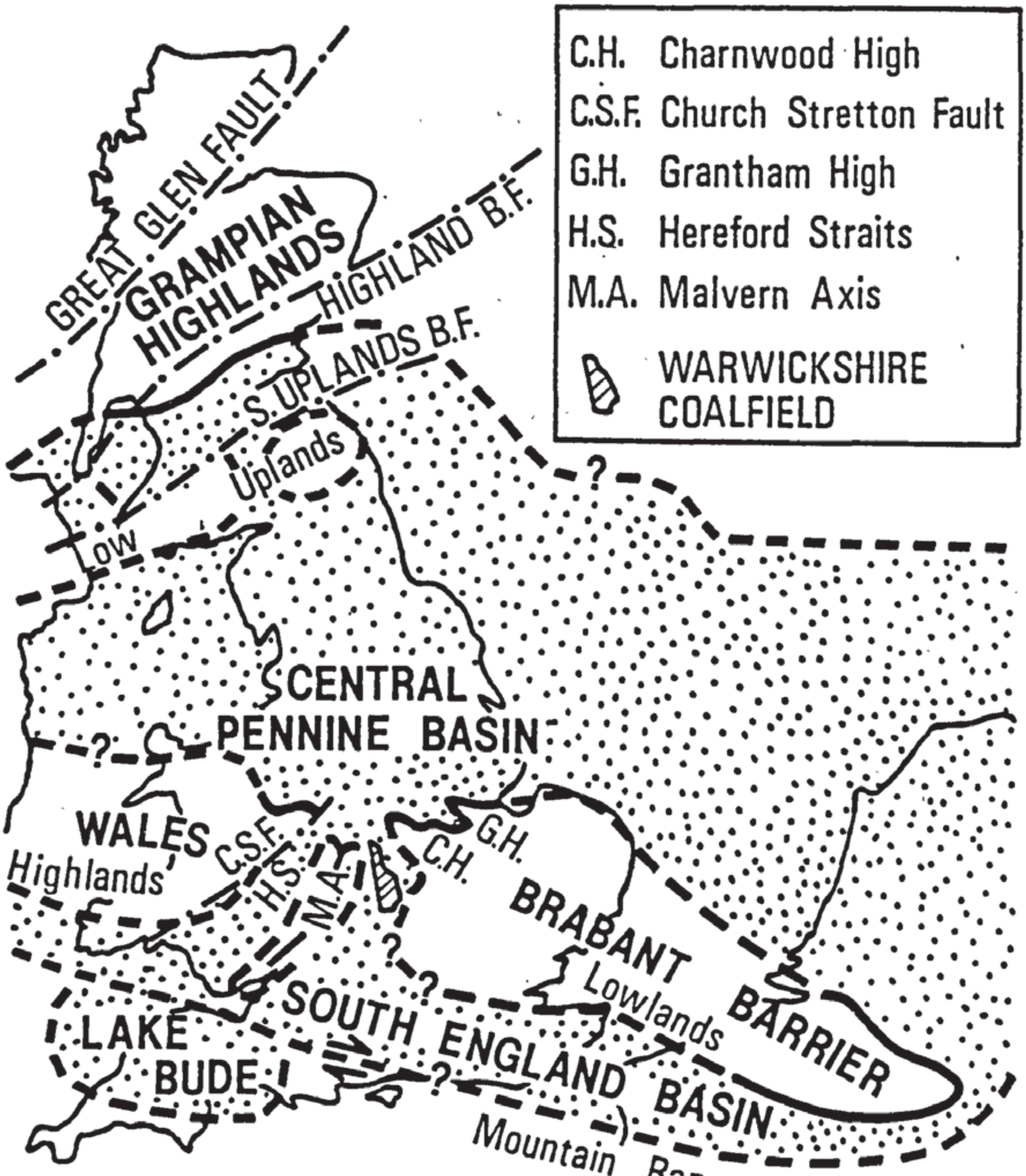


Fig. 4.11 Palæogeography of the Warwickshire Coalfield during the Westphalian B

Fig.4.12 Lowest Westphalian B palaeogeography of Britain (after Guion in press)



Westphalian D unconformity. To the southwest of the Coalfield the isopachytes thicken again. From this evidence it seems likely that by early Westphalian B times the Wales-Brabant Island was split in two, with a N-S link between the Pennine Basin and the South England Basin via Warwickshire, Oxfordshire and Berkshire (Fig.4.12).

4.5 CONTROLS ON THE EVOLUTION OF THE PENNINE BASIN

In recent years several models have been proposed to account for the evolution of the Pennine basin. These have been reviewed in Haszeldine (1984) and three basic hypotheses discussed. The model suggested by Arthaud and Matte (1977) involved the process of megashear. This is a broad zone of dextral transcurrent faulting forming the Variscan belt within which areas underwent local extension and compression creating both sedimentary basins and areas of provenance.

The model suggested by Leeder (1976) involved the collision of Gondwanaland and Laurussia and the subsequent consumption of oceanic crust during subduction. Later, following McKenzie (1978) who described a lithosperic stretching model, Leeder (1982) postulated that this type of stretching caused the production of a Lower Carboniferous rift province which developed into a major crustal sag. This created a setting of crustal tension during which sedimentary basins bounded by synsedimentary faults formed.

Finally Haszeldine (1984) building on the hypotheses of Russel (1973) and Russel and Smythe (1978) suggested a model of Carboniferous rifting of the north Atlantic producing N-S striking faults, reactivation of existing faults and the construction of rift parallel 'saucer' sedimentary basins.

It is not possible from a study only of the lower Silesian sediments in the Warwickshire Coalfield to decide which of these models is most likely to account for the evolution of the Pennine basin. However, any model used for this purpose must explain the nature of Silesian sedimentation within this Coalfield. Discussions of the mechanisms controlling subsidence during lower Silesian deposition in this Coalfield is given in Chapter 7.

CHAPTER 5

SEDIMENTOLOGY

This part of the study concerns the description and interpretation mainly of Westphalian A and B age borehole core although examples from faces and underground roadways are also used. A large amount of core from many boreholes drilled in the Warwickshire Coalfield was examined by the author, together with the description of core made by other N.C.B. geologists. Using this information a framework for the recording of sedimentary information was constructed. This framework which is both simple and adaptable enables comparison between the work of different geologists and can be applied to both borehole and underground and surface exposures. A universal framework has never been consciously adopted by the N.C.B. (Elliott et al. 1984); perhaps if enough geologists suggest similar frameworks (Guion 1978) whilst not recording descriptions wholly by numbers (Odell 1977), one may eventually be adopted.

Based on data recorded using the framework 10 rock types subdivided into 76 lithofacies were recognised. Each lithofacies was described in detail aided by a computer analysis of core from 5 boreholes drilled in the Warwickshire Coalfield. Also for each lithofacies the most likely process leading to its formation is discussed.

Using Markov Chain analysis on the five previously mentioned boreholes, together with an examination of many other boreholes, 10 lithofacies associations were recognised. Each association has been interpreted in terms of the depositional environment in which it formed and examples from borehole and underground exposures are given.

There are many mining reasons why detailed sedimentological recording of borehole core and underground exposure is important to the N.C.B. Only by this means can the amount of coal below the surface be accurately evaluated. It also governs how much of the coal can be extracted. Some sedimentary environments provide continuous seams of easily extractable coal. The ease of mining also depends on the geomechanical and hydrogeological properties of rocks both of which are partly determined by their sedimentological characteristics.

5.1 PRACTICAL TECHNIQUES

This sedimentological study reflects the present methods used by 'Deep Mines' geologists in the South Midlands Area of the N.C.B. The amount of information gained will be dependant upon the various levels at which the rocks under consideration are studied. These could vary from the microscopic study of thin sections to the megascopic study of field relationships. The majority of rock viewed by the author in the course of work and this study varies from hand specimen - seen in borehole core, to lateral exposures generally in tens of metres - seen underground.

5.1.1 Borehole Core

Core from surface boreholes is washed clean and examined on site in core-sheds. Initially the exterior is inspected over many metres to gain an overall appreciation of the sedimentation, marking obvious bed boundaries, and then the core is logged in detail. The core is broken horizontally to examine bedding planes and often vertically with a bolster chisel to examine any feature not apparent on the exterior. The only exception to this is coal which is transported to the laboratory for analysis. Because of the necessity to examine more or less flat surfaces to determine the lithofacies, yet preserve the material for analysis, coal is very carefully broken with a chisel on a workbench.

5.1.2 Underground Exposures

Colliery workings can be divided into two types - faces and roads, although they are connected. The commonest underground exposure inspected is the face which can vary between 1 - 3.5m in height and 180 - 230m in length. In the gate roads driven at 90° to the face and connecting it with the main roads, strata above and beneath the coal seam may be visible. These strata are termed in mining parlance roof and floor respectively. Any strata being left above the worked coal in the gate road is called a rip and any extracted below the worked horizon is called a dint. Roads - either gate or main roads are generally 'D' shaped in cross section, varying between 2 - 3.5m in height and 3 - 5m in width. Area of exposure is dependant upon age, the older roads sometimes being completely exposed, the newer ones often limited to exposures in refuge holes every 10m. When roads are driven at steep gradients it is necessary to construct level lines, so that measured sections can be related to each other. In all cases these were tied into existing survey stations to increase accuracy of map and section drafting. Rock exposed underground is relatively unweathered, readily comparable with borehole core and has the added advantage of lateral continuity. After a number of underground visits, composite sections can be constructed, which illustrate gross morphological sedimentary relationships.

5.1.3 Map and Section Drafting

Maps are constructed on a variety of scales based on amount and type of information to be shown. In the normal course of N.C.B. work only two scales are used 1:10560 where large areas are involved (reserve plans, five year plans, structure plans) and 1:2500 where faces are involved (face layout plan, detailed structure plans).

Vertical borehole sections are drawn at 1:500 scale in the South Midlands Area of the N.C.B. are useful for purposes of stratigraphy and gross sedimentology. Detailed sections in this study are drawn at 1:20, the minimum scale at which most sedimentological features can be plotted. Lithology is shown on the left and to the right of this is a graphical plot of grain size within which inorganic sedimentary structures are shown and to the left of this organic sedimentary structures are shown. Colour and qualifying remarks are placed within the graphical plot of grain size. A list of symbols used in this study is given in Appendix 'B'.

5.1.4 Laboratory Techniques

All coal seams sampled in the Warwickshire Coalfield are taken to Nuneaton Laboratory for analysis. Normally seams are divided into subsections according to the amount of dull, bright and canneloid coal together with their fusain and pyrite content. For those seams under special consideration in this study the method of division is outlined in section 6.1.1.

Coal lithofacies together with interseam partings, roof and floor are analysed using various parts of British Standard 1016 (1981). The analyses of coal, carried out on an air-dried basis unless otherwise stated are proximate analysis - moisture, volatile matter, fixed carbon and ash; mineral matter; specific gravity; calorific value also carried out on a dry mineral-matter-free basis; total sulphur; carbon dioxide; chlorine; phosphorous; crucible swelling number; Grey-King coke type; volatile matter also carried out on a dry mineral-matter-free basis; fusibility of ash in a reducing atmosphere related to deformation, hemisphere and flow temperatures; and colour of ash. The coal rank code is determined using the N.C.B. coal related to deformation, hemisphere and flow temperatures; and colour of ash. The coal rank code is determined using the N.C.B. coal classification system (1964) from the Gray King coke type and volatile matter on a dry mineral-matter-free basis. Most of the coals from the Warwickshire Coalfield are classified as low rank, with values between 802-902.

5.1.5 Computer analysis

As part of a joint study with the then N.C.B. geologist for the Leicestershire Coalfield (Richardson and Fulton 1981) five boreholes in the Warwickshire Coalfield were compared with a similar number in the Leicestershire Coalfield. The boreholes used from Warwickshire were Birch Tree Farm, Bockendon, Outwoods, Solomons Temple and Stareton. All of the Westphalian A and B age sediments within the boreholes were defined using 32 lithofacies and a statistical analysis carried out.

To facilitate the analysis a computer program was written by G. Crawford (N.C.B. Computer Programmer, South Midlands Area) in conjunction with the author and P. J. Richardson. This provided data on the number of lithofacies encountered within a borehole and details concerning their thicknesses e.g. average, maximum and minimum, together with embedded Markov Chain analysis.

Markov Chain analysis is carried out to test for Markovian properties. A first order Markov Chain has been described by Kemeny and Snell (1960) as "a stochastic process which moves through a finite number of states, and for which the probability of entering a certain state depends only on the last state occupied". The Markovian properties of a sequence of states can be examined by sampling at a fixed interval (Markov Chain) or by analysing each transition between states (embedded Markov Chain). Embedded Markov Chain analysis (M.C.A.) which is used in this study was first introduced into geology by Potter and Blakely (1968). Since then it has been used by a number of authors (Gingerich 1969, Krumbein and Dacey 1969, Selley 1970a, Miall 1973, Jerzykiewicz and LcLean 1980) and a summary of its use in geology together with the mathematical principles on which it is base is given in Harbaugh and Bonham-Carter (1970).

For each borehole studied the sediments were defined using the rock types 'Mudstone', 'Mudstone silty plus Siltstone', 'Sandstone', 'Conglomerate', 'Breccia', 'Seatearth' and 'Coal'. These form the first digit of the input state (see BED column of 'Print of borehole' table Appendix A) and are printed in the column down the left hand side of the 'State matrix' table (Appendix 'A'). Each rock type can be divided into nine possible lithofacies forming the second digit of the input state (see BED column of 'Print of borehole table, Appendix 'A') and are printed in the row along the top of the 'State matrix' table (Appendix 'A'), although only 32 were used. Each lithofacies is termed a state designated by L, so that the highest possible number of states S_1 is the largest figure in the 'State matrix' table and those figures within the table are internal matrix numbers. The key to these internal matrix numbers is given in the 'Bed thickness summary' where abbreviations for the lithofacies used in this study together with their numbers (see section 5.3) are shown. The lithofacies state together its thickness and type of contact with underlying state is put into the computer for each bed in the order in which they occur within the sequence studied (see 'Print of borehole' table, Appendix 'A').

Using this data a 'Transition array' table can be produced (Appendix 'A'), based on the following calculation. Let i be any bed, then the total number of beds = Ti. If a bed i of any lithofacies state is succeeded by a bed j of and state, then ij is the transition between those beds and Fij is the number of times that a specific transition between two states occurs. All transitions out of any bed i of a given state into any bed j of a given state are listed in the rows, and their row totals Si shown on the right-hand side of the matrix. All transitions into any bed j of any given state from any bed i of a given state are listed in the columns and their column totals Sj shown at the bottom of the matrix. The total number of transitions Sij is given in the bottom right-hand corner, and Si = Sij+1. Transitions between beds of the same state are not present, making this an embedded, first-order Markov chain.

From this an 'Actual probability array' table can be constructed (Appendix 'A') by comparing the actual number of transitions from beds i of a given state to beds j of a given state, with the number of transitions from i to beds of any other state, and totalling all rows to unity. Thus the row probabilities Pi are the odds of beds of that state being involved in a transition and the column probabilities Pj are the odds that beds of that state will be next, thus Pij = Fij/Si.

Next, the 'Independant trials array' table is produced by assuming that the beds of given state within a stratigraphic succession occurred at random, so that transitions from one state to another are governed by chance and hence the proportion of each state within the total population. Thus the random probability of any bed j of a given state overlying any other bed of any other state is given by Rij = Sj/Ti, but where transitions from a bed of a given state into itself are not permitted, then these must be deducted from the total number of beds i.e. ij = Sj/(Ti-Si).

Finally the 'Difference array' table is constructed by subtracting the 'Independant trials array' table from the 'Actual probability array' i.e. $Dij = Pij-Rij$. In this way the differences between what actually happened and what would have happened had the distribution been random are highlighted. Positive values mean that the change happened more often than random and negative values less often. Each row in this table should sum to zero.

If the events were truly random, then the 'Difference array' table would have all zero values. However, most populations are not that large or representative, so that non-significant, non-zero values are observed. The chi-square test is suitable for a test of significance, and is given by Anderson and Goodman (1957), chi-square $= 2 \sum_{ij}^{n} Fij. \log e \, (Pij/[Sj/Fij])$ with $[(n-1)^2-n]$ degrees of freedom for embedded first order Markov chains, where n is the tank of the matrix.

Although only 32 lithofacies (states) were used in the preceeding analysis, many are the same as those used in this study, and some are combinations used in this study. The significant transitions from each lithofacies (state) for all five boreholes were tabulated and an indication given of the number of boreholes in which that transition was significant (Table 5.1). In the lithofacies descriptions (Section 5.3) where available, data from Table 5.1 was noted together with information concerning thickness and prevalence of lithofacies. This table was also used together with observations from cores in other boreholes to construct facies relationship diagrams for each of the lithofacies associations.

Table 5.1 Significant transitions (determined following Markov Chain analysis) from each lithofacies state analysed up into another lithofacies state.

Transitions from lithofacies nos.	Transitions to lithofacies nos.
1.1	1.3, 1.6, 2.1 + 3.1, 3.3, 8.1
1.2	1.3, 1.5, 2.1 + 3.1, 2.2 + 3.2, 8.1, 8.1 + 8.3, 8.5, 8.6 + 8.7.
1.3	1.1, 1.4, 1.6, 8.1, 10.0
1.4	1.1
1.5	1.2, 1.3, 8.1, 8.5, 10.0
1.6	1.1, 2.6, 2.4 + 2.5, 3.3, 4.1 + 5.1, 8.6 + 8.7
1.7	Not recognised.
1.8	Not recognised
2.1 (+ 3.1)	1.1, 1.6 3.3, 2.9 + 3.7, 3.9, 4.1 + 5.1, 4.5, + 5.2, 4.6.
2.2 (+ 3.2)	1.1, 1.2, 1.5, 2.1 + 3.1, 3.9, 8.2 + 8,.3, 8.4
2.3 (+ 1.5)	1.2, 1.3, 8.1, 8.5, 10.0
2.4	1.1, 2.1 + 3.1, 2.2 + 3.2, 4.7
2.5	Not recognised
2.6	1.1, 1.6, 2.1 + 3.1, 3.9
2.7	Not recognised
2.8 (+ 3.6)	3.9, 4.5 + 5.2, 4.3, 4.2
2.9 (+ 3.7)	2.1 + 3.1, 3.3, 4.1 + 5.1, 4.5 + 5.2, 4.2, 7.1 -3
2.10	Not recognised.
2.11	Not recognised
2.12	Not recognised
3.1 (+ 2.1)	1.1, 1.6, 3.3, 2.9 + 3.7, 3.9, 4.1 + 5.1, 4.5 + 5.2, 4.6

Table 5.1/cont'd

3.1 (+ 2.1)	1.1, 1.6, 3.3, 2.9 + 3.7, 3.9, 4.1 + 5.1, 4.5 + 5.2, 4.6
3.2 (+ 2.2)	1.1, 1.2, 1.5, 2.1 + 3.1, 3.9, 8.2 + 8.3, 8.4
3.3	2.1 + 3.1, 3.9, 4.1er + 5.1, 4.5er + 5.2, 4.6er, 4.2
3.4	Not recognised
3.5	Not recognised
3.6 (+ 2.8)	3.9, 4.5 + 5.2, 4.3, 4.2
3.7 (+ 2.9)	2.1 + 3.1, 3.3, 4.1 + 5.1, 4.5 + 5.2, 4.2, 7.1 -3.
3.8	Not recognised
3.9	2.1 + 3.1, 3.3, 4.1er + 5.1, 4.5ne + 5.2, 4.3, 4.2
3.10	Not recognised
3.11	Not recognised
3.12	Not recognised
3.13	Not recognised
4.1er + 5.1	2.1 + 3.1, 3.3, 2.8 + 3.6, 3.9, 4.5er + 5.1, 4.2, 7.1-3
4.1ne + 5.1	2.1 + 3.1, 2.4, 3.3, 2.9 + 3.7, 4.,5ne +5.1, 4.2, 8.6 + 8.7, 8.8.
4.2	3.3, 2.8 + 3.6, 4.5er + 5.2, 4.5ne + 5.2, 4.6er, 8.2 + 8.3
4.3	3.3, 2.8 + 3.6, 4.5ne + 5.2, 8.2 + 8.3
4.4	Not recognised
4.5er + 5.2	2.1 + 3.1, 3.3, 2.8 + 3.6, 2.9 + 3.7, 3.9, 4.1ne + 5.1, 4.5ne + 5.2, 7.1-3, 8.2 + 8.3
4.5ne + 5.2	2.1 + 3.1, 3.3, 4.1ne + 5.1, 4.3, 4.2, 4.7, 8.2 + 8.3, 8.6 + 8.7.
4.6er	2.8 + 3.6, 2.9 + 3.7, 3.9, 4.1er + 5.1, 4.1ne + 5.1, 4.5ne + 5.2

Table 5.1/cont'd

4.7	2.4, 4.5ne + 5.2, 8.1
4.8 - 4.12	Not recognised
5.1 + 4.1er	2.1 + 3.1, 2.8 + 3.6, 3.9, 4.5er + 5.1, 4.2, 7.1-3
5.1 + 4.1ne	2.1 + 3.1, 2.4, 3.3, 2.9 + 3.7, 4.5ne + 5.1, 4.2, 8.6 + 8.7, 8.8
5.2 + 4.5er	2.1 + 3.1, 3.3, 2.8 + 3.6, 2.9 + 3.7, 3.9, 4.1ne + 5.1, 4.5ne + 5.2, 7.1-3, 8.2 + 8.3
5.2 + 4.5ne	2.1 + 3.1, 3.3, 4.1ne + 5.1, 4.3, 4.2, 4.7, 8.2 + 8.3, 8.6 + 8.7.
5.3	Not recognised
5.4	Not recognised
6.1	Not encountered in relevant boreholes
6.2	Not encountered in relevant boreholes
7.1 (+ 7.2 + 7.3)	2.2 + 3.2, 2.9 + 3.7, 4.1er + 5.1, 4.6er, 4.2, 8.2 + 8.3, 8.6 + 8.7.
7.2 (+ 7.1 + 7.3)	2.2 + 3.2, 2.9 + 3.7, 4.1er + 5.1, 4.6er, 4.2, 8.2 + 8.3, 8.6 + 8.7.
7.3 (+ 7.1 + 7.2)	2.2 + 3.2, 2.9 + 3.7, 4.1er + 5.1, 4.6er, 4.2, 8.2 + 8.3, 8.6 + 8.7.
8.1	1.2, 1.3, 1.5, 8.2 + 8.3, 8.5, 10.0, 2.2 + 3.2
8.2 (+ 8.3)	4.5er + 5.2, 8.1, 8.5, 8.6 + 8.7
8.3 (+ 8.2)	4.5er + 5.2, 8.1, 8.5, 8.6 + 8.7
8.4	1.3, 4.5er + 5.2, 8.2 + 8.3, 10.0
8.5	1.3, 1.5, 8.2 + 8.3, 8.6 + 8.7, 10.0
8.6 (+ 8.7)	1.1, 1.3, 8.1, 8.2 + 8.3, 8.5
8.7 (+ 8.6)	1.1, 1.3, 8.1, 8.2 + 8.3, 8.5
8.8	2.9 + 3.7, 8.5, 8.6 + 8.7

Table 5.1/cont'd

9.1	Not recognised
9.2	Not recognised
10.0	1.1, 1.3, 1.5, 8.5
10.1 - 10.9	Not recognised

Key

Numbers which are underlined are significant in two or more of the 5 boreholes examined using Markov Chain analysis.

er = erosive
ne = not erosive

5.2 ORGANISATION OF DESCRIPTION

The smallest packet of sediment used in this study is the lithofacies unit defined mainly on the basis of rock type, and inorganic and organic sedimentary structures. Each lithofacies is recognised solely on the basis of observed morphological characteristics and neither process nor environment are implied. In this context lithofacies is referring to "an objectively described rock unit" as defined by Reading (1978) although he also believed that "ideally a facies .... should reflect a particular process or environment."

Information about lithofacies is best recorded in a methodical orderly manner, so that none of the categories under which it is recorded are forgotten. This method is most easily demonstrated when logging borehole core, where information about thickness if recorded on the right and the main body of written information on the left, in the order (where applicable) rock type, grain size, coal macrolithotypes, colour, inorganic sedimentary structures, minerals, fracture, organic sedimentary structures, rock discontinuities, directional features and nature of contact with underlying bed. Any additional information not falling into these categories would be listed in the appropriate place. These categories will now be dealt with in the order listed above.

5.2.1 Thickness of Units

These are the thickness of lithofacies units and not the thickness of structures within the unit. Thicknesses in this study are given in metric units. Generally the minimum thickness of a lithofacies unit is 10mm, and although its maximum is unlimited, rapid vertical variation means that usually it will not exceed about 2m.

Lithofacies units cannot occur as laminae. Where a lithofacies is less than 10mm thick, it is necessary to create a new lithofacies defined by lamination with the under or overlying lithofacies. When this type of lamination exceeds 10mm some ambiguity may exist as to whether to divide the lithofacies into its component parts. This will usually depend on the vertical extent of the individual components present. Lithofacies units can be regarded as sedimentary building blocks.

5.2.2 Rock Type

In order to present a systematic approach, the descriptions of lithofacies given later in this Chapter have been artificially grouped under their appropriate rock types. There are 10 rock types which are differentiated because they are significant in terms of interpretation. The first 6 are separated on grain size - 'Mudstone', 'Mudstone silty', 'Siltstone', 'Sandstone fine' 'Sandstone medium to coarse', and 'Conglomerate' and the seventh on clast shape - 'Breccia'. The last three are all palaeosols distinguished on organic sedimentary structures, the eighth on the presence of abundant oblique roots - 'Seatearth', the ninth on the presence of rare oblique roots - 'Subseatearth', and the tenth on the mass accummulation of layered organic matter - 'Coal'.

5.2.3 Grain Size

Difficulty has always been experienced in the field in estimating the grain size of rocks. This is partly because the size of many of the particles is smaller than that able to be observed with a hand lens and also because Coal Measure sediment is often rather poorly sorted. The author has observed other N.C.B. geologists at work and found that the boundaries used to distinguish between mudstone, siltstone and sandstone are variable. As grain size affects many rock types it is best discussed at this stage.

Folk (1954) believed that grain size should be described independently of mineral composition but based his classification primarily on mineral and textural composition which could only be determined in the laboratory. Elliott and Strauss (1970) found that grain size could be directly linked to quartz content, in rocks dominated by quartz and clay minerals taken from the Coal Measures of the East Midlands. Although their measurements are based on % by wieght of quartz, which increases as rocks progress from mudstone through siltstone to sandstone, two tests (discussed below) and information on identification in the field are given allowing distraction to be made between rocks of different grain size.

The Wentworth (1922) scale modified by Udden appears most widely used by sedimentologists and for that reason has been adopted as a guide to grain size in this study.

The name given to the finest grain size on the scale is clay but the term used to describe the rock type composed of this sediment is mudstone. This is partly because of its common usage within the N.C.B. and partly because the majority of mudstones in Warwickshire are blocky - a characteristic used by Potter et al. (1980) to distinguish them from fissile claystones. The boundary between clay and silt is 1/256mm although Folk (1954) believed it should be placed at 1/64mm, and Potter et al. (1980) would prefer it placed at 2 micrometres (1/512mm) as they consider most clay minerals to be of this size. Elliott and Strauss (1970) believe that a self polishing test can be used to distinguish between mudstone and siltstone. This involves rubbing two pieces of the tested rock together, which, if they take a polish, prove the rock to be a mudstone.

Unfortunately the large number of divisions of silt(stone) made by Wentworth, unable to be seen by use of a hand lens, make this part of the scale impracticable in the field. For this reason only two grades are used in this study; following Elliott and Strauss (1970) with a boundary between them at 1/64mm. Mudstone silty is the name given to the finer grain size and siltstone to the coarser grain size. The boundary between siltstone and sandstone is 1/16mm although Folk (1954) believed it should be placed at 1/8mm and Elliott and Strauss (1970) place it at about 1/32mm. This latter size is the one above which Elliott and Strauss (1970) demonstrated that the rock in the East Midlands Coalfield will be composed of greater than 50% quartz. They also use a colour test to differentiate the grey coarser siltstones from the off white finer sandstones, but the author has commonly observed rocks with a grain size between 1/16 - 1/4mm which are grey in colour. This may be because of more poorly sorted or organic rock sandstones existing in the Warwickshire Coalfield.

For the sake of ease of data recording, the sandstone group on the Wentworth scale is divided in this study to give two grain sizes, fine 1/16 - 1/4mm, and medium to coarse 1/4 - 2mm although particles between 2 - 4mm in size may sometimes occur in the coarser grained rocks. Those above 4mm in size are clasts which occur in the rock types 'Sandstone fine', 'Sandstone medium to coarse', 'Breccia' and 'Conglomerate'.

TABLE 5.2 Grain size, its relationship to rock type and its recognision in the field

Grain Size mm	Rock Type	Diagnostic Characteristics	Remarks
4	Conglomerate/ Breccia		Use a comparator either chart or graded sample
2-4	Granulestone	Off white to pale grey granular, uneven fracture sparkling lustre	
1/4 - 2	Medium to Coarse Sandstone		
1/16 - 1/4	Fine Sandstone		
1/64 - 1/16	Siltstone	Pale to medium grey granular uneven fracture matt lustre	Use standard samples for comparison
1/250 - 1/64	Mudstone silty	Medium to dark grey granular, subconchoidal fracture, matt lustre, occasional listric surfaces, feels gritty when chewed	
1/256	Mudstone	Medium grey to black, smooth, subsubconchoidal fracture, matt to resinous lustre occasional to abundant listric surfaces, reflective increased by use of self polishing test (Elliott & Strauss 1970)	

Grain size in this study relates to the majority of grains as seen in hand specimen. Elliott and Strauss (1970) have demonstrated the range of grain size which can occur in a single specimen, often spanning Westworth boundaries. In practical terms, in the field, the best method to assess grain size are given in Table 5.2. There are exceptions to those characteristics mentioned in Table 5.2, eg dark grey siltstones caused by a large increase in organic content. Fining or coarsening upwards is also noted. Abbreviations and symbols used in this study for grain size are shown in Appendix 'B'.

5.2.4 Coal Macrolithotypes

Coal is a sedimentary floriclastic rock differing from siliciclastic rocks because it is formed mainly from plant and/or algal remains in various stages of preservation. The donor materials and the processes leading to and following their deposition, mean that different components or macrolithotypes, having macroscopically different morphological characteristics can be recognised. This is dealt with in detail in Section 5.3.8.5. Abbreviations and symbols used for these are shown in Appendix 'B'.

5.2.5 Colour

In the Warwickshire Coalfield the rocks of Namurian and Westphalian A and B age are usually grey in colour, sometimes brown and rarely green or red. Grey rocks have been divided into pale, medium and dark grey based on the experience of N.C.B. geologists, although the sequence between them is continuous. Two separate processes operate to produce shade changes of grey in Coal Measure rocks. Increase in the amount of quartz produces lighter coloured rocks and increase in the amount of fine organic particles (see relevant lithofacies sections) produces darker coloured rocks. The colour brown is related to the amount and species of iron mineral present.

Rocks of the Halesowen Sandstone Formation (Westphalian D age) are predominantly green in colour interbedded with grey rocks. In the case of the sandstones this is related to the mineralogy but the green colour in finer grained rocks may be part of a series between it and grey (Potter et al. 1980). This has been related by the latter authors to the percentage of organic carbon, as the iron is likely to occur in its reduced ferrous state with clay minerals.

Some of the rocks of Westphalian A - C age are red in colour and occasionally they are multicoloured (including ochreous and olive grey). The rocks of the Keele Formation and Enville Group (Westphalian D age) are also red. The variation in colour displayed by the rocks of Westphalian C age illustrates the second series recognised by Potter et al. (1980). This reflects the work carried out by Tomlinson (1916) who showed that the colour red was associated with high ferric/ferrous ratio and green with the inverse. Ferric iron usually occurs in the form of haematite (section 5.2.7.4 and relevant lithofacies sections).

Perhaps more use should be made of colour charts, eg. Goddard et al. (1975) and Munsell Color (1975), although these are a little complex for use whilst logging for the N.C.B. Symbols for colour are shown in Appendix 'B'.

5.2.6 Inorganic Sedimentary Structures

Primary sedimentary structures have been defined by Pettijohn and Potter (1964) as those formed at the time of deposition, or shortly after, and before consolidation of the sediment. In this study they have been divided into inorganic structures formed by particle movement and organic structures formed by any organism. The latter, termed biokinematic by Elliott (1965) are part of his genetic classification based on the rheological properties of the sediment. He divided inorganic structures into exokinematic if they are produced by action taking place outside the produced sedimentary structure and endokinematic if it is within it.

The term used to describe sedimentary layering is stratification if it is parallel to, or cross stratification if it is at an angle to the original dip of the formation McKee & Weir (1953). Each stratum is deposited under relatively constant conditions and is distinguished from the one above or below by a discontinuity. This is defined by Griffiths (1961) as a change in either composition, size, shape, orientation or packing of grains, although in this study any major change in sedimentary or biogenic feature would consitute a discontinuity. A set as defined by McKee & Weir (1953) is a group of essentially conformable strata separated from other units by surfaces of erosion, non-deposition or abrupt change of character. A lithofacies unit in this study may comprise a single stratum, a set, a coset, a composite set, or may be part of a set coset or composite set.

Many authors have divided stratification quantitatively on the basis of thickness and these are reviewed in Ingram (1954) who established the criteria used in this study. They have been expanded at the 'thin' end mainly for use in describing coal macrolithotypes, as below:-

mm

less than 0.3 Finely laminated
0.3-3 Thinly laminated
3-10 Thickly laminated

30-100 Thinly bedded
100-300 Medium bedded
300-1000 Thickly bedded
greater than 1000 Very thickly bedded
10-30 Very thinly bedded

For the sake of ease these semiquantitative terms were often used, although like Guion (1978) the present author believes that it is preferable to measure the thickness of stratification, and if necessary indicate its range of variation.

Another quantitative division used in this study is that between cross lamination (small scale cross stratification) and cross bedding (large scale cross stratification). Originally Allen (1936a) placed the boundary at 50mm believing it to represent a natural division between two bedforms - ripples and dunes, between which there was no continuum. Measurements of set heights in Warwickshire by the author shows that they are usually less than 40mm. This measurement is the new boundary between ripples and dunes used by Allen (1984), corresponding to the natural low in the frequency distribution of ripple and dune height, and is the one used in this study.

Although detailed description of stratification are given in the sections on lithofacies, it may be appropriate at this stage to outline briefly the morphology and origin of cross stratification, because of its abundance in coarser grained lithofacies.

Cross lamination is formed as the result of burial of transverse bedforms. It has been divided previously into ripples and dunes based on the height (H) of the bedform. Other important geometrical measurements can be used to define and classify bedforms and their products which form lithofacies viz. length (L) - distance between successive troughs/points, length of horizontal projection of stoss side (sL) and lee side (lL) and breadth (B) length along crest line. From these two important indices can be derived i.e. 'Vertical form' (Allen 1963a) or 'Ripple index': $RI = \frac{L}{H}$ and 'Ripple Symmetry index' (Tanner 1960) : $RSI = \frac{sL}{lL}$

Ripple wavelength and height are controlled by grain size and mean bed shear stress. The shape of the crest has been used to characterise ripples - straight, sinuous, linguoid and lunate (Allen 1963a) and also the shape of the lower bounding surface to define sets which are simple, planar (tabular) or trough (McKee and Weir 1953) and alpha to pi (Allen 1963b). The last paper also took into account the homogeneity of the sediment comprising the set - heterogeneous if composed of grain sizes greater than two Wentworth classes, homogeneous if less.

There is a range of hydraulic conditions which give rise to bedforms so that they may climb, progress horizontally or descend. For ripples, as the angle of climb increases the stoss slope becomes preserved and this type of cross stratification is called ripple drift. Allen (1984) has described this as a change from subcritical to supercritical stratification. He has shown that the angle of climb is directly related to the rate of sediment transfer and bedform height and that the latter is inversely related to the rate of bedform transport. They hydraulic conditions which give rise to bedload transport and the size of bedform constructed are dealt with in section 5.3 or in the appropriate lithofacies sections.

Ripples can be grouped into three categories according to the type of movement which produces them, although they may be part of a continuous morphological series (Allen 1984). Current ripples formed by translatory, undirectional movement are asymmetrical in outline and have internal cross laminae which relate morphologically to the ripple outline. They are said to be form concordant. Wave ripples formed mainly by oscillatory but also rotatory movement tend to be symmetrical in outline and have internal laminae which do not necessarily relate to the ripple outline. If they do not they are said to be form discordant. Wave current ripples are formed by a combination of translatory oscillatory and rotatory movement, and as a result of net transportation in one direction the ripples formed are asymmetrical. They may also be form discordant. Distinguishing features between the three categories are given in TABLE 5.3, and in this way hydraulic conditions of ripple formation can be related to ripple geometry. The most important criteria for easy identification underground are those features seen in cross section. In all three categories ripples may be sub- or supercritical.

Wave and current ripples have been found at a variety of depths dependant on environment. Normally in the lacustrine environment ripples affected by wave action are restricted to a depth of a few metres, but under storm conditions this can be extended to 15m (Allen 1984).

Other sedimentary structures are described in conjunction with the lithofacies in which they occur. Symbols and abbreviations used for sedimentary structures are shown in Appendix 'B'.

TABLE 5.3 Distinguishing features of the three categories of ripples .

			Asymmetrical Current Ripples	Asymmetrical Wave Current Ripples	Symmetrical Wave Ripples
TRANSVERSE FEATURES IN PLAN		(a)	longcrested - straight or sinuous	Straight or sinuous	Straight or sinuous
		(b)	shortcrested - linguoid, lunate	none	none
		(c)	Crests are curved, do not bifurcate	Crests are regular and bifurcated	Crests are regular and bifurcated.
		(d)	Crest height < ripple wavelength	Crests height > ripple wavelength	Crests height > ripple wavelength
IN SECTION			Crests rounded	Crests more rounded than current ripples	Crests rounded or pointed
STREAMWISE FEATURES			spurs & stoss side ridges common	spurs and stoss side ridges rare	spurs and stoss side ridges rare
MORPHOLOGY	R.I.		5-15+	?5(6-8)16	?3(6-7)15
OUTLINE	R.S.I.		> 2.5	1.5 - 3.8	<1.5
HEIGHT (mm)			4.5 - 40	?1 - 20	?4.5 - 40
WAVELENGTH (mm)			40 - 600	15 - 1050	5 - 2000
OUTLINE VS. CROSS LAMINAE INTERNAL STRUCTURE			form concordant	may be form concordant form concordant or discordant	often form discordant
CROSS LAMINAE			related to outline	may have chevrons in troughs or crests may have reactivation surfaces	may have chevrons may have reactivation surfaces
CROSS LAMINAE SETS			less regular	more regular	more regular
LOWER BOUNDING SURFACE.			regular	irregular	irregular

Data from Allen (1984); Boersma (1970); McKee (1965); Singh (1980); Reineck and Wunderlich (1968) and Tanner (1960, 1967), and own measurements.

Figure in brackets represent a range of commonly occurring values.

5.2.7 Minerals

The minerals listed at this point in the description of a lithofacies unit will usually exclude the major rock forming minerals - quartz and clay found in rocks of Silesian age. This is because of the previously mentioned link between grain size and mineral composition as shown in section 5.3.1.3 so that stating the former indicates the latter. Elliott and Strauss (1970) measured the % by weight of quartz on the following rocks as follows - mudstone less than 20%, siltstone 20-50% and sandstone geater than 50%.

Although not mentioned in lithofacies descriptions sandstones can be classified according to their mineral composition and Guion (1978) used the classification of Dott (1964) when examining sandstones petrographically in the East Midlands Coalfield. In nearly all cases the sandstones were designated quartz wackes. Examination of a few slides from the Warwickshire Coalfield, sent for routine petrographic analysis by the N.C.B., revealed that in nearly all cases the percentage of matrix exceeded 10% and percentages of feldspar and rock fragments were both below 10%, and they also were designated quartz wackes. The only exceptions were sandstones which are white, compact and strong in hand specimen which when examined in thin section showed quartz overgrowths and less than 10% metrix, feldspar and rock fragments and are classed as quartz arenites. Often these rocks are described as having recrystallised cement in lithofacies descriptions.

5.2.7.1 Mica

Another pervasive if less abundant mineral is mica, usually muscovite, which is easily perceived by the naked eye or by use of a hand lens. It is often omitted from descriptions because of its common occurrence.

5.2.7.2 Siderite

The next most common mineral is siderite ($FeCO_3$), usually called ironstone in N.C.B. descriptions. It is recognised in hand specimen by its brown colour and high specific gravity. Petrographic studies (Hallimond 1925, Dunham 1960) show that the siderite is microcrystalline. A wide range of morphological forms are present and they are classified in this study on the basis of these.

Very often it occurs as part of the cement in rocks of all grain sizes. Similarly it may occur in diffuse irregular patches.

Spherulitic ironstone, often called sphaerosiderite in N.C.B. logs, are mineral bodies especially common in seatearths of all grain sizes. They range in size from microscopic to about 2mm in diameter. Sphaerosiderite occurs widely scattered or in dense aggregates, so that they form large irregular nodules up to about 0.50m long. Although found in grey coloured rocks they are more prevalent in those of brown colour which have a sideritic cement.

For the purpose of this study nodules are mineral bodies which are not flattened in the plane of stratification, and range in size from 10-100mm and in shape from spherical to highly irregular. They most commonly occur isolated in seatearths, where they are often elongated oblique to the bedding, following the direction of roots. The nodules are pointed at either end and concentric in cross section. Occasionally they form irregular aggregates. They can occur in rocks of all grain sizes, within and outside seatearths, and their margins are generally abrupt but may be diffuse.

Lenses are mineral bodies which are flattened in the plane of stratification and are therefore disc shaped generally ranging in size from 10-600mm. They are often found in layers extending tens of metres. The larger lenses may be septarian with irregular cracks containing calcite and these lenses usually have sharp boundaries. Lenses can occur in rocks of all grain sizes where their margins may be abrupt or diffuse.

Layers of siderite are commonly found in fine grained rocks - 'Mudstone' and 'Mudstone silty', either singly or in alternating parallel laminae with the matrix. They generally have diffuse boundaries and although occurring in fine grained sequences, sometimes form within the coarser parts of the sequence.

Very often these siderites occur in abundance in stratigraphically preferred horizons and have been worked extensively in the last century in North Warwickshire where they have local names viz. the 'Brown Ironstone' below the Seven Feet coal (Howell 1859 p.17) the 'White Ironstone' above and below the Smithy (high Main) coal and the 'Black Ironstone' below the Bench Coal (Barrow et al. 1919 p.212).

Interpretation

To form siderite (ferrous carbonate) a source of both iron and carbonate are needed. A variety of mechanisms allowing the combination of these have been proposed, either during deposition of in early or late diagenesis. Some of the occurrences of siderite in rocks of Westphalian age in Warwickshire may throw light on its origin.

Krumbein and Garrels (1952) showed that siderite forms in reducing (low Eh) and slightly alkaline (higher pH) conditions. Other factors are also important, including temperature, degree of saturation, and other ions in solution. Curtis and Spears (1968) and Berner (1971) have showed that if sulphate ions are in solution (likely to be the case if the sediments were deposited in a marine environment) these are reduced to sulphide ions which then combine with iron to form pyrite.

Syngenetic precipitation of minerals at the interface between sediment and water has been shown to take place by Voight (1968). Hallimond (1925) believed siderite could form during deposition in a reducing environment and Dunham (1960) thought this the case for layers of clay ironstone forming in the presence of decaying organic matter. This was noted by Reiskind (1975) although this does not necessarily mean that siderite formed during deposition.

Hemingway (1968) believed that a process occurring in the Ob marshes of Siberia might be similar to the mechanism which formed Coal Measure siderites. Here iron is precipitated as a gel so that later it can be converted to siderite in the presence of organic matter. Boardman (1981) advocated a similar mechanism for the formation of 'Blackband' siderite in the Westphalian of Staffordshire. This is discussed under the relevant lithofacies heading.

Curtis and Spears (1968) thought that siderite was unlikely to form in open water because the thermochemical condtions would not be suitable. They considered it was more likely to develop beneath the sediment surface and thus be diagenetic. Curtis (1977) showed that a range of processes related to depth of burial could produce siderite in marine mudstones. The idea that changes take place systematically following burial was proposed by Curtis et al. (1975) following their discovery that the isotopic composition of carbon within the carbonate changes from the centre to the margin of siderite laminae. This may reflect changes in porewater composition. Curtis (1978) also discussed the source of carbonate which he believed to have been produced by microbiological degradation of organic matter. The source of iron is probably hydrated ferric oxides which are common in tropical soils (Young 1976) which may be reduced to the more mobile ferrous ion upon contract with organic matter.

There is substantial evidence for the early diagenetic formation of siderite in the Warwickshire Coalfield. Increase in thickness between the same laminae within siderite concretions when compared with outside shows that they must have formed before appreciable compaction. Further evidence of their early formation comes in the form of ironstone lenses with abrupt margins which have been cut by erosional surfaces and often intraformational conglomerates whose clasts consist mainly of siderite show that these must have been present in banks which were being eroded at the time of channel formation. A situation has been noted by Hemingway (1968) where an ironstone conglomerate rests directly on the Low Moor Ironstone near Bradford. It may be that TABLE 1 produced by Curtis (1978) for the marine environment could be modified for freshwater deposits by removing zone II and increasing zone III to replace it.

Siderite nodules, which are believed to be replacements after calcium carbonate and so of early diagenetic origin have been observed in poorly drained swamp environments in the Atchafalaya basin, Mississippi by Coleman (1966).

A special relationship appears to exist between 'Seatearths' and siderite. This may be because of the chemical conditions existing in adjacent environments, either laterally or vertically above, where peat is accumulating. Acid waters emerging from the peat may contain insoluble ions in the form of organic and inorganic colloids (e.g. phosphates Kenworthy 1971) and presumably from which may accummulate as a gel (Hemingway 1968) or may become oxidised to limonite at the peat surface (James 1966) and then be carried toward the seatearth environments where they may be converted to siderite.

Also Fitzpatrick (1971) has observed siderite as one of the mineral phases developed toward the base of peats which may evolve from iron rich solutions migrating downward into a more anaerobic reducing environment. McDonnell (1974) showed that siderite in Triassic palaeosols in the Sydney Basin probably formed early. He observed sand filled insect filled burrows approaching them from above, but moving around them rather than going through them.

Although the mechanisms listed above could produce either spherulitic or lenses of siderite different mechanisms must be responsible for their formation. This is because the size distribution for the two morphological forms are distinctly different. A clue to this may be that spherulitic siderite occurs preferentially in brown seatearths which formed in a different environment to grey seatearths (section 5.4.7.4).

It is likely from the previous discussion, that siderite may have been produced by a variety of mechanisms, the environmental implications of which will be discussed in later sections.

5.2.7.3 Pyrite

The next most common mineral to occur in Westphalian age rocks in Warwickshire is pyrite, which can appear in a variety of morphological shapes and rock types. It is almost universally associated with coal seams, occurring commonly in lenses (which are disc shaped) up to 0.15 m in diameter e.g. Thick Coal at Longmeadow Wood borehole. Finely disseminated pyrite may also be found, and rarely pyrite cubes. Pyrite is commonly found in mudstones which have an associated marine or brackish fauna e.g. mudstones forming the Nuneaton Marine band. It commonly occurs as cubes, often in aggregates, also finely disseminated in patches and as plant and animal replacements. Rarely pyrite is found in seatearths closely associated with roots. Pyrite also occurs in fissures, like cleat in coal, and joint surfaces in rocks of all grain sizes and associated with fault planes.

In the first half of this century pyrite was separated from coal on the surface at many mines in North Warwickshire e.g. from the Seven Feet seam at Birch Coppice Colliery and used mainly in the production of sulphuric acid.

Interpretation

The origin of pyrite in the rocks listed above may be as varied as that of siderite. Production of pyrite depends on the presence of both iron and sulphur. Derivation of iron has already been discussed in the section on siderite, and can be found in water which has come into contact with ferromagnesian minerals, especially those which have been weathered. Sulphur may be produced by the breakdown on plant, animal and bacterial protein (Teichmuller and Teichmuller 1982) especially in peat, or by bacterial sulphate reduction (Neavel 1966). This can take place within marine sediments or within peat following inundation of a swamp by marine waters (Williams and Keith 1963). Pyrite forms in slightly alkaline and strongly reducing conditions (Krumbein and Garrels 1952) which can occur in marine to freshwater sediments and in peat.

Recent marine peats have crystalline pyrite 0.30 m below the surface (Teichmuller and Teichmuller 1982) and Cohen (1983) noticed that in the peats of S. Florida the pyrite content tended to be lower in the top 0.30 m. He also noted that in peats with a small % of pyrite, it is inclined to occur as framboids, and preferentially in voids often associated with microorganisms. This accords with the arly formation of sulphide envisaged by Davies and Raymond (1983).

The association between marine waters and high sulphur coals was observed by Williams and Keith (1963), where the lower Kittanning coal overlain by marine shales had a higher pyrite content than that overlain by non-marine rocks. This has been noted by other workers in the USA (Gluskoter and Simon 1968, and Gluskoter and Hopkins 1970). They noted that the Herrin No.6 coal, when overlain by more than 5.5 m of non-marine rocks has a low sulphur content, whilst that overlain by thinner non-marine rocks or marine shale has a high sulphur content. A similar situation exists within the Warwickshire Coalfield, where a thin poorly developed coal beneath the Nuneaton (Aegiranum) Marine Band contains abundant pyrite in lenses and laminae (total sulphur content on air-dried basis is 9.9% in Muzzard's Wood borehole). Cohen (1983) also noted that when marine peats overlay non-marine peasts the pyritic sulphur is high in both seams. This may be analagous to the Seven Feet Thin and Seven Feet seams both of which have high pyritic sulphur contents, the topmost of which, the Seven Feet Thin seam, is overlain by the Seven Feet (Vanderbeckei) Marine Band.

As mentioned previously pyrite is not diagnostic of freshwater or marine sediments as the necessary chemical conditions can occur in either, and pyrite will form providing both iron and sulphur are present. Sulphate is abundant in marine waters and this explains the common occurrence of pyrite associated with marine faunas. Smyth (1966) believed that primary siderite could be changed to pyrite by solutions containing hydrogen sulphide. Pyrite and siderite together have been observed by the author in mudstones of Westphalian age in the Warwickshire Coalfield. Unfortunately, because of systematic diagenetic changes, ferruginous mineral species are not always a reliable guide to the chemistry of the waters in which they were first formed.

Pyrite within cleat in coal and in joints in other rocks is interpreted as being late diagenetic in origin.

5.2.7.4 Haematite

This is an important mineral in all red sediments found in Warwickshire (Besly 1983). It often occurs in a finely divided state in fine grained rock types - 'Mudstone' to 'Siltstone' and red palaeosols. In some cases red colouration is present throughout the whole rock, but in the case of red palaeosols it may be mottled or systematically decrease upward. This subject is dealt with in more detail in the relevant lithofacies sections.

Interpretation

The origin of haematite in ancient sediments has long been a subject for discussion (Turner 1980). Although some may be of syndepositional origin the latter author believed that most is diagenetic, ranging in age from very early to extremely late. Early diagenetic haematite may result from the breakdown of iron bearing detrital minerals in locally deposited sediments (Walker 1967a, 1976; et al. 1978). Alternatively, it may form in siliciclastic palaeosol lithofacies, as a result of mobilisation and concentration of iron during soil formation, in a similar way to the formation of modern laterites (Young 1976). Iron in the form of an oxyhydroxide may also be incorporated within accumulating sediment (Van Houten 1968) which with age could dehydrate to form haematite (Berner 1969). Haematite may also be produced by late post-depositional diagenesis brough about by oxidation of previously lithified sediments under sub-aerial conditions eg. below the Permian unconformity (Mykura 1960). Erosion of pre-existing haematitie rich sediments and their redeposition accounts for the syndepositional occurrence of haematite (Anderson and Picard 1974) which would be classified as secondary redbeds by Krynine (1949).

5.2.7.5 Less Common Minerals

One of the most noticeable minerals is ankerite which occurs in the cleat of coal, especially lithofacies high in vitrain. This is believed to be late diagenetic in origin.

Dolomite, calcite, galena, sphalerite and chalcopyrite have been observed by the author infilling veins generally in coarser grained rocks within the Warwickshire coalfield, all of which have similarly been interpreted as late diagenetic in origin.

None of this mineralisation is of economic significance.

The abbreviations and symbols for minerals used in this study are shown in Appendix 'B'.

5.2.8 Fracture

This includes all breakage not governed by stratification or cleavage, can aid in identification of lithofacies and is recorded where important. Homogeneous fine grained rocks are likely to have sub- to conchoidal fracture. This is true of the lithofacies cannel coal, and most of the lithofacies prefixed by the rock type mudstone or mudstone silty. Even fracture occurs in most coal lithofacies and in many lithofacies containing siltstone. Uneven fracture occurs in sandstones especially when poorly cemented.

5.2.9 Organic Sedimentary structures

This first list of flora and fauna of Silesian age found in the Warwickshire Coalfield was made by Vernon (1912). Since then the number of taxa recorded has been increased in the Geological Society

Memoirs for Lichfield (Barrow et al. 1919) and Coventry (Eastwood et al. 1923), and the wartime pamphlet published by Mitchell et al. (1942).

5.2.9.1 Fauna

Boreholes drilled in Warwickshire have increased the number of faunal species, the specimens having been sent to the British Geological Survey for identification. Details of fauna from the Millstone Grit identified in boreholes drilled in the north and east of the Warwickshire Coalfield are given by Taylor and Rushton (1971). The distribution of fauna located by these boreholes and in underground exposures is discussed in section 5.4.1.

5.2.9.2 Flora

Plant species and general were recognised by the author using the dichotomous key produced by Chaloner and Collinson (1975) although no new taxa have been recorded. Plant genera, whole, fragmented or comminuted can be found in many rock types and some lithofacies have strong associations between selected plant genera. Abundant plant fragments have been used to define three lithofacies, the accumulation of plant debris has been used to define the rock type 'Coal' and the rock types 'Subseatearth' and 'Seatearth' are defined by the effects of plants i.e. roots.

A palaeosol (fossil soil) has been defined simply by Retallack (1981) as a "former soil buried by later deposits". Soils he defines as "material on the surface of a planet altered by physical or chemical weathering, the action of organisms, or all of these". This is a very broad definition so to help in the recognition of Silesian palaeosols some features considered diagnostic are listed below:-

1. The presence of roots in the growth position (i.e. oblique to

stratification) was regarded as diagnostic by Brewer (1964) and Retallack (1981). Two types of root formed in rocks of Silesian age have been given generic names a) Stigmaria is the name given to the principal underground axes of Lycophtes from which helically arranged lateral appendages "rootlets" grew. These are often abbreviated to roots in NCB borehole logs and it may be that they are homologous with leaves as they are known to have abscized from the parent axes (Taylor 1981). b) Pinnularia - is the name given to fine branching roots probably of calamitean origin, although Chaloner and Collinson (1975) believe that the gnera has little biological or stratigraphical meaning.

2. The development of soil features because of the substantial period of pedogenic evolution was regarded as diagnostic by Brewer (1964) and Besly (1983).

Palaeosols formed from siliciclastic rocks are classified as the rock type 'Seatearth' in this study and in the grey coloured examples the presence of many in situ roots is considered most important. This is because the development of other soil features may be limited to mineral development and negative characteristics such as lack of stratification and plant foliage. If the rocks become coloured (anything but shades of grey) as well as possessing other soil features, then 'Seatearths' become more easily recognised. Where relatively few oblique roots are present, and there is indication of stratification, and other pedogenic features are poorly developed, the rock type is classified as a 'Subseatearth'.

Although coal contains no roots identifiable in hard specimen, the peat which formed it has clearly undergone considerable terrestrial, physical and chemical weathering and was undoubtedly rooted. In this sense, within this study it is considered a palaeosol, as peat is considered a histosol in the terms of the USDA 7th Approximation system (Soil survey staff 1960), and an organic soil by workers on tropical soils in the Far East (Haantjens 1968). The concentration of plant matter to form the original peat and eventually a floriclastic rock, and the lack of silicate minerals defines the rock type 'Coal'. Vertical trunks of aborescent Lycophytes are often present standing upright (often several metres in height) in strata overlying coal seams. The significance of these trunks which are often joined to Stigmaria and connected to the underlying coal is that they demonstrate rapid rates of sedimentation (Broadhurst and Loring 1970). Also they may possibly represent the drowned final stage of the peat forming plants from the underlying coal seam, or post peat flora (Scott and Collinson 1983).

5.2.9.3 Ichnofossils

These are not very common in rocks of Westphalian age in the Warwickshire Coalfield compared with rocks of a similar age in the adjacent East Midlands Coalfield (Guion 1978). They are biogenic sedimentary structures (Frey 1973) and are "evidence of the activity or of an organism in or on the sediment, produced by some voluntary action of that organism" (Osgood 1970). The definition of the term voluntary suggests that bioturbation produced by roots could not be classed as an ichnofossil, although how voluntary the actions of the organisms are which produce these structures may be in doubt.

Ichnofossils have been classified using many criteria each with advantages and disadvantages. Frey (1973) simply divided them into trails made by organisms undergoing directed locomotion on the surface of the sediment and burrows which are traces lying within the sediment. Seilacher (1953) classified them according to the purpose of the process which formed them and this ethological classification was modified by Simpson (1975) into six types locomotory (Repichnia), grazing (Pascicnia), resting (Cubichnia), feeding (Fodichnia), dwelling (Domichnia) and escaping (Fugichnia). The disadvantage of this system is that often (especially in borehole core) not enough of the fossil can be seen to determine any behavioural pattern. A descriptive classification was developed by Martinsson (1970) in which the critical feature was the contrast between the sediment in which the trace fossil was cast - usually sandstone and the surrounding sediment. Its disadvantage lies with trace fossils found in situations where there is no strong sediment contrast.

Many ichnogenera have already been named, and the best system for this study appears to rleate these to any ichnofossil found in the Warwickshire Coalfield. Ichnofossils are useful as sedimentological and palaeoecological indicators although it must always be remembered that the sediment and the fossil may be separated by a time difference. Some ichnofossils are very useful stratigraphic markers (in the Kent Coalfield, S. Warren pers. comm.) and Gyrochorte is often found above the Bench seam in the Warwickshire Coalfield.

"Tracks and trails" have been described by the author, on numerous occasions associated with dark grey mudstones which have marine or brackish fauna in them. They are curved bedding plane traces generally less than 20 mm long and about 3 mm wide picked out by colour differences in the sediment. It is possible they are related to Cochlichnus Hitchcock although the occurrences recorded by Smith et al. (1967) are associated with non-marine fossils.

Another ichnofossil usually found in dark grey mudstones is Gyrochorte Heer which consists of two ridges separated by a groove in epirelief up to 10 mm wide with poorly defined small undulations at right angles to the ridges. They are usually polished and have been called "double tubes" by some NCB geologists. This particular ichnogenus has often been found in the same stratigraphically position in mudstones above the Bench seam throughout the Warwickshire Coalfield. It may represent the collapse of a burrow prior to its infilling.

Planolites montanus Richter have been observed by the author preserved in sandstone as either exichnia or hypichnial ridges usually almost parallel to bedding surfaces. It can be up to 8mm in diameter and is irregular in direction, found in rocks of all grain sizes. Hallam (1970) believed the trace to be formed by deposit feeding worms.

Burrows oblique to bedding have been observed in rocks with a wide range of grain size. They are generally less than 5 mm in diameter and range from regular vertical, to irregular dipping at about 30°, and are easily recognised because they are exichnial and occur in groups. They may be Planolites montanus although these are not usually vertical. Care must be taken to distinguish these from roots which have siderite associated with them.

Pelecypodichnus Seilacher (sometimes called Lockeia James) has been widely observed by the author, usually in rocks of laminated siltstone and sandstone. It can occur in two closely related forms. The first are almond shaped hypichnial depressions with a length up to 15 mm, which have been interpreted as the resting places of non-marine bivalves, because of its association with Carbonicola (Eagar 1974). As Carbonicola is thought to have lived in habitats ranging from freshwater to brackish (Calver 1968a) Pelecypodichnus would also indicate this habitat. Often the long axes of these resting traces are orientated, and this has been interpreted by Hardy (1970) as being parallel to current direction because of the feeding habit of modern bivalves. Orientated Pelecypodichnus resting traces have been observed in the Dexter Manrider Road by the author (Guion and Fulton 1986) where they were associated with the second form of Pelecypodichnus. This occurs when the resting traces are stacked upon one another nearly vertically and these have been interpreted as Pelecypodichnus escape structures by Hardy (1970). Escape shafts up to 1 m in length have been observed by Guion (1978) who (1971) together with Hardy (1970) have interpreted them as "being produced by upward migration of bivalves in response to rapid sedimentation in order to avoid burial".

Guilielmites which are sub-circular and domed in epirelief are often found in dark grey mudstones. Wood (1935) believed them to result from the collapse of some central body, as a result of compaction, to produce slip marks - the name which he proposed to use for these pseudofossils. Their common occurrence in sediments containing bivalves, leads this author to believe there is a close relationship between the two. Guion (1978) believed the structure he called slip marks to be connected with rootlets.

The symbols for all biogenic features are given in Appendix 'B'.

5.2.10 Rock Discontinuities

Rock discontinuities are any breaks occurring in the rock all of which are logged in borehole core on a sheet designed by the author. They can be divided into three categories according to their morphological characteristics viz. partings, joints and faults, and all three are recorded underground for a variety of purposes.

5.2.10.1 Parting

Parting is the name given to any break which is parallel or sub-parallel to bedding, and bedding planes themselves can be partings. Some mudstones and siltstones have special types of partings, which are polished discontinuous curved planes termed listric surfaces (abbreviated to listrics by NCB geologists). The definition of listric given by Whitten and Brooks (1972) applies to ".... fracture planes which curve - either near horizontal ones which steepen or near vertical ones which become less steep" and although strictly refer to concave upward surfaces have also been applied to convex upward surfaces. For this reason, together with its ubiquitous use by NCB geologists it is suggested that the term be preserved (contrary to Guion 1978) so long as it is clearly defined. Its origin may be compactional (Guion 1978, Besly 1983) due to the alignment of platy clay minerals separated by abundant minute organic fragments (Schiller 1980). Listric texture has been used as a characteristic of seatearths by many NCB geologists, although it occurs in other fine grained lithofacies. The cause of parting is as a result of compaction, so that different rock types containing different arrangement of their components, will have different types and spacing of partings. Assessment of partings is important when the geomechanical properties of rocks are considered, especially in terms of rock movement on working faces and underground roadways.

5.2.10.2 Jointing

Jointing (and faulting) are the names given to more steeply dipping discontinuities, the former often extending many metres and including cleat. Joints are recorded both underground and in borehole core and salient features such as extent, type of surface, mineral infilling and alteration are all noted. Jointing arises as part of the response to major structural changes, and as such is useful in understanding and predicting the regional tectonic framework.

5.2.10.3 Faulting

Normally the meaning of the term fault - a discontinuity in a rock along which there has been observable amount of displacement (adapted from Whitten and Brooks 1972) would require no explanation. Unfortunately in mining parlance the term fault has been used too freely, ranging from any poorly understood geological phenomenon to the true meaning of the word. This can include channels filled with sandstone, which where they remove coal are called "washouts" by staff in the NCB. The author has even seen a peculiar form of mining schizophrenia resulting in the term washfault being shown on a plan.

Two categories of fault are recognised in this study, dependant on the time at which they were produced relative to the accumulation of the sediment which is faulted. Synsedimentary faults are those which occur during or shortly after accumulation, and tectonic are those generally occurring much later, as part of a regional response to major structural changes taking place within the earth's crust.

Synsedimentary faults which have small throws (generally less than 100 mm) and are often associated with sedimentary structures indicative of sediment instability are called microfaults or faultlets. These are interpreted as occurring contemporaneously with sedimentation and Elliott (1965) believed this type of faulting originated from "quasi-solid" sediment behaviour.

Another type of synsedimentary fault have large throws, usually between 1-4 m and are closely associated with the sides of channels. These will be discussed in section 5.4.6 (see also TABLE 5.4).

Three types of tectonic fault have been observed by the author in the Warwickshire Coalfield. The majority of faults are normal with dips of between 60-70° and considerable horizontal and vertical extension. They are believed to have originated as a consequence of large scale earth movements, taking place much later than the deposition of the faulted sediment. One near vertically dipping reverse fault has been observed by the author at Coventry Colliery (Keresley Fault Fig. 3.5). It appears difficult to explain unless it was a bulge on the fault plane, which was vertical but normal in throw for most of its length. The third group of faults recognised by NCB geologists are called "compactional faults". Their properties are listed by Guion (1978) - variable hade, small displacement, orientation differing from regional tectonic pattern and local occurrence. It is believed that these failure planes were produced following concentration of stress in relatively compressible rocks (mudstones, coals) which surround a body of relatively incompressible rock (sandstone). This mechanism has been referred to as differential compaction. He believed that insufficient work had been carried out either on criteria which may be used to differentiate them from normal tectonic faults, or on the theoretical basis for the interpretation of their mechanism. It has been shown by Bustin (1982) that when a stress field is applied to inhomogeneous rock, the weakest component will fail first. In Coal Measure rocks this is often a coal seam. Guion (1978) also mentions that compaction faults commonly accompany swilleys (local seam thickenings), and squashouts (local seam thinning due to compaction). It is possible that these faults have been confused with synsedimentary faults.

It is difficult to distinguish tectonic from synsedimentary faulting in borehole core except by association with other features.

TABLE 5.4 Fault Recognition

	Tectonic	Synsedimentary
Vertical extension	Long	Short
Horizontal extension	Long	Short
Fault plane dip	60-70°	20-70°
Nature of plane in side elevation	Fairly straight	Curved concave upward
Slickenside/ Polished surfaces	Common	Common
Fault breccia	Often, usually clay	Occasionally
Mineralisation	Occasionally	Rarely
Direction	Related to reqional trend	Related to sedimentary features
Water presence	Occasional	Occasional
Volume	Large; continues for some time	Small, short lived

It is even difficult sometimes to distinguish channel sides from faults - both may have polished surfaces separating different lithologies. Some of the differences between tectonic and synsedimentary faulting are listed in TABLE 5.4.

Discontinuities are important in prediction of hydrogeological and geomechanical properties (Fulton and Ball 1983), the discussion of which lies outside the scope of this study. Mining induced discontinuities (which are often associated with local steep dips) can be distinguished from natural discontinuities by reference to colliery working plans.

5.2.11 Directional Features

These can be divided into two categories - tectonic and sedimentary although there is a link between the two.

5.2.11.1 Tectonic

Tectonic dip represents the regional dip of stratification. This is best measured underground over a long horizontal base, using a consistent marker bed such as a coal seam. In this study dip was measured using either a clinometer, or from geometrical consideration after having constructed a level line. Direction of dip was measured relative to a face or roadway, as the abundance of steel supports and magnetic fields created by electrical equipment preclude the use of a compass. Dips in boreholes were measured on the core, choosing a sedimentary sequence likely to represent regional dip i.e. horizontal stratification. Direction of dip was determined from the dipmeter log - a geophysical device taking readings of resistivity at 3 or 4 horizontal points simultaneously.

5.2.11.2 Sedimentary

Directional sedimentary structures can either give the trend of palaeocurrent of the direction towards which the palaeocurrent flowed.

One of the most common sedimentary structures within sandstones in the Warwickshire Coalfield is trough cross lamination, derived from the burial of linguoid and lunate ripple bedforms. These have foresets which are concave downcurrent (Allen 1963a). Straightforward measurement of palaeocurrent direction in linguoid ripples can be achieved by observing the intersection of foreset laminae with the stratification surface, which gives rise to a U shaped trace, the open end of which points downcurrent (Allen 1963a, Harms 1975a). For a variety of sedimentological reasons these are likely to give a wide range of current directions. Because underground roads are mainly at right angles to each other it may only be possible to measure apparent dip, but if enough of these are aggregated it will give a fairly accurate palaeocurrent direction. Ripples with straight or sinuous crests have foreset laminations which give the current direction at right angles to the crest line (Allen 1968a).

Poor exposure, lack of time, and danger from rockfalls, often preclude the taking of many palaeocurrent measurements. In favourable circumstances, eg. old roadways more measurements can be taken.

Palaeocurrent trend can be measured most reliably by plotting channel margins on a plan. If the channels are meandering they may display epsilon cross stratification, the strike of which gives the channel trend and therefore current trend (Guion and Fulton 1986. When coupled with measurements from trough cross lamination this increases the accuracy of palaeocurrent direction data. A biokinematic structure - current aligned <u>Pelecypodichnus</u> (Hardy 1970) has also proved useful in establishing palaeocurrent trend.

Palaeocurrent directions are plotted on plans using a rose diagram orientated with respect to north. This gives the number of measurements taken and their distribution, and a guide to statistical reliability is also shown. Because tectonic dip is usually low there is no need to correct for it.

Illustration of symbols for current trend and orientations are shown in Appendix 'B'.

5.2.12 Nature of Contact

Considerable importance in this study is attached to the nature of contacts between lithofacies units. This is because conformable vertical sedimentary sequences (without time breaks) are believed to have formed in laterally adjacent environments following work by Walther (1894).

Those contacts between lithofacies units which are gradational and therefore conformable in this study are termed "passage" and "abrupt passage", the latter being defined as a gradational change taking place over less than 10 mm. This has been classified as abrupt by some authors (Guion 1978) but a distinction should be made between continuous and discontinuous accumulation of sediment. A break in the accumulation of sediment is marked in this study by the terms "erosive" if the stratification underlying the contact is truncated or "abrupt" if a sharp plane separates two lithofacies units. An abrupt transition (base or top of lithofacies unit) may represent a time gap during which sediments could form nearby, or in the case of an erosive base, sediment from many lithofacies associations could have accumulated and then been removed. Truncation is difficult to demonstrate in borehole core and many abrupt bases that have been recorded may actually be erosive.

Ambiguous situations may arise e.g. a fine grained lithofacies unit passing upward into a lithofacies unit consisting of the underlying lithofacies interbedded with a coarse grained lithotype. Even if the coarse grained lithotype has erosive bases, one of which forms the contact with the underlying lithofacies, it may be that sedimentation is 'continuous' and so the contact would be referred to as an abrupt passage.

Symbols for nature of contact are shown in Appendix 'B'.

5.3 DESCRIPTION AND INTERPRETATION OF LITHOFACIES

The object of describing and classifying lithofacies is to provide a systematic means of recording data so that it is easily interpreted. This has been carried out by other authors notably Guion (1978), but in this study a more rigorous approach is adopted with a resulting increase in the number of lithofacies. The basis for the description and classification of lithofacies is mainly Westphalian A and B cores derived from boreholes drilled in the Warwickshire Coalfield. Although the system is based primarily on borehole core it can also be used to describe surface and underground exposures. Also although the core is of Westphalian A and B age from the Warwickshire Coalfield, the system can also be used to describe Namurian and Westphalian C and D age rocks in both this and other coalfields.

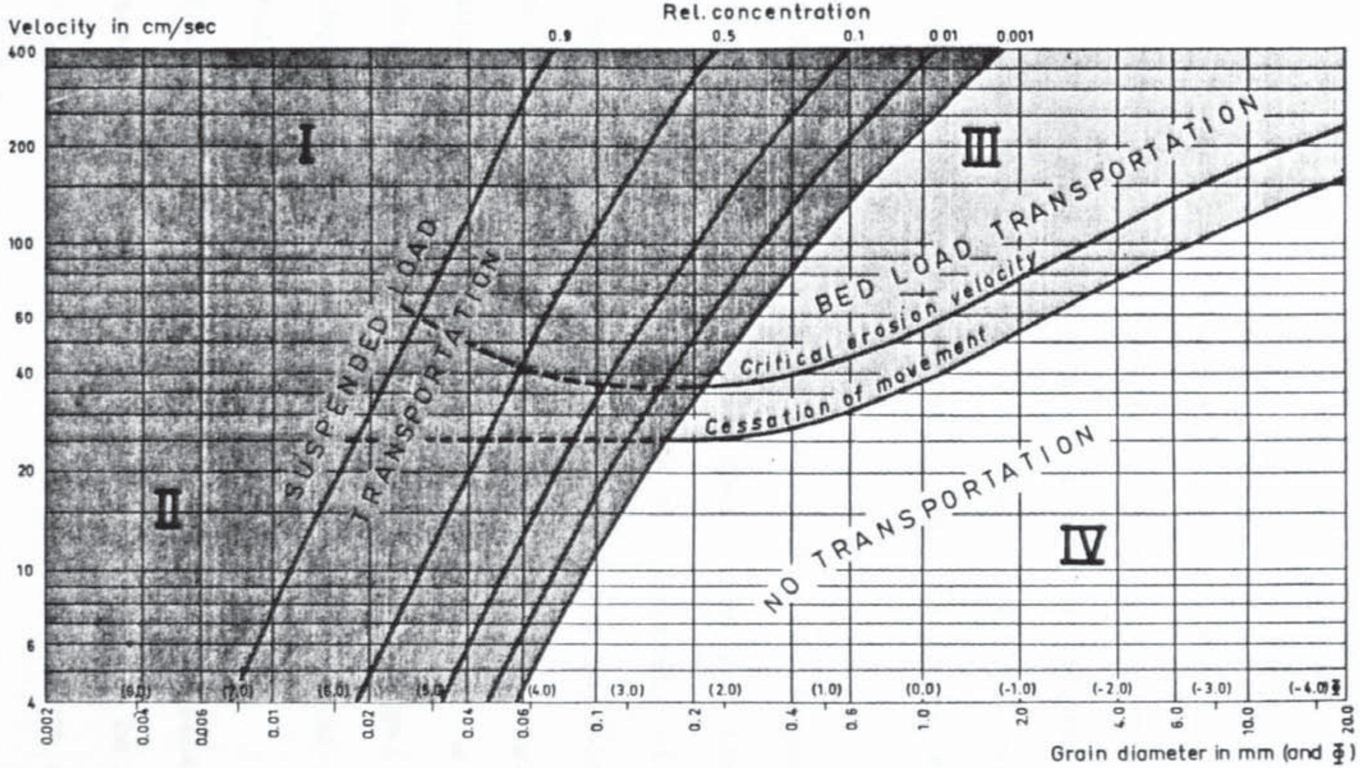
Lithofacies are grouped together in ten rock type categories. The characteristics of each rock type are described and then the lithofacies within each rock type are described in detail. Where possible information from the computer analysis of 5 boreholes (see section on practical techniques) is given, concerning the thickness and prevalence of lithofacies, together with the results of Markov Chain analysis in terms of transitions into and out of the lithofacies concerned. For the first seven and the last rock types described, the inferred process of formation of each lithofacies is given. For the rock types 'Seatearth' and Subseatearth' an interpretation is not given until the associations within which they occur are examined.

