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**Correlation, Facies Distribution and Sequence Stratigraphic
Analysis of the Westphalian B Coal Measures in Quadrant
44 of the Southern North Sea.**

Peter Timothy O'Mara

Submitted to the University of Durham for the degree of Master of Science

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Department of Geological Sciences

February 1995



Declaration

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Peter Timothy O'Mara.
Department of Geological Sciences,
University of Durham.

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Confidentiality

The data used in this study is owned by ARCO British Limited who requested that it was not published. Wells drilled in Quadrant 44 over five years ago are released, they are listed in the Appendix. This study was based on wells traded by ARCO British Limited also listed in the Appendix. The biostratigraphic and sedimentological reports were confidential and I am bound by contract not to publish their details.

Correlation, Facies Distribution and Sequence Stratigraphic Analysis of the Westphalian B Coal Measures in Quadrant 44 of the Southern North Sea.

Peter T. O'Mara

(Submitted in 1995 for the degree of M.Sc)

Abstract

In the early 1980's a number of significant gas discoveries were made in reservoirs of Westphalian B age in Quadrant 44, Southern North Sea. This study develops an integrated scheme to enhance the correlation of existing wells and to assist in future predictability. It allows for an improved understanding of the succession thickness and character, utilising the concepts of high-resolution non-marine sequence stratigraphy. This is based on a chronostratigraphic framework built on palynostratigraphy and the identification of the marine bands which subdivide the Silesian.

Conventional palynological analysis provides the basis for the chronostratigraphic framework; the palynological assemblages described from Quadrant 44 wells compare favourably with similar studies on equivalent sections onshore. This allows the upper Westphalian A to lower Westphalian C interval to be subdivided into 5 broad zones. However, there is a considerable margin of error in these deep Carboniferous exploration wells due to a number of sedimentological and drilling related factors. To achieve the chronostratigraphic resolution required it is necessary to identify the 9 well known marine bands which subdivide the Westphalian B to lower Westphalian C interval. In the subsurface marine band log recognition relies on spectral gamma ray logs, where the individual marine bands can be recognised from their uranium enrichment. This process required the definition of a marine band characterisation scheme, whereby 4 types of marine band are recognised from their uranium response, out of a total of 8 marine bands showing varying degrees of uranium enrichment. A further marine band relies on the location of marine macrofauna. The marine bands are then incorporated into the established chronostratigraphic framework. An additional stratigraphic marker, the Sub-Clowne tonstein, is identified from the spectral gamma ray logs, and provides an independently determined time line.

A method whereby the common Westphalian B facies could be identified in Quadrant 44 wells was developed in this study. It was based on the work of Fielding (1984, 1986), Giuon and Fielding (1989) and Haszeldine (1981, 1983a,b) combined with Westphalian B outcrops on the Northumberland coast and core material from Westphalian B intervals in Quadrant 44 wells. This facies identification scheme defined 13 lithofacies, which were grouped on typical wireline response into 8 wireline log facies associations (Leeder et al. 1990). Facies distribution, determined from the facies analysis within the chronostratigraphic framework was used to develop a high-resolution sequence stratigraphic scheme. This enabled a 3rd order sequence in the terminology of Galloway (1989a,b), from maximum flooding surface to maximum flooding surface to be defined with an important 3rd order sequence boundary and overlying alluvial transgressive systems tract. The remainder of the succession was interpreted as a transgressive sequence set, subdivided by a number of 4th order sub-regional flooding surfaces. Both the 3rd and 4th order surfaces were used to provide a high resolution correlation for Westphalian B sediments in Quadrant 44.

Scope of the project

The thesis was initiated in response to the need for increased confidence in well correlation in Quadrant 44. Problems had arisen in the conventional palynostratigraphic and lithostratigraphic techniques used by ARCO British Limited to correlate Westphalian B sediments in existing wells. Thus there was no knowledge of the true succession thickness and how this thickness varied across the inferred palaeoslope. There was a poor understanding of facies distribution and the relative stratigraphic position so consequently there was no confidence in correlating one well with the next. This thesis attempted to solve these correlation problems by using high resolution non-marine sequence stratigraphy.

Non-marine sequence stratigraphy requires a chronostratigraphic framework on which it can be based, so that sediments in equivalent time intervals are compared. Thus the initial step was to establish a chronostratigraphic framework. The onshore Westphalian is most effectively sub-divided chronologically using palynomorphs. However, there are numerous schemes that attempt to produce a palynostratigraphy for the onshore Westphalian of north west Europe, Britain and the Netherlands, so a standardisation was required. This produced a basic palynostratigraphic outline on which to re-interpret the palynological reports for Quadrant 44 wells. Previously these had been interpreted by individual contractors which had no standard scheme and there were differences in their respective schemes and interpretations. A palynostratigraphy for Quadrant 44 resulted. However, this was not of sufficient resolution for high resolution sequence stratigraphic purposes.

Marine bands are used to enhance the resolution of the palynostratigraphy in the onshore, their identification in the offshore was tenuous. No Westphalian B marine band had been successfully correlated without the recovery of marine macrofauna. It was known that marine bands had high uranium concentrations but not why these concentrations appeared to vary widely between marine bands. This Thesis established criteria for subsurface recognition of marine bands and classified them in terms of faunal content and expected uranium response. In the process explaining why different types of marine bands have different uranium responses. The marine bands were incorporated into the palynostratigraphic framework to produce the basic chronostratigraphic scheme. Additionally the Sub-Clowne tonstein an ash band known from the onshore succession was identified in Quadrant 44 wells, this had not previously been described from the Southern North Sea. The Sub-Clowne tonstein

may be identified on wireline log response alone, independent of palynostratigraphy and is therefore an important additional chronostratigraphic time line.

Non-marine sequence stratigraphy relies on the identification of important surfaces that separate packages of chronostratigraphically constrained strata. These surfaces are recognised by facies changes which occur in response to base level changes. To identify such facies changes in the Westphalian B of Quadrant 44 a facies identification scheme was required. Westphalian B facies associations and facies are described in detail from the onshore Pennine Basin by Fielding (1984a,b, 1986), Guion and Fielding (1988) and Haszeldine (1984) these are considered analogues for Westphalian B sediments in Quadrant 44 (Collinson et al. 1993). Based on these facies descriptions eight wireline log facies associations are defined in this study, these have a distinctive and easily recognisable wireline log response.

The sequence stratigraphic interpretation of Westphalian B sediments in Quadrant 44 used this wireline log facies identification scheme within the chronostratigraphic framework to identify the major surfaces within the succession. It was necessary to define stratigraphic base level before interpreting what its changes might mean. The effect of stratigraphic base level changes on Westphalian B sediments was discussed so that sequence boundaries and maximum flooding surfaces may be recognised. Several orders of base level change were recognised in Westphalian B sediments. Base level falls could only be recognised when they were of sufficient magnitude to create 3rd order sequence boundaries. However, base level rises of different magnitude were recognisable and were classified to allow for easy and consistent interpretation. A 3rd order sequence was defined for the Westphalian B. This had numerous 4th order sequences superimposed upon it. The maximum flooding surfaces of these 4th order sequences were shown to have a sub-regional extent and coincide with non-marine bivalve beds. It was shown that these were traceable across Quadrant 44 and that their use enhanced the correlation.

High resolution sequence stratigraphic correlation of the Westphalian B sediments of Quadrant 44 allowed better understanding of :

- 1) the succession thickness, and how this varied across the palaeoslope, including how this extra thickness was accommodated;
- 2) the unconformity at the base of the Westphalian C "red beds" and;
- 3) the diachronous relationship at the base of the well drained alluvial sediments, which was demonstrated to occur at an earlier stage than previously thought.

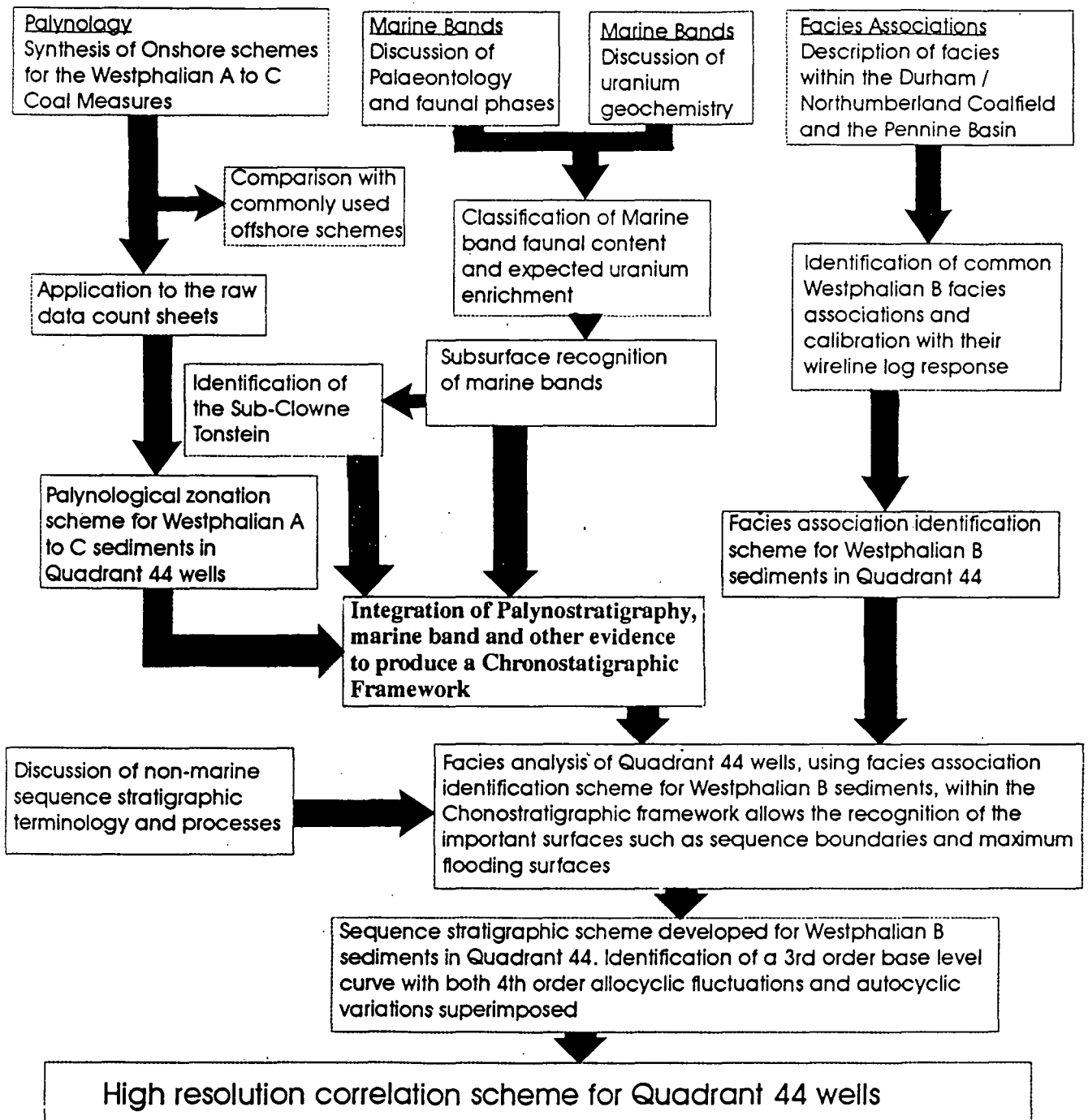


Fig. 1.0 Flow chart of how the project was structured.

Acknowledgements.

Firstly I would like to dedicate this thesis to Jane, without whose love and support, I would not have attempted such an undertaking. Secondly my parents, Pat and Anne, sister Sally and Auntie are thanked immeasurably for their constant encouragement over the years.

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ARCO British Limited contributed greatly to the smooth running of the project by allowing me a free run at their Library and photocopier and are acknowledged for letting me get on with it, without attempting to influence my opinions. In particular Jim Hollywood is thanked for the initial idea and adaptation of Brian's proposal, Colin Taylor is thanked for making sure the expenses were generous. Rod Crawford is thanked for his ideas and thoughts on the Carboniferous. Chris Atkinson provided the necessary late impetus and the chance to tour the Pennines in luxury and Diana Cooper made the Enclosures possible by her patience in teaching me the complexities of Stratlog.

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Contents

Title page	i
Declaration and copyright	ii
Abstract	iii
Scope of the project	iv
Acknowledgements	vii
Contents	vii

Chapter 1: Introduction

1.1 Aims of the Project	1
1.2 Geological Background	1
1.3 The Pennine Basin	6
1.4 The Southern North Sea	11
1.4.1 Exploration History	11
1.4.2 Carboniferous sub-crop and basin delineation	11
1.4.3 Structure of the Southern North Sea Basin	15
1.4.4 Stratigraphy and facies	17
1.4.4.1 Pre-Westphalian : Dinantian	17
1.4.4.1 Pre-Westphalian : Namurian	18
1.4.4.3 Westphalian	19
1.4.5 Quadrant 44	20

Chapter 2: Silesian palynostratigraphy

2.1 Introduction	
2.1.1 Introduction to Silesian stratigraphy	22
2.1.2 A review of the commonly used palynological zonations ...	24

2.2	Description of Westphalian A (Langsetian) zones	28
2.2.1	<i>Triquitrites sinani</i> - <i>Cirratriradites saturni</i> (SS) miozone	28
2.2.2	<i>Radiizonates aligerens</i> (RA) miozone	30
2.2.2.1	<i>Schulzospora rara</i> subzone	32
2.3	Description of Westphalian B (Duckmantian) zones	35
2.3.1	<i>Microrecticulatisporites nobilis</i> - <i>Florinites junior</i> (NJ) miozone	35
2.3.1.1	Smith and Butterworth (1967) subzones	35
2.3.1.2	<i>Dictyotriletes bireticulatus</i> subzone	36
2.3.1.3	<i>Vestispora magna</i> subzone	38
2.4	Description of Westphalian C (Bolsovian) zones	39
2.4.1	<i>Torispora Securis</i> - <i>Torispora laevigata</i> (SL) miozone	39
2.4.1.1	Discussion of Westphalian C zonation schemes	40
2.5	A Silesian palynostratigraphic scheme for Quadrant 44	43
2.5.1	Introduction to offshore palynostratigraphy	43
2.5.2	Problems with conventional palynostratigraphy	43
2.5.2.1	Data collection	43
2.5.2.2	Individual contractors appraisals	44
2.5.3	Comparison of contractors appraisal schemes	45
2.5.3.1	The Geochem Group	45
2.5.3.2	ECL/SSI	45
2.5.3.3	GAPS Geoconsultants	47
2.5.3.4	SHELL (UK) EXPRO	49
2.5.3.5	BGS (NERC)	49
2.5.3.6	Sheffield University Industrial Palynology Unit	51
2.5.4	The palynological scheme used in this study for Quadrant 44	55
2.5.4.1	Uppermost Westphalian A - <i>Schulzospora rara</i> (SR) zone	55
2.5.4.2	Lower Westphalian B - <i>Dictyotriletes bireticulatus</i> (DB) zone	56
2.5.4.3	Upper Westphalian B - <i>Vestispora magna</i> (<i>Triquitrites sculptilis</i>) (VM) zone	57
2.5.4.4	Lower Westphalian C - <i>Vestispora fenestrata</i>	

Contents

(VF) zone	58
2.5.5 Conclusions	59

Chapter 3: Westphalian B marine bands

3.1 Introduction	62
3.1.1 Marine bands and the Southern North Sea	64
3.2 Marine band macrofauna	64
3.2.1 Marine band faunal phases	65
3.2.2 Non-marine bivalves	69
3.3 Marine band recognition	70
3.3.1 Introduction to geochemical theory	70
3.3.2 Uranium enrichment in marine bands	70
3.3.3 Development of wireline log response recognition	72
3.3.4 Controls on uranium enrichment	76
3.4 Methodology of marine band identification in the subsurface ..	80
3.4.1 Introduction	80
3.4.2 The effects of borehole conditions on uranium concentration	82
3.4.3 The Sub-Clowne tonstein	84
3.5 Incorporating marine bands into the palynostratigraphy	89
3.5.1 A review of upper Westphalian A to lower Westphalian C marine bands	90
3.5.1.1 <i>Cambriense</i> , Shafton and Edmondia marine bands	92
3.5.1.2 <i>Aegiranum</i> marine band	93
3.5.1.3 Sutton and Haughton marine bands	94
3.5.1.4 Sub-Clowne tonstein/Clowne marine band	94
3.5.1.5 Maltby marine band	95
3.5.1.6 <i>Vanderbeckei</i> marine band	95
3.6 Conclusions	96

Chapter 4: Westphalian B facies associations

4.1 Introduction	99
-------------------------------	-----------

Contents

4.1.1	Lower delta plain association	101
4.1.2	Upper delta plain association	101
4.1.3	Alluvial plain association	102
4.1.4	Well drained alluvial "Red Bed" association	102
4.2	Facies associations	104
4.2.1	Upper delta plain / coastal alluvial plain associations	104
4.2.1.1	Introduction	104
4.2.1.2	Durham / Northumberland Coalfield	107
4.2.1.3	Coarse grained overbank facies	107
4.2.1.4	Fine grained overbank facies	109
4.2.1.5	Proximal major crevasse channel facies	109
4.2.1.6	Medial crevasse splay / minor delta facies	110
4.2.1.7	Distal crevasse splay / minor delta facies	111
4.2.1.8	Outer minor delta / overbank facies	111
4.2.1.9	Anoxic lake facies	112
4.2.1.10	Lake margin facies	113
4.2.1.11	Coal swamp facies	114
4.2.1.12	Minor distributary channel facies	115
4.2.1.13	Major distributary channel facies	116
4.2.1.14	Major stacked fluvial systems	117
4.2.2	Coal-bearing alluvial plain association	119
4.2.2.1	Introduction	119
4.2.2.2	Coal-bearing alluvial plain facies	121
4.2.2.3	Palaeosols	122
4.2.3	Well drained "Red Bed" alluvial facies	124
4.3	Quadrant 44 facies identification scheme	126
4.3.1	Introduction	126
4.3.2	Geophysical logs	128
4.3.3	Wireline log facies associations (WILFS)	128
4.3.3.1	Crevasse splay WILF (C/S)	128
4.3.3.1a	Crevasse channels and associated facies	128
4.3.3.1b	Crevasse splay and associated subfacies	130
4.3.3.2	Interfluvial floodplain WILF (IFL)	131
4.3.3.3	Interdistributary bay and lake WILF (I/D)	134
4.3.3.4	Marine band WILF (MB)	138

4.3.3.5	Minor distributary channel WILF (DC1)	138
4.3.3.6	Major distributary channel WILF (DC2)	139
4.3.3.7	Major stacked fluvial systems WILF (DC3)	142
4.3.3.8	Alluvial floodplain WILF (AFL)	143
4.4	Conclusions	145

Chapter 5: Westphalian B sequence stratigraphy

5.1	Introduction	147
5.2	Non-marine sequence stratigraphy: concepts and applications .	148
5.2.1	Stratigraphic base level	148
5.2.2	Sequence stratigraphic terminology	151
5.2.3	Accommodation space and base level control	152
5.2.4	Base level and stratigraphic architecture in a coastal plain setting	154
5.2.5	Sequence boundary recognition in a coastal plain setting	158
5.2.6	Relative base level fall and incised valleys in a coastal plain setting	159
5.2.7	Type 1 versus type 2 sequence boundaries	160
5.2.8	Recognition of maximum flooding surfaces with alluvial strata	161
5.2.9	Genetic sequence stratigraphy	162
5.2.10	System tracts and alluvial strata	163
5.3	Sequence stratigraphy for coastal-alluvial plain environments ..	165
5.3.1	Coal seam distribution	165
5.3.2	Flooding surface hierarchy	166
5.3.3	Sequence boundary recognition	170
5.3.4	A Westphalian B 3rd order sequence	175
5.3.5	High frequency 4th order sequences in the Westphalian B ..	177
5.4	Conclusions	180