Each lithofacies has a number of characteristics (from among those listed in the previous section) which form the basis for its distinction from other lithofacies. These are usually described first and may form part of the name of the lithofacies, but other characteristics which may also be present are recorded. Distinction between the lithofacies of the first seven rock types is by grain size. Within each of these seven rock types lithofacies are distinguished mainly by inorganic sedimentary structures. Because of the importance of these characteristics in the following seven sections some of the variables governing their formation are discussed below. Most of the variables producing these structures have been studied in the laboratory, and in that case are necessarily subject to certain limitations which may not reflect natural field conditions. These may include unidirectional flow, use of well sorted cohesionless sediment and limitations of flume size both in terms of depth and width. Also the bedforms produced in nature are often out of equilibrium with flow, and may undergo partial erosion so that only the bedford is preserved.

To produce inorganic sedimentary structures it is necessary firstly to entrain particles, secondly transport them and thirdly bury them. The latter two processes often happen simultaneously, unless a strongly erosive force is at work.

From work carried out by Hjulstrom (1939) and Sundborg (1967) the critical erosion (tractive) volocity was determined (Fig. 5.1). Other workers have since studied the threshold of sediment motion under unidirectional (Miller et al. 1977) and oscillatory water waves (Komar and Miller 1975). From Fig. 5.1 it can be seen that the lowest velocities are required to entrain fine and medium sand, rising for

Fig. 5.1 Entrainment velocities for various size particles (after Sundborg 1967)



finer particles because of increase in cohesive forces, and coarser particles because of the force of gravity. A critical factor in determining entrainment is the degree of consolidation.

Once in motion particles can be transported by a variety of methods including suspension, saltation, rolling and sliding. These can be broadly divided into two categories. Firstly suspension, which involves clay and silt size particles remaining in suspension until flow decelerates; and secondly bedload, which involves particle to sediment bed contact, in which particles are moved by tractional forces.

The velocity required to keep particles in suspension is dependant on relative concentration and grain size and the oblique lines in Fig. 5.1. A renewed interest in the dynamics of sediment suspension has resulted in Leeder (1983) confirming Bagnolds theory (1966) that the eddies of fluid turbulence which keep sediment in suspension are caused by anisotropy of shear turbulence. The power of these bust movements which carry with them some bedload sediment (immediately redeposited) together with saltation, are the principle forces which result in sediment sorting.

At about 0.2mm the boundary between bed and suspension load occurs, which means that fine grained sand can either be moved in suspension or as bedload. The line of cessation of movement shows the velocities required to keep bedload moving and deposition occurs in field no IV.

When particles are deposited from suspension the type of stratification which may result is parallel to the sediment surface.

Grains transported mainly by traction produce a variety of three dimensional bedforms, which on burial result in cross stratification.

The type of bedform produced depends on a number of flow variables viz.

1. Flow depth
2. Flow strength (either velocity or shear stress exerted on the boundary layer)
3. Fluid viscosity
4. Fluid density
5. Fluid temperature
6. Sediment size
7. Sediment density
8. Gravity

Following Southard (1971) if variables 3, 4, 5, 7 and 8 are kept constant then the relationship between variables 1, 2 and 6 can be examined, using laboratory flume experiments. When velocity is plotted against depth for 3 grain sizes viz. fine sand (0.10mm) Fig. 5.2A, medium sand (0.45 - 0.54mm) Fig. 5.2B, and coarse sand (1.14mm) Fig. 5.3A, the bedforms produced can be shown (Southard 1975). Results from other workers (Southard 1975) can be compared for medium sand (Fig. 5.3B), which shows that whilst the lines dividing bedforms are in similar positions, they are not exactly the same, and a new bedform sand waves is plotted. Those bedforms in phase with the water/air surface in the upper flow regime are shown cross-hatched to the right, and those independant of this surface to the left. From these it can be seen for a given grain size increasing flow and depth will not produce certain bedforms eg. no dunes in Fig. 5.2A, and no ripples in Fig. 5.3A. The latter has been shown by Leeder (1982) to be the result of roughness of the larger diameter grains causing increased verical mixing of the boundary layer fluid preventing flow separation and so the production of ripples. Also from Figs. 5.2 to 5.3, the most

Fig.5.2A Depth/velocity diagram for sand of 0.10mm (from Southard 1975)

Fig.5.2B Combined depths/velocity diagram for sand sizes of 0.45mm, 0.47mm and 0.54mm (from Southard 1975)

Fig.5.3A Combined depth/velocity diagram for 1.14mm and 1.35mm sand (from Southard 1975)

Fig.5.3B Depth/velocity diagram for 0.49mm sand (from Southard 1975) critical factor in determining bedform is flow velocity and a plot of this against grain size is shown in Fig. 5.4A (Southard 1975).

It is fortunate that most of the grains in the Coal Measure rocks are rounded and so can be compared to those used in laboratory experiments. Little work has been carried out on the generation of bedforms from silt size sediment or silt mixed with sand. Silt was used by Rees (1966) who demonstrated a relationship between suspension and bedload transport, in that small ripple bedforms would only be produced when sediment was in suspension. Mantz (1978) who also used cohesionless silt to produce ripples and sandwaves, showed that a suspended load was not needed to produce them, and that the possibility exists for the creation of dune size bedforms using silt.

The relationships between bedforms occurring in the laboratory and in the field have been compared to natural environments in which they can be found by Reineck and Singh (1980) Fig. 5.4B.

In conclusion, the fact that the same lithofacies are repeatedly observed in this study, shows that the same processes were in operation throughout the formation of the Westphalian A and B in Warwickshire. Unfortunately the products of these processes are found in many environments, eg. ripples (Allen 1968, and Reineck and Singh 1980, see Fig. 5.4B. Theoretical measurements in the laboratory do not necessarily reflect conditions in the field. Also processes measured in the laboratory may not be the most important in nature, eg. it is possible that one of the most important methods of sediment entrainment in the Coal Measures may have occurred during bank collapse. It has been shown that larger grain size may be indicative of higher energy (flow) levels, but as Selley (1970b) notes, if the grain size of the sediment source is limited to a fine grain size,

Fig.5.4A **Size velocity diagram for a flow depth of about 0.2m derived from depth/velocity sections (from Southard 1975)**

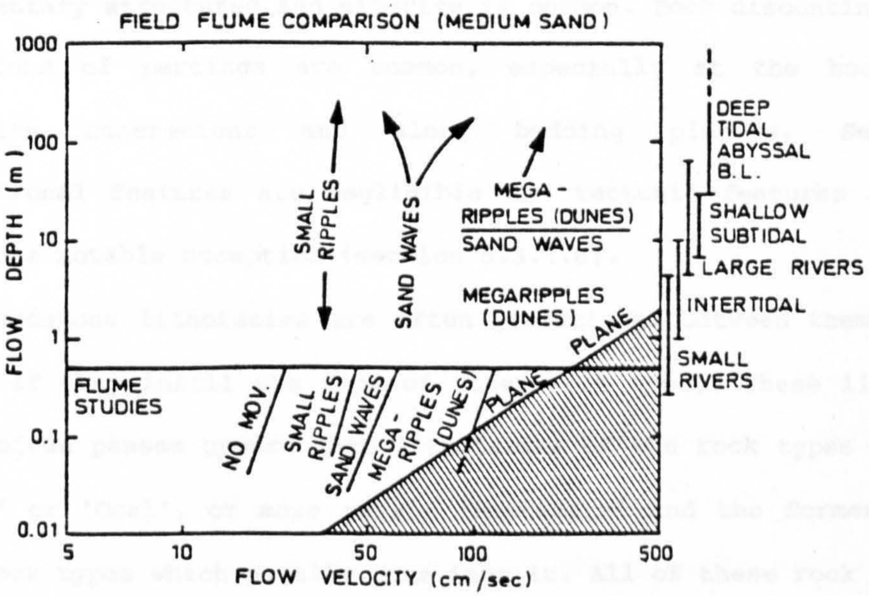


Fig.5.4B **Depth/velocity diagram for medium sand in flume experiments and natural environments.**

then only minimum energy levels can be revealed. A better guide to flow characteristics is given by inorganic sedimentary structures, products of bedforms which change according to energy levels even though grain size remains constant.

There now follows a detailed description of 11 rock types and their lithofacies.

5.3.1 Rock Type Mudstone

This is defined as a clay rich rock (less than 20% quartz) with a grain size smaller than 0.0039mm. Its colour ranges from medium grey to black because of low quartz or high organic content and the reducing conditions under which they formed. Although not mentioned in the lithofacies descriptions, in some cases the lighter coloured lithofacies may be green in colour. This may be caused by a high ferrous/ferric ion ratio and the presence of chloritic minerals.

There are a minimum of inorganic and maximum of organic sedimentary structures and siderite is common. Rock discontinuities in the form of partings are common, especially at the boundary of siderite concretions and along bedding plances. Sedimentary directional features are negligible and tectonic features are poor, with one notable exception (section 5.3.1.6).

Mudstone lithofacies are often gradational between themselves or sharp if they infill the tops of other rock types. These lithofacies most often passes upward into lithofacies of the rock types 'Mudstone silty' or 'Coal', or more rarely 'Seatearth' and the former two are the rock types which usually pass into it. All of these rock types are diagnostic of low energy domains.

The seven mudstone lithofacies recognised in this study and described in this section are listed below. Their coarse grained equivalents are listed in section 5.3.2.

1.1 Mudstone, massive, medium to dark grey

1.2 Mudstone, massive, with abundant plant fragments

1.3 Mudstone, massive, dark grey to black

1.4 Mudstone, massive, with marine/brackish fauna

1.5 Mudstone, with coal lenses

1.6 Mudstone, parallel stratified dark grey to black and medium grey

1.7 Mudstone, medium grey, with dark grey mudstone lenses

1.8 Mudstone, melange

5.3.1.1 Lithofacies 1.1

Mudstone, massive, medium to dark grey, sometimes with brown tinge, often coarsens upwards, occasionally fines upward. Rarely there may be parallel laminae of different coloured mudstone or siltstone. Often siderite beds, lenses or nodules occur. Sometimes there are stem and leaf fragments, also bedding surfaces with tracks and trails. Listrics may be rare to abundant.

The characteristics associated with this lithofacies vary according to the associated lithofacies. Coarsening upward and black parallel mudstone laminae are associated with mudstone sequences, fining upward and sandstone laminae with sandstone sequences.

Siderite beds and lenses have been observed to extend for tens of metres, whilst nodules usually occur scattered through the matrix.

Leaf and stem fragments are scarce, as are tracks and trails which are the same type found in 'Mudstone, massive, dark grey to black'.

The areal distribution of this lithofacies can vary immensely, depending on its environment of deposition, and may extend over many km2 eg. above the Thick Coal seam. It is often under or overlain by the lithofacies 'Mudstone parallel stratified dark grey to black/medium grey', 'Siltstone or Mudstone silty massive pale to dark grey' and sometimes by 'Coal' lithofacies, and often passes upwards into 'siltstone parallel stratified with sandstone' and 'Mudstone, massive dark grey to black'.

Other workers on British Coal Measures have grouped this lithofacies with similar mudstones under the headings 'Faunal mudstone', Elliot (1968); 'Mudstone with trace fossils', Guion (1978), 'Facies 6 - Outer minor delta/overbank claystones' and 'Facies 8 - Passive lake margin', Fielding 1984a).

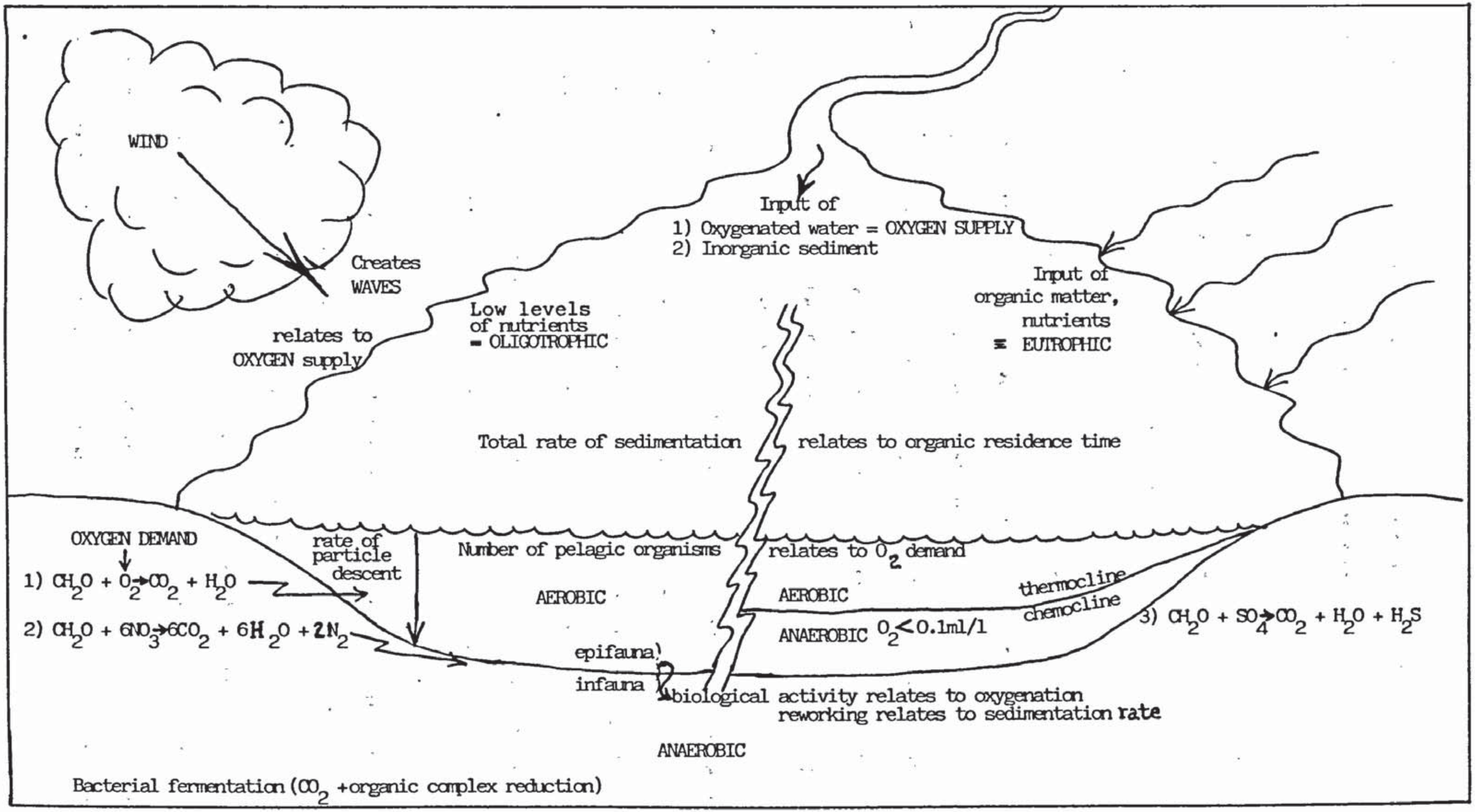
In modern envornments massive clay deposits have been recognised from the Mississippi as 'Prodelta clays'm, Fisk (1961) and this lithofacies and its coarser equivalent 'Mudstone silty, massive, medium to dark grey' have been recognised in 'Interdistributary Bay' deposits from the same delta compex by Coleman and Prior, (1980 Figs. 18, 22).

Interpretation

The process which leads to the formation of homogeneous mudstone, with a minimal amount of coarser grains, results from the setting of sediment because of different modes of transport (section 5.3), and the low current velocity, which is strong enough only to carry mud in suspension but too weak to carry coarser grade material. When the current decelerates sufficiently, the mud falls out of suspension and accumulates at the water/sediment interface.

The colour of the lithofacies is probably related to the amount of fine organic particles within it, which have also been carried in suspension. Factors affecting the accumulation of organic matter are discussed by Demaison and Moore (1980) and summarised in Fig. 5.5. Below is a simple functional relationship to explain the quantity of

Fig. 5.5 Factors affecting the accumulation of organic matter



organic matter in sediments expressed by Potter et al. (1980), although anaerobic decomposition is missing from the equation

$$C = (P-O)/S$$

where C = % organic carbon

P = flux of organic carbon to sediment

O = rate of oxidation of organic matter

S = sedimentation rate

In this way the grey colour of this lithofacies could be due to lack of organic particles relative to mud or to their subsequent removal by oxidation or bacterial decomposition.

The common presence of siderite, particularly in areally extensive beds, implies accumulation in freshwater conditions that were reducing, allowing the formation of siderite in the method suggested by Curtis et al. (1975).

If reducing conditions existed below the sediment surface and oxidising above, then non-marine lamellibranchs could have lived within this environment. As these are rarely present this indicates that the habitat was inimical to their existence, which could have been because of a continual concentration of mud within the water. This was not the case for all benthos as evidence by the presence of Gyrochorte.

A plentiful source of terrestially produced organic matter is believed to have been nearby, as was a continual supply of clay rich sediment from a distant source. Aerobic decomposition of organic matter is more efficient than any of its anaerobic counterparts (Claypool and Kaplan 1974). Therefore whilst other factors shown in Fig. 5.5 such as rate of input of organic matter may have been important, perhaps the division between aerobic and anaerobic conditions was the most critical factor in its preservation and hence colour of sediment. Although few shallow tropical lakes have been studied in detail, investigation of several sub-tropical African lakes (Talling 1963, Degens _et al._ 1971 and 1973, Mothersill 1975, Yuretich 1979, Demaison and Moore 1980, Cohen 1984) have shown that a wide range of conditions exist in lakes of various depths, from those which are unstratified and aerobic to those stratified and anaerobic, and those containing abundant microorganism or few of them. Coal Measure lakes in which this lithofacies are found may be expected to display a similar variation, with perhaps size playing a key role in determining fetch and therefore oxygenation of water by wind/wave action.

Lack of clearly defined burrows may mean that the sediment has been completely bioturbated, but more work is needed in the laboratory to prove or disprove this.

The brown tinge of siderite seen in some lithofacies units is interpreted as the result of the appropriate ions (see section 5.2.7.2) migrating within pore waters during early diagenesis.

In summary this lithofacies was deposited by currents of low velocity, in a freshwater regime, carrying abundant mud and lower amounts of organic particles in suspension. Where the lithofacies is areally large, the source of the sediment may have been at a great distance. In any case regular or continual discharges of sediment took place, preventing the existence of large populations of lamellibranchs. A reducing environment was present below the surface allowing preservation of organic matter, and early formation of siderite.

5.3.1.2. Lithofacies 1.2

Mudstone, massive, with abundant plant fragments, details as the previous lithofacies 1.1, but siderite lenses and nodules are noticeably more abundant.

The plant fragments are preserved usually as compressions or impressions and consist of stems (non-coalfield) and leaves - either pinnules, pinnae or fronds. Most common stems are SPHENOPHYTES belonging to the genera Calamites and Sphenophyllum, rarely the LYCOPHYTE Sigillaria occurs. Most common pinnules are PTERIDOSPERMOPHYTES including the genera Neuropteris, Mariopteris, Alethopteris and Sphenopteris, CONIFEROPHYTES of the genus Cordaites and PTERIDOPHYTES of the genus Pecopteris.

Some of the siderite occurs as diffuse patches concentrated around small accumulation of plant fragments.

The lateral extent of this facies is usually small. It is under or overlain most frequently by the lithofacies 'Mudstone silty massive medium to dark grey' and 'Mudstone silty or Siltstone massive with abundant plant fragments', and it often passes upward into 'Mudstone with coal lenses'.

Other workers generally only make brief mention of the presence of plant fragments. One exception to this is Scott (1976) who carefully noted the presence of plant remains within his facies associations, and these are compared in the section on lithofacies associations. NB: This lithofacies does not correspond to Guion's (1978) 'Mudstone with plants' (section 5.3.1.5).

Interpretations

The basic process for deposition of this lithofacies is the same as the previous two lithofacies. As indicated by Scheihing and Pfefferkorn (1984) when studying the incorporation of plants into recent sediments of the Orinoco delta, the most important factor in preserving plant material is swift burial. Lithofacies in which this process is taking place are more likely to preserve plants. This is why the coarser grained equivalents of this lithofacies are more important quantitatively. Another factor Scheihing and Pfefferkorn (1984) demonstrated was that the serial parts of plants are buried relatively close to the site of growth. This fact had enabled Scott (1978) to identify plant assemblages occurring in different Coal Measure environments in the Yorkshire Coalfield. To relate these to assemblages in Warwickshire it is necessary to highlight rocks containing plants (by making special lithofacies of them) and identify them. The relationship of plants and environments will be dealt with in the section on lithofacies associations.

5.3.1.3 Lithofacies 1.3

Mudstone, massive, dark grey to black, generally carbonaceous with brown streak, common siderite beds, layers of large lenses and isolated lenses; fauna consists of mussels (lamellibranchs), fish spines and seales and ostracods; flora consists of plant stems and megaspores; ichnofossils consist of curved tracks and trails on stratification surfaces, Gyrochorte, faecal pellets preserved in siderite and Guilielmites.

The siderite lenses can be up to 0.15m thick and commonly occur in layers extending tens of metres horizontally. In borehole core it is impossible to distinguish lenses from layers, although partings and crushed mudstone caused by compaction usually occur around lenses.

Fauna is generally sparse, but may be locally abundant, lamellibranch genera identified are Anthracomya, Carbonicola and Naiadites which are usually preserved whole in siderite, although they are sometimes decalcified leaving only imprints. Guilielmites are often associated with lamellibranchs and may result from the flattening of the void left by decalcified valves.

Apart from unidentified plant stem fragments the only other flora found in this lithofacies are LYCOPHYTES represented by stems of Lepidodendron.

Tracks and trails are common and best seen where there is a contrast in sediment type either in colour or mudstone or in siderite.

This lithofacies can extend over many km^2 (eg. immediately above the Bench and Thick Coal seams) and may laterally pass into 'Mudstone with brackish/marine fossils'. It is commonly under and overlain by lithofacies of the rock type 'Coal' and also 'Mudstone massive, medium to dark grey' and most commonly passes upward into 'Mudstone parallel laminated dark grey to black/medium grey'.

This lithofacies corresponds well with the 'Black mudstone' facies of Haszeldine (1984a). Other workers on British Coal Measures have included this lithofacies with similar mudstones 'Faunal mudstone' Elliott (1968) 'Mudstone with non-marine fossils', 'Mudstone with trace fossils' Guion (1978). This lithofacies may occur in 'Facies 8 Passive lake margin' and 'Facies 7 Anoxic lake floor' Fielding (1984a), although it is more likely to be transitional to the latter facies because it is "often pyritous and contains brachiopods".

Interpretation

A similar process is envisaged for the formation of this lithofacies as the previous two lithofacies. Lack of primary inorganic sedimentary structures and well sorted fine grained mudstone suggest low current velocities with mud settling.from suspension, and the possibility of bioturbation.

The dark colour of the lithofacies is caused by the high content of minute organic particles. Using the factors shown in Fig. 5.5 and the discussion in the interpretation of 'Mudstone, massive, medium to dark grey' it is probable that the volume of organic particles carried in suspension must have been high compared to clay minerals. The faecal pellets are produced as the last stage of a pelagic food chain (Spencer et al. 1978). Where these survive in abundance and so have not been reworked by benthos, it is possible that towards the base of the body of water anaerobic conditions existed, increasing the preservation potential of organic matter. These organic particles are probably derived from drainage of adjacent peat accumulations although 'flotant' has been suggested as a source by Zangerl and Richardson (1963). The abundance of anemophilous miospores within the black mudstone above the Thick Coal at Longmeadow Wood borehole suggests that 'flotant' was probably not present at this location and no other evidence for flotant (eg. remains of a mat) has been found. It is believed that plants forming flotant did not arise until the Jurassic, when angio sperms first colonised this habitat (Scott, pers.comm.)

As lamellibranch valves are usually articulated, only low current velocities are suggested (Broadhurst 1964). However, they must have been strong enough to prevent the habitat from becoming euxinic and transport food to the lamellibranchs (which by comparison with modern bivalves were probably filter feeders).

A factor which may have contributed to the homogeneity of the sediment is the presence of epifaunal organisms moving on the sediment surface leaving tracks and trails. Whether infaunal organisms lived within the sediment is difficult to establish, for no oblique burrows have been found by the author. Infauna was found to be rare by Cohen (1982) when compared to epifauna in the profundal region of Lake Turkana, Kenya.

Although the water must initially have been shallow, loading of peat by water could result in considerable compaction. This would increase with sediment loading (Elliott 1985) and rapid increase in depth could incur, dependent on the thickness of peat. Concentration of lamellibranchs indicates that the habitat was not uniform, and residual ponding (hence relatively shallow water) has been suggested as an explanation for these concentrations by Zangerl and Richardson (1963). However, no evidence of desiccation has been found by the author.

The common presence of siderite suggests a freshwater accumulation - the limited amount of pyrite present is interpreted as a product of later diagensis. Stunted lamellibranchs found together with marine fauna (Calver 1968), indicate that whilst they can tolerate moderately saline conditions, they prefer a freshwater habitat.

The preservation of large amounts of organic particles suggest anaerobic conditions, which whilst not in the water may have been close to the sediment surface. This would account for the lack of bioturbation within the black mudstone.

The exclusive but sparse occurrence of Lepidodendron stems may reflect the parent plants growing near the edge of the water, but that rates of sedimentation were low, following Scheihing and Pfefferkorn (1984).

In summary this lithofacies was deposited in fairly shallow freshwater, often at a great distance from the source of clay sediment, with much of the water derived from past swamp drainage channels. Currents were of small velocity and below the surface of the sediment conditions were anoxic.

5.3.1.4 Lithofacies 1.4

Mudstone, massive, with marine/brackish fauna, medium grey to black, often with abundant pyrite cubes and spherules throughout, occasionally laminae/elongate lenses of pyrite. Rare siderite nodules and lenses occur with rare stem fragments. Fauna varies from sparse to abundant, very often with fish spines and scales and the brachiopod Lingula, sometimes with other brachiopods, marine lamellibranchs and rarely cephalapods. Rarely the sediments contain trace fossils including faecal pellets. Natural gamma radiation is high compared with non-marine mudstones.

No inorganic sedimentary structures have been observed by the author although sometimes gradual changes of colour occur upward from medium grey to black and back to medium grey.

Pyrite is ubiquitous and was found by the author, in one form or another, in every example of this lithofacies examined. Siderite lenses are most common towards the top and bottom of the lithofacies unit.

Stem fragments are rare and when identifiable, prove usually to be LYCOPHYTES, principally Lepidodendron.

The distribution of fauna in this lithofacies in the Warwickshire Coalfield can be divided into that occurring within the Namurian and that in the Westphalian. Within the Namurian, examples of this lithofacies have a high diversity fauna, dominated by cephalopods -

principally 'goniat~~i~~tes', and pectinoid lamellibranchs (Taylor and Rushton 1971), together with other fauna occurring in the Westphalian lithofacies. This latter lithofacies has a low diversity fauna and most commonly contains fish spines and scales and Lingula. Sometimes STROPHOMENIDS including Productus occur and rarely ACROTRETIDS and marine lamellibranchs (Vernon 1912, Eastwood et al. 1923, Mitchell et al. 1942.

Trace fossils are confined to curved tracks and trails on bedding surfaces.

A discussion of the high natural gamma radiation found in marine mudstones when compared to non-marine mudstones is given by Ponsford (1955) and Knowles (1964). This allows them to be recognised by the use of geophysical logs, and their variable response, related to different faunas by Knowles (1964), has been noted in the Warwickshire Coalfield.

This lithofacies has the widest areal extent of any in the Warwickshire Coalfield and all these lithofacies units extend beyond the Coalfield. Contacts are often abrupt at the base, with the lithofacies 'Mudstone massive dark grey to black' or lithofacies of the rock type 'Coal' underlying it. The top of this lithofacies is usually gradational, with 'Mudstone massive, medium to dark grey' often overlying it.

For a long time these lithofacies units, no matter how thin, have been called 'marine bands' (eg. Barrow et al. 1919). Five Namurian marine bands (M.B.) have been identified in boreholes in the northern part of the Warwickshire Coalfield (Taylor and Rushton 1971) viz. Gracile M.B., Bilingue M.B., Super-bilingue M.B., Cancellatum M.B., and Cumbrience M.B. Five Westphalian M.B.s have been identified, Subcrenatum and Listeri M.B.s (Taylor and Rushton 1971), Seven Feet Vanderbeckei) M.B. (Vernon 1912), Four Feet (?Maltby M.B. and the Nuneaton (Aegiranum) M.B. (Mitchell 1942). 'Prodelta clays' with marine fossils and bioturbation have been recognised by Coleman and Prior (1980 Fig. 29, 32C) in sediments of the Mississippi delta.

Interpretation

Lack of inorganic sedimentary structures within this lithofacies is interpreted as the result of sediment settling out from low velocity currents together with bioturbation. Although it is believed to have accumulated slowly, figures given by Zangerl and Richardson (1963), indicate that 0.3m of marine shale was deposited in four years. This figure was determined using rates of aerobic decomposition of fish remains, which appears to give a relatively high rate of sedimentation.

The fauna has been shown to be marine (eg. Calver 1968, 1973). Westphalian rocks of marine aspect have been recognised by many authors in the Pennine Coalfield and a summary of their work is given in Calver (1968). This paper is a detailed study of the distribution of marine fauna, with phases representing conditions ranging from open, deep sea to near-shore shallow (ie. brackish - transitional to non-marine). This and other sequential relationships are best discussed in the section on lithofacies associations. Marine bands in the Namurian have been studied by Ramsbottom (1969).

Much of the fauna preserved in these rocks is scattered and lying parallel to bedding and probably represents a thanatacoenosis. The cephalopods are nektonic and where they occur without benthonic fauna, conditions at the sediment water interface may have been deoxygenated. Although it is clear from spines and scales that fish inhabited the water, there is little evidence of articulated skeletal remains. This may be due to predation (Zangerl and Richardson 1963) or the result of bacterial decomposition. Modern LINGULIDS are benthonic and live in burrows usually in shallow coastal waters (Craig 1952). This may have been the case for Westphalian Lingula although no evidence of their burrows has been found by the author. The presence of benthos may indicate shallower water with oxygenated conditions above the sediment/surface interface.

Ubiquitous presence of pyrite can be attributed to the processes outlined in section 4.2.1.7.4, principally bacterial sulpate reduction. This may have taken place during sedimentation, if reducing conditions existed within the water, or during early diagenesis if these conditions lay below the sediment surface. Reducing conditions also allowed the survival of organic debris which accounts for the lithofacies commonly having a dark colour.

Siderite may have been formed in early diagenesis when there was insufficient sulphate available to form pyrite and may be a reflection of the return of freshwater conditions. Alternatively it may be the result of chemical reaction during late diagenesis following burial as outlined by Curtis (1978). Where both occur together they may be chemically out of phase.

5.3.1.5. Lithofacies 1.5 (Plate 5.1)

Mudstone with coal lenses, medium grey to black, sometimes with siderite laminae or nodules usually with abundant listrics.

The coal lenses are bright, vitrainous and generally about 2mm thick although they can be up to 25mm thick. In borehole core they look like laminae and have been described as 'discontinuous laminae' by some NCB geologists. On examination of bedding planes they are

Plate 5.1 Lithofacies 1.5 Mudstone, with coal lenses. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B.
Thick bed in top of picture, thin beds below.

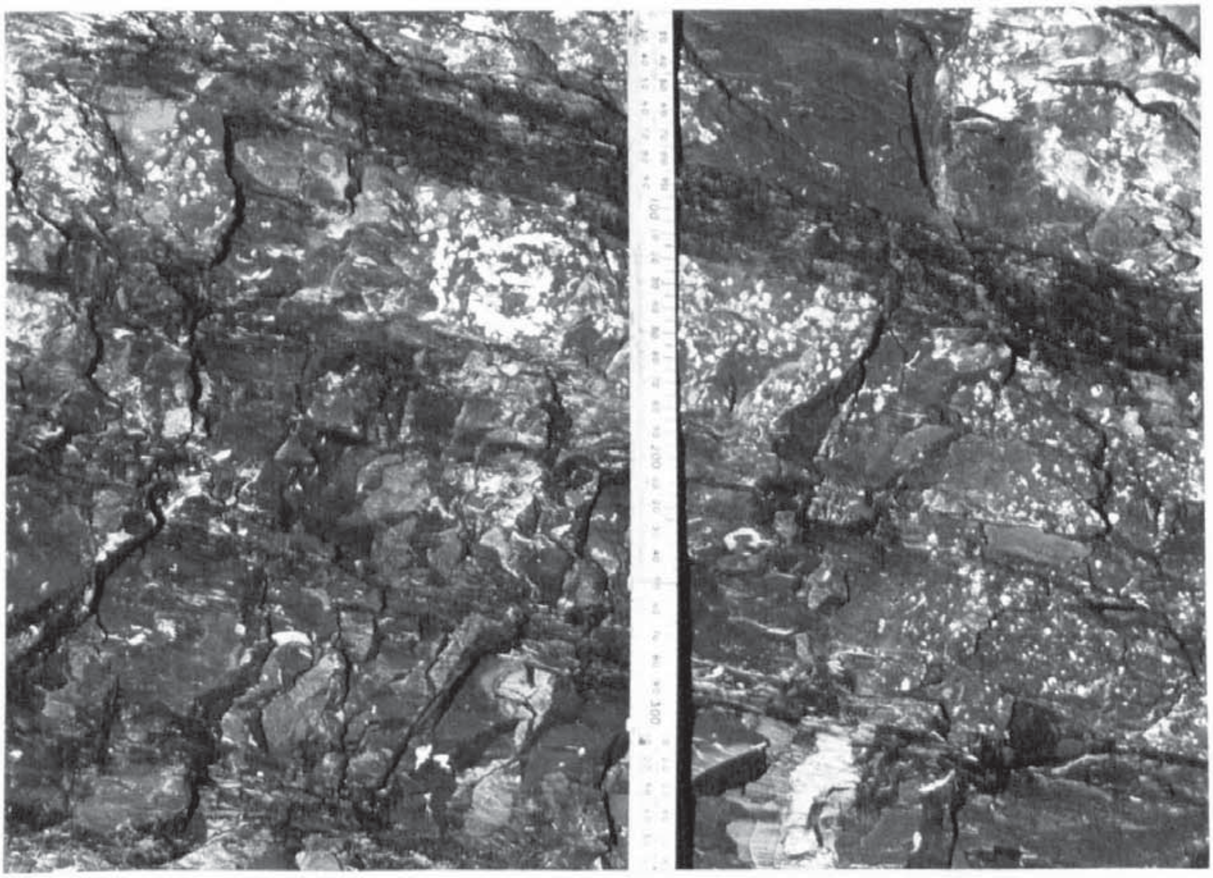
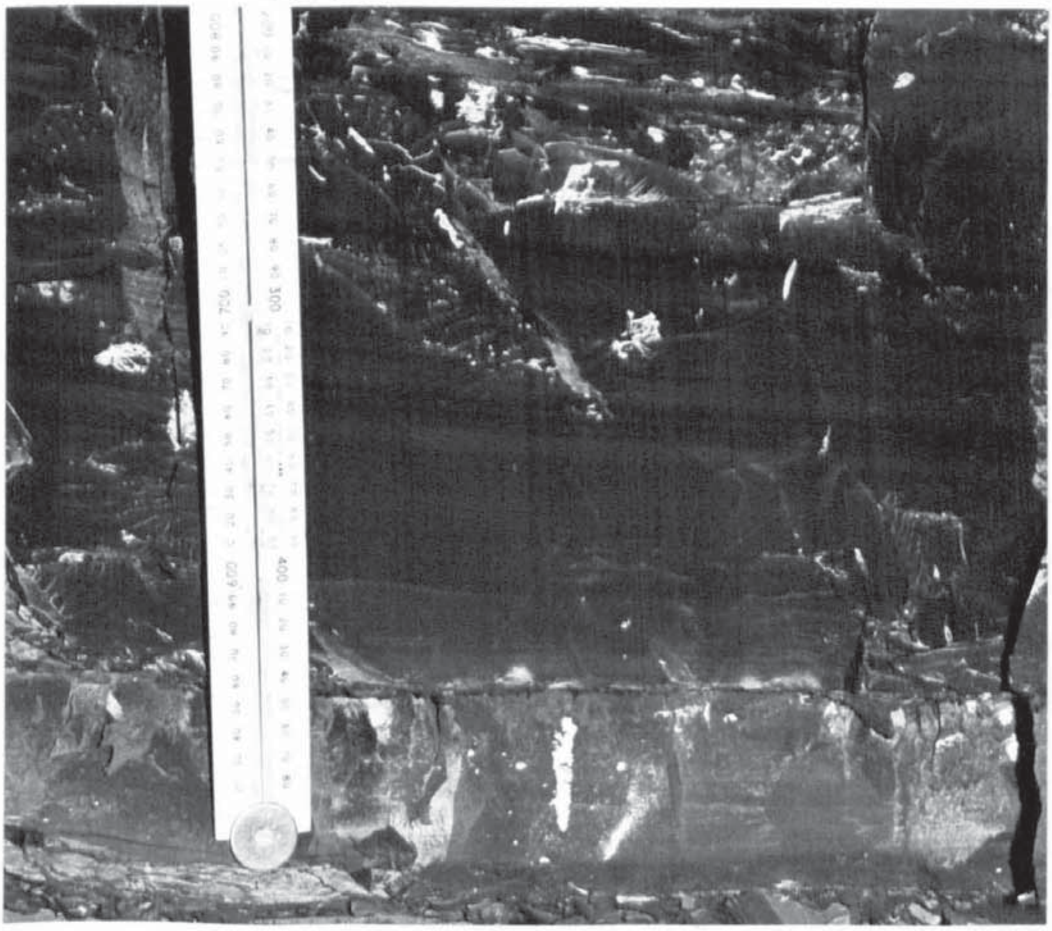


Plate 5.2 Lithofacies 1.6 Mudstone parallel stratified dark grey to black/medium grey. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B.



found to be large coalified stems often up to 0.6m long, generally of LYCOPHYTES although rarely Calamites occur with them. They can be occasional to abundant.

Colour ranges from medium grey to black, generally with fewer coal lenses in the darker sediment. Siderite usually occurs as diffuse laminae and nodules but can be absent. Listrics are variable and often occur around the plant stems.

It is possible that this lithofacies could extend over fairly large distances perhaps up to 1 km (eg. several beds between the Seven Feet and Bench in the southern part of the Warwickshire Coalfield). Contacts between under and overlying lithofacies are usually sharp but gradational boundaries are also found. It is often under or overlain by lithofacies of the rock type 'Coal', and sometimes by the lithofacies 'Mudstone, massive, medium to dark grey with abundant plant fragments' or lithofacies of rock types 'subseatearth' or 'seatearth'.

Other workers on Coal Measures in the Pennine Coalfield generally only make brief mention of plants. Exceptions to this are Guion (1978) whose facies 'Mudstone with plants' corresponds well to the lithofacies 'Mudstone with coal lenses' and Scott (1976) whose observations on the relationship between plant associations and environment are discussed in the section on lithofacies associations.

Interpretations

The mud size clay minerals are believed to have accumulated following fall out from suspension. Lack of inorganic sedimentary structures demonstrates the low velocity of the current. This together with the homogeneity may represent continuity of sedimentation, which must have been fairly rapid to preserve large numbers of stems (Scheihing and Pfefferkorn 1984).

It is suggested that an increase in the ratio of mud and organic carbon (more than changes in rate of decomposition of organic debris) is responsible for the lighter colour of the medium grey mudstone. This implies increased rates of sedimentation with a greater possibility of preserving plant stems, which are found in larger numbers in the medium grey mudstone. However, there may also have been an increase in the Eh, so that siderite was not formed early in diagenesis but later. Evidence for this is its diffuse appearance and association with the abundant stem fragments.

The presence of abundant coalfield LYCOPHYTE stems, is interpreted as the dispersed reamins of waterlogged, peat forming plants. These are hypautochthonous if underlain by a palaeosol (either coal, subseatearth or seatearth) or allochthonous if this is not the case. Because the relationship between other lithofacies is important in making a full interpretation of this lithofacies it is dealt with under the section of lithofacies associations.

In summary the accumulation of sediment and stems took place from slow moving water, but at a greater rate than that needed to form lithofacies 1.3 'Mudstone massive dark grey to black'. Stems accumulated either hypautochthonously or allochthonously, as oxygenated waters moved across the surface of a peat deposit.

5.3.1.6. Lithofacies 1.6 (Plates 5.2 and 5.3)

Mudstone parallel stratified dark grey or black and medium grey, often with siderite laminae, lenses or layers of lenses. Rarely tracks and trails are preserved at the light/dark mudstone interface, similarly bioturbation and occasionally high concentrations of plant fragments occur.

Stratification usually varies from thinly to thickly laminated but can be bedded. Thickness of stratification superficially appears random, but generally both the thickness of the medium grey mudstone laminae/beds and the grain size increases upwards. Where more than 50% of the lithofacies unit is dark grey/black it is referred to as 'Mudstone dark grey/black parallel stratified with grey mudstone .....' and vice-versa.

Contacts between the laminae generally become more gradational (sometimes referred to as "diffuse") upwards, but sharply based laminae of any colour can occur with gradationally based laminae. Horizontally the laminae can extend for many metres.

It is within this lithofacies (or its silty equivalent) that siderite beds with the greatest areal extend are found in Warwickshire. In the South Main Return at Coventry Colliery, just above the Four Feet Marine band, several siderite layers varying from 0.03 - 0.1m thick were traced a distance of 300m. This gives a width : thickness ratio of about 10^3 comparable with that observed by Haszeldine (1984a). Because they passed out of the road at each end, this distance could be much greater. In the North Rock Head road 1.5km away near Coventry Colliery Shaft at the same stratigraphic horizon, an almost exact arrangement of several ironstone layers can be seen. If they are laterally continuous this gives a much larger width : thickness ratio of 10^4.

Tracks and trails similar to those observed in previous mudstone lithofacies are best observed on the interface between light and dark mudstone, or associated with siderite, ie. where there is a sediment contrast. Rarely bioturbation is seen (above the Four Feet, M.B. at Moat House Farm borehole in a black mudstone parallel laminated with sideritised mudstone).

Because of the type of stratification, the sedimentary dip will reflect the tectonic dip, and this is most useful in determining regional gradients from boreholes using the dipmeter geophysical log.

This lithofacies can be as areally extensive as the lithofacies 'Mudstone, massive dark grey to black' extending over many Km^2 (eg. above the Thick Coal). It usually has gradational contacts with both under and overlying lithofacies. Most frequently it is underlain by 'Mudstone, massive dark grey to black' and overlain by 'Siltstone, parallel stratified with sandstone'. Often it is overlain by 'Mudstone, massive, medium to dark grey'.

Other workers have included this lithofacies within similar mudstones eg. Guion (1978) 'Mudstone with Trace fossils' (Plate 6.1), Elliott (1965) 'Faunal mudstone'. Although superifically similar, this lithofacies does not correspond to the 'Rhythmite muds' of Haszeldine (1984a) which may be coarser and commonly displays erosive surfaces. The 'Varved mudstone' facies of Boardman (1981) may correspond to this lithofacies. Parllel laminated mudstones have been commonly observed in recent lacustrine sediments (Sturm and Matter 1978, Yuretich 1979) and in deltaic deposits of the Mississippi viz. 'Prodelta clays' 'Interdistributary bay deposits' and 'Marsh Environment' Coleman and Prior (1980 Figs. 16, 18, 28, 32C). They also have been recognised in ancient lacustrine (Cole and Picard 1975, Zangerl and Richardson 1963) and fluviatile (Picard and High 1970) sediments.

Interpretation

Superficially similar deposits of mud have been interpreted by Haszeldine (1984a) as the product of turbid underflows, with lamination resulting from a dynamic sorting mechanism similar to that proposed by Stow and Shanmugham (1980). Turbidity current deposits of modern glacial lakes are characterised by grading, ripples and thicker units than overflows (Gustavson 1975). A complication is introduced by Sturm and Matter (1978) who correlated a sand/silt lamina produced by a turbidity current with a silt lamina produced from suspension, proving that lateral gradation between the two is possible.

Because of the fine grained nature of both light and dark layers in this lithofacies they are interpreted as fallout from suspension. The lithological stratification could be produced in one of two ways, dependant on whether or not the water in which the sediment accumulated became stratified, and subsequently underwent overturn.

If it did, then particles would be transported in over - or interflows, and coarser grained particles would be deposited whilst the thermocline was formed. The finer grained particles, held in suspension by it, would be deposited following the destruction of the thermocline. This process is seasonally controlled in Lake Brienz and produces coarser dark grey laminae and finer pale grey laminae all with sharp bases (Sturm and Matter 1978). Although seasons were probably present during the Namurian and Westphalian A and B neither great changes in temperature nor prolonged dry periods are envisaged (section 3.1). However, stratification of tropical waters can occur in both shallow lakes - Nakuru, 2m deep (Meluck in Cohen 1984) lagoons - Fergusons gulf, (part of Lake Turkana) hypolimnion below 1m (Cohen 1984) and deeper lakes - Albert, 50m deep and Victoria, 100m deep (Demaison and Moore 1980), and depends on the mixing of water by wind/wave action. In some of the deeper lakes, eg. Victoria, seasonal overturn occurs, whereas in Lake Albert and the shallower lakes and lagoons listed above are only periodically stratified (Cohen 1984).

If water stratification did not occur, then primary alteration of sediment type from organic rich to poor (Pollard 1969) could account for the lithological stratification. This could be on a seasonal basis (Spears 1969) or could relate to high and low stage flows (Cole and Picard 1975) which may be only loosely linked with the seasons. As the medium grey mudstone layers thicken upwards within lithofacies units, this may be attributed to increase in proximity of source. (Proximity of this source would not radically alter thickness of low stage dark grey/black mudstone layers, which represent uniform input over the same time period). The source/s of the sediment is more closely examined in the section on lithofacies associations. Also, as the source moved nearer, more medium grey mudstone forming events would be present perhaps allowing insufficient time to form black laminae, and causing mixing to take place between the two, generating gradational boundaries.

Presence of bioturbation indicates that at some time the upper layer of the sediment was capable of supporting fauna, and therefore oxygenated. This would also account for the scarcity of plant fragments. Siderite which often has gradational boundaries may have formed during late diagenesis.

In summary this lithofacies was probably deposited from suspension as the result of periodic organic rich and poor sedimentation. The latter could have been derived from distant high stage alluvial events, the former from proximal or distal low stage flows. Periodicity of sedimentation could have been seasonal, and it allowed fauna to exist within the sediment for at least some of the time during deposition.

5.3.1.7 Lithofacies 1.7 (Plate 5.4)

Mudstone, medium grey, with dark grey mudstone lenses, often becoming fewer upwards, and rare dark grey mudstone parallel laminae especially near the base of units, sometimes coarsening upwards. There are often siderite laminae, lenses and layers of lenses with gradational boundaries. Rarely tracks and trails and plant fragments occur.

The mudstone lenses are up to 5mm thick and 0.5 long, although usually much shorter, with gradational or sharp boundaries. Siderite layers of lenses are up to 0.1m thick.

This lithofacies can have considerable horizontal extent (eg. above the Four Feet coal) and usualy has gradational boundaries with other lithofacies. It is usually underlain by 'Mudstone parallel stratified dark grey or black/medium grey', and overlain by the coarse grained equivalent of this lithofacies or 'Mudstone silty parallel laminated with sandstone'. This lithofacies is fairly rare and may be useful as a stratigraphic marker bed, eg. above the Four Feet coal.

Guion (1978) recognised the coarse grained equivalent of this lithofacies which he named 'Laminated siltstone with mudstone lenses'. No mention of this lithofacies has been made by previous workers on Coal Measures in the Pennine Coalfield.

Interpretation

The origin of the inorganic sedimentary structure displayed in this lithofacies is difficult to interpret. It does not resemble the product of mudstone 'bedforms' produced by fluid stressing (ridges, from the crests of which mud shreds are torn - Allen 1984), yet demonstrates stronger current action than that required to produce horizontal stratification. Guion (1978) believed that the

Plate 5.3 Lithofacies 1.6 Mudstone parallel stratified dark grey to black/medium grey. Location: Coventry Colliery North Rock Head. Age: upper Westphalian B.

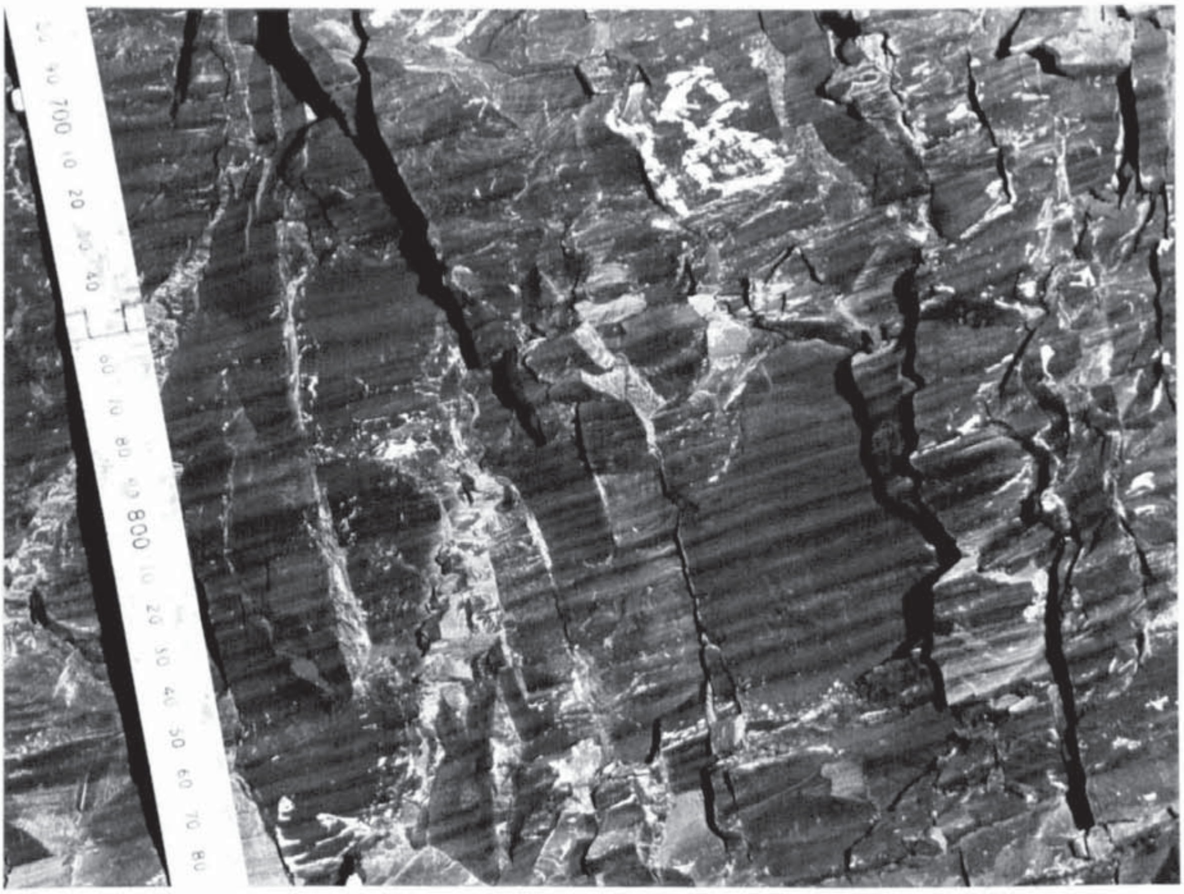
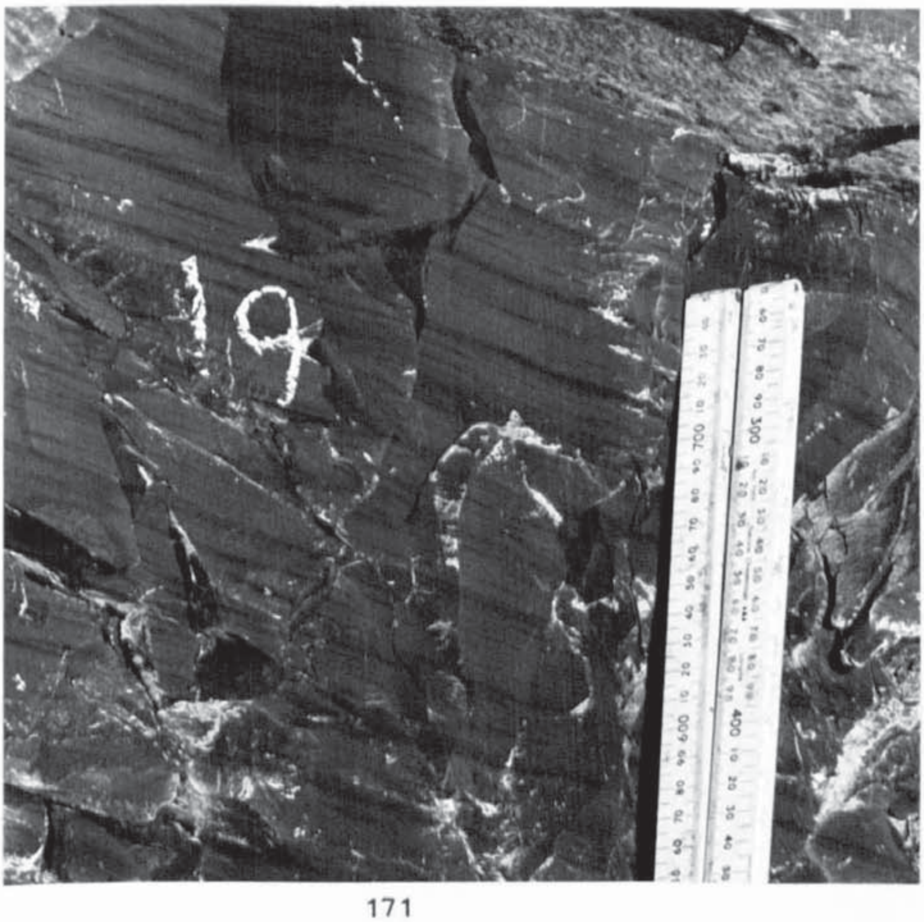


Plate 5.4 Lithofacies 1.7 Mudstone medium grey with dark grey mudstone lenses. Location: Coventry Colliery North Rock Head. Age: upper Westphalian B



stratification formed in a similar fashion to flaser bedding (Reineck and Wunderlich 1968), although the irregular distribution of lenses suggests a less well organised bedform. Succeeding lithofacies often have stratification indicative of higher current velocities. This suggests that the lenses are a response to intermediate velocity or fluctuating currents. After particles forming the medium grey mudstone had settled from suspension, but before they became cohesive, they may have been subjected to currents which mildly sculptured the surface. The dark grey to black mudstone settling from suspension would preferentially fill these hollows, but time would not allow the crest to be covered before the next influx of medium grey mudstone. If the frequency of influxes increases with time this would account for the decrease in number of lenses upwards.

Scarcity of bottom dwelling fauna suggests more or less continual sediment supply with higher velocity currents producing more oxygenated bottom conditions, so that gradationally bounded siderite is formed in late diagenesis.

In summary this lithofacies was probably formed under higher energy conditions than previously described lithofacies, as the response to fluctuating currents and increased rates of sedimentation.

5.3.1.8 Lithofacies 1.8

Mudstone, melange see section 5.3.3.12 siltstone, melange.

5.3.2 Rock Type: Mudstone silty

This is defined as a clay rich rock (20 - 30% quartz) with a grain size between 0.0039 and 0.156mm. It is important to recognise an intermediate grain size between mudstone and siltstone, because in low energy environments lateral changes often take place slowly over hundreds of metres. Identification of this progression, aided by the extra grain size category, is useful in determining the direction of higher energy environments. It is sometimes difficult to distinguish between mudstone silty and siltstone in hand specimen, especially when a lithofacies is composed of two grain sizes the finer of which is thickly laminated.

Its grain size means that it is usually carried in suspension (Fig.5.1), but being coarser than mudstone is sometimes associated with sediment sizes only capable of moving by traction. If these particles occur in very high concentrations they may be transported by traction.

Colour of this rock type usually ranges from medium to dark grey, but it is rarely black, depending on organic content. Although not mentioned in the lithofacies descriptions in some cases the lighter coloured lithofacies may be green in colour.

The distribution of organic structures is slightly different to that found in the rock type mudstone. There are few examples of this lithofacies containing faunal body fossils. Ichnofossils are fairly common but some are different to those observed in mudstones. Plant fragments and fronds are also more common than in mudstones.

Siderite is common in the form of laminae, lenses and layers of lenses, usually with gradational boundaries. Most of this is believed to have originated in later diagenesis.

Rock discontinuities in terms of partings are fairly common, joints are not so well developed.

Mudstone silty lithofacies units are variable in horizontal extent, depending upon their environment of deposition. Those in the lacustrine environment are widespread and usually have gradational contacts. Those in alluvial environments may have a small lateral extent and abrupt contacts.

Because the rock type 'Mudstone silty' accommodates lithofacies which are similar to both 'Mudstone' and 'Siltstone' lithofacies they are described, compared and interpreted under both those headings. The twelve 'Mudstone silty' lithofacies recognised in this study are given below, and as can be seen not all 'Mudstone' and 'Siltstone' lithofacies occur as 'Mudstone silty lithofacies'.

2.1 Mudstone silty, massive medium to dark grey
2.3 Mudstone silty, massive, with abundant plant fragments
2.3 Mudstone silty, with coal lenses
2.4 Mudstone silty, parallel stratified with mudstone
2.5 Mudstone silty, medium grey, with dark grey mudstone lenses
2.6 Mudstone silty, parallel stratified with sandstone
2.7 Mudstone silty, with undulating sandstone laminae
2.8 Mudstone silty, with lenticular sandstone stratification
2.9 Mudstone silty, wavy stratified with sandstone
2.10 Mudstone silty, slurried
2.11 Mudstone silty, with load casts
2.12 Mudstone silty, melange

5.3.3 Rock Type Siltstone

This has previously been defined as a rock type relatively rich in quartz (30-60%) with a grain size between 0.0156-0.962mm. This means that whilst it usually carried in suspension, at higher concentrations it may be transported by traction. Often it is associated with sediment sizes capable of moving only by traction, and because of this a wide range of inorganic sedimentary structures are present.

The colour of this rock type varies from pale to medium grey, and with reduced organic content is usually dependant on the amount of quartz content. Although not mentioned in the lithofacies descriptions, in some cases the lighter coloured lithofacies may be green in colour.

Siderite is rarer than in the more clay rich rock types, consisting of laminae, lenses, and layers of lenses with gradational boundaries, and similar to the rock type silty mudstone it is believed to have originated in late diagenesis.

Organic structures are restricted to rarely occurring 'Domichnia' and 'Fugichnia', and plant remains. Comminuted plant debris is almost ubiquitous, but plant fragments vary from rare to abundant, and include fronts and upright LYCOPHYTE tree trunks. The presence of the latter, infilled with sediment, have been interpreted as implying rapid burial (Broadhurst and Loring 1970). The latter authors believed this was brought about by periodic flooding, evidenced by changing Na/K and Si/Al ratios reflecting changes in conditions of turbulence.

Rock discontinuities formed by partings are rarer than those in more clay rich rocks but joining is more common.

The lateral distribution of lithofacies dominated by the rock type 'Siltstone' is variable in the same way as those dominated by the rock type 'Mudstone silty'. A greater percentage of 'Siltstone' over 'Mudstone silty' lithofacies occur in or adjacent to the alluvial environment, and therefore can be expected to have restricted lateral extent and abrupt contacts with lithofacies units above and below. In the Warwickshire Coalfield, it most often passes upward and downward into the rock types 'Mudstone silty' and 'Sandstone fine'.

Many 'Siltstone' lithofacies defined in this study occur in a number of facies described by other workers in the Pennine Coalfield (see below).

Elliott (1968) East Midlands Coalfield	Lithofacies in this Study
'Massive siltstone facies	3.1, 3.2
'Complex silt-sandstone facies'	3.3 - 3.3
'Layered sand-siltstone facies'	3.7
'Flaser silt-sandstone facies'	3.5 - 3.7
Fielding (1984a) Durham Coalfield	
'Facies 1 Coarse grained overbank deposits'	3.1
'Facies 2 Siltstone dominated overbank deposits'	3.1 - 3.4
'Facies 3 Proximal major crevasse splay channel'	?3.1
'Facies 4 Medial crevasse splay/minor delta'	3.1
'Facies 5 Distal crevasse splay/minor delta'	3.1-3.9, 3.12

As the facies of these authors are related to environment of deposition they are dealt with under the heading of lithofacies associations.

Many of the rock sub-types of Guion (1978) correspond with lithofacies recognised in this study and for this reason are mentioned under the individual lithofacies descriptions. The only exception to this is 'Rock Type G - Interstratified Siltstone/Sandstone' which includes in its sub-types 'Complex stratification'. Guion (1978) believed it to be created, as Allen (1973) had predicted, by externally controlled fluctuation in flow, as well as random processes which act on the bedform itself. It appears that this rock type is made up of combinations of previously described sub-types, many of which are defined in this study. Thus 'Rock Type G' is best described as a lithofacies association, even though it may represent a larger scale bedform which is internally structurally complex.

Siltstone lithofacies are found in many environments so that each one is diagnostic of process and not environment. Because of this the interpretation of the lithofacies is carried out in groups, which reflect variants of the same process, producing different sedimentary structures.

Where a lithofacies has finer or coarser grained equivalents the description will include them unless otherwise stated. For heterogeneous, lithofacies, whichever is dominant in percentage terms is stated first in the description. A list of 'Siltstone' lithofacies recognised in this study is given below, all of which are described except 'Lithofacies 3.9 Siltstone/Sandstone fine with small scale cross lamination', the coarse grained equivalent of which is described in section 5.3.4.

3.1. Siltstone, massive, pale to medium grey

3.2. Siltstone, massive, with abundant plant fragments

3.3. Siltstone, parallel stratified with sandstone

3.4. Siltstone, with undulating sandstone laminae

3.5. Siltstone, with sandstone mine ripples

3.6. Siltstone, with lenticular sandstone stratifications

3.7. Siltstone, wavy stratified with sandstone

3.8. Siltstone, ripple drifted with sandstone

3.9. Siltstone/Sandstone fine, with small scale cross lamination

3.10. Siltstone, with convolute sandstone stratification

3.11. Siltstone, slurried

3.12. Siltstone, with load structures

3.13. Siltstone, melange

5.3.3.1 Lithofacies 3.1

Siltstone, massive, pale to medium grey may coarsen or fine upwards, with rare to common ironstone laminae, lenses and layers of lenses. Rarely sphaerosiderite is present. Comminuted plant debris is common and plant fragments occur occasionally. Rarely bioturbation in the form of indistinct oblique burrows is visible.

Sphaerosiderite in this lithofacies usually occurs in sequences associated with palaeosols. Depending whether the lithofacies is fining or coarsening upward it is most commonly under or overlain by fine or coarse grained equivalents of this lithofacies. Commonly overlying are the lithofacies 'Silstone parallel stratified with sandstone' and a variety of sandstone lithofacies. It is usually has gradational boundaries.

This lithofacies may be equivalent to that part of the rock sub-type 'Unlaminated silstone with flat lying plants' which contain relatively few plant fragments described by Guion (1978) and also 'Ferruginous siltstone with plant debris' and 'Unlaminated siltstone with trace fossils'.

Massive siltstone has been found in a wide range of sub-environments in the Mississippi delta deposits including 'Interdistributary bay fill' and 'Distal Bar' sediments by Coleman and Prior (1980, Figs. 18, 29).

5.3.3.2 Lithofacies 3.2

Siltstone massive with abundant plant fragments, pale to dark grey may coarsen or fine upwards, with rare to common ironstone laminae, lenses and layers of lenses. Comminuted plant debris is common.

This lithofacies is similar to that previously described except for the concentration of plant fragments. Both stems and leaves are present the latter varying in size from pinnae to fronds, usually PTERIDOSPERMOPHYTES or CONIFEROPHYTES. Rarely larger coalified LYCOPHYTE stems are present.

Relatively few lithofacies commonly pass upward into this lithofacies. They include the finer grained equivalents of this lithofacies, 'Mudstone silty parallel stratified with mudstone', and 'Seatearth siltstone grey'. It commonly passes upward into a wider variety of lithofacies including finer grained equivalents of this lithofacies and 'Seatearth mudstone silty or siltstone, grey' and often the massive lithofacies of 'Mudstone', 'Mudstone silty' and 'Siltstone'. The boundary between this and other lithofacies is usually gradational.

This lithofacies may be equivalent to that part of 'Unlaminated siltstone with flat lying plants' with many plant fragments described by Guion (1978) and 'Unlaminated siltstone with oblique plants'.

Guion (1978) found the 'Rock Type D - Unlaminated Siltstone' occurred in units ranging from 0.3 - 10.0m in thickness, although he included in this rock type siltstone having faint laminations. This has been excluded by this author, and laminated siltstone, no matter how faint, has been included in the lithofacies 'Siltstone parallel stratified with sandstone'. It is possible that the siltstone described in this work as massive, have lamination which is not visible to the eye which could be revealed by techniques such as exposure to X-rays (Hamblin 1965). The thickness of massive siltstone lithofacies is usually much less than 10m but can be over 1m thick.

Interpretation

Blatt et al. (1980 p.136) believe that lack of lamination in sandstones is due to rapid deposition from suspension or by deposition from highly concentrated sediment influxes. Reineck and Singh (1980 p,130) arrive at a similar conclusion for rock of all grain sizes if the homogeneity is primary, or if secondary, highly bioturbated sediment may appear massive. Where bioturbation of an originally stratified sediment has taken place the author has usually found irregular, oblique, discontinuous laminae. The same is true of lamination which has been destroyed by thixotropic or quasi-liquid deformation (Elliot 1965a). Fining upwards of units can be attributed to differential settling of particles in unstratified or stratified water (Sturm 1979), or the sedimentary product of a waning flow. Coarsening upward can be attributed to increasing velocity of flow allowing transport of larger size particles.

Sturm and Matter (1978) have shown that turbidite produced siltstone and sandstone beds up to 0.57m thick can grade into suspension produced siltstone laminae 5-7mm thick. It is possible that this lithofacies was produced either from turbiditic underflows or from suspension. Ungraded units may be the result of pre-sorting of the material during transport.

Increase in the number of plant fragments may be caused by varying current velocities causing sorting of floating debris, which on becoming waterlogged is rapidly buried. Epifaunal Spirobis has been observed rarely by the author attached to Medullosa and Calamites stems.

Conditions for the formation of these and other siltstone lithofacies were optimum for the accumulation and preservation of plant fragments.

5.3.3.3 Lithofacies 3.3. (Plates 5.5 and 5.6)

Siltstone parallel stratified with sandstone, fine grained, siltstone is usually medium grey, sandstone usually fine grained and pale grey. Stratification may have sharp or graditional boundaries, but the former predominate. Sometimes the stratification is cut by low angle erosion surfaces. Occasionally siderite laminae, lenses and nodules occur. Comminuted plant debris is common and sometimes laminae containing abundant plant fragments are found.

Stratification is usually confined to lamination, sandstone being thinly laminated, siltstone varying from thinly to thickly laminated. Often the stratification changes incrementally throughout a unit giving rise to laminated grading *sensu* Reineck and Singh (1980).

The thicker sandstone laminae sometimes have loaded bases into the underlying siltstone. Rarely the siltstone laminae have small sandstone mini-lenses within them. Sometimes this lithofacies has mudstone laminae and lenses associated with it.

Low angle erosion surfaces usually cut several laminae and decrease in dip downwards. They are called gentle erosion surfaces by Guion (1978) and some NCB geologists.

This lithofacies is usually gradational with other lithofacies and within vertical sequences is the most quantitatively important siltstone lithofacies in the Warwickshire Coalfield. Many 'Sandstone' lithofacies pass upward into this lithofacies but most commonly it is

Plate 5.5 Lithofacies 3.3 Siltstone parallel stratified with sandstone. Location: Broadacres borehole. Age: mid Westphalian A

Plate 5.6 Lithofacies 3.3 Siltstone parallel stratified with sandstone. Location: Rookery Farm borehole. Age: upper Westphalian B

the lithofacies 'Mudstone, parallel stratified dark grey to black/ medium grey. 'Sandstone' lithofacies also commonly overlie this lithofacies especially 'Sandstone fine, with small scale cross lamination (with an erosive base).

This lithofacies has been recognised by Guion (1978) 'Parallel laminated siltstone' and a similar lithofacies 'Rhythmite muds' has been described by Haszeldine (1984). The grain size referred to by Hazeldine is mud and in this respect, together with the trace fossils, more closely resembles the fine grain equivalent of this lithofacies ('Mudstone silty parallel stratified with sandstone'). Sandstone is mentioned as appearing in the dark layers near the top of his facies. Low angle erosion surfaces are visible in (Haszeldine 1984 Fig. 3C) and on p.82 it is stated that bases of pale layers are less erosive than dark layers, although both appear equally erosive in the Warwickshire Coalfield (and in Fig. 3C).

Parallel lamination of this type has been found in a variety of modern environments including the marine dominated deposits of the Mississippi delta (Coleman and Gagliano 1965) in the sub-environments 'Distal Bar', 'Interdistributary bay deposits' and 'Distributary channel fill' of Coleman and Prior (1980), (Figs. 15, 18, 29). It has also been observed in the lacustrine environment (Sturm and Matter 1978) and alluvial environment (Taylor and Woodyer 1978).

5.3.3.4 Lithofacies 3.4 (Plate 5.7)

Siltstone with undulating sandstone laminae fine grained, siltstone usually medium grey, sandstone pale grey. Stratification usually has sharp boundaries and low angle erosion surfaces are common. Siderite and plant fragments occur in a similar way to the lithofacies above.

Plate 5.7 Lithofacies 3.4 siltstone with undulating sandstone laminae. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B

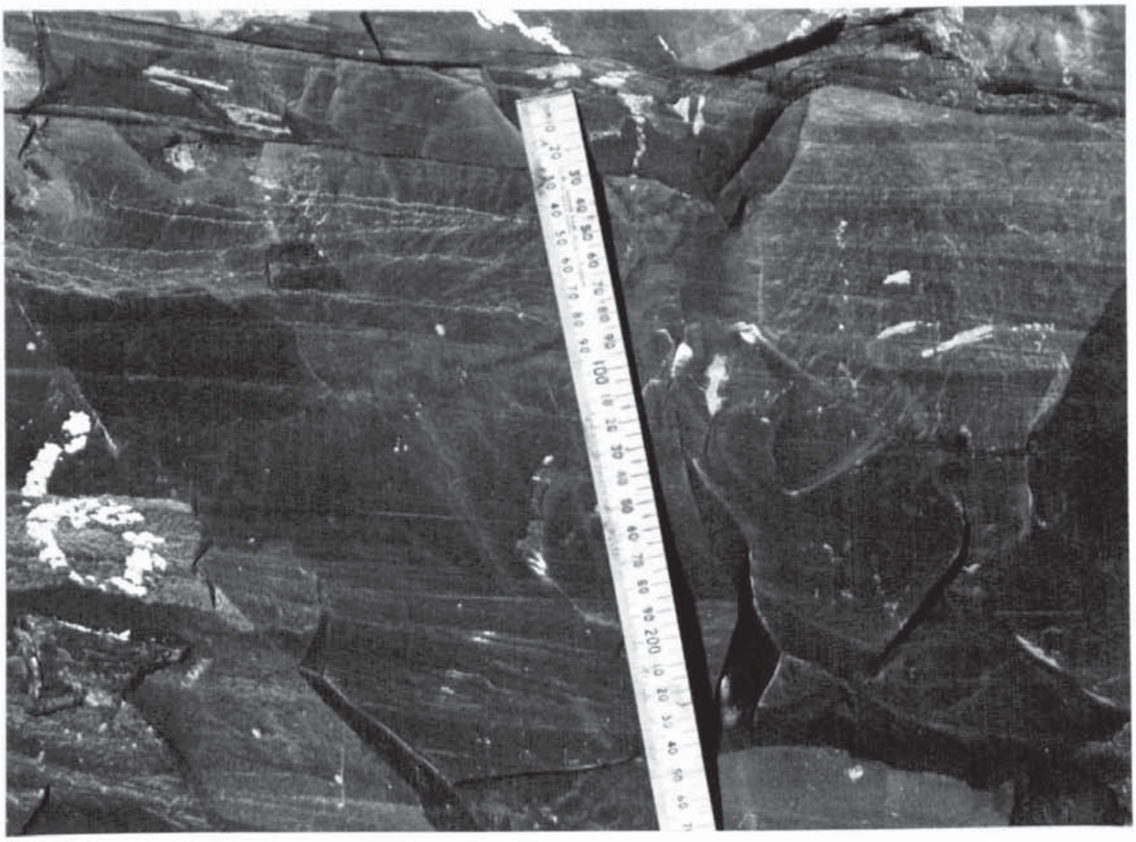
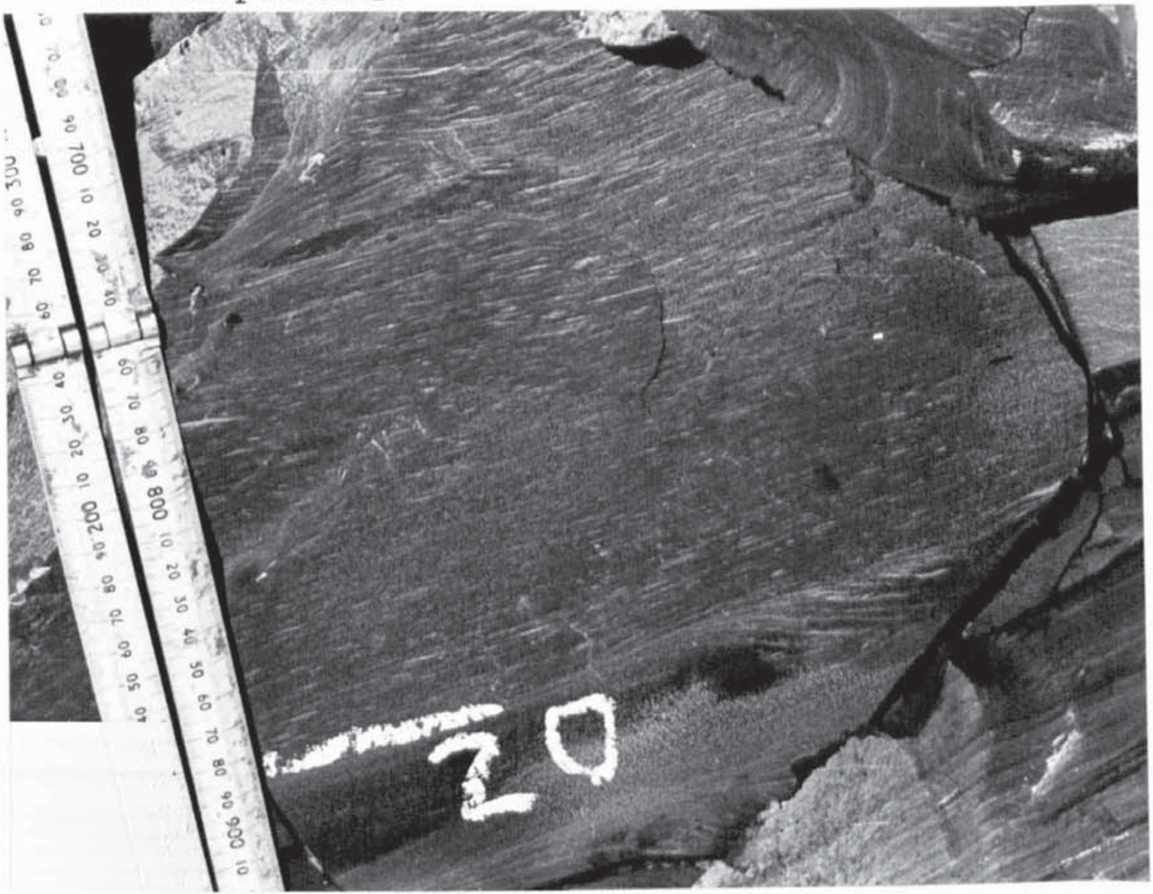


Plate 5.8 Lithofacies 3.5 Siltstone with sandstone mini lenses; Lithofacies 3.8 Siltstone ripple drifted with sandstone. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B.