Chapter 6: Westphalian B correlation in Quadrant 44

6.1	Introduction	182
6.2	A high resolution correlation scheme for Quadrant 44	182

Contents

6.2.1	Caister / Murdoch fields and the surrounding area	182
6.2.1.1	Biostratigraphy	185
6.2.1.2	<i>Vanderbeckei</i> marine band to Hutton flooding surface	185
6.2.1.3	Caister sandstone	186
6.2.1.4	Caister sandstone to Hutton flooding surface	190
6.2.1.5	Hutton flooding surface to Brass Thill flooding surface	192
6.2.1.6	Brass Thill flooding surface to Durham Low Main flooding surface	193
6.2.1.7	Durham Low Main flooding surface to Blackhall Estheria Bed	195
6.2.1.8	Blackhall Estheria Bed to Metal flooding surface	197
6.2.1.9	Metal flooding surface to High Main flooding surface	198
6.2.1.10	High Main flooding surface to Maltby marine band	200
6.2.1.11	Conclusions	202
6.2.2	The Southern Blocks : 44/26, 44/27, 44/28 and adjacent areas	204
6.2.2.1	Comparison of the Southern Blocks with the established flooding surface hierarchy	204
6.2.2.2	Maltby marine band to <i>Aegiranum</i> : onshore section	208
6.2.2.3	Maltby marine band to Lower seam flooding surface	209
6.2.2.4	Lower seam flooding surface to Upper seam flooding surface	210
6.2.2.5	Upper seam flooding surface to Moorland flooding surface	210
6.2.2.6	Moorland flooding surface to Manton Estheria Bed	210
6.2.2.7	Manton Estheria Bed to Clowne marine band	211
6.2.2.8	Clowne marine band to Haughton marine band	213
6.2.2.9	Haughton marine band to	

Contents

Unnamed seam flooding surface	214
6.2.2.10 Unnamed seam flooding surface to Sutton marine band	214
6.2.2.11 Sutton marine band to <i>Aegiranum</i> marine band	215
6.2.2.12 Conclusions	217
6.2.3 Correlation of block 44/21	219
6.2.3.1 Introduction	219
6.2.3.2 Comparison of block 44/21 with the established flooding surface hierarchy	219
6.2.3.3 Conclusions	223
6.2.4 Correlation of northern wells in blocks 44/18 and 44/19 ...	224
6.2.4.1 Introduction	224
6.2.4.2 Comparison of the northern wells with the established flooding surface hierarchy	224
6.2.4.3 Stratigraphic details	227
6.2.4.3 Conclusions	229

Chapter 7: Summary and Conclusions

7.1 Palynostratigraphy	230
7.2 Marine bands	231
7.3 Facies associations and facies	232
7.4 Sequence stratigraphy	233
7.5 Correlation	235
7.6 Future work	236
References	237
Appendix	A

Enclosures

Enclosure 1 to 4 are contained within the envelope

Chapter 1

Introduction

1.1 Aims of the project

The primary objective of this project was to produce a high resolution stratigraphic correlation of the Westphalian B Coal Measure sediments of Quadrant 44 in the Southern North Sea. It was established to enhance the correlation and understanding of Westphalian B sediments following the discovery of a number of important gas fields in Carboniferous age reservoirs (Fig. 1.1). This was achieved by initially establishing a biostratigraphic zonation scheme, based on palynostratigraphy, but with the integration of available macropalaeontological and palaeobotanical information as well, in order to produce a coarse or broad stratigraphic subdivision of the succession. Based on this biostratigraphic zonation the zonal bounding marine bands were identified from analysis of spectral gamma ray logs, their position in the succession and the extent to which marine conditions were established across the Quadrant. This approach allows for direct comparison with the equivalent onshore Silesian succession which is sub-divided using these marine bands. These provide a chronostratigraphic framework for correlation and the production of isopachs, based on local and regional thickness variations. A facies identification scheme, based on common Westphalian B facies described from the onshore succession allowed for the recognition of wireline log facies associations within this chronostratigraphic framework and provided the basis for sequence stratigraphic analysis of the succession. The purpose of this was to relate Westphalian B facies development to relative stratigraphic base level, thereby increasing the reliable predictability of the facies. This in turn allows for a precise understanding of the stratigraphic distribution, location and depositional architecture of the important sandstone reservoir horizon in Quadrant 44.

1.2 Geological background

The Carboniferous of North West Europe is subdivided into the major biostratigraphic zones shown in Fig. 2.1. The individual methods of zonation vary depending upon the gross facies association. Dinantian lower Carboniferous marine carbonate successions are zoned on the basis of corals and brachiopods, with more precise fine-tuning



provided by conodonts and foraminifera. The predominantly clastic Namurian and Westphalian successions, are mainly fresh to brackish water even in deep basins.

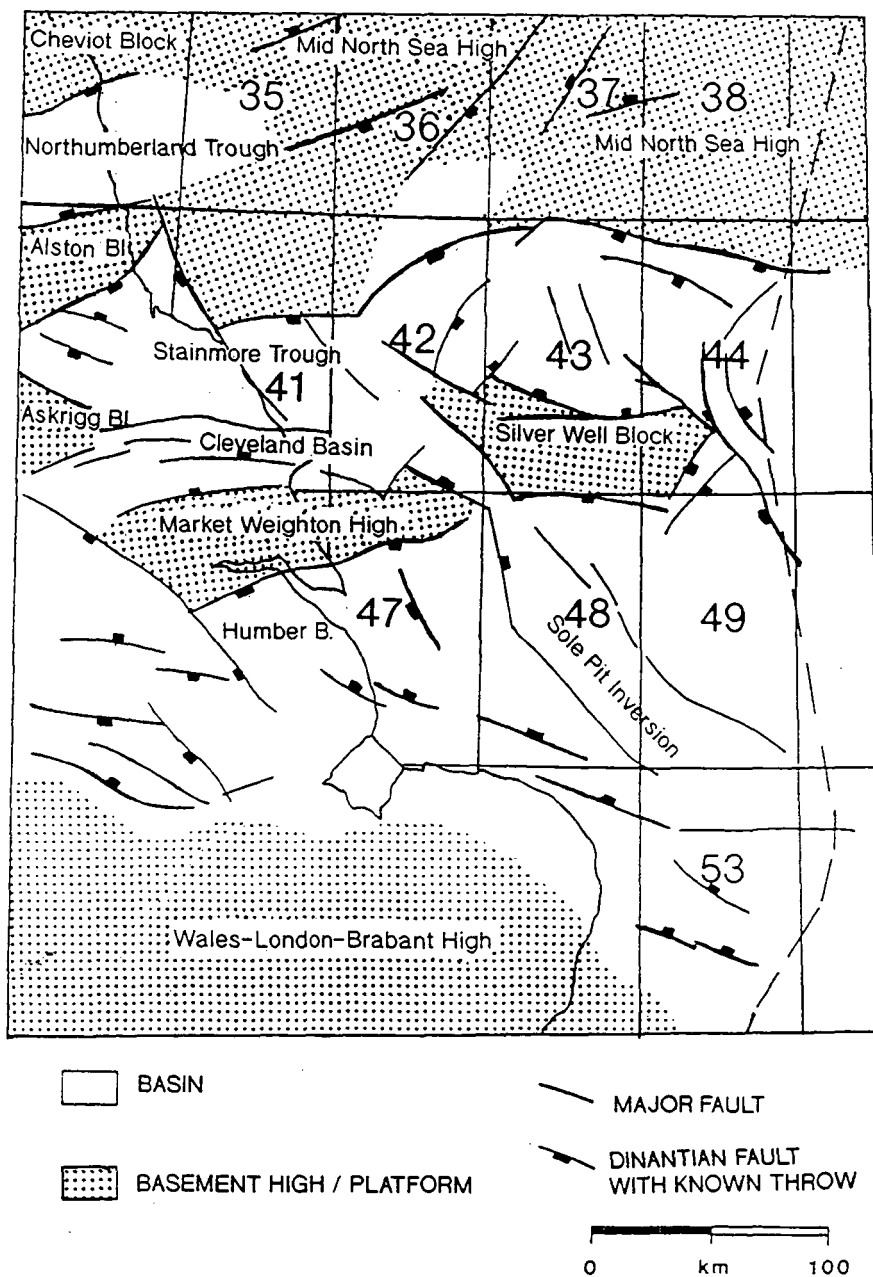


Fig. 1.1 Palaeogeographic map of the Southern North Sea and adjacent Pennine Basin showing the modern day structural units and relative position of Quadrant 44 (adapted from Besly 1990; Collinson et al. 1993; Fraser and Gawthorpe 1990).

Nevertheless, repeated short-lived transgressions forming marine bands allow for a precise subdivision (George et al. 1976; Ramsbottom et al. 1978) owing to the rapid evolution of goniatites in the open ocean that sourced these incursions. These marine bands often have distinctive and unique faunas. Where no goniatites occur other distinctive organisms confirm the marine salinities. To supplement the marine band stratigraphy various other organisms are used including conodonts for the Namurian (Higgins 1976) and the non-marine bivalves (Trueman and Weir 1946) and plant megafossils (Crockhall 1955) for the Westphalian. However, the most widely applicable zonation scheme is that based on palynomorphs (Smith and Butterworth 1967; Neves et al. 1972, 1973; Clayton et al. 1977; Owens et al. 1977). This achieves a fairly even biostratigraphic subdivision (Besly 1990) from the Dinantian to the mid Westphalian, but loses definition in the late Westphalian C. For the Westphalian C dates have only been obtained from plant macrofossil impressions (Wagner 1983) and from tetrapod occurrences (Paton 1974).

The regional plate tectonic setting (Fig. 1.2) of the Carboniferous of North West Europe is summarised by Leeder (1988). The Southern North Sea and adjacent Pennine Basin lay in an equatorial to sub-equatorial position (Parrish 1982; Rowley et al. 1985) north of the Variscan Orogenic belt. This orogen resulted from the east-west oriented collision, with northerly directed subduction (Fig. 1.2 and 1.3), of the African portion of Gondwanaland and the European portion of Laurussia (Besly 1990). The deformation front associated with this orogen, which had started in the late Devonian in a zone passing from Galicia to Southern Germany, migrated northwards during the Carboniferous (Fig. 1.2). As it did so it closed a broad back-arc seaway (known as the Rheno - Hercynian zone) floored by mildly deformed lower Palaeozoic sediments which were thought to have been deposited on the southern portion of Laurussia (Cameron 1993). In response to this northwest directed relative crustal shortening (Leeder 1988; Leeder and Hardman 1990) these sediments were subsequently deformed into a series of major thrust / nappe complexes (Fig. 1.3), which led to loading and formation of a flexural foreland basin (Fig. 1.2). The continued northward migration of this orogenic belt led to corresponding northward migration of the foreland basin during the Namurian and Westphalian, which reached its maximum northward extent in central England by the latest Westphalian or Stephanian (Besly 1990). Regional Variscan deformation reached these areas soon afterwards, in the Autunian, giving rise to widespread folding and block faulting. This was followed by major erosion, forming the Saalian Unconformity, hereafter known as the Sub-Permian unconformity. The Southern North Sea and adjacent onshore areas were largely peripheral to the orogen, although the tectonic effects associated with it increased with time, influencing the tectonic history of the basin.

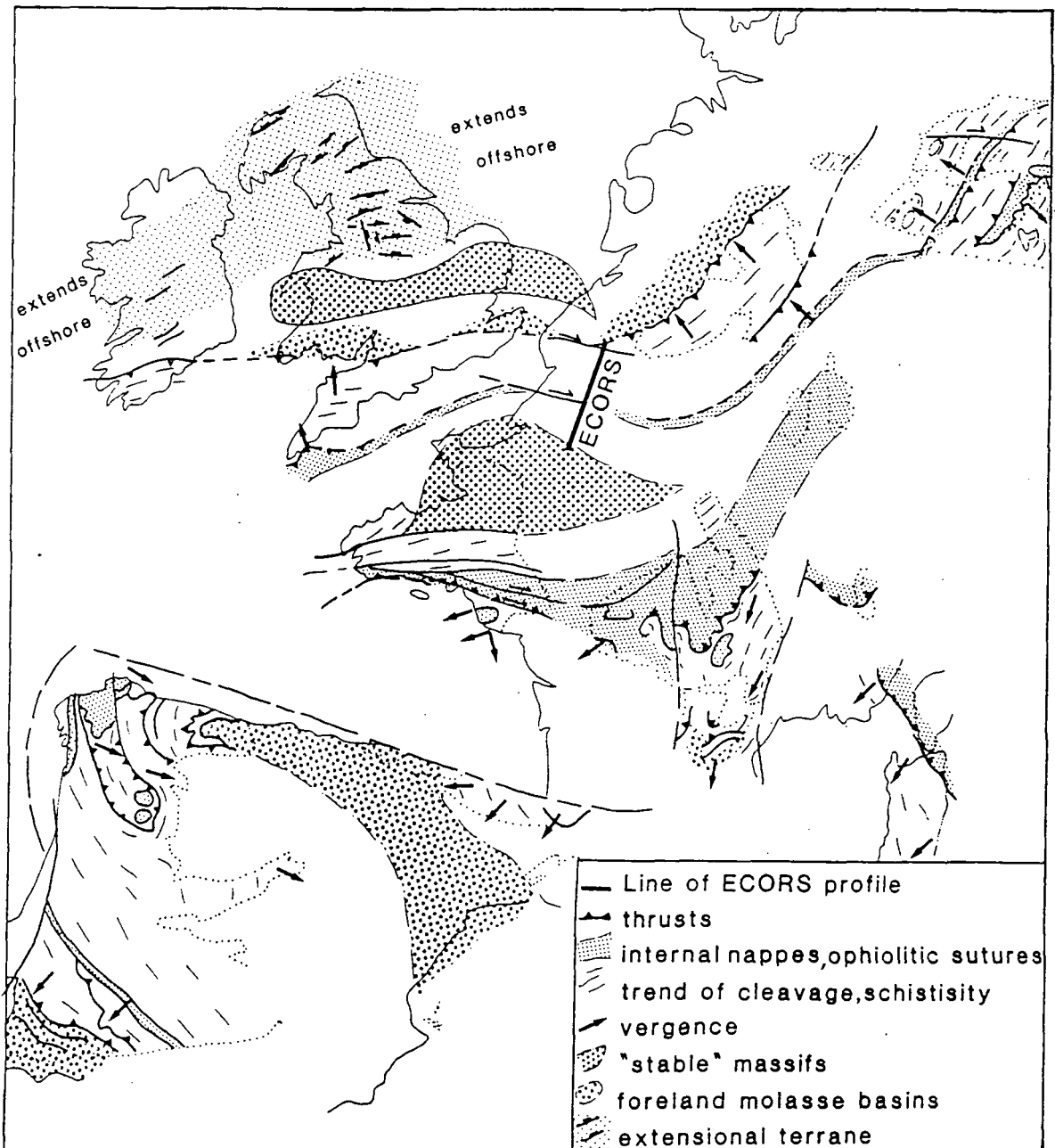


Fig. 1.2 Map to show the main tectonic elements of the European Hercynides. Note the location of the lower to early middle Carboniferous extensional terrane of northern Britain and Ireland, north of the active tectonic shortening zones of mainland Europe. (after Leeder 1988). ECORS profile is a line of section shown in Fig.1.3.

The basins of northern Britain (Fig. 1.4) were separated from the seaway of the Rheno - Hercynian zone and its north flanking flexural basins by a stable basement massif known as the Wales-London-Brabant High, which became an increasingly important

structural element during the Carboniferous (Besly 1990). The origin of this block is attributed to peripheral bulging formed by flexural response to thrust loading (Besly 1988; Kelling 1988).

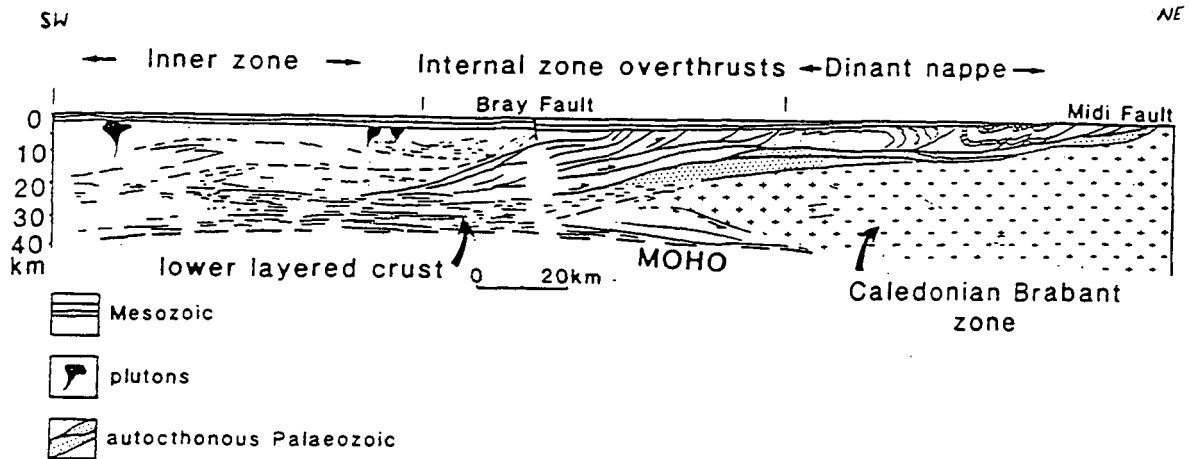


Fig. 1.3 Simplified section along the ECORS deep seismic line (location see Fig. 1.2) to show loading imparted by the nappe emplacement (after Leeder 1988).

The Variscan tectonic effects were superimposed on a Carboniferous structural history that recorded the break up of the stable Old Red Sandstone (Pangaea) continent established during the Caledonian Orogeny. This began in the late Devonian in response to widespread lithospheric extension. The reason for this is unclear and is the subject of debate (see Leeder (1988) and Leeder and Hardman (1990) for discussion). In northern England and Ireland north of the Wales-London-Brabant High, this extension produced a zone of rapidly subsiding fault bounded asymmetric grabens and half grabens, which formed individual basins (Fig. 1.4), separated by horsts and half horsts (blocks) (Fig. 1.5) (Fraser and Gawthorpe 1990). The location of these more slowly subsiding blocks, appears to have been controlled by basement heterogeneities, in particular, the location of Devonian and Pre-Cambrian granitoids (Bott 1967) and the tectonic grain inherited from earlier orogenic events (Caledonian) (Fraser et al. 1990, Fig. 1.2 and 1.3). On these blocks lower Carboniferous carbonate platforms or condensed sections accumulated. These either remained as relic highs (Collinson 1988) or collapsed due to changes in subsidence patterns culminating in very rapid deepening (Grayson and Oldham 1987). The Namurian infill of this relic basin and block topography proceeded from north to south in response to major deltaic progradation. During this period the crustal extension regime gave way to more uniform patterns of subsidence which Leeder (1982, 1988) considered to represent a period of regional, post-rift (Leeder and Hardman 1990) thermal "sag" subsidence caused by the thermal

re-equilibration of thinned lithosphere. Consequently the late Namurian and the early to mid Westphalian have much more uniform subsidence patterns and succession thickness (Fig. 1.5), although syn-depositional fault activity continued to affect the southern margins of the Pennine Basin in England (Fulton and Williams 1988). By the Westphalian the infill basin topography was nearly complete so that emergent or near-emergent conditions prevailed during the Westphalian A to Westphalian C (Fig. 1.5) over the whole of the Variscan foreland area (Van Wijhe and Bless 1974; Diessel 1988; Guion and Fielding 1988). Syn-depositional fault activity was much reduced, affecting sedimentary facies distribution in subtle ways, including the splits of coal seams and stacking patterns of channel sandstones (Fig. 1.6) (Fielding 1984a,b; Guion and Fielding 1988) or influencing minor intrabasinal uplift (Turner and O'Mara 1995).

1.3 The Pennine Basin

During the Westphalian A and B a continuous area of sediment accumulation existed in a position corresponding to northern England, bounded in the north by the Southern Uplands and associated small scale landmasses such as the Cheviot Block (Wills 1951; Kirk 1982, 1983; Guion 1987), and to the south by the Wales-London-Brabant High (Fig. 1.4) (Trueman 1947, 1954; Wills 1948, 1951, 1956; Calver 1968a,b, 1969). The Westphalian A to B succession throughout much of the basin is complete, (Calver 1968a,b; Ramsbottom et al. 1978), thus continued subsidence is inferred. However, sedimentation is thought to have kept pace with subsidence as the sedimentary facies indicate that deposition took place in shallow water environments, with periodic emergence enabling peat development and ultimately coal seam formation. The coalfields of northern England are known to have been originally part of a continuous depositional area (Calver 1968a,b, 1969; Wills 1951) which became separated by later Variscan folding and subsequent erosion.