This lithofacies has only rarely been observed by the author and because of its form is difficult to detect in borehole core. The lamination is sub-parallel but undulating, with a wavelength of about 0.5m and an amplitude of about 0.05m. Low angle erosion surfaces often mark the boundary between separate buried beforms or this lithofacies can pass laterally into 'Siltstone parallel stratified with sandstone'. Abundance of low angle erosion surfaces in borehole core may be diagnostic of this lithofacies.

It is usually gradational with under and overlying lithofacies and is most commonly associated with 'Mudstone silty/Siltstone parallel stratified with sandstone', 'Mudstone silty/siltstone with lenticular stratification' and 'Siltstone/Sandstone fine ripple drifted with sandstone/siltstone'.

Plate 5.7 shows this lithofacies as it occurs in the North Rock Head road at Coventry Colliery. It also occurs in the South Main roads at the same colliery extending laterally over many tens of metres.

This lithotype may be related to those rock sub-types defined by Guion (1978) with common low angle erosion surfaces.

Interpretation

No work has been found which has been carried out in the laboratory, to quantify the hydraulic processes responsible for the formation of sandstone/siltstone/mudstone silty parallel laminae. There have been several laboratory investigations into the formation of parallel laminated sand. As already shown (section 5.3) if enough sediment is available parallel laminated sand can be deposited at volocities just below those creating ripple bedforms. Reineck and Singh (1972) using such velocities produced parallel lamination from suspension clouds. Keunen (1966) demonstrated that parallel lamination could be formed when a current carrying particles in suspension was allowed to decelerate. He believed the sorting mechanism to be based on the principle of grouping of similar sized grains.

McBride _et al._ (1975) using small current velocities and depths produced low relief ripples which formed thin laminae by hydraulic sorting of coarse grains on the lee-side and fine grains on the stoss-side. Guion (1978) believed this mechanism produced the parallel laminations observed in his siltstone dominated lithofacies in the East Midlands Coalfield. This type of ripple has been called transcurrent by Allen (1984) because deposition takes place on a moving surface inclined to the plane of accumulation.

The difference in grain size between laminae has been interpreted as the product of separate events. Whilst Spears (1969) suggested this could be seasonally related in finer grained (mudstones) rocks, Reineck and Wunderlich (1969) thought it could be related to tidal cycles as a result of pulsations in current activity with settling from suspension clouds. Poorly defined parallel lamination (silt/sand streaked mud) in shallow marine sediments superficially similar to these lithofacies allowed de Raaf _et al._ (1977) to conclude that they had been deposited from suspension, possibly affected later by wave action. Separate events of deposition could also be caused by water stratification with either dis- or continuous influx of suspended sediment (Sturm 1979) similar to that observed in the lithofacies mudstone parallel stratified dark grey to black and medium grey. Processes operating within turbidity currents (e.g. Keunen 1966) may also cause parallel lamination similar to that seen in this lithofacies. Piper (1972) suggested that changes in concentration of clay and silt grade sediment in suspension might be brought about by increased deposition of clay flocs onto an adhesive base, reducing its concentration in the suspension. Silt is then deposited onto a granular bed by tractional forces. Alternatively Stow and Bowen (1978) believed the lamination may result from depositional sorting of silt grains from clay flocs due to increased shear in the boundary layer. Clay flocs are broken up by the boundary layer and can only be deposited when they reach a critically large size. Stow and Shanmugham (1980) studying the marine environment postulated this mechanism as the cause of lamination interpreted as turbiditic in origin. They recognised eight divisions (T_0-T_8) within a turbiditic unit although not all the divisions may be present at any one locality. Haszeldine (1984) believed this dynamic sorting mechanism produced the lamination in his 'Rhythmite muds' façies, similar to that seen in the divisions T_3-T_8 of Stow and Shanmugham (1980). Because the same inorganic sedimentary structure can be found in a variety of environments, it is possible that more than one mechanism may have produced them. It is possible that a difference in mechanism may produce morphological differences.

In the majority of this lithofacies in the Warwickshire Coalfield the finer and coarser elements comprising the laminae appear well sorted, thinly laminated and without great horizontal extent (Plate 5.5). This resembles the lamination produced by McBride <u>et al</u>. (1975) from low relief bedforms in shallow water (less than 50mm) at low current velocities (less than 50cm/sec). It would be useful to see similar laboratory experiments carried out on grains ranging from silt to fine grained sandstone.

In the other type of this lithofacies the laminae are thicker or bedded (Plate 5.6) and fining upward is clearly visible. This resembles these features outlined by Kuenen (1966) and Stow and Shanmugham (1980) in lamination produced by turbidity currents. Turbidite produced parallel laminations characteristically produces sandstone laminae traceable over long distances (Sturm and Matter 1978) although as they point out sandstone laminae produced from suspension (inter- or over flows) can grade into those produced by turbidity currents.

Increase in current volocity could change the flow from depositional to erosional creating the gentle erosion surfaces in the lithofacies 'silstone with undulating sandstone laminae'. Whether these structures have in some cases been altered later by wave action remains unclear. Gross increase in grain size upward through a unit may be the result of increase in proximity of source. The lack of fauna suggests the creation of inhospitable conditions as a result of more or less continual sedimentation.

5.3.3.5 Lithofacies 3.5 (Plate 5.8)

Siltstone with sandstone mini-lenses, siltstone usually medium grey, may coarsen or fine upward, often associated with undulating or parallel sandstone laminae and occasionally form sets of sandstone. Low angle erosion surfaces occasionally occur. Siderite, plant fragments and trace fossils are rare.

The mini-lenses are usually formed of fine grained, pale grey sandstone, up to 3mm thick and 30mm in length, although they often extend longer distances as very thin laminae. No internal cross lamination is visible.

Units of this lithofacies are fairly rare and it is gradational with a variety of under and overlying lithofacies which are of the same rock type.

This lithofacies was given the name mini-lenses by Guion (1978) in his rock sub type 'Laminated siltstone with mini-lenses' who showed that they consist of straight crested ripples with wavelengths of about 40mm. Reineck and Singh (1980) believed that ripples smaller than 4.5mm were known only as asymmetrical wave ripples although mini-lenses appear to fit this size criteria, yet are symmetrical. Earlier however, Singh and Wunderlich (1978) used the term mini-ripples to describe asymmetrical or symmetrical, straight or slightly curved ripples with wave lengths between 5-30mm. Unfortunately, neither photographs or cross-sections nor the height of the ripples was given. In the same paper ripples with heights less than 1mm were described termed millimetre ripples with crests between 2-5mm in length. It is possible that the size of the mini-lenses in this lithofacies lie between those of millimetre and mini-ripples.

5.3.3.6 Lithofacies 3.6 (Plates 5.9 and 5.10)

Siltstone with lenticular sandstone stratification, wilstone usually medium grey, often coarsens upward may fine upward, often associated with parallel or undulating sandstone laminae, mini-lenses and rare continuous beds of cross stratified sandstone. Siderite, plant fragments and trace fossils are rare.

The majority of sandstone is fine grained, pale grey and occurs as lenses in cross section well separated horizontally and vertically by siltstone. Horizontally discontinuous ripples have been called incomplete ripples (Shrock 1948) or isolated ripples Allen (1968). They are up to 40mm in height, usually less than 10mm and often possess the characteristics of wave of wave current ripples (Table 5.3). Where form concordant they are called form sets (Imbrie and Buchanan 1965). Usually both the top and base of the lens are sharply

Plate 5.9 Lithofacies 3.6 Siltstone, with lenticular sandstone stratifaction. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B.

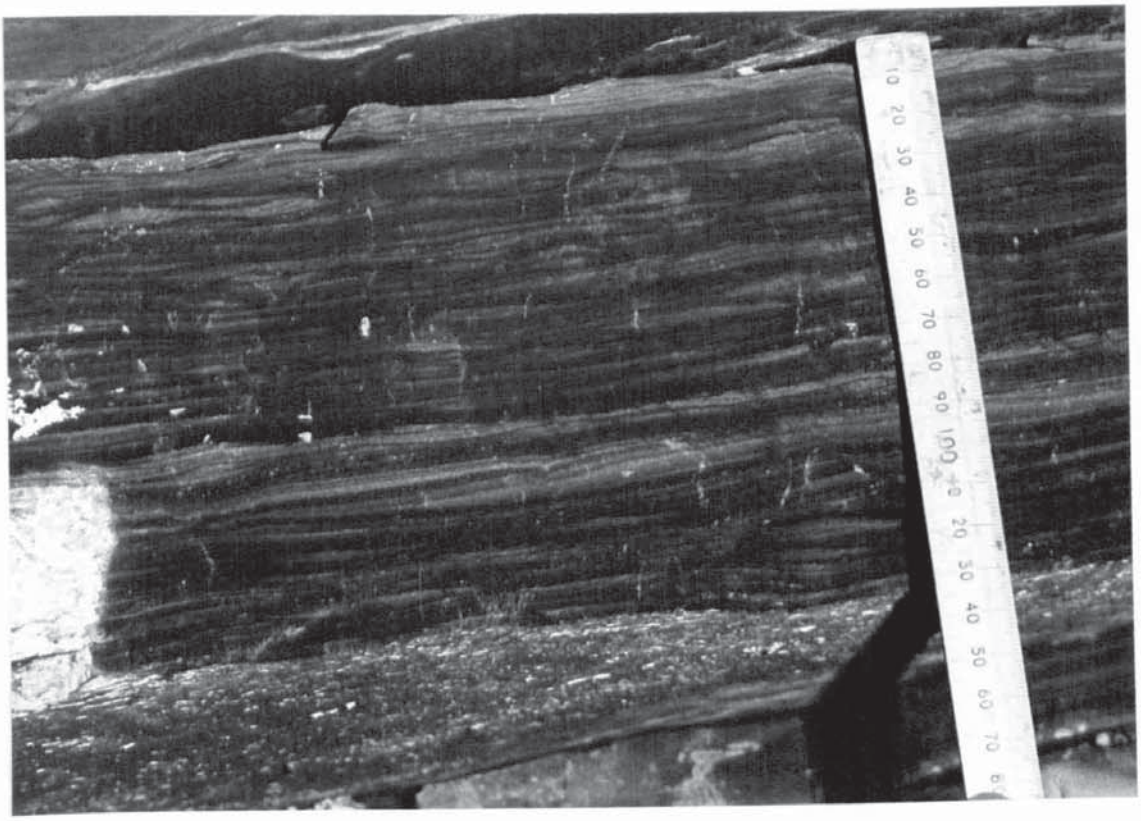


Plate 5.10 Lithofacies 3.6 Siltstone, with lenticular sandstone stratification. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B.

defined and the base may or may not be erosional. The amount of siltstone exceeds the amount of sandstone within a unit. This lithofacies is distinguished from the lithofacies 'Siltstone wavy stratified with sandstone' by its lack of connected sandstone lenses. However, there may be a continuum between the two lithofacies. This is reflected in the description of facies alternating between sandstone and mudstone given by Reineck and Wunderlich (1968 Fig.1). In this paper lenticular stratification is divided into four groups dependant on the amount of connected sandstone lenses and shape of the lenses.

This lithofacies is often underlain by 'Sandstone fine, with small scale cross lamination' and 'Sandstone fine flaser stratified' and these lithofacies together with 'Sandstone fine, wavy stratified' often overlie it.

This lithofacies may correspond to the rock sub-types 'Siltstone with erosively based sandstones lenses' and 'Siltstone with isolated sandstone lenses' of Guion (1978). Lenticular stratification was recognised by de Raaf _et al_. (1977) and divided into two groups, one of which - linsen bedding corresponds to two lithofacies in this study, Silstone with lenticular sandstone stratification and 'Silstone wavy stratified with sandstone'.

Coleman and Prior (1980, figs. 15, 18, 28, 29) found lenticular stratification in several sub-environments of the Mississippi delta including 'Crevasse splay deposits', 'Interdistributary bay deposits', 'Distal bar' and 'Predelta clays'. Coleman (1966) also found the same sedimentary structure in the lacustrine deltaic deposits of the Atchafalya basin. It was also found fairly commonly by Taylor and Woodyer (1978) in the lower bench deposits of a meandering suspended load river in Australia.

5.3.3.7 Lithofacies 3.7 (Plates 5.11 and 5.12)

Siltstone wavy stratified with sandstone, siltstone usually medium grey often coarsens upward may fine upward, often associated with parallel or undulating sandstone laminae, sandstone mini-lenses and ordinary lenses. Siderite, plant fragments and trace fossils are rare.

The sandstone is pale grey fine grained, more or less continuous horizontally but separated vertically by layers of siltstone. Although the sandstone may be homogeneous, usually internal lamination composed of carbonaceous micaceous debris or siltstone can be seen, which may form con- or discordant. Sets are up to 40mm high (small scale cross lamination), usually less than 20mm and may be symmetrical or asymmetrical. They are often grouped into cosets, usually less than 0.1m thick. The amount of sandstone in this lithofacies varies between 30-70%. Occasionally the sandstone bed is composed of ripple drifted cosets.

Units of this lithofacies are usually associated with coarser grained lithofacies including 'Breccia of plant stems' and 'Sandstone fine, with small scale cross lamination', the latter being the most commonly overlying lithofacies.

This type of stratification closely resembles the wavy bedding described by Reineck and Wunderlich (1968). It also resembles the rock sub-types 'Siltstone with irregular sandstone lenses' and 'Wavy bedded siltstone/sandstone' of Guion (1978). Coleman and Prior (1980, Figs. 15, 21, 22, 29) found wavy stratification in several sub-environments of the Mississippi delta including 'Crevasse splay deposits', 'Bay fill deposits', 'Distal bar' and 'Distributary channel fill'. Wavy lamination was observed by Taylor and Woodyer (1978) in alluvial

Plate 5.11 Lithofacies 3.7 Siltstone, wavy stratified with sandstone.
Location: Broadacres borehole
Age: mid Westphalian A.
Note that the sandstone has only poorly defined trough cross lamination.

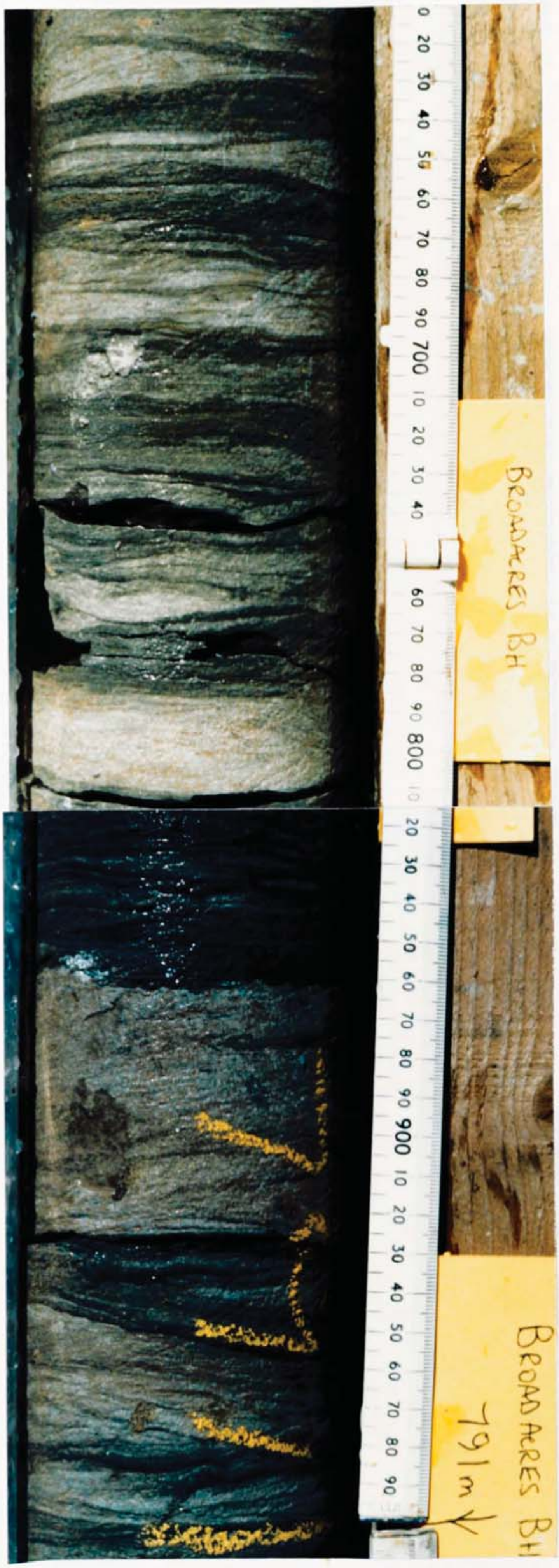


Plate 5.12 Lithofacies 3.6 Siltstone with lenticular sandstone stratification Lithofacies 3.7 Siltstone wavy stratified with sandstone

Location: Broadacres Bh.

Age: mid Westphalian B.

This example shows a transition upwards from lithofacies 3.6 to 3.7.

channel deposits towards the top of the lower bench and at the base of the middle bench of the Barwon river.

Interpretation

The process which formed the last three lithofacies is believed to be similar, in that they result in the alternation of sediment capable of being transported by lower and higher velocities.

However, Guion (1978) believed that the lithofacies 'Siltstone with sandstone mini-lenses' originated from the migration of low relief bedforms in a similar way to that demonstrated by McBride *et al.* (1975). Reineck and Singh (1980) maintain that ripples below 4.5mm in height are produced by wave action and the straight crests observed by Guion (1978) and the author suggests this as a possible origin. Singh and Wunderlich (1978) have shown that mini and millimetre ripples are produced under very shallow water or quasi-emergent conditions by oscillatory water movement. This leads to a rounding or flattening of the crests during emergence although no other signs of emergence have been observed by the author. Sandstone mini-lenses may be generated by the movement of limited supplies of sand in a similar way to that demonstrated by Mantz (1978) or possibly through wave reworking of 'Siltstone parallel laminated with sandstone' at another location. The siltstone would form as fallout from suspension during the time wave action was not operating.

With increased coarser sediment supply, isolated ripples of greater magnitude could form, which on burial would be converted to the isolated lenses found in the lithofacies 'Siltstone with lenticular sandstone stratification'. Horizontal discontinuity of lenses suggests a restricted sediment supply. Occurrence of both symmetrical and asymetrical lenses which are form discordant indicates a wave origin for at least some of these lithofacies units. The vertical discontinuity of the lenses indicates a type of pulsed activity.

One form of pulsed activity is that created by tidal processes, with wave or current action producing sand ripples and slack water resulting in deposition of fine grained sediment. Reineck and Wunderlich (1968) believed this twice daily cycle to be the mechanism for the deposition of lenticular stratification. In the tidal environment a delicate balance exists between deposition and erosion based on sediment supply and water velocities. McCave (1970) believed that only part of a mm of mud could be deposited in one tidal cycle. Terwindt and Breusers (1972, 1982) thought a layer of mud greater than 3mm thick could be a multi-event product related to a seasonal cycle between spring and neap tides. In each tidal cycle consolidated mud would not be eroded, but unconsolidated mud and sand could be reworked, depending on current velocity, and resulting in slow aggretation of mud. However, Wunderlich (1969) has shown that under certain conditions 16mm of mud accumulated as grain aggregates from 1m of water in 8 minutes at Jade Bay in the North Sea.

Apart from the presence of lithofacies which alter in grain size between coarse and fine, there is a lack of independant evidence for the presence of tidal generated deposits in the Westphalian sediments of Warwickshire. This evidence in the form of typical characteristics of tidal deposits, as outlined by Evans (1965) and de Raaf and Boersma (1971), include herringbone cross stratification, complex ripple patterns, bipolar palaeocurrent directions, marine fauna and a lack of bioturbation. Because of this, the explanation for this lithofacies must be sought elsewhere.

McCave (1970) outlined a mechanism for the formation of the inorganic sedimentary structures seen in these lithofacies involving periodic storm activity. This would allow fine sand and mud to be taken into suspension, the former also transported by traction, and the latter on return to quiescent conditions would be deposited from the viscous sub-layer, de Raaf et al. (1977) believed that lenticular and wavy stratification found in a shallow marine succession in the Lower Carboniferous of Ireland could have been formed by wave and storm activity. Coarsening upwards, observed within many lithofacies units in the Warwickshire Coalfield was commonly found by de Raaf et al. (1977), who thought it indicated a shallower depth of water with higher energy conditions.

Coleman and Gagliano (1965) believed wave action to be responsible for the lenticular lamination in the marine deltaic deposits of the Mississippi. It would be expected that the lenticular stratification found in channel deposits by Taylor and Woodyer (1978) would be of current origin and asymmetrical in shape.

Usually the sandstone lenses have non-erosive bases testifying to the low wave velocities needed to move the sandstone. Where erosive bases are seen they may be either related to a previous higher velocity scouring event or the sandstone itself may be erosive.

The process responsible for the formation of 'Siltstone wavy stratified with sandstone' is thought to be similar to that outlined for the lithofacies 'Siltstone with lenticular sandstone stratification' except that a greater amount of sand was available.

Both Taylor and Woodyer (1978) and Coleman and Gagliano (1965) attribute wavy stratification to deposition of mud over pre-existing irregularities, presumably formed by the sand bedforms.

In all three of the lithofacies the lack of plant fragments may be due to winnowing during the wave reworking of preformed deposits. Lack of trace fossils suggests an environment unfavourable to them possibly due to the continual supply of sediment within the water.

5.3.3.8 Lithofacies 3.8 (Plate 5.8)

Siltstone ripple drifted with sandstone, siltstone medium grey, sandstone fine grained, pale grey, the small scale cross laminae of which enable the characteristic preservation of the stoss slope surfaces to be identified. Plant fragments and ichnofossils are rare, and occasionally siderite is associated with the sandstone laminae. This lithofacies is distinguished from its coarser grained counterpart by the amount of siltstone (50-90%) present within it. Sandstone ripple drifted with siltstone contains less than 50% siltstone.

The angle of climb measured at successive crests points usually varies between 15-30° in the Warwickshire Coalfield. Because this is generally steeper than sets of trough cross laminated strata without stoss slope preservation, the name climbing ripple lamination has been given to this type of cross stratification by some workers (Reineck and Singh 1980). Some N.C.B geologists also use this term although it is not preferred on this study.

The term ripple drift was first used by Sorby (1859) for a form of cross lamination in which the stoss surfaces of ripple bedforms were preserved. Since then other workers have subdivided this type of cross lamination, and have even included cross lamination in which stoss surfaces are not preserved ('ripple drift cross lamination type A' of Jopling and Walker 1968, and 'type 2 climbing ripple laminae-in-drift' of Reineck and Singh 1980). It has been recognised (Allen 1984) that a series exists between cross laminae whose crest points 'drift' in the direction of the current ('ripple laminae-in-drift' of McKee 1965, and 'type B and C of Jopling and Walker 1968) and those whose laminae are super-imposed directly onto one another with a 90° angle of climb ('ripple laminae in-phase' of McKee 1965, and 'sinusoidal ripple lamination' of Jopling and Walker 1968). In this study only one lithofacies form is used to cover all types of cross lamination in which stoss surfaces are preserved. This is because of the rarity in the Warwickshire Coalfield of ripple drift with a high angle of climb, and because a series exists between low and high angles of climb.

Another inorganic sedimentary structure is sometimes associated with this lithofacies. First described by Clarke (1963) it was later named train drift by Elliott (1968) and consists of thin sandstone cross laminae between the preserved lee (foreset) laminae. These laminae are convex upward and thicken slightly towards the base. (Plate 5.8).

Rarely the bivalve escape structure <u>Pelecypodichnus</u> is found in this lithofacies.

In the Warwickshire Coalfield this lithofacies is more common than its coarser grained equivalent and is usually fairly thin (usually not more than 0.3m). Where observed underground it has a limited lateral extent (less than 10m) and passes laterally into other 'Siltstone' lithofacies including 'Siltstone parallel stratified with sandstone'. In boreholes it is commonly under and overlain by the latter and 'Siltstone with sandstone mini ripples' and 'Siltstone with lenticular sandstone stratification'.

The coarser grained equivalent has been recognised by Guion (1978) as 'fine sandstone with ripple drift' in the East Midlands

Coalfield. This inorganic sedimentary structure is most commonly observed associated with turbidites and alluvial or alluvial related deposits (Allen 1984). Coleman and Gagliano (1965) found it commonly associated with subaqueous levee deposits and Coleman and Prior (1980, Fig.21, 29, 30) observed it in 'Crevasse splay deposits', 'Distar bar deposits' and 'Distributary mouth bar deposits', all in the deposits of the Mississippi delta.

Interpretation

As already mentioned in Section 5.2.6. only when the angle of climb of sets exceeds the angle of the stoss surface can the latter be preserved. The conditions which allow this have been investigated in the laboratory by many authors. McKee (1965) produced sets with a low angle of climb by dropping sediment onto active current ripples. As part of a series of experiments Allen (1972) produced ripple drift in fine grained sand, with a nearly vertical angle of climb when tractional transport was excluded. However, at a flow velocity only slightly above the entrainment threshold of the particles, an angle of climb was achieved between that of the sinusoidal ripple drift of Jopling and Walker (1968) and nearly vertical. This is in contrast to Jopling and Walker (1968) who concluded that burial of the sinusoidal bedform by sediment from suspension occurred before any could be moved by traction. They also believed that the rate of climb was related to the ratio of suspended to traction load. Allen (1984) believed this explanation to be too generalised and determined theoretically that

$$\tan a = \frac{RH}{2J_B}$$

where a = Angle of climb

R = Net transfer of sediment from flow to the bed

H = Height of the bedform

J = Bedload transport rate

Thus where J_B is low and R is high, the angle of climb will be greatest resulting in the inorganic sedimentary structure ripple drift.

Train drift is believed to have formed by migration of small ripples up the lee slope of larger ripples (Clarke 1963) in the same way that back flow ripples form during the construction of megaripples (Boersma et al. 1968).

High rates of fallout can rapidly decrease in velocity which may explain their presence in subaqueous levees (Coleman and Gagliano, 1965). It may also be expected to occur in channels carrying a high suspended load during falling stage, but this may have a low preservation potential. Guion (1978) believed that sediment transport rates within channels would normally be too high relative to rate of sediment fallout for the formation of this lithofacies.

5.3.3.9. Lithofacies 3.10 (Plates 5.13 and 5.14 show the coarse grained equivalent).

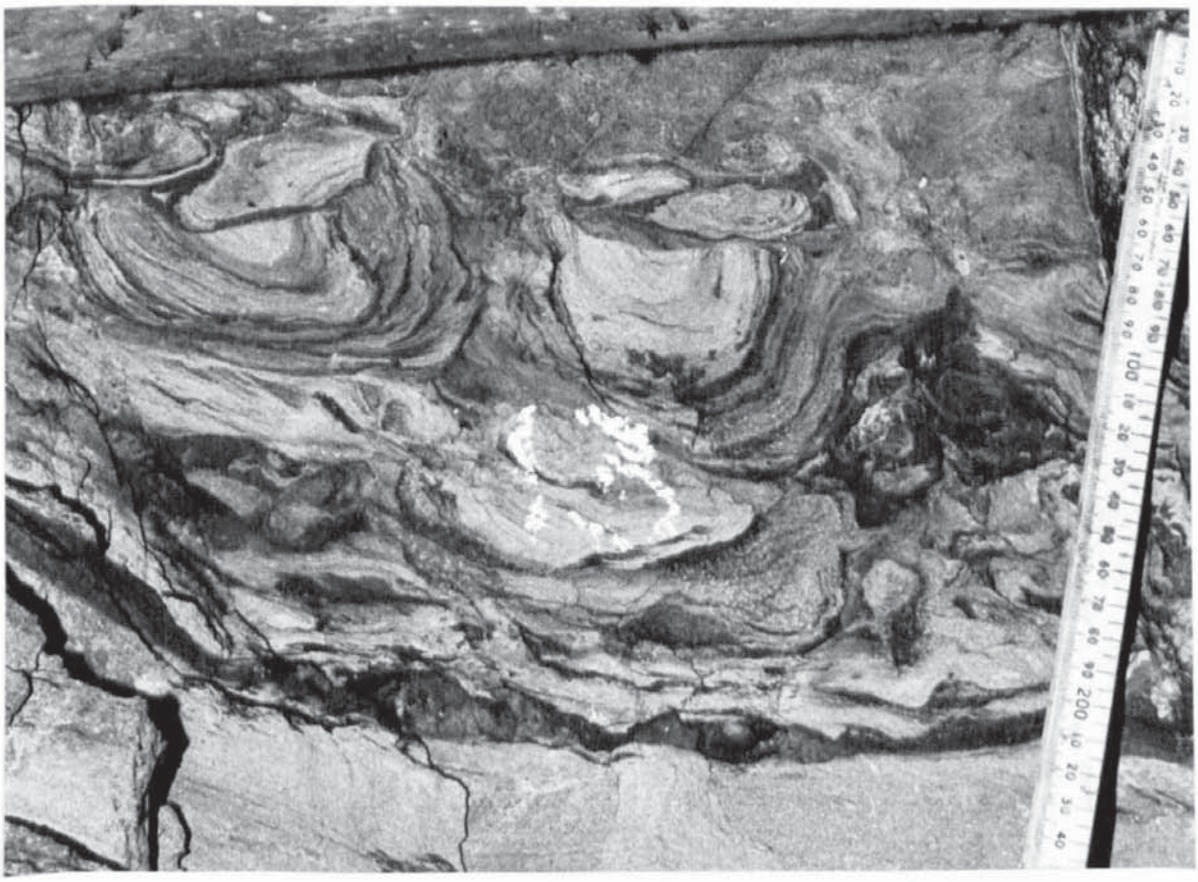
Siltstone with convolute sandstone stratification, siltstone medium grey, sandstone fine grained pale grey, both folded into a series of anticlines and synclines which are often symmetrical.

The continuity of the laminae when traced laterally is diagnostic of this lithofacies although they may alter in thickness or be truncated. Rarely small folds may be superimposed on larger ones giving a ptygmatic appearance. The folding usually becomes less intense downward and may become less intense upward or more commonly truncated. When truncated the stratification may have the appearance of U-shaped bodies separated by cusp shaped masses.

In the Warwickshire Coalfield this lithofacies occurs far less frequently than its coarser grained equivalent which is fairly common.

Plate 5.13 Lithofacies 4.9 Sandstone fine, with convolute siltstone stratification. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B

Plate 5.14 Lithofacies 4.9 Sandstone fine with convolute siltstone stratification. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B.



Its description is included here for the sake of completeness. Often it is associated with the lithofacies 'Sandstone fine with small scale cross lamination'. Convolute lamination is common in the East Midlands Coalfield (Guion 1978) and has been described from modern deltaic deposits (Coleman and Gagliano 1965) alluvial deposits (Coleman 1969), and in association with turbidites (Kuenen 1953).

5.3.3.10. Lithofacies 3.11. (Plate 5.15)

Silstone slurried, medium grey with small irregular discontinuous or diffuse laminae of sandstone or carbonaceous micaceous debris, often imparting a mottled appearance.

Superficially the lithofacies may appear massive but remnant lamination is often found on close inspection. There is no evidence of bioturbation in the form of burrows (which also may impart a mottled appearance to the rock).

In the Warwickshire Coalfield this lithofacies has a limited vertical extent usually not exceeding 0.30m. It occurs rarely as isolated beds within thick sequences dominated by 'Siltstone' lithofacies or in association with 'Siltstone or Sandstone melange'. The contact with under or overlying lithofacies may be sharp or gradational.

Although this lithofacies has been recognised in the East Midlands Coalfield (Elliott 1965a, Guion 1978) the term has been applied to homogeneous beds lacking internal stratification. This follows the original use of the term by Wood and Smith (1959) to describe structureless lithofacies of slump slurry origin in which the original bedding was destroyed. The difficulty in distinguishing a massive bed from one which has been slurried, may account for the lack of data within geological literature regarding this lithofacies.

Plate 5.15 Lithofacies 3.12 Siltstone with load structures
Location: Coventry Colliery North Rock Head. Age: Westphalian B. Irregular laminations visible at the top and a load pouch towards the base.

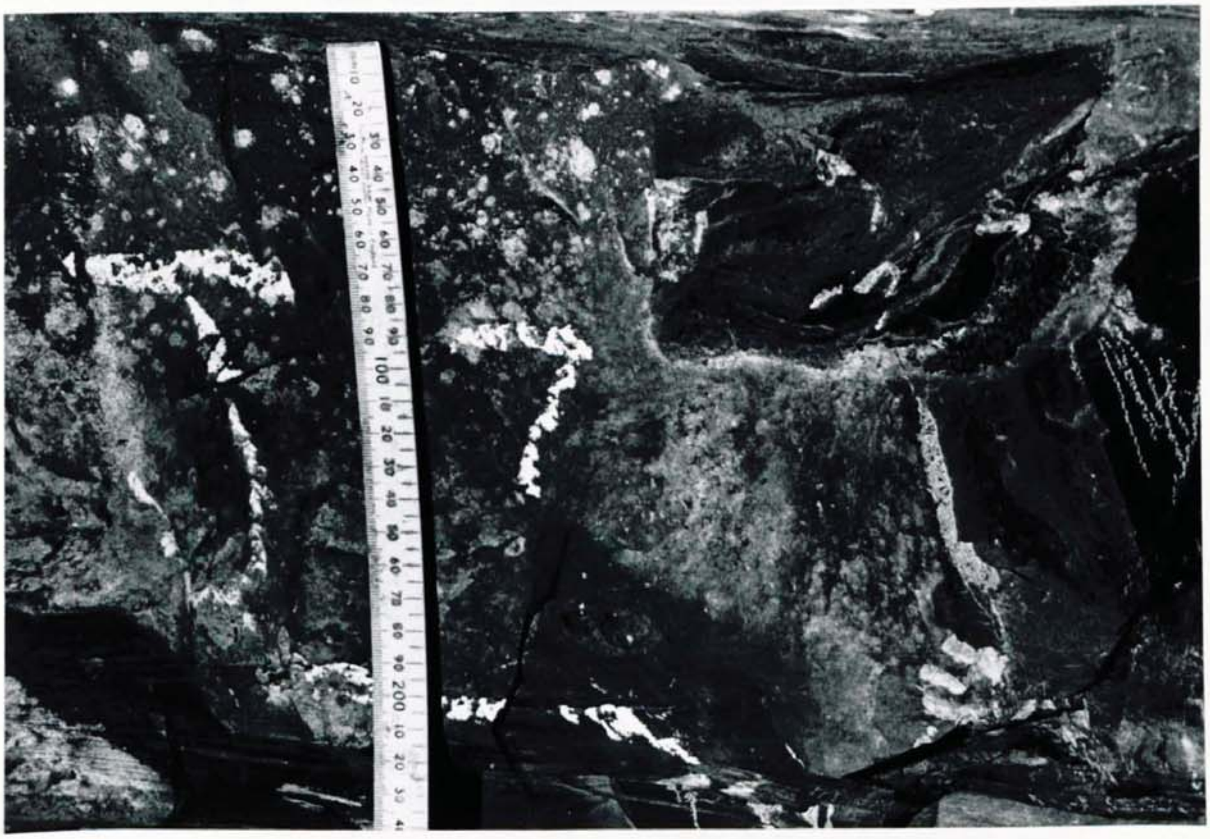


Plate 5.16 Lithofacies 3.12 Siltstone with load structures
Location: Broadacres Borehole. Age: mid Westphalian A. Basal 0.05m display this lithofacies.

5.3.3.11. Lithofacies 3.12. (Plates 5.16 and 5.17, the latter showing the coarse grained equivalent).

Siltstone with load structures, medium grey usually with fine grained pale grey sandstone occurring in lobes, elongate stringers or detached oval bodies within the siltstone.

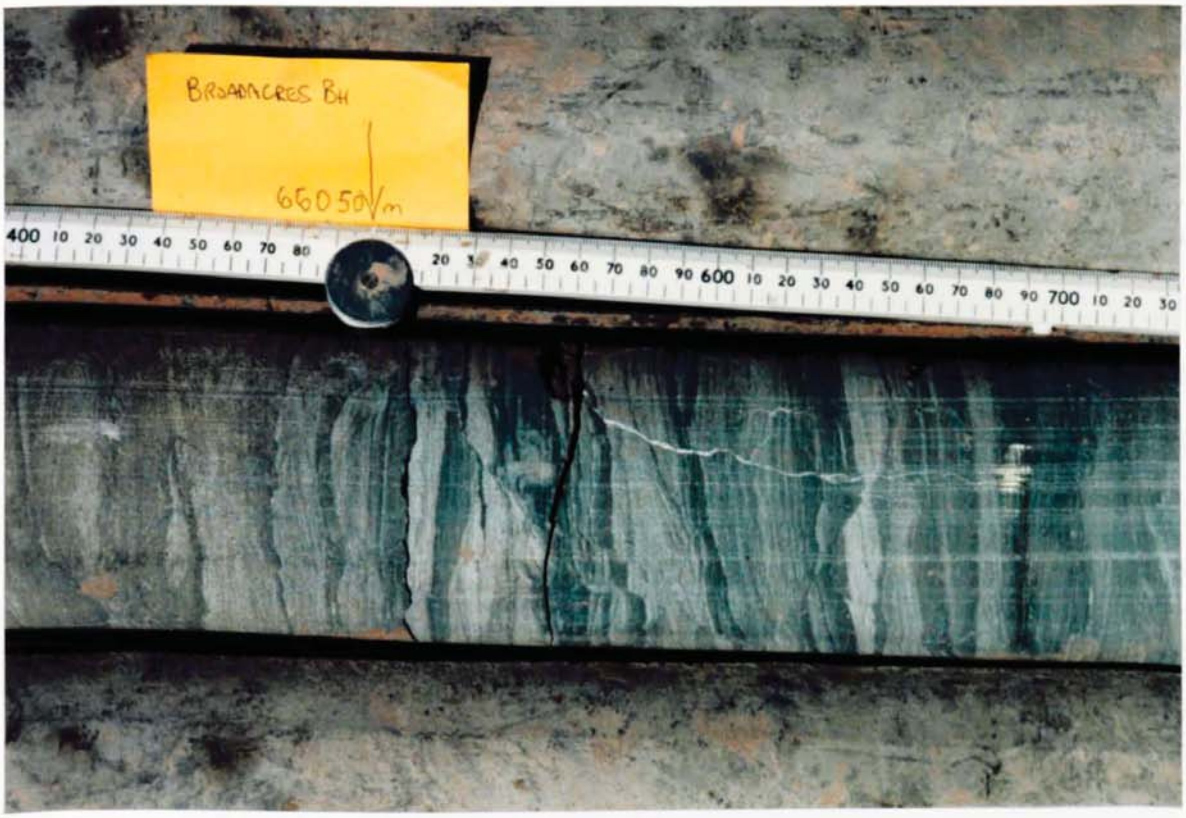
Load structures can vary considerably in shape and size. Its smaller scale form consists of thin sandstone laminae which have irregular lobed bases projecting downwards into the underlying siltstone. These would be noted in the description of the relevant lithofacies as sandstone with loaded bases. When a sandstone overlying a siltstone projects downwards on a larger scale (cm) it would be referred to this lithofacies or the term load casts (after Kuenen 1953) mentioned in the description.

This inorganic sedimentary structure was first described as Fliesswulste by Fuchs in Allen (1984) and since then many authors have given different names to characterise them, eg. load marks (Elliott 1965a), and an asymmetrical variety has been called flow casts by Prentice (1956). Between the load casts projecting upward into the sand are thin streaks of the underlying siltstone called flame structures (Kelling and Walton 1957).

Usually in association with the load masses at the sandstone/ siltstone interface are detached bodies of sandstone within the siltstone. They are variously shaped and have been termed pseudonodules by Macar (1948) and load pouches by Elliott (1965a). NCB geologists use the latter term, or detached load casts to describe this inorganic sedimentary structure which are usually less than 0.1m in diameter and have upturned laminae at their edges. The coarser grained counterpart of this lithofacies contains different inorganic

Plate 5.17 Lithofacies 4.11 Sandstone fine with load structures. Location: Broadacres Borehole. Age: low Westphalian B.

Plate 5.18 Lithofacies 3.13 Siltstone melange
Location: Broadacres Borehole. Age: Westphalian C



sedimentary structures which may be diagnostic of a different mechanism of formation.

In the Warwickshire Coalfield this lithofacies usually has a limited vertical extent (less than 0.50m) and in the few cases observed underground, eg. Coventry south roads, has a horizontal extent of less than 10m. It occurs commonly in thick sequences of siltstone associated with most 'Siltstone' lithofacies in which beds or laminae of sandstone occur. The contact with the underlying lithofacies usually reflects the primary conditions of deposition of the siltstone.

The lithofacies occurs frequently in the East Midlands Coalfield (Guion 1978) and has been found in a wide range of environments including alluvial, deltaic and lacustrine deposits but Allen (1984) believes them to be commonest in association with turbidites.

5.3.3.12. Lithofacies 3.13. (Plate 5.18)

Siltstone melange, consists dominantly of medium grey siltstone with other lithofacies in beds and blocks showing considerable deformation and faulting.

This lithofacies is commonly part of a large scale (several metres vertically and tens of metres horizontally) feature, that is characterised by a variety of inorganic sedimentary structures one or more of which may be present within it. These include folding, discontinuities in the form of block edges or faults and heteolithic texture.

The fold structures present have been given many names which fall under the general heading of contorted or distorted bedding. Most display simple folding which is often asymmetrical and more than one set of folding may be present. Elliott (1965a) in his classification of subaqueous sedimentary structures used the term crumpled bedding to distinguish V-shaped monoclinic intraformational folding from U-shaped folding which he termed corrugated bedding.

The smallest discontinuities observed in this lithofacies are microfaults or faultlets (Plate 3.13) with throws less than 0.1m, which reach a maximum in the centre and die out above and below. Large faults with throws of several metres often have planes which are concave upwards. The dip and throw of these faults decrease downwards. Both often occur in a stepped arrangement which may give rise to an imbricate structure. Faulting is often associated with folding and the term shredded bedding was used by Elliott (1965a) to describe "bedding which consists of slightly folded fragments with acute and re-entrant edges set in a matrix of minutely fragmented sediment".

Because of the faulting and folding this lithofacies is characterised by a juxtaposition of sediment of different grain sizes giving rise to a heterolithic texture.

In the Warwickshire Coalfield this lithofacies and its equivalents occur occasionally but are often many metres thick. The under and overlying lithofacies vary widely and contact between them and this lithofacies is often abrupt at the base (related to a fault plane) and gradational at the top. This lithofacies has been recognised by Guion (1978) and the inorganic sedimentary structures which comprise this lithofacies have been observed in sheet slumps in fluviatile, lacustrine and deltaic environments (Allen 1984) and in slump deposits from a distributary mouth bar in the Mississippi delta Coleman and Prior (1980, Fig.51).

Interpretation

The previous four lithofacies are believed to derive from the action of penecontemporaneous deformation which occurs during the process of deposition or shortly afterwards. Many authors have attempted classification of structures produced by this deformation on the basis of the forces which produced them (Elliott 1965a), Anketell et al. 1970, Lowe 1975, Allen 1984). These can be divided into four categories viz. 1) The force of gravity acting on unstable bulk density profiles; 2) The force of gravity acting on geometrically unstable masses of sediments; 3) The force of sediment bearing flows of water; 4) The force of non-uniform confining loads. Unfortunately this form of classification suffers from the fact that more than one category of force can act on the sediment at the same time. The type of behaviour undergone by the sediment depends on its rheological properties which are summarised in Table 5.5 (Allen, 1984 p.344).

Liquefaction is the most common alteration in physical state undergone by sediments in the Warwickshire Coalfield. It involves the support between loosely packed grains (underconsolidated, with excess pore pressure) failing under a small shear stress, resulting in them becoming fluid supported, and then consolidating again in a denser arrangement.

Other authors have used morphological characteristics to classify some of them, eg. load structures, convolute bedding etc. whilst implying origin in others, eg. slump structures (Brenchley and Newall 1977, Blatt et al. 1980, Reineck and Singh 1980). In this work classification of the lithofacies is based solely on morphological criteria and interpretation is applied afterwards.

A variety of mechanism for the production of convolute stratification have been proposed by a number of authors reviewed by Mills (1983) and Allen (1984). These vary from an almost primary depositional structure, by upward suction in the troughs of current

Table 5.5 Rheological properties of sediments (from Allen 1984) ripples (Kuenen 1953), or by fluid drag acting on alternating cohesive-cohesionless beds (Sanders, 1960); to a syn/post depositional Rayleigh-Taylor instability (Allen, 1984); or a post depositional water escape structure (Migliorini in Allen 1984). It is apparent that different mechanisms can produce convolute stratification, dependant on processes occurring in the environment of deposition. Some of these can be very specialised, eg. de Boer (1979) air entrapment in sand forming reverse density stratification in the tidal environment. Most of the processes believed to form convolute stratification involve liquefaction of the sediment (Allen 1984) and the common occurrence of symmetrical folding in the lithofacies 'Siltstone with convolute sandstone stratification' suggests the operation of near vertical forces. Mechanisms involving liquefaction and vertical forces have been put forward by Anketell et al. (1970) who emphasise reverse density gradients brought about by vertical changes in grain concentration, and Allen (1984) who believes syndepositional liquefaction can be brought about by pressure fluctuations in a turbulent current. This may explain the association of erosion surfaces truncating this lithofacies.

'Siltstone slurried' is interpreted as being the product of sediment which has been almost completely liquidized. Lack of sediment produced structures (eg. dish and pillar structures) probably means that the sediment was liquefied. Its association with melange lithofacies may mean that the force causing the liquefaction of the sediment was transmitted as a shock wave through the sediment. Alternatively it could be due to overloading of under-consolidated sediment.

The origin of load structures has been the subject of controversy for many years (reviewed by Mills 1983 and Allen 1984). Keunen (1958) produced load casts and detached load casts in the laboratory by applying a shock to a layer of sand overlying a layer of clay. Recently the most convincing process advanced by Dzulynski and Walton (1963), Dzulynski (1966), and Anketell et al (1970) has been liquefaction together with gravity induced loading in a system with a reverse density gradient. This results in a denser sand layer sinking into a less dense underconsolidated finer grained layer producing the lithofacies 'Siltstone with load structures' Anketell et al. (1970) have shown that kinematic viscosity as well as density must be taken into account and Visher and Cunningham (1981) have incorporated time into the analysis allowing a temporal and genetic interpretation of load structures.

Siltstone melange is interpreted as the product of forces producing a lateral translation of sediment. Discontinuities in the form of faults or faultlets are interpreted as post-depositional evidence of brittle failure of fairly well consolidated beds. This may result in large blocks of relatively underformed sediment becoming implaced within deformed sediment. Shredded bedding would also fall into this category (Elliott 1965a). Crumpled bedding is often associated with microfaulting but may result partly from hydroplastic deformation. This latter mechanism is also thought to be responsible for the more rounded folding seen in corrugated bedding (Elliott 1965a). In its broadest sense lateral translation of sediment can be described as slumping. Because of the large scale of this lithofacies, and the importance of relationships with other lithofacies in the understanding of its interpretation, this is best left until the appropriate section on lithofacies associations.

5.3.4. Rock Type 'Sandstone fine'

This is defined as a rock containing greater than 60% quartz with a grain size between 0.125-0.25mm. Because of this, much of the grain movement is brought about by traction producing the bedforms mentioned in section 5.3. On burial these form cross stratification providing enough silt grade for comminuted plant debris is present - otherwise they appear massive. It is possible that larger size bedforms than those mentioned in section 5.3 can produce cross stratification (Rein eck and Singh 1980 p.104-109). The most common of these in deposits of Westphalian A and B age in Warwickshire are formed by the migration of fluvial bars. In channels of high sinuosity deposition often occurs in the form of point bars by lateral accretion producing epsilon (longitudinal) cross bedding (Allen 1963b). Lithofacies of this rock type, because of its well developed cross lamination, are the best for measuring palaeocurrent direction, and are found in higher energy domains than those lithofacies previously described. Often the lithofacies have abrupt or erosive bases.

The colour of this rock type usually varies from pale grey to off-white which is related to the low organic and high quartz content. Occasionally the sandstone is green - associated with a high content of green mineral species.

Organic sedimentary structures are low in frequency consisting of occasional large plant stem body fossils, comminuted plant debris and rare Pelecypodichnus.

Occasionally siderite occurs as a cement between quartz grains, rarely it occurs as sphaerosiderite. Rarely a lithofacies unit is cemented with a translucent siliceous cement, and the term 'recrystallized' has been used to describe this by some N.C.B.

geologists. In both cases it makes the rock extremely strong - resulting in a 50% increase in uniaxial compressive strength. Jointing is usually well developed in this rock type and accounts for the bulk of water transmission within Westphalian rocks.

From a study of Westphalian A and B lithofacies of this rock type in 5 boreholes in the Warwickshire Coalfield, they most often pass upwards into lithofacies of the rock types 'Seatearth' and 'Siltstone'. Lithofacies of the rock type 'siltstone' most commonly pass upwards into lithofacies of the rock type 'Sandstone fine'.

Lithofacies of this rock type occur in a number of facies described by other workers in the Pennine Coalfields (see below).

	'Sandstone, fine' lithofacies recognised in this study,
Elliott (1868) East Midlands Coalfield	
Facies 4 'Complex silt-sandstone facies'	4.4, 4.6
Facies 5 'Layered sand-siltstone facies'	4.2
Facies 6 'Washout sandstone facies'	4.1
Facies 7 'Rippled sandstone facies'	4.5
Fielding (1984a) Durham Coalfield	
Facies 1 'Coarse grained overbank deposits'	4.5, ?4.7
Facies 3 'Proximal major crevasse splay channel'	4.1, 4.5
Facies 4 'Medial crevasse splay/minor delta'	4.2, ?4.11
Facies 5 'Distal crevasse splay/minor delta'	4.2, 4.5, 4.10
Facies 6 'Outer minor delta/overbank claystones'	4.5

As the facies of these authors are related to the enviroment of deposition they are dealt with under the heading of lithofacies associations. Many of the rock sub-types of Guion (1978) correspond with lithofacies recognised in this study and for this reason are compared under the individual lithofacies descriptions (except 'Rock-type G, Interstratified Siltstone/Sandstone - see section 5.3.2.). Only those lithofacies not previously described as finer grained equivalents under the heading rock type 'Siltstone' are described in this section (see below).

'Sandstone fine grained' lithofacies recognised in this study	Lithofacies described in this section = x
4.1 Sandstone fine, massive, pale grey to off white	x
4.2 Sandstone fine, wavy stratified	
4.3 Sandstone fine, flaser stratified	x
4.4 Sandstone fine, ripple drifted with siltstone	
4.5 Sandstone fine, with small scale cross lamination	x
4.6 Sandstone fine/siltstone with small scale cross lamination	x
4.7 Sandstone fine, parallel laminated	x
4.8 Sandstone fine, with rare clasts	x
4.9 Sandstone fine, with convolute siltstone stratification	
4.10 Sandstone fine, slurried	
4.11 Sandstone fine, with load structures	
4.12 Sandstone fine, melange	

5.3.4.1. Lithofacies 4.1 (Plate 5.20)

Sandstone, fine, massive, pale grey to off white, sometimes green, rarely with poorly defined cross stratification. The pale grey colour results from a poorly sorted sandstone containing finer grained sediment as well as organic debris. The term off white refers to a

Plate 5.19 Lithofacies 3.13 Siltstone melange.
Location: Broadacres Borehole. Age: upper Westphalian B.

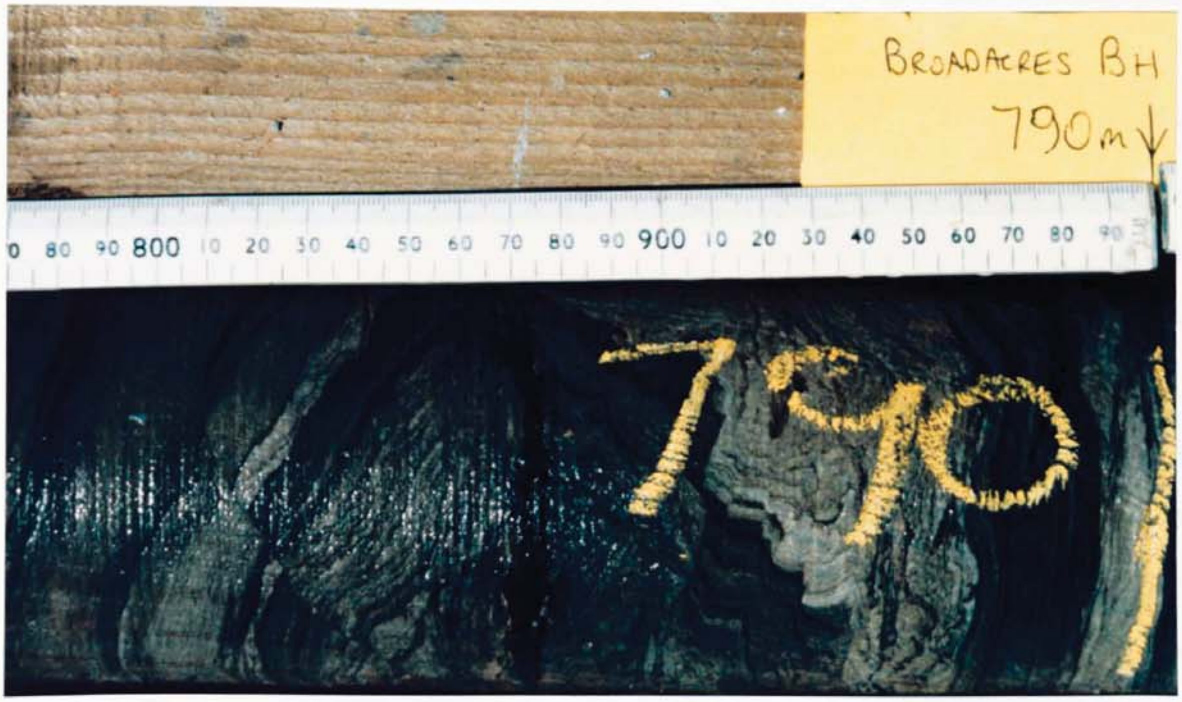


Plate 5.20 Lithofacies 4.1 Sandstone fine massive pale grey to off white. Location: Coventry Colliery North Rock Head. Age: mid Westphalian B.

white which is not pure but has a slightly grey tinge. Sometimes the matrix is sideritised, occasionally widely scattered coal lenses and plant fragments are present and often comminuted plant debris.

Its thickness varies from less than 0.1m to 4.4m which is the largest of the lithofacies examined by Markov Chain analysis whilst its lateral extent may vary from tens to hundreds of metres. It is morely likely to have a sharp (erosive or abrupt) base than a gradational (passage or abrupt passage base).

In an analysis of 5 boreholes in the Warwickshire Coalfield this lithofacies was divided into those with an erosive base and those with a non-erosive base. There was a difference in the commonest lithofacies occuring above and below those with an erosive and those with a non-erosive base. This lithofacies with an erosive base is most often underlain by the lithofacies 'Mudstone silty or siltstone' and most commonly overlain by 'Breccia plant stems'. and 'Sandstone, fine, wavy stratified'. With a non-erosive base it most commonly passes upward into the last mentioned lithofacies together with a variety of 'Mudstone silty', with 'Siltstone' and 'Seatearth' lithofacies and is commonly underlain by 'Mudstone silty or siltstone massive, medium grey' and 'Sandstone fine/siltstone with small scale cross lamination'.

Very little reference is made to massive sandstone within the literature, although it is mentioned in Reineck and Singh (1980) and from Coleman and Prior (1980, Fig. 14 and 32A) it appears to occur in 'Abandoned channel deposits' and 'Distributary mouth bar deposits'.

Interpretation (See section 5.3.4.3)

5.3.4.2. Lithofacies 4.3 (Plate 5.21)

Sandstone fine, flaser stratified, sandstone usually pale grey, small scale trough cross laminated, with base of the trough infilled

Plate 5.21 Lithofacies 4.3 Sandstone fine, flaser stratified. Location: Coventry Colliery North Rock Head. Age: upper Westphalian B.

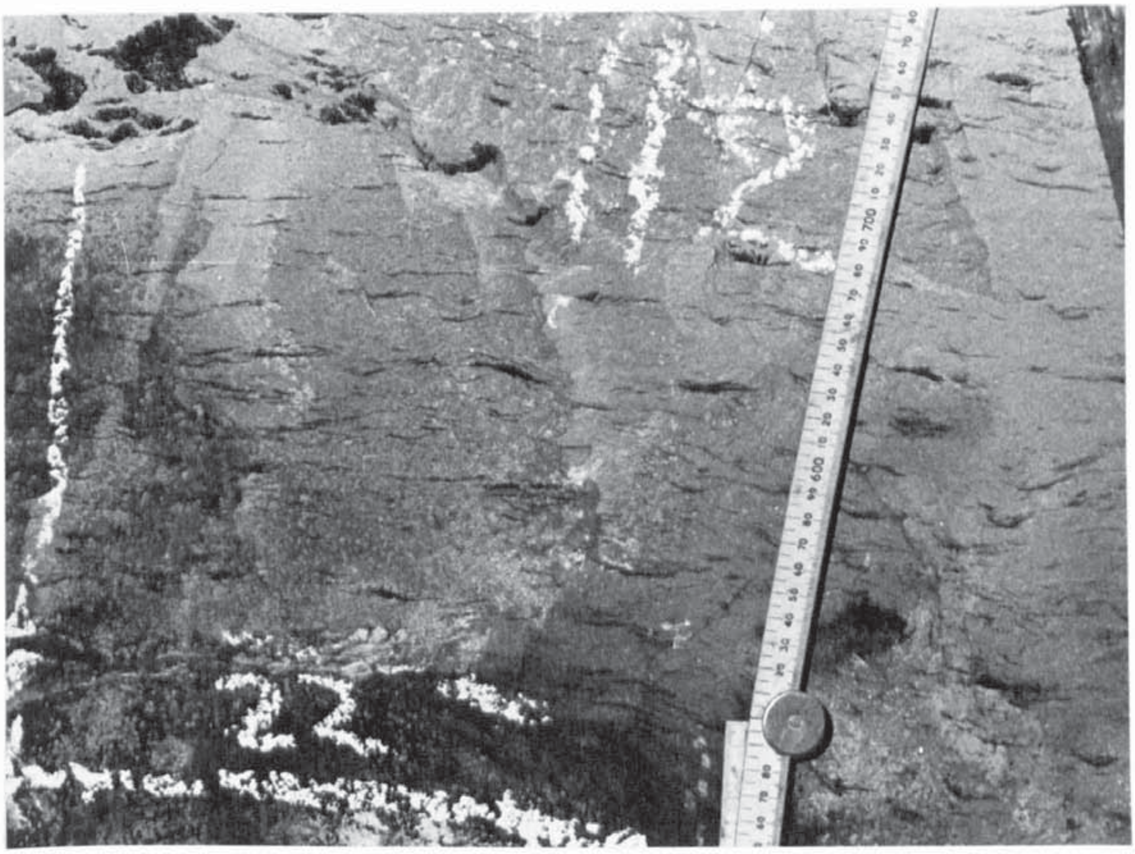
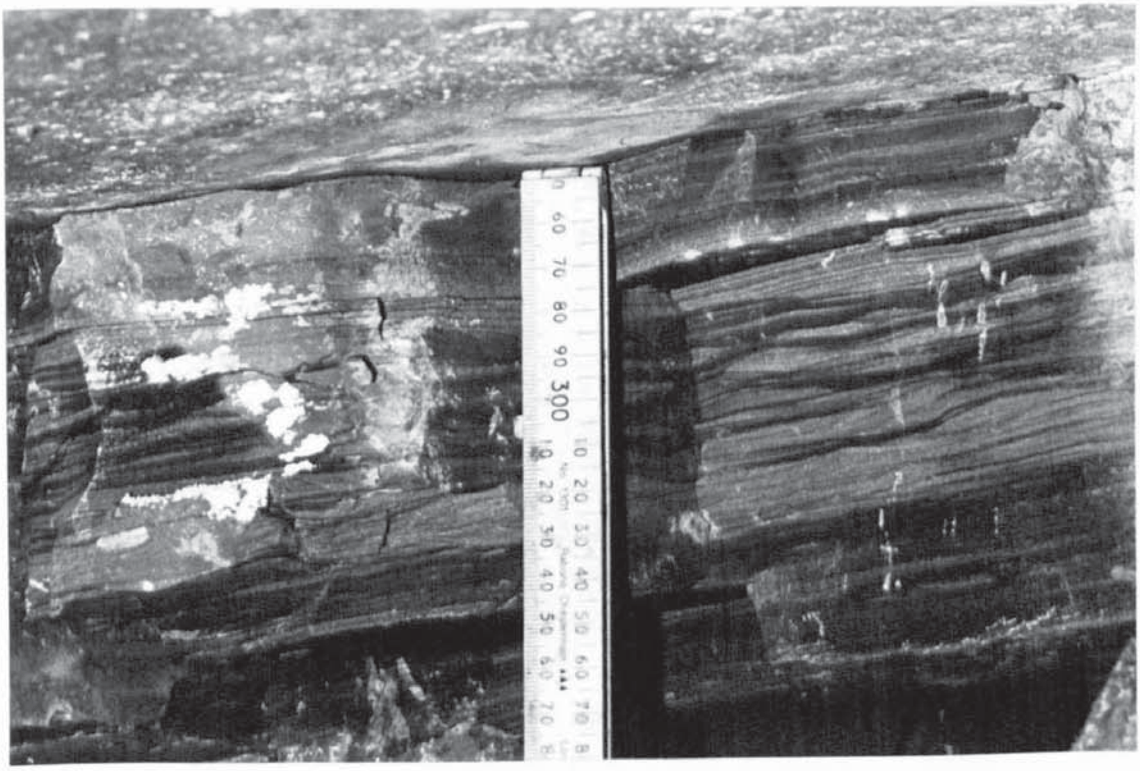


Plate 5.22 Lithofacies 4.6 sandstone fine/siltstone with small scale cross lamination. Location: Coventry Colliery North Rock Head. Age: Westphalian B.



by dark coloured fine grained sediment ranging from mudstone silty to siltstone often with carbonaceous micaceous debris. Siderite and trace fossils are rare, comminuted plant debris is common.

Normally the sandstone is asymmetrically trough cross laminated. The fine grained laminae are usually less than 3mm thick and only rarely are some of them draped over ripple crests.

This lithofacies occurs rarely in the Warwickshire Coalfield with thicknesses not exceeding 1m and gradational tops and bases. Most commonly it passes upwards into 'Siltstone or Mudstone silty parallel stratified with sandstone' as well as 'siltstone or Mudstone silty with lenticular sandstone stratification'. This latter lithofacies most commonly pass upwards into 'Sandstone fine, flaser stratified'.

Reineck and Wunderlich (1968) recognised flaser bedding in their paper on alternating fine and coarse grained sediment, although they subdivided it on the basis of whether the fine grained laminae bifurcated and/or were partially draped over ripple crests. This lithofacies has been recognised in the East Midlands Coalfield by Guion (1978), and although one of Elliot's (1968) facies is labelled 'Flaser silt-sandstone', it is clear from the description of the inorganic sedimentary structures that he is referring to lenticular or wavy stratification. Flaser bedding was identified by de Raaf et al. (1977) in a shallow marine succession as well as intertidal flats (Evans 1965), in the tidal environment (de Raaf and Boersma 1971) and in alluvial and deltaic environments (Terwindt and Breusers 1972).

Interpretation

Most of the discussion in the interpretation of the lithofacies 'Siltstone lenticular stratified with sandstone' and 'Siltstone wavy stratified with sandstone' applies to this lithofacies. Storm action

(McCave 1970, 1971, Hawley 1981) has been suggested as a mechanism for the production of flaser bedding, following flume experiments by the latter author. Terwindt and Breusers (1982) argued that flaser bedding is produced by reversing the tidal currents, and that if the mud layer was produced by settling following wave activity graded beds would result and storm activity cannot explain its wide occurrence within the tidal environment nor its systematic variation.

However as shown in section 5.3.3.7 there is no independent evidence for tidal deposits in the Warwickshire Coalfield. Stratification terms 'flaser' by a few N.C.B. geologists and consisting of micaceous carbonaceous debris perhaps mixed with siltstone, may form as a result of hydraulic sorting (see section 5.3.4.4.) and as such perhaps should not be termed flaser. Because of the paucity of this lithofacies, the majority of flaser stratified sediment in the Warwickshire Coalfield is believed to be the product of fluctuating currents, with enough time between different episodes of tractional movement to allow a small amount of fine grained material to settle in the troughs.

5.3.4.3 Lithofacies 4.5

Sandstone fine with small scale cross lamination, sandstone ususally pale grey to off white, sometimes green, with foresets picked out commonly by carbonaceous laminae composed of finely comminuted plant debris and mica. Set bases and tops are usually erosive. Sometimes the matrix is sideritised, rarely it contains small clasts.

Because the set thicknesses are normally between 5-34mm and the basal set surfaces are usually concave upward and the thickness of the foreset strata are usually less then 3mm, this type of stratification is known as small scale trough cross lamination. The minimum wavelength observed by the author is 75mm. The shape of the cross laminated sets is usually asymmetrical, although rarely symmetrical cross lamination has been observed by the author. The thickness of cosets varies from a few centimetres to several metres and may extend over tens of metres. Usually they have an erosive or abrupt base and an abrupt top.

In a similar fashion to the lithofacies 'Sandstone fine, massive, pale grey to off white' this lithofacies was divided into those with an erosive and non-erosive base when transitions between lithofacies in 5 boreholes were analysed. This lithofacies with an erosive base commonly passes upwards into a wide variety of lithofacies most commonly 'Siltstone or Mudstone silty parallel stratified with sandstone'. With a non-erosive base it similarly passes upward into a wide variety of lithofacies, most commonly 'Sandstone fine, wavy stratified' although 'Seatearth' lithofacies are well represented. The lithofacies 'Siltstone or Mudstone silty, parallel stratified with sandstone' and 'Siltstone or sandstone fine, wavy stratified' most commonly pass upwards into the lithofacies under consideration with an erosive base. In the case of this lithofacies with a non-erosive base those lithofacies most commonly passing upwards into it are 'Sandstone fine, wavy stratified with siltstone', 'Sandstone/Siltstone with small scale cross stratification' and 'Sandstone fine parallel laminated'.

This lithofacies has been recognised by Guion (1978) as the rock sub-types 'Current rippled Fine Sandstone' and 'Wave rippled Fine Sandstone in the East Midlands Coalfield. It has been recognised in a wide range of modern environments viz. alluvial - Taylor and Woodyer (1978) in 'Distributary channel fill deposits' and 'Cravasse splay deposits' within the deltaic environment- Coleman and Prior (1980

Figs. 15, 21) and lacustrine where signficiant sand bodies are deposited Forstner <u>et al</u>. (1968).

Interpretation

Both the lithofacies 'Sandstone fine, massive pale grey to off white' and 'Sandstone fine, with small scale cross stratification' are believed to have originated from a similar process. This involves the migration of ripples under sub-critical conditions and their subsequent burial to form small scale cross stratification (section 5.2.5). Also within this section are the criteria for the distinction of wave from current ripples. It has also been shown (section 5.3) that the type of three dimensional bedform produced by traditional movement depends on many variables. For the grain size of these lithofacies, the most commonly occuring bedform over a wide range of flow velocities is the current ripple.

It is probable that the difference between the two lithofacies under discussion is related to the range of grain sizes transported by the movement of water and the process operating on them during deposition as outlined by Reineck and Singh (1980). If a mix of grain sizes is present the lithofacies 'Sandstone fine, with small scale cross lamination' is produced. This is because during the construction of a bedform the stoss surface becomes enriched in finer grains due to the removal of coarser ones; whilst on the lee surface, during the continuous avalanching larger grains accummulate on the outer surface, and under the influence of gravity larger grains also become concentrated near the base. The most notable particles taking part in the sorting are finely comminuted plant debris which are dark coloured.

Where grain sizes is limited the lithofacies 'Sandstone fine, massive, pale grey to off white' is produced. This means sediment which looks homogeneous may be stratified as contested by Allen (1971) following the description of massive bedded sandstone infilling channels in the Kinderscout Grits and Grindslow Shales of North Derbyshire by Collinson (1970). Another method of forming this lithofacies may be through dumping of sediment brought about by a sudden reduction in current velocity (Reineck and Singh 1980). The latter authors and Allen (1971) recommend that the term massive should only be used where all methods (including x-rays, staining thin sections etc. fail to reveal stratification. This is impractical in the field, so in this study whilst every effort is made to discern stratification no matter how poorly defined, if it is undetectable the field term massive is used.

As might be expected those lithofacies units with erosive bases show a wide range of lithofacies passing upward into them (ranging from siltstone to sandstone) whilst those with a passage base are sand dominated and may be part of a sequence of sandstone lithofacies, or if underlain by siltstone part of a coarsening upwards sequence (see relevant section on lithofacies associations).

5.3.4.4 Lithofacies 4.6 (Plate 5.22)

Sandstone fine,/Siltstone with small scale cross laminations, sandstone pale grey to off white, sometimes green with foresets picked out by medium grey to green siltstone and micaceous carbonaceous debris. The stratification mostly consists of trough cross lamination, with sets of similar shapes and sizes to the last described lithofacies. Occasionally the sets are separated by thicker laminae of siltstone or mudstone silty usually at a high angle to the stratification of the sandstone. The difference between this and its fine equivalent is the ratio of sandstone to siltstone.

The thickness of cosets varies from a few centimetres to about 1 metre, and they invariably have an erosive base. Lithofacies which pass most commonly upwards into both the fine and coarse grained equivalents of the lithofacies under consideration are 'Siltstone or Mudstone silty, massive pale to medium grey', 'Siltstone, parallel stratified with sandstone' and 'Sandstone fine, massive pale grey to off white. This lithofacies passes upwards into a wide range of lithofacies, most commonly the last mentioned lithofacies as well as 'Sandstone fine, with small scale cross lamination' and 'Siltstone or Mudstone silty wavy stratified with sandstone'. More fine grained lithofacies are associated with the finer equivalent of this lithofacies and vice-versa.

This lithofacies may correspond to part of Guion's (1978) 'complex stratified sandstone/Siltstone' although the latter facies contains many types of inorganic sedimentary structure. It is possible that part of the photographs in Coleman and Gagliano (1965, Fig. 2) labelled "cross laminations" correspond to this lithofacies. It also appears to occur in 'Crevasse splay deposits' and 'Distributary mouth bar deposits' of the Mississippi delta (Coleman and Prior 1980, Figs. 21 and 30).

Interpretation

The formation of small scale cross lamination, mostly of the trough variety, is similar to that discussed for the previous lithofacies. This is almost always derived from asymmetrical current ripples. During construction of these ripples it is envisaged that there is a mix of grain sizes being transported, and during deposition avalanching down the lee slope of the ripple is discontinuous. Because of this sand laminae formed by tractional movement alternate with siltstone laminae formed by fallout from suspension. This type of deposition is believed to result when current velocities and sediment concentration are low (Reineck and Singh 1980). Thicker laminae of siltstone may indicate longer periods of lower current velocities.

5.3.4.5. Lithofacies 4.7 (Plate 5.23)

Sandstone fine, parallel laminated, usually with carbonaceous micaceous debris about 1mm thick, separated by less than 10mm of fine pale grey to off white sandstone. Amongst the carbonaceous debris are unidentifiable fragments of plant stems and leaves. Sometimes the sandstone laminae undulate and are truncated by gently dipping erosion surfaces. This lamination has been termed crenulate by some N.C.B. geologists because of the presence of small (less than 1mm) upward projecting cusps of carbonaceous debris.

This lithofacies occurs rarely in the Warwickshire Coalfield and is generally thin (less than 0.1m). It is invariably associated with sandstone sequences with the lithofacies 'Sandstone fine, with small scale cross lamination' commonly passing upwards into it, and the lithofacies under consideration passing upwards into the last mentioned lithofacies together with 'Mudstone silty parallel stratified with mudstone'. This lithofacies may be similar to the rock sub-type 'Fine Sandstone with plant debris' of Guion (1978, Plate 6.20) which shows a fine sandstone with gently undulating laminae picked out by micaceous carbonaceous debris.

Parallel laminated sandstone has been produced in the laboratory by a number of workers (Guy et al. 1966, Jopling 1967, Middleton and Hampton 1973 and McBride et al. 1975). It has been recognised in the alluvial (Picard and High 1973) and intertidal Wunderlich (1969) environments.

Plate 5.23 Lithofacies 4.7 Sandstone fine, parallel laminated. Location: Coventry Colliery North Rock Head. Age: Westphalian B.

Plate 5.24 Lithofacies 6.1 Conglomerate, intraformational Location: Solomons Temple Borehole. Age: lower Westphalian D. Granule and pebble size coal clasts in a course grained sandstone matrix.

This lithofacies is invariably associated with sequences of 'Sandstone' lithofacies.

Interpretation

Mention has already been made in section 5.3 of the origin of parallel laminae in sandstone. Low cuspate projections may indicate the presence of parting lineations but examination of bedding surfaces failed to reveal this structure.

It is possible that this lithofacies may have originated from the migration of long wavelength antidunes (Middleton and Hampton 1973) or under conditions arising from flow in the plane bed phase of the upper flow regime (Jopling 1967). However, the laminae observed in this lithofacies appear not to possess parting lineation, which should be present if the process mentioned above were responsible for its formation. The laminae in this lithofacies are relatively continuous, clearly defined and fairly thin, criteria which Picard and High (1973) believe are characteristic of lamination produced in the lower flow regime. Although the latter explanation for this lithofacies appears most likely, its common association with other sandstone lithofacies in the Warwickshire Coalfield and the fact that Guion (1978) found an equivalent rock sub-type commonly associated with channels, may favour formation in a higher energy domain.

5.3.4.6 Lithofacies 4.8

Sandstone fine, with rare clasts, which may be isolated within the matrix or occurring in small lenses. Clasts found in Westphalian A-C age rocks are rare and formed mainly of ironstone or sandstone usually less than 20mm in diameter. A greater variety of clasts is visible in rocks of Westphalian C and lower Westphalian D age (see coarser grained equivalent of this facies). The matrix is usually massive.

Interpretation

This lithofacies is important as an indicator of powerful currents capable of transporting large particles. It illustrates the circumstances outlined in section 5.3 that grain size may be only indicative of minimum current velocity, and that when larger particles than the matrix are available to be transported the current is capable of moving them.

5.3.5 Rock type 'Sandstone medium to coarse grained'

This is defined as a rock type containing greater than 50% quartz with a grain size between 0.25-2mm. In the field this rock type is sub-divided into medium (0.25-0.5mm) and coarse grained (0.5-2mm), to help in the identification of fining and coarsening sequences, but because they form similar lithofacies they are grouped together in this study. Frequently the lithofacies range in grain size from fine to medium grained, medium to coarse grained or coarse to granule size and occasionally from fine to coarse grained with larger clasts of various minerals and rock types. In general the better sorted lithofacies are poorly cemented whilst those which contain silt size grains may be well cemented. Sometimes secondary cementing has taken place resulting in a hard siliceous, calcite or siderite rich cement. Often this rock type occurs in beds which are massive, although micaceous carbonaceous debris is sometimes present which picks out stratification. This usually takes the form of cross bedding, although when there is a high proportion of fine grained sand, cross lamination occurs.

The colour of this rock type varies from green to pale pale grey, or off white depending on the percentage of quartz present and green coloured clay minerals. Organic content is usually low limited to carbonaceous debris and large LYCOPHYTE stems.

Jointing may be well developed varying from sub-linear to irregular with or without secondary concentration. The well developed stratification makes this an excellent rock type for determining palaeocurrent direction.

Stratigraphically there is a variation in the distribution of the lithofacies of this rock type. They are well represented in rocks of Namurian and Westphalian C/lower Westphalian D age and poorly represented in rocks of Westphalian A, B and lower Westphalian C age. From their scarcity in the latter rocks it is also probably that they are horizontally limited in extent. In rocks of upper Westphalian C/lower Westphalian D age individual lithofacies units have been observed to have limited horizontal extents of tens of metres. A similar situation may exist in rocks of Namurian age, although there is evidence that associations dominated by this rock type may extend for many km. Green coloured sandstones are only common in rocks of upper Westphalian C/lower Westphalian D age. Beds of this lithofacies usually have abrupt or erosive bases.

Lithofacies of this rock type are most commonly associated with lithofacies of the rock type 'Conglomerate' and fairly commonly associated with those of rock type 'Sandstone fine grained'.

Facies described by other workers contain lithofacies of this rock type and are best dealt with under individual lithofacies descriptions.

Four 'Sandstone medium to coarse grained' lithofacies are recognised in this study viz:

5.1 Sandstone, medium to coarse, massive.

5.2 Sandstone, medium to coarse with small scale cross stratification.

5.3 Sandstone, medium to coarse with large scale cross stratification.

5.4 Sandstone, medium to coarse with rare clasts.

5.3.5.1. Lithofacies 5.1

Sandstone, medium to coarse, massive, pale grey to off white or green. The pale grey colour results from a poorly sorted sediment containing organic debris. Occasionally the matrix is cemented secondarily in irregular patches; alternatively in quartz rich off-white sandstones there may be so little matrix that grains can be rubbed from the rock by the fingers. Sets are defined by erosion surfaces and cosets vary in thickness from 0.1-13.6m.

Apart from other lithofacies of this rock type it most often passes upwards into the lithofacies 'Sandstone, fine, massive, or with small scale cross lamination' and 'Breccia with abundant coalified stems', and the lithofacies most commonly underlying it is 'Conglomerate'.

As mentioned in section 5.3.4.1 very little reference to massive sandstone occurs within the literature.

5.3.5.2 Lithofacies 5.2

Sandstone medium to coarse with small scale cross lamination

Details of this lithofacies are similar to those given in section 5.3.4.4.

5.3.5.3 Lithofacies 5.3

Sandstone medium to coarse with large scale cross stratification, foresets are picked out by carbonaceous laminae or by thick laminae or beds of differing grain size and composition. Set thicknesses usually range from 0.1-0.3m. Normally the basal surface of sets are concave upwards and because the thickness of sets exceeds 0.04m this type of stratification is called large scale trough cross lamination or bedding. The shape of the cross sets is usually asymmetrical. Cosets may be up to 5m thick with a lateral extent of tens of metres.

This lithofacies has similar relationships with other lithofacies as described in section 5.3.5.1.

Facies similar to this lithofacies have been recognised in the Pennine Coalfield by Guion (1978) as the rock sub-type 'Cross bedded sandstone' and it occurs in Elliott's (1968) 'Washout sandstone facies' and Fielding's (1984a) 'Facies 3 - Proximal major crevasse splay channel', 'Facies 4 - Medial crevasse splay/minor delta' and 'Facies 5 - Distal crevasse, splay/minor delta'.

Taylor and Woodyer (1978) identified cross bedding in medium grained sandstone in all benches of a high sinuosity river in Australia. Trough cross bedding was also recognised in 'Distributary mouth bar deposits' (Fig. 30) of the Mississippi delta by Coleman and Prior (1980). Trough cross bedded sets between 0.3-1.0m thick occurred in braid bars of a Westphalian A low sinuosity river at Headlesscross, Scotland (Kirk 1983).

5.3.5.4 Lithofacies 5.4

Sandstone medium to coarse, with rare clasts

Details of this lithofacies are similar to those given in section 5.3.4.6. However, a greater variety of clast is visible in rocks of Westphalian C and lower Westphalian D age than those of Westphalian A-B age. In the latter mainly ironstone and sandstone clasts occur but in the former sedimentary clasts include those of mudstone, siltstone, calcareous sandstone and coal. They commonly range in size from 20-25mm in diameter, with occasional larger clasts in rocks of Westphalian C/D age. The matrix may be massive or cross stratified.

Interpretation

The lithofacies 'Sandstone medium to coarse with small scale cross lamination' is believed to have formed in a similar way to its fine grained counterpart (section 5.3.4.4). Ripples can be produced by a range of grain sizes dependant on other physical variables (section 5.3).

Both the lithofacies 'Sandstone medium to coarse grained, massive' and 'Sandstone medium to coarse grained with large scale cross stratification' are considered to have formed in a similar manner. This involves the migration of dune size bedforms under sub-critical conditions and their subsequent burial. The fact that many cross bedded sets are grouped together in festoon like shape excludes mechanisms for their formation such as microdeltas, cut and fill (McKee 1957) and channel fill (Harms and Fahnstock 1965). In a similar way to their fine grained counterparts the difference between the two lithofacies is related to the range of grain sizes which are transported (section 5.3.4.3). The examples of cross bedding cited by various authors in the previous sections occur mainly within channels, and this is believe to be the case for these lithofacies in the Warwickshire Coalfield.

5.3.6 Rock type 'Conglomerate'

This is defined as a rock type containing rounded clasts, implying more transport than the other rudaceous rock type (breccia) recognised in this study. The clasts commonly range in size from 4-100mm although rarely large clasts are observed. Various grades of sand size particles usually form the matrix. Two types of conglomerate are recognised dependant on the origin of the clasts viz:

6.1 Conglomerate, intraformational

6.2 Conglomerate, extraformational

5.3.6.1 Lithofacies 6.1 (Plates 5.24 and 5.25)

Conglomerate, intraformational, consisting of rounded clasts of rock types resistant to fluvial mechanical abrasion eg. sandstone and

Plate 5.25 Lithofacies 6.1 Conglomerate, intraformational
Lithofacies 7.1 Breccia, intraformational
Location: Broadacres Bh.
Age: Westphalian B
At the base is lithofacies 7.1 with irregular sideritised mudstone clasts. Above cobble size sandstone clasts occur in a medium grained sandstone matrix.

siltstone in a matrix of sandstone. The former rock types (especially those with a siliceous or sideritic cement) usually constitute the larger clasts whilst the smaller clasts may consist of siderite or coal pebbles 5-25mm in diameter. Usually this lithofacies is polymictic, polymodal and matrix supported. The proportion of clasts ranges from about 15-50% and would be described by Greensmith (1978) as a paraconglomerate (greater than 15% matrix).

In most cases the beds appear massive, the only ordering of pebbles occurring where discoidal clasts are orientated parallel to bedding. Because of this stratigraphic bias in distribution of coarse grained rocks, this lithofacies is most common in rocks of Namurian and lower Westphalian D age, where they may form up to 10% of coarse grained sediments. In rocks of other ages in the Warwickshire Coalfield the volumetric percentage is very small. Usually the beds are thin, less than 0.5m. It is probable that they only have a limited lateral extent. Normally the base of the beds are erosive and they pass up gradually into a lithofacies with a similar grain size to the matrix.

Elliott (1968) mentioned the occurrence of conglomerate within his 'Washout facies', whilst Guion (1978) distinguished three subtypes of intraformational conglomerate depending on the dominant clast type viz: 'Intraformational conglomerate', 'Coal clast conglomerate' and 'Ironstone clast conglomerate'. Because of the rarity of this lithofacies and its similar lithological interpretation these are grouped together within this study. Haszeldine (1981) described a very thick (3m) Westphalian B intraformational conglomerate with angular siltstone and rounded ironstone clasts, matrix supported by sandstone, with an erosive base. Conglomerates in the Old Red Sandstone have been described by Allen (1962) and Bluck (1967), whilst modern examples occur in both meandering (Bluck 1971) and braided alluvial deposits (Bluck 1979) as well as alluvial fans and fan deltas (Rachocki 1981).

5.3.6.2 Lithofacies 6.2 (Plate 5.26 and 5.27)

Conglomerate, extraformational, consisting of clasts of no-sedimentary origin - quartzites, vein quartz, jasper, and various pale buff and orange acid igneous and dark green basic igneous rocks. They range in size from 10-15mm in diameter and usually form a bimoidal, polymictic matrix supported lithofacies. The matrix is sandstone and it forms up to 85% of the unit which usually have erosive bases.

This lithofacies has only been observed in rocks of Westphalian C and D age in the Warwickshire Coalfield. Guion (1978) recognised a similar lithofacies which was rare within the Westphalian of the East Midlands Coalfield.

Interpretation

The majority of conglomerates found in the Silesian rocks of the Warwickshire Coalfield contain clasts of sedimentary rocks which are believed to have formed by the contemporaneous erosion and deposition of beds of sediment recently previously deposited, and can thus be described as intraformational (Whitten and Brooks 1972). Non-sedimentary clasts in extraformational conglomerates are derived from much older rocks through which the alluvial channels flowed. These were carried downstream to be deposited by distributary channels in the Pennine basin.

The association of conglomerates with coarse grained lithofacies and the common presence of erosion surfaces suggests that these lithofacies were deposited within the channels. These lithofacies are

Plate 5.26 Lithofacies 6.2
Conglomerate
extraformational
Location: Solomons Temple
borehole
Age: Westphalian D

interpreted as forming during periods of maximum current velocity, when smaller particles would be removed by winnowing and the larger pebbles moved by traction, to be deposited in thin layers onto a newly created erosion surface. The small percentage of conglomerate present and the absence of cross bedding suggests they were not the deposits of channels regularly carrying particles of this size. Lack of correlation (qualitatively) between bed thickness and particle size suggest reworking, although the typical lag conglomerate would be clast supported (Bluck 1967). Lag conglomerates were believed by the latter author to have been produced by a change from a braided to meandering stream during low stage flow. Clast and grain size of matrix of these lithofacies are consistent with Bluck's (1967) 'Type C Braided stream' conglomerate but lack of cross bedding and thinness of beds is consistent with 'Type D (floodpath) river channel' conglomerate.

During the Namurian and Westphalian A and B either the ultimate sediment source was at a great distance from the Warwickshire Coalfield or currents were insufficient to carry extraformational clasts into this part of the basin, hence the dominance of intraformational conglomerate. Even when these conditions changed during Westphalian C extraformational conglomerates are rare.

5.3.7 Rock type 'Breccia'

This is defined as a rock type containing angular clasts, with particular emphasis in this study on their local derivation. The clasts vary in composition from irregular inorganic mudstone, siltstone and sandstone to organic plant remains and a large range of clast size can be found. In Westphalian A and B conglomerates in Warwickshire the clasts are invariably rounded and tend towards the spherical because of the long time spent in transit. The angularity and shape of inorganic clasts in breccias are dependant upon inherent geomechanical properties of the donor lithofacies. Laminated strong lithofacies eg. sandstone tend to produce lath shaped clasts in cross section, in contrast to laminated weak mudstones produce discs. The rock type breccia has been divided into intra- and extraformational lithofacies in a similar manner to that of conglomerate. An additional organic rich lithofacies is also described (see below).

7.1 Breccia, intraformational

7.2 Breccia, extraformational

7.3 Breccia of plant stems

5.3.7.1 Lithofacies 7.1 (Plate 5.25)

Breccia, intraformational, consisting of angular clasts of any of the main rock forming lithofacies previously described in a matrix usually of sandstone. The most commonly occurring clasts are of mudstone, producing an oligomictic, bimodal, matrix supported breccia. This lithofacies is very rare within the Warwickshire Coalfield and where it occurs the beds are thin - less than 0.1m. Normally the base of these beds is erosional and they pass upwards into lithofacies with a similar grain size to the matrix.

5.3.7.2 Lithofacies 7.2

Breccia, extraformational, oligomictic, consisting of disc shaped clasts of pale green, grey and black Upper Cambrian mudstones usually set in a mudstone matrix although siltstone and sandstone matrixes do occur. The size of clasts often range between 4-60mm although occasionally clasts up to 90mm in diameter are present, with thickness from a few mm to 10mm. They form between 10-70% of any unit which are often matrix supported and usually biomodal. The only imbrication present consists of the clasts lying parallel to bedding. Sometimes broken plant stems or fronds are incorporated into the breccia. The thickness of units varies from less than 5cm to 0.8cm and most have erosive bases. Often they pass upwards or become interbedded with lithofacies of the same grain size as the matrix.

This lithofacies occurs at two specific stratigraphic horizons in the Warwickshire Coalfield viz. the base of the Carboniferous and in rocks of Westphalian C age.

5.3.7.3 Lithofacies 7.3 (Plate 5.28)

Breccia of plant stems, consisting of high numbers of large plant stems which are often coalified LYCOPHYTES and SPHENOPHYTES, although sometimes casts of Calamites may also be present. They are usually flattened parallel to bedding with or without their centres filled with matrix. Frequently the stems are orientated. The matrix is usually sandstone and may vary from fine to coarse grained sometimes with erosive bases.

'Sandstone fine, massive pale grey to off white' and 'Siltstone with wavy stratification' are the two lithofacies which most commonly pass upwards into this lithofacies. It most commonly passes upwards into the latter two lithofacies. This lithofacies has been recognised in the East Midlands Coalfield by Guion (1978) and in the South Wales Coalfield by Bluck and Kelling (1963).

Interpretation

In this study emphasis is placed on the local derivation of the clasts which are speedily buried allowing their preservation. The rarity of the lithofacies 'Breccia intraformational' suggests that during normal Coal Measure sedimentation once the donor materials enter the transport medium the weaker rock types disintegrate, whilst

Plate 5.27 Lithofacies 6.2 Conglomerate extraformational. Location: Rookery Farm Borehole. Age: Westphalian C.

Plate 5.28 Lithofacies 7.3 Breccia of plant stems. Location: Rookery Farm Borehole. Age: Westphalian C.

the stronger rock types are abraided to form rounded clasts through intermittent revolving. (These could then go on to form lithofacies of the rock type conglomerate).

The lithofacies 'Breccia extraformational' may indicate a special combination of circumstances within the basin of deposition in Warwickshire, in which a local source of sediment is more important than the regional source. This is emphasised when both the clasts and matrix are formed of similar mudstone. These circumstances can arise when deposition takes place on an older land surface (at the base of the Carboniferous) or when a newly uplifted area creates a local source of sediment (rocks of Westphalian C age). The discoidal shape of the mudstone clasts suggest some abrasion, and the mudstone matrix which often supports the clasts indicates that it was primary. It is possible that some of the deposits were produced by conditions similar to those which are found in alluvial fans. The horizontal bedding of the clasts suggests that the transporting medium was not viscous enough to produce a random orientation of clasts as with normal debris flows (Larsen and Steel 1978), although fragments aligned parallel to the flow surface have occasionally been recognised in debris flow (Fisher 1971). Similarly debris flows are not expected to have erosive bases unless currents are very strong (Beaty 1974). In most cases this lithofacies is interpreted as a waterlain deposit. In those cases where this lithofacies forms part of an alluvial fan deposit this would fit into an analysis by Blissenbach (1954) who believed that in areas where annual rainfall exceeded 47cm, 90-95% of the alluvial fan deposits are waterlain.

The lithofacies 'Breccia of plant stems' is believed to have formed following the waterlogging and sinking of large plant stems and their speedy incorporation into the accummulating sediment (Scheihing and Pffeferkorn 1984). It is difficult to estimate the time required for waterlogging to take place, but the lack of hard wood and presence of an easily removed central pith suggests that this may be quicker than many modern tree species. In cases where the stems are in contact it is possible that reworking has resulted in their concentration, especially those deposited on an erosive base. It is probable that in some cases the alignment of stems is parallel to flow direction (Bluck and Kelling 1963).

5.3.8 Palaeosols

The purpose of this introduction to palaeosols studied mainly in Westphalian A and B sediments in the Westphalian Coalfield is to discuss their definition, recognition and classification within this study by comparing them to modern soils.

Vast literature exists concerning the study of modern soils principally because of their importance to man, both in agriculture and engineering. Palaeosols have been less intensively studied and even their definition has been the subject of confusion and controversy (Ruellan 1971). The broad definition of the term palaeosol given in section 5.2.9.2 by Retallack (1981) is intended to include both subaqueous and subaerial sediment. Its recognition within this study is important because of both its environmental significance, particularly the length of time required to form these sediments. Buried fossil soils of Westphalian age are definitely palaeosols, and they may contain elements of relict soils (indicating polyphase soil development) and pedoliths (formed by the deposition of previously eroded modern or ancient soils with retention of their original properties) all three of which have been defined as palaeosols

(Gerasimov 1971). The definition of soil given Retallack (1981) is different from that of Bridges (1978) who differentiated soil from weathered mantle (regolith) by virtue of the former's development of a profile containing various horizons. This is not believed by the author to be a reliable basis for the recognition of Westphalian palaeosols because some modern soils have very poorly defined horizons. It is expected that any sediment which has a water level standing just above its surface, or a water table just below its surface would be able to support plant life. Thus palaeosols in this study are defined as lithofacies formed by either sediment which once lay just below the air/water interface and was modified by root action and attendant chemical changes, or sediment with a water table just below its surface which was modified by physical and chemical weathering and the action of organisms.

Although their lithofacies may be closely genetically related (see relevant lithofacies associations), two major categories of Westphalian palaeosol are recognised within this study dependant on their composition viz.

1) Siliciclastic palaeosols which are mineral rich and have been subdivided into two rock types - 'Seatearth' and 'Subseatearth'.
2) Floriclastic palaeosols which are organic rich and form the rock type 'Coal'. The division between coal and other rock types is arbitrary and dependant on ash content (NCB 1972) on an air dried basis ie. coal should not exceed 40% ash by weight.

Siliciclastic palaeosols differ from previous rock types in that many of them are formed from pre-existing lithofacies and so can be regarded as two stage products. Floriclastic palaeosols are believed to be derived mostly from in-situ accummulation of degraded plant material.

The recognition of siliciclastic palaeosol lithofacies is dependant, like previously described lithofacies, on a number of morphological characteristics developed during their formation. Because the processes leading to their development are different from those found in previous lithofacies (the principles for which were outlined in section 5.3) it is felt that an outline of modern soil forming processes and the environmental factors affecting them is required.

5.3.8.1 Environmental factors affecting soil processes

These factors were originally expressed by Dokuchaev and Hildegard and expanded by Jenny (1941, 1946), Stephens (1947) and Young (1976) to seven viz.

1. Climate
2. Topography
3. Parent material
4. Hydrology
5. Organisms
6. Time
7. Man

Hopefully the influence of the last of these factors can be eliminated from the study of Westphalian palaeosols leaving six factors to be discussed. Although the effect of one or more of these factors may outweigh others (and thus give some independancy to the factors) they are interdependant.

1) Climate

The climate during the deposition of Westphalian A and B sediments is believed to have been tropical - pure equatorial within the depositional area of the Warwickshire Coalfield. In general increase in temperature results in increased rate of chemical activity promoting weathering (Bridges 1978), increase in redness of sediment (Birkeland 1974) and a decrease in organic matter and nitrogen content near the soil surface. Precipitation as part of the water balance (evaporation/transpiration/surface run off/soil retention) is important for the growth and preservation of peat forming plants, and in the process of leaching. Leaching was probably more important in the sediment source area, which may have had a different climate to that in the Warwickshire Coalfield. Precipitation may have been more important in controlling the accummulation of peat.

2) Topography

Relief on the earth's surface can be divided into five different scales depending on their areal magnitude (Young 1976) viz. major relief units 10^2 to 10^3km (sub continental scale), relief units 20 to 2 x 12^2km, landforms 0.1-5km, slopes 0.1-2km and slope units which are divisions of individual slopes. The relief unit (of which the Warwickshire Coalfield is a part) which formed the environment of deposition for Westphalian sediments is believed to have been a flat delta plain. One of the greatest influences of topography (apart from the influence on climate) is the effect on drainage which increases up-slope, producing different soil types from the top of the slope (an interfluve crest or hill summit) to the valley floor (Young 1976). This series is called a soil catena and was originally defined by

Milne (1935) as "a regular repetition of a certain sequence of soil profiles in association with a certain topography".

3) Parent material

In the active depositional enviroment envisaged for the Warwickshire Coalfield in Westphalian times, the parent material for siliciclastic soil production was relatively unconsolidated sediment, which would need no weathering before soil formation could proceed. Lithofacies analysis shows that Westphalian depositional processes led to rapid lateral variation in sediment grain size from clay to sand and this was reflected in siliciclastic palaeosol lithofacies, although between channels a higher proportion of fine grained sediment is likely to exist.

For siliciclastic palaeosols the grain size determines the texture of the soil, which in turn for fine grained sediment leads to a relative increase in organic matter, cation exchange rate, clay translocation and soil moisture, and a decrease in depth of leaching. Soil moisture retention (smr) is related to parent material and is an important property which affects plant growth. It combines field capacity (fc) - moisture retained by the soil after drainage of water by gravity, wilting point (wp) - moisture content at which plants wilt to the point of non-recovery and available water capacity in the formula smr = fc - wp x depth of soil.

Floriclastic palaeosols are derived from the remains of plants growing on the surface of siliciclastic palaeosols.

4) Hydrology

The low lying nature of the Westphalian depositional setting had an important effect on the hydrology. Distributary channels carried the main volume of water but were subject to periodic high stage flow which caused overbank flooding over large areas of the delta plain resulting in either a standing water level or water table near the sediment surface. Thus many of the soils formed at this time were frequently or permanently waterlogged and the effect of this factor on soil formation may have been more important than any other environmental factor (Young 1976). Of the seven drainage classes interpreted by Young (1976) from the FAO manual the three wettest are probably most important in soil formation during the Westphalian sediments in this study ranging from 'Very poorly drained' where water table remains at or above the sediment surface for much of the year to 'Imperfectly drained' where the soil is waterlogged for significant periods and mottled B horizons are produced.

5) Organisms

Vegetation is the most visually conspicuous biological component to affect soil development. Through its accummulation an organic rich layer can form at the surface which if preserved leads to the formation of the rock type 'Coal'. Woody plants are known to contribute most volumetrically to modern tropical peats because of their resistance to decomposition (Young 1976). During the Westphalian it has been shown by Philips and DiMichele (1981) that the LYCOPHYTES with their relatively large amounts of xylem contributed significantly to peat deposits. Apart from plants affecting climate at soil level their living roots penetrate the sediment to alter it physically, and the accummulation of peat modifies the sediment chemically. Other organisms which may have been important during the formation of Westphalian A and B palaeosols in Warwickshire are decomposers. These include microbes which may decompose a large percentage of any peat accummulation (Moore and Bellamy 1974) and others which may have contributed to the homogenisation of siliciclastic sediment.

6) Time

Time is one of the most important factors in soil development, because without it an immature soil forms with most of the characteristics of the parent material preserved and without clear horizonation. Thus one of the means of identifying a palaeosol is lost. Unfortunately little is known about absolute rates of modern soil formation in the tropics (Young 1976), although organic rich horizons in other areas are known to reach a steady state more rapidly than others (10^2 to 3 x 10^3 years in the USA) when compared with the development of B horizons which may take 10^3 x 10^4 years (Birkeland 1974). In the active depositional environment envisaged for the palaeosols in this study siliciclastic palaeosol formation may have been sporadic, often being terminated by a new influx of sediment. Where both the interval between successive influxes of sediment and their thickness are small, soil forming processes in the top palaeosol may penetrate and interfere with the lower one leading to a polygenetic palaeosol. Alternatively the time taken to produce a palaeosol may be so great that the factors under which it was forming at its commenc~~e~~ment eg. hydrology may change, leading to a polyphase palaeosol which contains relict characteristics of the previously forming palaeosol. The surface at the top of a siliciclastic palaeosol lithofacies unit may represent a widely variable hiatus in sedimentation. This may be reflected within the underlying unit.

5.3.8.2 Soil forming processes and their products

Soil forming processes lead to the formation of different textural features which define soil horizons. Their potential for preservation in palaeosols is variable as is their distinction from similar features which may be of diagenetic origin and unrelated to pedogenesis. To some extent soil formation can be considered diagenetic in that it takes place below the sediment surface, but in order to distinguish those early diagenetic features of pedogenesis from other later diagenetic products the mechanics of modern soil formation must be analysed together with their products.

Soil forming processes are brought about as a result of a number of chemical and physical actions taking place within the soil. Those simple processes are outlined below and discussed in Birkeland (1974) and Young (1976). In Westphalian A and B palaeosols it is believed that chemical processes and translocation in solution are more important than translocation in suspension. Leaching involves the removal of soluble constituents from sediments and is dependant on Eh/pH values. Salts such as chlorides and sulphates, and bases such as calcium, magnesium, potassium and sodium are highly soluble, whilst aluminium and quartz are relatively immobile, the former being soluble below a pH of 4.5 and the latter only in very alkaline conditions. The solubility of carbonate is increased with a decrease in pH and temperature and increase in carbon dioxide in the soil voids. Silica has a low but constant solubility in the pH range 3.5-8.0. The solubility of iron depends upon the Eh, so that in its reduced condition ferrous ions are fairly mobile, whilst its oxidised ferric counterpart is not. Precipitation results from a reversal of the conditions which led to the initial leaching, and this may be at some distance horizontally or vertically from the site of the original leaching. In this way clay minerals may be synthesized and this is important in the composite process of gleying which occurs in many Westphalian A and B palaeosols. Eluviation is defined as the removal in suspension of finely dispersed organic matter and clay particles from the upper eluvial part of a soil and illuviation involves their deposition at some distance below as clay skins (cutans or gleyans). Both leaching/precipitation and eluviation/illuviation are promoted in freely draining soils and are thus less important in many Westphalian A and B palaeosols in this study which were poorly drained.

Composite soil forming processes involve the combination of several simple processes. These are listed below together with a brief explanation of the process involved.

1) Peatification - chemical and microbial changes taking place up to 10m below the surface of the peat
2) Ripening - draining of excess water from clay together with oxidation of organic matter and iron compounds
3) Gleying - under anaerobic conditions iron compounds are reduced, and mobilised resulting in their removal and possible concentration at depth. If oxidation takes place ferric red iron mottles may be produced.
4) Solodization - removal of sodium ions from the clay humus complex and their replacement with hydrogen resulting in an acid soil.
5) Solonization - also called alkalization, it occurs when slight leaching removes the soluble salts the more insoluble of which precipitate leaving sodium ions to attach themselves to the clay humus complex.

6) Podzolization - removal of silica, aluminium and iron as organic complexes by the percolation of humic acids and their deposition at a lower horizon.

7) Salinization - enrichment of soil with salt which is drawn to the surface by capilliary action and deposited.

8) Calcification - weak leaching results in the translocation of carbonates from upper to lower horizons.

9) Ferrugination - complete leaching of soluble salts and carbonates, moderate leaching of bases and partial leaching of silica. Hydrated ferric oxides are dehydrated to give haematitic coatings (rubefaction).

10) Ferrallitization - complete breakdown of all minerals except quartz and including partial leaching of iron and aluminium oxides.

Various environmental factors together with soil forming processes give rise to modern soil textures for which Brewer (1964) has produced a ranked system of description based on size and organisation of soil features viz.

1) <u>Peds</u> - "individual natural soil aggregates consisting of clusters of primary particles and separated from adjoining peds by surfaces of weakness" (Sleeman 1963), the surfaces of weakness may be voids or planes created by illuviated clay particles.

2) <u>Pedological features</u> are those which form by modification of the sediment during pedogenesis through chemical action producing concretions and mottles, mechanical action producing clay skins, listrics, slickensides, and biological action involving the reworking of the sediment by burrowing and rooting with subsequent mineral preservation of the latter.

3) S-matrix is the material formed around the pedological features and may consist of grains of quartz surrounded by plasma - those soil constituents capable of being translocated or concentrated during pedogenesis ie. fine particles, organic matter and sesquioxides.

To allow recognition of palaeosols within Westphalian A and B rocks in the Warwickshire Coalfield, it is necessary to distinguish those features which are clearly pedological and liable to survive, from those which may be produced by other processes.

Although slickensides may be produced during pedogenesis (eg. by expansion and contraction of montmorillenite (Young 1976) later compaction may also lead to their formation without recourse to pedogenesis (Roeschmann 1971). Compaction is also likely to make the recognition of peds difficult in palaeosols of the Warwickshire Coalfield. Mottles are listed by Yaalon (1971) as soil features altered easily or relatively persistent dependant on the stability of the mineral species - red ferruginous mottles result from the concentration of ferric oxides which are relatively insoluble and more likely to be an original pedological property. Another relatively persistent feature, given early diagenetic preservation, is peat. Fossil root traces either as carbonaceous smears or minerlised are clearly diagnostic of palaeosols when they are in-situ. Plasmic fabrics regarded by Brewer (1964) as uniquely diagnostic of soil formation may also be produced during later diagenesis and thus be reduced in value as an indicator of palaeosols.

These textural characteristics are often preferentially disposed vertically, and together with other features, eg. development of layers of organic matter, they form soil profiles consisting of a number of horizons. Birkeland (1974) recognised six master soil horizons shown in capital letters (Table 5.6) to which a number of small letters may be attached as descriptive suffixes. Definition of these horizons is precise (Soil Survey manual 1975 pp.173-178) and dependant upon laboratory measurement of chemical and physical properties which change as diagenesis proceeds. Some soil horizons have greater preservation potential than others (Yaalon 1971) depending on the occurrence of irreversible processes with the soil, the products of which have been mentioned previously. This means that whilst exact equivalents of modern soil horizons are impossible to define in palaeosols, it is still feasible as mentioned by the Working Group (1971) to use horizon nomenclature in the description of those surviving horizon features.

Vast literature exists for the classification of modern soils and Young (1976) describes the principles behind the two international systems - the CCTA classification from the soil map of Africa (D'Hoore 1964) and the FAO classification (1974), and eight national systems which describe tropical soils, including the widely used US 7th Approximation (Soil Survey Staff 1960, 1967) and the French ORSTM classification (Aubert 1965). The organisation of most modern soil classifications is partly based on physiographical and climatological relationships. Two different approaches to classification are demonstrated by the Australian classification (Northcote 1971) which is based on morphological properties and the CCTA classification which is largely genetic.

In a similar way to the definition of soil horizons, in all classifications the soil unit is defined by a description including the results of physical and chemical tests which are impossible to apply to palaeosols. However the Working Group (1971) believed that

modern soil classification systems could be adapted to describe palaeosols at Great Soil Group level. Classifications are designed to meet the needs of the user, which in the case of most modern soil systems is to produce maps which will be useful to man in ways previously mentioned. The study of Westphalian A and B palaeosols is most useful in elucidating the environmental conditions at the time of their formation, and in this respect difference in process is important. This aspect will be emphasised in the classification used in this study, although as with previous lithofacies it will be based on morphological description.

There now follows a description of the three rock types and their lithofacies which are recognised in this study. In the case of the lithofacies of the rock types 'Seatearth' and 'Subseatearth' process will be interpreted in the relevant section on lithofacies associations. This is because whilst all of the lithofacies can be interpreted individually as products of palaeo-pedogenesis, only when associations are studied can process-based relationships between these lithofacies be fully appreciated. Each lithofacies association will also be related to modern soil classifications with examples.

5.3.8.3 Rock type 'Seatearth'

The grain size of this rock type ranges from mudstone to fine grained sandstone, although the finer grained lithofacies are more abundant. Colour ranges from grey to brown, or occasionally these colours may have associated red and ochreous mottling. Inorganic sedimentary structures are rarely visible giving rise to a massive appearance, which on microscopic examination may give rise to asepic or undulic plasmic fabrics cf. Brewer (1964) in Fielding (1982). Both siderite and sphaerosiderite are common and may occur as nodules and lenses. Abundant oblique carbonaceous roots are present, and more rarely Stigmaria ficoides is preserved through replacement by siderite. Listrics are very common within mudstones, often so closely spaced that the rock is considerably weakened and during mining operations will flow into roadways (Fulton and Ball 1983).

Lithofacies of this rock type are very laterally extensive occurring in areas exceeding 1000km^2, and their thickness varies from a few cm to about 3m. The contact with underlying lithofacies is usually gradational in the case of siliciclastic palaeosols (seatearth characteristics reducing with depth from free surface) but the original lithofacies from which they were formed have a variety of contacts. Abrupt basal contacts are usually found in the case of floriclastic palaeosols. This rock type most commonly passes upwards into lithofacies of the rock type 'Coal' and 'Mudstone' and these rock types together with 'Subseatearth' and 'Mudstone silty' most often pass upwards into it. The rock type 'Seatearth' has been recognised by many authors studying the Pennine basin including most recently Elliott 1968, 1969; Guion 1978; Haszeldine 1984; and Fielding 1982, 1984. In this study eleven lithofacies are recognised on the basis of two parameters - grain size and colour viz.

8.1 Seatearth, mudstone grey

8.2 Seatearth, mudstone silty grey

8.3 Seatearth, siltstone grey

8.4 Seatearth, sandstone grey

8.5 Seatearth, mudstone brown

8.6 Seatearth, mudstone silty brown

8.7 Seatearth, siltstone brown

8.8 Seatearth, sandstone brown

8.9 Seatearth, mudstone grey and/or brown with red mottling

8.10 Seatearth, mudstone silty grey and/or brown with red mottling

8.11 Seatearth siltstone grey and/or brown with red mottling

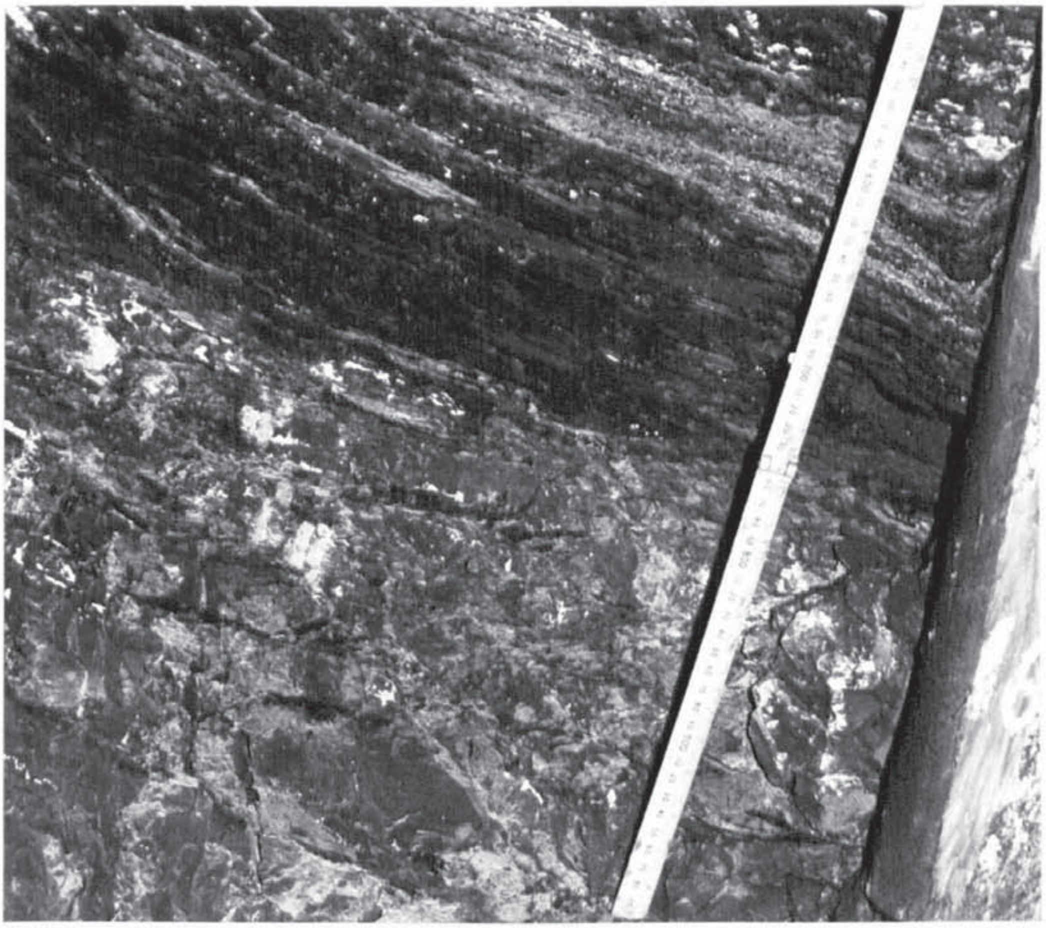
The division into grain size is a matter of convenience and is more useful in assessing the original conditions of deposition of the lithofacies than its relationship to pedogenesis. The division on the basis of colour is similar to that made by Elliott (1968, 1969) who inferred that it was connected with pedogenesis taking place under different environmental conditions. The division between grey and brown seatearth was subsequently used by Guion (1978) who studied similar facies in the East Midlands Coalfield. Fielding (1982) recognised similar lithofacies within his facies associations forming different Coal Measure palaeosol types.

Many of the characteristics associated with each colour of seatearth lithofacies are similar and for this reason only three (representing the finest grained in each case) are described below. Any differences between them and their coarser grained equivalents are noted within these descriptions.

5.3.8.3.1 Lithofacies 8.1-8.4 (Plate 5.29)

'Seatearth mudstone grey', 'Seatearth mudstone silty grey', 'Seatearth siltstone grey' and 'Seatearth sandstone grey', massive, usually with common oblique carbonaceous roots and listrics and often with siderite nodules. The colour usually varies from medium to dark grey and is commonly mottled. Oblique roots occur at a range of angles to the bedding, usually from 30 to 90°, although sub-horizontal roots have also been discovered. This varies with the observations of Fielding (1982) who found that they were most commonly vertical. Stigmaria ficoides are sometimes preserved as sideritised casts often

Plate 5.29 Lithofacies 8.1 Seatearth mudstone grey. Location: Coventry Colliery North Rock Head. Age: Westphalian B. Lithofacies 8.1 is overlain by lithofacies 1.5 Mudstone with coal lenses.



preferentially towards the base of lithofacies units. Listrics vary from rare to abundant in this lithofacies, and are rare in the 'Mudstone silty' equivalent and absent in other coarser grained equivalents. Siderite nodules vary in size and shape from rounded up to 30mm in diameter or elongate up to 200mm long oblique to bedding. Occasionally more siderite is found in the lower part of a lithofacies unit and this may make it distinctive enough to be described separately by some NCB geologists. Sphaerosiderite is occasionally found together with siderite nodules and rarely sphaerosiderite may be scattered throughout the matrix. Rarely pyrite occurs as streaks or blebs.

These lithofacies have a wide lateral extent. The grey seatearth lithofacies most commonly pass upwards into their finer grained equivalents or brown seatearths of the same grain size except 'Seatearth, mudstone grey' which often passes upwards into the lithofacies 'Mudstone massive dark grey to black' or lithofacies of the rock type 'Coal'. They are often underlain by lithofacies of the rock type 'Subseatearth'.

5.3.8.3.2 Lithofacies 8.5-8.8 (Plate 5.30A)

'Seatearth mudstone brown', 'Seatearth mudstone silty brown', 'Seatearth siltstone brown' and 'Seatearth sandstone brown', massive, usually with common oblique carbonaceous roots, listrics and common sphaerosiderite. The colour ranges from pale beige to dark brown and occasionally it is mottled with grey. Sometimes the lithofacies unit fines upwards. Occasionally well preserved sideritised casts of *S. ficoides* occur and their distribution together with those of listrics is similar to the previous lithofacies. Sometimes in highly listric brown seatearth mudstones no evidence of oblique roots can be found.

Plate 5.30A Lithofacies 8.5 Seatearth mudstone, brown Lithofacies 8.6 Seatearth mudstone silty brown.
Location: Broadacres Bh.
Age: upper Westphalian A

Lithofacies 8.6 which contains sphaerosiderite is overlain by Lithofacies 8.5 (continued below on Plate 5.30B).

Sphaerosiderite can occur as spherulitic concretions up to 2mm in diameter scattered throughout the matrix or as nodules constructed of aggregates of spherulitic concretions with an irregular outline up to 300m thick. They may also occur in beds. Rarely pyrite occurs as blebs, streaks or as a partial replacement of sphaerosiderite.

Brown seatearth lithofacies most commonly pass upward into their fine grained equivalents or grey or red mottled seatearths of similar grain size, except 'Seatearth mudstone brown' which often passes upwards into lithofacies of the rock type 'Coal'. They are often underlain by lithofacies of the rock type 'Subseatearth', or 'Mudstone, massive, medium to dark grey - with or without plant fragments'.

5.3.8.3.3 Lithofacies 8.9-8.11

'Seatearth mudstone grey and/or brown with red mottling', 'Seatearth mudstone silty grey and/or brown with red mottling', and 'Seatearth siltstone grey and/or brown with red mottling' with rare oblique carbonaceous roots, common listrics and occasional sphaerosiderite. Usually the overall colour of the lithofacies is grey and the red mottling may take the form of streaks, veining or diffuse irregular patches. The amount of red colouration may increase with depth. Roots are rare and preserved preferentially towards the base of a lithofacies unit. Sphaerosiderite occurs in similar morphological forms to the previous lithofacies and the size of the spheroidal concretions may increase with depth.

These red mottled 'Seatearth' lithofacies most commonly pass upwards into their finer grained equivalents or grey or brown equivalents of the same grain size. They are often underlain by the latter lithofacies or those of the rock type 'Subseatearth'.

5.3.8.4 Rock type 'Subseatearth'

The main characteristic of this rock type is that whilst it shows features associated with palaeosol development it clearly retains many of the original features of the parent lithofacies from which it is has formed. Its grain size covers the complete range between mudstone and coarse sandstone and its colour ranges from grey to various shades of brown. Siderite may be present as nodules or in the form of sphaerosiderite. Inorganic sedimentary structures reflecting the processes of deposition of the original lithofacies are varied and oblique carbonaceous roots are rare but ubiquitous. S. ficoides is also rare, preserved as sideritised casts. Listric surfaces are rare except in mudstones.

These beds are thin usually less than 0.5mm and most often reflect the original processes of deposition (see relevant section on lithofacies associations). Their lateral extent is likely to be variable and dependant on the lithofacies association in which they are found. The basal contact is usually gradational below which a wide variety of lithofacies are found. Lithofacies of this rock type often pass upward into lithofacies of the rock type 'Seatearth' although they may pass upwards into a wide variety of other lithofacies.

This rock type has been recognised by workers on the Pennine Coalfield - Guion (1978) as the sub-type 'Immature Seatearth', and in a general sense by Fielding (1982) who grouped the lithofacies under the heading 'Inceptisols'. Other authors have preferred to include them with the original lithofacies in which they were found (Besly 1983). Because the possibility exists for roots to penetrate a wide variety of lithofacies, the number of 'Subseatearth' lithofacies is only limited by the number of previously described lithofacies (excluding those of the rock type 'Seatearth'). Two lithofacies are recognised (see below) and as the characteristics outlined in the description of the rock type 'Subseatearth' apply to both they are not described individually.

9.1 Subseatearth grey (Plates 5.31 and 5.32)

9.2 Subseatearth brown (Plate 5.30B)

5.3.8.5 Rock type 'Coal'

Coal has been defined previously as a floriclastic palaeosol which on combustion yields less than 40% ash on an air-dried basis (a.b.d.). It is composed mainly of plant and/or algal remains in processes acting on plant remains after their initial deposition. The first stage of this process is peatification (Teichmüller and Teichmüller 1982) which involves microbial, physical and chemical changes taking place up to about 10m below the peat surface. After peatification the coalification processes continues as the peat is progressively buried and physical changes take place including compaction. The thickness changes involved in the transformation of peat to coal have long been the subject of discussion (summarised in Ryer and Langer 1980) and the variety of compaction ratios for bituminous coal range from 1.4:1 to 30:1. The range is explicable because of the different methods of investigation used, together with the variety of starting material and physical and chemical changes undergone. Each lithotype may have undergone a different amount of compaction (cf. Winston 1986). Elliott (1985) divided the change from forest peat to bituminous coal into five stages and believed that the range of compaction ratios varied from 13.5:1 to 20:1. Chemical changes taking place during coalification include decrease in volatile matter, moisture and hydrogen and increase in calorific value and carbon content. The amount of coalification undergone leads to a range of coals of different rank from lignite to anthracite which can be

Plate 5.30B Lithofacies 9.2 Subseatearth brown.
Location: Broadacres Borehole. Age: upper Westphalian A.
(Continued below Plate 5.30A)
The subseatearth consists of sandstone with siltstone laminae which has been bioturbated by the action of roots. This lithofacies forms part of a fining upwards unit through 8.6 to 8.5 (see plate 5.30A)

Plate 5.31 Lithofacies 9.1 Subseatearth grey. Location: Broadacres Borehole. Age: Westphalian B. Evidence of bioturbation can be seen in the sandstone laminae and when split apart, *Stigmaria ficoides* is found on the bedding plane.

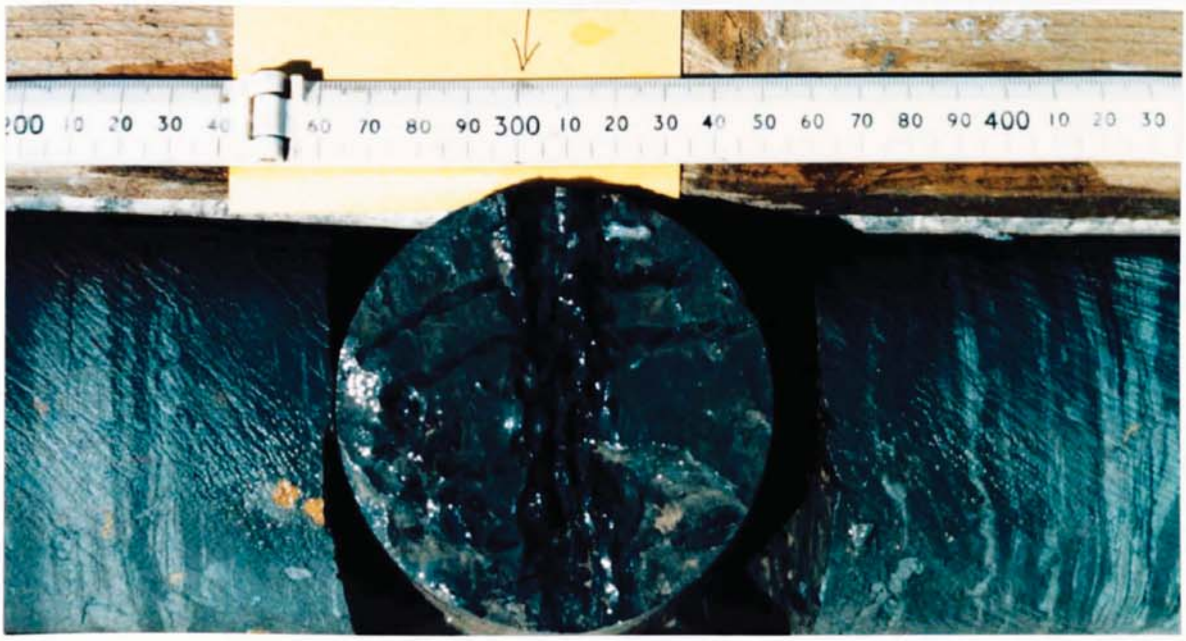


Plate 5.32 Lithofacies 9.1 subseatearth grey. Location: Broadacres Borehole. Age: Westphalian A. The original lithofacies Sandstone wavy stratified is clearly visible together with vertical sideritised root casts which resemble burrows.

determined using a variety of methods (Mackowsky 1982). Most of the coals in the Warwickshire Coalfield can be classified as high volatile bituminous, ranging in rank from 702-902 (various N.C.B analyses of seams of the Warwickshire Coalfield). Following these changes plant remains are undetectable in a hand specimen of coal, but fragments of plant tissue are observable if the coal is macerated and viewed with a microscope.

The most commonly occurring mineral within coal is pyrite, the various stages of preservation which have been buried and compacted to form a combustible rock. Plant remains constitute the majority of coal in the Warwickshire Coalfield and it is believed by the author that most of this forms autochthonously although some may be hypautochthonous (Potonie 1958).

It is likely that various groups of plants existed at different times and so contributed different donor materials to the coal. Peat is the name loosely applied to an accumulation of dead plant material in a good state of preservation with a high moisture content.

Kearns and Davison (1983) reviewed the North American classification of peat and in most cases the separation between peat and muck is 75% organic matter (25% ash content) although the figure of 50% was used by Lytle 1955 (in Kearns and Davison 1983). Anderson (1964a) studying peats in Borneo quoted the figure of 65% organic matter recommended by the ISCC in 1930 in Russia. Unfortunately no system uses the division between coal and siliciclastic sediment of 60% 40% by weight ash content used by the NCB. Andrejko <u>et al.</u> (1983) subdivide peat into low, medium and high ash, the division between the former two and the latter corresponding to that used by the NCB to distinguish coal from inferior coal i.e. 15% ash content. Freshwater ecosystems in which organic matter is accumulating are termed mires. If the thickness of organic matter is great enough the coal which it produces is classified in this work as a histosol (FAO/UNESCO 1974) providing it has an ash content of less than 40% by weight.

The colour of coal varies from light grey to black dependant on the composition of the donor materials and processes which took place during and after its deposition. Coalification (Teichmüller and Teichmüller 1982) is the term used collectively to describe the distribution and origin of which has been discussed in section 5.2.7.5. Occasionally siderite is associated with coal especially with the cannel lithofacies, where it may form beds decimetres thick. Ankerite also commonly occurs within coal (see below).

During the later stages of coalification jointing is imparted to coal, and this takes the form of either microjoints in bright coal or larger joints cutting a complete coal leaf, both of which are called cleat. Two sets usually form approximately at right angles, related to the direction of tectonic strain, and this is important when working coal (Fulton and Ball 1983). They also form sites for the accumulation of epigenetic minerals such as pyrite and ankerite. The plant remains which become flattened during coalification result in a series of 'bands' or elongate lenses which are sub-parallel to bedding and these may be used to determine regional dip.

Leaf is the term used to describe a single bed of the rock type 'Coal' above and below which are siliciclastic rock types. It is possible that a leaf may be simple, or composite formed from several simple leaves but without a detailed correlation study it may not be possible to distinguish between them. Superimposed on this situation are the historical seam names applied by the mining industry. A seam may be formed of a simple leaf or a composite leaf or even groups of leaves separated by siliciclastic partings, eg. the 'Warwickshire Thick Seam'. This latter use of the term seam is to be discouraged and another term employed, perhaps just using the word 'coal' eg. The Warwickshire Thick Coal. The thickness of a leaf varies from a few cm to several metres, the maximum composite leaf thickness observed in the Warwickshire Coalfield is about 2.7m. Leaves have a horizontal extent which appears to vary with thickness. Some of the thickest in Warwickshire extend as a recognisable unit for greater than 850km^2 (limited only by the size of the Warwickshire Coalfield) so that their original extent may have been a magnitude larger.

The rock type 'Coal' is often underlain by lithofacies of the rock type 'Seatearth' and overlain by the latter rock type together with lithofacies of the rock type 'Mudstone'.

Originally Potonie (1906) divided coal into two groups. Those which are stratified and believed to have undergone changes in the presence of oxygen are termed humic, whilst those which are massive and where the organic matter is believed to have putrefied are termed sapropelic.

Sapropelic coal is divided into two types (ICCP 1963) on the basis of its microscopic content. Cannel coals have a high spore content, and boghead coals contain abundant algae although transitions between the two are possible. Stach (1982) distinguished between them macroscopically on the basis of colour and streak. Low rank boghead coals are brown and have a brown streak.

Humic coals were first described in detail macroscopically using four terms, viz. fusain introduced by Grand 'Eury (1882) and vitrain, clarain and durain introduced by Stopes (1919). The number of ingredients was increased to give by introducing the term clarodurain (Cady 1942 p.341, although he appears to use the term duroclarain synonymously p.345) to define coal intermediate between clarain and durain. Seyler (1954) proposed the term lithotype to cover Stopes' four ingredients and they were redefined by the ICCP (1963) without reference to microscopic composition.

Since then several attempts have been made to describe coal macroscopically (summarised in Davis 1978). These range from relatively simple descriptions using four varieties based on bright and dull properties (Taylor 1967) which is similar to the system used by the NCB, to those based on % of bright coal with five varieties (BHP system, Hawthorne and Tweedale 1967) or those involving the use of a low power binocular microscrope to separate lithologies based on shade of grey (Chao 1983). Some authors have used a combination of plant and spore assemblages, maceral composition and texture, and type and concentration of mineral matter to create a genetic description related to specific environment (Ting and Spackman 1975).

Numerous workers on the Coal Measures in the Pennine basin have recognised the rock type 'Coal' although usually they subdivide it into relatively few lithofacies. Elliott (1968) divided coal into three types - layered, non-layered dominated by durite, and cannel. Guion (1978) increased the number to four by including inferior coal.

Previous descriptions of coal lithofacies were believed to be inadequate, so a method was chosen by the author which was flexible and related to the existing terminology. It allows a more detailed description of the rock type than that fiven by Stopes' and Cady's five ingredients, but is not too cumbersome or time consuming when dealing with large thicknesses of coal. It enables comparison between leaves of coal with respect to their lithofacies and related chemical and biological components. Detailed macroscopic description can also be more readily related to microscopic description (Cameron 1978).

Six fundamental macroscopic 'building blocks' of coal are recognised in this study and termed macrolithotypes. These are then used to construct the coal lithofacies described in the next section. Three grades of structure within macrolithotypes are visible to the unaided eye. They all occur as lenses (although some resemble laminae, they have limited lateral extent) and are defined by their thickness as follows:-

Fine lenses : less than 0.5mm
Thin lenses : 0.5 - 2.0mm
Thick lenses : greater than 2.0mm

The finest grade of structure is only recognised within macrolithotypes. The macrolithotypes are recognised by virtue of their bright and dull characteristics. Macrolithotype A) *Bright* can be regarded as macroscopically pure, whilst macrolithotype B) *Bright finely lensed with dull* and C) *Dull finely lensed with bright* are heterogeneous and composed of intimately mixed fine lenses. Macrolithotype D) *Dull* and E) *Fusain* each have two varieties (see relevant lithofacies) whilst F) is composed of *Siliciclastic* sediment mixed with coal.

Characteristics of the macrolithotypes

1) *Microlithotype A) Bright* - black, massive, with shiny lustre and cubic fracture. The fine cleat which give it a cubic fracture often contain ankerite and occasionally pyrite. Within lithofacies it occurs as thin to thick laminae and occasionally may also form beds (see lithofacies 7.6). This macrolithotype is similar to the lithotype vitrain.

2) Macrolithotype B) Bright finely lensed with dull - black, bright, fine lenses intimately mixed with fine lenses of grey dull coal with the bright lenses forming more than 50% of the whole. It has a shiny lustre and a weak conchoidal frature. Within lithofacies if occurs usually as thin or thick lenses and very rarely as beds. This macrolithotype is similar to the lithotype clarain.

3) Macrolithotype C) finely lensed with bright - grey dull fine lenses intimately mixed with bright black lenses with the grey dull lenses forming more than 50% of the whole. It has a pearly lustre and a fracture that varies from subconchoidal to uneven. Within lithofacies if occurs usually as thin or thick lenses and rarely as beds. This macrolithotype is similar to the lithotype clarodurain.

4) Macrolithotype D) Dull - grey, either smooth with a pearly lustre and conchoidal fracture (see lithofacies 10.1) or granular with a resinous lustre and uneven fracture (see lithofacies 10.2). Within lithofacies it occurs as thin or thick lenses and beds. This macrolithotype may be similar to the lithotype cannel or the lithotype durain.

5) Macrolithotype E) Fusain - grey, with a satin lustre, which when rubbed marks objects, either soft and easily powdered with chaotic bedding (see lithofacies 10.7) or hard and massive (see lithofacies 10.8). Within lithofacies they occur as thin or thick lenses and beds. This macrolithotype is equivalent to the lithotype fusain.

6) Macrolithotype F) Siliciclastic sediment and coal - the siliciclastic sediment ranges from grey argillaceous sediment to white quartzitic sediment. Within lithofacies it may occur as isolated grains and thin or thick lenses.

Lithofacies description and interpretation

From a practical consideration of time taken to describe a coal lithofacies, a minimum lithofacies bed size of 10mm was used in this study. This thickness is the same as used for lithotype description in Germany (Stach et al. 1983). Most coal lithofacies are formed of more than one macrolithotype and in this study each macrolithotype present within a lithofacies is recorded as a percentage. Associations of macrolithotypes have been observed repeatedly within leaves of coal in the Warwickshire Coalfield. A classification of these associations has been created by the author based mainly on both the dominance of one of the macrolithotypes and the percentage of the macrolithotype 'Bright' coal. Classification of coal using the percentage of 'Bright' coal was a method adopted by Schopf (1960). The morphological relationships of the macrolithotypes in respect to their juxtaposition, thickness and percentage within a coal lithofacies lead to different physical characteristics which help to define eight 'simple' lithofacies (10.1-10.8). In the case of 'complex' lithofacies containing siliciclastic sediment the primary coal lithofacies number is given first followed by the siliciclastic number eg. 10.2/9. A list of coal lithofacies recognised in this study is given below.

10.1 Coal, grey, dull, smooth, canneloid

10.2 Coal, grey, dull, granular

10.3 Coal, grey, predominantly dull finely lensed with bright

10.4 Coal, grey mainly dull finely lensed with bright

10.5 Coal, black, mainly bright finely lensed with dull

10.6 Coal, black, bright, massive

10.7 Coal, grey, fusainous, soft

10.8 Coal, silver grey, fusainous, hard

10.9 Coal, plus siliciclastic sediment

Unless otherwise stated the characteristics and properties mentioned in the following descriptions refer to coal found in the leaves of the Thick Coal at Longmeadow Wood and Moat House Farm boreholes (Figs. 5.45, 5.46). For an analysis of ash and sulphur contents for each lithofacies see Table 5.7. The properties associated with coal lithofacies following maceration ie. volume of residue left after maceration, miospore associations, species diversity and density come from an investigation of the Thick Coal at Longmeadow Wood borehole (for details see Appendix 'C or D'). Comparisons of coal lithofacies and bulk characterising species (bcs) miospore types (section6.3.2) are given in TABLE 5.8.

Interpretation is based on information contained within the lithofacies description and by comparison with the interpretation of similar facies by other authors. Because the microscopical composition of coal is often mentioned by these authors, a comparison of the macroscopical and microscopical composition of lithotypes, microlithotypes and macerals is given in Table 5.9.

5.3.8.5.1 Lithofacies 9.1

Coal, grey, dull, smooth, canneloid (part of macrolithotype D) massive, with a waxy or pearly lustre, and a well developed sub-conchoidal fracture. Only rarely are thin bright (macrolithotype A) lenses present. This coal lithofacies has the highest non-fusainous average ash content (7.5%) in this study. Moore (1968) also found that cannel coal had high ash contents (11-20%). The miospore content of this lithofacies is variable and as noted by Sullivan (1959) rapid changes in species present can take place when compared with underlying coal lithofacies.

This lithofacies occurs rarely (average less than 1%) in this beds (1-4cm) within the Warwickshire Thick Coal, often at the top of

TABLE 5.7 Relationship of Coal Lithofacies to ash and sulphur content in seams of the Thick Coal at Longmeadow Wood and Moat House Farm boreholes.

COAL LITHOFACIES NOS. (See Appendix H for key to nos.)	10.1	10.2	10.3	10.4	10.5	10.6	10.7	10.8	10.9
Two Yard Seam									
No. of beds	-	5	12	20	11	-	-	1	1
Thickness (cm)	-	9	78	129	63	-	-	1	2
S.G.	-	1.36	1.35	1.34	1.34	-	-	1.57	1.84
Ash	-	3.1	4.1	2.7	2.6	-	-	19.4	34.3
Sulphur	-	1.4	1.2	1.8	1.4	-	-	0.5	16.8
Bare Seam									
No. of beds	-	2	3	7	2	-	-	1	4
Thickness (cm)	-	4	17	32	11	-	-	2	12
S.G.	-	1.38	1.38	1.38	1.36	-	-	1.41	1.56
Ash	-	4.3	5.8	6.2	5.6	-	-	8.7	25.0
Sulphur	-	1.9	1.3	3.4	2.4	-	-	4.4	2.6
Ryder Seam (Lmw 448-61) (Mhf 250-64)									
No. of beds	1	5	11	9	10	-	-	-	1
Thickness (cm)	2	23.5	62	30	88	-	-	-	5
S.G.	1.42	1.40	1.38	1.54	1.34	-	-	-	1.62
Ash	4.7	9.0	7.9	9.1	4.2	-	-	-	33.9
Sulphur	1.0	1.4	1.9	3.4	2.0	-	-	-	1.2
Ell/Top Nine Feet (T.N.F.)									
No. of beds	-	6	9	4	22	1	1	2	2
Thickness (cm)	-	13	42	72	131.5	2	1	1.5	5
S.G.	-	1.36	1.39	1.35	1.35	1.32	1.45	1.42	1.55
Ash	-	5.5	6.2	5.8	4.9	2.3	10.8	13.4	20.1
Sulphur	-	2.6	2.2	2.2	2.8	2.1	1.3	2.1	2.3
B.N.F./High Main									
No. of beds	1	16	9	18	19	3	1	-	-
Thickness (cm)	1	31	29	104	121	10	1	-	-
S.G.	1.40	1.34	1.35	1.34	1.33	1.34	1.41	-	-
Ash	13.1	3.9	5.6	4.2	3.6	4.7	7.2	-	-
Sulphur	1.8	1.7	1.6	2.1	1.8	2.8	1.2	-	-
Total No. of beds	2	34	44	58	64	4	2	4	8
Total Thickness (cm)	3	80.5	228	367	414.5	12	2	4.5	24
Average Ash	7.5	5.6	5.7	4.2	4.0	4.3	9.0	12.9	26.7
Average Sulphur	1.3	1.7	1.6	2.2	2.1	2.7	1.3	2.7	3.6

TABLE 5.8 The relationship between Coal Lithofacies and Miospore types

COAL LITHOFACIES (See Appendix B for descriptions)	COAL SUBSECTIONS CONTAINING THE RELEVANT MIOSPORE ASSOCIATION			
	Densosporites spp.	*Laevigatosporites minor*	*Fabasporites* cf. *exilis*	*Lycospora pusilla*
10.1	2	1	0	0
10.2	6	4	5	4
10.3	5	3	1	2
10.4	5	10	5	8
10.5	3	6	6	14
10.6	0	0	1	2
10.7	0	0	0	2
10.8		1	2	3
10.9	1	1	2	1

TABLE 59 The relationship between lithotypes, microlithotypes, maceral groups and macerals (from Stach et al.1982) leaves, where it is succeeded by siliciclastic lithofacies. It occurs more commonly in siliciclastic sequences where sometimes the underlying lithofacies is not a palaeosol. Elliott (1968) recognised this lithofacies as microlithic cannel coal and showed that it occurred in regional splits, long narrow belts, and associated with palaeo-river courses (Elliott 1965b).

Interpretation

This lithofacies is interpreted as the product of a subaqueous setting (Smith 1962, Moore 1968, Teichmüller 1982) in which peat accumulation was terminated by drowning but without a large amount of siliciclastic input. It is probable that much of the organic debris forming this lithofacies was allochthonous (Moore 1968) possibly from peat drainage channels. It is likely that this plant material underwent fermentation, and a considerable amount of the preserved organic matter may consist of bacterial remains (Lijmbach 1975). The higher ash content may result from a concentration of resistant plant debris together with a small amount of siliciclastic sediment.

Rapid change in miospore content probably resulted from a change to allochthonous accumulation from autochthonous accumulation. This may be brought about by subaqueous conditions, or increased subaerial travel. It is possible that this lithofacies together with 'Coal plus siliciclastic sediment' may be interpreted in part as lacustrine rather than palaeosol lithofacies.

5.3.8.5.2 Lithofacies 9.2

Coal, grey, dull, granular (part of microlithotype D) with resinous lustre and uneven fracture. Rarely thin bright (macrolithotype A) lenses, usually forming up to 5% of the bed, occur at an angle to other stratification. Pyritised plant remains and lenses are rare, and this lithofacies has a lower than average sulphur content (1.7%). On average the ash content of this lithofacies at Longmeadow Wood and Moat House Farm boreholes is relatively high (5.6%), although those lithofacies characterised by the Fabasporites cf. exilis bcs miospore type in the Thick Coal at Longmeadow Wood borehole have slightly higher ash contents (5.3%) than those characterised by other miospore types (4.2%).

The miospore content of this lithofacies is variable with no particular connection with any miospore type. Many examples of this lithofacies contain large amounts of residue left after maceration. Those examples connected with the Fabasporites cf. exilis bcs have lower species diversities than those connected with other miospore types.

The thickness of this lithofacies varies from 1-12cm with the majority being between 1-2cm thick, and it forms a small percentage of the leaves of the Thick Coal (7%). Beds of this lithofacies extend for tens of metres horizontally and are vertically distributed evenly throughout the Thick Coal. This lithofacies is often under- and overlain by either the lithofacies 'Coal, black, mainly bright finely lensed with dull', or 'Coal, grey, predominantly dull finely lensed with bright' and sometimes by the lithofacies 'Coal, grey, mainly dull finely lensed with bright'.

Interpretation

The conditions under which organic matter accumulated to give rise to durain (the lithotype equivalent of the macrolithotype forming the majority of this lithofacies) has long been the subject of controversy. Some authors maintained that its principal maceral micrinite was of subaquatic origin (Tasch 1960) and formed autochthonously (Williamson 1967, Hacquebard and Donaldson 1969) or allochthonously (Raistrick and Marshall 1939). Other authors have argued that aerobic conditions may have occurred during the formation of micrinite (Karmasin 1952, Svoboda 1955). Also two different origins of durain dependant on the presence of different miospores have been proposed by some authors. Spore rich durite (the principle microlithotype of durain) was believed by Teichmüller (1952) to be formed subaquatically, whilst spore poor durite (rich in the maceral fusite) formed subaerially. Smith (1962) postulated that densospore-rich durains accumulated in an environment subject to aerobic decomposition, whilst durains characterised by the Incursion phase formed subaqueously as a result of oxygenated water passing over the surface of the peat. Originally Smith (1962) also believed that climatic change may have influenced the sequence of miospore phases (and hence the formation of durain). He also found that coal samples high in the microlithotype durite were dominated by two miospore phases - the Densospore and Incursion phases and that these were petrologically different. Those of the Incursion phase had an equal or greater amount of seimifusinite when compared with micrinite, and vice-versa for the Densospore phase.

Unlike Smith (1962, 1968) the author believes that all examples of this lithofacies originated under similar aerobic conditions. However they can be broadly divided into two types: those which are thick (greater than 2cm) and connected with both the Densosporites spp. bcs miospore type and the lithofacies 'Coal, grey, predominantly dull finely lensed with bright': and those which are thin (less than 2cm) and often connected with both the Fabasporites cf. exilis bcs miospore type and other lithofacies, most commonly 'Coal, black mainly bright finely lensed with dull'. The principal difference between them is believed to be the length of time that the water table lay at some distance below the surface of the peat.

Those examples of this lithofacies which contain miospores of the Densosporites spp. bcs type and adjoin the lithofacies 'Coal, predominantly dull finely lensed with bright' are believed to have formed in an environment with a fairly variable water table which allowed aerobic conditions to occur over long periods of time and large distances. Conditions similar to this exist in the centre of well established raised forest mires (Anderson 1964a, 1973) where variations in the water table of up to 19cm have been observed, compared to 10cm towards the periphery of the mire. Boddy (1938) believed that durain was formed as a result of progressive drying of the peat, and whilst a continual dry environment cannot account for thick drains (Smith 1962), the combination of a fairly variable water table and heavy precipitation may account for its origin. It is believed that durain is mostly formed from the maceral pyrofusite.

Prolonged aerobic conditions in peat and changes in the pH towards the centre of the mire may also have affected other factors which could account for the formation of this lithofacies. These include selection of the donor plants which formed the coal, together with bacteria and fungi whose activities result in the disintegration of organic matter to produce hydrogen poor humic substances later to become the inertinite group of macerals (Teichmüller and Teichmüller 1982) which occur in large amounts within durain.

Aerobic conditions are also believed to have been responsible for the production of this lithofacies associated with the Fabasporites cf. exilis bcs miospore type and which may be equivalent to Smith's (1962) Incursion phase. However it is believed that the length of time over which the aerobic conditions existed were quickly curtailed by flooding of the surface of the peat. Only in topographically higher areas and those of better drainage were the aerobic conditions persistent for any length of time. This accounts for the relative impersistence of these beds vertically and laterally. This explanation is in contrast to the interpretation of Smith (1962), who believed that the durains associated with the Incursion phase were the result of irregular floods of oxygenated water from outside the swamp, carrying mud, charred wood and spores. It is believed by the author that the plants growing on the surface of the mire would reduce the speed of water movement especially at any distance from the source of the water. Therefore the water may have initially contributed to the production of inertinite, but quickly would loose its power of oxidation. The slightly higher ash content of this lithofacies connected with miospores of the Fabasporites cf. exilis bcs type is not enough to demonstrate that formation of this lithofacies was related to mud bearing water. Increase in semifusinite found by Smith (1962) may be related to the type of vegetation in the surrounding area - see section on the lithofacies 'Coal, grey, fusainous, soft'.

5.3.8.5.3 Lithofacies 9.3

Coal, grey, predominantly dull, finely lensed with bright (Macrolithotype C but with a low bright content) with occasional thin bright lenses (macrolithotype A); rare thick bright lenses, thin dull lenses (macrolithotype D), and thin lenses of bright finely lensed with dull (macrolithotype B). Often the lenses are at an angle to regional stratification and the total amount of bright lenses varies between 6-15%. The more homogeneous examples of this lithofacies have a poorly developed sub-conchoidal fracture, those with a higher bright content have an uneven fracture. In common with the previous lithofacies the ash content is higher than average (5.7%) and the pyrite content is lower than average (1.6%).

This lithofacies is clearly connected with miospores of the Densosporites spp. bcs miospore type and also contains the highest number of miospores/gram of coal. Most examples of this lithofacies have relatively low species diversity.

The thickness of this lithofacies varies from 2-22cm and on average it forms 20% of the leaves of the Thick Coal. It usually occurs in the middle or upper parts of coal leaves and may extend for tens or perhaps hundreds of metres.

Both 'Coal, grey, dull, granular' and 'Coal, grey, mainly dull finely lensed bright' commonly under or overlie this lithofacies. When associated with the Densosporites spp. bcs this lithofacies probably contains large amounts of crassidurite and crassiclarite.

Interpretation

The interpretation of this lithofacies in terms of its conditions of deposition is very similar to that proposed for the previous coal lithofacies when connected with the Densosporites association. The higher miospore density when compared with under or overlying lithofacies is probably due to physico-chemical conditions during accumulation and diagenesis which resulted in their preferential preservation. This supports the hypothesis that this lithofacies underwent oxidation during or shortly after its accumulation, which resulted in an enrichment of those components (including miospores) resistant to oxidation. Stach (1982) believed the dull element seen in hand specimen in clarite was related to the number of spores present, which correlates well with the properties seen in this lithofacies.