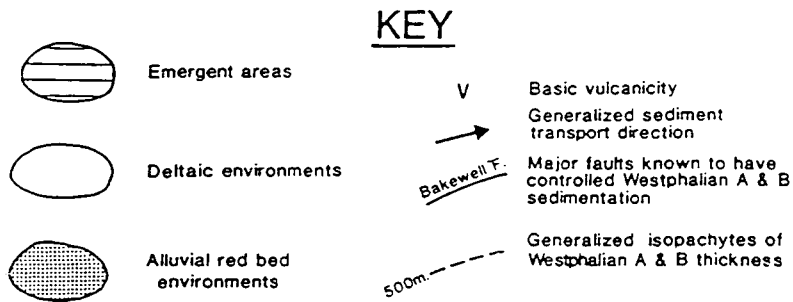
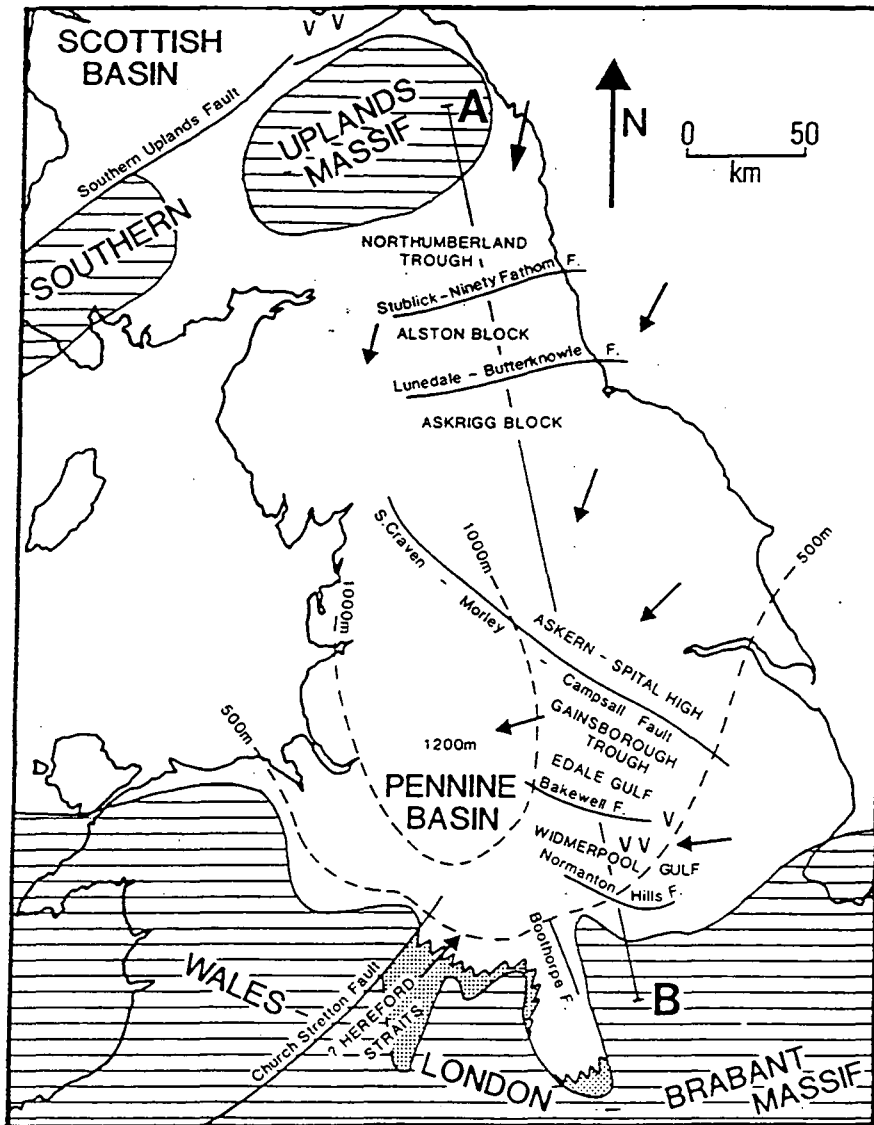


Fig. 1.4 Generalised palaeogeographic map of the Pennine Basin during Westphalian A and B times, showing major faults known to have controlled sedimentation (after Guion and Fielding 1988).

The sedimentology of the Westphalian interval (Fig. 1.7 and 4.4) of the Pennine Basin suggests that the deposition of the Westphalian A and B took place in a deltaic to broad coastal alluvial plain environment, in which lower and upper delta plain and coastal alluvial plain environments may be differentiated (Guion and Fielding 1988). Sediment was dispersed by a system of channels of several types, with a range of sinuosities. These had a mainly south-southwesterly directed palaeoflow (Haszeldine 1981) down an inferred low gradient south-southwesterly palaeoslope, although not all channels conformed to this flow direction (cf. Haszeldine 1983a,b; Turner and O'Mara 1995). These channel systems provided sediment for the infilling of interdistributary bays and lakes, crevasse splay / minor delta systems and floodplain overbank areas via a complex network of distributary channels. Coal seams, which represent swamp deposits, were deposited slowly on infilled and abandoned lakes and bays, channels and floodplain areas, predominantly in the upper delta plain / coastal alluvial plain environment. The controls on sedimentation were both allocyclic mechanisms such as eustasy and tectonism as well as autocyclic controls such as channel and crevasse splay / minor delta switching and differential compaction.

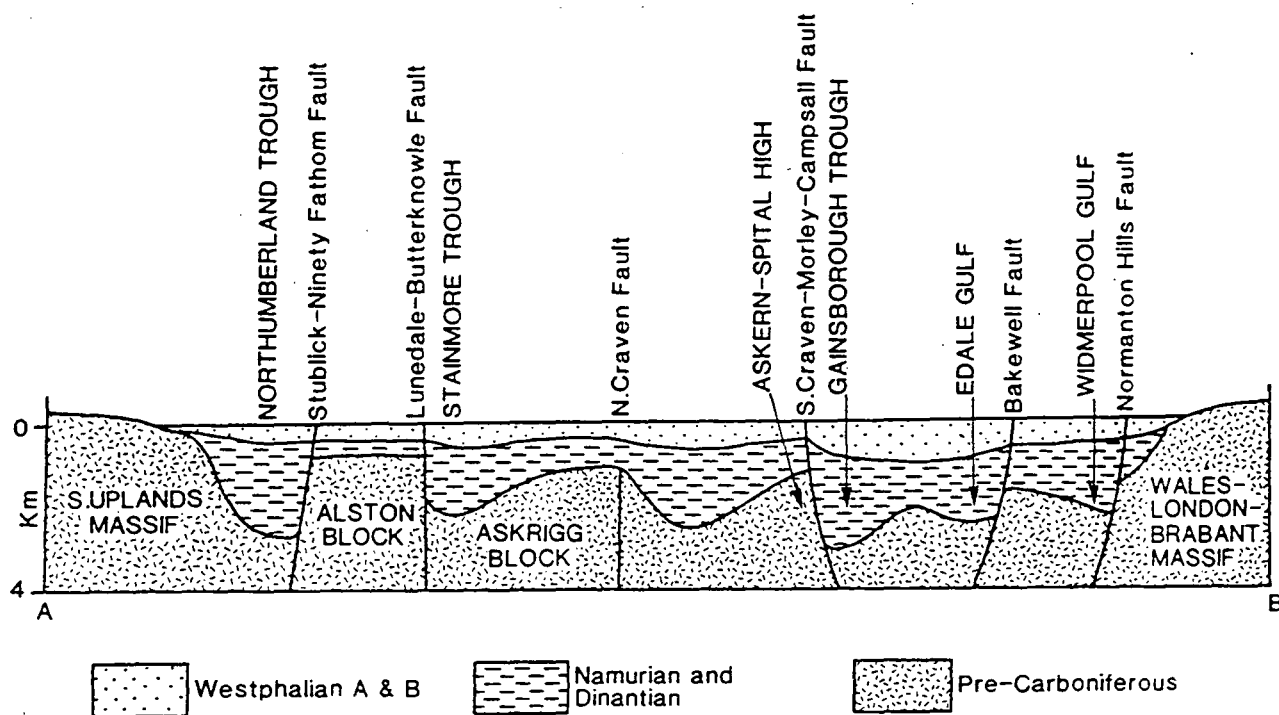


Fig. 1.5 Schematic north-south cross section of the Pennine Basin from the Southern Uplands High to the Wales-London-Brabant High, showing the major faults that influenced Westphalian A and B sedimentation (after Guion and Fielding 1988).

In the more elevated marginal areas of the basin, relic highs or terminal fans (Besly and Turner 1983) were probably associated with well drained "red bed" alluvial sediments, which interdigitated with the poorly drained environments (Besly and Turner 1983; Besly 1988) described above. These became increasingly important in the Westphalian C when climatic conditions became markedly more arid and the level of the water table (stratigraphic base level) fell, leading to deposition of better drained facies types.

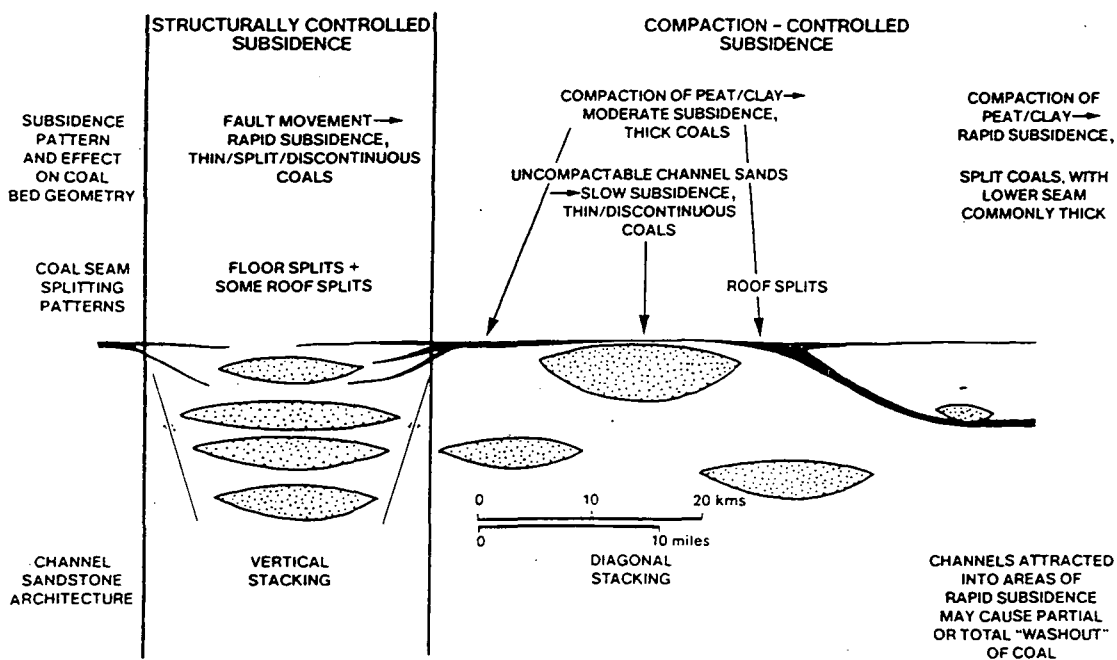


Fig. 1.6 Models for controls on channel sandstone stacking and coal seam geometry in Westphalian coal-bearing successions in northern England (after Besly 1990, based on Fielding 1984b).

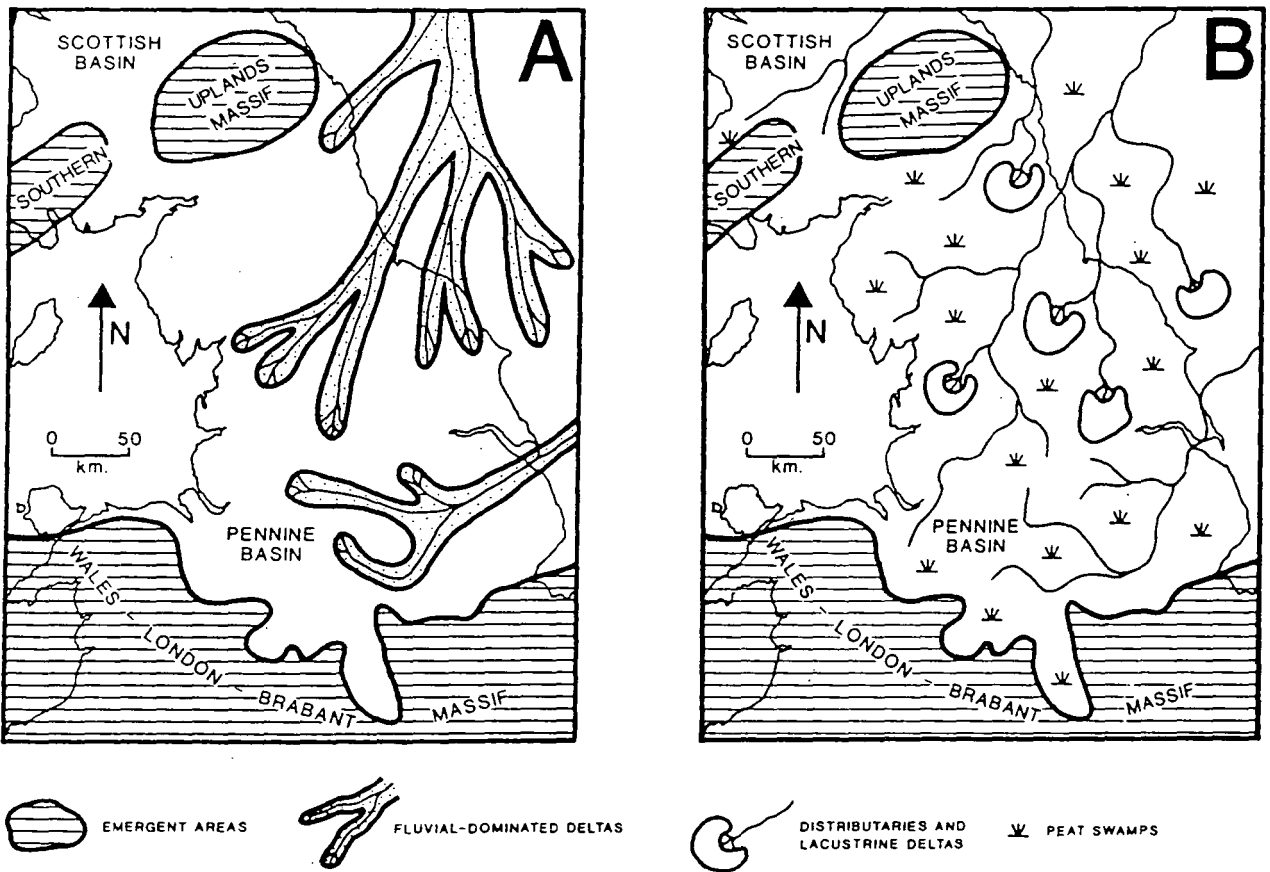


Fig. 1.7 Generalised depositional models for the Westphalian A and B of the Pennine Basin, A) lower delta plain; B) upper delta plain. (after Guion and Fielding 1988).

1.4 The Southern North Sea

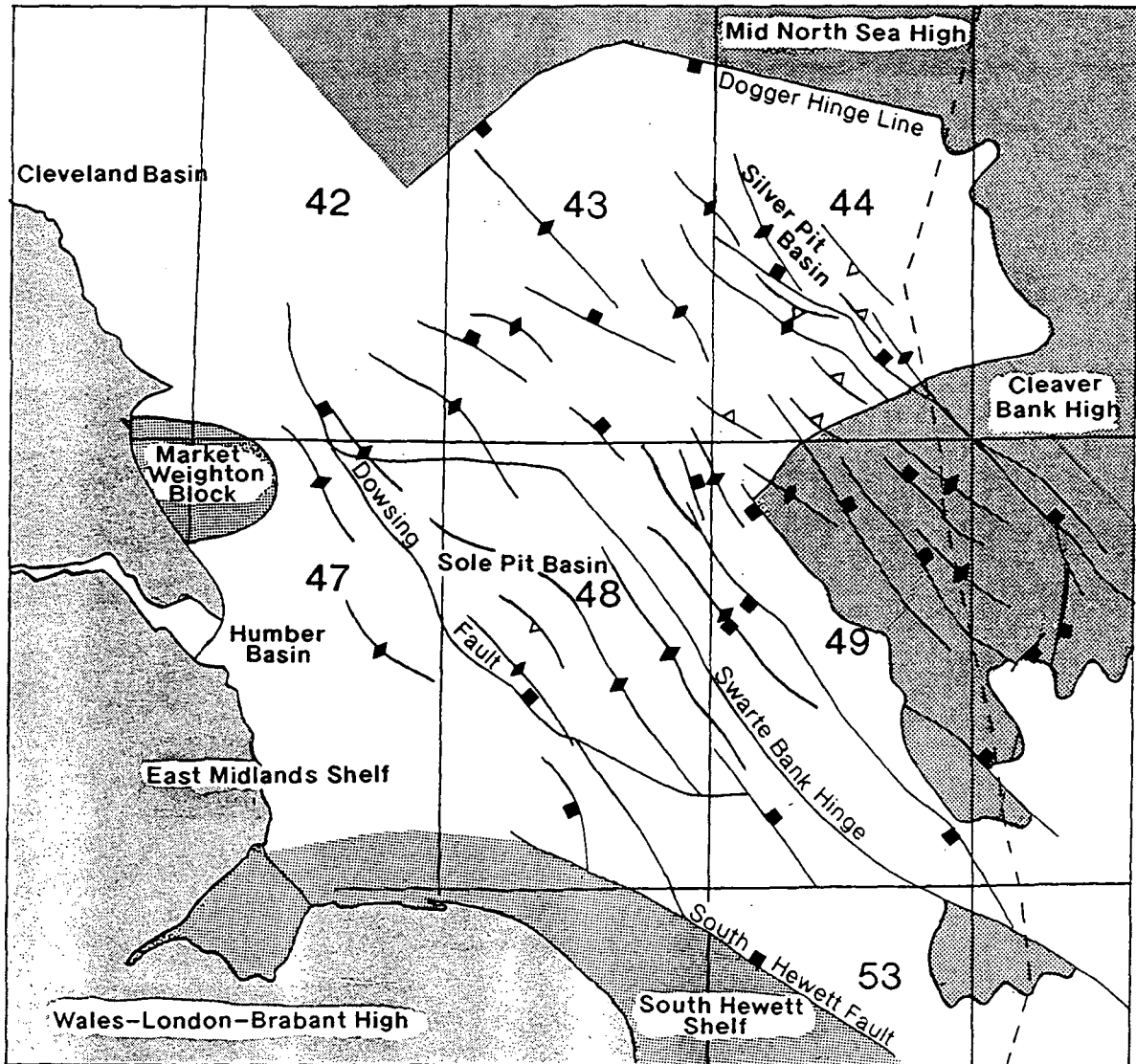
1.4.1 Exploration history

The coals in the upper Carboniferous of the Southern North Sea basin (Fig. 1.8) have long been known to source the huge Permian Rotliegende gas accumulations (Eames 1975). The exploration of the Carboniferous, as a potential reservoir horizon, however, was largely confined to the onshore Netherlands and Germany where gas reserves were discovered in Westphalian C and D reservoirs (Hedemann 1980; Nederland Aardolie Maatschappij and Rijks Geologische Dienst 1980). Hydrocarbon exploration in the Southern North Sea, and on the Mid North Sea High, prompted by these onshore finds, began in the early 1960s and the first wells were drilled soon after. Unfortunately the results suggested that the Carboniferous was generally unprospective, having an unpredictable development of heavily cemented sandstone reservoirs (Besly 1990). A dramatic decline in the level of interest in Permian objectives in the Southern North Sea together with a growth in the understanding of Carboniferous depositional systems led to the Carboniferous forming primary objectives in a number of frontier areas in the early 1980s. This coincided with favourable economic conditions, the availability of good quality seismic data beneath the Permian and the indications of gas potential already found in the Carboniferous of Quadrant K in the Netherlands. A combination of these factors led to important discoveries in the eighth round of licensing blocks 44/22 (Murdoch) and 44/28 (Ketch) (Glennie et al. 1987) and subsequent discoveries in blocks 44/19, 44/21, 44/23 (Caister), 44/26 (Schooner), and more recently 44/18 (Tyne). To date more than 60 deep wells (Hollywood and Whorlow 1993) have been drilled to evaluate the Carboniferous, focused on Quadrant 44 and the surrounding area.

1.4.2 Carboniferous sub-crop and basin delineation

Carboniferous rocks underlie the whole of the Southern North Sea Basin with the exception of small areas of the Mid North Sea High, and the Wales-London-Brabant High. Details of the Sub-Permian subcrop are given in Fig. 1.9. In a broad belt flanking the Mid North Sea High, to the north part of Quadrant 44, the Dinantian to Namurian successions subcrop the Permian, where they rest conformably on or onlap onto the

underlying Devonian in a similar situation to the Southern Uplands onshore area, of which the Mid North Sea High is an extension (cf. Collinson et al. 1993).







-  Folds affecting the Carboniferous
-  Late Carboniferous thrust faults
-  Major basin faults affecting the Carboniferous
-  Older platform / Intrabasinal Highs

Fig. 1.8 Palaeogeographic details of the Southern North Sea showing Quadrant 44 and the important structural elements (adapted from Besly 1990; Collinson et al. 1993; GAPS 1994).

Rocks of this age also extend southwards as tongues in the cores of at least 5 major southeast plunging anticlines (Fig. 1.8) known as the Sole Pit, Amethyst, Ravenspurn 43/17 and 43/18, 44/7 and 44/9 anticlines. The Westphalian succession overlies the Namurian conformably and subcrops the Permian extensively across the centre of the Southern North Sea basin. The succession is subdivided into Westphalian A/B (which may include the very base of the Westphalian C) and the Westphalian C/D units (Fig. 1.10). The Westphalian A/B is thought to have a major depocentre in the southern portion of Quadrant 43. In contrast the Westphalian C/D has a limited subcrop (Fig. 1.9) associated with localised shedding of sediment from the folding of earlier sediments during late stage Variscan uplift. On the southern margin the succession is seen to thin, as in Quadrant 53 (Tubb et al. 1953), onto the northern flanks of the Wales-London-Brabant High where the Westphalian is seen to overstep (Leeder and Hardman 1990) the Namurian to overly older rocks.

Thus the basin may be delineated in the north by the Mid North Sea High (Fig. 1.8) which is an extension of the Southern Uplands massif (Leeder and Hardman 1990) that bounds the Pennine Basin, and is similarly cored by granites (Donato et al. 1983). The Mid North Sea High was probably a site of major condensation of the Carboniferous and fault reactivation inducing uplift during Variscan tectonism. The offshore extension of the Wales-London-Brabant High forms the southern boundary of the basin (Fig. 1.8) is also thought by Allsop (1987) to be cored by an extensive granitoid, which Leeder and Hardman (1990) named the North Norfolk Pluton. The East Midlands High and its offshore extension into Quadrant 47 separates this basin or sub-basin (Leeder and Hardman 1990) from the Pennine Basin in the west. This high is also cored by granitoids and represents an area of slow subsidence rates. The eastern boundary of the basin (Fig. 1.8) lies well into the Dutch Sector, and consequently Quadrant 44 lies predominantly within the region of Westphalian subcrop (Fig. 1.9), with some Namurian subcrop in the north adjacent to the Mid North Sea High and in the central structural province of Leeder and Hardman (1990).

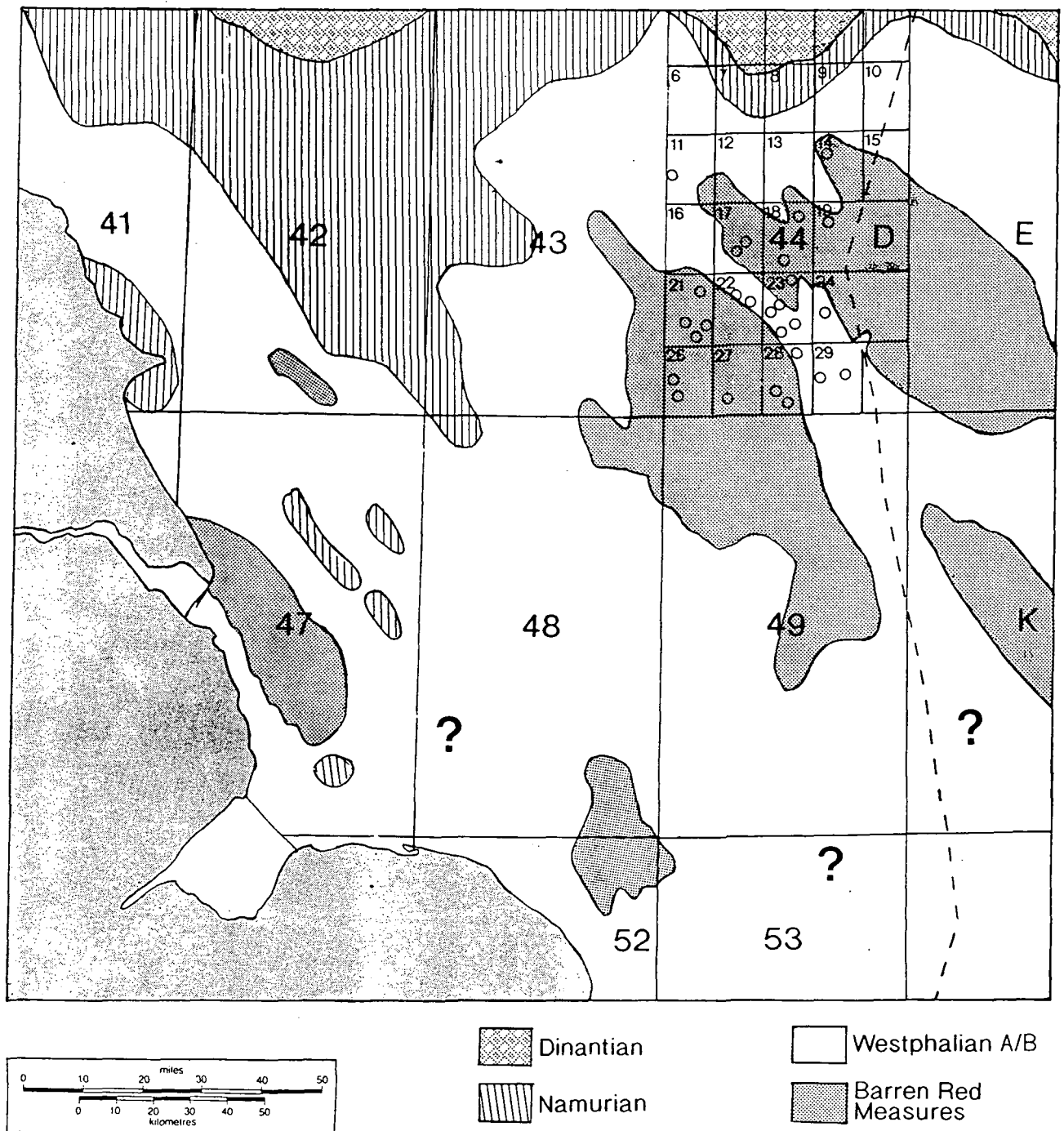


Fig. 1.9 Pre-Permian subcrop of the Southern North Sea, showing blocks and principal well locations. (after Leeder and Hardman 1990; GAPS 1994).

1.4.3 Structure of the Southern North Sea Basin

Covering most of the Southern North Sea basin, from the southern Quadrants 48 and 49 to the central parts of 42 to 44 (Fig. 1.8), is an impressive en-echelon fold belt (Leeder and Hardman 1990) lying in a 100 km wide zone between the southern flanks of the Mid North Sea High to the northern flanks of the Wales-London-Brabant High. Its western margin is bounded, as is the whole basin, by the East Midlands High and its offshore extension into Quadrant 47. Within this central fold belt upwards of 47 individual anticlines may be recognised (Leeder and Harman 1990) which trend consistently northwest - southeast (Fig. 1.8), but with a noticeable tendency for the northern folds to trend more west-northwest to east-southeast (Leeder and Hardman 1990). These orientations parallel trends in the Carboniferous subcrop of the onshore East Midlands (Smith 1987; Fraser et al. 1990) which may result from a lower Palaeozoic (Caledonian) basement fabric (Soper et al. 1987). Truncations of the intra-Carboniferous reflectors such as the Westphalian and late Namurian coals across the crests of such structures date the majority of them as Pre-Permian folds. However, Leeder and Hardman (1990) demonstrate that these folds (Fig. 1.11) were true growth folds, as evidenced by the fact that during the Westphalian C/D interval conformable successions of well drained alluvial sediments "red beds" occur in adjacent synclines that onlap unconformably onto the partly eroded flanks of the anticlinal structures. This situation occurs across the southern part of Quadrant 44 and the Ravenspurn Anticline in Quadrant 43 both of which are significant northwest - southeast structures flanked by conformable successions of well drained alluvial sediments "red beds" up to 1500' thick.

The southern flanks of the Mid North Sea High, to the north of this zone, and in the north of Quadrant 44 are characterised by homoclinal strata separated by large normal faults (Fig. 1.12) of broadly east-west orientation analogous to the onshore structures such as the Closehouse / Lunedale / Butterknowle fault and the Stublick / 90 fathom fault. These were active as syn-rift structures located at the margins of tilt blocks and half grabens that dominated the early Carboniferous. Leeder and Hardman (1990) have named these normal faults to the south of the Mid North Sea High, which down throw thick successions of Silesian strata against the Dinantian, as the Dogger Hinge line (Fig. 1.8). They assume that the whole of the Mid North Sea High was initially covered by onlapping Silesian, which has subsequently been removed by Pre-Permian erosion. As discussed in section 1.4.2 the Silesian succession thins onto the northern flanks of the Wales-London-Brabant High. However, Leeder and Hardman (1990)

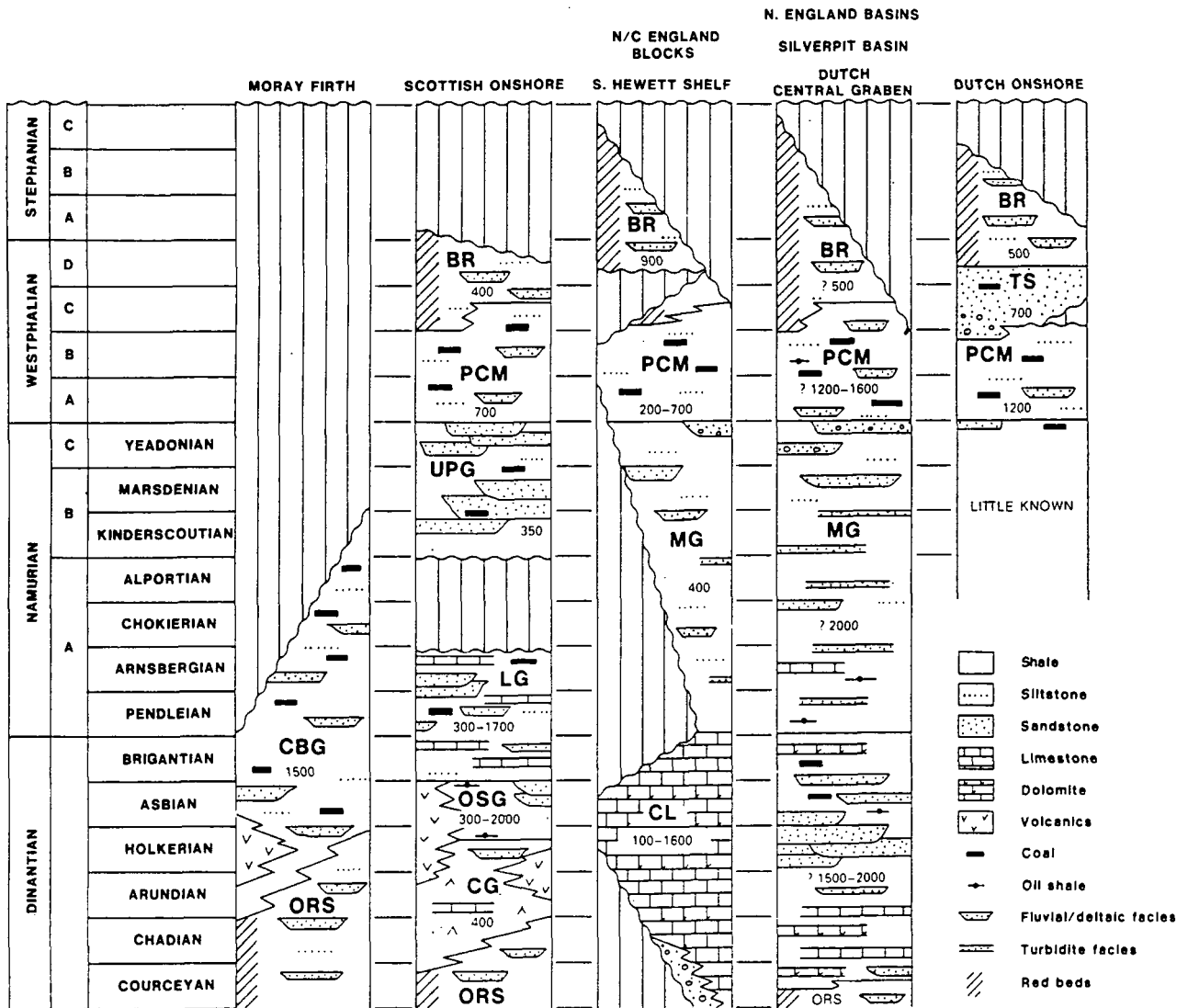


Fig. 1.10 Lithostratigraphic units of the Carboniferous of the Southern North Sea and adjacent onshore areas. (adapted from Besly 1990). BR = Barren Red Group; CBG = Coal Bearing Group (Moray Firth = informal name); CG = Cementstone Group; CL= Carboniferous Limestone; LG = Lower and Upper Limestone Groups and Arnsbergian part of Passage Group; MG = Millstone Grit; ORS= Old Red Sandstone facies; OSG = Oil Shale Group; PCM = Productive Coal Measures; UPG= Post-Alportian part of Passage Group; and TS = Tubbergen Sandstone Formation.

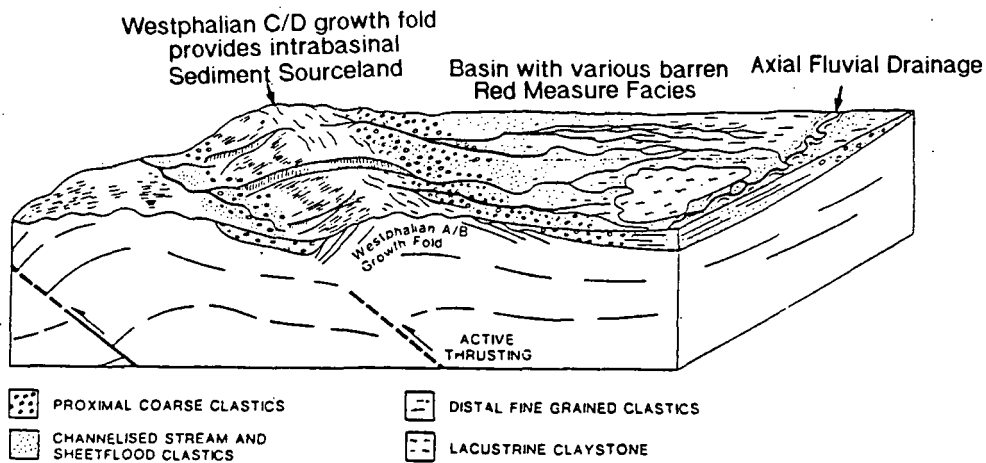


Fig. 1.11 Summary block diagram to show the growth fold / synclinal basin tectono-stratigraphic model for the Westphalian C/D unit (after Leeder and Hardman 1990).

1.4.4 Stratigraphy and Facies

It was beyond the remit of this thesis to detail the Dinantian and Namurian facies and stratigraphy but for completeness they are briefly summarised here.

1.4.4.1 Pre-Westphalian : Dinantian

The Dinantian of the Southern North Sea (Fig. 1.10) occurs only in scattered well penetrations in the centre of the basin but this information is supplemented by wells in the extreme south, which are not typical of the succession as a whole (Besly 1990) and as a consequence the stratigraphy is poorly known. Besly (1990) describes two broad areas recognised on facies development: a northern and central area, and a southern area. In the northern and central areas the predominantly clastic Dinantian sediments resemble the succession seen in the coastal sections of the Northumberland Coast. In the extreme south on the South Hewitt Shelf the Dinantian is similar to that seen in the East Midlands and is characterised by marine carbonate shelves. The succession is thought to record the initial phases of crustal extension characterised by the formation of a block and basin topography typical of the equivalent Dinantian succession (Fig.

1.5) onshore. The clastic successions in the north indicate the first stages of deltaic progradation that typifies the later Namurian.

1.4.4.2 Pre-Westphalian : Namurian

Significant penetrations of Namurian rocks have been made in an increasing number of wells following important discoveries in the Rough Rock equivalent (ARCO pers. comm.). Besly (1990) suggests that Namurian facies and stratigraphy (Fig. 1.10) show a broad similarity to those in the equivalent onshore setting with early Namurian deltaic facies in the north of the Southern North Sea resembling those of Northumberland overlain by major basin-fill episodes comprising basinal muds, turbidites, slope and emergent delta-top facies. These are in turn overlain by shallow water delta systems which parallel those seen onshore (Collinson 1988). These then pass into the lower delta plain Westphalian A sediments. In the extreme south where the Namurian onlaps the lower Palaeozoic at the northern edge of the Wales-London-Brabant High, in the most distal setting, a thick mudstone package suggests that major deltas never reached this far south. The Namurian succession is believed to record the infill of the block and basin topography developed in the Dinantian, by repeated progradation of a major north-south delta system.

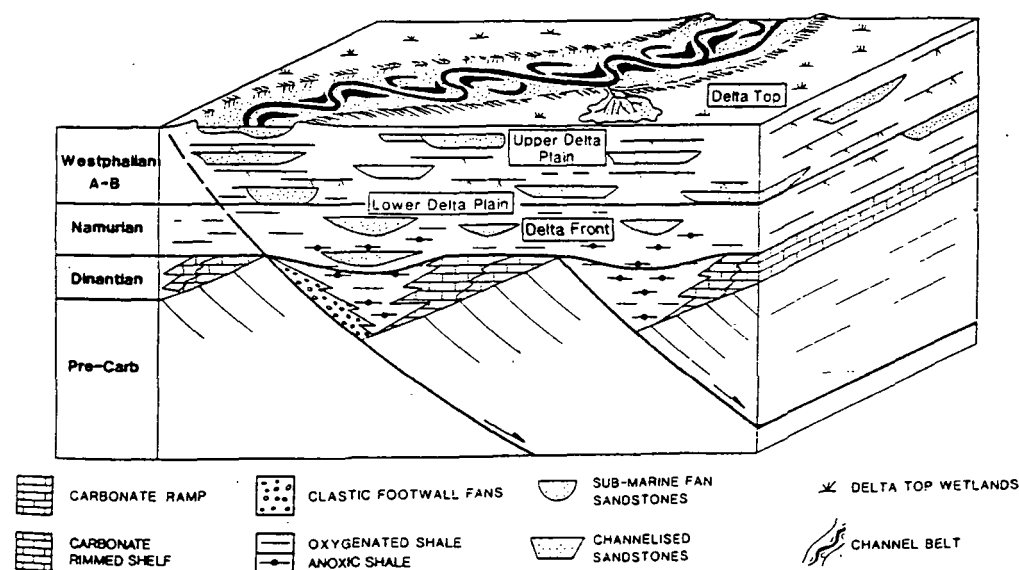


Fig. 1.12 Schematic block diagram to show the extensional tectono-stratigraphic model proposed for the Dinantian to Westphalian B evolution of the Southern North Sea basin (after Leeder and Hardman 1990).