The low sulphur content may be related to the formation of this lithofacies either under aerobic or freshwater conditions (Davies and Raymond 1983).

5.3.8.5.4 Lithofacies 9.4

Coal, grey, mainly dull finely lensed with bright (Macrolithotype C) but with a greater bright content than that in the previous lithofacies (with common thin bright lenses) (macrolithotype A); occasional thick bright lenses, and rare thin dull lenses (macrolithotype D) and thin lenses of bright finely lensed dull (macrolithotype B). The total amount of bright lenses varies between 15-50%. Occasionally fusain (macrolithotype E) lenses several mm thick occur, and occasionally pyrite lenses up to 5mm thick are sometimes found, together with pyrite in micro-cleat in bright lenses.

This lithofacies has an uneven fracture. The ash content is slightly lower than average (4.2%) and it has a higher than average sulphur content (2.2%).

This lithofacies has no particular link with any of the miospore assocations recognised in this study. Many examples of this lithofacies have fairly high species diversities.

The thickness of this lithofacies varies from 2-26cm and on average it forms about one third of the leaves of the Thick Coal and is evenly distrubuted throughout them. It probably extends laterally for tens of metres although the percentage of bright coal within it may vary. This lithofacies is associated with most of the other coal lithofacies.

Interpretation

According to Cady (1942) clarodurain (the equivalent of macrolithotype C - Coal, grey, mainly dull finely lensed with bright) has a limited maceral content of micrinite and residuum and the microlithotype clarodurite is defined as having a greater proportion of inertinite to vitrinite (ICCP 1963). In this respect the interpretation of this part of the lithofacies is similar to the previous lithofacies. However the increased content of other macrolithotypes relates to the preservation of a greater number of donot plant materials probably under anaerobic conditions. For details of the interpretation of these macrolithotypes see the following lithofacies sections.

The high sulphur content may relate to the conditions under which this lithofacies accumulated. It is possible that some sulphur may have been fixed by plants in a similar way to that demonstrated by Casagrande et al. (1977). Alternatively it may be formed by the introduction of sulphate within water moving over the peat surface, or within the upper 'active' (Romanov 1968) layer, which can then be reduced by bacteria (Neavel 1966). This may then occur as organic sulphur or combine with ferrous ions within the water to form pyrite. In peats of the southern USA Davies and Raymond (1983) found that this pyrite occurred as microscopic euhedral crystals and framboids. Those examples of this lithofacies which have high sulphur values but no pyrite observed by the naked eye may have formed in an environment influenced by marine or brackish waters which give high organic sulphur contents and greater amounts of microscopically pyrite (Davies and Raymond 1983).

This is in contrast to the massive anehdral pyrite which the latter authors believed was emplaced during later coalification through the permeability of cleat and joints. Those examples of this lithofacies in which pyrite was observed as lenses or in cleat may have high sulphur contents as a result of this process.

5.3.8.5.5 Lithofacies 9.5

Coal, black, mainly bright finely lensed with dull (macrolithotype B) with occasional to common thin and thick bright lenses (macrolithotype A), and rare thin to thick lenses of dull finely lensed with bright (macrolithotype C). The amount of bright lenses is often greater than 15%. Fusain lenses several mm thick are rare to common. A poor subconchoidal fracture often develops. Occasionally pyrite lenses and beds several mm thick and pyritised plant remains occur. This lithofacies has a lower than average ash content (4.0%) of the four main coal lithofacies and a higher than average sulphur content (2.1%).

Some examples of this lithofacies have high species diversities and there is a range of miospore densities from below average to fairly high numbers. It is strongly linked with miospores of the Lycospora pusilla bcs miospore type.

The bed thickness of this lithofacies varies between 3-34cm and it forms the highest percentage (36%) of the leaves of the Thick Coal. It is usually located at the bottom of a coal leaf but may also occur at the top, and it probably extends laterally for tens of metres although the percentage of bright coal within it may vary. This lithofacies often surrounds beds of the lithofacies 'Fusain' and is also commonly associated with the lithofacies 'Coal, black, bright, massive', 'Coal, grey, mainly dull finely lensed with bright' and 'Coal, grey, dull granular'.

Interpretation

It is likely that the macrolithotype forming the majority of this lithofacies is formed from the trimaceral microlithotype duroclarite. This is formed of the maceral groups vitrinite, exinite and inertinite with the proportion of vitrinite exceeding that of inertinite (ICCP 1963). Vitrinite rich trimacerites have origins probably resembling vitrinite clarites (Teichmüller 1982), which are believed to have formed from forest litter initially under anaerobic conditions (Teichmüller 1982). The origin of macrolithotype A - bright, black, massive, which is formed mainly of vitrite is given in the next section. Although other authors believe that some of the macerals (telecollinite = pseudovitrinite) forming vitrinite result from the passage of oxygenated waters (Kravitts and Crelling 1981), the connection of this lithofacies with the Lycospora pusilla bcs miospore type accords well with the observations of (Teichmüller 1982). Those examples of this lithofacies with high numbers of miospores/gram of coal presumably have a greater exinite content.

The low ash content of this lithofacies appears to be linked with an increase in vitrinite which may be related to the donor plant materials and the processes acting on them during peatification and coalification (see next section). The explanation for the low ash content is also given in the next section, and would be even lower if the contribution made to it by the increase in pyrite was removed. The higher than average sulphur content of this lithofacies may be connected to the anaerobic conditions prevailing at the time of deposition, or it may be secondary, related to an increase in the macrolithotype black, bright, massive (see next section).

5.3.8.5.6 Lithofacies 9.6

Coal, black, bright, massive (macrolithotype A) which may occur as a bed or be associated with thin or thick lenses of black mainly bright, finely lensed with dull (macrolithotype B) or rarely grey mainly dull, finely lensed with bright (macrolithotype C). Rarely fusain lenses several mm thick occur. The main macrolithotype commonly has a cubic fracture and microcleat in which ankerite and pyrite often occur. Where this lithofacies is composed entirely of the macrolithotype black, bright massive it has an ash content of less than 2%, where heterogeneous its value is still lower than average for the four main coal forming lithofacies (4.3%). Sulphur contents are higher than average (2.7%).

This lithofacies has the lowest volume of residue left after maceration (less than 1 cu cm) and is associated with the Lycospora pusilla bcs miospore type.

It occurs in beds between 2-5cm thick and is rare, forming only about 1% of the leaves of the Thick Coal. Usually it occurs towards the base of a leaf of coal and has the most limited of lateral extents (a few metres only) often passing laterally into the lithofacies 'Coal, black, mainly bright, finely lensed with dull'. It is associated with a wide variety of coal lithofacies.

Interpretation

It is probable that the macrolithotype black, bright, massive forms from the woody material of plants, which is the origin given to the microlithotype vitrite by (Teichmüller 1982). She believed that for the woody material to survive it must be protected from the atmosphere by enclosure in peat in an anaerobic environment caused by a high water table. It is probable that during the wet season water may have been above the peat surface. Stach (1982) showed that different varieties of vitrite dependant on the plant type which formed them viz. cordaito-, lepidophyto-, fern, and calamito-vitrite could be recognised from their petrographic properties.

The low ash content and volume of residue left after maceration reflect the lack of oxidative processes which have previously taken place on this lithofacies, and support its formation within an anaerobic environment. Higher than average sulphur values reflect the amount of secondary pyrite found within the micro-cleat of the macrolithotype black, bright, massive.

The connection of this and the previous lithofacies with the Lycospora pusilla bcs miospore type confirms the link between certain arborescent woody LYCOPHYTES from which these miospores were derived and the macrolithotype which forms the majority of this lithofacies and much of the previous lithofacies.

5.3.9.5.7 Lithofacies 9.7

Coal, grey, fusainous, soft with a satin lustre, which when rubbed marks objects and with chaotic bedding formed from antular fragments. Its sulphur content is low (1.3%) and both its ash (9.0%) and chlorine contents (0.41%) are relatively high.

This lithofacies is connected with the Lycospora pusilla bcs miospore type and has a very low number of miospores/gram of coal. It has a fairly high volume of residue left after maceration.

This lithofacies occurs rarely (less than 1% of the leaves of the Thick Coal) in beds up to 1cm thick, usually in the lower parts of coal leaves. It has a limited lateral extent (usually less than 10m) and both the lithofacies 'Coal, black, mainly bright, finely lensed with dull' and 'Coal, grey, mainly dull finely lensed with bright' are closely associated with it vertically. This lithofacies was extensively studied by Scott (1976) in coal seams of the Pennine basin.

Interpretation

This lithofacies is believed to be formed of the microlithotype fusite with empty cell lumens (Stach 1982). The macerals which form finite may be produced via a variety of processes from a number of sources (Scott 1976, Teichmüller 1982). Those which form fusain are belived to be pyrofusinites resulting from the burning of woody plant materials. This origin for fusain was also supported by Scott (1976). The type of pyrofusinite is determined by the parent plant and the degree of charing which has taken place (Teichmüller 1982).

The origin of the burning may be by lightning damage or fire caused by the latter or spontaneous combustion. Lightning damage has been studied by Anderson (1964b) in the forest peat swamps of Borneo. Some of the conclusions he reached are that lightning damage is most likely to be severe in single species forests, with a high, pure canopy in areas of flat topography, and that some trees are more or less resistant to this damage. Although group lightning damage was frequent, only rarely was charring seen and no mention was made of subsequent fire damage. The burning of subaerial vegetation has already been mentioned, but in dry periods the peat itself may burn (Cypert 1961, Staub and Cohen 1979) producing an extensive bed of fusain. These have not been found in the leaves of the Thick Coal and the author believes that this lithofacies most commonly originated from the burning of subaerial vegetation as a result of lightning damage and subsequent fire, producing thin scattered lenses of a variety of sizes.

Its origin explains the high ash content and residue left after maceration, together with the low numbers of miospores/gram. The low sulphur content is related to the division between this and the following lithofacies (see next section). The connection between this lithofacies and miospores of the Lycospora pusilla bcs miospore type may be related to their parent plants (see previous paragraph) and although fusain is found in other lithofacies most of these are also associated with the Lycospora pusilla bcs type.

5.3.9.5.8 Lithofacies 9.8

Coal, silver grey, fusainous, hard, with a satin lustre which when rubbed marks objects and is massive or chaotically bedded. Both its sulphur content (average 2.7%) and ash content (average 12.9%) are high.

This lithofacies is connected mainly with the Lycospora pusilla bcs and Fabasporites cf. exilis bcs miospore types, has a very low numer of miospores/gram of coal and a fairly high volume of residue left after maceration. It occurs rarely (less than 1% of the Thick Coal) in beds up to 2m thick, usually in the lower parts of coal leaves. The lithofacies 'Coal, black, mainly bright, finely lensed with dull' is usually associated with this lithofacies and it has a limited lateral extent (usually less than 10m).

Interpretation

The primary origin of this lithofacies is similar to the previous lithofacies, but it is believed that at a later stage the empty cell lumens became mineral filled. Often this mineral is pyrite which accounts for the higher than average sulphur content, but sometimes it may be siliciclastic sediment which together with the pyrite produces a higher than normal ash content for this lithofacies.

5.3.9.5.9 Lithofacies 9.9

Coal plus siliciclastic sediment, the former consisting of any combination of coal macrolithotypes and the latter sediment of any grain size. (An indication of the macrolithotypes present within the lithofacies is given in the graphic log, Figs. 5.45 & 5.46), although where uncertainly exists only the symbol for this lithofacies is shown). In practice the combination of macrolithotypes commonly results in a lithofacies resembling that of 'Coal, grey, dull granular', although all other coal lithofacies associated with siliciclastic sediment have been recognised. The siliciclastic sediment ranges from lenses several mm thick which are clearly visible to the naked eye, to scattered grains intimately mixed with coal, whose presence can only be inferred either by a brown streak, listric partings or increased ash content.

Ash content ranges from 3% in those lithofacies with rare discrete siliciclastic lenses to the maximum permitted 40% (before the sediment is not regarded as floriclastic) with an average ash content of 28.8%. All coal with an ash content exceeding 15% is assumed to contain siliciclastic sediment and has been termed inferior coal by the NCB.

This lithofacies is connected mainly with the Lycospora pusilla bcs miospore type and has a low number of miospores/gram of coal and a high volume of residue left after maceration. It is fairly rare and makes up 2% of the leaves of the Thick Coal, ranging in thickness up to 5cm. Usually it occurs at the top and bottom of coal leaves and may have wide lateral extent up to 100's km^2. It passes upwards into a wide variety of coal lithofacies and a wide variety of coal lithofacies pass upwards into it.

Interpretation

Siliciclastic sediment is believed to have been carried onto the peat from outside by water moving over the peat surface. Its progress across the peat surface is partly dependant on sediment composition and partly on the speed of water movement. This latter factor is likely to be low because of the density of the luxuriant vegetation so that only small particles may be carried, and if they are composed of clay minerals they may quickly become flocculated due to increase in the pH of the water (Staub and Cohen 1979). Siliciclastic sediment is likely to be deposited either in local depressions in the peat surface producing isolated lenses, or to infiltrate through the pore spaces between plant debris producing isolated grains within the peat. Dispersal of this sediment within the peat is likely to be aided further by root bioturbation if plant growth is not terminated.

The preferential presence of this lithofacies at the top or bottom of coal leaves, demonstrates the advance or retreat of flood events carrying siliciclastic sediment. When this lithofacies occurs within leaves of coal it may denote the distal edge of a split between leaves, and laterally change into a bed of siliciclastic sediment. The high volume of residue left after maceration is probably related to the presence of siliciclastic sediment and the low numbers of miospore may be explained by their selective removal by the flowing water.

5.4 LITHOFACIES ASSOCIATIONS

Lithofacies associations are recognised in this study so that an interpretation of depositional environments can be made. From their disposition, a model can be constructed showing their interaction on a regional scale (section 7.1).

For each association a facies relationship diagram (F.R.D.) was produced where possible, using Table 5.1. Embedded Markov Chain analysis used to make Table 5.1 has some disadvantages in that it emphasises the most statistically important transitions, so that rare events are not distinguished. Following from this repetition between lithofacies is likely to mask other important transitions. Also other important characteristics such as thickness, fining and coarsening upwards and boundaries between beds are not emphasised within this analysis. For these reasons boreholes are inspected for the presence of these F.R.D's and any additional transitions which are believed to be characteristic are added to the F.R.D. In some cases it is not possible construct an F.R.D. directly from Table 5.1 either because the key lithofacies are missing from the table e.g. 'Subseatearth' lithofacies or, the association is based partly on characteristics not found in Table 5.1 e.g. thickness in 'Lacustrine thickly interbedded coarse and fine deposits.'

A total of ten lithofacies associations have been recognised in this study viz.

1 Marine deposits

2A Lacustrine suspension deposits

2B Lacustrine dominantly coarsening upwards deposits

2C Lacustrine thickly interbedded coarse and fine deposits

2D Lacustrine siltstone dominated deposits

3 Channel fill deposits

4A Impoverished siliciclastic palaeosol/s

4B Very poorly drained siliciclastic dominated palaeosol/s

4C Long-residence histosol/s

4D Alternate poorly and imperfectly drained siliciclastic palaeosol/s

The characteristic lithofacies found in each association are described with reference to examples mainly from borehole core, and the features distinguishing them from other associations within this study are noted. Comparison is also made with the associations/facies of other authors. The relationships between the under and overlying associations within this study are determined on the F.R.D.'s so that a depositional model can be constructed.

5.4.1 Lithofacies Association 1

'Marine deposits'

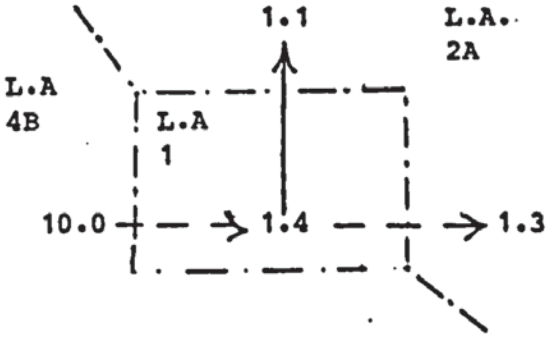
Within this study only one lithofacies characterises this association but an F.R.D. has been drawn to show the relationship with other associations (Fig.5.6). Division of the lithofacies can be achieved on the basis of the four marine phases and four marine/brackish phases described by Calver (1968) for Westphalian marine bands (M.B). Not all of the phases are identified for each M.B. and very often phases are grouped together. Using this method it is often possible to identify lateral transitions from lithofacies containing fully marine goniatite/pectionoid phases which are interpreted as marine nectonic, to productoid/*Myalina* phases which are interpreted as marine benthonic, to *Lingula*/Foraminifera phases which are interpreted as benthonic fauna which can occur in marine or

Fig. 5.6 Facies relationship diagram for Lithofacies association 1

Marine deposits

Key

-·-·-	Boundary of the associations
⟶	Transitions from Markov Chain analysis
- - →	Transitions from visual observations of borehole core



Lithofacies present

1.1 Mudstone, massive, medium to dark grey

1.3 Mudstone, massive dark grey to black

1.4 Mudstone massive with marine/brackish fauna

10.0 Coal (lithofacies unspecified)

Lithofacies associations present

L.A. 2A Lacustrine suspension deposits

L.A. 4B Very poorly drained siliciclastic dominated palaeosol/s.

brackish water. Finally these lithofacies pass laterally into those which contain fish remains and non-marine bivalves. These changes can be illustrated vertically by reference to an example from both the Aegir and Vanderbeckei M.B's in the Warwickshire Coalfield (Figs.5.7A,B) As may be expected the thickness of M.B. lithofacies vary, although they are not necessarily at their thickest either at their most marine or in the Pennine basin depocentre e.g. Subcrenatum M.B. (Calver, 1968, p.18).

Distribution of marine phases within Namurian M.B. found in the Warwickshire Coalfield has already been carried out by Ramsbottom (in Taylor and Rushton, 1971) where goniatite/pectinoid, calcareous brachiopod and *Lingula* phases were recognised. Since Calver (1968) plotted the distribution of Westphalian M.B. exploration in Warwickshire has continued so that a more comprehensive and accurate account can now be given.

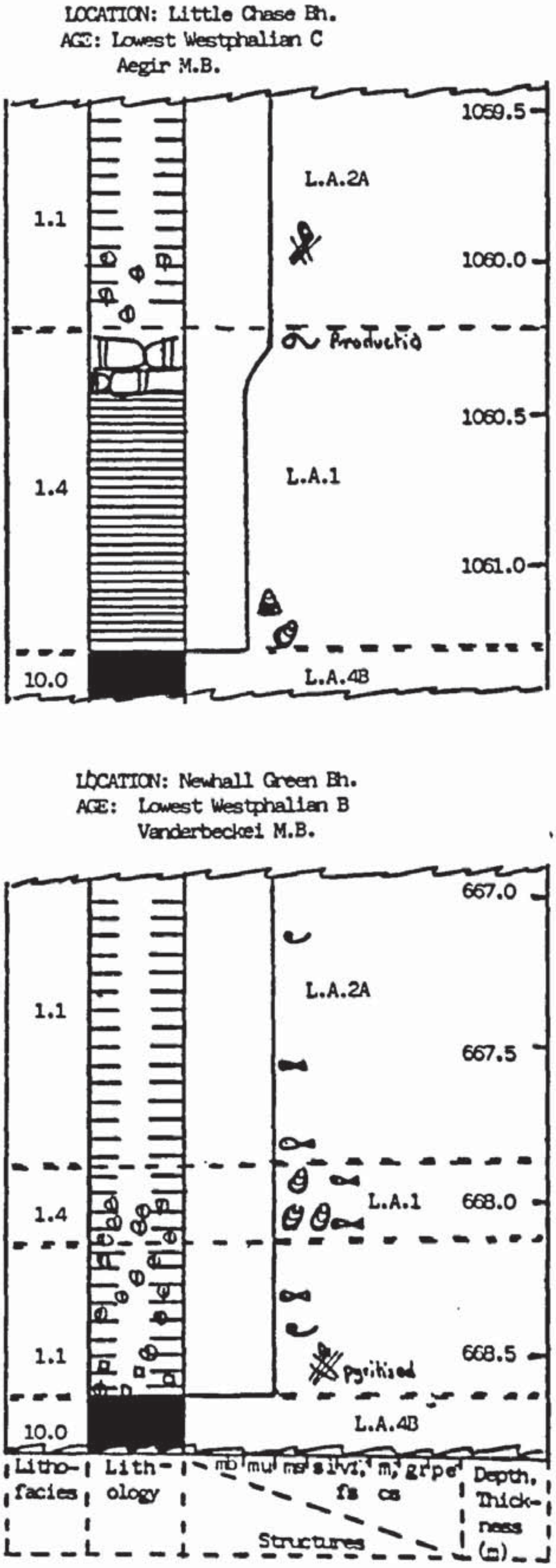
1) Subcrenatum M.B.

The only borehole in the Warwickshire Coalfield in which it is probable tht the Subcrenatum M.B. exists, lies in the extreme north at Statfold borehole. It has tentatively been identified by Taylor and Rushton (1971) although only the *Lingula* phase exists. To the south-east the same authors conjectured that this M.B. existed in Merevale No.2 borehole although some doubt concerning its identification exists (see Listeri M.B.). It appears therefore that the southern limit of this M.B. may lie farther north in the Warwickshire Coalfield than shown by Calver (1968) (Fig.5.8).

2) Listeri M.B.

The *Lingula*/Foraminera phases of this M.B. have tentatively been identified in three boreholes in the north of the Coalfield (Taylor and Rushton, 1971). In the most northern borehole it lies about 3m

Fig. 5.7 Examples of Lithofacies association 1 'Marine deposits'



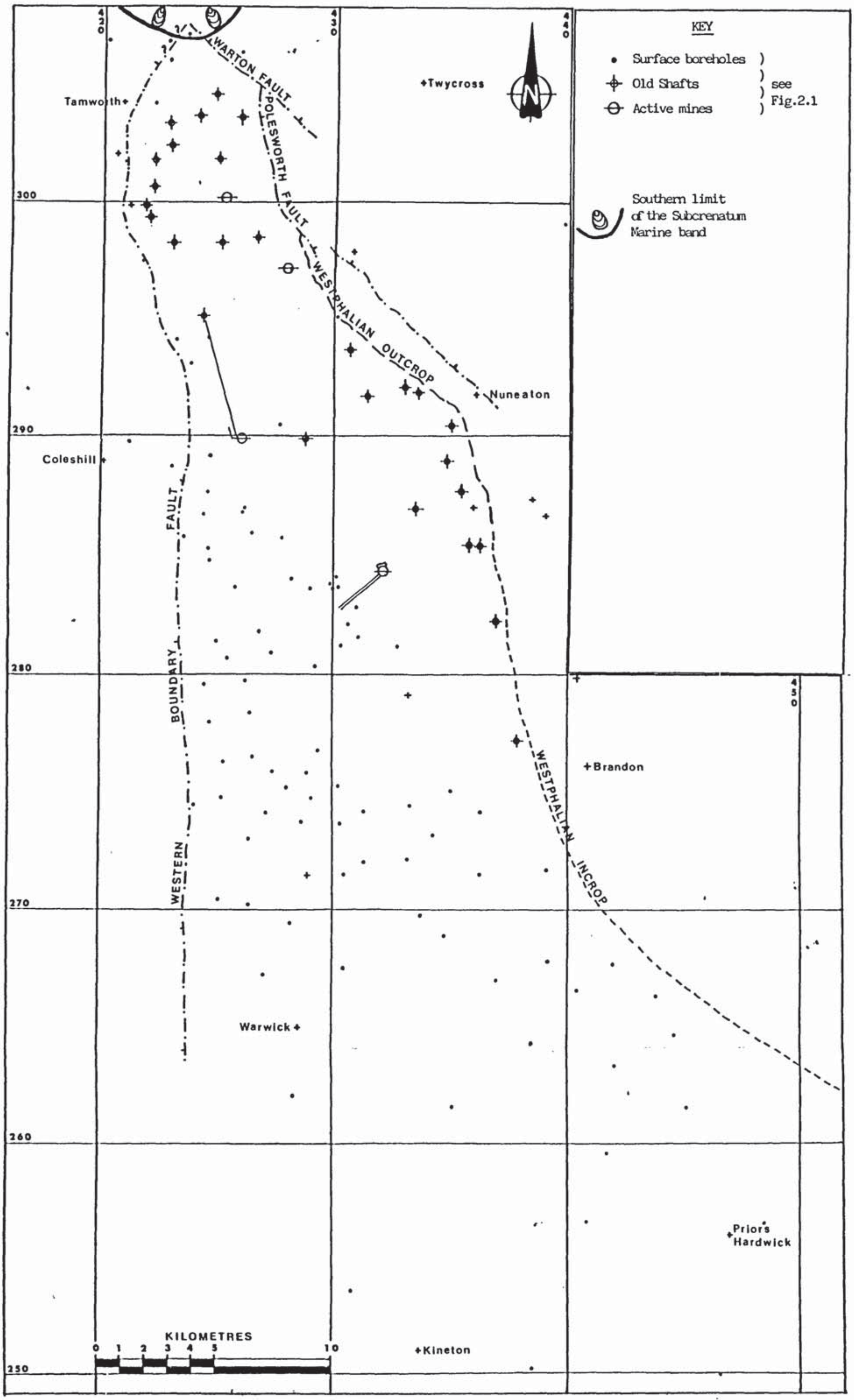


Fig.5.8 Areal extent of the Subcrenatum M.B. in the Warwickshire Coalfield

above the Subcrenatum M.B. and thus the map of Calver (1968, p.9) needs emendation (see below). Farther south at Whitehouse Farm borehole the *Lingula* phase of this M.B. has tentatively been identified (Fig.5.9). It may be that the M.B. in Merevale No.2 borehole which Taylor and Rushton (1971) conjectured was the Subcrenatum M.B. is infact the Listeri M.B. Although Calver (1968) did not recognise the Listeri M.B. in Warwickshire, the southern limit of its *Lingula* phase in this Coalfield corresponds well with the southern limit in the adjacent S. Staffordshire Coalfield (Calver 1968 p.24).

3) Vanderbeckei M.B. (Seven Feet M.B.)

Calver (1968) used information from Mitchell *et al.* (1942) to trace the productoid and *Lingula* phases of this M.B. It may also be possible to identify a *Myalina* phase from fauna collected by Vernon (1912) and data provided by Mitchell *et al.* (1942) although its southern limit is very tentative (Fig. 5.10). From this figure it can be seen that the productoid phase (Calver 1968) corresponds well with the productoid and Myalina phases in this work. The southern extent of the *Lingula* phase can now be more accurately determined (Fig.5.10) although it accords fairly well with that of Calver (1968 p.38). Farther south a rapid lateral transition occurs firstly to lacustrine 'Mudstone' lithofacies containing non-marine bivalves and then into 'Seatearth' lithofacies. This transition is presumed to be related to the proximity of the Wales-Brabant Barrier. However, in Holmes House borehole in the southeast of the Coalfield a M.B. has been identified which has tentatively been correlated with the Vanderbeckei M.B. (N. Riley 1982 and pers. comm. 1986). It is possible that this part of the M.B. was derived from a southerly source and further investigation is required.

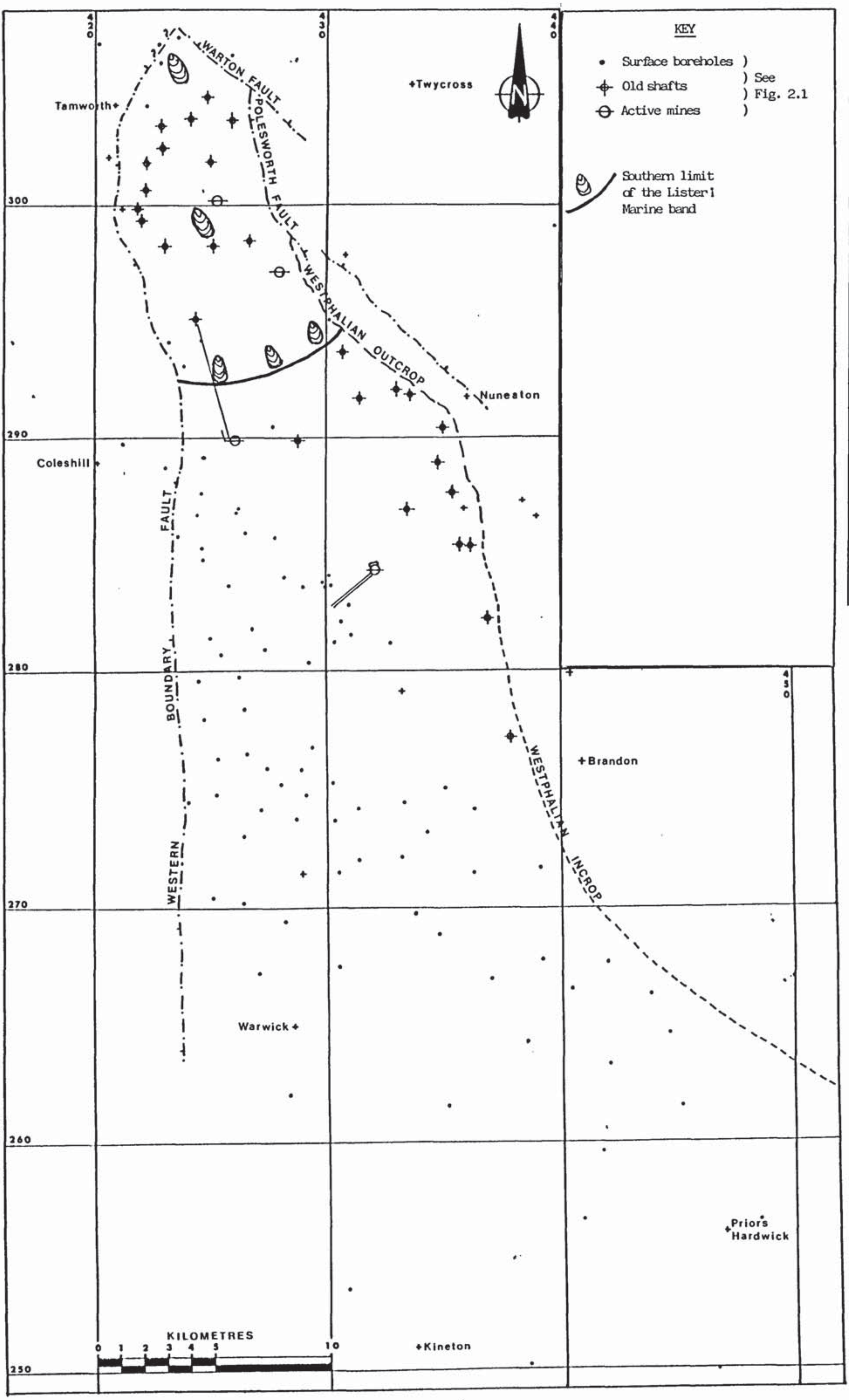


Fig. 5.9 Areal extent of the Listeri M.B. in the Warwickshire Coalfield

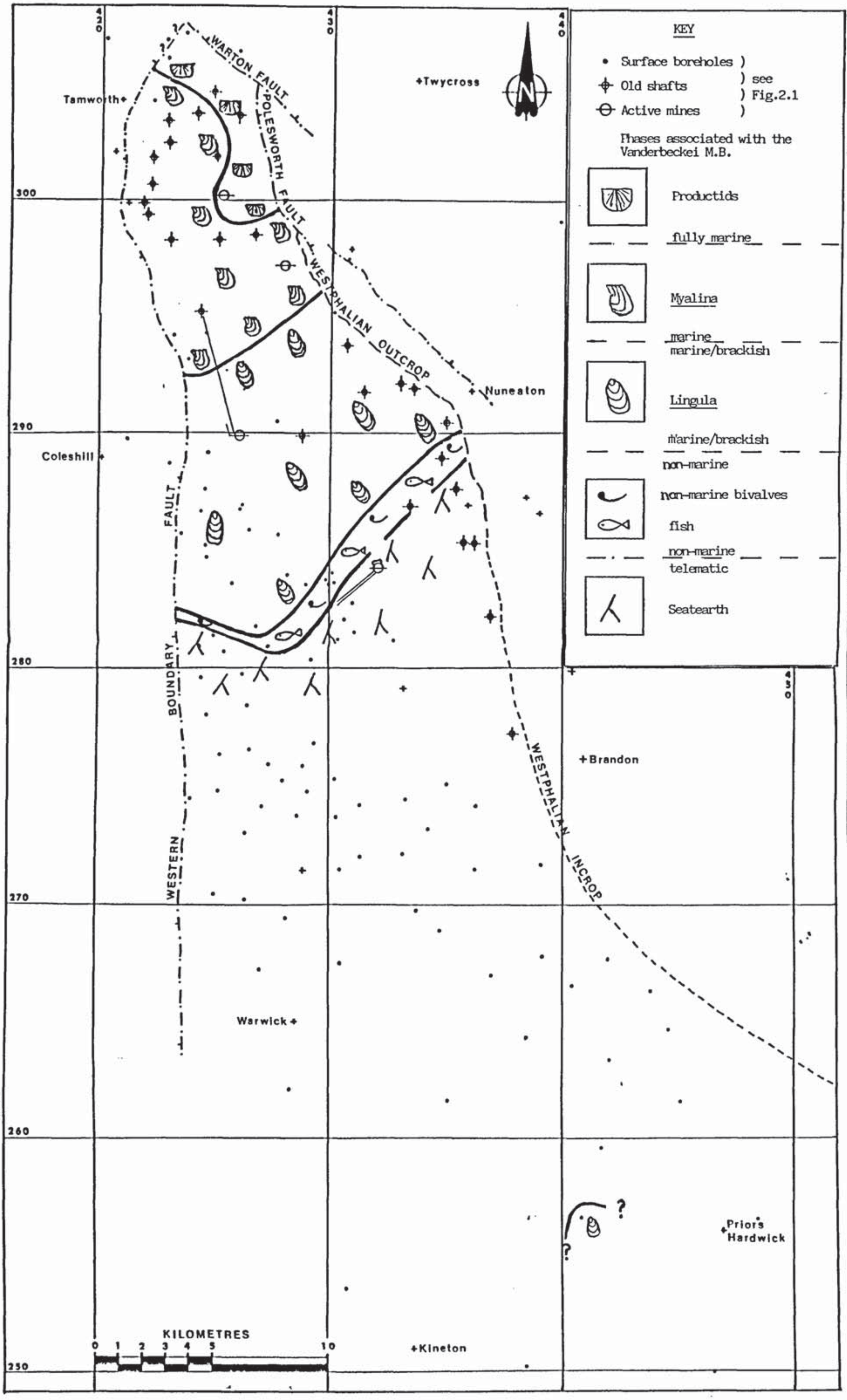


Fig. 5.10 Areal extent and distribution of phases in the Vanderbeckei Marine Band in the Warwickshire Coalfield

4) Maltby M.B. (Four Feet M.B.)

Above the Four Feet seam over the majority of the Coalfield a massive black mudstone or siltstone containing pyrite occurs. Very sparse faunal remains are associated with it, usually restricted to fish spines and scales, and occasionally ostracods and non-marine bivalves occur. Rarely Lingula has been observed in boreholes in the centre of the Coalfield e.g. Rookery Farm, Woodcock Wood. Due to the lack of an associated workable coal seam this horizon has not been studied in detail in the north of the Coalfield, where perhaps the fauna may be more abundant. Non-marine bivalves are more in evidence in the south of the Coalfield. The features listed above lead the author to believe that this horizon may be on the marine/brackish boundary of one of the M.B's between the Vanderbeckei and Aegir M.B's.

Both the Haughton and Maltby M.B's were recognised by Mitchell and Stubblefield (1948) in the South Derbyshire Coalfield. The Haughton M.B. consists of a dark grey mudstone with a fauna consistent with productoid phase i.e. Levipustula, Orbiculoidea, Lingula and crinoids (Calver 1968 p.45) and occurs just below the Aegir M.B. Some distance below this the Maltby M.B. occurs and consists of a pyritous black mudstone containing a fauna of Myalina, Lingula and foraminifera. The Maltby M.B. has also been recognised in the S. Staffordshire Coalfield where Lingula was found in Hampstead No.1 borehole.

As the Four Feet M.B. occurs several cycles below the Aegir M.B. and consists of a black pyritous mudstone or siltstone, with Lingula the only representative of marine/brackish conditions, it would appear that this M.B. is most likely to be equivalent to the Maltby M.B.

Aegir M.B. (Nuneaton M.B.)

This M.B. was not mapped by Calver (1968) but he showed that it typically contains a rich benthonic and nektonic fauna, as found in the northeast of the Warwickshire Coalfield (Mitchell *et al.* 1942). In a similar way to the Four Feet M.B., a lack of workable coal seams near the Aegir M.B. means that little information about it has been collected in the northern part of the Coalfield. Further south the productoid phase of this M.B. has been identified in many boreholes (Fig.5.11).

From Fig.5.11 it can be seen that in both the northwest and southeast lateral transitions occur from mudstones containing the productoid phase to those containing *Lingula*, and then to a presumed non-marine phase with dark grey pyritous mudstones containing fish remains. Finally the assumed horizon of the M.B. is replaced by 'Seatearth' lithofacies. In the southeast this change may be attributed to the presence of the Brabant Barrier which may have been topographically higher than the area farther north. Similarly it is also possible that a topographic high existed in the northeast of the Coalfield. In both cases the M.B. is closely followed by reddened sediments in contrast to the central area in which grey sediments persist for some thickness above the M.B.

The method of formation of this lithofacies association is believed to involve a mechanism operating beyond the Pennine Basin. It is possible that eustatic rises in sea level similar to those invoked for the development of Namurian M.B's (Ramsbottom 1977) were also responsible for the Westphalian M.B's. In the Warwickshire Coalfield they occur frequently in the Namurian and Lower Westphalian A but are very infrequent in the Westphalian B, and C.

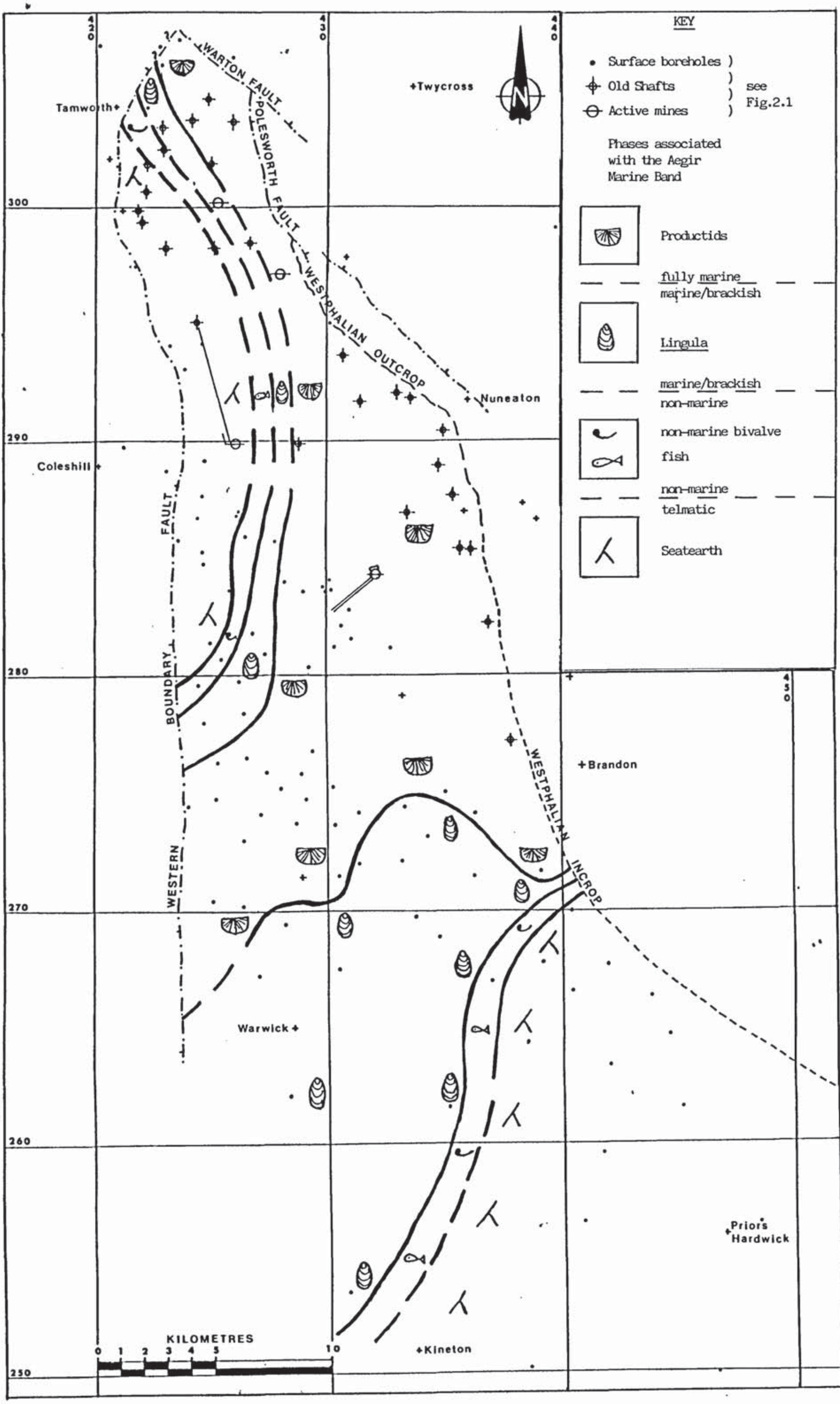


Fig. 5.11 Areal extend and distribution of phases in the Aegir M.B. in the Warwickshire Coalfield

5.4.2 Lithofacies association 2A

Lacustrine suspension deposits

This association is clearly defined by the F.R.D. constructed following M.C.A., although it is divided into two groups (Fig.5.12). Over much of the area above the Two Yard seam the fine grained group of this lithofacies association is well represented usually commencing with 'Mudstone dark grey to black' and passing upwards into 'Mudstone parallel stratified dark grey to black and medium grey'. Where this lithofacies is thick e.g. Moat House Farm borehole 2.25m (Fig.5.13A) the thickness of the dark grey to black laminae can be seen to be relatively constant between 1-3mm (apart from the top where they become thin and diffuse), whereas the interval between them of medium grey mudstone increases from 1-3mm at the base to greater than 10mm upwards. Above this a variety of lithofacies occur, either of similar grain size (Fig.5.13A) or similar lithofacies of coarser grain size (Fig.5.13B) or coarser lithofacies (Fig.5.14A). Alternatively 'Mudstone parallel stratified dark grey to black and medium grey' may pass upwards into another association (Fig.5.15B). Occasionally the association above the Two Yard seam is not of this type and 'Mudstone dark grey to black' passes upwards into other lithofacies of this association e.g. Fig.5.15A. Other well developed fine grained examples of this association occur e.g. above the Four Feet seam Fig. 5.14B in those instances which can be considered non-marine.

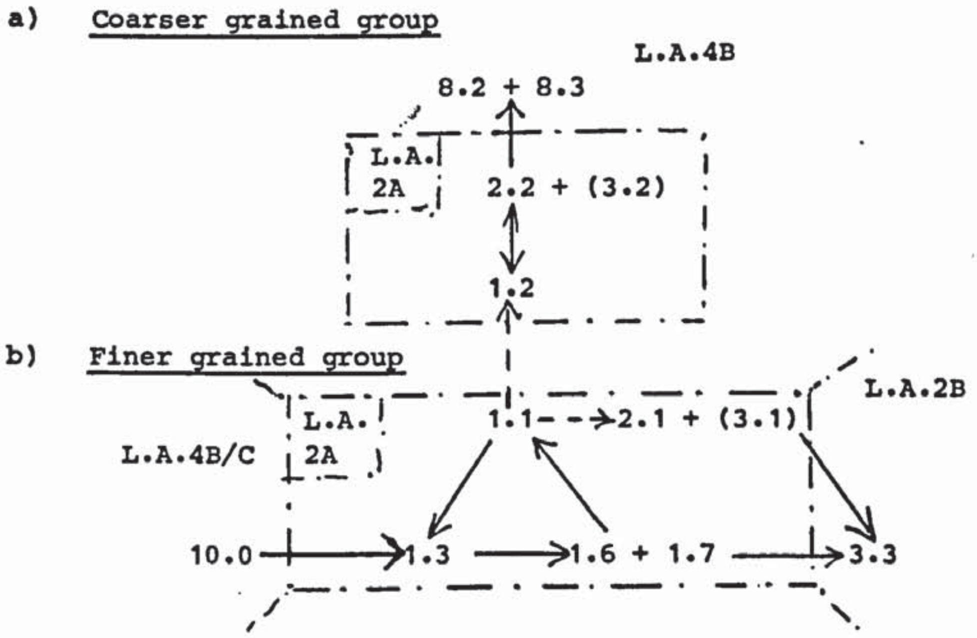
Although previous examples of the fine grained group of this association contained coarser grained lithofacies towards their tops, it is possible for this association to be characterised by a greater proportion of coarser grained lithofacies and abundant plant fragments similar to the coarser grained group shown in Fig.5.12. In these cases the association often coarsens upwards e.g. Fig. 5.16B, 5.16C.

Fig.5.12 Facies relationship diagram for Lithofacies association 2A

Lacustrine suspension deposits

Key

—·—·—	Boundary of the associations
——→	Transitions from Markov Chain analysis
- - →	Transitions from visual observations of borehole core


a) Coarser grained group

b) Finer grained group

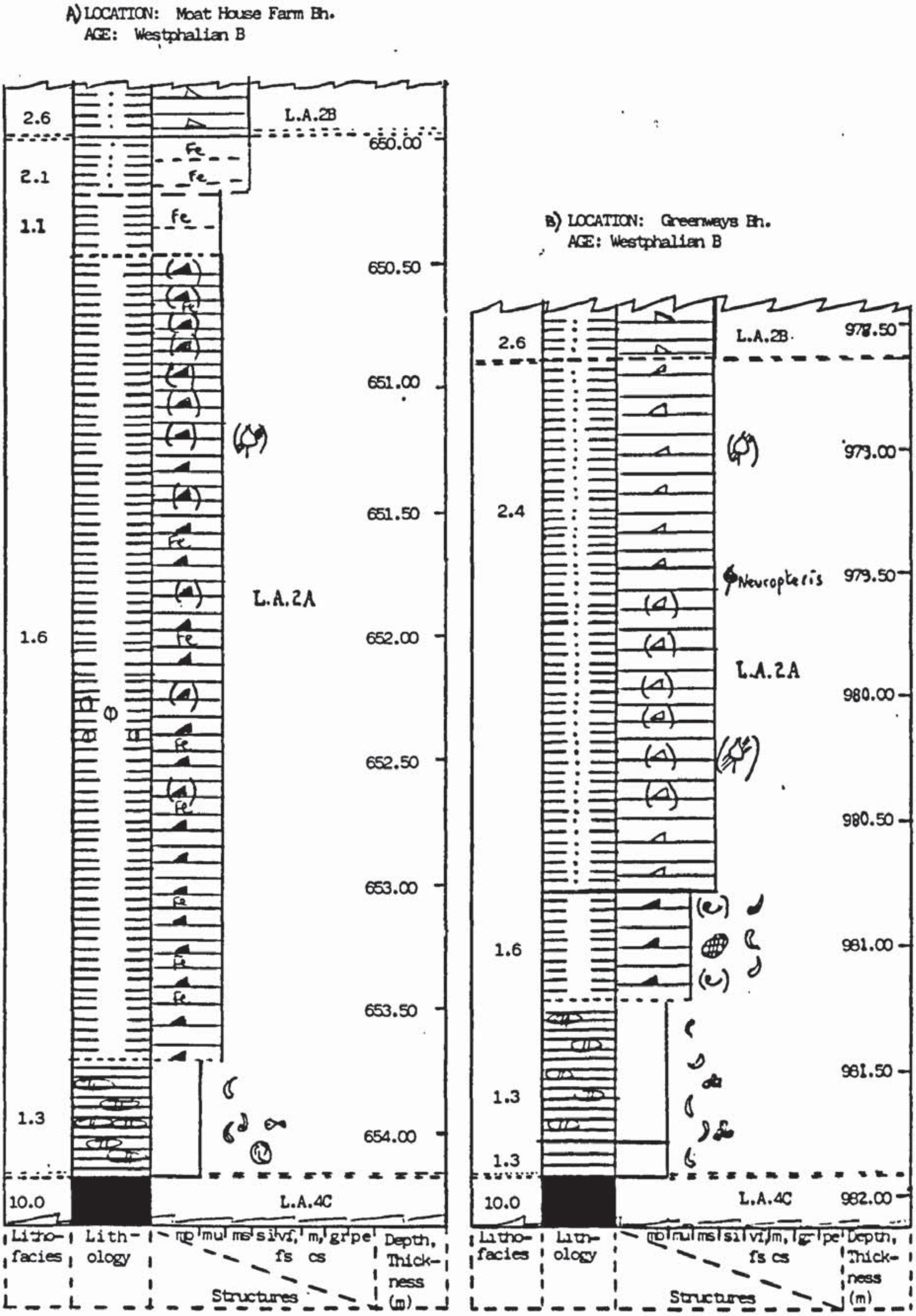
Lithofacies present

1.1	Mudstone, massive medium to dark grey
1.2	Mudstone, massive, with abundant plant fragments
1.3	Mudstone, massive, dark grey to black
1.6	Mudstone, parallel stratified dark grey to black/medium grey
1.7	Mudstone, medium grey with dark grey mudstone lenses
2.1	Mudstone silty, massive medium to dark grey
2.2	Mudstone silty, massive with abundant plant fragments
3.1	Siltstone, massive, pale to medium grey
3.2	Siltstone, massive, with abundant plant fragments
3.3	Siltstone, parallel stratified with sandstone
8.2	Seatearth, mudstone silty, grey
8.3	Seatearth, siltstone grey
10.0	Coal (lithofacies unspecified)

Lithofacies associations present

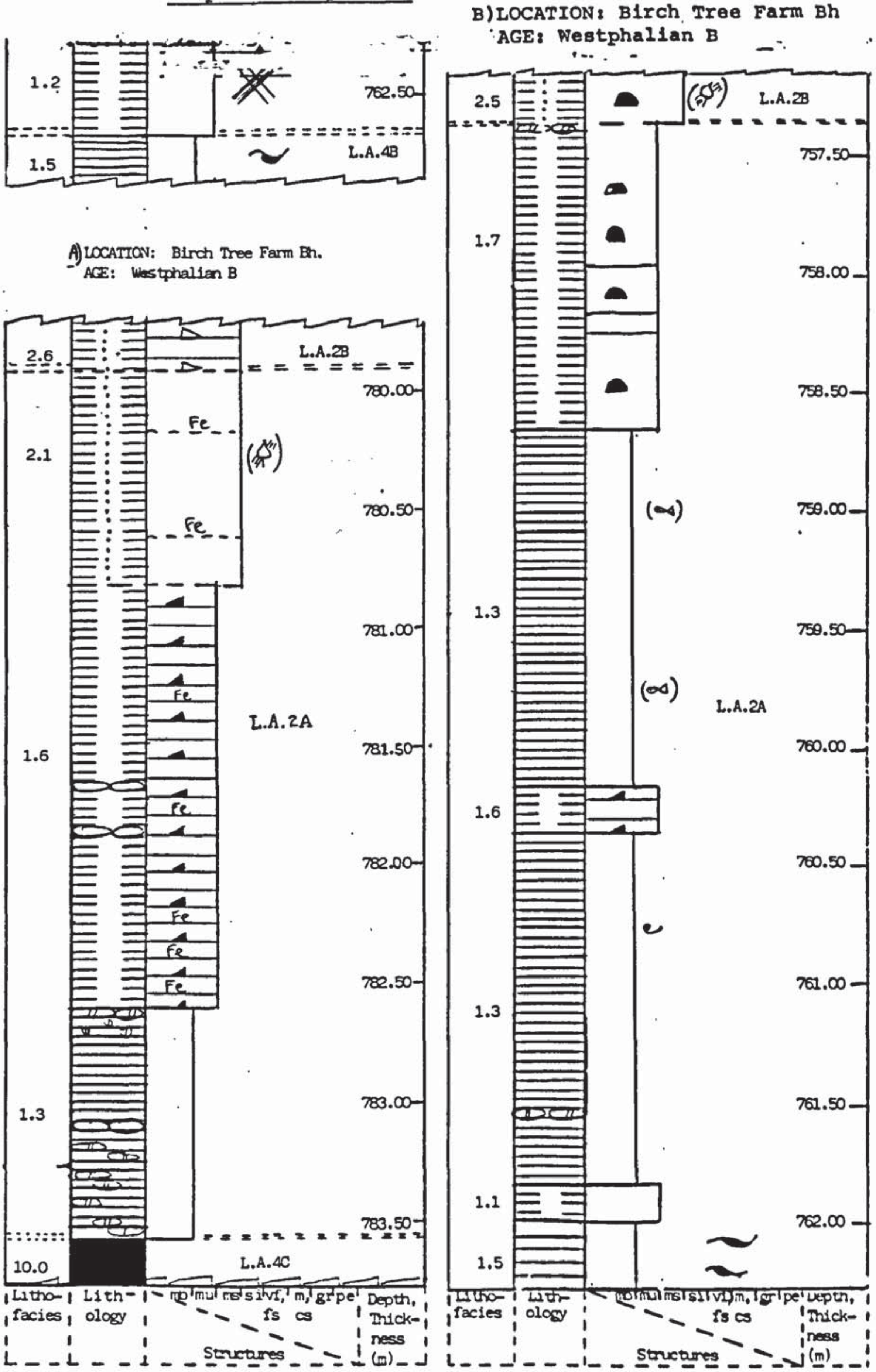
L.A.2B	Lacustrine dominantly coarsening upwards deposits
L.A.4B	Very poorly drained siliciclastic dominated palaeosols/s
L.A.4C	Long-residence histosol/s

Fig. 5.13 Examples of Lithofacies association 2A, 'Lacustrine suspension deposits'


A) LOCATION: Moat House Farm Bh.
AGE: Westphalian B

B) LOCATION: Greenways Bh.
AGE: Westphalian B

Fig. 5.14 Examples of Lithofacies association 2A, 'Lacustrine suspension deposits'


B)LOCATION: Birch Tree Farm Bh
AGE: Westphalian B

A)LOCATION: Birch Tree Farm Bh.
AGE: Westphalian B

Fig. 5.15 Examples of Lithofacies association 2A 'Lacustrine suspension deposits'

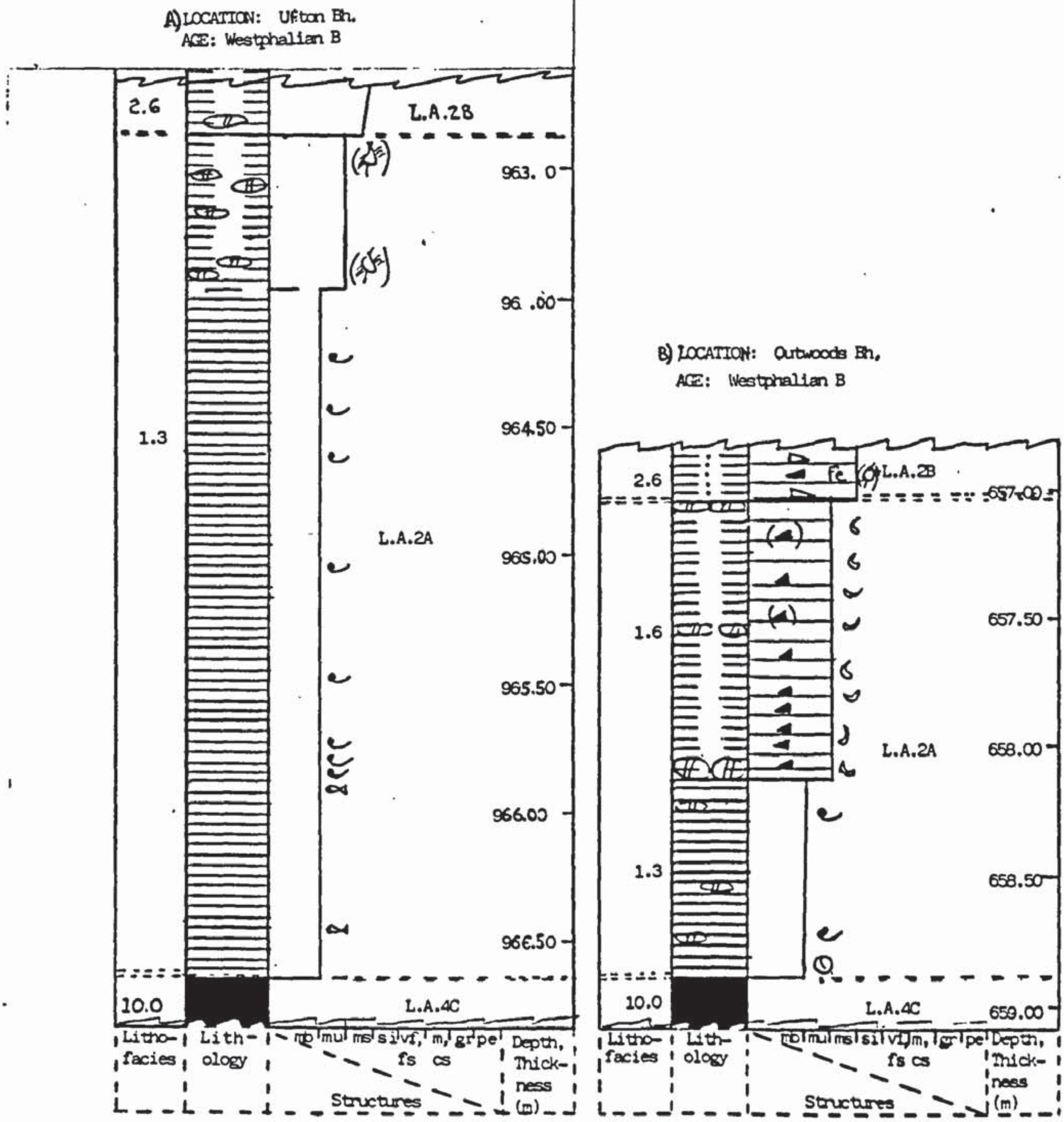
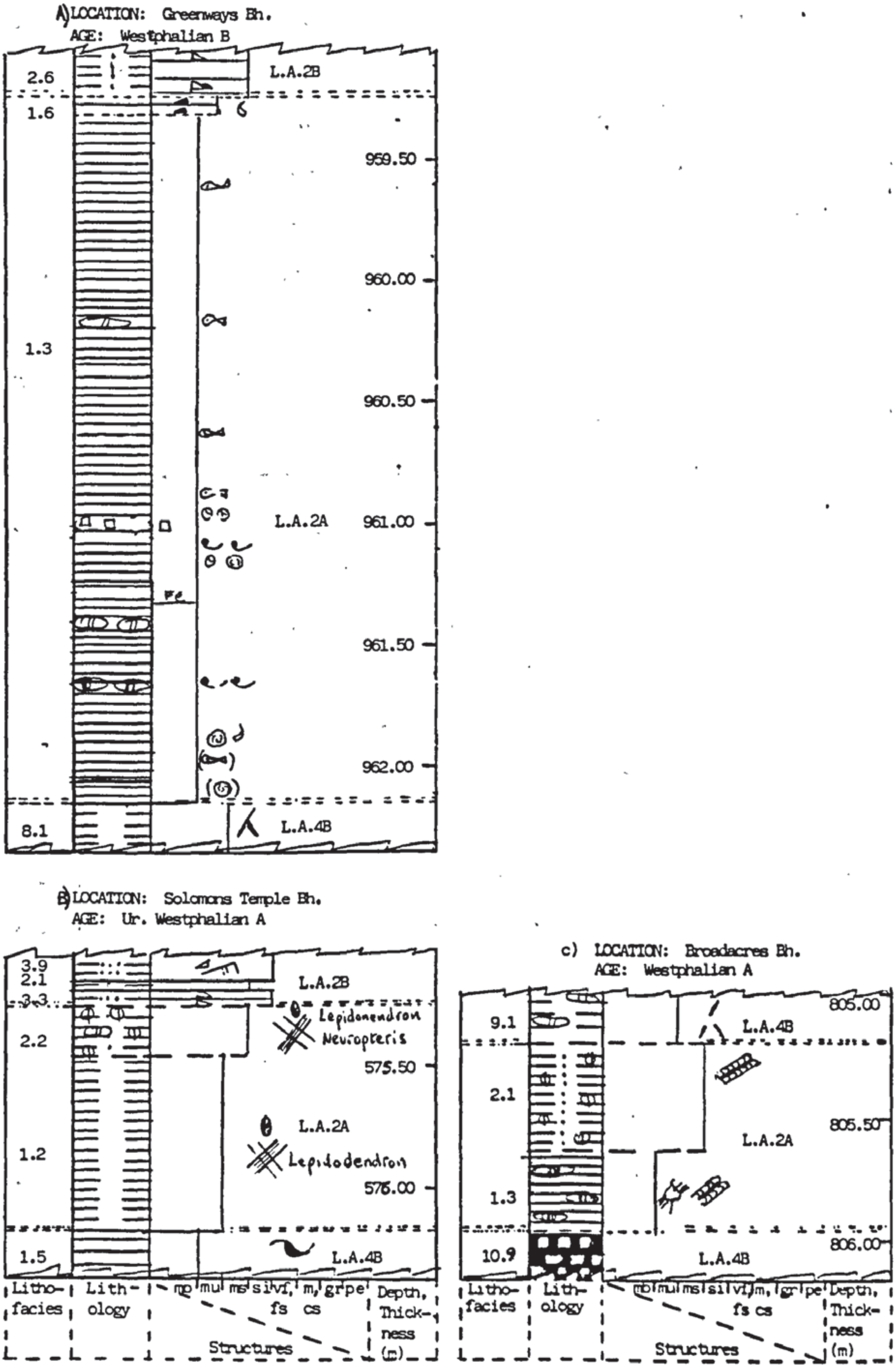


Fig. 5.16 Examples of Lithofacies association 2A 'Lacustrine suspension deposits'



This association is distinguished from other lacustrine associations by its fine grained nature and lack of evidence of tractional movement of sediment.

In the majority of cases this association is underlain by palaesol associations principally 'Very poorly drained siliciclastic dominated palaeosol/s' or 'Long-residence histosols'. The coarsening upwards variety of this latter association most often overlies 'Lacustrine suspension deposits' although occasionally it is overlain by palaeosol associations.

Similar associations have been recognised by other workers on Westphalian sediments in the Pennine Basin. The faunal mudstone facies of Elliott (1968) is comparable except that he included Lingula bands and siltstone lithofacies within it. Fielding (1982) described a facies ('Quiet water claystones') similar to that of Elliott (1968) but later (Fielding 1984a) divided it into two facies 'Anoxic lake floor' which corresponds to the lithofacies 'Mudstone dark grey to black' and 'Outer minor delta/overbank claystones' which corresponds partly to this association and partly to the following association 'Lacustrine coarsening upwards deposits'. This was because Fielding (1984a) recognised claystone containing layers of sandstone, a combination which does not occur in the rocks of the Warwickshire Coalfield. Haszeldine (1984a) described 'Black mudstones' which are examples of the lithofacies 'Mudstone dark grey to black'. The overlying 'Rythmite muds' display characteristics of erosion and tractional sediment movement, and whilst superficially resembling 'Mudstone parallel stratified dark grey to black and medium grey' would be exluded from the association under consideration. Scott (1976, 1978) illustrated an association corresponding to this one under the heading 'Pro-delta lake clays'. These are similar to deposits described as 'Pro-delta silty clays by Coleman et al. (1964) and Coleman and Prior (1980) of the Mississippi delta and the 'Lacustrine deposits' of the Atchafalaya basin described by Coleman (1966). Yuretich (1979) studied laminated sediments within a tropical African rift lake which resemble those of the lithofacies 'Mudstone parallel stratified dark grey to black and medium grey'.

Interpretation

The interpretation of the lithofacies constituting this assocation demonstrate that it was formed by the accumulation of sediment deposited from suspension in the same way that the two equivalent facies of Fielding (1984a) were formed.

The palaeosol associations which usually underlie this association (Figs.5.15, 5.16A, 5.17, 5.18C) are characteristic of near terrestial (telmatic) conditions. Where this is the case it is envisaged that relatively rapid subsidence caused the creation of a lake. The size of the lake was governed by the area over which rapid subsidence occurred, aided by the extent of the flat lying palaeosol associations, especially that of 'Long-residence histosol/s'. In the case of this association above the Two Yard seam it is likely that the size of the lake was in excess of the size of the Coalfield i.e. 850 km^2. Other lakes are expected to be much smaller, similar to those observed by Coleman (1966). Enlargement of lakes may be caused by wind initiated wave action as described by Coleman (1966). The depth of lakes is discussed in the section on 'Lacustrine thickly interbedded coarse and fine deposits'.

It is possible that at first the majority of channels draining into lakes contained organic rich sediment derived from nearby histosols forming the lithofacies 'Mudstone dark grey to black' (Figs. 5.13-16). This may be because the vegetation forming the histosol caused channels carrying organic poor sediment to divert elsewhere (see section on 'Long-residence histosol/s'). 'Mudstone dark grey to black' continued to accumulate as long as the effects of channels remained a great distance away. Haszeldine (1984) believed that his 'Black mudstones' accumulated very slowly i.e. 5mm/10^4 yr based on the lifespan of bivalves. The thickest occurrence of the equivalent lithofacies above the Four Feet seam is at Greenways borehole (Fig. 5.18A) which means that this may have taken up to 5.7 x 10^5 yrs to accumulate. This appears to be a very slow rate of sedimentation for an active depositional environment, especially compared with other lithofacies in this association and a variety of other lakes (Johnson 1984) where sedimentation vaies from 0.1 to greater than 1mm/yr.

Two possible interpretations were given in the relevant lithofacies section for the overlying 'Mudstone parallel stratified dark grey to black and medium grey' and these can be analysed in the context of the association in which they occur. If seasonal overturn was responsible for the lithological alternations it is difficult to understand why they should be no evidence for this in the under- or overlying lithofacies, or why it should suddenly start and then cease within the lithofacies association. A more plausible explanation is that the ligher laminae represent distant flood events either as a result of channel related processes i.e. overbank flooding, crevassing or progradation of distributary mouth bars. Initially it is possible that these laminae represent seasonal flood events perhaps at the start of the wet season. Yuretich (1979) also believed the laminae he observed represented seasonal flooding of the Omo river, although he thought that the lithological alternation could be due to differential settling. It is believed by the author that the boundary within the couplet would be more gradational if this was the case. Increase in thickness of the ligher organic poor laminae upwards (Figs. 5.13A, 5.14A) may be attributed to increasing proximity of this sediment source. Relative constancy of the dark grey to black mudstone laminae may relate to uniform input over similar time periods. Spears (1969) suggested that these couplets may be annual but if there were two wet seasons/yr it is possible that near the base of the lithofacies each couplet may be biannual. If this were true, then rates of sedimentation at the base of the lithofacies may be between 5-9mm/yr rising to in excess of 15mm/yr at the top of this lithofacies. At the top of this lithofacies flood events other than those of a seasonal nature may be recorded resulting in this diffuse dark grey to black mudstone laminae near the top. Preservation of the laminae is probably due to anoxic conditions existing just below the sediment/water interface.

Klein (1974) proposed that the thickness of lacustrine sediment separating root penetrated horizons was equivalent to the maximum depth of the lake which was infilled. Fielding (1982) argued that the method adopted by Klein (1974) was unsuitable for Westphalian lakes because of the slow rate of accumulation of clays (muds) at the base of the lacustrine fills. For this reason he excluded claystone (mudstone) lithofacies from the calculations so that only those appearing in the association 'Lacustrine dominantly coarsening upwards deposits' would be used. It appears however from the possible rapid rate of deposition of the lithofacies 'Mudstone parallel stratified dark grey to black/medium grey' that its thickness should be included in the calculation.

Assuming that the rate of subsidence exceeds that of deposition and that the rate of movement of channels and related processes together with the deposition rate are constant, then the thickness of this lithofacies can be inversely related to the proximity of the channels producing the organic poor sediment. A larger distance to the channels is envisaged at Moat House Farm borehole (Fig. 5.13A) than at Outwoods borehole (Fig. 5.15B).

If the lithofacies 'Mudstone dark grey to black' in the area near Ufton borehole (Fig. 5.15A) was accumulating at the same time that both this lithofacies and 'Mudstone parallel stratified dark grey to black and medium grey' were being deposited farther north at e.g. Moat House Farm borehole, then it is possible that the channels were moving from north to south.

Above this latter lithofacies the presence of massive or coarser lithofacies indicates increasing proximity of channels, with more continuous flooding often on a non-seasonal basis masking input from organic rich channels.

Examples of this association without some of the preceeding fine grained lithofacies demonstrate the proximity of channels feeding organic poor sediment into a lake at an early stage with (Fig. 5.16C) or without (Fig.5.16B) the formation of an anoxic environment. The example at Birch Tree Farm (Fig.5.14B) illustrates that the transition from a telmatic to a lacustrine environment was at first near to a source of organic poor sediment, which was apparently cut off to allow the formation of a large thickness of the lithofacies 'Mudstone, dark grey to black'.

This association is likely to be found where subsidence is sustained enough to create a lake too deep for colonisation by plants, and where channels carrying organic poor sediment are at a distance. It is fairly common throughout the Westphalian of the Warwickshire Coalfield, although in the centre and southerly parts of the Coalfield it is more common the the Westphalian B than in Westphalian A.

5.4.3 Lithofacies Association 2B

Lacustrine dominantly coarsening upward deposits

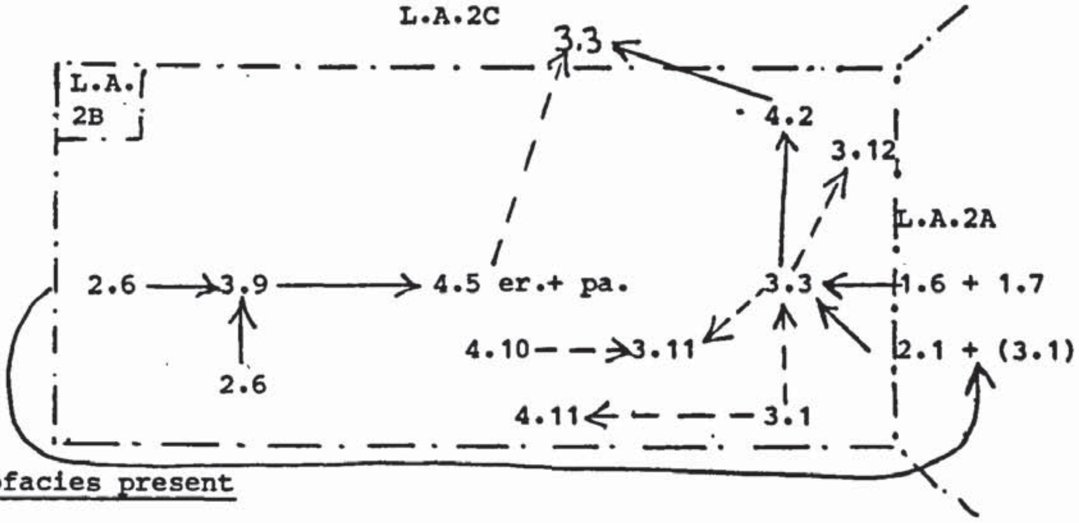
Certain aspects of this association are revealed by M.C.A. in the F.R.D. for this association (Fig.5.17), most notably a change from finer to coarser grained lithofacies. In the simplest case (Fig.5.18A) this association consists of a coarsening upwards sequence from 'Mudstone silty' lithofacies often 'Mudstone silty parallel stratified with sandstone' to a variety of 'Siltstone' lithofacies with gradational or abrupt boundaries between beds. Normally only small amounts of plant fragments are present. A range exists from Fig. 5.18B which has no 'Mudstone silty' lithofacies to Fig.5.19A which contains a thick sequence of these lithofacies at its base. Individual beds may coarsen up especially at the base of the association (Figs.5.18B, 5.21). Siltstone and sandstone lithofacies may display convolution and loading even in the thinner examples of this association (Fig.188). In many cases both convoluted and slurried lithofacies are present in the upper half of this association (Figs.5.18C, 5.21). The thicker examples of this association often contain 'Sandstone' lithofacies with gradational or abrupt bases (Figs.5.19B, 5.20, 5.18C) and rarely erosive bases (Fig. 5.18B). They are commonly trough cross laminated and may be formed of two grain sizes as is another important sandstone lithofacies in this association - 'Sandstone wavy bedded with siltstone'. Although predominantly developed in the upper half of associations (Figs.5.18B, 5.23) these sandstones may also occur throughout the association (Fig.5.18C).

Fig.5.17 Facies relationship diagram for Lithofacies association 2B

Lacustrine dominantly coarsening upwards deposits

Key

┌ ─ · ─ ┐	Boundary of the associations
⟶	Transitions from Markov Chain analysis
- - →	Transitions from visual observations of borehole core



Lithofacies present

1.6	Mudstone, parallel stratified dark grey to black/medium grey
1.7	Mudstone, medium grey with dark grey mudstone lenses
2.1	Mudstone silty, massive medium to dark grey
2.6	Mudstone silty, parallel stratified with sandstone
3.1	Siltstone, massive, pale to medium grey
3.3	Siltstone parallel stratified with sandstone
3.9	Siltstone sandstone with small scale cross stratification
3.11	Siltstone slurried
3.12	Siltstone with load structures
4.2	Sandstone, fine, wavy stratified
4.5	Sandstone, fine, with small scale cross lamination
4.10	Sandstone, fine, slurried
4.11	Sandstone, fine with load structures

Lithofacies associations present

L.A.2A	Lacustrine suspension deposits
L.A.2C	Lacustrine thickly interbedded coarse and fine deposits

Fig. 5.18 Examples of Lithofacies association 2B 'Lacustrine dominantly coarsening upwards deposits'.