1.4.4.3 Westphalian

Westphalian coal-bearing rocks are known from a large number of well penetrations in both the United Kingdom and Dutch North Sea sectors. The facies present are similar to those described from the Durham (Fielding 1984a,b, 1986) and Northumberland (Haszeldine 1981, 1983a,b, 1984) Coalfields, and consist of crevasse splay / minor delta systems, prograding into predominantly lacustrine interdistributary bay and floodplain areas, producing coarsening- and shallowing-upward fills. These are capped by minor distributary channels or coal seams, with interspersed major distributary channels. Occasional major braided channel systems (Cowan 1989; Ritchie and Pratsides 1993) are interpreted to occur in response to tectonically induced base level fall (Turner and O'Mara 1995). Sediment provenance was dominantly from the north (Besly 1990; Collinson et al. 1993) and systems were thought to flow down a regional south-southwesterly palaeoslope which resulted in a southward decrease in the amount of sandstone in the succession (Besly 1990; Collinson et al. 1993). Even in the more proximal areas in the north some well sections show low sandstone content, with others appearing to concentrate channel sandstones, suggesting that the major distributary channels may have been concentrated by local syn-depositional faulting, in a similar manner to that inferred from the onshore (Fielding 1984b; Guion and Fielding 1988).

The late Westphalian B and early to mid Westphalian C (Fig. 1.10) are characterised by well drained commonly red coloured alluvial sediments colloquially known as "red beds" or "Barren Red Measures" which are either primary or secondary in origin (Besly et al. 1993). Primary well drained alluvial sediments are well developed in the Silverpit Basin and adjoining areas of the Dutch sector and the South Hewitt area (Fig. 1.8 and 1.9) (Tubb et al. 1986). Interdigitation of well drained "red beds" and poorly drained grey coal bearing measures in some parts of this area suggests a diachronous facies relationship comparable to that noted by Besly and Turner (1983) and Besly (1988) in the English Midlands. These well drained alluvial sediments or red bed interdigitations may have an unconformable relationship with the underlying Coal Measures, or they may be part of a conformable succession. A second phase of well drained alluvial sediments occurred some time in the Westphalian C/D, although due to the lack of dating methods the timing is unresolved. Leeder and Hardman (1990) attribute these sediments to further crustal shortening associated with the continued northward migration of the Hercynian thrust front in the Westphalian C/D into the foreland basins of South Wales, Kent, and Calais. This caused the development of the growth folds (Fig. 1.11) discussed in section 1.4.3. and subsequent syn-tectonic

unconformity development along the margins of these folds. A surrounding apron of coarse-grained, often conglomeratic, fluvatile red beds of Westphalian C/D age occurs in response to the formation of this unconformity with the result that these sediments lie unconformably above either the Coal Measures or the well drained alluvial measures.

1.4.5 Quadrant 44

Quadrant 44 (Fig. 1.8 and Fig. 1.14) lies 150 to 200 km to the east of the Yorkshire Coast, adjacent to the United Kingdom-Netherlands median line. The Pre-Permian subcrop is given in Fig. 1.9 where the most striking feature is the major northwest-southeast directed Murdoch anticlinal structure that occurs in the southern blocks of Quadrant 44. The Westphalian C/D lies in two broad belts (synclines) either side of the anticline. In the north of the Quadrant, and in the crest of the anticline, the Westphalian A and B, which are undifferentiated, subcrop. In blocks 11-13 it is believed that it is the Westphalian A that subcrops. This is proved in the adjacent block 44/16 but in other areas it is the Westphalian B that subcrops. The Namurian and Dinantian occur in a broad belt adjacent to the Mid North Sea High associated with the Dogger Hinge Line (Fig 1.8 and 1.9). The majority of the wells available for study are located in the southern blocks as these are the only wells with significant portions of Westphalian B section in areas of Westphalian B to Westphalian C subcrop. This frequency of wells also corresponds to positions on the Murdoch anticline which forms a structural trap for the important gas discoveries discussed in section 1.4.1. Several wells also occur in the synclinal belt to the north and south of the anticline although the primary objective in these wells, was the Westphalian C/D well drained alluvial sediments. Nevertheless they display significant sections of Westphalian B succession.

There is a variety of data of variable quality, quantity and type associated with individual wells as summarised in Fig. 1.13 which gives the database used. Well 44/22-1, for instance, has an accompanying data suite of composite log (with gamma ray, sonic and inferred lithology), spectral gamma ray log (complete section), core descriptions (Geochem, Gaps), palynological report (BGS, Geochem), palynological integrations (Geochem Group, Turner and McLean 1990), sedimentological report (Geochem, SPM Geos), heavy mineral analysis (Geochem) and vertical profile log (integration by GAPS of sedimentology and palynofacies). In comparison traded wells in 44/21-4, 44/21-7 and 44/21-6 have only a gamma ray trace and sonic log.

Introduction

WELL	COMPOSITE LOG	GAMMA LOG	SONIC LOG	NATURAL GAMMA RAY LOG	FGR	PALYNO REPORT	BIOSTRAT REPORT	SED REPORT	CORE REPORT	CONSULTANT REPORT
44/14-1x	Y	Y	Y			Y				
44/17-1	Y	Y	Y			SU				
44/17-2	Y	Y	Y			SU				
44/18-1	Y	Y	Y	Y		SSI		GAPS**		
44/18-3		Y					BGS		GAPS	
44/19-3	Y	Y	Y	Y		GEO	BGS			
44/21-1	Y	Y	Y		Y	Y			Y	
44/21-2	Y	Y	Y		Y	BP			Y	GAPS '94
44/21-3	Y	Y	Y	Y						
44/21-4		Y	Y							
44/21-6		Y	Y							
44/21-7		Y	Y							
44/21-9	Y	Y	Y		Y	SU				
44/22-1	Y	Y	Y	Y	Y	GEO,SU		GEO,SPM	GEO	GAPS '94
44/22-2	Y	Y	Y							ABANDONED
44/22-3	Y	Y	Y	Y	Y	GEO,SU		GEO,SPM	GEO	GAPS '94, GEO'88
44/22-4	Y	Y	Y	Y	Y	GEO,SU		GEO,SPM	GEO	
44/22-5	Y	Y	Y	Y	Y	GEO,SU		GEO,SPM	GEO	
44/22-6z	Y	Y	Y	Y	Y	GEO,SU		GEO,SPM	GEO	
44/22-7	Y	Y	Y	Y	Y	GEO,SU		GEO	GEO	
44/22-8	Y	Y	Y							
44/23-4	Y	Y	Y	Y		PS*,GEO			GEO, CJ	ECL '90,GAPS '94
44/23-5	Y	Y	Y	Y		PS*,GEO			GEO	GAPS '94
44/23-6	Y	Y	Y			GEO				GAPS '94
44/23-7	Y	Y	Y	Y	Y	GEO		GEO***	GEO	GAPS '94
44/23-8	Y	Y	Y	Y		GEO				
44/24-2	Y	Y	Y		Y	BGS*	BGS			
44/26-2	Y	Y	Y		Y			BAD		GAPS '94
44/26-4	Y	Y	Y		Y	SHELL		LOMOND		
44/27-1	Y	Y	Y	Y				BAD		GAPS '94
44/28-1	Y	Y	Y			SHELL*			Y	GAPS '90','94,ECL '90
44/28-2	Y	Y	Y	Y		SHELL*	SHELL		Y	GAPS '90,'94
44/28-3	Y	Y	Y							GAPS '94
44/29-1	Y	Y	Y	Y		ROB*				ECL '90,GAPS '94
44/29-3		Y	Y							GAPS '94

Fig. 1.13 Database available for Quadrant 44 Wells used in this study. Key: Natural gamma ray log=natural gamma spectrometry log; FGR=final geological report; Palyno report=palynological report with count sheets (* without count sheets); Biostrat report=biostratigraphic report with or without palynological integration; Sed report=sedimentological report (** with palynological zonation also, *** includes comparison with other wells); SU=Sheffield University Industrial Palynology Unit; SSI=Stratigraphic Services International; Geo=the Geochem Group; BGS=British Geological Survey; SPM=SPM Geos; PS=Palaeoservices; CJ=Collinson Jones Consultants; Bad=Badley Ashton & Associates; Rob=Robertsons Research. Note: GAPS '94 includes palynological zonation and core descriptions.

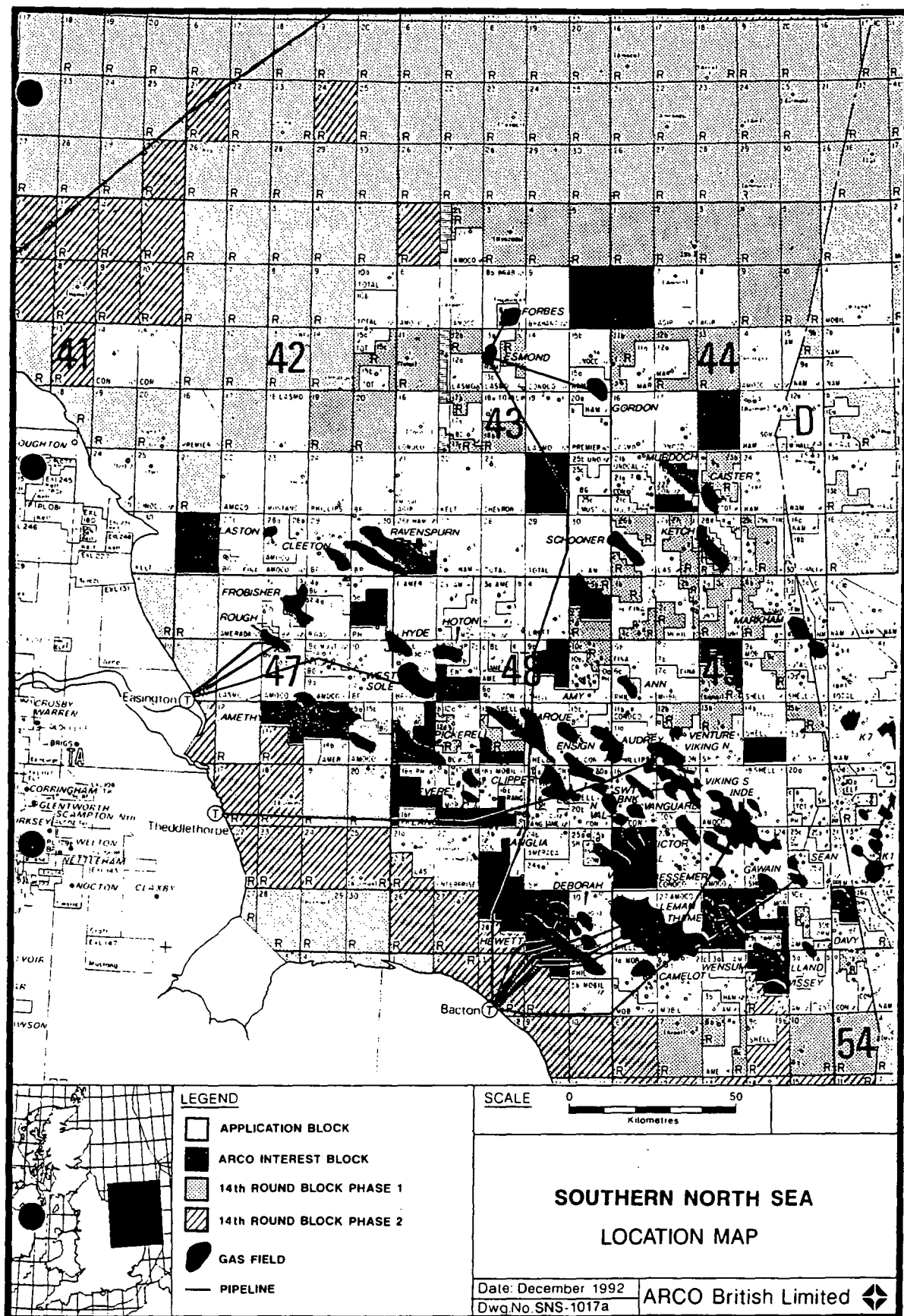


Fig. 1.14 Southern North Sea location map (ARCO British Limited pers. comm.)

Chapter 2

Silesian Palynostratigraphy

2.1 Introduction to Silesian stratigraphy

Westphalian B successions in onshore Britain are dominated by coastal plain clastic sediments consisting of a variety of largely non-marine lithofacies (see Chapter 4 for details). Precise local, regional and intercontinental correlation of such laterally impersistent facies are only possible because of the repeated occurrence of short lived but widespread marine incursions or "marine bands" (see Chapter 3 for more details), with their rapidly evolving and distinctive goniatite faunas. Sixty of these marine mudrock horizons occur throughout the Silesian and nineteen within the Westphalian A to Lower Westphalian C succession.

The Silesian can therefore be subdivided using these marine bands to establish a stratigraphy, which was used as the basis for a comprehensive stratigraphic synthesis of the Westphalian by Ramsbottom (1978) (Fig. 2.1), with re-evaluations and refinements by Guion and Fielding (1988) and Besly (1990) (Fig. 2.2). These syntheses utilised the goniatite data from the marine bands combined with various other organisms that offer reasonably precise zonations (Fig. 2.1) in particular non-marine bivalves (Trueman and Weir 1946; and plant megafossils Crookall 1955). However, the most widely applicable zonation used in the British onshore Westphalian and in Western Europe is that based on palynomorphs, utilising the work of Clayton et al. (1977), Owens (1991), Smith and Butterworth (1967) and Van Wijhe and Bless (1974).

Although palynological assemblages achieve an even biostratigraphic subdivision of consistently spaced markers, it is less precise than that obtained from the identification of marine markers, leading to some difficulty in making detailed correlation in thick sequences of non marine strata. Nevertheless, a regional Western European palynological zonation scheme, shown in Fig. 2.3, was established by Clayton et al. (1977) based on earlier work by Lobioziak (1974) in Northern France, and Smith and Butterworth (1967) in the Pennine Coalfields of the United Kingdom.

SUB-SYSTEM	SERIES	STAGES	GONIATITES			NON-MARINE BIVALVES		SPORES		PLANTS		CONODONTS		DIVISIONS SHOWN ON GEOLOGICAL SURVEY MAPS			OTHER DIVISIONS			STAGES	
			INDEX	ZONES (chronozones) (Ramsbottom 1969)	Subchronozones (Ramsbottom 1969)	marker goniatile bands	Zones (Trueman & Weir 1946)	Faunal belts (Calver 1956; Eagar 1956)	(Owens et al. 1977)	Dix 1934	Kidston/Crookall (Crookall 1955)	Zones and subzones (Higgins 1976)	England & Wales (Stubblefield & Trotter 1957)	Scotland (MacGregor 1960)	N. Devon and Cornwall	Trueman 1946	Heerlen 1935	Mesohems (Ramsbottom 1977)			
S I L E S I A N	STEPHANIAN	STEPHANIAN																	STEPHANIAN		
		CANTABRIAN																	CANTABRIAN		
	WESTPHALIAN	WESTPHALIAN D		'A' 'Anthracoceras'		A. prolifera		XI	Thymospora obscura	I	RADSTOCKIAN pars (Radstock Group)	YORKIAN	Upper Coal Measures	Upper (Barren) Coal Measures	AMMANIAN	WESTPHALIAN D	WESTPHALIAN C	WESTPHALIAN B	WESTPHALIAN A		
		WESTPHALIAN C			A. tenuis		X	Torispora securis	H	RADSTOCKIAN pars (Farrington Group)	Middle Coal Measures		Middle Coal Measures								
		WESTPHALIAN B			A. phillipsii		IX	Vestispora magna	G	STAFFORDIAN	Lower Coal Measures		Lower Coal Measures								
		WESTPHALIAN A			Upper similis-pulchra	adamsi-hindi	VIII	Dictyotrites bireticulatus	F												
					Lower similis-pulchra	caledonica	VII	Schulzospora rara	E												
					A. modiolaris	phrygiana ovum regularis cristagalli pseudorobusta bipennis torus proxima extenuata fallax-protea	VI	Radiizonates aligerens	D												
	NAMURIAN	YEADONIAN	G ₁	G. listeri G. subcrenatum	G. subcrenatum																
		MARSDENIAN	R ₂	Gastrioceras cumbriense Gastrioceras cancellatum	(not divided) G. crenulatum G. cancellatum G. branneroides																
		KINDERSCOUTIAN	R ₁	Reticuloceras superbilingue R. bilingue R. gracile	G ₇ sigma R. superbilingue R. metabilingue R. bilingue (not divided)																
		ALPORTIAN	H ₂	R. reticulatum R. nodosum R. circumplicatile	R. coreticulatum R. reticulatum (not divided) R. dubium R. todmordenense R. circumplicatile																
		CHOKIERIAN	H ₁	Homoceras undulatum Hudsonoceras proteus	Ht. prereticulatus V. eostriolatum (not divided)																
		ARNSBERGIAN	E ₂	Homoceras beyrichianum Homoceras subglobosum	(not divided)																
		PENDLEIAN	E ₁	Nuculoceras nuculum Cravenoceratoides nitidus Eumorphoceras bisulcatum	N. nuculum N. stellarum Ct. nitidus Ct. edalensis E. bisulcatum C. cowlingsense (not divided)																
		DINANT-VISEANIAN (pars)	BRIGANTIAN (pars)		Cravenoceras malhamense Eumorphoceras pseudobilingue Cravenoceras leion	(not divided) E. hudsoni E. stubblefieldi E. tornquisti															

Fig. 2.1 Summary diagram of Westphalian stratigraphy from Ramsbottom (1978), showing comparison of palynological schemes to other zonation methods.

2.1.2. A review of the commonly used palynological zonation

Owens (1991) writes "The concept that an ideal fossil group for biostratigraphic zonation purposes should be one that encompasses a rapidly evolving lineage of forms which occur in the widest possible range of sedimentary environments, suggests that dispersed miospores should offer considerable potential." But he then adds that "Despite 60 years of detailed investigations in the Carboniferous of the Northern Hemisphere that potential has not been fully achieved. No fully comprehensive integrated zonation scheme is yet available to substantiate long range correlations."

The composite scheme published by Clayton et al. (1977) (Fig. 2.3) for Western Europe is generally considered the most workable in a regional context. It combines work from the United Kingdom, and the Netherlands, and is therefore the most useful guide for the Carboniferous sediments in the Southern North Sea. The scheme is based on the composition of miospore assemblages throughout the Westphalian and is characterised by the process of gradual change, with a small number of horizons being recognised as major palynological events. The criteria employed in the definition of these "miospore zone" boundaries are commonly based on the appearance and disappearance of diagnostic taxa.

The scheme proposed by Clayton et al. (1977) (Fig. 2.3) consists of 5 "miospore zones" that encompass the entire Westphalian. It is beyond the scope of this study to investigate the whole of the Westphalian, so that only those miospore zones directly affecting the Westphalian B and its boundaries will be summarised and discussed here. The following discussion incorporates data from Clayton et al. (1977) and Owens (1991) compared with that of Smith and Butterworth (1967) and Van Wijhe and Bless (1974). The comparison of these schemes is shown in Fig. 2.4.

SUB-SYSTEM	SERIES	STAGES	AGE Ma	GONIATITES		SPORES				
				ZONES	MARKER BANDS					
SILESIAN	WESTPHALIAN	STEPHANIAN	C	300			NBM	<i>P. novicus-bhardwajii</i> <i>Cheiledonites major</i>		
			B	303			ST	<i>Angulisporites splendidus</i> <i>Latensina trileta</i>		
			A							
		WESTPHALIAN	D	305				OT	<i>Thymospora obscura</i> <i>Thymospora thiesseni</i>	
			WESTPHALIAN	C	308	A 'Anthracoceras'	A. cambriense	SL	<i>Torisporea securis</i> <i>Torisporea laevigata</i>	
				B	311		A. aegiranum	NJ	<i>Microreticulatisporites nobilis</i> <i>Florinites junior</i>	
			WESTPHALIAN	A			A. vanderbeckei	RA	<i>Radiizonites aligerens</i>	
		NAMURIAN	C	YEADONIAN	G2		G. listeri G. subcrenatum G. cumbriense	G. subcrenatum	SS	<i>Triquitrites sinani</i> <i>Cirratiradites saturni</i>
					G1		G. cancellatum R. superbilingue R. bilingue R. gracile	G. cancellatum	FR	<i>Raistrickia fulva</i> <i>Reticulatisporites reticulatus</i>
					R2		R. reticulatum R. nodosum R. circumplicatile	R. gracile	KV	<i>Crassispora kosankei</i> <i>Grumosporites varioreticulatus</i>
	B		KINDERSCOUTIAN	R1	R. nodosum H. prereticulatus H. undulatum		Hod. magistrorum			
				H2	Hd. proteus H. beyrichianum H. subglobosum		Hd. proteus	SO	<i>Lycospora subtriquetra</i> <i>Kraeuselisporites ornatus</i>	
				H1	N. nuculum Cd. nitidus		H. subglobosum			
	A	ARNBERGIAN	PENDLEIAN	E2	E. bisulcatum C. malhamense E. pseudobilingue C. leion		C. cowiingense	TR	<i>Stenozonotriletes triangulus</i> <i>Rotaspora knoxi</i>	
				E1		C. leion	NC	<i>Bellisporites nitidus</i> <i>Reticulatisporites carnosus</i>		

Fig. 2.2 Re-evaluated Westphalian stratigraphy (Besly 1990).