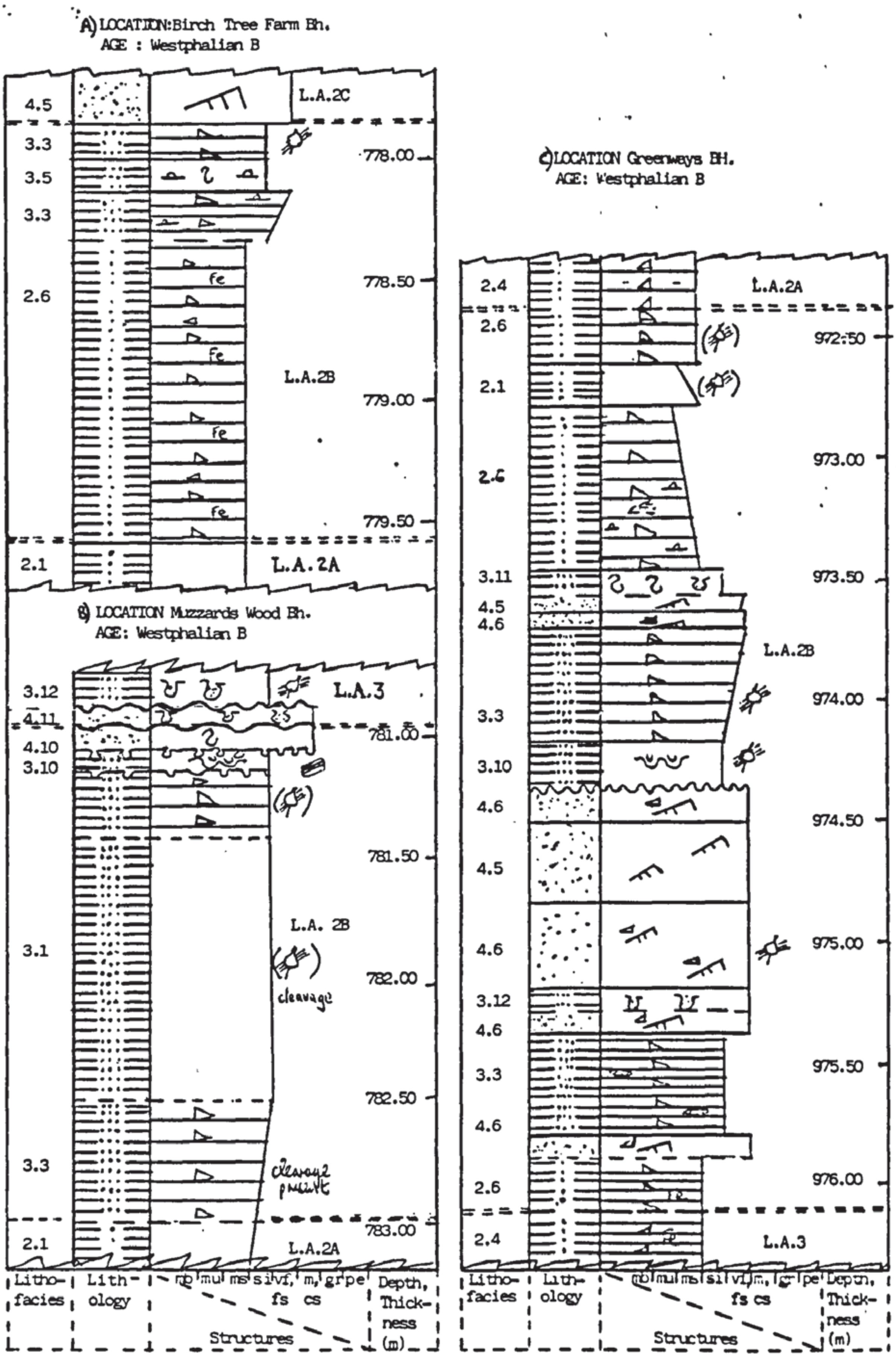
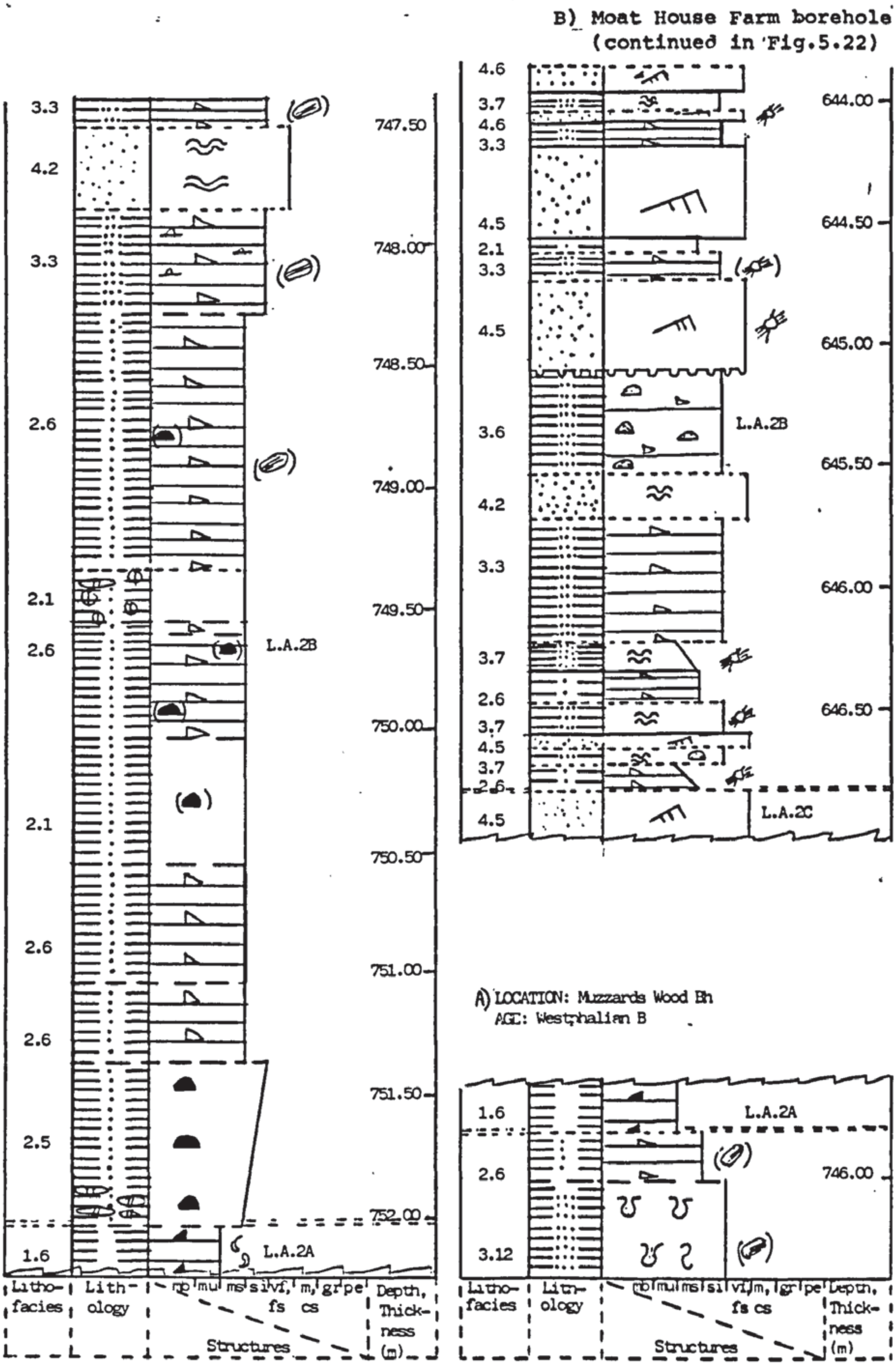


Fig. 5.19 Examples of Lithofacies association 2B 'Lacustrine dominantly coarsening upwards deposits'


B) Moat House Farm borehole (continued in Fig.5.22)

A) LOCATION: Muzzards Wood Bh
AGE: Westphalian B

Fig. 5.20 Example of Lithofacies association 2B 'Lacustrine dominantly coarsening upwards deposits'.

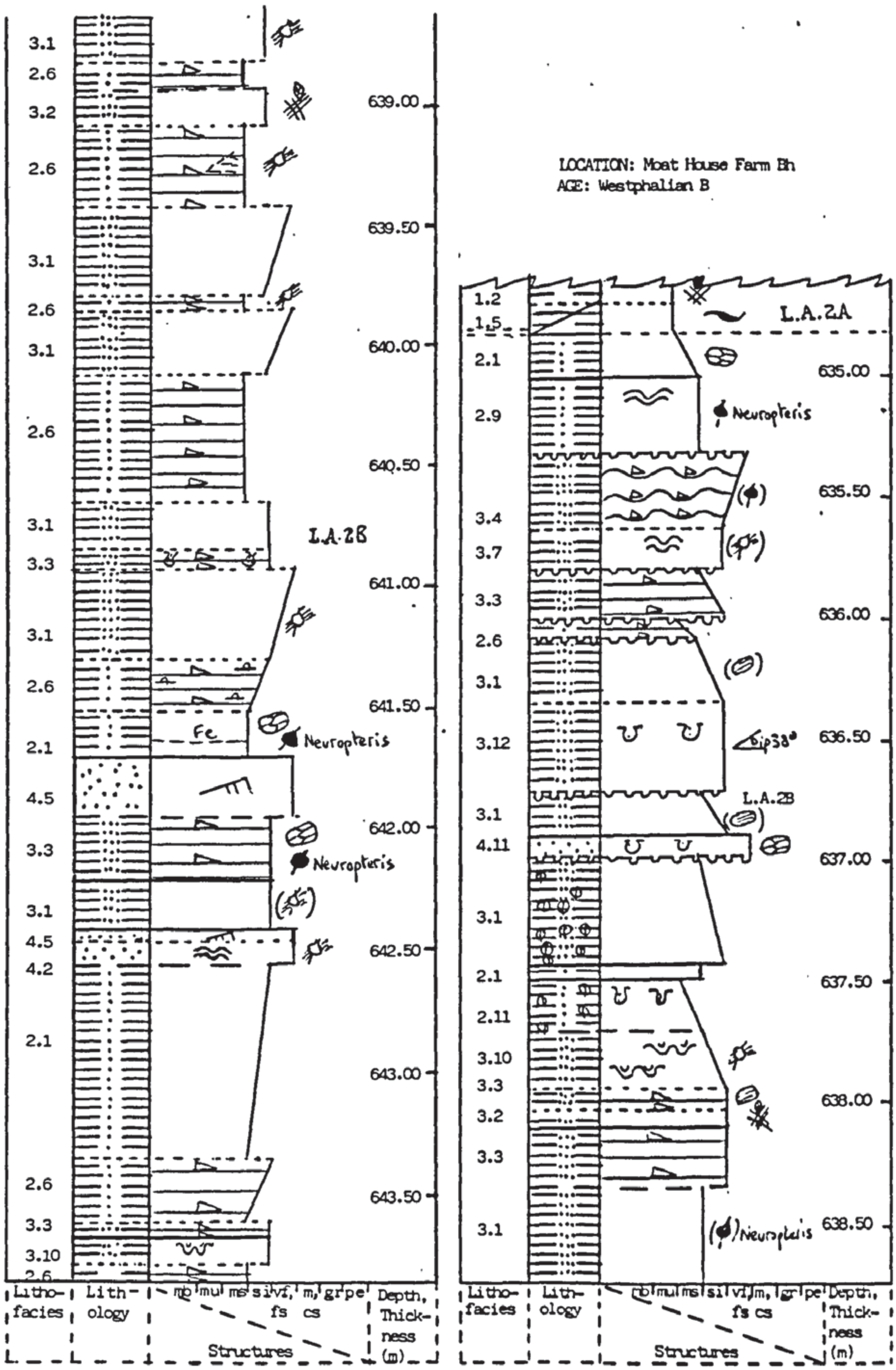
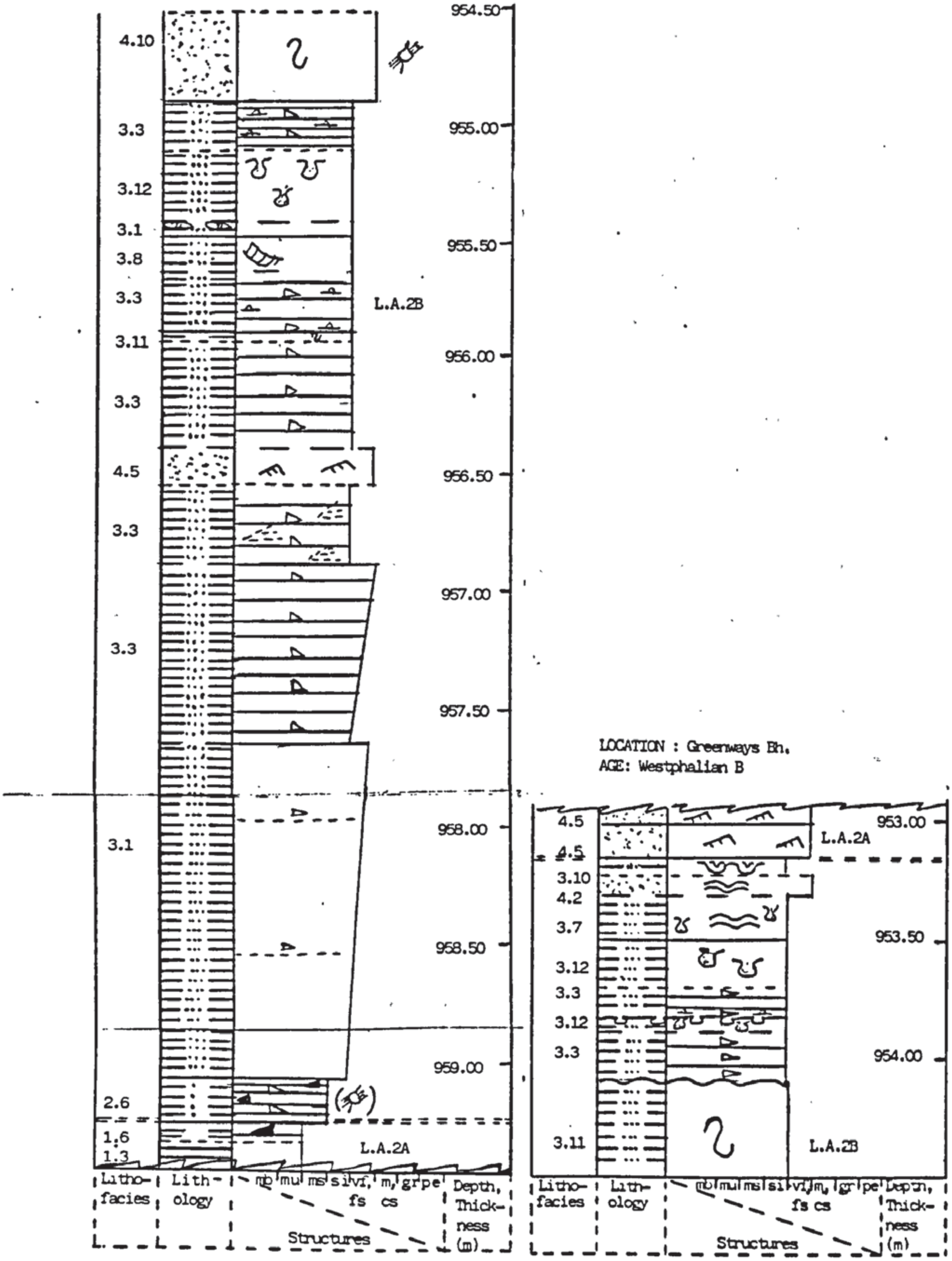


Fig. 5.21 Example of Lithofacies association 2B 'Lacustrine dominantly coarsening upwards deposits'



Previously described examples of these associations have been less than 6m, it is probable that this association could be as thin as 0.5m, although occasionally very thick examples can be found (Fig. 5.19B/5.20). On inspection this sequence may be divided into two coarsening upwards cycles. The first cycle between the base and 641.55m contains only a small amount of 'Mudstone silty' lithofacies towards the base and a few sporadic 'Sandstone' lithofacies towards the top. In contrast the second cycle contains more 'Mudstone silty' lithofacies towards the base and no sandstone lithofacies at the top. It should be noted that whilst the association and individual lithofacies often coarsen upwards, there are individual lithofacies which fine upwards. This is most noticeable in the upper cycle at Moat House Farm borehole (Fig. 5.19B/5.20).

Occasionally towards the top of this association, usually in those cases where it is overlain by a fine grained association, a distinct fining upwards is observable Figs.5.19B.5.20).

This association is distinguished from 'Lacustrine suspension deposits' by its coarser grained lithofacies and from 'Lacustrine thickly interbedded coarse and fine lithofacies' by the lack of thick 'Sandstone fine or Sandstone/siltstone with small scale cross lamination' lithofacies. It is differentiated from 'Channel fill deposits' by its coarsening upward. 'Lacustrine siltstone dominated deposits' can be distinguished from this association by some of the following characteristics viz. presence of burrows oblique to bedding, ubiquitous occurrence of stem and leaf fronds and fragments, massive nature of some of the siltstone beds and steeply dipping bedding.

Most commonly this association is underlain by 'Lacustrine suspension deposits' although other lacustrine (Fig.5.20) and 'Channel fill deposits' (Fig.5.18C) can underlie it. Palaeosol associations rarely underlie it and only occasionally overlie this association. Often it is overlain by 'Lacustrine thickly interbedded coarse and fine deposits' and rarely by 'Channel deposits'.

Elliott (1968) recognised two facies 'Rippled sandstone' and 'Flaser silt-sandstone' in the East Midlands Coalfield which may be equivalent to the majority of the lithofacies within this association. Scott (1976, 1978) recognised an association 'IB Distributary mouth bar' which corresponds closely to the coarsening upwards part of this association, although the interbedding of thin fine and coarse sediments in his association. '2B Interdistributary lake' is more typical of the upper part of this association. It may be that his association 2C Marginal lake/Delta top is similar to the fining upward part of this association, although the presence of coals and seatearths within it suggest a closer analogy with the lithofacies association 'Impoverished siliciclastic palaeosol/s'. The 'Rhythmite muds' and 'Rippled silts' facies of Haszeldine (1984) and the facies 'Distal crevasse splay/minor delta' described by (Fielding 1982, 1984a) contain lithofacies consistent with this association. In the modern environment of the Mississippi delta similar siltstone dominated deposits have been termed 'Lacustrine Delta fill' (Coleman 1966) 'Interdistributary bay' and 'Distal bar' deposits (Coleman and Prior 1980).

Interpretation

The presence of coarser grained lithofacies than 'Lacustrine suspension deposits' and upward coarsening of the association is interpreted as the result of progradation of channels and their related deposits into lakes. It is believed that much of the siltstone was deposited from suspension. The sandstone was moved as a result of tractional flow and may represent the distal portions of distributary mouth bars and crevasse splays. Elliott (1968) interpreted his 'Flaser silt-sandstone' and 'Rippled sandstone' facies as the products of interdistributary bays and outer mouth bars respectively, the latter being the explanation used by Scott (1976, 1978) for his association 'IB Distributary mouth bar'. Although similar processes were invoked by Coleman and Prior (1980) for the formation of their 'Interdistributary bay' and 'Distal bar deposits' these were probably of a much larger scale than those envisaged for the Westphalian lakes in the Warwickshire Coalfield. The lithofacies in this association resemble those attributed broadly to overbank flooding by Elliott (1974a) but formed as a combination of minor crevasse splay and overbank flooding together with sediment in suspension. Lithofacies with gradational bases suggest continual but rapid rises in the rate of water flowing whilst abrupt bases indicate episodic sedimentation. Weak currents and small quantities of sand together produce parallel laminations. Stronger currents produce higher ripples and therefore lenticular stratification and with increase in the quantity of sand and higher current velocities wavy laminations are produced. The shape of the ripples are suggestive of predominantly unidirectional currents. Fielding (1984a) believed the lack of wave formed sedimentary structures was due to a combination of factors, but given the range of lake sizes and climate it seems that lake depth and water turbidity are the most likely explanation. The cross laminated sandstone lithofacies may represent the distal end of exceptional flood events which extended farther than normal from their origin, whether from crevasse or distributary channels. As a result of waning currents still carrying sediment, some of the lithofacies fine upwards.

Lithofacies exhibiting evidence of slurrying, convolute lamination and loading have previously (see lithofacies descriptions) been interpreted as the result of initial high pore pressures maintained by pore fluids which on drainage allow a denser packing arrangement of the sediment. This may be indicative of increased rates of deposition, and as these lithofacies often occur in the upper part of the association is suggestive of a rapid progradation of sediment across the lake bottom. Coleman (1966) believed the rate of infill of the Atchafalaya lakes to be relatively rapid if they were comparable to the rates observed by Fisk (1947) in the Grand Lake. Haszledine (1984) asserted that similar lacustrine sediment accumulated at the rate of several cm/yr.

Fining upwards at the top of this association can be interpreted as the result of a decrease in current velocities because channel related processes were moving away from the location. Any increase in plant debris may be attributed to the close proximity of palaeosol lithofacies. If the lake became shallow enough for plant colonisation this association would pass upwards into a palaeosol association. Where 'Lacustrine thickly interbedded coarse and fine deposits' overlie this association they may represent part of the continuing process of progradation (see next association). However, where 'Channel fill deposits' overlie this association it is possible that the channel in which they lie was the one supplying the sediment for this association and that it has eroded medial deposits (see next association) lying between this association and the 'Channel fill deposits'.

Mapping of changes between lacustrine associations at similar stratigraphic horizons may demonstrate the direction in which channels are moving. Figs 5.19A, 5.21 are from the interval above the Four Feet seam about 6km apart, and the fact that this association is overlain by 'Lacustrine thickly interbedded fine and coarse deposits' at Greenways borehole and 'Lacustrine suspension deposits' at Muzzards Wood borehole with progressive changes between them may indicate that at this time channel related processes were migrating from the southwest towards the northeast.

It is likely that this association will be found where relatively high subsidence rates maintained lake depths beyond the reach of plant colonisation and where organic poor sediment transported in suspension and through tractional movement began to fill the lake through the operation of distant channel related processes.

5.4.4 Lithofacies Association 2C

'Lacustrine thickly interbedded coarse and fine deposits'

The F.R.D. for this association (Fig.5.22) is similar to the previous association in terms of the lithofacies present except that coarser grained lithofacies occur - 'Sandstone medium to coarse with small scale cross stratification' and also 'Sandstone fine, massive, pale grey to off white' and 'Sandstone fine, flaser stratified'. However the lack of coarsening upwards sequences and the dominance of two way transitions so that most of the fine lithofacies can pass into coarse lithofacies makes it distinctive from 'Lacustrine dominantly coarsening upwards deposits'.

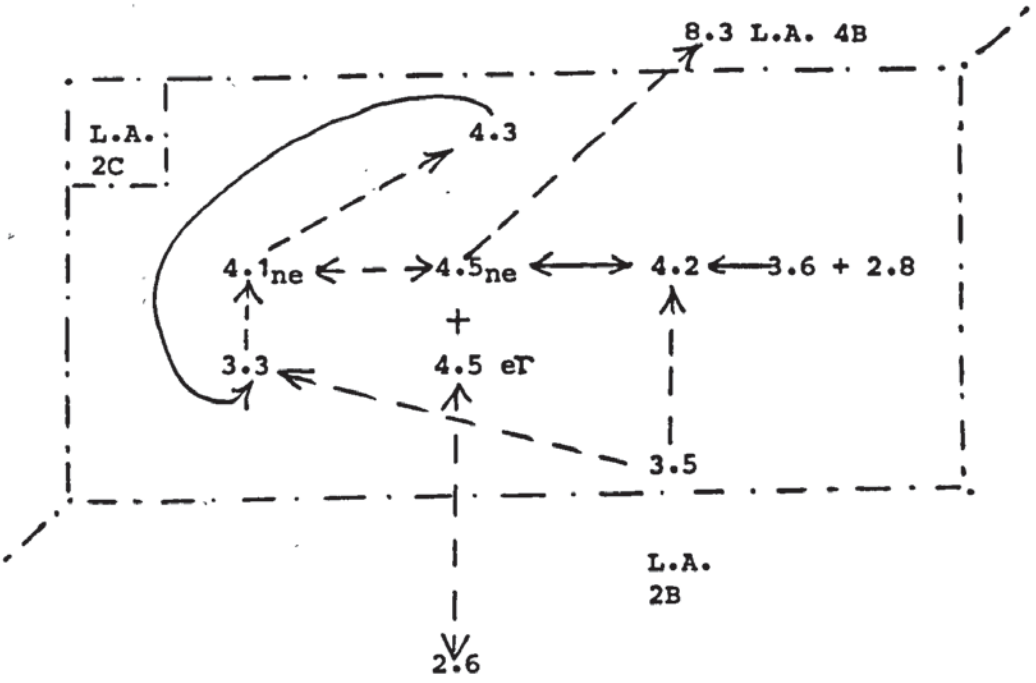
The base of this association is often marked by a 'Sandstone fine' lithofacies greater than 0.3m thick (Figs. 5.23, 5.24B) or if slightly less thick it may be a 'Sandstone, medium to coarse' lithofacies (Fig. 5.24A). Above this lithofacies are a sequence of alternating fine and coarse lithofacies. Some of the siltstone

Fig.5.22 Facies relationship diagram for Lithofacies association 2C

Lacustrine thickly interbedded coarse and fine deposits

Key

▭	Boundary of the associations
⟶	Transitions from Markov Chain analysis
- - →	Transitions from visual observations of borehole core



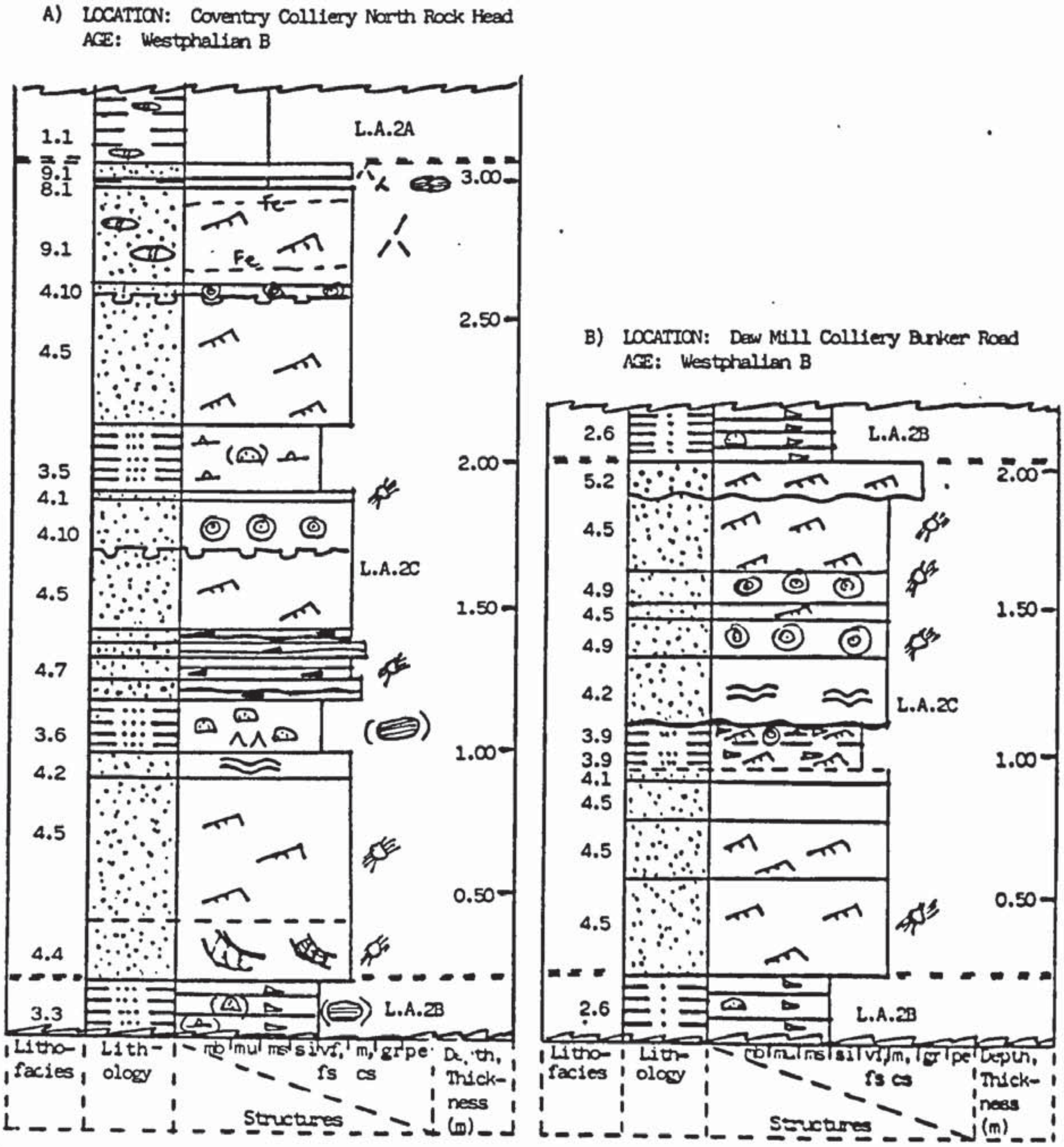
Lithofacies present

2.6 Mudstone silty, parallel stratified with sandstone
2.8 Mudstone silty, with lenticular sandstone stratification
3.3 Siltstone, parallel stratified with sandstone
3.5 Siltstone, with sandstone mini lenses
3.6 Siltstone, with lenticular sandstone stratification
4.1 Sandstone, fine, massive, pale grey to off white
4.2 Sandstone, fine, wavy stratified
4.3 Sandstone, fine, flaser stratified
4.5 Sandstone, fine, with small scale cross lamination
8.3 Seatearth, siltstone grey

Lithofacies associations present

L.A.2B Lacustrine dominantly coarsening upwards deposits
L.A.4B Very poorly drained siliciclastic dominated palaeosols/s

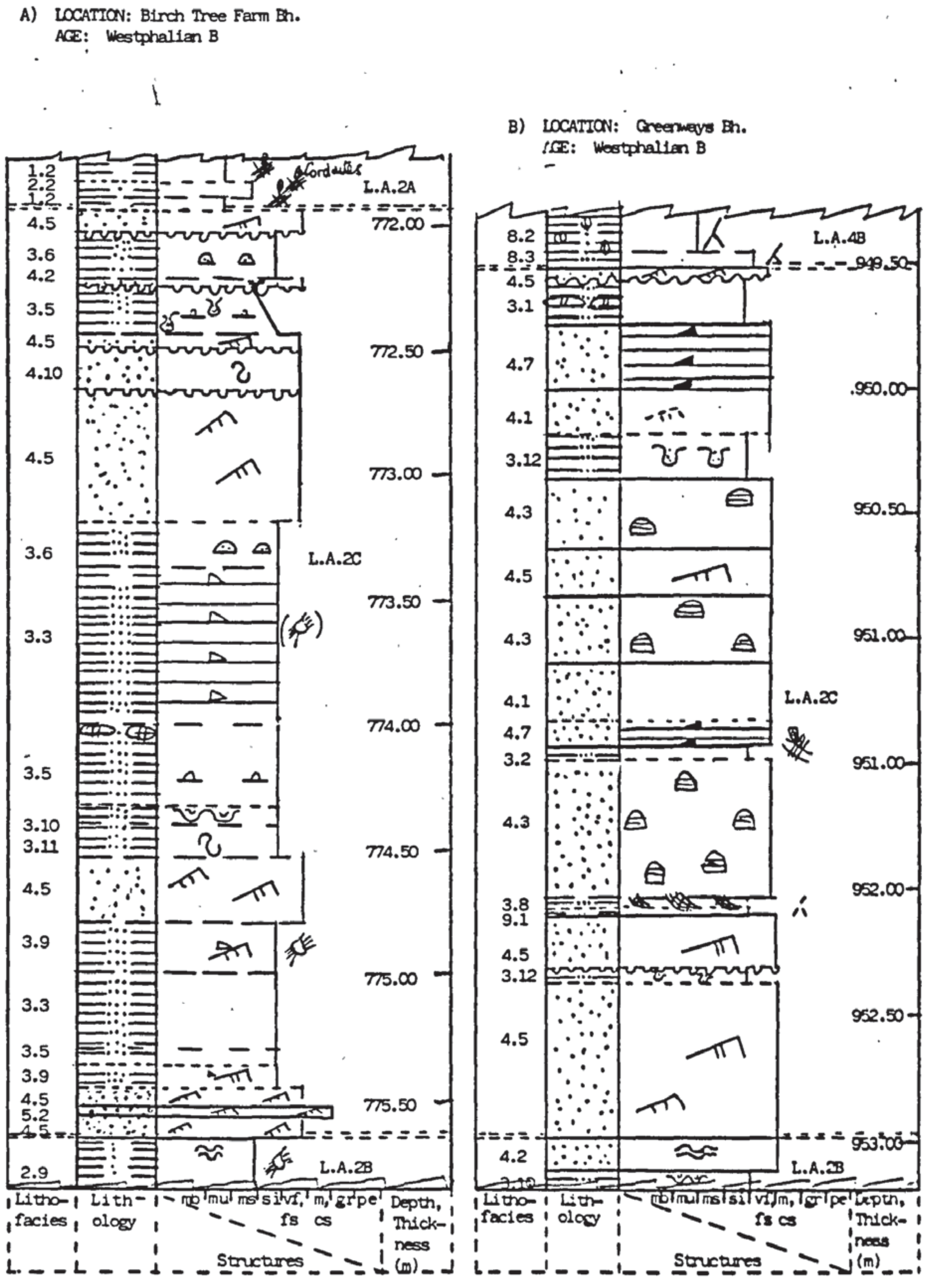
Fig. 5.23 Facies relationship diagram for Lithofacies association 2C
Lacustrine thickly interbedded coarse and fine deposits



A) LOCATION: Coventry Colliery North Rock Head
AGE: Westphalian B

B) LOCATION: Daw Mill Colliery Bunker Road
AGE: Westphalian B

Fig. 5.24 Examples of Lithofacies association 2C 'Lacustrine thickly interbedded coarse and fine deposits'.



A) LOCATION: Birch Tree Farm Bh.
AGE: Westphalian B

B) LOCATION: Greenways Bh.
AGE: Westphalian B

lithofacies fine upwards (Figs. 5.23B, 5.24) and some of the sandstone lithofacies fine upwards into siltstone lithofacies (Fig. 5.23B). Coarsening upwards lithofacies may also be present. In all the examples found in this study one or more lithofacies displayed either convolute laminations, slurrying or loading. Lithofacies containing ripple drift are also common (Figs.5.23A, 5.24B) and Haszeldine (1984) found this sedimentary structure to be ubiquitous in his facies 'Fining-up sandstones'. The variety of sedimentary structures within the siltstone is large and includes mini-ripples, a lithofacies also recognised by Fielding (1982) in his association 'Medial crevasse splay/minor delta' facies. Rarely 'Subseatearth' lithofacies occur within an association (Fig. 5.24B).

Sandstone lithofacies within this association display a variety of basal contacts from erosional to gradational. These contacts may be between underlying fine grained lithofacies or lithofacies of the same grain size. Where sandstone lithofacies containing only small percentages of siltstone are not separated by finer grained lithofacies they can be grouped together as units. Sometimes if the boundaries separating sandstones within a unit are abrupt or erosive the 'Sandstone' lithofacies beds forming the unit thin upwards (Fig. 5.23B lower unit). Sometimes sandstone units are capped by the lithofacies 'Sandstone, fine, massive, off white to pale grey' (Fig. 5.23B). Overall the thickness of the sandstone units often increases towards the top of the association (Figs. 5.24A,B although at the top they may thin again (Fig. 5.24B).

This association is distinguished from 'Lacustrine dominantly coarsening upwards deposits' by the presence of thick 'Sandstone fine' lithofacies units and occasional 'Sandstone medium to coarse' lithofacies. The lack of abundant erosion surfaces and 'Conglomerate' and 'Breccia' lithofacies aid in the distinction of this association from 'Channel fill deposits'. However it is sometimes difficult using borehole core to differentiate this association from 'Channel fill deposits' which are wholly fine grained, or fine upwards and are overlain by this association. This association is distinguished from the association 'Impoverished siliciclastic palaeosol/s' by the lack of in-situ roots.

'Lacustrine dominantly coarsening upwards deposits' almost invariably underlie this association, but it may be overlain by a variety of associations either of lacustrine origin - most commonly 'Lacustrine dominantly coarsening upwards deposits' or by one of the palaeosol associations. This is in contrast to Fielding (1982, 1984a) who believed that a similar facies was "rarely if ever overlain by sediments than those of channel or swamp environments".

Other workers within the Pennine basin have recognised similar associations. The 'Layered sand-siltstone' facies of Elliott (1968) is similar in its juxtaposition of fine and coarse lithofacies, except that within this association the sandstone lithofacies are thicker. Some of the characteristics of his 'Complex silt-sandstone' facies also commonly occur within this association e.g. ripple drift. The thicker sandstones within this association are consistent with those found in Scott's (1976, 1978) '2A Proximal distributary mouth bar' association, although the alternating fine and coarse lithofacies of this association are better represented in his association '2B Interdistributary lake'. Alternation of fine and coarse lithofacies also characterises Fieldings (1982, 1984a) 'Medial crevasse splay/minor delta' facies, although claystones present within it were not found by the author in his equivalent association 'Lacustrine thickly interbedded fine and coarse deposits. In the modern environment thin sheets of sand interbedded with fine grained sediments have been described from the Mississippi delta by Fisk et al. (1954), Coleman et al. (1964) and Arndorfer (1973) and from the Rhone delta by Kruit (1955).

Interpretation

In a similar manner to the previous association, the association under consideration is believed to have resulted from a combination of suspension dominated processes producing most of the 'Mudstone silty' and 'Siltstone' lithofacies and traction dominated processes producing the sandstone lithofacies. However the thickness of the sandstone units together with the erosive nature of some of their basal surfaces indicates that this association was deposited relatively closer to the channel which supplied the sediment than the association described in the previous section. This association is believed to have been produced near the mouths of crevasse and distributary channels, as a result of the mostly unconfined movement of crevasse splays and mouth bars into a lake receiving sediment in suspension. This interpretation is consistent with that of Fielding (1982, 1984a) for his association 'Medial crevasse splay/minor delta. Elliott (1969) believed his 'Layered sand-siltstone' to be the product of inner distributary mouth bars. This is just one of the mechanisms envisaged for the production of this association. Scott (1976, 1978) interpreted thin sandstones in his association '2B Interdistributary lake' as crevasse splay deposits formed in interdistributary lakes between the thicker sandstones (1-2m) which formed his association '2A Proximal distributary mouth bars'.

Alternation of coarse and fine lithofacies testifies to the eposidic nature of deposition probably resulting from changes in stage discharge (Elliott 1974a) from high to low respectively. The fining upwards observed in and between successive lithofacies may be due to waning currents as they emerged from a channel. Episodic deposition is also postulated as the cause of the abrupt bases between 'Sandstone' lithofacies, each of which may be the result of high stage events. It may be that the thinning upwards of successive 'Sandstone' lithofacies beds can be attributed to diagonal stacking of the sandstone beds, which may have formed local subaqueous 'topographical highs' similar to those observed by Kruit (1955) and Arndorfer (1973). Abrupt surfaces between 'Sandstone' lithofacies may also be interpreted as reactivation surfaces, which would be expected where changes in stage are envisaged (Elliott 1974a). Successively thicker sandstone units upwards can be interpreted as the result of increasing proximity of the source of the sediment. Although this coarsening upwards resembles distributary mouth bar sequences (Coleman <u>et al</u>. 1964, Elliott 1974a, Fig. 1,F) it also resembles crevasse splay systems (Elliott 1974a Fig. 1, C).

It is possible that some of the 'Sandstone' lithofacies displaying evidence of higher current velocities - erosive bases, medium to coarse grain size, could be interpreted as the deposits of channels. This is hardly surprising as the transition between crevasse and distributary channels and their proximal deposits - splays and mouth bars is gradual and continual. Fielding (1982, 1984) also has deposits of channel origin included in his association 'Medial crevasse splay/minor delta'. Those deposits termed 'Proximal crevasse splays' by Guion (1984) which are tongue shaped and have erosive bases often overlain by intraformational conglomerate and plant stem breccias would probably be classified in this work as 'Channel fill deposits' (see relevant section).

The presence of increased numbers of lithofacies characterised by loading, slurrying, and convolute lamination in this association when compared with the previous association, together with the occurrence of ripple drited lithofacies is interpreted as the product of rapid rates of deposition as a result of current deceleration when moving from confined to unconfined flow. Increase in the amount of massive 'Sandstone' lithofacies may also have resulted from sediment dumping, and when graded is the only evidence of turbiditic flow which was believed by Haszeldine (1984) to have produced most of his 'Fining-up sandstone' facies. The rate of sediment accumulation in distributary mouth bars was believed by Coleman and Gagliano (1965) to be higher than any other delta front environment, and the life of crevasse systems of the Mississippi delta on average is usually about 100 years during which time from 3-12m of sediment can be deposited (Coleman and Gagliano 1964). As the deposits of this association infill a lake the shallowing may cause an increasing amount of sedimentary structures believed to have been wind/wave generated, e.g. symmetrical ripples, mini-lenses. Fisk et al. (1954) observed that the upper surface of some splay deposits were reworked in this way to form sand spits. At some stage during the infilling it is possible for the lake to become shallow enough for plant colouration producing 'Subseatearth' lithofacies.

It is apparent from descriptions of modern crevasse splay systems and minor mouth bars that distinction between them in ancient rocks is difficult, and dependant on the recognition of geometrical relationships between them and the channels which produced them. This is especially evident when two interdistributary areas of the Mississippi delta are considered (Fisk et al. 1954, Fig. 7) where crevasse splay systems fill the East bay whilst the adjoining Garden Island Bay is filled by minor mouth bars.

This association is likely to form where subsidence is high enough to allow continued accumulation of crevasse splays and minor mouth bars (Coleman and Gagliano 1964) adjacent to the channels which produced the sediment. Filling of the crevasse channel or avulsion of the distributary channel with continuing subsidence is likely to result in a reversion to conditions existing in the underlying association 'Lacustrine dominantly coarsening upwards deposits'. If the rate of subsidence is low then the lake will fill and pass upwards into palaeosol associations. Occasionally the channel sourcing the sediment for this association may migrate to overlie this association.

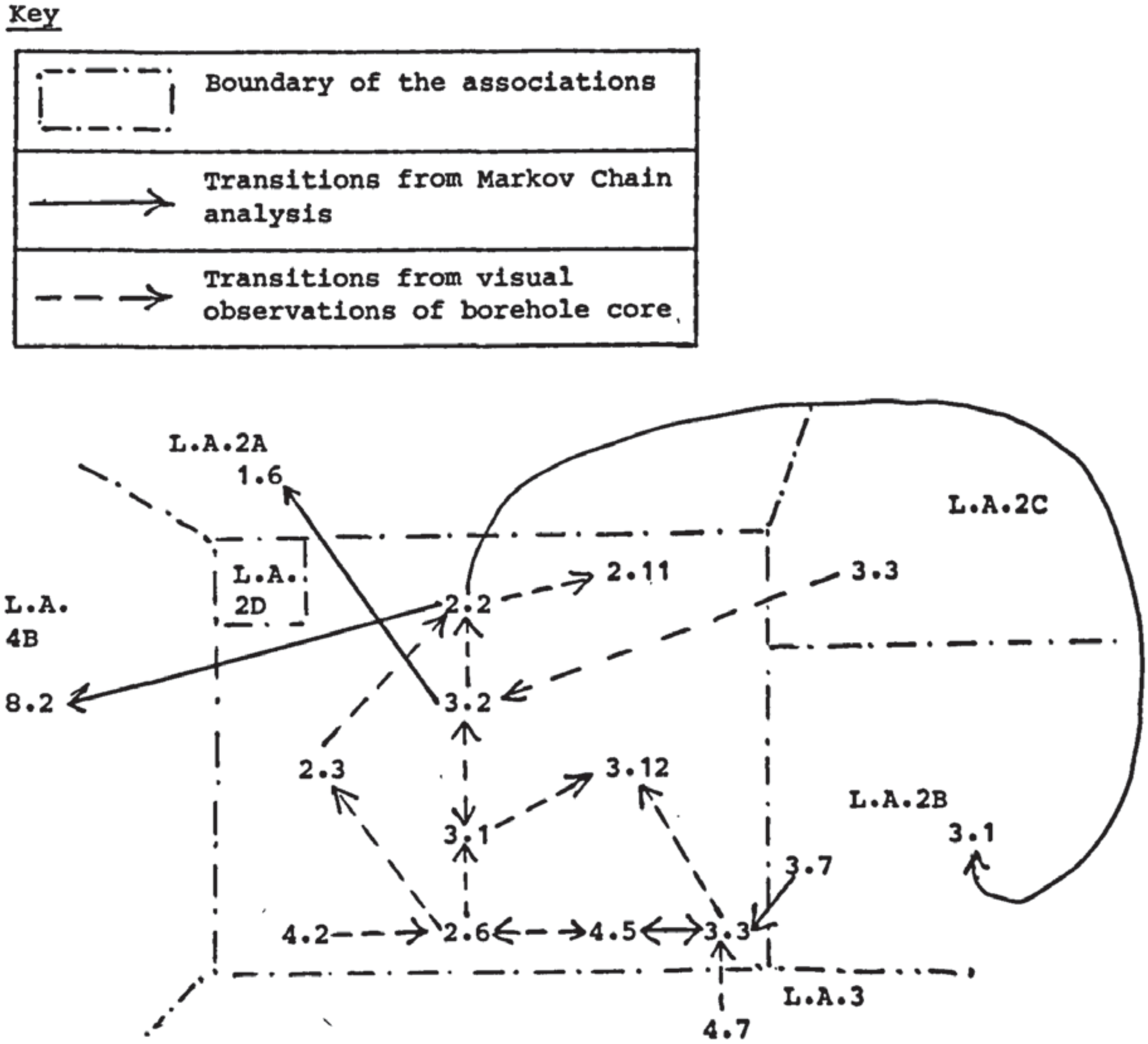
5.4.5 Lithofacies Association 2D

Lacustrine siltstone dominated deposits

Because the diagnostic characteristics of this association are not recognised as separate lithofacies e.g. presence of ichofossils large thicknesses of similar lithofacies, dip of bedding it is not possible to distinguish the F.R.D. from M.C.A. However, examination of borehole core has allowed the construction of an F.R.D. for this association (Fig. 5.25).

The base of this association is usually abrupt (Figs. 5.26, 5.27B) but may be gradational (Fig.5.27A) and a mixture of abrupt and gradational bases exist between lithofacies within the association. In all of the examples of this association (Figs 5.26, 5.27) thick beds (up to 2m) of 'Mudstone silty' or 'Siltstone' lithofacies occur and some of these beds display fining upwards. Associations vary from those which contain no sandstone (Fig.5.27) to those containing well defined 'Sandstone' lithofacies (Fig.5.27A) but 'Siltstone' (Figs.5.26, 5.27B) of occasionally 'Mudstone silty' (Fig. 5.27A)

Fig.5.25 Facies relationship diagram for Lithofacies association 2D 'Lacustrine siltstone dominated deposits'



Lithofacies present

1.6	Mudstone, parallel stratified dark grey to black/medium grey
2.2	Mudstone silty, massive with abundant plant fragments
2.3	Mudstone silty, with coal lenses
2.6	Mudstone silty, parallel stratified with sandstone
2.11	Mudstone silty, with load casts
3.1	Siltstone, massive, pale to medium grey
3.2	Siltstone, massive, with abundant plant fragments
3.3	Siltstone, parallel stratified with sandstone
3.7	Siltstone, wavy stratified with sandstone
3.12	Siltstone with load structures
4.2	Sandstone, fine, wavy stratified
4.5	Sandstone, fine, with small scale cross lamination
4.7	Sandstone, fine, parallel laminated
8.2	Seatearth, mudstone, silty, grey

Lithofacies associations present

L.A.2A	Lacustrine suspension deposits
L.A.2B	Lacustrine dominantly coarsening upwards deposits
L.A.2C	Lacustrine thickly interbedded coarse and fine deposits
L.A.3	Channel fill deposits
L.A.4B	Very poorly drained siliciclastic dominated palaeosols/s

Fig. 5.26 Example of Lithofacies association 2D 'Lacustrine siltstone dominated deposits'.

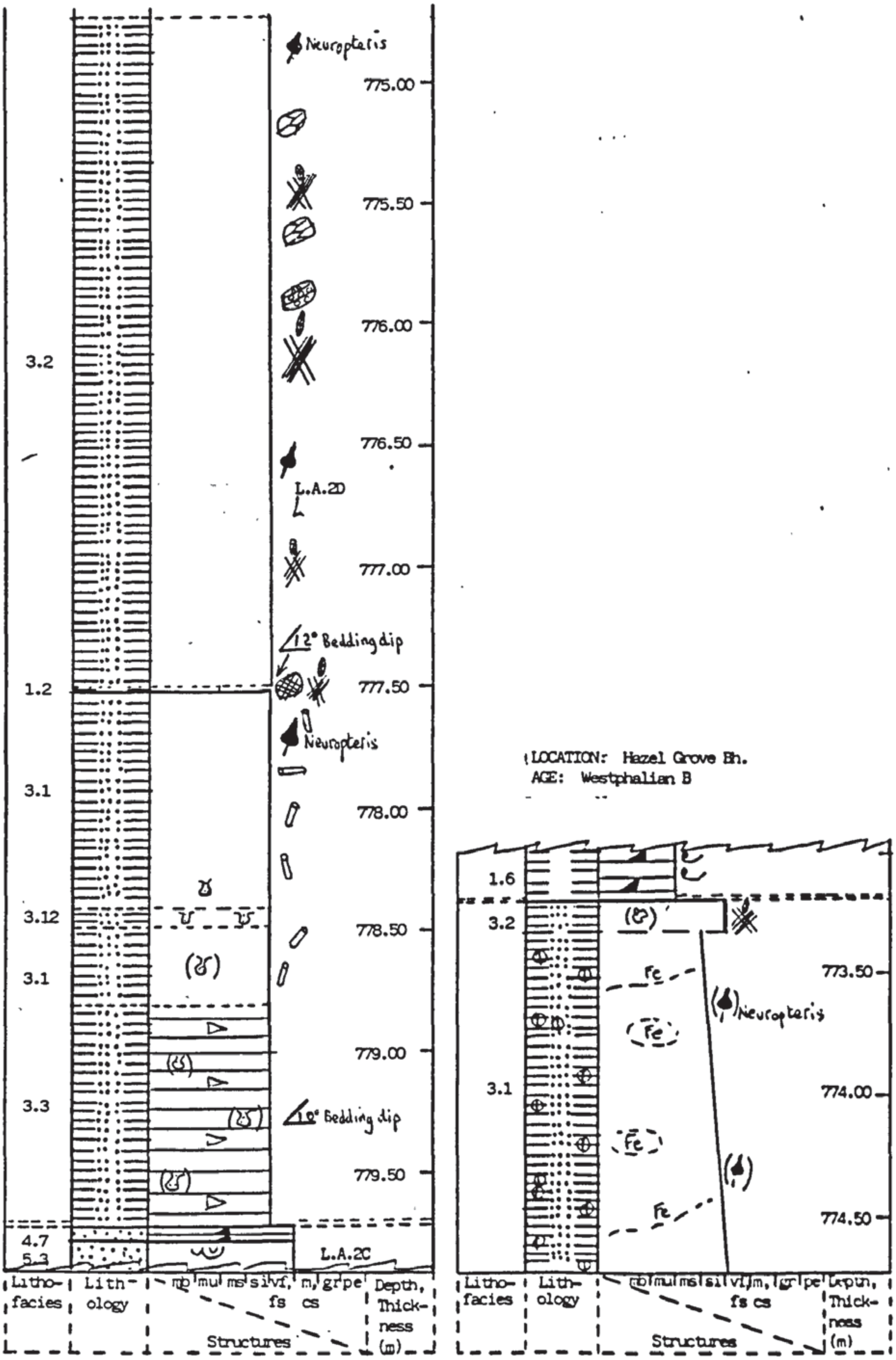
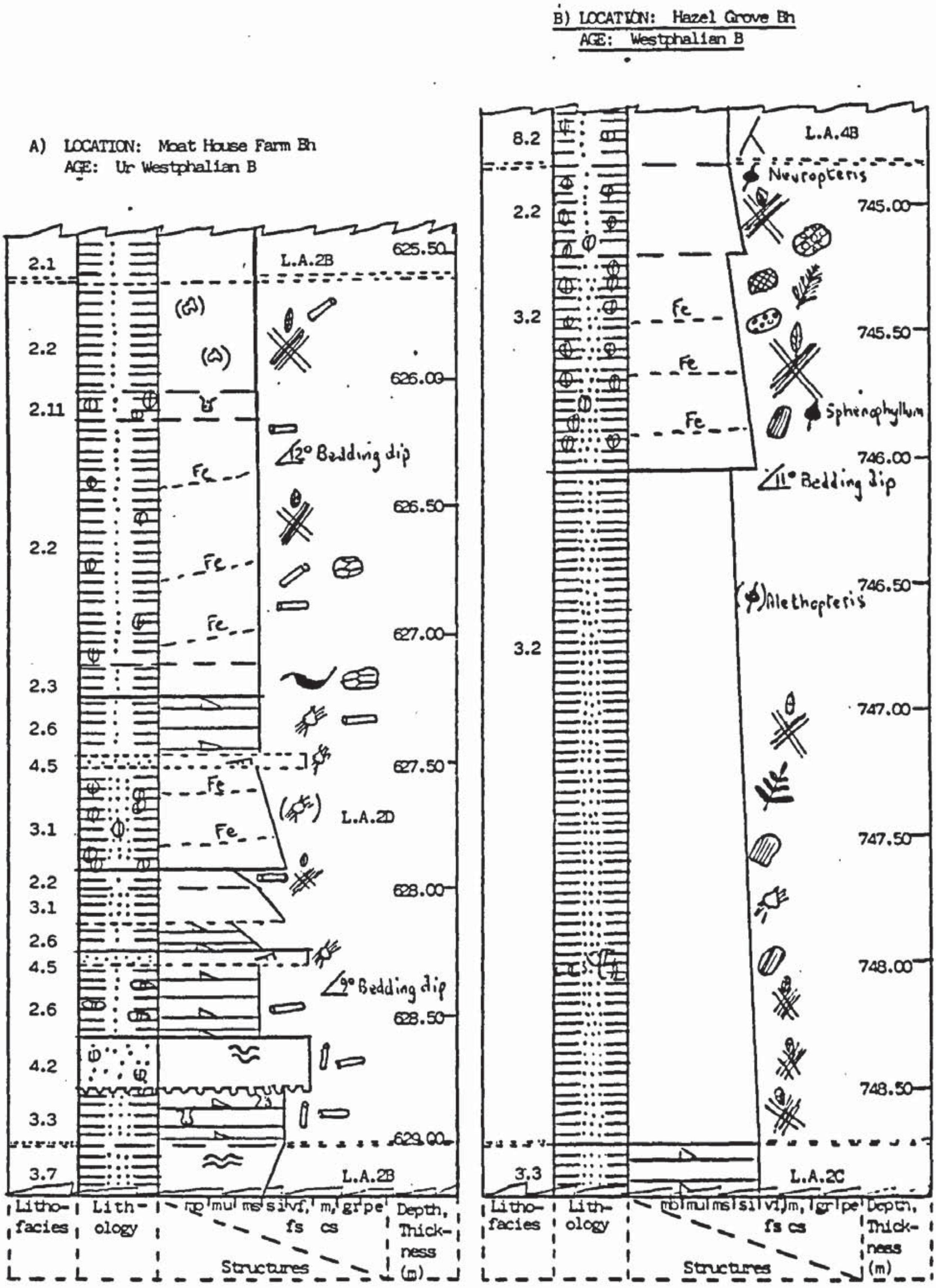


Fig. 5.27 Examples of Lithofacies association 2D 'Lacustrine siltstone dominated deposits'.



A) LOCATION: Moat House Farm Bh
AGE: Ur Westphalian B

B) LOCATION: Hazel Grove Bh
AGE: Westphalian B

lithofacies predominate. Bedding may be clearly recognisable with alternating grain sizes (Fig.5.27A) or almost absent (Fig.5.27B), although in all cases thick beds without lamination occur. Only rarely do mudstone lithofacies occur as thin layers (Fig. 5.26). Usually ironstone nodules occur towards the top of the asociation (Figs. 5.26, 5.27B) and in all cases lithofacies contain abundant plant fragments. These may be stems or foliage, the latter often derived from PTERIDOSPERMOPHYTES although stems of SPHENOPHYTES (Fig. 5.27B) and stems and shoots of LYCOPHYTES (Fig. 32.27B) also occur.

In those instances where sandstone occurs within an association (Figs. 5.26, 5.27A) loading is common either forming the dominant sedimentary structure within a lithofacies or scattered throughout the relevant beds. Sandstone lithofacies are usually trough cross laminated and do not exceed 0.3m in thickness but are usually much thinner (Centimetres). Dark grey mudstone clasts occur in the top bed of two examples of this association (Fig. 5.26, 5.27A).

In many examples of this association ichnofossils in the form of either horizontal burrows infilled by siderite (Fig.5.27A) which may be <u>Planolites</u> or vertical to oblique burrows up to 3mm in diameter (Figs. 5.26, 5.27A) which resemble the 'colonial' burrows of Elliott (1968), and are filled with either sandstone or ferruginous mudstone ovoids.

One prominent feature of this association is the dip of bedding planes which is much steeper than the tectonic dip of under- or overlying associations (Fig. 5.26, 5.27). The contrast in dip usually to about 12°, and in some cases (Fig.5.27A) an increase in dip upwards is visible.

This association is distinguished from other lacustrine associations by an increase in the dip of bedding, the presence of large amounts of plant fragments and/or burrows, and the domination of 'Siltstone' and 'Mudstone silty' lithofacies which sometimes fine upwards.

Often this association is underlain by 'Lacustrine dominantly coarsening upwards deposits' or 'Lacustrine thickly interbedded coarse and fine deposits', the latter often containing small crevasse channels at the top. It is overlain by a wide range of associations including 'Lacustrine suspension deposits' 'Lacustrine dominantly coarsening upwards deposits' and palaeosol associations.

Elliott (1968) recognised a similar facies dominated by siltstone termed 'massive siltstone' although bedding was minimal and burrowing is not mentioned. However, colonial burrows occur in another of his facies 'Complex silt-sandstone' but a large number of inorganic sedimentary structures are also present. Fielding (1982, 1984a) described a facies containing abundant siltstone and plant material 'Siltstone-dominated overbank deposits, although no mention is made of ichnofossils. In contrast Fielding (1982) describes trace fossils as abundant in his 'Levée' facies, although this comprises regularly, thinly interbedded sandstone, siltstone and claystone, and in this respect resembles the lower part of this association in Fig. 5.27A.

Siltstone dominated deposits which occur in thick massive beds and fine upwards have not been described in detail in modern sedimentary environments. Bioturbated alternating fine and coarse sediments have been described from overbank deposits on the Mississippi delta (Coleman et al. 1964, Prior and Coleman 1980) although the latter authors believed these deposits to contain coarsening upwards sequences.

Interpretation

These deposits are interpreted as a product of overbank flooding, one of the processes by which levées adjoining river channels are constructed. Initially a river may be flowing relatively unconfined (see next section), but once it has incised itself into the floodplain high stage flow will result in water rising above bankfull height and sheetflow will take place constructing an overbank levée. (Levées may also be formed of crevasse splay deposits where excess floodwaters are removed by crevasse channels e.g. Brahmaputra river, Coleman 1969). Levées can occur on both the outer concave bank of a river where they have a low preservation potential due to erosion (Collinson 1978, p.38), and the inner convex bank where they are difficult to distinguish from and may form part of the upper point bar deposits (Ray 1976).

One of the characteristics of both this association and levées is the steeper dip of bedding when compared with other associations found in the deltaic environment. This is because the levée forms a ridge dipping steeply towards the channel and less steeply away from it (Blake and Ollier 1971). The steeply dipping inner bank forms the side of the channel and because of bank collapse has a low preservation potential (see next section). It would appear that the deposits dipping away from the river are most likely to be preserved, and those on the convex bank are more likely to be preserved than those on the concave bank which can only be so following abandonment of the channel.

The grain size of the overbank deposits reflects that carried by the channel from which they were derived, because during high stage Taylor and Woodyer (1978) believe that turbulence can result in mud to fine grained sand being taken into suspension. The presence of small mudstone clasts in two of the examples (Figs.5.26,5.27A) suggests that in some circumstances limited amounts of these may be taken into suspension. Lack of sand in channels from which the overbank deposits in Figs. 5.26, 5.27B were derived suggests that they mainly carried a fine grained bedload, in contrast to those in Fig. 5.27B where appreciable quantities of sand exist in the lower part of the association. Fielding (1984a) believed that the overbank deposits of minor channels can be distinguished from those of major channels by their finer grain size reflecting a finer grained bedload.

The fining upwards of thin beds of fine grained lithofacies may reflect waning currents as the high flood stage reverts back to normal stage. Thicker 'Sandstone' lithofacies may have been deposited as high stage sheet floods, or may be the product of crevasse splays. The common occurrence of loaded sandstones suggests that the underlying siltstones were unstable due to large amounts of water being retained within pore spaces. This together with the lack of rootlet penetration indicates that most of the levée was subaqueous. In contrast Elliott (1969) believed that his 'Massive siltstone' facies was subaerial in origin.

The massive nature of some of the lithofacies may be explained by the slow rate in sedimentation, perhaps overtopping only occurs a few times per year and therefore it allows burrowing organisms to homogenise the sediment (Coleman _et al_. 1964). It is believed that the abundance of burrows reflects the suitability of the habitat, well oxygenated water and low rates of deposition, for the animals which formed them. Horizontal burrows such as _Planolites_ occur in other associations but the abundance of the vertical colonial burrows and their apparent confinement to this association suggests they were particularly suited to the habitat.

The profusion of plant fragments and fronds in this association reflects the short distances travelled before their incorporation into the sediment, and that overbank flooding occurred fairly frequently allowing rapid burial. Oxidation of plant remains was reduced by the subaqueous nature of these levées, in contrast to the levées of the Orinoco river (Scheihing and Pfefferkorn 1984) which are subaerial for half the year and thus preserve very little organic material. The abundance of foliage derived from PTERIDOSPERMOPHYTES within this association compares well with the observations made by Scott (1978), that the majority of plants incorporated within a Westphalian bank collapse structure came from this phylum. It appears therefore that although the plant fragments were allochthonous, transported floating or in suspension within the channel to be deposited in overbank sediments at floodstage, they reflect the riparian vegetation.

The thickness of this association reflects the temporal stability of the channel, and when calculating bankful depth it must be added to the depth of incision of the channel into previous deposits. This association is found adjacent to river channels and where underlain by other lacustrine associations, it is assumed that the levées were moving with the channels across an interdistributary area. On abandonment of the channel, depending on the rate of subsidence, either further lacustrine deposits may form, or if the water depth became shallow enough one of the palaeosol associations could develop. The low preservation potential accounts for its paucity within Westphalian sediments in the Warwickshire Coalfield.

5.4.6 Lithofacies Association 3

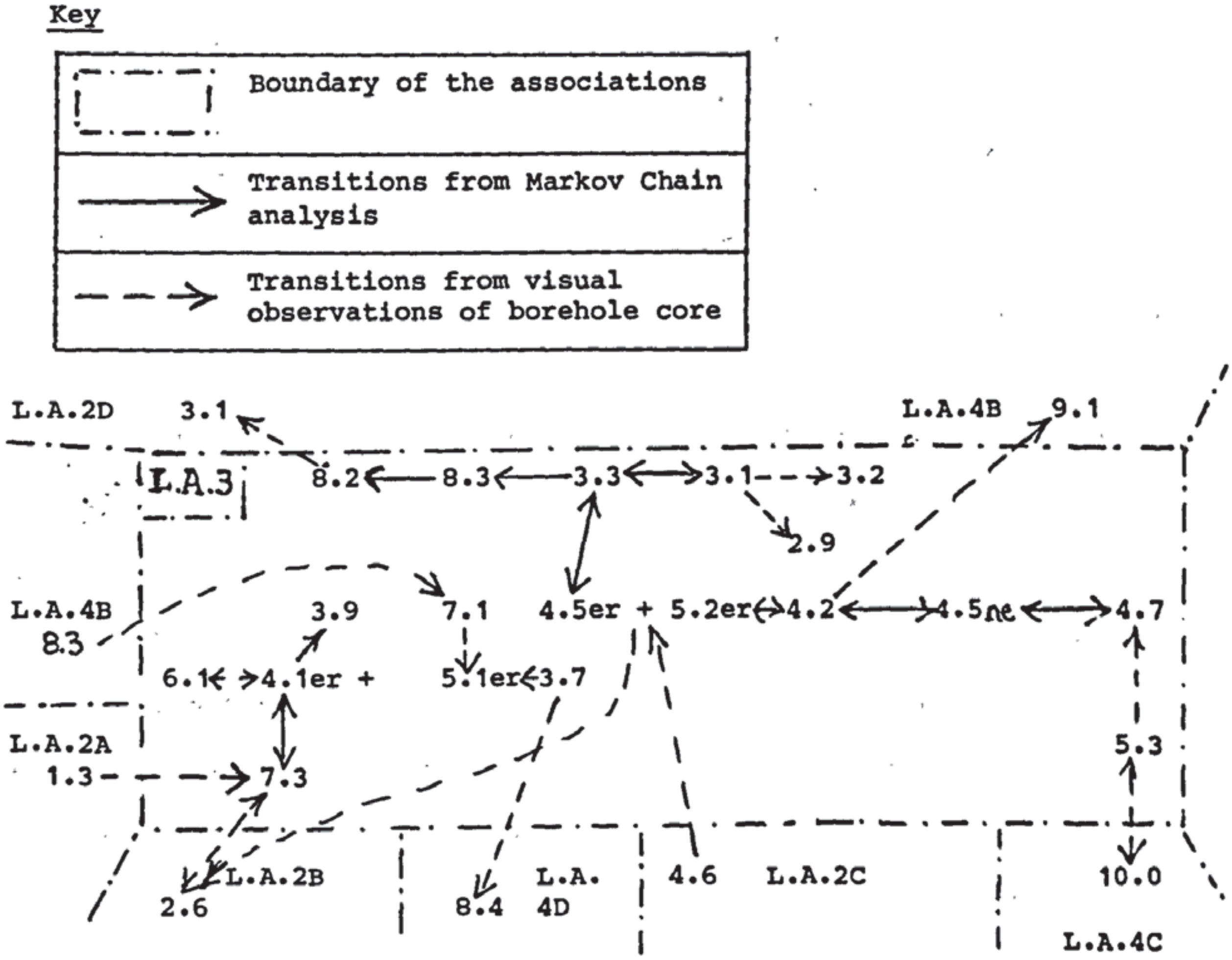
'Channel fill deposits'

Recognition of the association 'Channel fill deposits' using borehole core is difficult because it comprises a wide variety of lithofacies many of which occur in other associations. This variety also occurs in the point bars deposits of the Mississippi (Ray 1976) and in the bars of suspended-load streams in eastern Australia (Taylor and Woodyer 1978). One of the most diagnostic features of channels is their geometry. They are U-shaped in cross section corresponding to the width of the channel and have lengths far exceeding their widths. Another difficulty in recognition of this association therefore, is that only a small part of the geometry can be viewed in borehole core.

However, combinations of certain features does allow recognition of 'Channel fill deposits' in borehole core. Because of the geometry of channels, water in them can flow at much greater velocities than if found in previous associations. The increased flow rate can cause erosion of pre-existing associations and enables particles of larger grain size to be transported. From the discussion above it follows firstly that within borehole core the presence of erosive surfaces may be indicative of 'Channel fill deposits'. Secondly the abundance of coarse grained lithofacies, e.g. sandstone, especially coarser in grade than fine grained sandstone, together with conglomerate and breccia lithofacies are also indicative of 'Channel fill deposits'. Following from this during M.C.A. those 'Sandstone' lithofacies with erosive bases were separated from the others, allowing an F.R.D. to be constructed which includes many of the commonly occurring diagnostic lithofacies (Fig. 5.28).

Other important characteristics associated with this association are fining upwards lithofacies/sequences of lithofacies, and abundant

Fig.5.28 Facies relationship diagram for Lithofacies association 3 'Channel fill deposits'



Lithofacies present

3.1	Siltstone, massive pale to medium grey
3.2	Siltstone, massive, with abundant plant fragments
3.3	Siltstone, parallel stratified with sandstone
3.7	Siltstone, wavy stratified with sandstone
3.9	Siltstone/sandstone with small scale cross stratification
4.1	Sandstone, fine massive, pale grey to off white
4.2	Sandstone, fine, wavy stratified
4.5	Sandstone, fine, with small scale cross lamination
4.7	Sandstone, fine, parallel laminated
5.1	Sandstone, medium to coarse grained massive
5.2	Sandstone, medium to coarse grained, with small scale cross stratification.
6.1	Conglomerate intraformational
7.3	Breccia of plant stems
8.2	Seatearth, mudstone silty, grey
8.3	Seatearth, siltstone, grey

Lithofacies associations present

L.A.2A	Lacustrine suspension deposits
L.A.2B	Lacustrine dominantly coarsening upwards deposits
L.A.2D	Lacustrine siltstone dominated deposits
L.A.4B	Very poorly drained siliciclastic dominated palaeosols
L.A.4C	Long-residence histosols/s
L.A.4D	Alternate poorly and imperfectly drained siliciclastic palaeosol/s

plant remains, either in the form of comminuted plant debris found in cross and parallel laminae within sandstones, or fragments of leaves and stems found in other lithofacies. Bank collapse structures formed of mélange lithofacies are also occasionally associated with 'Channel fill deposits'.

Many authors have described channels occurring within Westphalian rocks of the Pennine basin, including most recently Elliott (1965b, 1968, 1969), Scott (1976, 1978), Guion (1978), Fielding (1982, 1986) and Williams (1986). Although the first two authors describe a variety of channels only the latter three authors provide a classification of channel types based on an examination of 3 dimensional exposures. Guion (1978) recognised six channel variants (Table 5.10A) defined on their morphology viz. meandering or straight and the presence or absence of underlying 'deltaic' deposits. He attempted to characterise both the width of the channel belt and the length of time it was occupied by channels, together with the likelihood of channels within the belts removing coal seams. Fielding (1982, 1986) devised a classification based on the origin of the channel viz. crevasse or distributary and their size-major or minor (Table 5.11). Fine channel variants were recognised on the basis of their morphology, channel belt width, channel width, deposit thickness and channel bankful depth. Williams (1986) classified channels into three types according to the way in which they were filled viz. actively filled, atrophied and abandoned channels (Table 5.10B). Recognition of these types was dependant on the lithology together with organic and inorganic sedimentary structures contained within the fill.

Each of the three classifications mentioned previously are simplifications and overlap occurs in the channel variants defined by them eg. in the classification of Guion (1978) a channel with

TABLE 5.10 Classification of Westphalian A and B channel types

A) After Guion (1978)

CHANNEL TYPE	LITHOLOGY	CHANNEL BELTWIDTH	LIFE	INCISION
1. Major meandering	Mainly sandstone	Several km	Long lived, multi-storey	Likely to remove several seams
2. Minor meandering	Variable	1-2km	Short lived	Max. erosion one seam only
3. Straight with no underlying 'deltaics'	Variable	Narrow	" "	Erodes deeply into one seam
4. Straight with underlying 'deltaics'	Variable	Narrow	" "	Possibly erodes one seam
5. Meandering with underlying 'deltaics'	Variable	Wide	" "	Local erosion of one seam
5. Minor drainage	Fine Sediments? + Coal	Very Narrow	" "	Unlikely to erode seams

B) After Williams (1986)

CHANNEL TYPE	LITHOLOGY	INORGANIC SEDIMENTARY STRUCTURES	ORGANIC SEDIMENTARY STRUCTURES	THICKNESS
1. Actively filled	Mainly sandstone +Intraformational clasts Fining upwards Fine grained top	Epsilon cross bedding Trough cross bedding and cross lamination Rare parallel bedding or massive sandstone Convolute stratification Load casts, slurried bedding Climbing ripples Wavy lamination	Occasional plant stems and fronds Rare trace fossils	3.5 to 17.5 m
2. Atrophied	Siltstones, Silty Sandstones, Mudstones Fining upwards Fine grained top	Epsilon cross bedding Trough cross lamination Parallel Laminations Wavy and lenticular Lamination Rarely load casts, slurried bedding, climbing ripples	Abundant vertical and horizontal shafts Abundant coalified stems and rootlets	7 to 12 m
3. Abandoned	Mudstones Silty mudstones Siltstones Occasional sandstones	Massive Parallel lamination Lenticular lamination	Abundant coalified stems plant fronds and stems Rare trace fossils	?

TABLE 5.11 Classification of Westphalian A and B channel types after Fielding (1984a, 1986)

CHANNEL TYPE	LITHOLOGY	INORGANIC SEDIMENTARY STRUCTURES	ORGANIC SEDIMENTARY STRUCTURES	DEPOSIT THICKNESS	CHANNEL WIDTH	CHANNEL BELT WIDTH	MORPHOLOGY	CHANNEL BANKFUL DEPTH
1. Major distributary	Mainly sandstone intraformational clasts Fine grained top	Parallel lamination Primary current lineation Trough cross bedding. Ripple cross lamination coarser sandstones are massive	Coalified plant stems Rare trace fossils	Mostly 10-20m	Mostly 1-2km	Mostly up to 5km	Straight to sinuous	Mostly 10-12m
2. Proximal Major crevasse	Mainly sandstone +intraformational clasts Fine grained top	Trough cross bedding Trough shaped scours Ripple cross lamination	Rootlet penetration at top	Up to 7m	Up to 400m	Up to 400m	Straight	Up to 6m
3. Minor distributary	Interbedded fine grained sandstone siltstone and mudstone. Some fine upwards, many do not.	Coarse fills display epsilon cross bedding +ripple cross lamination Fine grained fills are massive or parallel laminated	Abundant plant fragments Rare trace fossils	Up to 6m	Up to 150m	Up to a few hundred m.	Straight to sinuous	Mostly up to 6m
4. Minor crevasse	Mainly fine grained sandstone	Trough cross bedding Ripple cross lamination Climbing ripples	—	Mostly up to 1.5m	Mostly up to 20m	Mostly up to 20m	Straight	Mostly up to 0.7m
5. Distal feeder	Siltstone and mudstone. Rare sandstone	Parallel lamination Uneven Lamination	Comminuted plant debris	About 1m	Up to 200m	Up to 200m	Straight	About 2m

underlying deltaics at one locality may not have any at another; it is obvious from Fielding (1986, Fig.2) that a continuum exists between his 'Proximal major crevasse channel', 'Minor distributary channel' and 'Distal feeder channel' facies; and that the distinction between actively filled and atrophied channels (Williams 1986) on the basis mainly of lithology is likely to be difficult if the sediment source in both cases is restricted to a fine grain size.