SUB-SYSTEM	SERIES	STAGE	STAGE	MARKER BANDS	MIOSPORE ZONES	NON-MARINE BIVALVES
			Heerlen 1935		Clayton et al 1977	Trueman & Weir 1947
SILESIAN	WESTPHALIAN	BOLSOVIAN	WESTPHALIAN C	Aegiranum M.B.	<i>Torispora securis</i> <i>Torispora laevigata</i> SL	Upper <i>Similis-pulchra</i>
		DUCKMANTIAN	WESTPHALIAN B		<i>Microreticulatisporites nobilis</i> <i>Florinites junior</i> NJ	Lower <i>Similis-pulchra</i>
		LANGSETTIAN	WESTPHALIAN A	Vanderbeckei M.B.	<i>Radiizonates aligerens</i> RA	<i>A. modiolaris</i> <i>C. communis</i>
	NAMURIAN	YEADONIAN	NAMURIAN C	Subcrenatum M.B.	<i>Triquitrites sinani</i> <i>Cirratiradites saturni</i> SS	<i>C. lenisulcata</i>
				Cancellatum M.B.	<i>Raistrickia fulva</i> <i>Reticulatisporites reticulatus</i> FR	

Fig. 2.3 Relationship between stage names and the biostratigraphic scheme for the British Westphalian of Clayton et al. (1977).

Stages	Marine Bands	Clayton et al. (1977)	Smith and Butterworth (1967)	Grebe (1972)	Van Wijhe and Bless (1974)
Westphalian C	Cambriense	Torispora securis	Torispora securis X	VII	Vestispora fenestrata V
		Torispora laevigata SL	Vestispora magna IX	VI	Vestispora magna IV
Westphalian B	Aegiranum	Microreticulatisporites nobilis		V	
	Maltby		Dictyotriletes bireticulatus VIII	IV	
Westphalian C	Vanderbeckel	Radiizonates aligerens RA	Schulzospora rara VII	III	Radiizonates aligerens II
			Radiizonates aligerens VI	II	
		Triquitrites sinani Cirratriadites saturni SS	Densosporites anulatus V		Apiculatisporis I

Fig. 2.4 Comparison of commonly used palynological zonation schemes. (Clayton et al. 1977; Smith and Butterworth 1967; Van Wijhe and Bless 1974) adapted from Owens (1991).

2.2 Description of Westphalian A (Langsettian) zones

2.2.1 *Triquitrites sinani* - *Cirratriradites saturni* (SS) miozone

Miospore assemblages from the SS miozone are characterised by the presence of numerous representatives of a variably complex group of miospores which show complete morphological intergradation between the genera *Triquitrites* and *Ahrensia*. Representatives of the monolete genus *Laevigatosporites* become quantitatively significant in the assemblages from the middle part of the zone at an horizon approximately equivalent to the middle part of the *Lensiculata* non-marine bivalve chronozone (Fig. 2.3) and its sudden quantitative increase represents a potential marker at this horizon. *Cirratriradites saturni* becomes common and other species including *Cristatisporites splendidus*, *Planisporites granifer* and *Florinites mediapudens* make their appearance at the base of the SS miozone which corresponds to the Westphalian / Namurian boundary and the *Gastrioceras subcrenatum* marine band. The upper boundary is located approximately at the boundary between the *Lensulcata* and *Communis* non-marine bivalve chronozones.

Smith and Butterworth (1967) from their *D. annulatus* (V) assemblage (Fig. 2.5 and 2.6), which roughly corresponds to the SS miozone, describe common components of the assemblage to be ; *Punctatisporites sinuatus*, *Apiculatisporites variocorneus*, *Raistrickia fulva*, *Reinschospora speciosa*, *Dictyotriletes bireticulatus*, *Radiizonates striatus*, *Cingulizonates bialatus*, *Crassispora kosankei*, *Florinites similis* with rare *Schulzospora rara*, *Schopfipollenites ellipsoides* and *Mooreisporites fustis* together with *Bellisporites nitidus* which become extinct in the lower part of the miozone.

Van Wijhe and Bless (1974) working in the Netherlands, (Fig. 2.7) describe an *Apiculatisporis* assemblage marked by the extinction of *Schulzospora campyloptera* at the base and *Radiizonates aligerens* at its top. The assemblage includes frequent occurrences of various species of the genus *Apiculatisporis* with *Densosporites annulatus*, *D. sphaerotriangularis* and *Savitrissporites nux* and rare *Dictyotriletes bireticulatus*, *Cirratriradites saturni*, *Radiizonates difformis* and *Florinites* spp. This zone corresponds to the *D. annulatus* zone (assemblage V) of Smith and Butterworth (1967), (Fig. 2.8) and equates to the SS biozone of Clayton et al. (1977) but may also continue into the lower part of the overlying *Radiizonates aligerens* biozone.

Miospore Assemblages			Lithological Divisions	Heerian Classification	Miospore index genera and species																			
Bohme and Butterworth (1952)	Butterworth and Millott (1960)	Present work			Cadospore	Thymospore	Schopites	Tarispore	Vestispore fenestrata	Triquiritites sculptilis	Vestispore magna	Cristatospores solaris	Endospores globiformis	Schulzospore	Laevigatospores	Florinites mediobundens	Radizonates algerens	Densospores sphaerotrangularis	Florinites	Dictyotritetes bireticulatus	Chaetosphaerites pollenisimilis	Crassispora lasantei	Rotaspore	Tripertites
Upper S4 Assemblage	Verrucosporites obscurus	Thymospore obscura (XI)	Upper Coal Measures	WEST D																				
Lr. S4 Assemblage	Tarispore securis	Tarispore securis (X)	Middle Coal Measures	WEST C																				
S3-S4 Transition		Novispores magnus			Vestispore magna (IX)																			
S3 Assemblage	Dictyotritetes bireticulatus	Dictyotritetes bireticulatus (VIII)	Lower Coal Measures	WEST B																				
S2-S3 Transition					Ceratotriletes algerens	Schulzospore rara (VII)																		
S1-S2 Transition	Cincurasporites carnosus	Crassispora lasantei (IV)	Passage Group	WEST A																				
S1 Assemblage					Rotaspore knosi (III)	Radizonates algerens (VI)																		
S0 Assemblage	Schulzospore ovata	Densospores anulatus (V)	Oil-shale Group	Viséen																				
	Rotaspore knosi	Diatomotrilitetes iurlovii (II)																						
	Comptotritetes verrucosus	Crumispores verrucosus (I)																						

* Scotland † Northumberland

Fig. 2.5 Late Viséan to Westphalian ranges of index genera and species in coal bearing deposits of Britain. Adapted from Smith and Butterworth (1967).

In other parts of Europe (Fig. 2.9) Kmieciak (1987) and Teteriuk (1976) showed the Westphalian / Namurian boundary to be marked by a slow progressive change in assemblage composition which may reflect the existence of specialised parent flora at this time in Great Britain only. No influx of *Triquitrites* spp. and *Ahrensisporites* spp. was noted.

2.2.2 *Radiizonates aligerens* (RA) miozone

The *Radiizonates aligerens* miozone was originally defined by Loboziak (1974) and referred to as Zone 1. See Fig. 2.3 for the subdivision scheme developed for Westphalian deposits of Western Europe. The base of the *Radiizonates aligerens* miozone is indicated by the appearance of the zonal index species *R. aligerens* at the base of the *communis* non-marine bivalve chronozone (Fig. 2.3). This species is known to have limited stratigraphic distribution; limited to the extent of the miozone, and in some parts of Britain it is not thought to extend to the top of the miozone as defined by Clayton et al. (1977). The lower boundary is marked by the appearance of *Punctatosporites* spp. (particularly *P. minutus*), the disappearance of *Spelaeotriletes triangulus* and the increased frequency of *Florinites* spp., *Laevigatosporites* spp., *Reticulatisporites reticulatus* and *R. polygonalis* when compared to the preceding SS miozone. Other common components are representatives of the genera *Lycospora*, *Densosporites* and the species *Cingulizonates loricatus*, while *Schulzospora rara*, *Punctatisporites sinuatus*, *Savitrissporites nux*, *Endosporites zonalis* and *Grumosporites varioreticulatus* occur sporadically throughout the interval. The middle part of the miozone marks the top of *Kraeuselisporites ornatus* and in the uppermost part of the miozone the first isolated *Westphalensisporites irregularis* and *Disaccates non striatiti* have been noted. The upper boundary corresponds to the *Vanderbeckei* marine band and Westphalian A/B boundary.

Smith and Butterworth (1967) (Fig. 2.5) comment that the base of the *Radiizonates aligerens* zone (assemblage VI) is marked by the appearance of *Florinites mediapudens*, *Endosporites zonalis* and *Pitysporites westphalensis*. The definition of the top corresponds to the extinction of the zonal species *Radiizonates aligerens*, a point that will be discussed in the following section.

WESTPHALIAN							CHRONOSTRATIGRAPHY
A		B		C	D		
<i>Lenisulcata</i>	<i>Communis</i>	<i>Modiolaris</i>		<i>Similis - Pulchra</i>	<i>Phillipsii</i>	<i>Tenuis</i>	NON-MARINE BIVALVE ZONATION
* GS Zone	Zone VI	Zone VII	Zone VIII	Zone IX	Zone X	Zone XI	
							<i>Thymospora obscura</i>
							<i>Cadiospora magna</i>
							<i>Schopfites dimorphus</i>
							<i>Alatisporites trialatus</i>
							<i>Torispora securis</i>
							<i>Vestispora fenestrata</i>
							<i>Punctatosporites granifer</i>
							<i>Triquitrites sculptilis</i>
							<i>Endosporites globiformis</i>
							<i>Endosporites zonalis</i>
							<i>Laevigatosporites spp.</i>
							<i>Crassispora kosankei</i>
							<i>Florinites mediapudens</i>
							<i>Reticulatisporites reticulatus</i>
							<i>Microreticulatisporites nobilis</i>
							<i>Cingulizonates loricatus</i>
							<i>Cirratriradites saturni</i>
							<i>Vestispora magna</i>
							<i>Cristatisporites solaris</i>
							<i>Cristatisporites indignabundus</i>
							<i>Dictyotriletes muricatus</i>
							<i>Planisporites granifer</i>
							<i>Raistrickia fulva</i>
							<i>Dictyotriletes bireticulatus</i>
							<i>Mooreisporites fustis</i>
							<i>Grumosporites varioreticulatus</i>
							<i>Savitrissporites nux</i>
							<i>Ahrensissporites guerickei</i>
							<i>Schulzospora rara</i>
							<i>Radiizonates aligerens</i>
							<i>Kraeuselisporites ornatus</i>
							<i>Lycospora subtriquetra</i>
							<i>Punctatisporites sinuatus</i>
							<i>Reticulatisporites carnosus</i>

Fig. 2.6 Details of Westphalian miospore zonation of the British Coalfields, (after Smith and Butterworth 1967).

Van Wijhe and Bless (1974) (Fig. 2.7) define the limits of the zone by the first and last occurrence of the zonally diagnostic species *Radiizonates aligerens*, and describe common components as *Densosporites sphaerotriangularis*, *Raistrickia saetosa*, *Apiculatisporis* spp., *Florinites* spp. and *Laevigatosporites minor*. In the uppermost parts of the zone are the first recorded appearances of *Vestispora costata*, *V. tortuosa* and *Endosporites globiformis*. The occurrence of the latter species, a common component of the Westphalian B, is interesting as Van Wijhe and Bless (1974) defined the upper limit of the zone to be below the uppermost part of the Westphalian A. Therefore, the description of this species within such assemblages disagrees with Smith and Butterworth (1967) and Clayton et al. (1977) who suggest that the first appearance of this species is immediately below the Westphalian A/B boundary.

2.2.2.1 *Schulzospora rara* subzone

The *Radiizonates aligerens* miozone as defined by Clayton et al. (1977) (Fig. 2.4), differs from the subdivision proposed by Smith and Butterworth (1967). The latter scheme is based on work in the British Coalfields using coal seam assemblages. Smith and Butterworth (1967) noted that *Radiizonates aligerens*, the zonal index species for the miozone, was not present in the uppermost part of the zone towards the *Vanderbeckei* marine band. They were able to demonstrate a distinctive and persistent unit termed the *Schulzospora rara* zone (assemblage VII).

This subzone has its base at the last coal assemblage containing *Radiizonates aligerens*, which forms the top of the underlying *Radiizonates aligerens* zone (assemblage VI). The *Schulzospora rara* subzone (assemblage VII) then consists of the remaining two or three coals between this level and the *Vanderbeckei* marine band, where *Schulzospora rara* becomes extinct, marking the top of the zone (Fig. 2.6). There is an increased abundance of *Dictyotriletes bireticulatus* and *Densosporites sphaerotriangularis*, corresponding to the onset of this subzone in some cases, otherwise the absence of *R. aligerens* is the only criteria for distinguishing the two zones. Owens (1991) suggests that the proposal of Smith and Butterworth (1967) only applies in situations where coal seam assemblages are examined, as was the case with the work by Smith and Butterworth (1967). Owens (1991) also indicates that where argillaceous samples are investigated *R. aligerens* can be found up to the Westphalian A/B boundary.

Van Wijhe and Bless (1974) only rarely recorded *Schulzospora rara* and therefore did not use this species as a zonal or subzonal indicator (Fig. 2.7 and 2.8). However, they

did note that *Radiiizonates aligerens* did not extend to the Westphalian A/B boundary even working on mixed lithology assemblages. Their equivalent to the *Schulzospora rara* subzone is encompassed within a *Dictyotriletes bireticulatus* assemblage that occupies the range of uppermost Westphalian A to middle Westphalian B. It straddles the Westphalian A/B boundary and begins with the frequency increase of *Dictyotriletes bireticulatus* and *Densosporites sphaerotriangularis* that coincides with the demise of *Radiiizonates aligerens*.

Grebe (1972), working in the Rhur, (Fig. 2.8) established a scheme similar to Smith and Butterworth (1967) in identifying a *Schulzospora rara* assemblage (II) between the Westphalian A/B boundary and the top of *Radiiizonates aligerens*.

Quadrant 44 well biostratigraphic reports (see section 2.5.3) tend to reinforce the views of Smith and Butterworth (1967) rather than Clayton et al. (1977) and Owens (1991) in that *Schulzospora rara* is relatively common and makes a first down hole appearance at or near the Westphalian A/B boundary or *Vanderbeckei* marine band. The *Vanderbeckei* marine band can be independently identified, and where found *S. rara* can be a useful zonal or subzonal indicator marking the top of the Westphalian A, whether the *Radiiizonates aligerens* miozone or *Schulzospora rara* subzone is utilised, and regardless of the presence of *R. aligerens*. Data from Quadrant 44 wells also suggest that in the Southern North Sea as in the Netherlands, *R. aligerens* does not extend to the Westphalian A/B boundary and is absent from sediments up to 200' beneath the *Vanderbeckei* marine band, reiterating the importance of *S. rara*. To summarise, there are two significant events. The downhole influx of *S. rara* at or near the Westphalian A/B boundary, and the incoming of *R. aligerens* some 200' below indicating the onset of the *R. aligerens* miozone.

NAMURIAN	WESTPHALIAN A			WESTPHALIAN B		WESTPHALIAN C	STAGE
	BAARLO		WILHELMINA	HENDRIK	MAURITS	JABEEK	LITHOSTRATIGRAPHY
	FINEFRAU NEBERBANK SARISDANK		MASSERFALL	KATHARINA	DOMINA	AEGIR	MARINE HORIZONS
ZONE OF HIGH COALIFICATION NO MIOSPORES RECORDED							Thymospora pseudothiessenii
							Laevigatosporites minimus
							Torispota securis
							Vestispota fenestrata
							Camptotriletes bucculentus
							Triquitrites velensis
							Cristatisporites solaris
							Dictyotriletes reticulocingulum
							Alatisporites pustulatus
							Triquitrites tribullatus
							Triquitrites sculptilis
							Vestispota magna
							Laevigatosporites vulgaris
							Vestispota pseudoreticulata
							Vestispota costata
							Endosporites globiformis
							Punctatosp. granifer-minutus
							Vestispota tortuosa
							Cristatisp. indignabundus
							Cristatisporites connexus
							Radiizonates aligerens
							Cirratriradites saturni
							Densosporites anulatus
							Crassispora kosankei
							Laevigatosporites minor
							Densp. sphaerotriangularis
							Apiculatisporis sp.
							Raistrickia saetosa
							Bellisporites nitidus
							Dictyotriletes bireticulatus
Radiizonates striatus							
Radiizonates difformis							

Fig. 2.7 Stratigraphic distribution of Westphalian A - D miospores in the area outside the Limburg mining area, the Netherlands (after Van Wijk and Bless 1974).

2.3 Description of Westphalian B (Duckmantian) zones

2.3.1 *Microreticulatisporites nobilis* - *Florinites junior* (NJ) miozone

The *Microreticulatisporites nobilis* - *Florinites junior* or NJ miozone (Fig. 2.3) as defined by Clayton et al. (1977) coincides with the entire Westphalian B. Its lower limit is marked by the *Vanderbeckei* marine band at the Westphalian A/B boundary and its upper limit by the *Aegiranum* marine band at the Westphalian B/C boundary. Clayton et al. (1977) defined the lower extent at the extinction of *Radiizonates aligerens* (see section 2.2.3 for discussion), *Punctatosporites sinuatus* and *Schulzospora rara* which corresponds to the appearance of *Microreticulatisporites nobilis*, *Florinites junior* and *Endosporites globiformis*. The latter species may make its appearance as rare individuals, at some localities below the *Vanderbeckei* marine band, and presumably this is why it is not used as the zonal index species. However, it only becomes significant above the *Vanderbeckei* marine band.

Many of the taxa from the preceding *Radiizonates aligerens* miozone continue to be important constituents of the assemblages including *Dictyotriletes bireticulatus*, *Vestispora costata*, *V. tortuosa*, *V. cancellata*, *Cirratriradites saturni*, *Crassispora kosankei* and *Cingulizonates loricatus* with representatives of the genera *Laevigatosporites*, *Densosporites*, *Lycospora*, and *Florinites*.

2.3.1.1 Smith and Butterworth (1967) subzones

Significant differences exist between the schemes proposed by Clayton et al. (1977) and that introduced by Smith and Butterworth (1967) for the Westphalian B (Fig. 2.4). The entire range of the Westphalian B is encompassed within the *Microreticulatisporites nobilis* - *Florinites junior* (NJ) miozone of Clayton et al. (1977) whereas the Smith and Butterworth (1967) scheme invokes the use of two zones, described here as subzones.

Van Wijhe and Bless (1974) (Fig. 2.4) agree with Smith and Butterworth (1967) in allocating two zones to the Westphalian B, although as previously discussed in section 2.2.3.2 their *D. bireticulatus* zone crosses the Westphalian A/B boundary to include the uppermost Westphalian A sediments. This corresponds to the *Schulzospora rara*

(assemblage VII) of Smith and Butterworth (1967) and is combined with the equivalent of the *D. bireticulatus* zone (assemblage VIII) of Smith and Butterworth (1967) to form a zone from the uppermost Westphalian A to the middle Westphalian B Maltby marine band. The *D. bireticulatus* zone or subzone of Smith and Butterworth (1967) is equivalent to the lower part of the NJ miozone of Clayton et al. (1977), whereas Van Wijhe and Bless (1974) include the top portion of the RA miozone of Clayton et al. (1977).

The remainder of the Westphalian B, above the Maltby marine band, and including the lower Westphalian C up to the *Cambriense* or Top marine band (the boundary of the upper *Similis pulchra* / *Phillipsi* non-marine bivalve chronozones) is allocated to the *Vestispora magna* zone (assemblage IX) by Smith and Butterworth (1967). Van Wijhe and Bless (1974) are in agreement with this synopsis. This zone equates to the upper part of the NJ miozone and lower part of the overlying SL miozone of Clayton et al. (1977).

2.3.1.2 *Dictyotriletes bireticulatus* subzone

Smith and Butterworth (1967) assign this subzone "Assemblage VIII" (Fig. 2.5). It runs from the *Vanderbeckei* marine band at the Westphalian A/B boundary, as in the case of the NJ miozone, to the top limit at the Maltby "Two Foot" marine band, in the middle part of the *Similis - Pulchra* non-marine bivalve chronozone (Fig. 2.3), some distance beneath the Westphalian B/C boundary. The base of the zone, as defined by Smith and Butterworth (1967), is marked by the appearance of *Radiizonates tenuis*, *Endosporites globiformis* and *Vestispora pseudoreticulata* and the extinction of *Schulzospora rara*. Other common components recorded are *Dictyotriletes bireticulatus*, *Radiizonates striatus*, *Cristatosporites connexus*, *Cingulizonates loricatus*, *Crassispora kosankei* and *Vestispora tortuosa*. The upper limit is recognised by the sudden quantitative reduction in the frequency of *D. bireticulatus*

Van Wijhe and Bless (1974) delineate the base of their *D. bireticulatus* zone (Fig. 2.7) by the incoming of *Vestispora pseudoreticulata* and the upper limit by the sudden quantitative reduction in the frequency of *D. bireticulatus* (cf. Smith and Butterworth 1967). Their assemblages are similar, but with the added common taxa *Cristatosporites indignabundus*.

In Poland Kmieciak (1986) concurs with the idea of two zones for the Westphalian B (Fig. 2.9) and introduces a lower Westphalian B *Endosporites globiformis* (Eg) zone with *E. globiformis* as the zonal index taxa, which is equivalent to the *D. bireticulatus* zone (assemblage VIII) of Smith and Butterworth (1967). The assemblages described are very similar and correlate closely to those described above.

2.3.1.3 *Vestispora magna* subzone

Smith and Butterworth (1967) describe the base of the *Vestispora magna* zone (assemblage IX) (Fig. 2.6) as being marked by the appearance of *Triquitrites sculptilis*, *Cristatosporites solaris* and *Vestispora magna*, although they comment that these components are rare and sometime absent in the seams between the Maltby marine band and the *Aegiranum* (B/C boundary) marine band, the lower part of the zone. This implies that it may be difficult to distinguish the *V. magna* zone from the underlying *D. bireticulatus* zone, with which the lower part is otherwise similar. Subtle differences noted by Smith and Butterworth (1967) are the increased abundance in the upper part of the zone of *Cingulizonates lorincatus*, *Endosporites globiformis*, *Florinites mediapudens* and *Cristatosporites solaris*. The base of the zone coincides with the extinction of several species at or just below the top of the underlying *D. bireticulatus* zone, including *Ahrensisporites guerickei*, *Grumosporites varioreticulatus*, *Mooreisporites fustis* and *Savitrissporites nux*, which help to delineate the lower limit of the zone.

The *Vestispora magna* (assemblage IV) zone of Van Wijhe and Bless (1974) (Fig. 2.7) is defined at its lower limit by the marked decrease in frequency of *D. bireticulatus* and by the incoming of *Vestispora fenestrata* at its upper limit. They too noted that the zonal species *Vestispora magna* was rare in the lower part of the zone but becomes common from the *Aegir* or *Aegiranum* marine band at the base of the Westphalian C upward. They described similar assemblages to those of Smith and Butterworth (1967) with a mention of *Laevigatosporites vulgaris* common throughout and infrequent occurrences of *Triquitrites sculptilis* and representatives of the *Punctatosporites granifer / minutus* complex in the lower Westphalian C only.

Kmieciak (1986) working in Poland describes the upper of his two zones as the *Triquitrites sculptilis* (Ts) zone (Fig. 2.9) which equates to an upper Westphalian B zone only and is not carried over the Westphalian B/C boundary to include the lower Westphalian C, unlike Smith and Butterworth (1967) and Van Wijhe and Bless (1974). Kmieciak (1986) uses *Triquitrites sculptilis* as the zonal indicator, as the species is a

common component of the assemblages. This is in agreement with the British Coalfields where the range and abundance concurs with the data from Poland. It may be appropriate to substitute *T. sculptilis* for *Vestispora magna* as the zonal indicator of the upper Westphalian B subzone in the United Kingdom, as the former species appears to have a higher abundance and is more likely to occur in the whole of the time range extending down to the Maltby marine band, the lower limit of this zone.

Owens (1991) suggests that since the recognition of the base of the *Vestispora magna* zone is difficult, due to the scarcity of the zonal indicators, it seems preferable to utilise the subdivision of the Clayton et al. (1977) scheme (Fig. 2.3). However, this scheme was developed with regional correlation in mind, and therefore established broad or coarse zonation bands. This is not sufficient in the offshore realm where a higher degree of resolution is required, hence it is argued here that where *Vestispora magna* and *Triquitrites sculptilis* are available they should be used where possible to increase the awareness of stratigraphic position (refer to section 2.5 for details). Coupled with the disappearance of these two taxa downhole, is a marked downhole frequency increase of *Dictyotriletes bireticulatus* in coal seams beneath the Maltby marine band, (see Smith and Butterworth 1967 and Van Wijhe and Bless 1974) and the first occurrence of *Ahrensia sporites guerickei*, *Mooreisporites fustis* and *Grumosia sporites varioreticulatus*, (Fig. 2.6), but probably not *Savitrisporites nux* which both Owens (1991) and Clayton et al. (1977) believe continues to the Westphalian B/C boundary. The points noted above can thus be used to define a *Vestispora magna* subzone, which can be used to enhance correlation where available.

2.4 Description of Westphalian C (Bolsovian) zones

2.4.1 *Torispora securis* - *Torispora laevigata* (SL) miozone

Clayton et al. (1977) defined the base of the SL miozone (Fig. 2.3) just above the *Aegiranum* marine band by the appearance of the monolete genus *Torispora* together with *Vestispora fenestrata*, both of which subsequently become quantitatively significant components of the assemblages. The boundary also marks the top of the epibole *Cingulizonates loricatus*, *Grumosia sporites maculatus*, *Savitrisporites nux* and *Raistrickia fulva*. They disagree with Smith and Butterworth (1967) (Fig. 2.4) in that they believe *Grumosia sporites varioreticulatus* also disappears here and not at the Maltby marine band (the top of the underlying *Dictyotriletes bireticulatus* zone).

In the middle part of the miozone representatives of the genera *Triquitrites* and *Punctatosporites* become quantitatively important, with the appearance of *Punctatosporites granifer* together with a perceptible reduction in the number of spores of the *Densosporites* group. Whilst in the upper part of the unit *Westphalensisporites irregularis* and *Vestispora fenestrata* show a marked increase in relative abundance, but it is in the succeeding zone that they reach their maximum development. It is also possible to recognise the beginning of the biozone by the rare presence of isolated specimens, of *Disaccates striatiti* and *Lundbladispota gigantea* which become more significant later.

Throughout the miozone representatives of the genera *Lycospora*, *Laevigatosporites*, *Punctatosporites*, *Torispora* and *Florinites* constitute the common components in the assemblages with accessory *Crassispora kosankei*, *Densosporites spp.*, and *Triquitrites spp.* Many of the taxa characteristic of the preceding NJ miozone including *Reticulatisporites polygonalis*, *R. reticulatus*, *Microreticulatisporites nobilis*, *Florinites junior* and the *Vestispora costata / cancellata* lineage continue to occur.

2.4.1.1 Discussion of Westphalian C zonation schemes

The lower part of the interval occupied by the *Torispora securis* - *Torispora laevigata* (SL) miozone of Clayton et al. (1977) from the *Aegiranum* marine band to the *Cambriense* marine band (Fig. 2.3) is equivalent to the upper part of the *Vestispora magna* zone (assemblage IX) of Smith and Butterworth (1967) (Fig. 2.4). The remainder of the Westphalian C is assigned by Smith and Butterworth (1967) to the *Torispora securis* zone (assemblage X), the base of which was originally defined by Butterworth and Millott (1960) on the basis of the appearance of *Torispora securis*, *Vestispora fenestrata* and *Punctatosporites granifer*. Most of the other components of the zone are compatible with those recorded in the SL miozone of Clayton et al. (1977) although it is worth mentioning that Smith and Butterworth (1967) noted increased numbers of *Cirratriradites megaspinosus* and an abundance of *C. solaris* near the top of the zone.

SYSTEM	SERIES	STAGE	British Isles	Warsaw Basin	Lubin Basin	Eastern Polish	Donetz Basin
CARBONIFEROUS	WESTPHALIAN	Westphalian D	OT	Pg		Pg	C-VL
		Westphalian C	SL	Vf	Vf	Vf	TS-KH
					Vm		
		Westphalian B	NJ	Eg	Ts	Ts	EG-BB
					Eg		
	Westphalian A	RA	FI	Sr	Ra	AG-SR	
		SS		Ra			Lpp
	NAMURIAN	Yeadonian	FR	D-C	Gv	Gv	CC-MT

Fig. 2.9 Correlation of European Westphalian Miospore Zones (after Owens 1991).

Van Wijhe and Bless (1974) agree with Smith and Butterworth (1967) in that they note the appearance of *Vestispora fenestrata* at the *Cambriense* (lower Westphalian C) marine band, not the *Aegiranum* (Westphalian B/C Boundary) marine band (Fig. 2.4). They use *V. fenestrata* as the zonal index species and their *V. fenestrata* zone (V) extends at least to the top of the Westphalian C and is marked by the extinction of *Cirratiradites saturni*. Their assemblage consists of common *Cristatosporites indignabundus*, *C. connexus*, *C. solaris* and *Densosporites annulatus* with accessory *Densosporites sphaerotriangularis*, *Microreticulatisporites nobilis*, *M. silicates*, *Cirratiradites saturni*, *Laevigatosporites minimus*, *Savitrissporites concavus*, *Triquitrites sculptilis*, *T. bransonii*, *T. tribullatus*, *Vestispora costata*, *V. magna*, *V. pseudoreticulata* and *V. tortuosa*. This is similar to the SL miozone assemblage described by Clayton et al. (1977)

In Poland Kmieciak (1986) concurs with Clayton et al. (1977) in Fig. 2.9 in distinguishing *Vestispora fenestrata* at the base of the Westphalian C at the *Aegiranum* marine band. The taxa is then utilised as an index species to define a *Vestispora fenestrata* (Vf) zone equivalent to the *Torispora securis* - *Torispora laevigata* (SL) miozone of Clayton et al. (1977). The assemblages described by Kmieciak (1986) have similar taxa content and ranges to those described by Clayton et al. (1977) so it can be assumed the zones are equivalent.

Discrepancies exist between the position assigned to the base of the *Torispora securis* - *Torispora laevigata* (SL) miozone of Clayton et al. (1977) and the *Torispora securis* zone (assemblage X) of Smith and Butterworth (1967), and the *Vestispora fenestrata* (V) zone of Van Wijhe and Bless (1974) (Fig. 2.4). The latter is located close to the top of the upper *similis* - *pulchra* non-marine bivalve chronozone (Fig. 2.3) at the *Cambriense* marine band in the lower Westphalian C, whereas the base of the SL miozone is located just above the *Aegiranum* marine band in the lower part of the non-Marine chronozone. Owens (1991) notes this but suggests that the scheme of Clayton et al. (1977) (Fig. 2.3) is more widely applicable to other parts of Europe, including Poland and is thus more useful regionally. The major disagreement seems to be on the range of the important taxa *Vestispora fenestrata*. The scheme developed by Clayton et al. (1977) and utilised by Owens (1991) is more recent and is based on a greater quantity and quality of data and therefore I suggest that the range of *V. fenestrata* does extend to the Westphalian B/C boundary, and thus the SL miozone, encompassing the whole Westphalian C of Clayton et al. (1977), should be adopted.

2.5 A Silesian palynostratigraphic scheme for Quadrant 44

2.5.1 Introduction to offshore palynostratigraphy

Macrofossils are only preserved in offshore well sections in exceptional cases and direct comparison with the macrofossil zones (Fig. 2.1), defining the onshore stages of the Silesian using marine bands, is not feasible. The positions of the marine incursions have therefore to be identified by other methods and palynological analysis of the Carboniferous sediments has evolved as the most effective biostratigraphic technique to evaluate these offshore well sections. The palynological zonation that have been derived are relatively well constrained against onshore sections, although the method as a "stand alone" stratigraphic tool is not precise. This is due to the reliance on terrestrially derived spores and pollen which have an erratic facies related distribution and preservation potential in the upper delta plain sediments of the Westphalian Coal Measures. Consequently they can occur at slightly different levels in different wells, especially as the zonation schemes are based on palynological events such as evolutionary inceptions (first down hole occurrence) and extinctions (last down hole occurrence) and quantitative acmes (down hole frequency increases or reductions).

2.5.2 Problems with conventional palynostratigraphy

2.5.2.1 Data collection

Conventional palynological zonation schemes are based on the analysis of drill cuttings, side wall core plugs and core chips. However, correlations cannot be relied upon with a high degree of confidence for several reasons.

(1) Reworking of taxa occurring during deposition: Spores and pollen may be reworked at the time of deposition of the sediments, as they are remarkably resistant to abrasion and thus may be on their second or third cycle of sedimentation. This problem is compounded by the fact that the source for the Westphalian B is thought to include components of the underlying Westphalian A and Namurian, both of which show similarities in their miospore assemblages.

(2) Down hole contamination: The evolutionary inception of species is identified by last down hole occurrences. However, these are not always diagnostic due to the presence of caved material in the drill cuttings, which is a common problem in deep wells with a significant proportion of "open hole". This problem is compounded by rapid lithological variations especially in Carboniferous wells which often experience these difficulties.

(3) Rapid facies variations: Local ecological factors may have an impact on miospore assemblages, in that these affect the extent to which the life assemblage is captured in the rock record. Thus appreciation of the Carboniferous palaeoenvironment and its lack of horizontal continuity must be taken into account when using such palynological events as abundance peaks (acmes) and reworking events for correlation. Before using such events local reworking or facies related events must be confidently distinguished from those of regional importance.

(4) Rig site conditions: Miospore assemblages can be drastically affected by conditions at the rig site in that the increased use of down hole turbines and PDC drilling bits significantly reduces assemblage diversity and quantity of miospores. Striving for increased rate of down hole penetration will destroy the majority of the palynomorphs. Sampling error, where samples were not taken at the right place due to lag time calculation error or due to poor supervision on the part of the well site geologist or mudlogging contractor will affect the data quality. This may be compounded by poor sample labelling or transport. Sample spacing is important for high resolution correlation potential.

The above criteria control data quality so that good quality reports satisfy less of the above criteria than bad ones.

2.5.2.2 Individual contractors appraisals

The palynological data from the original contractors appraisals varies in content and quality. It commonly comprises the original routine biostratigraphic reports and raw data count sheets commissioned or undertaken by the operator, occasionally complimented by additional reports highlighting certain aspects of the wellbore. The individual contractors differ in the zonation schemes each utilises to subdivide the Westphalian. Variances occur due to differences in the marker taxa used and in the interpreted age significance of these taxa in time and between consultants.

2.5.3 Comparison of contractors appraisal schemes

In Quadrant 44 wells there are 7 major schemes, which are briefly worth commenting on.

2.5.3.1 The Geochem Group

The Geochem Group (Fig. 2.10) undertook the work on the Murdoch and Caister wells in blocks 44/22 and 44/23 for Conoco and Texas Gas in the early exploration and appraisal drilling. Their biozonation scheme is the least useful as it is based on palynoevents, palynofacies and reworking events, which clearly are palaeoenvironmentally or palaeogeographically influenced. The Geochem Group appear to place little significance on extinctions and inceptions of particular taxa, and do not relate their scheme to the marine band hierarchy. The zonation established by the Geochem Group was not utilised, but where available, the count sheets proved particularly useful for correlation of the Murdoch / Caister fields.

The Geochem scheme uses an *Ibrahimisporites microhorridus* zone of reworked taxa at or near the Westphalian A/B boundary. This may relate to reworking at the base of the Caister Sandstone and may not be an unequivocal regional correlation tool, although it may tell us something about erosion relating to Caister Sandstone generation. They also have a *Vestispora pseudoreticulata* zone (zone 22) that may correspond to the negative interval discussed in section 2.5.3.3 and a *Triquitrites sculptilis* zone above the Westphalian B/C boundary. Both of these intervals display an increase in the respective zonal species, which may be a local palaeoenvironmental factor, as it is not mentioned in any other literature.

2.5.3.2 ECL / SSI (Exploration Consultants Limited / Stratigraphic Services International)

The ECL / SSI palynomorph zonation scheme (Fig. 2.11) follows that of Smith and Butterworth (1967) (Fig. 2.5). Consisting of a latest Westphalian A *Schulzospora rara* biozone beneath the Westphalian A/B boundary, an early Westphalian B *Dictyotriletes bireticulatus* biozone up to the Maltby marine band and a late Westphalian B *Vestispora magna* biozone, the latter ceases at the Westphalian B/C boundary. A *Vestispora fenestrata* biozone then encompasses the early Westphalian C, which is

more comparable to the SL miozone of the Clayton et al. (1977) scheme (Fig. 2.3), but ceases at the *Cambriense* marine band.

CHRONO-STRATIGRAPHY		GONIATITES	NON-MARINE BIVALVES	GEOCHEM PALYNOZONES	CLAYTON ET AL 1977	SMITH & BUTTENWORTH 1967	V. WIJHE & BLESS 1974	
S I L E S I A N	Stephanian	D	GOLDFUSSIANA	SB	N-BM			
		C	STEPHANIENSIS					
		B		SA	ST			
		A	PROLIFERA					
	Westphalian	D	G2	PHILLIPSI	WD	3	OT	XIII
						2		XII
						1		XI
		C	SIMILIS PULCHRA	WC	3	SL	X	V
					2			
					1			
		B	MODIOLARIS	WB	6	NJ	VIII	III
					5			
					4			
		A	COMMUNIS	WA	3	RA	VII	II
	2							
	1							
	Namurian	C	G1	LENISULCATA	NC	2	FR	V
						1		
		B	R2	NB	2	KV	IV	
			R1		1			
		A	H2	NA	3	SO	III	
			H1					
			E2		2			TK
		E1		1	NC			

Fig. 2.10 The palynological zonation scheme of The Geochem Group (1990).

The early Westphalian B is subsequently subdivided into 5 subzones, based on prominent coal seams defined by sonic log peaks. I would comment that it is unlikely that these coal seams could be correlated regionally due to the rapid lateral facies variations (see Chapter 4) and problems in identifying which coal is which, thereby preventing this part of the scheme being utilised. A similar situation is seen in their late Westphalian B and early Westphalian C which is subdivided by the various marine bands. Although they are regionally correlateable it is not always possible to identify them in the wellbore, and they have no palynological significance and cannot be identified palynologically. I have not used this part of the scheme.

2.5.3.3 GAPS Geoconsultants

The GAPS zonation (Fig. 2.12) is based on the Smith and Butterworth (1967) zonation scheme (Fig. 2.5), utilising the last down hole and first down hole occurrences of diagnostic taxa with further subdivisions based on faunal acme's or frequency increases. The zone WP 4 is equivalent to a *Schulzospora rara* zone (Smith and Butterworth 1967), but extends slightly above the *Vanderbeckei* marine band, where the *Endosporites globiformis* / *S. rara* faunal changeover is thought to occur. The Westphalian B is split into three zones: WP 5, WP 6 and WP 7. WP 5, which encompasses the lower Westphalian B, is based by the extinction of *S. rara* and the inception of *E. globiformis*, and its top is marked by the downhole frequency increase of *Dictyotriletes bireticulatus*. GAPS suggest that this does not correspond to the inception of *Triquitrites sculptilis* and *Vestispora magna* and thus the Maltby marine band, but occurs some distance beneath it. This establishes a "negative" zone where few *D. bireticulatus* are found and upper Westphalian B taxa are not present.