There now follows a description of a number of examples of different channel types from the Westphalian of the Warwickshire Coalfield found mainly in borehole core. Those aspects of the three classifications above (Guion 1978; Fielding 1984a, 1986; Williams 1986) which are visible in borehole core viz. lithology, inorganic and organic sedimentary structures and thickness of sequence are used to interpret the examples.

When interpreting borehole core difficulty exists in determining the base of channels, distinguishing between channels in a multi-storey sand body and determining the top of the channel fill sequence. The easiest example of this association to identify should be one individual channel located between other associations. Even this may be difficult if the base of the channel does not have an erosive base at that particular locality. Distinction between erosive bases within individual channels and those erosive surfaces which mark the bases of different channels within a multi-storey example of this association is difficult. As an aid to interpretation, examples of this association may be divided into one or more units using erosive bases, changes in lithology and or sedimentary structures. Finally difficulty may be experienced in distinguishing the top of this association when it contains a fine grained fill, from an overlying fine grained association e.g. 'Lacustrine thickly interbedded coarse and fine deposits' or palaesol associations.

From the discussion above it appears that when using data from such a limited exposure as a borehole core, the interpretation given for this association is the one considered most likely in the circumstances, but it does not preclude other interpretations.

Example 1. Histosol drainage channel

Daw Mill 62's Upper Thick Coal face (Fig.5.29A)

This example is taken from an underground face at Daw Mill Colliery working the upper part of the Thick Coal. Although not from a borehole it is easy to imagine what would happen if this sequence was cored. The association would be recognised by a decrease in the expected thickness of coal. In every other respect the lithofacies present are the same as those overlying the Two Yard seam a few metres away forming the associations 'Lacustrine suspension deposits'. The cross section of this channel is very small, being 6m wide and about 1m deep. Its length is unknown but weak roof indicates that it was in excess of 100m and may have been much longer.

Interpretation

The palaeodepth of this channel is problematical because of the high compaction ratios for peat (see relevant lithofacies section) and the time of formation of the channel which is also uncertain. Like other channels in this section it could have eroded the underlying sediment, in this case part of a 'Long-residence histosol'. However this type of sediment is difficult to erode (Guion 1978) and would require high velocities. When velocities reduced it would be expected that some of the bedload or load carried in suspension would be deposited, but none was found. Alternatively it is possible that the channel was formed contemporaneously with the histosol and merely acted as a drainage channel conducting excess water from the histosol. The lack of effect on the adjacent coal lithofacies suggests that little siliciclastic sediment was carried. It is believed that channel fill occurred following termination of the 'Long-residence histosol' by drowning, so that 'Lacustrine suspension deposits' were draped over the channel and were continuous over the adjacent full thickness of the Two Yard.

The fill of this channel has clearly followed abandonment (cf. Williams 1986) and although minor drainage channels were recognised by Guion (1978) neither he nor Fielding (1984a, 1986) recognised channels believed to have formed as a result of peat drainage.

Example 2. Proximal minor crevasse/minor distributary channels

Greenways Borehole (Fig. 5.29B)

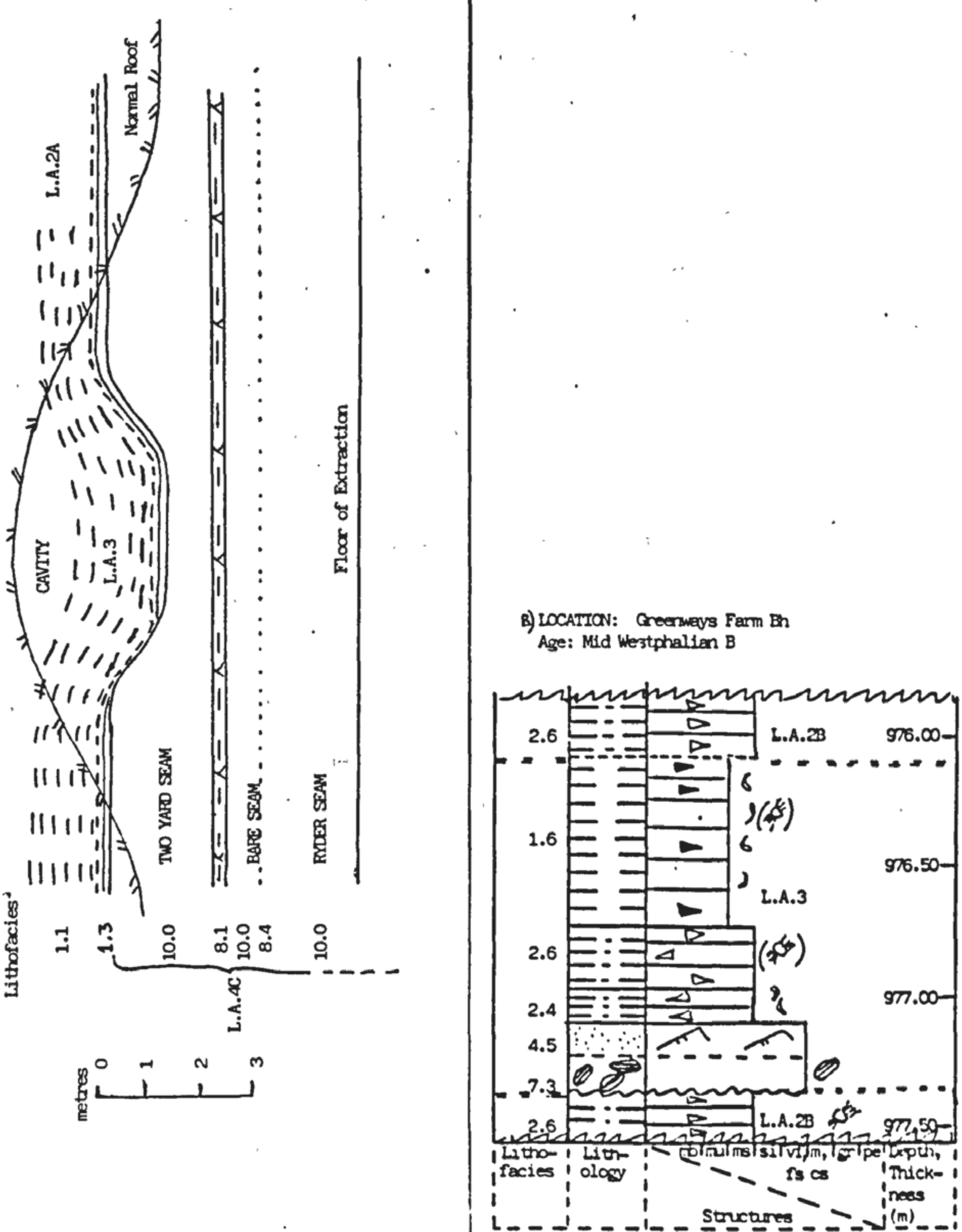
The association in this borehole consists of an erosive base over which a fining upwards sequence 2.33m thick occurs. It commences with a 'Plant stem breccia' with a sandstone matrix and fines upward through 'Mudstone silty' lithofacies to 'Mudstone' lithofacies. 'Lacustrine coarsening upwards deposits' both under and overlie the 'Channel fill deposits'. The top of this association is defined by the commencement of a coarsening upwards sequence in the overlying association.

Interpretation

The presence of the 'Breccia' and 'Sandstone' lithofacies at the base of the association suggests that these were deposited following high rates of water flow whilst the channel was active.

The finer grained lithofacies above indicate a passive infill mainly from suspension following abandonment of the channel (cf. Williams 1986), and allowing colonisation by burrowing animals.

Fig. 5.29 Examples of Lithofacies association 3 'Channel fill deposits'.



A) LOCATION: Daw Mill Colliery
62's Thick Coal Face
AGE: Westphalian B

B) LOCATION: Greenways Farm Bh
Age: Mid Westphalian B

Channel deposits of similar lithology were termed 'Distal feeder channels' by Fielding (1984a, 1986) although he believed they would be difficult to identify in borehole core. In thickness these deposits resemble the 'Minor crevasse channels' of Fielding (1984a, 1986) although they were mostly sandstone filled. The presence of this association in the middle of 'Lacustrine coarsening upwards deposits' may be consistent either with Fielding's interpretation of these channels as distal extensions of minor distributary channels, or they could represent the abandoned channelised part of a minor crevasse splay. This example is of similar size to those termed 'Minor drainage channels' by Guion (1978), and therefore unlikely to erode any underlying coal seams.

Example 3. Proximal major crevasse channel

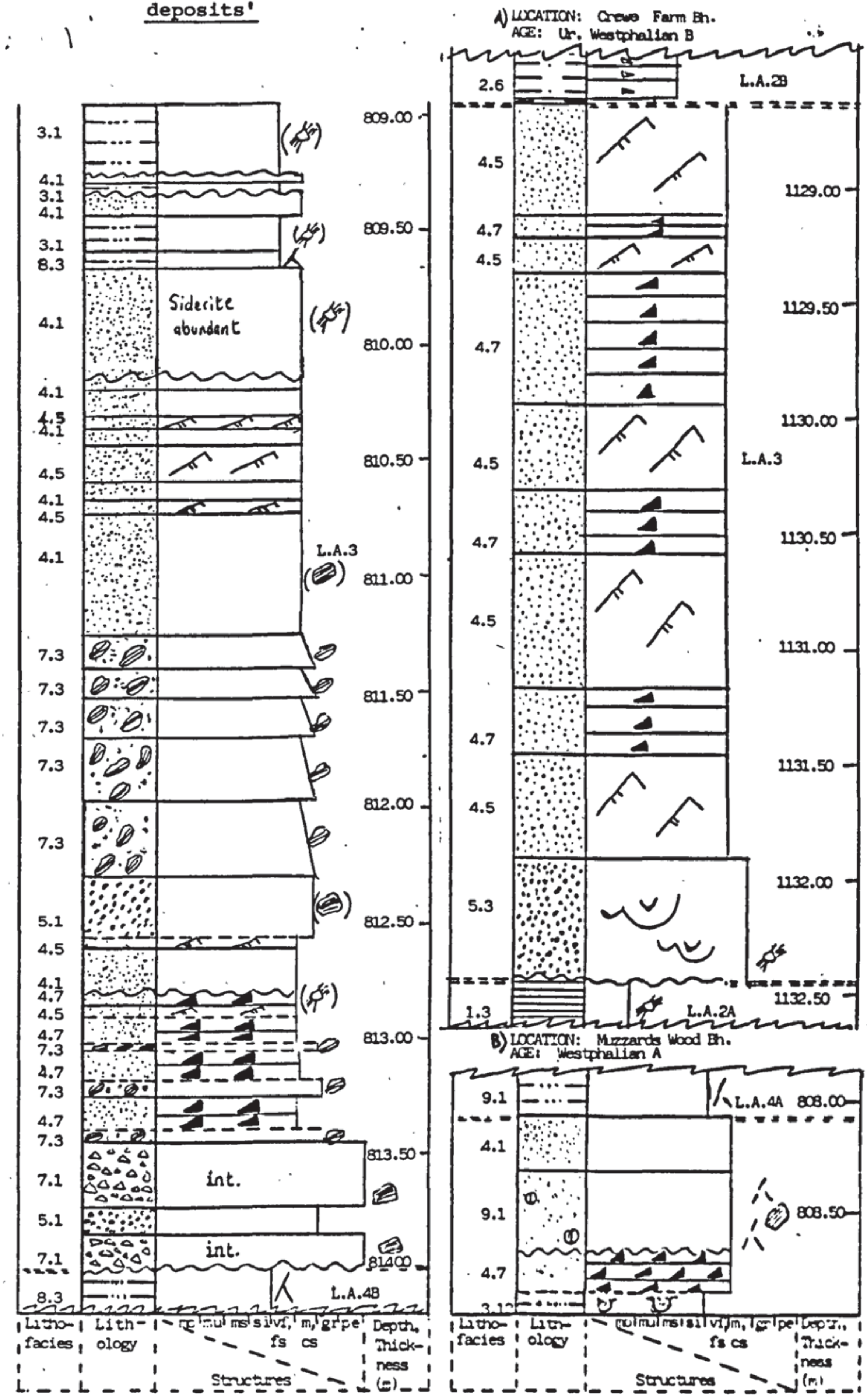
Crewe Farm borehole (Fig.5.30A)

Sandstone lithofacies dominate this example of 'Channel fill deposits' which are 3.73m thick overlying an erosive base below which is the association 'Lacustrine suspension deposits'. A slight fining upwards occurs at the base, but the majority of lithofacies are of two varieties viz. 'Sandstone fine with small scale cross lamination' and 'Sandstone fine parallel laminated'. Directly above this association the lithofacies display coarsening upwards and contain few plant remains and are referrable to the association 'Lacustrine coarsening upwards deposits'.

Interpretation

The coarse grained nature of these 'Channel fill deposits together with the presence of trough cross bedding indicates that this channel was actively filled (Williams 1986) during a period of fairly constant discharge. Although both 'Proximal major crevasse' and 'Minor distributary' channels (Fielding 1984a, 1986) may have a similar

Fig. 5.30 Examples of Lithofacies association 3, 'Channel fill deposits'



deposit thickness, the former often contain coarser sediment perhaps because they tapped the bedload of major distributary channels. The lack of fine grained sediment capping this example may be attributed to the method of filling of the channel. If this example is a 'Proximal major crevasse' type perhaps a large volume of bedload sediment from the main channel was available to fill the crevasse channel. This type of channel is often straight (Fielding 1986). In this particular case there are nearly 3m of sediment below the 'Channel fill deposits' before a coal seam is reached, so that this channel could be classified according to Guion (1978) as 'Straight with underlying deltaics'. There is a possibility that in the down current direction this channel may erode deep enough to remove the underlying seam.

Example 4. Proximal major crevasse channel

Muzzards Wood (Fig.5.30B)

This example can be divided into two units the lowermost being 4.23m thick and the uppermost 1.47m thick. The lowest 4m are dominated by 'Sandstone' lithofacies in a similar way to previous example although a wider variety of these are present. Both 'Conglomerate' and 'Plant stem breccia' lithofacies occur within the lower part of this association. A 'Seatearth' lithofacies separates the lower unit of this example from the upper unit and also occurs towards the top of this example. The upper unit is formed from a variety of interbedded 'Sandstone fine' and 'Siltstone' lithofacies. It is under and overlain by the association 'Very poorly drained siliciclastic dominated palaeosol/s'.

Interpretation

The lower unit of this example is interpreted as the product of active fill (Williams 1986) in the same way as the previous example, although more powerful currents may have been operating because of the presence of the 'Breccia' and 'Conglomerate' lithofacies. Each of the five 'Breccia of plant stems' lithofacies which fine upwards found in the lower unit of this example may have formed during separate flood events. The seatearth lithofacies marks a hiatus in sedimentation, during which the water was shallow enough to allow plant colonisation. Above this the unit of alternating 'Siltstone' and 'Sandstone fine' lithofacies, many of which have erosive bases, is interpreted as the product of a channel within which discharge was irregular. 'Sandstone' lithofacies formed during high stage events and 'Siltstone' lithofacies were then draped over them during low stage. This type of fill probably corresponds with Williams (1986) 'atrophied' channels, in which sedimentation took place in those reaches partially cut off from the main channel.

The abundance of sandstone together with intraformational clasts suggest that these may have been the deposits of a 'Proximal major crevasse' channel, although at this location there is no indication of 'Lacustrine' associations above or below the channel. This implies that this may be a 'Minor distributary' channel (Fielding 1984a, 1986). The small thickness (less than 1m) between the base of this example and the underlying coal seam suggest that erosion of that seam is likely to occur (Guion 1978).

Example 5. Channel type unknown

Rookery Farm borehole (Fig.5.31A)

This example is erosively based and overlies the lithofacies association 'Very poorly drained siliciclastic dominated palaeosol/s'. It is very similar to the previous example except that the 'Sandstone' lithofacies are coarser grained and no 'Seatearth' lithofacies separate the coarser lower part from the finer upper part. Both the

Fig. 5.31 Examples of Lithofacies association 3, 'Channel fill deposits'.

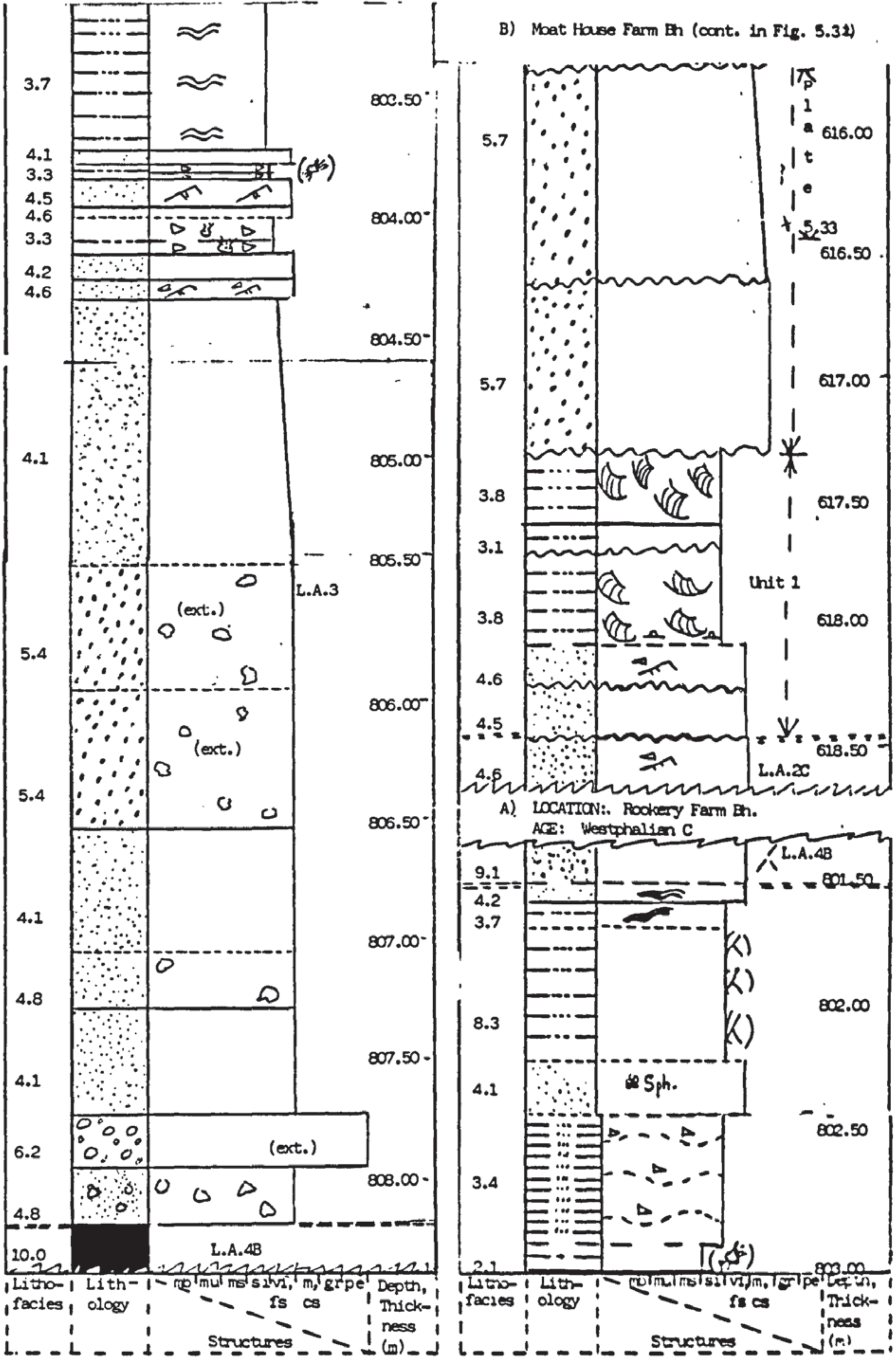
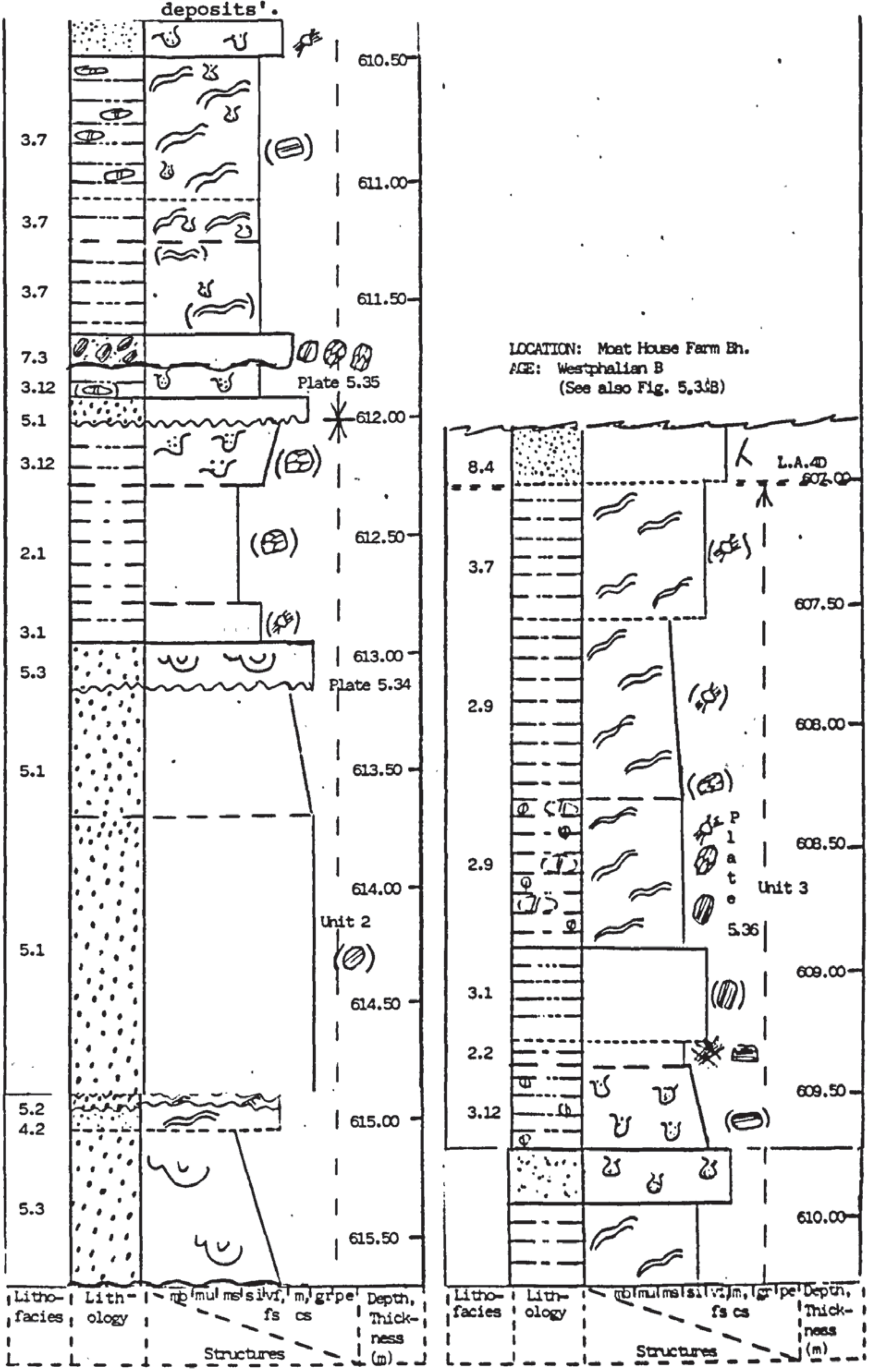


Fig. 5.32 Example of Lithofacies association 3, 'Channel fill deposits'.



'Sandstone' and 'Conglomerate' lithofacies contain respectively a variety of coloured grains and clasts, sometimes with prismatic quartz crystals. The clasts are of siltstone and sandstone predominantly and vary from red to yellow and green. Similar to the previous example alternating 'Siltstone' and 'Sandstone' lithofacies occur in the upper part together with the lithofacies 'Seatearth siltstone grey' towards the top of this example. It is overlain by the same association which underlies it.

Interpretation

Once again the lowest 4m, is interpreted as active channel fill (Williams 1986) with fairly continuous high current velocities. This example is of Westphalian C age, and the variety of grains and clasts present can be interpreted as the product of a different source area from previously shown examples of Westphalian A and B age. For this reason the 'Conglomerate' lithofacies is interpreted as extra-formational. The alternating 'Siltstone' and 'Sandstone' lithofacies at the top of this example may be interpreted as passive fill of an abandoned channel (Williams 1986). None of these 'Sandstone' lithofacies have erosive bases and 'Siltstone' lithofacies which coarsen upwards do occur in active channel fill deposits (Taylor and Woodyer 1978, Williams 1986) but the latter author has only rarely found them in channels of Westphalian A age. Further evidence for channel abandonment over periods long enough for plant colonisation is shown by the presence of the 'Seatearth' lithofacies. Because this example lies outside the stratigraphic range of those channels classified by Guion (1978), Fielding (1984a, 1986) and Williams (1986), and because few channels of this age within the Pennine Basin have been studied, no attempt is made to interpret the type of channel which formed it.

Example 6. Minor crevasse channel overlain by Proximal major crevase channel

Moat House Farm borehole (Figs. 5.31B/532)

This example has been divided into three units each with an erosive base. Unit 1 is underlain by 'Lacustrine thickly interbedded coarse and fine deposits and consists of 'Sandstone' lithofacies at its base with 'Siltstone' lithofacies above it. Unit 2 is of a similar lithology to the previous example with the lowermost 'Sandstone' lithofacies being coarse grained and massive (Plate 5.33) with those above showing erosive scour surfaces (Plate 5.34) and capped by fine grained lithofacies with ptygmatic sandstones dipping obliquely to the bedding (Plate 5.35). Unit 3 alternates between coarser and fine lithofacies at the base (Plate 5.35) but above that fines upwards into 'Siltstone' and 'Mudstone silty' lithofacies both of which contain thin beds of medium grained sandstone with occasional microfaults (Plate 5.36) and common *Calamites* and *Medullosa* stems. This upper unit is overlain by the association 'Poorly to imperfectly drained siliciclastic palaeosol/s'.

Interpretation

The lowest unit is interpreted as either a 'Minor Crevasse' or 'Distal Feeder' channel (Fielding 1984a, 1986) which has been actively filled (Williams 1986) with both 'Sandstone' and 'Siltstone' lithofacies, both of which display erosive bases. Unit 2 appears again to have been mostly actively filled, with much of the sediment dumped forming massive lithofacies. Only in the top 1m are indications of low stage products forming the finer grained lithofacies. It is possible that this unit may be a 'Proximal major crevasse' channel (Fielding 1984a, 1986) eroding into the deposits of one of its earlier 'Minor crevasse' channels. Unit 3 may be a separate channel from that below

Plate 5.33 Lithofacies association 3 'Channel fill deposits'. Location: Moat House Farm Borehole. 615.80-616.25m. Age: Westphalian B. 'Sandstone medium to coarse grained massive, off white' (see Fig. 533B).

Plate 5.34 Lithofacies association 3, 'Channel fill deposits'. Location: Moat House Farm Borehole. 613.00 - 613.30m. Age: Westphalian B. 'Sandstone, medium to coarse grained with large scale cross stratification with a scour base into underlying' Sandstone medium to coarse grained massive.

Plate 5.35 Lithofacies association 3 'Channel fill deposits'.
Location: Moat House Farm Borehole. 611.70 - 612.10m.
Age: Westphalian B.

Plate 5.36 Lithofacies association 3, 'Channel fill deposits'. Location: Moat House Farm Borehole. 608.40 - .80m. Age: Westphalian B.

or may be a reactivation of the same channel. Initially it was actively filled in the lowerst 0.3m, but above this the finer grained lithofacies containing medium grained sandstone suggest a regime of variable discharge with limited amounts of bedload sediment only deposited during high stage. This is typical of atrophied channels (Williams 1986) which are only partially abandoned.

Example 7. Major distributary channel

Broadacres borehole (Figs. 5.33-5.35)

This example overlies a 'Long-residence histosol' and comprises six units. The lowest unit is 3.68m thick, has an erosive base, and consists mainly of two 'Sandstone' lithofacies similar to the example at Crewe Farm borehole. Above this Unit 2 is 2.78m thick and consists mainly of 'Siltstone with lenticular sandstone stratification' interbedded with 'Sandstone fine with small scale cross lamination', with erosive bases throughout. Unit 3 is just over 2m thick and also erosively based with a coarse grained lower third and a finer grained upper two thirds with an occasional erosive base.

Whereas many erosively based lithofacies occur within the lowest three units only the basal two lithofacies of Unit 4 are erosive. Above them occur a variety of 'Siltstone' lithofacies mainly with gradational bases, totalling nearly 8m in thickness.

Unit 5 is subdivided into 3 subunits each with an erosive base overlying which is a thin 'Sandstone fine' lithofacies and thicker 'Siltstone' lithofacies. Each subunit is about 1.5m thick so that the whole unit totals 4.4m thick. Finally unit 6 comprises alternating 'Sandstone fine' and 'Siltstone' lithofacies in the basal 2m, topped by 2m of alternating thin 'Mudstone silty' and thicker 'Siltstone' lithofacies and finally nearly 1m of 'Seatearth' and 'Subseatearth' lithofacies. Above this unit the association 'Lacustrine siltstone dominated deposits' occurs.

Interpretation

Unit 1 is interpreted as the deposits of an actively filled channel (Williams 1986) apart from the 'Siltstone' lithofacies at the top which may be a low stage deposit. The erosive bases within Unit 2 suggest that it also was actively filled at times with the alternation of 'Sandstone' and 'Siltstone' lithofacies imply variable discharge. It is probable that both these units form part of the same channel, the upper unit being deposited following partial abandonment as atrophied channel deposits (Williams 1986). The interpretation of Unit 3 is probably similar to that of units 1 and 2 in that the lower third resembles the products of actively filled channels whereas the upper two thirds resembles those of atrophied channels. It is possible that all three units were deposited by the same channel which meandered across a wide channel belt (see end of this interpretation).

Unit 4 is more difficult to interpret than the previous three units, because of the abundance of gradational bases. Whilst the lower part of this unit is possibly confined to a channel, it is believed that most of the unit can be attributed to overbank deposition. Although like the association 'Lacustrine siltstone dominated deposits' this unit consists almost exclusively of 'Siltstone' lithofacies, other features diagnostic of the association e.g. abundance of plant fragments and ichnofossils are missing. However inorganic sedimentary structures within this association reveal that the lithofacies are dipping about 5° steeper than tectonic dip.

Subunits 5A, 5B and 5C are all interpreted as 'Channel fill deposits' and may represent the products of successive high stage flows during which the 'Sandstone' lithofacies were deposited,

Fig.5.33 Examples of Lithofacies association 3, 'Channel fill deposits'.

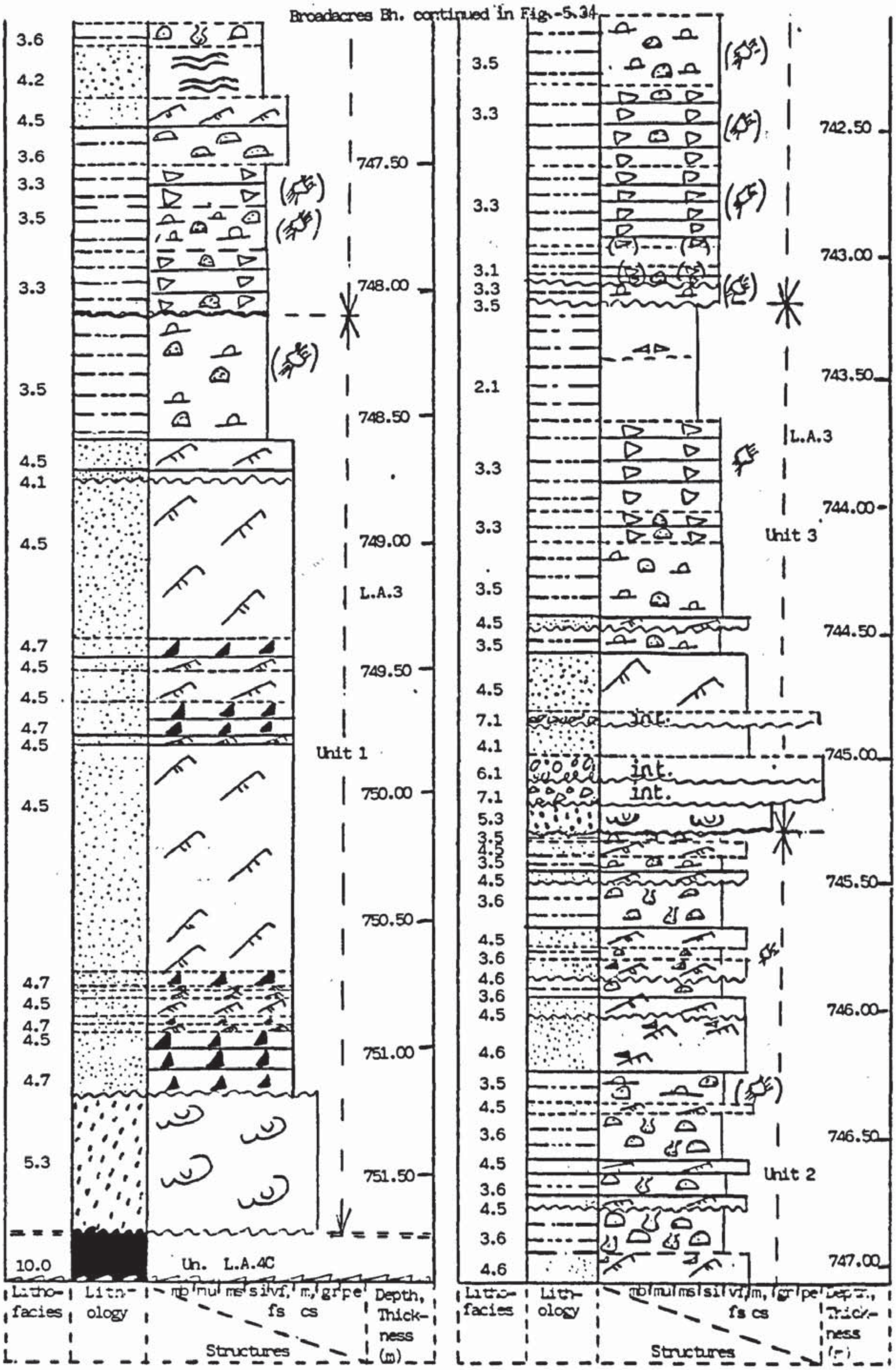


Fig. 5.34 Example of Lithofacies association 3, 'Channel fill deposits'.

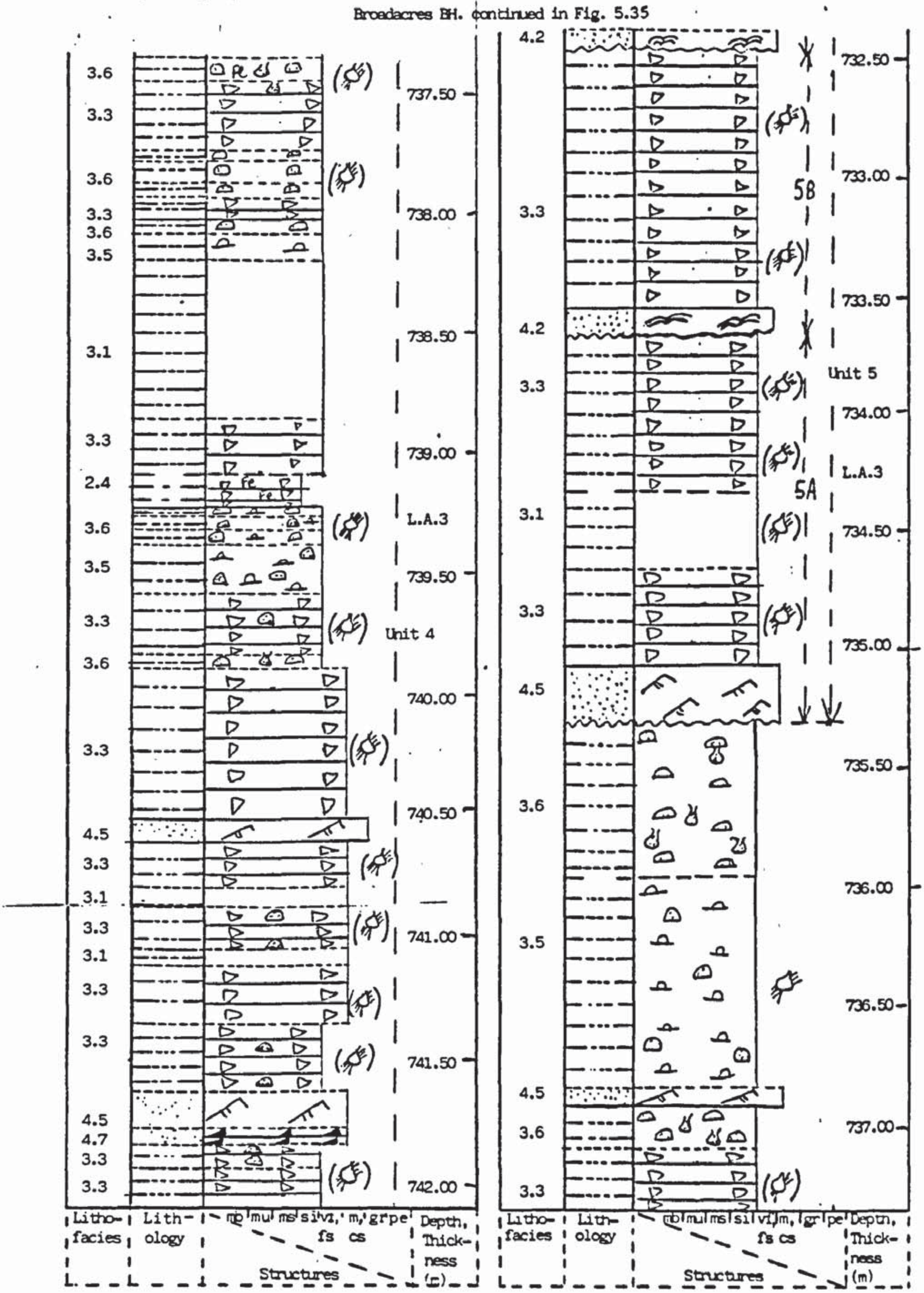
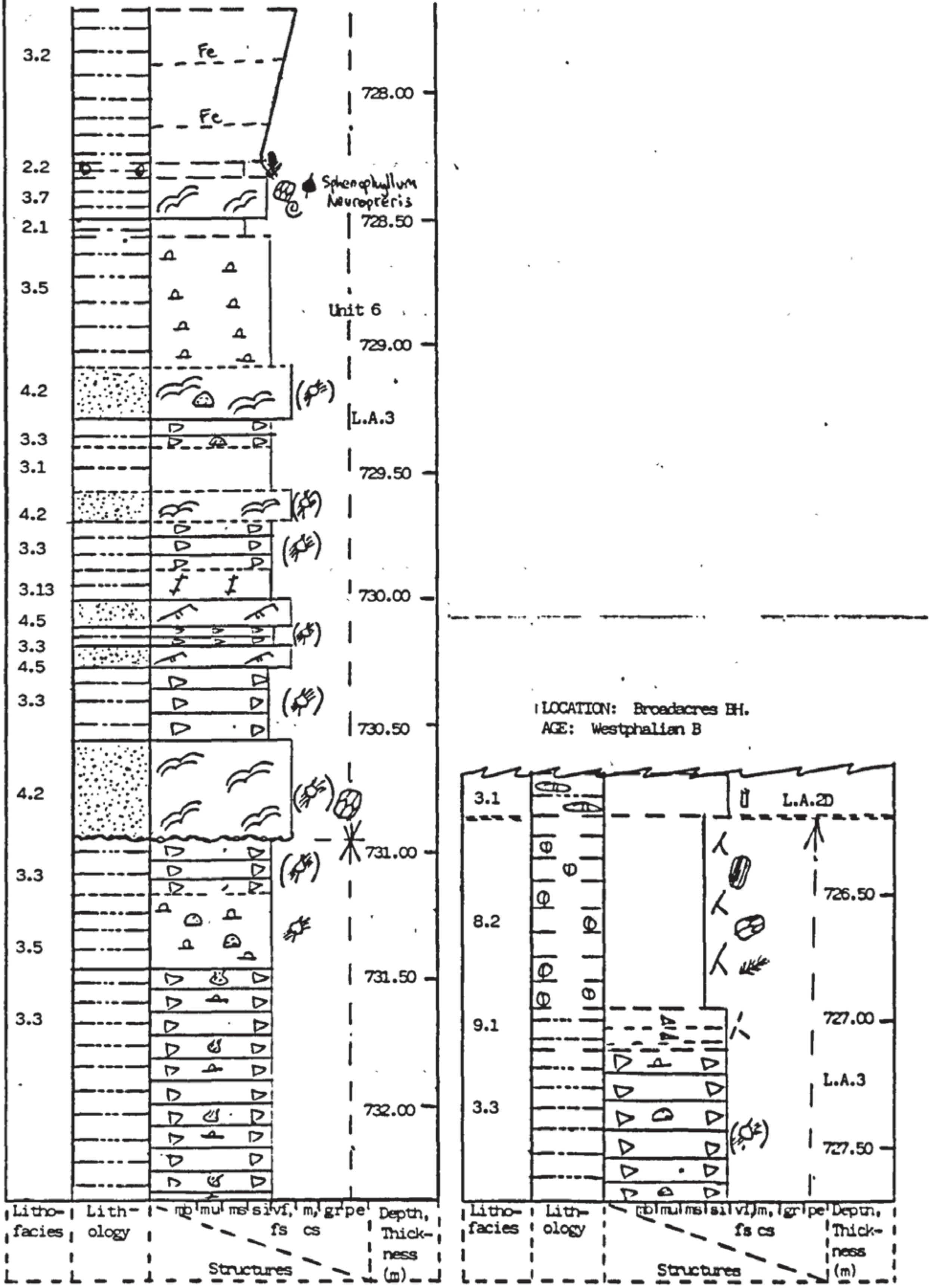


Fig. 5.35 Example of Lithofacies association 3, 'Channel fill deposits'.



followed by low stage deposits of the 'Siltstone' lithofacies. The similarity in thickness of each of the subunits suggests similar flood events which may have been seasonal. Unit 6 is again interpreted as 'Channel fill deposits' with the basal 2m resulting from active fill, whereas the lack of erosive bases and the presence of abundant plant fragments in the 2m above this suggests that this may be abandoned fill deposits. Abandonment at the top of this unit was eventually of long enough duration to allow plant colonisation and 'Seatearth' lithofacies were produced. The 'Lacustrine siltstone dominated deposits' above are interpreted as overbank sediments produced by an adjacent channel.

If the 2m of overbank sediments referred to above are included then this example is composed of over 27m of channel and near channel derived sediments. Thicknesses of this magnitude are very rare within the Warwickshire Coalfield and according to Fielding (1986) occur only within the deposits of 'Major distributaries'. Guion (1978) expected that a similar channel type 'Major meandering' was likely to erode more than one seam, and this is the case in workings both adjacent to Broadacres borehole and to the northwest where both the Two Yard and Bare seams have been removed. To the northwest removal of these seams can be clearly traced a length of 12km, and reveals a channel belt up to 1.2km wide at this stratigraphic horizon. If as suspected the deposits of this major distributary extend southeast to Broadacres borehole and beyond toward Binley Colliery, the length of this major distributary would be in excess of 30km limited only by the boundaries of the Warwickshire Coalfield.

Example 8. Channel type unknown

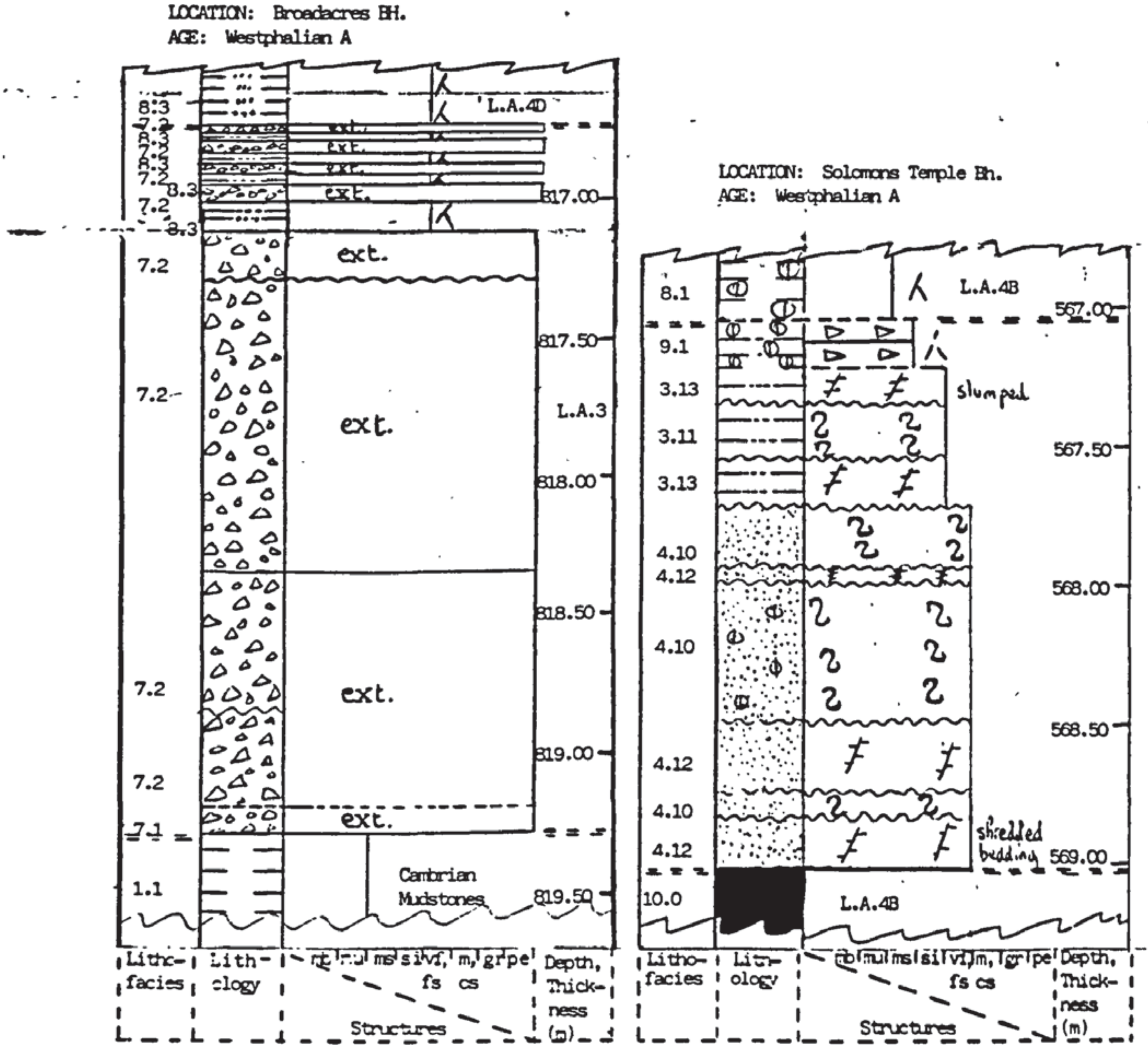
Broadacres borehole (Fig. 5.36A)

This example consists almost exclusively of the lithofacies 'Breccia extraformational' and occurs at the base of the Westphalian in this and many other boreholes in the Warwickshire Coalfield. It is underlain by Cambrian mudstones. The clasts in the breccias are commonly composed of black, grey or green mudstone, disc shaped, and poorly sorted usually less than 20mm diameter and 5mm thickness, but may be up to 60mm diameter. They usually lie parallel to bedding and the breccia may be clast or matrix supported. The grain size of the matrix ranges from mudstone silty to siltstone. There are six beds in this example forming three couplets in which the size of clasts fines upwards. The uppermost bed is formed of interbedded breccia and siltstone penetrated by occasional oblique roots.

Interpretation

The clasts are believed to have been derived from the underlying Cambrian mudstones, so that whilst they are extraformational they are locally derived. The size of clasts indicates that fairly powerful currents must have been involved in their transport and this example is interpreted as 'Channel fill deposits'. Although the dimensions of the channel forming this and other examples are unknown, the widespread occurrence of this association at the base of the Westphalian suggests sheet like deposits perhaps originating from braided channels. The widespread erosion may help to explain the lack of weathering in the underlying Cambrian sediments. Each couplet may be the product of a decelerating current. The larger clasts were probably transported as bedload, but the smaller clasts may have been carried in suspension by turbulent flows, and dropped to lie parallel to bedding as the current waned.

Fig. 5.36 Examples of Lithofacies association 3, 'Channel fill deposits'.



Bank Collapse Structures

Bank collapse structures which are associated with channels are easily recognised in borehole core. These often form when the outer bank of a meandering channel becomes unstable, due either to undercutting or following the withdrawl of water support during low stage. Alternatively, at low stage changes of hydrostatic pressure during dewatering of recently deposited channel fill on bars, may promote movement and cause a lobate mass of sediment to accumulate within a channel. Preservation of this type of bank collapse structure is likely in channels with low current velocities (Taylor and Woodyer 1978) or if channels become abandoned shortly after movement takes place. Both Turnbull et al. 1966 and Laury 1971 studied bank collapse structures and two types of failure were recognised dependant on the location of the rotational shear plane along which the sediment moved. If the base of the plane was above the channel thalweg it was termed slope failure and if below it was termed base failure. An example of each type is given below.

Example 9. Bank collapse caused by slope failure

Solomon's Temple borehole (Fig. 5.36B)

This example consists of slurried and melangé lithofacies of both sandstone and siltstone. The top 0.16m has been penetrated by oblique roots. It is both under- and overlain by the association 'Very poorly drained siliciclastic dominated palaeosol/2' the beds of which dip normally.

Interpretation

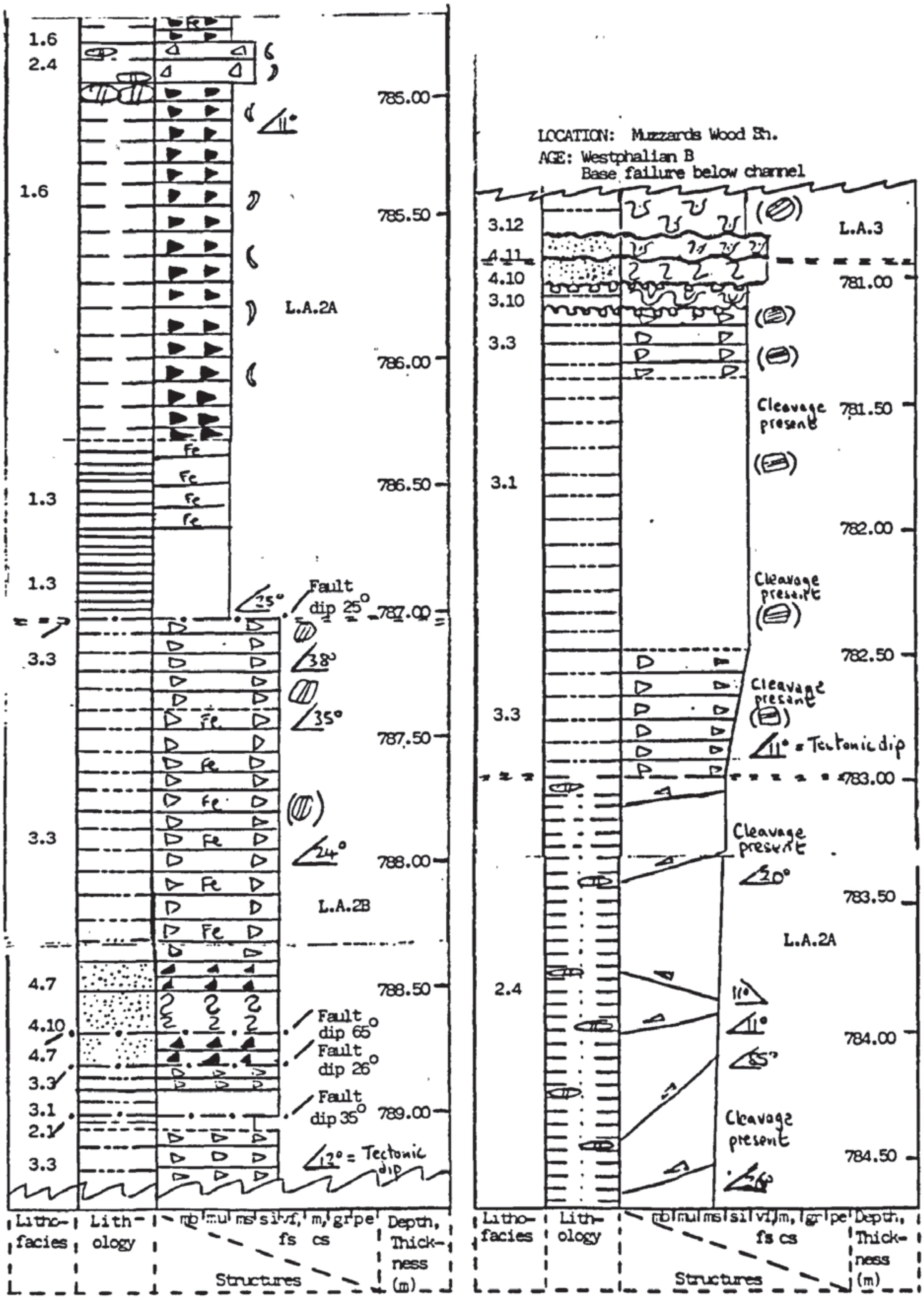
It is believed that this example of 'Channel fill deposits' represents a bank collapse structure formed by slope failure. This is because of the lithofacies present and the lack of deformation in the palaeosol association below. It is characterised by steeply dipping beds, melangé lithofacies in which slumping, folding and microfaulting are found, and lithofacies with load structures, all penecontemporaneous deformation structures produced by stressing of the sediment during failure. No other evidence for the channel exists, so it may be presumed that the bank collapse structure filled the channel at this location, and that subsequently the channel was abandoned.

Example 10. Bank collapse caused by base failure

Muzzards Wood borehole (Fig. 5.37)

This example consists of 'L.A.3, Channel fill deposits' underlain successively by 'L.A."B, Lacustrine coarsening upwards deposits', 'L.A."A, Lacustrine suspension deposits' and another association of 'L1A.2B Lacustrine coarsening upwards deposits'. Although the 'Lacustrine coarsening upwards deposits' lying directly below the 'Channel fill deposits' dip at a similar rate (11°) to the regional tectonic dip (9°) in the basal 1.58m a distinct vertical cleavage occurs. When the core was broken the cleavage took the form of occasionally bifurcating parallel ridges about 1mm apart. In the 'Lacustrine suspension deposits' the dip of bedding rapidly increases to 85° and then decreases again over a thickness of about 2m. At the boundary of the 'Lacustrine suspension deposits' and the underlying 'Lacustrine coarsening upwards' a polished 25° dipping surface occurs with steeper dips of bedding for 1m below. Within this association lithofacies with fairly steeply dipping (up to 35°) polished surfaces at their junctions occur for 3m from the top of the association. One fault plane dipping at 65° is also present. Below this depth dips are normal.

Fig. 5.37 Examples of Lithofacies association 3, 'Channel fill deposits'.



Interpretation

It is believed that this example forms part of a bank collapse structure produced by base failure. This failure is characterised by steeply dipping bedding (folding) and a number of fault planes which dip at angles less than the normal dip (60°-70°) of tectonically formed faults. The base failure may be related to the 'Channel fill deposits' lying at the top of this example. It is postulated that in the outer bank of the channel above failure took place along curved planes which extended below the base of the channel and flattened out at depth, resulting in planes dipping between 25°-35° in the lowest 'Lacustrine coarsening upwards deposits'. Movement also took place above this resulting in folding and the formation of a vertical cleavage related to the direction of movement.

From the examples in this section it can be seen that 'Channel fill deposits' are underlain by a wide variety of associations, but are most commonly overlain by a 'Palaeosol' association. 'Channel fill deposits' are distinguished from 'Lacustrine thickly interbedded coarse and fine deposits' by the increased thickness and sometimes the coarseness of 'Sandstone' lithofacies together with the presence of erosively based lithofacies. 'Breccia' and 'Conglomerate' lithofacies are almost always confined to this association. Fine grained examples of this association are distinguished from 'Lacustrine dominantly coarsening upwards deposits' by the common occurrence of fining upwards lithofacies and sequences, and the common occurrence of plant fragments. Erosive based lithofacies also help to distinguish both the last association and 'Lacustrine siltstone dominated deposits' from 'Channel fill deposits'.

The presence of 'Channel fill deposits' overlying a wide variety of other associations is partly explained by the ability of channels to erode pre-existing associations. Because of this, the lateral relationships of 'Channel fill deposits' and other associations is difficult to determine from borehole core, and thus the mechanisms controlling channel distribution are difficult to determine. The fact that a wide variety of channels can be recognised indicates that they may be found in a variety of depositional situations. However, the preservation of 'Channel fill deposits' and their subsequent upward transition into 'Palaeosol' lithofacies suggests following channel abandonment plants were quickly able to establish themselves often on a surface undergoing a minimum of subsidence and deposition.

5.4.7 Palaeosol Lithofacies Associations

The interpretation of coals and seatearths have to address questions which have long been the subject of controversy. Where coal is concerned this can be resolved primarily into whether it was an autochthonous e.g. Logan (1841) or an allochthonous e.g. Fayol (1887) deposit. It has been argued that seatearths are subaqueous deposits without subsequent modifications e.g. Grim and Allen (1938) or that they have been altered following deposition by a variety of processes, which may include pedogenesis e.g. Weller (1957). Finally the question of the relationship between coal and seatearths revolves around the time of genesis of the former in relation to the latter. This varies from well before e.g. Weller (1931), to immediately preceeding e.g. Stout (1923) or concurrently Logan (1841).

Most modern soils are terrestial and are therefore forming in destructive environments. These are very different from soils occurring in depositional environments, which although interpreted by some authors as abandonment facies (Elliott 1974b) are subject to intermittent sedimentation.

Four palaeosol lithofacies associations are recognised in this study based on features that reflect the activity of the depositional environment, the amount of pedogenesis undergone, the drainage situation during pedogenesis and the type and amount of organic matter remaining after pedogenesis. These associations are genetically related and often occur as alternations within a Coal Measure sequence.

5.4.7.1 Lithofacies Association 4A

Impoverished siliciclastic palaeosol/s

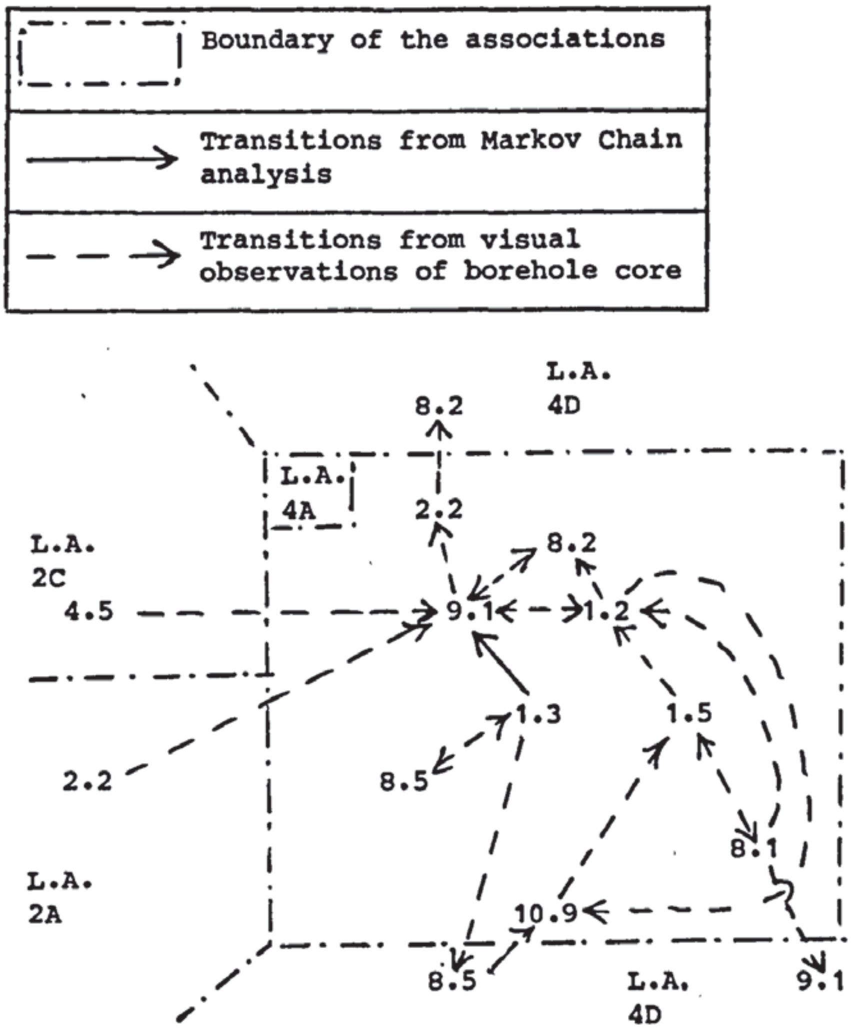
An indication of this association is given by the F.R.D. for palaeosols, although the rock type 'Subseatearth' was not separated from that of 'Seatearth' in the M.C.A. (Fig. 5.38).

Inspection of many borehole logs reveals the association to be usually composed of couplets of either fine grained 'Seatearth' or 'Subseatearth' lithofacies, with other 'Mudstone' lithofacies i.e. 'Mudstone, massive medium to dark grey', 'Mudstone' massive with abundant plant fragments and 'Mudstone with coal lenses' (See Fig. 5.39A,D). The plant fragments and coal lenses are often of the SPHENOPHYTE *Calamites* and occasionally foliage of PTERIDOSPERMOPHYTES. Rarely thin coals with mudstone laminae are associated with the 'Mudstone' lithofacies. Each lithofacies bed is usually thin (less than 0.5m) although occasionally thicker 'Subseatearth' (Fig. 5.39B) and 'Seatearth' (Fig.5.39A) lithofacies are present. Occasionally coarser examples of this association occur (Fig. 5.39C). The whole association rarely exceeds 2m in thickness.

It is distinguished from other palaeosol associations by interbedding of rooted and non-rooted lithofacies, occurrence of 'Subseatearth' lithofacies, and the lack of thick 'Seatearth'

Fig.5.38 Facies relationship diagram for Lithofacies association 4A 'Impoverished siliciclastic palaeosol/s'

Key



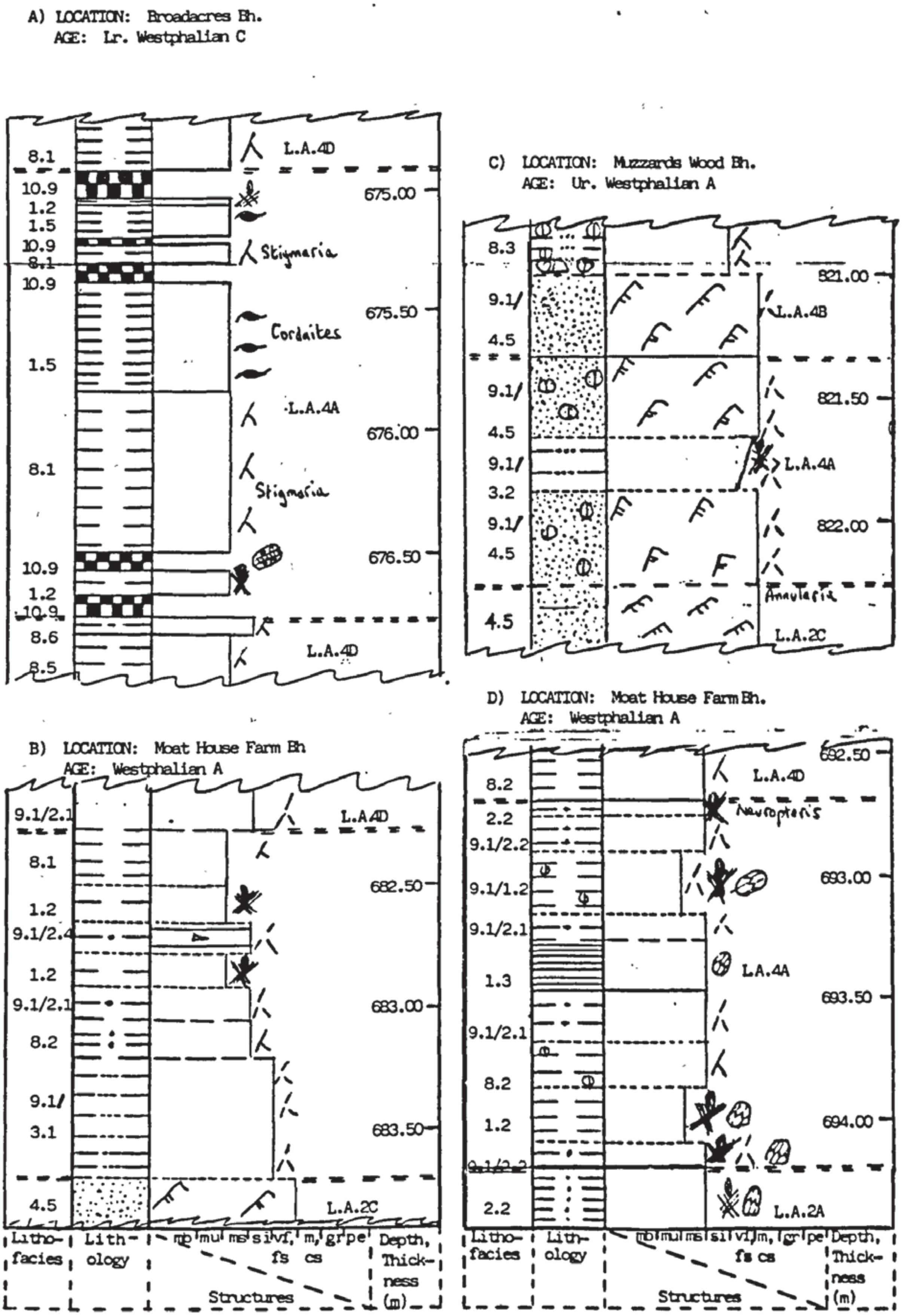
Lithofacies present

1.2	Mudstone, massive, with abundant plant fragments
1.3	Mudstone, massive dark grey to black
1.5	Mudstone, with coal lenses
2.2	Mudstone silty, massive with abundant plant fragments
4.5	Sandstone, fine, with small scale cross lamination
8.1	Seatearth, mudstone grey
8.2	Seatearth, mudstone silty grey
8.5	Seatearth, mudstone, brown
9.1	Subseatearth, grey
10.9	Coal, plus siliciclastic sediment

Lithofacies associations present

L.A.2A	Lacustrine suspension deposits
L.A.2C	Lacustrine thickly interbedded coarse and fine deposits
L.A.4D	Alternate poorly and imperfectly drained siliciclastic palaeosol/s

Fig. 5.39 Examples of Lithofacies association 4A 'Impoverished siliciclastic palaeosol/s'.



A) LOCATION: Broadacres Bh.
AGE: Lr. Westphalian C

B) LOCATION: Moat House Farm Bh
AGE: Westphalian A

C) LOCATION: Muzzards Wood Bh.
AGE: Ur. Westphalian A

D) LOCATION: Moat House Farm Bh.
AGE: Westphalian A

(usually less than 0.5m) and 'Coal' lithofacies. Other lacustrine associations which may be similar lithologically lack in-situ roots.

It is often under- and overlain by the lithofacies associations 'Very poorly drained siliciclastic dominated palaeosol/s' and 'Alternate poorly to imperfectly drained siliciclastic palaeosol/s'. A variety of 'Lacustrine' lithofacies associations may also underlie it, most noticeably 'Lacustrine suspension deposits' and 'Lacustrine dominantly coarsening upwards deposits'.

Scott (1976, 1978) recognised a similar facies association which he termed '3B Floodplain' consisting of mudstones grading upwards into seatearths and thin coals, although in contrast to the association under consideration sphaerosiderite and thin sandstones were also present. Two other facies associations recognised by Scott may also be included in the lithofacies association 'Impoverished siliciclastic palaeosol'. These are '2C Marginal lake Deltatop' (Scott 1976, 1978) which are thin units of Calamites bearing mudstones and seatearths, and '3E Swamp/lake' consisting of boghead and shaly boghead coals, although Scott (1976) found this association mainly above normal bituminous coals. Lithofacies occurring within the association 'Impoverished siliciclastic palaeosols/s' are similar to those in the 'Shaly coal' facies of Fielding (1982) except that he lays more exmphasis on the presence of coal. There appears to be some overlap in terms of lithofacies present and geometrical considerations between Fielding's (1982) 'Passive lake margin' and 'Shaly coal' facies, resolved by the latters later inclusion in his 'Swamp' facies (Fielding 1984a). Only one grey mudstone facies was recognised by Besly (1983) when studying the Etrunia formation. As this was usually penetrated by infrequent roots it may be equivalent to the lithofacies association 'Impoverished siliciclastic palaeosol'.

Very few examples of this association have been described from modern depositional environments. This may be because the soils are too poorly developed to interest pedologists, whilst difficulty in obtaining cores may have discouraged sedimentologists. Cores taken from the 'Marsh' environment by Coleman and Prior (1980, Fig. 16) resemble this association, in that parallel or lenticular laminated siltstones are interbedded with rooted mudstones. Interdistributary areas of the Sepik river of New Guinea which are subject to periodic flooding by siliciclastic sediment bearing waters produce lithofacies described as very poorly drained to swampy young alluvial soils (Pandago and Kabuk Land Systems Haantjens et al. 1968, p. 44), which may be similar to the lithofacies association 'Impoverished siliciclastic palaeosols'.

Interpretation

The distinguishing feature of this lithofacies association is that it was formed in a more active depositional environment than other siliciclastic palaesol associations recognised in this study. It is believed from the ubiquitous grey colourations, that this association formed subaqueously in a reducing environment. The beds of mudstone unpenetrated by roots are interpreted as lacustrine in origin formed by periodic influxes of sediment in standing water, the depth of which was beyond that capable of allowing plant growth. As the lake became infilled, the water became shallow enough to support plant growth allowing pedogenesis to act on the underlying lacustrine sediment. Discontinuous subsidence is believed to have continued so that eventually either the water became too deep for plant growth or influx of lacustrine sediment may have terminated plant growth. The length of time over which pedogenesis took place is reflected in the paucity of oblique roots (producing a 'Subseatearth' lithofacies) and the fact that the whole of the sequence is not penetrated by roots. The abundance of plant fragments within both the lacustrine and pedogenecally altered lacustrine lithofacies probably resulted from the close proximity of growing vegetation. A similar abundance of <u>Calamites</u> in dark grey mudstones was noted by Scott (1978, 1979) who believed that these plants may have lived at the edge of lakes adjacent to swamps. This corresponds to the environment proposed for the lithofacies association 'Impoverished siliciclastic palaesols'. The thin coals are believed to be either allochthonous transported from nearby lake margins, or autochthonous but subject to flooding which accounts for thin mudstone laminae and the presence of the lithofacies Coal, grey, dull, smooth, canneloid. Any siderite nodules present probably originated diagenetically and not as a result of pedogenesis.

It is believed that the majority of the 'Mudstone' lithofacies were deposited after pedogenesis in the underlying 'Seatearth' and 'Subseatearth' lithofacies had ceased. If any organic rich 'Mudstone' lithofacies was deposited whilst pedogenesis was taking place then in terms of soil horizon nomenclature, this bed may be regarded as an 'A' horizon. The barely modified 'Subseatearth' and 'Seatearth' lithofacies may be regarded as 'C' horizons. The most important aspect of this palaesol association is its intermittent development between episodes of lacustrine deposition. Soils accumulating in active depositional environments on tropical coastal plains can be classified as fluvisols (FAO/UNESCO 1974). Alternatively poorly developed soils can be classified as inceptisols (Soil Survey Staff 1975) or weakly developed riverine or lacustrine soils (CCTA, D'Hoore 1964).

This association is expected to occur in areas undergoing relatively low rates of subsidence but adjacent to a source of siliciclastic sediment.

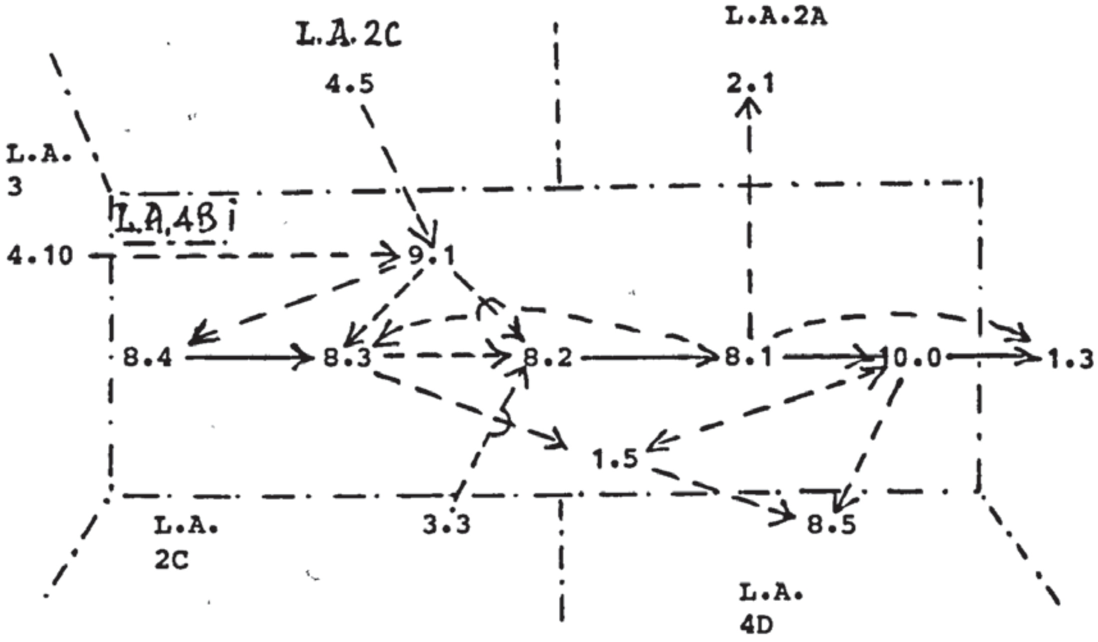
5.4.7.2 Lithofacies Association 4B
Very poorly drained siliciclastic dominated palaeosol/s

One aspect of this association is reflected in the F.R.D. for palaeosols shown below, determined by M.C.A. (Fig. 5.40). This is the fining upwards sequence from coarse grey 'Subseatearth' or 'Seatearth' lithofacies to fine grained 'Seatearth' lithofacies and then into 'Coal' lithofacies. Inspection of borehole logs reveals that instead of 'Coal' lithofacies the 'Seatearth' lithofacies may pass upwards into the lithofacies 'Mudstone, massive medium to dark grey' (Fig. 5.41C), 'Mudstone massive with abundant plant fragments,' (Fig. 5.41C) 'Mudstone massive dark grey to black, (Fig. 5.42) or 'Mudstone with coal lenses' (Fig.5.41B). Alternatively the 'Seatearth' lithofacies may alternate between coarser and finer grained sediment, and in places coarsen upwards (Fig. 5.43). Each episode of pedogenesis constitutes a profile so that within a particular example of this lithofacies association there may be one (Figs.5.41A,D) or several stacked profiles (Figs.5.41C, 5.43). Examples of this association formed of single profiles may be up to 2m thick, but stacked profiles may increase the thickness to 10m. This association is characterised by grey colouration although it may darken upwards to almost black (Fig. 5.41D) Roots are preserved

Fig.5.40 Facies relationship diagram for Lithofacies association 4B 'Very poorly drained siliciclastic dominated palaeosol/s'

Key

–·–·–·	Boundary of the associations
⟶	Transitions from Markov Chain analysis
– – →	Transitions from visual observations of borehole core



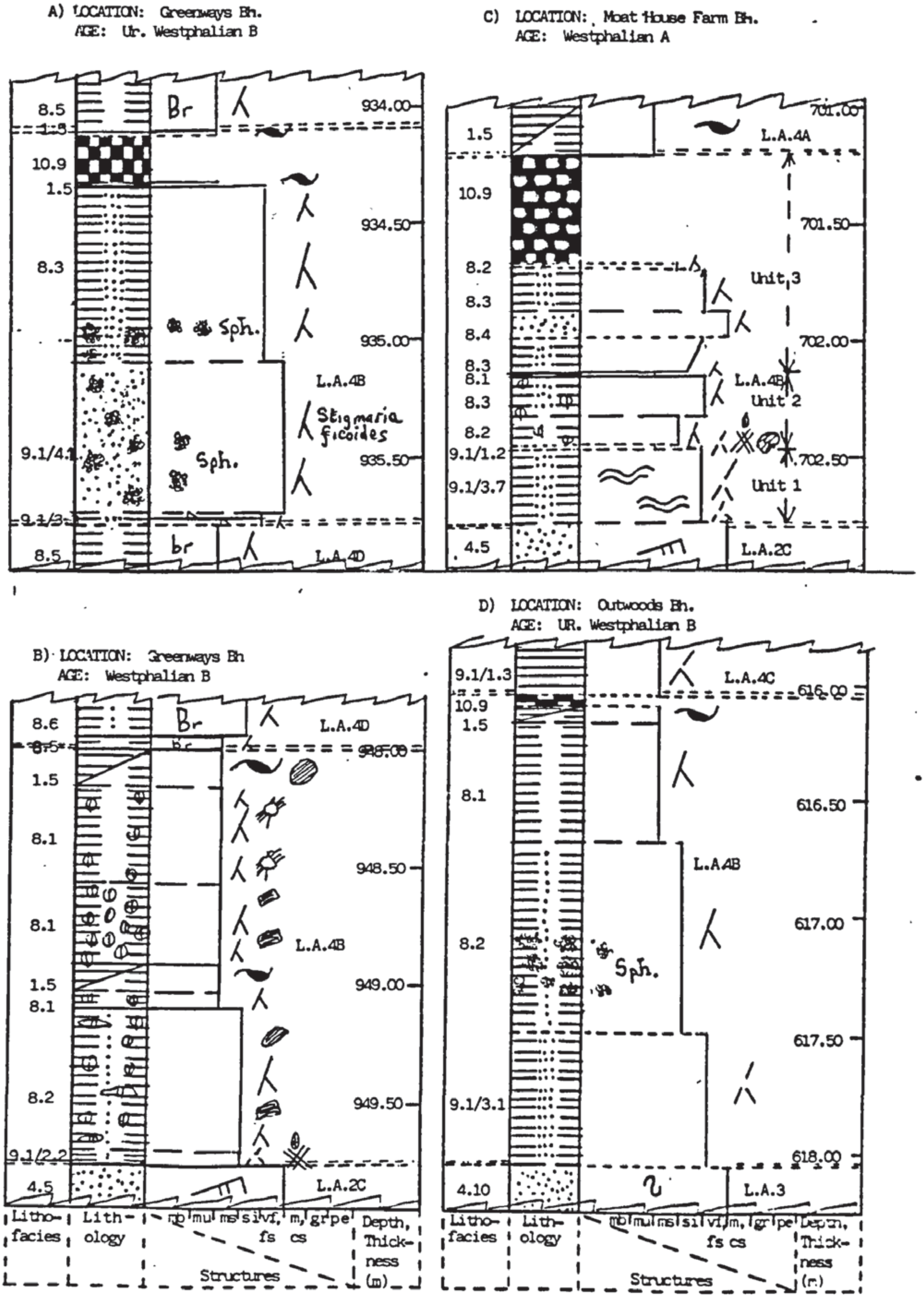
Lithofacies present

1.3	Mudstone, massive dark grey to black
1.5	Mudstone, with coal lenses
2.1	Mudstone, silty, massive medium to dark grey
3.3	Siltstone, parallel stratified with sandstone
4.5	Sandstone, fine, with small scale cross lamination
4.10	Sandstone, fine, slurried
8.1	Seatearth, mudstone grey
8.2	Seatearth, mudstone silty, grey
8.3	Seatearth, siltstone, grey
8.4	Seatearth, sandstone, grey
8.5	Seatearth, mudstone, brown
9.1	Subseatearth, grey
10.0	Coal, cannel

Lithofacies associations present

L.A.2A	Lacustrine suspension deposits
L.A.2C	Lacustrine thickly interbedded coarse and fine deposits
L.A.3	Channel fill deposits
L.A.4D	Alternate poorly and imperfectly drained siliciclastic palaeosol/s

Fig. 5.41 Examples of Lithofacies association 4B 'Very poorly drained siliciclastic dominated palaeosol/s'.



A) LOCATION: Greenways Bh.
AGE: Ur. Westphalian B

C) LOCATION: Moat House Farm Bh.
AGE: Westphalian A

B) LOCATION: Greenways Bh
AGE: Westphalian B

D) LOCATION: Outwoods Bh.
AGE: UR. Westphalian B

Fig. 5.42 Example of Lithofacies association 4B, 'Very poorly drained siliciclastic dominated palaeosol/s'.

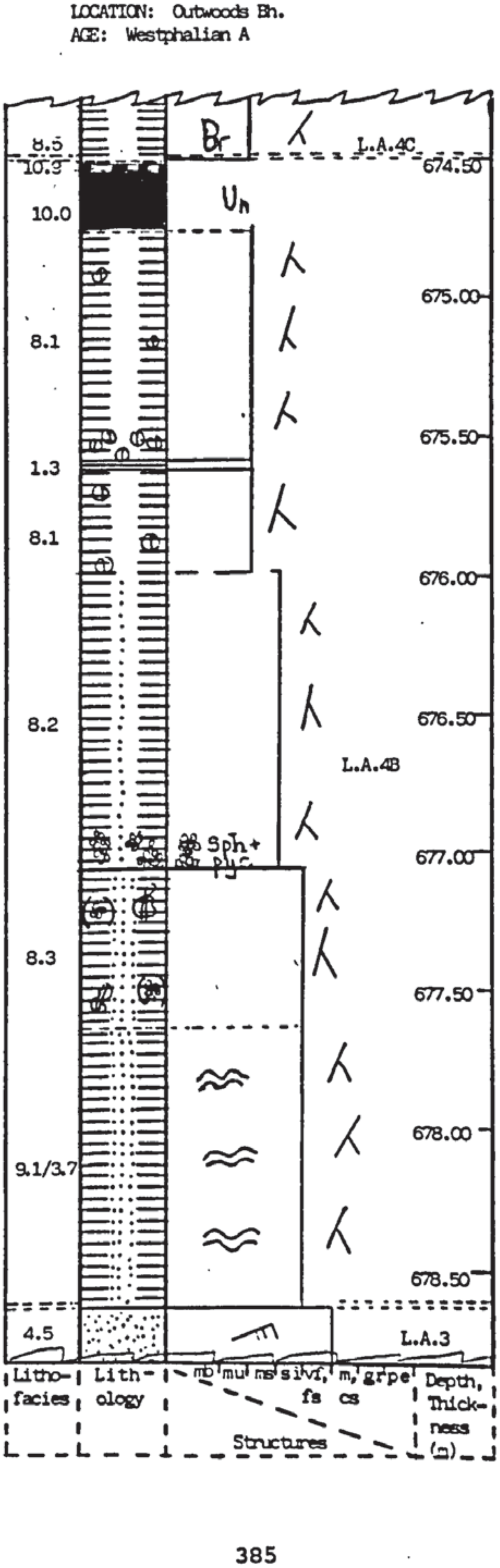
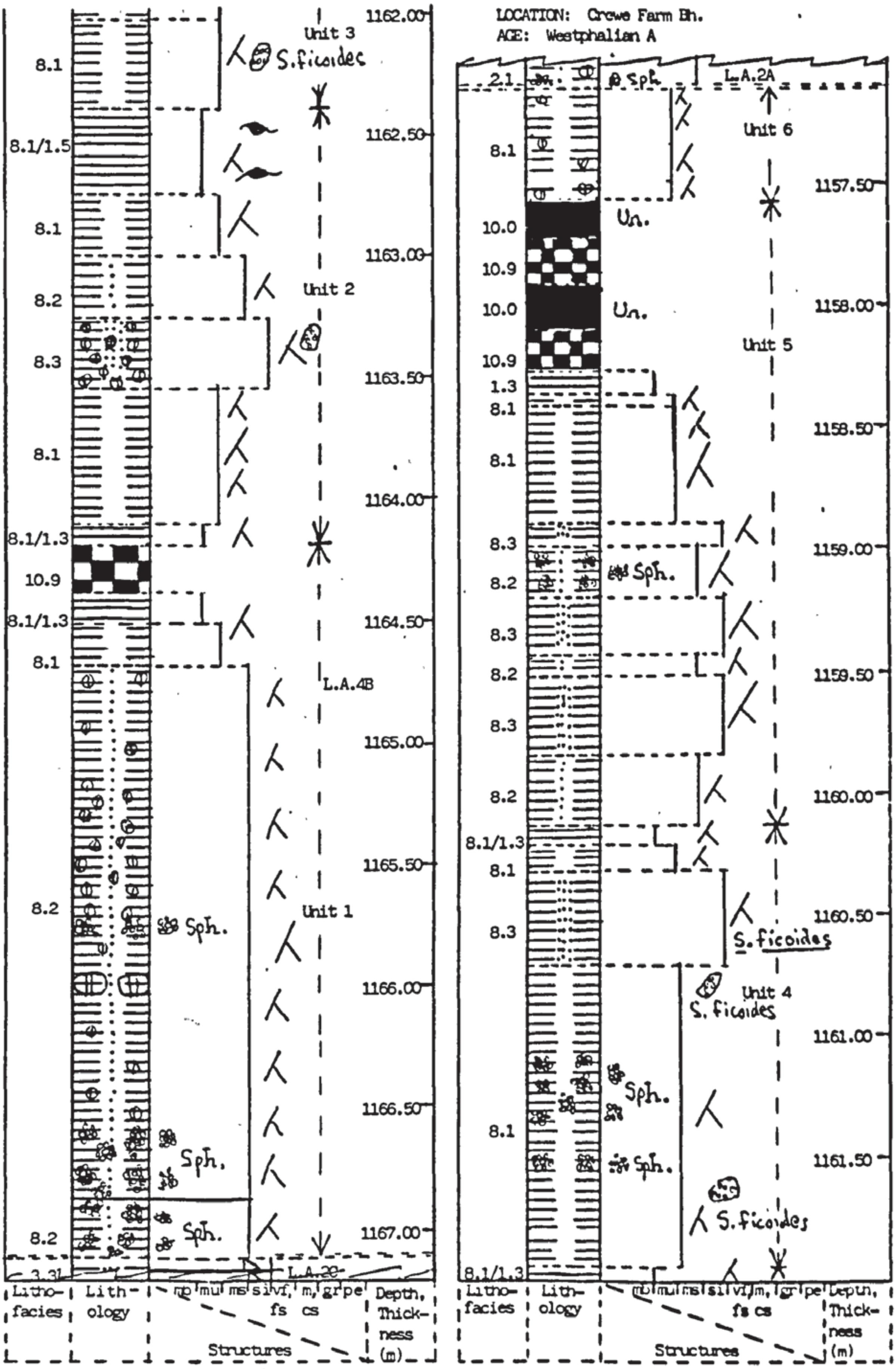


Fig. 5.43 Example of Lithofacies association 4B, 'Very poorly drained siliciclastic dominated palaeosol/s'.



as carbonaceous compressions, and often decrease in abundance in the lower part of profiles, resulting in 'Subseatearth' lithofacies at their bases (Fig. 5.41A). Towards the base especially in coarser grained lithofacies Stigmaria ficoides are sometimes preserved (Fig. 5.41A). Sphaerosiderite may form in the centre of a profile (Fig. 5.41D) or towards its base (Fig. 5.41A), often in the coarser lithofacies. Siderite nodules are often found concentrated at certain levels within the profile (Fig. 5.41A). Occasionally sphaerosiderite may be partially replaced by pyrite (Fig. 5.42).

Coals located at the top of profiles are characterised by the presence of the lithofacies 'Coal plus siliciclastic sediment' at the base and/or top of the leaf as well as the centre (Figs. 5.42, 5.43). Other lithofacies commonly represented are 'Coal, grey, fusainous soft, occurring towards the base of the leaf, and Coal, grey, mainly dull finely lensed with bright' and 'Coal, black mainly bright finely lensed with dull' the latter lithofacies forming the bulk of any leaf. These leaves usually have high ash contents and are generally less than 1m in thickness.

The distinction between the association under consideration and 'Impoverished' siliciclastic palaeosol/s' is that the former association is dominated by thicker seatearth lithofacies, has relatively thin 'Mudstone' lithofacies, and where present thicker 'Coal' lithofacies. A variety of colours may be present in the association 'Alternate poorly to imperfectly drained siliciclastic palaeosol/s' which distinguishes it from the association 'Very poorly drained siliciclastic dominated palaeosol/s' in which only grey and black colours are found. The association 'Long-residence histosol/s' contain much thicker leaves of coal (in excess of 1m) than those found in this association. This lithofacies association is most often underlain by the association 'Lacustrine thickly interbedded coarse and fine deposits, and commonly overlain by other palaeosol associations and 'Lacustrine suspension deposits'.

In studies on sediments deposited in the Pennine Basin Fielding (1982, 1984) recognised a grey facies dominated by rootlet bearing claystones which he termed 'Passive lake margin'. This is very similar to the lithofacies association under consideration except that no mention is made of coals within the facies although it is under and overlain by them. Facies association '3A Swamp' (Scott 1976, 1978) with abundant coal would probably correspond to a combination of lithofacies associations 'Very poorly drained siliciclastic dominated palaeosol/s' and 'Long-residence histosol/s'. The lithofacies association under consideration is also similar to the 'Type 1 palaeosol' of Besly (1983), although leaves of coal do not reach the same thickness as those found in the Warwickshire Coalfield. Westphalian palaeosols have also been studied in the USA by Huddle and Patterson (1961) and in Germany by Roeschmann (1971).

Recent examples of this lithofacies association may include sediments accumulating in interdistributary areas of the Sepik river in New Guinea which are less liable to flooding with present 'permanent' vegetation producing alluvial black clays and peat (Sanai and Pora Land systems, Haantjens et al. 1968, p. 46, 47). Poorly drained swamp deposits recognised by Coleman (1966) in the Atchafalaya basin appear similar to those in this lithofacies association.

The coals found in this association resemble thin peat deposits found in both the Mississippi delta (Kosters and Bailey 1983) and in NW Borneo (Anderson 1964a, 1983). The latter author

(1964) recognised two types of mire, freshwater swamps characterised by ash contents greater than 25% and peat bogs characterised by ash contents less than 25%. A similar distinction can be made in terms of ash contents for leaves of coal found in the Warwickshire Coalfield. Those with ash contents less than 10% are termed low-ash histosols and those with between 10-40% are termed high ash histosols (pedogenic lithofacies with ash contents in excess of 40% are termed siliciclastic palaeosols). Most of the leaves of coal in this association are high-ash histosols, although some of the thicker leaves are low-ash histosols.

Interpretation

The siliciclastic sediment upon which pedogenesis acts reflects depositional processes prior to the formation of a palaeosol. Often this is a fining upwards sequence reflecting increasing distance from siliciclastic sediment source. As the depth of water decreased it is postulated that plants colonised the area. The increase in plant fragments and debris may be due to the proximity of the plants as well as the paucity of siliciclastic sediment. This can be seen in the top half of profile No. 2 in Fig. 5.43. In the lower half of the profile roots have penetrated lithofacies from the association 'Lacustrine coarsening upwards deposits. The roots are mostly Stigmarian appendages and their decrease in abundance downwards through a profile reflects the distance from the parent plants. Their flattening out towards the base of a profile may demonstrate the need to support a rapidly growing arborescent LYCOPHYTE. The common occurrence of siderite and sphaerosiderite in this lithofacies association, and the abundance of the latter in the association 'Alternate poorly to imperfectly drained siliciclastic palaeosol/s' suggests a genetic relationship with these associations. Whether these minerals resulted from pedogenesis or diagenesis is difficult to determine, but the partial replacement of sphaerosiderite by pyrite (Fig.5.42) indicates the formers earlier formation. Roeschmann (1971) who studied German Westphalian palaeosols suggested that siderite may form and be remobilised several times during pedogenesis and diagenesis.

It is believed that the length of time during which pedogenesis took place allowed the formation of thicker pedogenic profiles (greater than 0.5m) in this lithofacies association when compared with 'Impoverished siliciclastic palaeosol/s', although a continuum probably exists between the two associations. The thick 'Seatearth' lithofacies in Fig. 5.42 place it within the association 'Very poorly drained siliciclastic palaeosol/s although it is transitional to the association 'Impoverished siliciclastic palaeosol/s'. Although it is believed that this association accumulated in a less depositionally active area than the association 'Impoverished siliciclastic palaeosol' it is still difficult to determine how much of the 'Mudstone' lithofacies accumulated during lithofacies, or whether pedogenesis was terminated prior to its formation. Once again assuming it accumulated at least partially during pedogenesis then this or dark grey to black 'Seatearth' lithofacies may be regarded as an 'A' horizon. Where present, peat (later metamorphosed to coal) may form an 'O' horizon above the 'A' horizon. Interpretation of the coal lithofacies forming the bulk of the leaves (see relevant lithofacies section) indicates that they accumulated in subaqueous settings. The presence of the lithofacies 'Coal plus siliciclastic sediment' indicates that flooding of the swamp by groundwater carrying siliciclastic sediment often in the form of fine mud in suspension occurred at regular intervals. Leaves of high-ash histosols are similar to those interpreted by Anderson (1964a) as the product of freshwater rheophilous (Kulczinski 1949) swamps which are subject to regular flooding, have pH values in excess of 4.0 and an approximately level surface. The 'Seatearth' lithofacies often containing pedogenically formed minerals occurs as a 'B' horizon below the 'A' horizon. Where the pedogenic profile is fully developed it is in the form OABC. Besly (1983) believed that the rooted mudstone and overlying coal seam were not genetically related, and instead represented polyphase development of firstly an alluvial and secondly an organic soil. While it is here maintained that during pedogensis the soil surface may or may not have been suitable for histosol development, roots from the growing plants undoubtedly penetrated the underlying lithofacies so that if a histosol did form it was genetically related to the 'Seatearth' lithofacies below.

Intermittent sedimentation resulted in up to 3 stacked pedogenic profiles at Moat House Farm (Fig. 5.41C). It is possible that the missing 'A' horizon in cycle No. 2 may have been eroded before the sediments of the overlying profile were deposited.

Both Scott (1976, 1978) and Fielding (1982, 1984a) believe these deposits to have been palaeosols, the latter author drawing an analogy with modern groundwater gleys. Although these soils can be regarded as fluvisols (<u>sensu</u> <u>lato</u> Young 1976) their better developed profiles and ubiquitous grey colouration allow them to be classified as 'Gleysols' (FAO/UNESCO 1974) or hydromorphic soils

(CCTA, d'Hoore 1964). Lack of horizons other than histic or cambic means that they would again be classified by Soil Survey Staff (1975) as inceptisols. Where coals occur they may be separately termed histosols (FAO/UNESCO 1974).

This lithofacies association is expected to occur commonly in areas undergoing relatively low rates of subsidence, at a fair distance from active depositional areas.

5.4.7.3 Lithofacies Association 4C

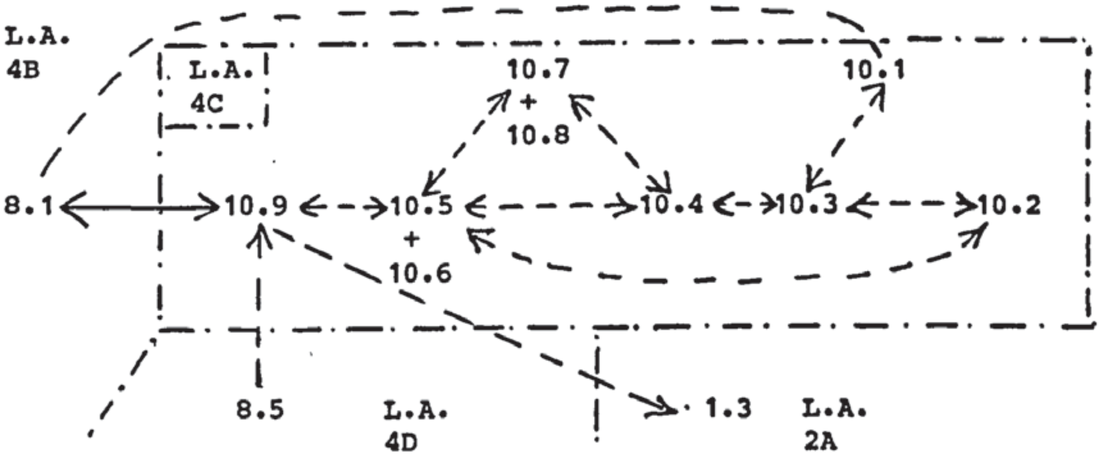
'Long-residence histosols'

A detailed lithofacies analysis has been carried out on the Thick Coal at Longmeadow Wood and Moat House Farm boreholes which lie 11.5 km apart west of Coventry. The Thick Coal is of Westphalian B age, formed by a combination of many leaves of coal, although unlike the implication of Smith (1968) only rarely are they joined to form a single leaf. Farther north up to 7 seams have been recognised which join together to form the Thick Coal (Fig. 3.2) Cope and Jones (1970) believed that the Smithy seam should be included in the Thick Coal, but it is excluded in this work because the area over which it is close to the seam above is small and irregular and its chemical and lithological properties are similar to the high-ash histosols present in the previous lithofacies association. The lowest seam (the High Main) of the Thick Coal is the uppermost seam of the Modiolaris chronozone in Warwickshire and the other seams (Bottom Nine Feet to Thin Rider) occur in the Lower Similis-Pulchra Chronozone. Towards the centre of the Pennine Basin, in Yorkshire about 100m of sediment separates the Haigh Moor and Kents Thin seams which may temporally be the lateral equivalents of the lower and upper seams of the Thick Coal.

Fig.5.44 Facies relationship diagram for Lithofacies association 4C 'Long - residence histosol/s'

Key

‐ · ‐ ·	Boundary of the associations
⟶	Transitions from Markov Chain analysis
‐ ‐ →	Transitions from visual observations of borehole core



Lithofacies present

1.3 Mudstone, massive, dark grey to black
8.1 Seatearth, mudstone grey
8.5 Seatearth mudstone, brown
10.1 Coal, cannel
10.2 Coal, grey, dull, granular
10.3 Coal, grey, predominantly dull finely lensed with bright
10.4 Coal, grey, mainly dull finely lensed with bright
10.5 Coal, black, mainly bright finely lensed with dull
10.6 Coal, black bright, massive
10.7 Coal, grey, fusainous, soft
10.8 Coal, grey, fusainous, hard
10.9 Coal, plus siliciclastic sediment

Lithofacies associations present

L.A.2A	Lacustrine suspension deposits
L.A.4B	Very poorly drained siliciclastic dominated palaeosol/s
L.A.4D	Alternate poorly and imperfectly drained siliciclastic palaeosol/s

g.5.45 Example of Lithofacies association 4C, 'Long-residence histosol/s' Longmeadow Wood borehole

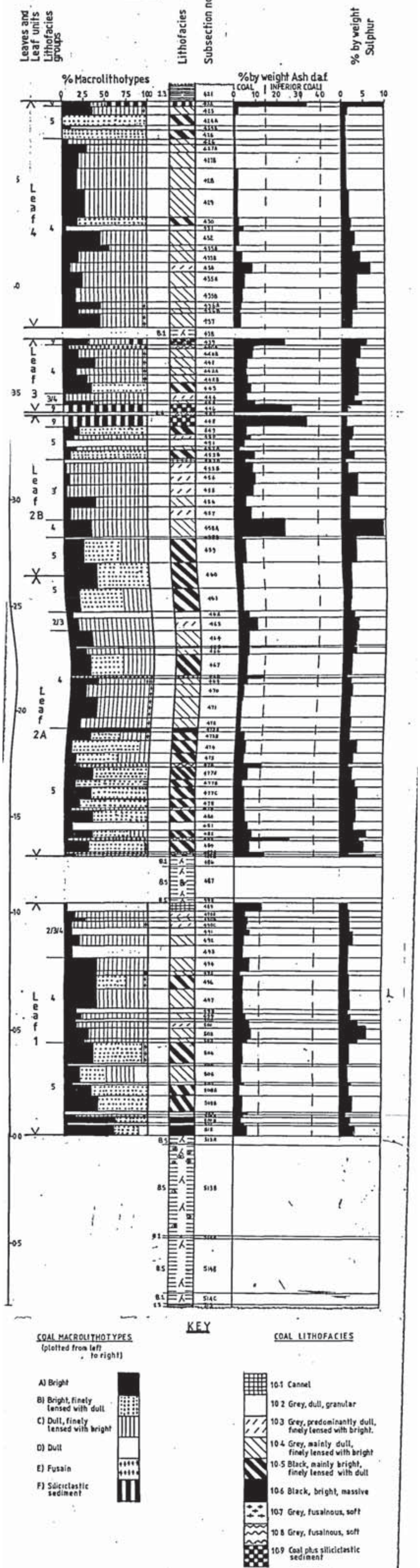
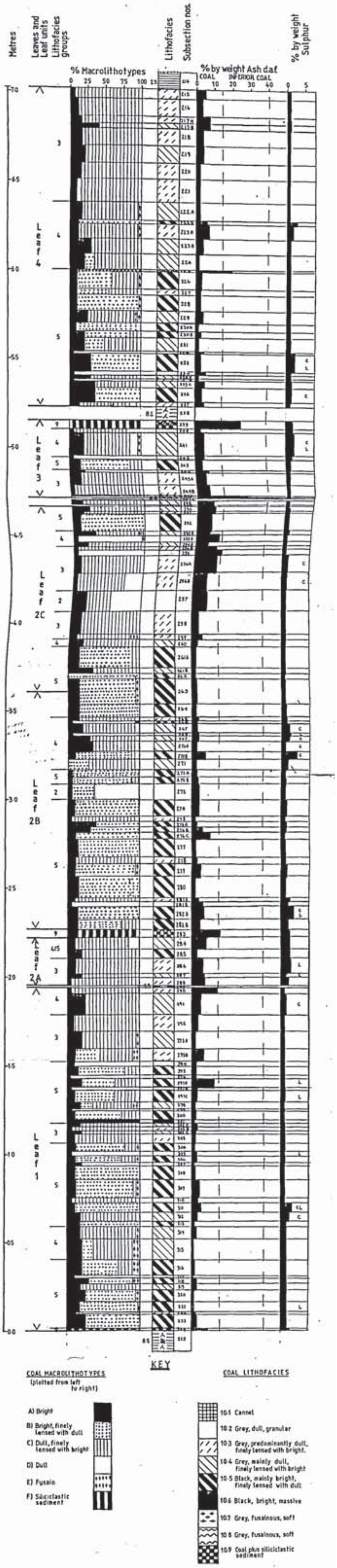


Fig.5.46 Example of Lithofacies association 4C, 'Long-residence histosol/s', Moat House Farm borehole



The area covered by the Thick Coal is just over 100 km^2, and its boundaries are defined where siliciclastic palaeosols between the leaves increase in thickness beyond 0.3m (Fig.7.3). Thus an increase in thickness between Leaves 2 and 3 forms the northern and southern boundaries, that between Leaves 1 and 2 forms the western boundary, and the eastern boundary is formed by a combination of increase in thickness between Leaves 1 and 2, and Leaves 4 and 5. It must be noted that the split leaves of the Thick Coal extend for many km^2 beyond the boundaries of the Thick Coal. To the south-east the leaves of the Thick Coal become thin and are separated by increasing thicknesses of brown siliciclastic palaeosols, whilst in the north they also become thin but are separated by a much greater thickness of sediments deposited in a variety of environments.

At Longmeadow Wood and Moat House Farm boreholes the Thick Coal comprises four leaves which are directly correlated, numbered 1 to 4 from the base (Figs.5.45, 5.46) and which vary in thickness from 0.34 to 2.7m. Below Leaf 1 is a palaeosol association, and between the other leaves a variety of siliciclastic palaeosol lithofaces exist. These are formed of mudstone except the palaeosol between Leaves 2 and 3 which is composed of fine grained sandstone. Above Leaf 1 is the lithofacies 'Mudstone, massive, dark grey to black' containing non-marine bivalves. The nine 'Coal' lithofacies and the occurrence of pyrite were used to divide the leaves into 104 subsections, with a minimum thickness of 5mm and a maxim of 120mm.

The lithofacies used to define the rock type 'Coal' were not analysed using M.C.A. However, inspection of the leaves of the Thick Coal at the above boreholes has allowed the construction of the F.R.D. (Fig. 5.44).

From the F.R.D. it can be seen that the two lithofacies most closely associated with siliciclastic lithofacies are 'Coal, grey, dull, smooth, canneloid' and 'Coal, plus siliciclastic sediment'. The former lithofacies often lies at the top of leaves of coal (Fig. 5.45), whilst the latter in this association usually lies at the top and bottom of leaves (Leaf 2 Fig. 5.46 and Leaf 3 Fig. 5.45). Occasionally this lithofacies occurs as thin beds within leaves (Leaf 2 Fig. 5.46).

Other coal lithofacies can be combined into groups which are either dominated by one lithofacies (base of Leaf 2 Fig. 5.45, or base of Leaf 1 Fig.5.46) or comprise several lithofacies different from the under- or overlying lithofacies (top of Leaf 1 Fig. 5.45). This method of grouping is similar to that adopted by Cameron (1978) except that he used combinations of lithotypes. Very often within each leaf a succession of lithofacies groups occurs, which is similar to that shown in the lithofacies F.R.D. It commences at the base with a group dominated by 'Coal, black, mainly bright finely lensed with dull' and then passes upwards successively into groups dominated by 'Coal, grey mainly dull finely lensed with bright', 'Coal, grey, predominantly dull finely lensed with bright' and 'Coal, grey, dull, granular'. The whole of leaf 1 (Fig. 5.45) is formed of this succession, although the upper group is formed of equal parts of the latter three lithofacies. A similar succession occurs in Leaf 4 (Fig. 5.46) although the lithofacies 'Coal, grey, dull granular' is not represented. This succession is also found forming the basal part of a leaf e.g. base of Leaf 2 (Fig. 5.45). Occasionally the succession occurs within leaves (e.g. towards the top of Leaf 2 Fig.5.45) or it may be obscured either by alternations between lithofacies groups or the missing out of one of the lithofacies groups (e.g. base of Leaf 1 Fig. 5.45 where two groups dominated by 'Coal, black, mainly bright finely lensed with dull' are separated by a group of 'Coal, grey, mainly dull finely lensed with bright' at the base, and there is none of the latter lithofacies group between the uppermost of the group 'Coal, black mainly bright finely lensed with dull and the overlying lithofacies group 'Coal, grey, predominantly dull finely lensed with dull'.

A cycle of lithofacies groups is completed when there is a reversion from groups dominated by 'Coal, grey, dull granular' to Coal, black, mainly bright lensed with dull ' in the reverse order to the lithofacies group succession previously described. This is best seen at the top of Leaf 2 (Fig.5.46). Very often this reversion is compressed into a single lithofacies group e.g. at the top of Leaf 2 (Fig. 5.45 'Coal, black, mainly bright lensed with dull) or Leaf 1 (Fig.5.46 'Coal, grey, mainly dull lensed with bright).

It is possible to divide Leaf 2 at each borehole into a number of units. The simplest method of dividing a leaf by use of the lithofacies 'Coal plus siliciclastic sediment'. Thus the basal unit of Leaf 2 (Fig. 5.46) comprises subsections 284-288 formed of 2 lithofacies groups, underlain by a siliciclastic palaeosol and overlain by lithofacies 'Coal plus siliciclastic sediment'. This unit may correspond to the Middle Nine Feet seam (Fig. 3.2).

Another method of dividing leaves is to distinguish between cycles of lithofacies groups occurring within a single leaf. Thus within Leaf 2 (Fig. 5.45) two lithofacies cycles exist. The lowest comprises a sequence of lithofacies groups from 'Coal, black, mainly dull lensed with bright' to 'Coal grey mainly bright lensed with dull' to a combination of 'Coal grey predominantly bright lensed with dull and 'Coal, grey, dull, granular' with a reversion back to 'Coal, black, mainly bright lensed with dull' at subsection LMW 461. Above this the second unit comprises a similar sequence from 'Coal, black mainly bright lensed with dull' to 'Coal, grey, predominantly dull lensed with bright' and a reversion back to first, the initial lithofacies group and then 'Coal plus siliciclastic sediment' at the top. The boundary between the two cycles and thus the two units lies between subsections Lmw 459 to 461. Because the greatest amount of the microlithotypes 'Bright' and 'Bright finely lensed with dull' occur in subsection 460 the boundary between the two units is drawn in the centre of this subsection.

Leaf 2 at Moat House Farm borehole (Fig. 5.46) can be divided into 3 units. Above the basal unit previously described are two further units, although the location of the division between them is difficult to determine on a lithogical basis. The lowest of the units commences at subsection 282b and consists of two groups of 'Coal, black, mainly bright finely lensed with dull' split by a bed of 'Coal, grey, dull, granular' above which lies a group of 'Coal, grey, mainly dull finely lensed with bright' and then back to 'Coal, black, mainly bright finely lensed with dull' at subsection MHF 264. Above this are two more subsections of the same lithofacies and the rest of the cycle above to subsection MHF 250 is the most symmetrical of all cycles examined in the leaves of the Thick Coal at the two locations examined. The boundary between units is difficult to establish but probably occurs in subsection MHF 263. This could be checked using a palynological analysis of the coal.

The lithofacies 'Coal, grey, dull, granular' occurs in thin beds often associated with the lithofacies group 'Coal, black, mainly bright finely lensed with dull' (e.g. a little above the base of Leaf 1, Fig. 5.46) and occasionally with the group 'Coal, grey, mainly dull finely lensed with bright (e.g. a little above the base of Leaf 1, Fig. 5.45). It occurs in thicker beds associated with the group 'Coal, grey, predominantly dull finely lensed with bright'. The differences in miospore content found in this lithofacies when in thin and thick beds associated with different lithofacies groups has been detailed in the relevant lithofacies description.

The lithofacies 'Coal, grey, fusainous, soft' and 'Coal, silver grey, fusainous, hard' also occur preferentially within the lithofacies groups 'Coal, grey, mainly dull finely leased with bright' and more commonly 'Coal, black, mainly bright finely lensed with dull' (e.g. base of Leaf 2, Fig. 5.45).

Although it has previously been shown (see Coal lithofacies descriptions) that high sulphur values are obtained preferentially from certain lithofacies, they also can occur within whole leaves (Leaf 3, Fig.5.45), or at certain horizons within leaves (base of Leaf 2, Fig.5.46) regardless of lithofacies. Average sulphur contents for each leaf do not normally exceed 4.0% by weight, with a minimum of just below 1% by weight.

Ash content has also been shown to vary with lithofacies (see coal lithofacies description). Oxidation of pyrite during analysis for ash content increases the total ash content for each subsection (e.g. subsections 501-503, Fig. 5.45). Increase in the amount of the macrolithotype fusain within a lithofacies also increases the ash content for that lithofacies bed (e.g. Leaf 1, subsection 293b, Fig.5.45, and Leaf 2, subsection 279 Fig.5.45). However, total ash contents for the leaves of the Thick Coal only vary between 3-7% d.d.b. and even the highest ash content of a unit within a leaf is less than 9%.

The connection between miospore associations and coal lithofacies in the Thick Coal at Longmeadow Wood borehole has been explained in the sections on coal lithofacies descriptions. Successions of miospore bcs types within the leaves of the Thick Coal at this location are discussed in section 6.4.2. The most important aspect of this lithofacies association is that the two lithofacies 'Coal, grey, predominantly dull finely lensed with bright' and 'Coal, grey, dull, granular' contain abundant miospore species characteristic of the <u>Densosporites</u> spp. bcs miospore type. It should also be noted that the boundary between units in Leaf 2 (Fig.5.45) made on a lithological basis at subsection Lmw 460 is very similar to that made on a palynological basis at subsection Lmw 459.

The thickness of the leaves of the Thick Coal varies between 0.34m for Leaf 3 (Fig.5.45) to 2.7m for Leaf 2 (Fig. 5.46) with the thinnest unit occurring at the base of Leaf 2 (Fig. 5.46) with a thickness of 0.28m.

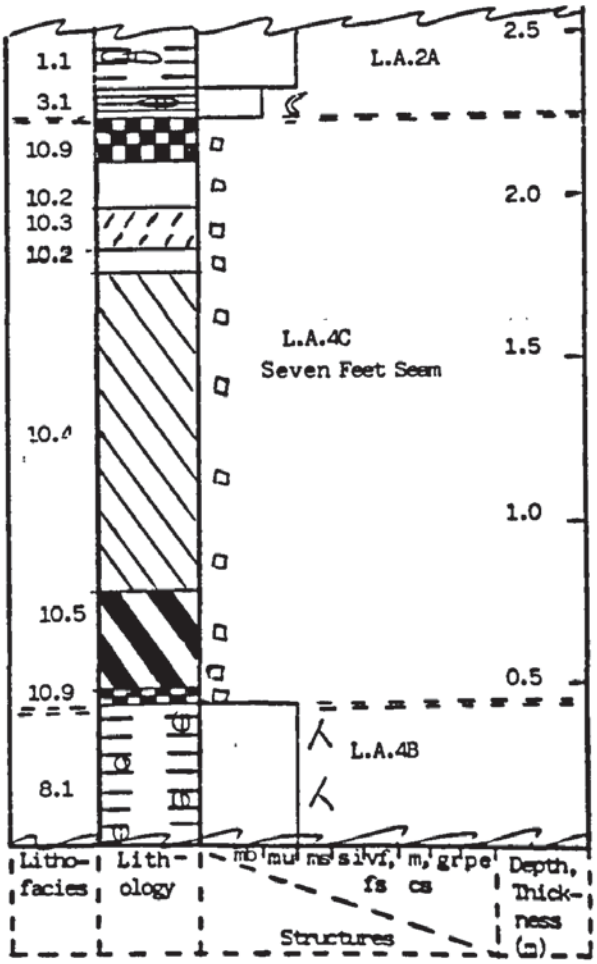
Other examples of this lithofacies association can be recognised from laboratory description of seam analyses by the presence of thick dull coals near the top of coal leaves. These probably correspond to the lithofacies 'Coal, grey, predominantly dull finely lensed with bright' or 'Coal, grey, dull granular'. Fig. 5.47 illustrates a section through an Upper Westphalian of coal seam taken at Birch Coppice Colliery. The common presence of large numbers of Densosporites spp. in this seam is confirmed in Smith and Butterworth (1967).

Siliciclastic interleaf partings may also form part of this lithofacies association. Because of the proximity of coal seams the lithofacies forming them are usually of the rock type 'Seatearth' and are penetrated by many in-situ oblique roots. Most of these 'Seatearth' lithofacies are fine grained and either grey e.g. between Leaves 3 and 4 (Fig.5.45) or brown in colour e.g. between Leaves 1 and 2 (Fig.5.45). However between Leaves 2 and 3 of the Thick, over an area exceeding 80 sq.km (Fulton 19784) and including Moat House Farm and Longmeadow Wood boreholes, there exists a thin sandstone 'Seatearth' lithofacies.

This association is distinguished from other palaeosol lithofacies associations by the presence of relatively thick leaves of coal within which the lithofacies 'Coal, grey, dull, granular' and 'Coal, grey predominantly dull finely lensed with bright' are well developed either in the middle or towards the top of the leaf. These leaves often have low ash contents when compared with leaves of coal developed in the association 'Very poorly drained siliciclastic dominated palaeosols'. Identification of this lithofacies association is confirmed by the presence of miospores of the Densosporites spp. miospore type. These coal seams are termed long-residence histosols to distinguish them from others without the Densosporites spp. miospore type which are termed short-residence histosols.

Fig. 5.47 Example of Lithofacies association 4C 'Long-residence histosols.

LOCATION: Birch Coppice Colliery
AGE: Westphalian A



The lithofacies associations 'Very poorly drained siliciclastic dominated palaeosols' and 'Alternate poorly to imperfectly drained siliciclastic dominated palaeosols' always underlie this association. They may also overlie it or it may be overlain by the association 'Lacustrine suspension deposits'.

Although Fielding (1982, 1984a) recognised a facies termed 'Swamp' which he divided into 'Coal' and 'Shaly Coal' he did not recognise this lithofacies association. Thus, coals recognised by Fielding (1982, 1984a) may fall into either the association 'Very poorly drained siliciclastic dominated palaeosols' or 'Long-residence histosols'. Smith (1957) first recognised coal seams which could be assigned to this association in 5 seams of Westphalian A and B age in the Yorkshire Coalfield. In both this paper and later Smith (1962, 1964) was able to relate miospore phases to coal microlithotypes. He found that high numbers of Densosporites spp. occurred in durainous coals towards the centre or top of seams, similar to their distribution within the leaves of the Thick Coal.

It is believed that there are very few examples of this lithofacies association which have been studied in the modern environment. Histosols thick enough to produce coal seams in excess of 1m thick i.e. 13.5m of peat were not reported in the Mississippi delta peat deposits by Kosters and Bailey (1983). The only example which approaches this thickness is the 13m thick peat found in a borehole at Marudi N.W. Borneo and studied by Anderson and Muller (1975). Although no ash contents were given for peat in this borehole it is expected that above the basal 2m (which is peat mixed with siliciclastic sediment) the ash content would be the same as that found in similar peat bogs in the area i.e. up to 4% (Anderson 1983). Apart from noting the type of organic matter present e.g. woody, cuticle, root etc. no detailed lithological description is given. The ash contents of coal leaves within this association resemble the low ash deposits (less than 25%) of peat bogs described by Anderson (1964a).

Interpretation

The low-ash peats described by Anderson (1964a) were found in ombrophilous (Kulczynski 1949) bogs in N.W. Borneo. These are not subject to flooding from groundwater sources, have pH values less than 4.0 and a markedly convex surface. The leaves of coal in this association are interpreted as the products of mainly ombrophilous bogs.

'Coal plus siliciclastic sediment' often found at the base and top of leaves represents a time when the vegetation was subject to periodic flooding by groundwater carrying siliciclastic sediment, which accounts for its higher ash content. Beds of this lithofacies represent the only part of these leaves which can be considered rhesphilous.

The succession of lithofacies groups above the lithofacies 'Coal plus siliciclastic sediment' or from the base of a leaf upwards are believed to have formed primarily in response to increasing variability of the water table. Anderson (1964a) discovered that during the dry season variations in water table at the periphery of raised bogs were minimal (9-11cm) whereas at their centre variations up to 19cm were observed. It is believed that lithofacies groups 'Coal, black, mainly bright finely lensed with dull' and 'Coal, grey mainly dull finely lensed with bright' accumulated in a setting where the water table varied little during the dry season and may even have been above the level of the peat in the wet season (see interpretations in relevant lithofacies sections). Those examples of the lithofacies 'Coal, grey, dull, granular' associated with these latter two lithofacies groups may have resulted from prolongation of the dry season over several years (the interpretation in relevant lighofacies section). It is postulated that as the surface of the bog became more raised, due to accumulation of organic remains on a slowly subsiding surface, a greater variation in the water table occurred especially during the dry season. This accounts for the more aerobic aspect of the lithofacies groups 'Coal, grey, predominantly dull finely lensed with bright' and 'Coal, grey, dull, granular' (see interpretation in relevant lithofacies section). An increase in subsidence so that eventually it exceeded organic accumulation is believed to have resulted in a reversion initially to the conditions allowing the accumulation again of 'Coal, grey, mainly dull finely lensed with bright' and then 'Coal, black, mainly bright finely lensed with dull', and finally to rheophilous accumulation of the lithofacies 'Coal plus siliciclastic sediment'. Where increase in rate of subsidence was rapid this either suppressed full development of the lithofacies cycle e.g. at the top of Leaf 2 Fig. 5.45 and the top of Leaf 1 Fig.5.46, or siliciclastic lithofacies are found directly on top of the lithofacies 'Coal, grey, predominantly dull finely lensed with bright' e.g. the top of Leaf 4 (Fig.5.45), thus abruptly terminating plant growth.

Although it is believed that lithofacies successions occur due to changes in hydrological conditions as a result of accumulation of organic debris in the form of a raised bog, this can only happen if the rate of accumulation exceeds the rate of subsidence. If subsidence kept pace with plant accumulation the same hydrological conditions would persist producing a similar type of peat/coal lithofacies. This may account for the large thickness of lithofacies groups 'Coal, black, mainly bright finely lensed with dull' and 'Coal, grey mainly dull finely lensed with bright' at the base of Leaf 2 (Fig. 5.46).

It is possible that other edaphic factors apart from the bog hydrology affect the production of lithofacies successions, by influencing the type of vegetation which could grow and chemical and biological processes occurring within the bog (see section on interpretation of miospore successions/cycles).

The distribution of the lithofacies 'Coal, grey, fusainous soft' and 'Coal, silver grey, fusainous, hard' appears to be a paradox, for the origin of these lithofacies is believed to be the burning of woody plants, yet the lithofacies with which they are mainly associated are presumed to be of subaqueous origin. However, the answer to the paradox may be that the subaerial parts of the parent plants associated with these lithofacies (see relevant lithofacies descriptions) were more susceptible to fire.

The presence of more than one lithofacies unit within a leaf reflects the presence of an adjacent siliciclastic parting between leaves at this horizon. The expression of this parting may commence within a leaf as a division between lithofacies cycles e.g. subsection Lmw 460 Leaf 2, (Fig.5.45), then moving towards the source of the siliciclastic sediment at this horizon a bed of the lithofacies 'Coal, plus siliciclastic sediment' e.g. subsection MHF

283 Leaf 2 (Fig.5.46) may develop, and finally this may pass laterally into a siliciclastic lithofacies.

The ash content of all coal lithofacies except 'Coal plus siliciclastic sediment' is believed to be derived from the plant material forming the coal. A variety of mechanisms may account for the low ash content of these lithofacies, but the simplest answer may be the raised surface of the bog was above the base level of deposition. Alternatively if deposition of siliciclastic sediment was not taking place near the bog a low-ash histosol would be produced. The vegetation itself may have contributed to the exclusion of siliciclastic sediment from the histosol by decreasing the flow rate of water passing across its surface (Robertson 1952). Staub and Cohen (1979) suggested that clay could be flocculated by acid bog waters, dumping it at the edge of the bog, although the ash contents of the histosols which they studied were in excess of 12% (Renton *et al.* 1979). Finally the effect of diagenetic processes outlined by Cecil *et al.* (1979) and Renton and Cecil (1979) may have contributed to the production of low-ash histosols.

The siliciclastic partings between leaves of coal normally formed of fine grained 'Seatearth' lithofacies are believed to be deposited initially in a shallow lacustrine environment at some distance from the sediment source. However, examples are known of channels up to a few hundred metres wide occurring within these partings (Fulton 1978a) and distributing siliciclastic sediment across the bog surface during high stage flow. It is presumed that these channels were able to cross the bog during periods of higher subsidence, when its surface was subaqueous and at a similar level to adjacent siliciclastic depositional areas. The origin of the sandstone parting between Leaves 2 and 3 e.g. (Figs. 5.45 and 5.46) was probably as a result of the processes outlined above. However, as the only available sediment was of fine grained sand the lithofacies 'Seatearth sandstone grey' was eventually produced. This lithofacies association is expected to occur in areas undergoing relatively low rates of subsidence in areas very distant from siliciclastic sediment deposition.

5.4.7.4 Lithofacies 4D

Alternate poorly and imperfectly drained siliciclastic palaeosol/s

Use of M.C.A. allows an F.R.D. to be constructed for this lithofacies association which is closely comparable with the association 'Poorly drained siliciclastic dominated palaeosol/s' in that a fining upwards sequence is recognised (Fig. 5.48). This association is characterised by the occurrence of grey together with either brown or red/ochreous mottled 'Seatearth' lithofacies, and two variants of this association can be recognised depending on which of the two coloured 'Seatearth' lithofacies are present.

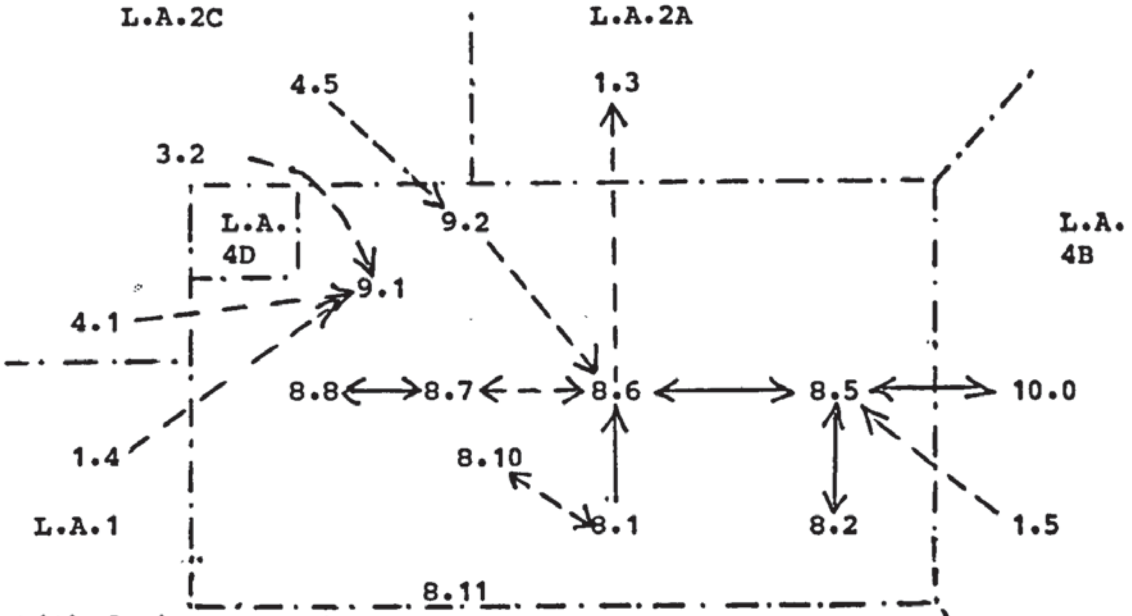
An ideal example of the brown variant composed of a single profile would consist of a fairly coarse 'Subseatearth' at the base which may be grey or brown (Figs.5.49D, 5.51A). This would be overlain by successively finer 'Seatearth' lithofacies which may be grey or brown, although towards the top one or more beds would be brown (Figs. 5.40C,D, 5.50, 5.51). Both within these beds (more usually towards their base) and in the underlying 'Subseatearth' lithofacies sphaerosiderite often develops (Figs. 5.49A,C, D, 5.51A). It varies in size with depth and grain size, becoming larger at depth in coarse grained lithofacies. At the top of the

Fig.5.48 Facies relationship diagram for Lithofacies association 4D

'Alternate poorly and imperfectly drained siliciclastic palaeosol/s'

Key

-·-·-	Boundary of the associations
——→	Transitions from Markov Chain analysis
– – →	Transitions from visual observations of borehole core



Lithofacies present

1.3	Mudstone, massive, dark grey to black
1.4	Mudstone, massive with marine/brackish fauna
1.5	Mudstone with coal lenses
3.2	Siltstone, massive, with abundant plant fragments
4.1	Sandstone, fine, massive, pale grey to off white
4.5	Sandstone, fine, with small scale cross lamination
8.1	Seatearth, mudstone grey
8.2	Seatearth, mudstone silty, grey
8.5	Seatearth, mudstone, brown
8.6	Seatearth, mudstone silty, brown
8.7	Seatearth, siltstone brown
8.8	Seatearth, sandstone, brown
8.10	Seatearth, mudstone silty grey and/or brown, with red mottling
8.11	Seatearth, siltstone grey and/or brown, with red mottling
9.1	Subseatearth, grey
9.2	Subseatearth, brown
10.0	Coal (lithofacies unspecified)

Lithofacies associations present

L.A.1	Marine deposits
L.A.2A	Lacustrine suspension deposits
L.A.2C	Lacustrine thickly interbedded coarse and fine deposits
L.A.4B	Very poorly drained siliciclastic dominated palaeosols/s

Fig. 5.49 Examples of Lithofacies association 4D 'Alternate poorly and imperfectly drained siliciclastic palaeosol/s'

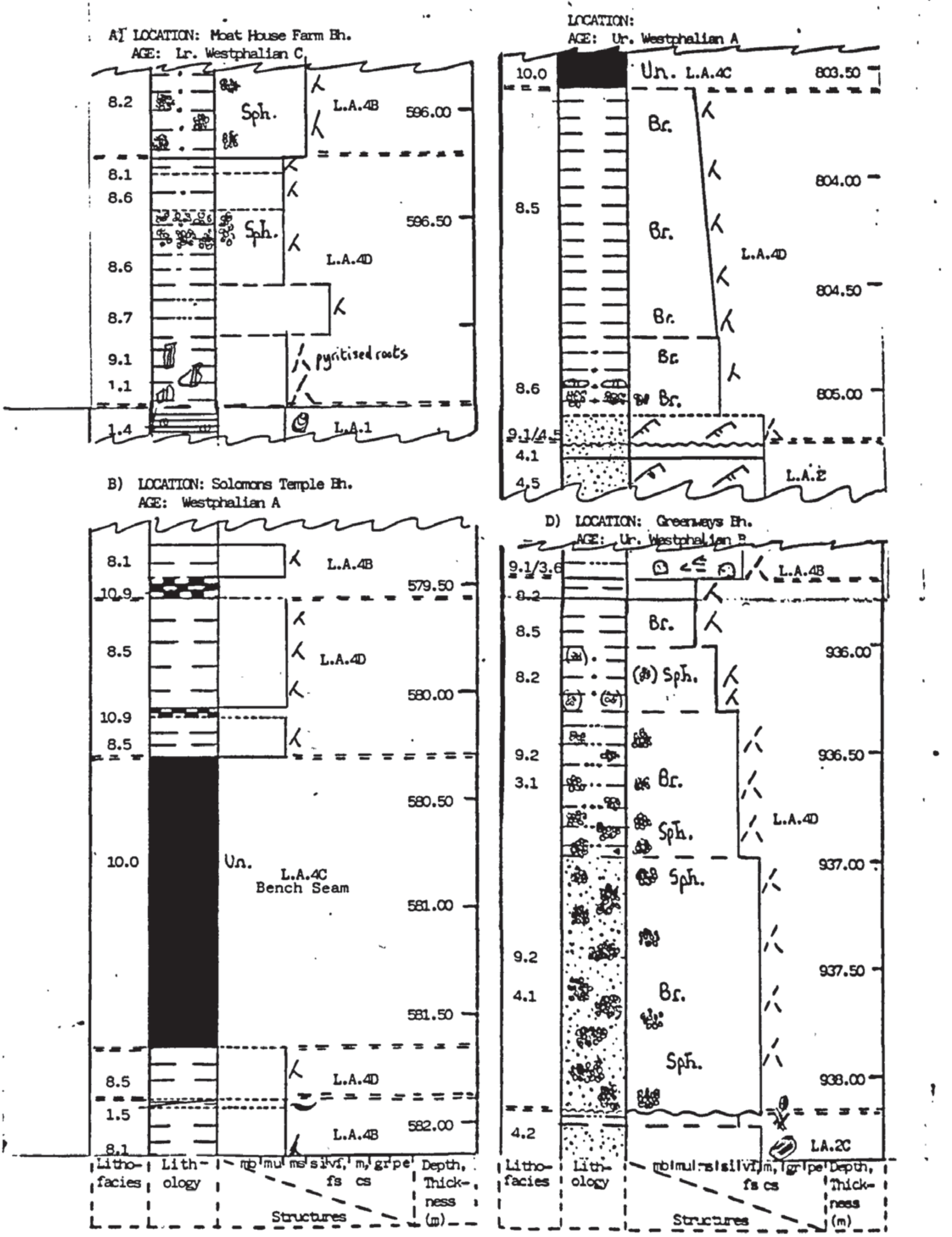


Fig. 5.50 Examples of Lithofacies association 4D 'Alternate poorly and imperfectly drained siliciclastic palaeosol/s'.

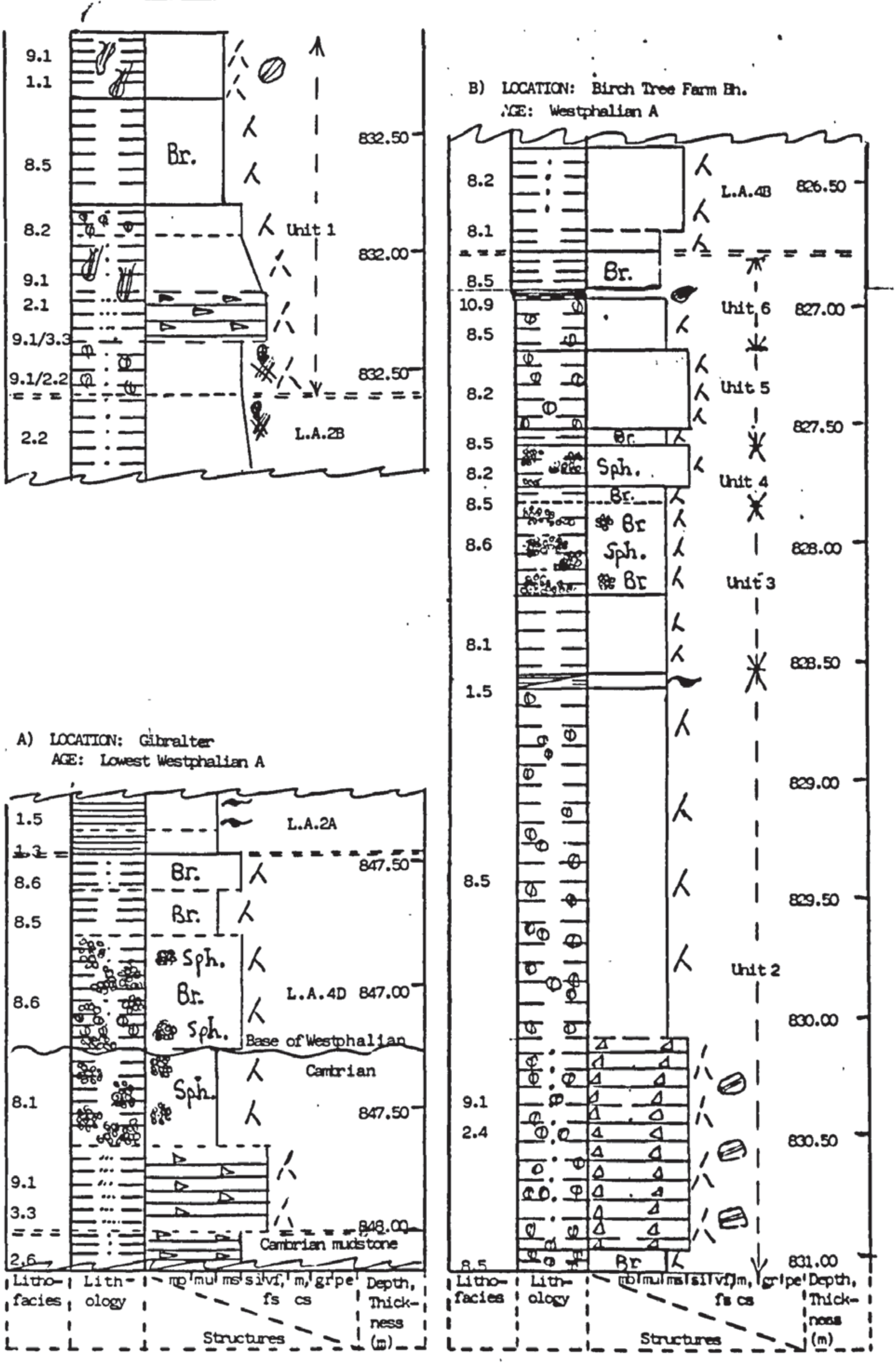
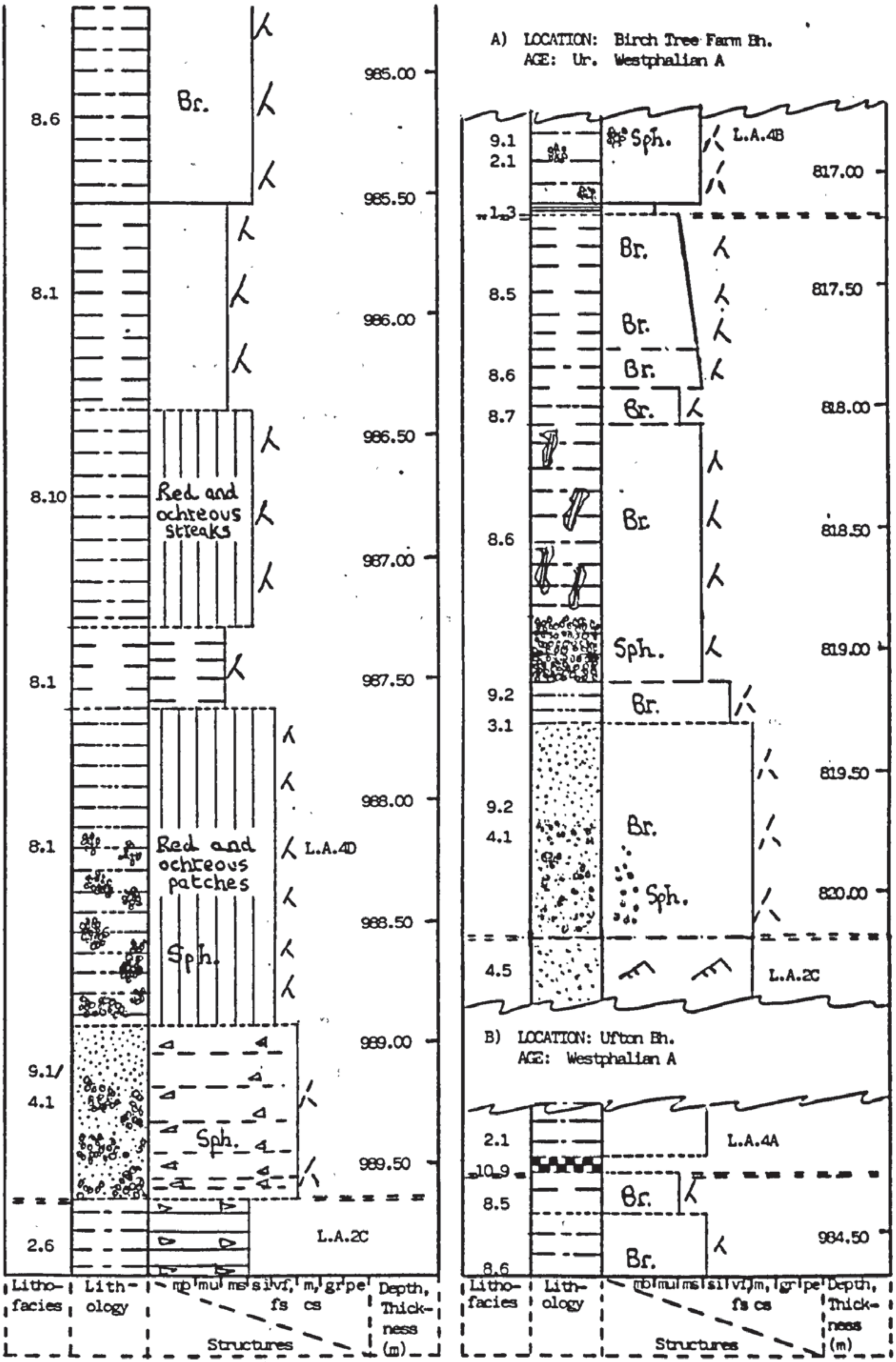


Fig. 5.51 Examples of Lithofacies association 4D 'Alternate, poorly and imperfectly drained siliciclastic palaeosol/s'.



profile are usually grey 'Mudstone' or 'Seatearth' lithofacies (Figs. 5.49B,C) although occasionally a coal may be present. This may form part of an overlying lithofacies association.

Variations from this ideal may include the development of mottles in either the brown (Fig. 5.49A*) or grey (Fig. 5.49D) 'Seatearth' lithofacies. In the latter figure a relict of the pre-existing bedding within the lithofacies 'Seatearth, siltstone brown' is present in the form of patches of sandstone. Occasionally elongate sub-vertical slightly irregular pipes of siderite up to 2cm diameter and 15cm long develop in the 'Seatearth' lithofacies (Fig. 5.51A). An unusual example of this association is shown in Fig.5.50A where it has developed at the base of the Carboniferous. Cambrian sediments form the lowest 'Seatearth' and underlying 'Subseatearth' lithofacies in this association, with the presence of sphaerosiderite and the numbers of oblique roots decreasing with depth, and relict bedding in the 'Subseatearth' lithofacies.

The brown variety of this lithofacies association ranges in thickness from about 1-3m for single profiles and up to about 7m for stacked profiles in the Westphalian A and B sediments of Warwickshire. A 5.84m thick stacked example of this association is illustrated in Fig.5.50B. The lowest two profiles are fairly clearly defined, although the 'A' horizon of profile No.1 forms the 'C' horizon for the overlying profile No.2. Above this latter profile are four more which comprise couplets of medium to dark grey 'Seatearth' lithofacies overlying brown 'Seatearth' lithofacies. The second variety of this lithofacies associations is shown in Fig. 5.51B and consists of two profiles overlain by a brown variety of this association. Features similar to the ideal profile of the brown variety include fining upwards, development of sphaero-siderite and grey lithofacies at the top of each profile. In addition to these red and sometimes ochreous irregular streaks and patches develop with or without the remnants of oblique carbonaceous root casts.

This lithofacies is often underlain by the association 'Lacustrine coarsening upwards deposits' and commonly by 'Very poorly drained siliciclastic dominated palaeosol/s' as well as a variety of other associations including 'Marine'. It is most often overlain by 'Very poorly drained siliciclastic dominated palaeosol/s' and occasionally 'Lacustrine suspension deposits' or 'Long-residence histosols'. Rarely but importantly this latter association is found both above and below the association under consideration (Fig. 5.49B).

The colouration in this association distinguishes it from other palaeosol lithofacies associations.

Other workers on Westphalian A and B sediments in the Pennine basin have recognised similar associations, including Elliott (1968) who found both brown and red mottled facies both with associated sphaerosiderite in the East Midlands Coalfield. Fielding (1982) identified palaeosols containing brown horizons and elongate siderite nodules in the Durham Coalfield. Besly (1983) also identified a palaeosol which contained brown pigmentation and/or red mottles viz. Palaeosol type 2 seatearth with a contemporaneous oxidised horizon. In the Reading Beds of Paleocene age Buurman (1980) described examples similar to the two varieties of this lithofacies association. A group of brown mottled red beds with rare grey beds were overlain by grey beds intercalated with red, yellow and grey mottled beds in a sequence up to 40m thick.

Coleman (1966) described the deposits of a well drained swamp in the Atchafalaya basin, although no indication of colour changes within it were given. These deposits were characterised by a lack of organic remains and the presence of iron oxide nodules up to 6mm in diameter. Similar recent deposits to those of this association which formed in a tropical environment have been examined in Surinam, South America by Slager and van Schuylenborgh (1970), and profiles described which are grey but have red ferric oxides especially around root channels. Van Wallenburg (1973) studied brown and grey brown mottled recent alluvial and soils in Holland which resemble the brown variety of this lithofacies.

Interpretation

The interpretation of the fining upwards sequence is the same as for the association 'Very poorly drained siliciclastic dominated palaeosol/s'. It is also possible that conditions at first within the association under consideration were the same as the latter association. However, during pedogenesis it is postulated that oxidation took place in those lithofacies which are now brown or mottled red/ochreous. Partial oxidation of the sediments was believed by both Slager and van Schuylenborgh (1970) and Van Wallenburg (1973) to be responsible in turn for red and brown mottling. The latter author found that in the majority of soils which he studied brown mottles began above the mean high watertable (M.H.W) and that sometimes changes from brown to brownish grey matrix indicated the position of the M.H.W.

Brown 'Seatearth' lithofacies in this study are believed to have formed above the M.H.W., but subject to enough time to allow the whole profile to become brown. It is not thought to be the result of a brown coloured sediment source which was postulated by Buurman (1980) to be the origin of the brown palaeosols in the Reading Beds. If this were the case in this association, alternation of brown and grey lithofacies would mean alternation of sediment source, which is difficult to imagine in the postulated environmental setting. Red/ochreous mottled 'Seatearth' lithofacies are similarly believed to have formed above the M.H.W. It is believed that ochreous, red and brown colouration is related to the species of iron mineral present ranging from red coloured haematite to the yellow and brown of limonite and goethite. The stability fields for iron and its metastable phases are very complex (van Schuylenborgh 1973) and depend not just on pH/Eh relationships but on the presence of other minerals and organic substances. It may be the presence of these which determine the species of iron minerals present in the lithofacies of this association. However, the brown mineral goethite believed to be present in the brown variety of this association is only metastable and may be expected either to reduce in the presence of organic matter to liberate ferrous cons or dehydrate to haematite. Obviously the conditions within these lithofacies are relatively stable, in that insufficient organic matter exists for reduction, and perhaps insufficient time or lack of correct physical conditions prevent dehydration. Brown colouration is caused following the oxidation of pyrite and vivianite (Bloomfield 1973) the two minerals which Coleman (1966) found in 'Well drained swamp deposits'. It would appear that the lack of these minerals and the presence of brown colouration may imply that the lithofacies in this association have undergone a greater amount of oxidation than those studied by Coleman (1966).

The almost ubiquitous occurrence of sphaerosiderite within this association tends to suggest that if it was not pedogenic in origin, then the products necessary for its formation must have been in place from an early stage. Ease of movements of the ions necessary to form sphaerosiderite was probably facilitated by increased intergranular movement within coarse grained lithofacies which resulted in larger concretions. Siderite pipes may also have developed as the result of water containing ferrous ions moving along the voids left by roots during water table fluctuations and combining with carbonate released during microbial degradation of organic matter.

Following the formation of brown or red/ochreous mottled lithofacies a return to anaerobic conditions is marked by the presence of grey 'Seatearth' or 'Coal' lithofacies. Alternatively it is possible that these lithofacies accumulated above a perched water table formed from an impermeable layer, and that oxidative processes took place below it, above the regional groundwater table. However, the common lack of grey mottling in the uppermost brown lithofacies (which could have formed as a result of reducing conditions penetrating from above along e.g. roots) and the fine grained and therefore impermeable character of many of these brown lithofacies suggests that the oxidative phase occurred before the formation of the grey 'Seatearth' or Coal lithofacies. The close juxtaposition of 'Coal' and brown Seatearth lithofacies indicates the possibility of rapid changes in drainage conditions.

Elliott (1968) believed that brown seatearths accumulated in better drained areas than grey seatearths, in one case over a palaeotopographical high formed by differential compaction over a thick sandstone body. The correlation which he noted between decrease in interval between the Blackshale and Main Bright seams and increase in number of brown seatearths can be attributed to better drained conditions in areas of lower subsidence. Elliott (1968) also postulated that red mottled seatearths were more emergent than the brown variety and had therefore undergone more oxidation. Besly (1983) regarded his 'Palaesol type 2' seatearths as alluvial in origin, probably commencing in waterlogged conditions and later becoming partially oxidised.

If these beds have been formed in a similar way to those of the Reading Beds (Buurman 1980) by superimposition of gley features upon a well drained soil they can be interpreted as pseudogleys or surface-water gleys. The change in colour of these palaeosols may mean that they can be classified as Cambisols (FAO/UNESCO 1974). Once again the Soil Survey Staff (1975) would classify these as inceptisols.

The better drained conditions required for these soils are likely to occur in slightly elevated areas towards the edge of the basin of deposition in areas undergoing relatively low amounts of subsidence.