The problem with this "negative" zone is that it is difficult to identify and delineate with any confidence, especially for regional correlation, as the taxal recovery may be affected by local conditions at deposition or subsequent operational factors that can extend the zone in some wells by destroying taxa. It would be more useful to identify a particular assemblage at this point. Other workers (Smith and Butterworth 1967; Van Wijhe and Bless 1974; Kmiecik 1986) noted that both *T. sculptilis* and *V. magna* do extend to the Maltby marine band contradicting GAPS argument and therefore if either of the two taxa extend down to the Maltby marine band, uncertainty is always present. Unusually the downhole frequency increase of *D. bireticulatus*, that marks the lower limit of the zone, does appear to be of regional extent and is not a facies related phenomenon. It probably does occur some distance beneath the Maltby marine band (cf section 2.5.4.2) thereby constraining the lower limit of this "negative" zone.

Fig. 2.11 The Palynological zonation scheme of ECL / SSI (1989).

FORMATION ZONATION		UPPER COAL MEASURES		MIDDLE COAL MEASURES				LOWER COAL MEASURES				PALYNOMORPH ZONATIONS		MARKER TAXA	PALYNOMORPH ASSEMBLAGE CHARACTERISTICS SUMMARY														
NON-MARINE BIVALVE ZONATION	STAGE	PHILLIPSII/TENUIS	WEST-D-CANT	U. SIMILIS-PULCHRA	WESTPHALIAN C	LOWER SIMILIS-PULCHRA	WESTPHALIAN B	MODIOLARIS	WESTPHALIAN A	COMMUNIS	WESTPHALIAN A	WA 1	WA 2			WA 3	SS												
GENERALISED LITHOLOGY		BARREN RED MEASURES		SHAFTON		EDMONDIA		MAGRANUM		HALIGHTON		SUTTON		MALTBY		VANDER-BECKE		ESTHERIA		AMALIAE		SUBCREN-ATUM							
MARINE BANDS (BRITISH)		LATE WEST. C		EARLY WESTPHALIAN C		LATE WESTPHALIAN B		EARLY WESTPHALIAN B		LATEST WESTPHALIAN A		MIDDLE TO LATE WESTPHALIAN A		EARLY WESTPHALIAN A															
AGE		WC 1 D		WC 1 C		WC 1 B		WC 1 A		WB 2		WB 1		WB 1 B		WB 1 A		WA 3		WA 2		WA 1		N 2					
SSI STRATIGRAPHIC ZONATION		X		IX		VIII		VII		VI		V																	
ONSHORE BRITAIN (SMITH & BUTTERWORTH (1967))		X		IX		VIII		VII		VI		V																	
NORTHERN EUROPE (CLAYTON ET AL)		X		IX		VIII		VII		VI		V																	
		Thymospora spp. Schopffites dimorphus		Raistrickia fulva Cirratriadites satumi		Vestispora fenestrata Torispora securis		Vestispora magna Triquitrites sculpilis Cristatisporites solaris Increase frequency of Dictyotriletes bireticulatus in coals below Maltby M.B.		Schulzospora rara		Radiizonetes aligerens		Radiizonetes aligerens															
		Due to the diachronous nature of the Barren Red Measures/Coal Measures boundary the preservation of Westphalian D strata in productive measures is sporadic. Assemblages of this age dominated by small monoletes such as <i>Thymospora</i> spp., <i>Punctatosporites</i> spp., and <i>Latosporites</i> spp., with <i>Schopffites dimorphus</i> , <i>Mooreisporites</i> spp., and common <i>Vestispora</i> spp.		Assemblages generally dominated by <i>Vestispora</i> spp., with <i>V. fenestrata</i> and <i>V. laevigata</i> the marker species. Regular <i>Torispora securis</i> , <i>Punctatosporites</i> spp. and <i>Latosporites</i> spp., with <i>Endosporites globiformis</i> also indicative of this age.		The downhole appearance of such miospores as <i>Raistrickia fulva</i> , <i>Cirratriadites satumi</i> and <i>Dictyotriletes bireticulatus</i> indicates this age or older strata. True age designation is based on assemblage characteristics which often include frequent to common <i>Endosporites globiformis</i> , <i>Vestispora pseudoreticulata</i> and <i>Florinites mediapudens</i> , together with more age diagnostic taxa such as <i>Vestispora magna</i> , <i>Cristatisporites solaris</i> and <i>Triquitrites sculpilis</i> . These latter species are generally more regular in the Early Westphalian C strata but are rare and sporadic in the Late Westphalian B. No diagnostic taxon or assemblage changes mark the Westphalian B/C boundary and it is often very difficult to split the two ages. However, taxa such as <i>Ahrensisporites guerickei</i> , <i>Radiizonates tenuis</i> and <i>Cristatisporites indignabundus</i> indicate definite penetration of Westphalian B strata when they appear. In addition, <i>in situ</i> <i>Vestispora fenestrata</i> and <i>Torispora securis</i> indicate, if present, a Westphalian C or younger age.		Coal seams below the Maltby M.B. generally contain more frequent representation of <i>Dictyotriletes bireticulatus</i> . This species may also be more regularly represented in the non-coal horizons but not always. Palynomorph assemblages usually contain increased frequency of <i>Densosporites sphaerotriangularis</i> , especially from the thick coal seams. Also characterised by frequent <i>Vestispora costata/tortuosa</i> , <i>Savitrissporites nux</i> , <i>Raistrickia</i> spp., <i>Cristatisporites indignabundus</i> , <i>Granulatisporites granulosus</i> and <i>Florinites</i> spp. <i>Endosporites globiformis</i> remains numerically significant although not so abundant as the overlying age. <i>Vestispora pseudoreticulata</i> exhibits a gradual reduction in abundance coinciding with the rise in <i>V. costata/tortuosa</i> numbers. A background abundance of <i>Lycospora pusilla</i> , <i>Laevigatosporites</i> spp. and <i>Crassispora kosankei</i> is noted in most assemblages of this age.		Assemblages are very similar to above. However presence of <i>Schulzospora rara</i> together with other species with recorded Westphalian A tops such as <i>Auraraspora stolidata</i> = Westphalian A. <i>Endosporites globiformis</i> extremely rare or absent and has a stratigraphic 'base' in this age. <i>Vestispora pseudoreticulata</i> also does not extend below this age, although <i>Vestispora costata/tortuosa</i> remains frequent. <i>Dictyotriletes bireticulatus</i> often reduces in numbers at the base of this age.		Age marked by the downhole incoming of <i>Radiizonates aligerens</i> , which is often frequent to common in the upper part, but becomes sparse near the base of the zone. The age is additionally detected by the downhole appearance of <i>Kraeuselisporites ornatus</i> in the middle/upper part and <i>Cirratriadites rarus</i> near its base. In addition, <i>Vestispora costata/tortuosa</i> has its stratigraphic base in the upper part of this zone. General assemblage contains abundant <i>Crassispora kosankei</i> , <i>Lycospora pusilla</i> , <i>Laevigatosporites minor</i> and <i>Florinites</i> spp., together with regular <i>Radiizonates</i> spp., <i>Cristatisporites connescus</i> and <i>Calamospora</i> spp.		Difficult to determine if caving is a problem in wells. Definite penetration of this age indicated by the occurrence of <i>in situ</i> <i>Spelaotriletes arenaceus</i> , <i>Knoxisporites dissidius</i> and <i>Trinidulus dimorphus</i> . <i>Cirratriadites rarus</i> is generally more regular than above. A downhole reduction in <i>Laevigatosporites</i> spp. occurs in the upper part of the age. Onshore, large numbers of <i>Triquitrites</i> and <i>Ahrensisporites</i> spp. occur in this age but this is generally not recorded offshore. The Westphalian/Namurian boundary is very difficult to determine palynologically.															

GAPS zone WP 7 is split by a downhole frequency increase of *T. sculptilis*, a factor not noted by other workers and which may be difficult to identify regionally. The problems of faunal acme's are that they can vary in time and with facies. Zone WP 8 is marked by the inception of *Vestispora fenestrata*, which GAPS consider to be at this point (see section 2.2.5.1. for discussion), and striate bisaccates and the extinction of *Raistrickia fulva*. The WP 8 zone is subdivided into WP 8a and WP 8b on the inception of *Torispora securis* between the *Aegiranum* and *Cambriense* marine bands, thereby concurring with Smith and Butterworth (1967) (see section 2.2.5.1. for discussion).

2.5.3.4 SHELL (UK) EXPRO

Shell (UK) EXPRO's palynological scheme (Fig. 2.13) uses a *Schulzospora rara* zone, (Smith and Butterworth 1967) beneath the *Vanderbeckei* marine band (Fig. 2.6). As with GAPS (see section 2.5.3.3) they identify a "negative" zone separating a *Dictyotriletes bireticulatus* or lower Westphalian B equivalent zone from an upper Westphalian B *Vestispora magna* equivalent. This latter zone extends to the *Cambriense* or Top marine band, and thus differs from many other zonations by continuing across the *Aegiranum* marine band (see discussion 2.2.5.1). Alternatively Shell (UK) Expro adopt a two zone subdivision system for the Westphalian B with a sliding boundary across the "negative" zone indicating that in some cases the criteria for identifying the zone boundaries lack consistency. This latter observation suggests that this boundary could not be rigidly applied to all Westphalian B sections in the region.

2.5.3.5 BGS (British Geological Survey)

The British Geological Survey offer technical advice via several biostratigraphic reports, although do not publish a zonation scheme. They use both Smith and Butterworth (1967) (Fig. 2.6) and Clayton et al. (1977) (Fig. 2.3) as a basis to subdivide the Carboniferous. Where available, I preferentially use both the reports and count sheets which draw on the greater experience and stratigraphic awareness of the workers. A brief summary of their notes is given here.

AGE	GONIATITE ZONE		BIVALVE ZONE	CONODONTS	PALY. (Clayton 1977)	PALY. GAPS	PALYNOLOGICAL MARKERS	
	PERMIAN	STEPHANIAN						
300 Ma	UPPER	D	Goldfussiana		DS		KEY □ Common ■ Abundant	
								VC
305 Ma	LOWER	C	Stephaniensis		N.BM		NO PALYNOMORPHS RECORDED ABOVE WP8 IN THE STUDY AREA.	
		B						
		A						
		D						
308 Ma	D	A. prolifera	A. tenuis		DT			
311 Ma	WESTPHALIAN	C	A. cambriense	A. phillipsii	SL	WP8	Polysporites spp	
							Vesicisporites pseudobaculatus	
		B	A. aegiranum	Upper similis pulchra	Lower similis pulchra	NJ	WP7	Tonipores spp (Tonipores securis)
								Vesicisporites fenestrata, Striate bisaccates
315 Ma	NAMURIAN	C	A. vanderbeckei	A. modiolaris	RA	WP6	Consistent Retriobolus fulvus	
							Consistent Dictyobolus bisaculatus	
		B	C. communis	C. lenisulcata	Id. sulcatus parvus	SS	WP5	Schulzeisporites raris
								Endosporites globiformis
319 Ma	BRIGANT.	A	G. subcrenatum	Id. sinuatus	FR	NP6	Radizonites aligerens	
							Radizonites aligerens	
		B	A. cumbriense	I. primulus	Id. corrugatus	KV	NP4	Levigatospores vulgaris
								Cerastrioides raris
326 Ma	DINANTIAN	C	G. cancellatum	Id. sulcatus sulcatus	SO	NP3	Levigatospores vulgaris	
							Increase Kreusselsporites ornatus / spp. consistent Cerastrioides raris	
		A	R. superbilingue	S. lateralis	G. bilineatus bollandensis	TK	NP2	Dictyobolus bisaculatus
								Cristatospores pennosus, Ibrahimpores magnificus, Rugosipores corporata corporata
V3	E. cowlingense	G. girtyi simplex	G. girtyi collinsoni	NC	NP1	Increase Vesicisporites spp. increase Spelaeobolus araneosus Bescaudisporites conope		
						Reboulatisporites ornatus, Retriobolus niger, Retriobolus fructus, Tripartites vetustus, Tripartites bilinguis		
VISEAN	E. leion	G. girtyi collinsoni		VF			Cressisporites aculeata (sporadic)	
							Cingulizonites of oespiratus, C. kosaneki, Valvulinella spp (foraminifer)	

Fig. 2.12 The Palynological zonation scheme of GAPS Geoconsultants (1987, 1988a, 1988b, 1994).

Westphalian C sediments are identified using complex forms of the genus *Triquitrites* and the occurrence of *Torispora* spp. and *Vestispora magna*. They note that the definition of the Westphalian B/C boundary using palynology is difficult due to the reduced incidences of miospore evolutionary inception and extinction events and the poor stratigraphic control of the Westphalian B/C boundary in non marine facies.

A mid to late Westphalian B assemblage is characterised by *Dictyotriletes bireticulatus*, *D. castaneaeformis*, and *D. muricatus*, whereas an early Westphalian B assemblage contains a high frequency of cingulate miospores *Cingulizonates loricatus*, *Cristatosporites indignabundus*, *Densosporites annulatus*, *D. pseudoannulatus* and *D. sphaerotriangularis*. The distinctive miospore taxon *Endosporites globiformis* makes its first stratigraphic appearance at the base of the Westphalian B just above the *Vanderbeckei* marine band. Latest Westphalian A microfloras are characterised by the occurrence of the short range taxon *Schulzospora rara* which makes its last stratigraphic appearance immediately below the *Vanderbeckei* marine band, thus the Westphalian A/B boundary is well confined palynologically.

2.5.3.6 Sheffield University Industrial Palynology Unit

The Industrial Palynology Unit at Sheffield University worked for CONOCO on establishing a correlation scheme based on coal seam assemblages, for the Murdoch field wells 44/22-1, 44/22-3, 44/22-4, 44/22-5, 44/22-6z and 44/22-7 (Fig. 2.14). The high degree of well spacing and good data quality allowed distinctive coal seam assemblages to be identified in these wells and provided a higher resolution than all comparable schemes. The scheme, however, is specific to Murdoch wells and may not be widely applicable to the whole of Quadrant 44, due to reduced well spacing away from the Murdoch field and the lack of confidence in coal seam identification. The zonation concurs with that of Smith and Butterworth (1967) who also worked on coal seam assemblages.

The Sheffield University Industrial Palynology Unit recognise three highly distinctive seams in all of the wells and the stratigraphic interval studied. These are the "+1", "-1", and "-2" seams respectively (Fig. 2.14) and are supplemented by the recognition of six groups of palynologically similar seams identified in four of the six wells (Fig 2.14). The assemblages quoted are similar to those described in section 2.3.1 with the zonally diagnostic taxa *Endosporites globiformis*, *Schulzospora rara* and *Radiizonates aligerens* equating to those of Smith and Butterworth (1967) (Fig. 2.5).

Lithological Divisions	Major goniatite horizons	Non-marine bivalves	Heerlen classification	Palynological schemes			
				CLAYTON et al. 1977	SMITH & BUTTERWORTH '67	SHELL UK	
						S zones	S subzones

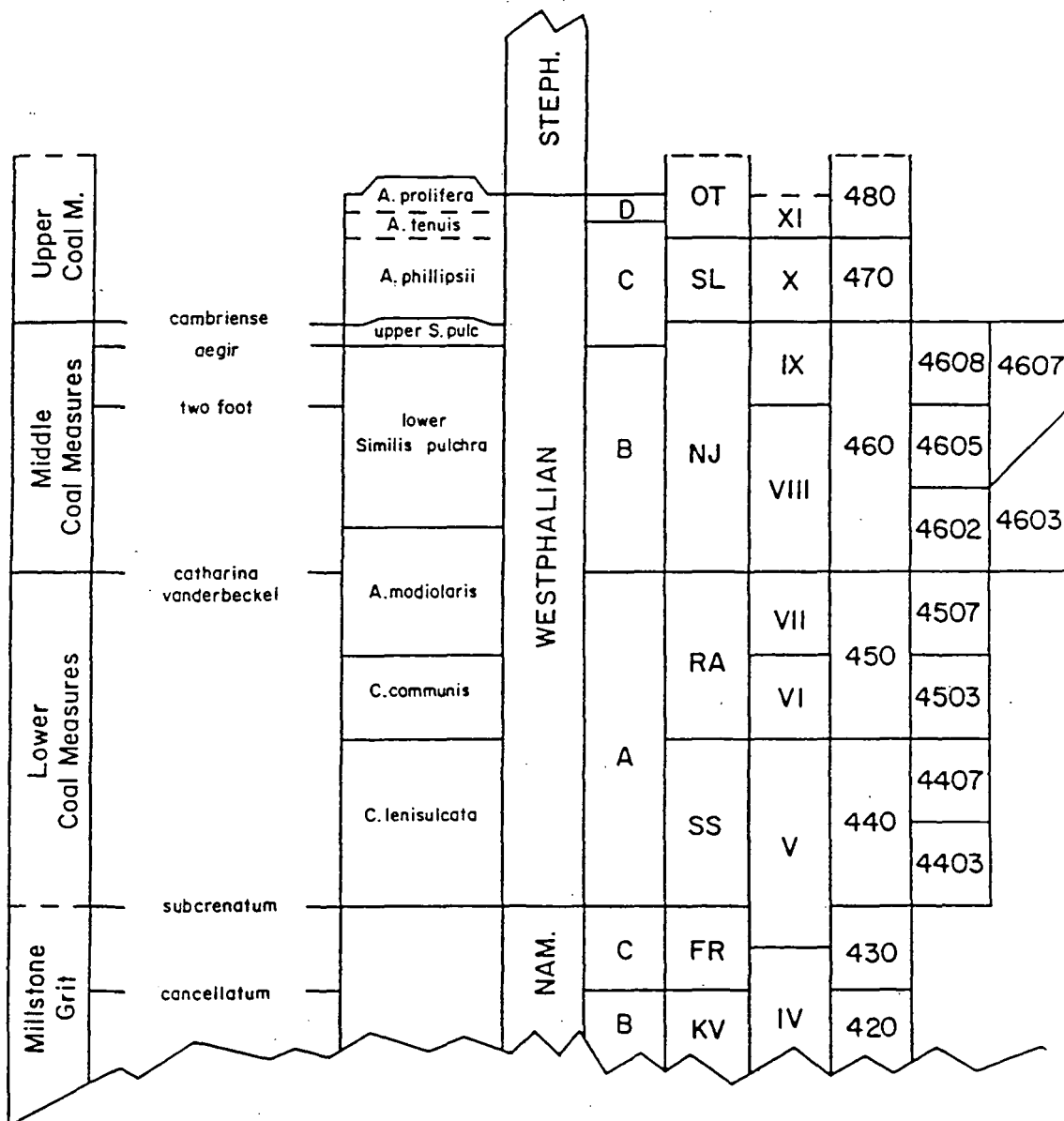


Fig. 2.13 The Palynological zonation scheme of Shell (UK) Expro (after Shell 1986).

The problems with the scheme are outlined below.

(1) The palynological nature of coal seams is such that a section through an individual seam will contain several different palynological assemblages or "phases". In order to identify an ideal "palynological signature" for any individual seam it would be necessary to obtain a "channel sample" of the coal in which all of these phases are equally represented. In practise this is never attained with offshore data, even with core material. The recovery of drill cuttings and the curation of core is such that it is impossible to know whether all of a seam is represented in a core, and commonly it is not. In some cases complete seams maybe absent from curated cores.

(2) The use of the method and its correlation to those areas reliant on drill cuttings are such that even though drill cuttings appear to represent a "channel sample" from a drilled section, it is impossible to know what proportion of a seam is actually represented in a drill cuttings sample and whether any "phases" are over represented. One gram of coal may yield up to one million spores and pollen grains, so clearly one cutting out of place will greatly affect data, especially quantitative data.

(3) Where seams are closely spaced several seams can be represented in one sample.

(4) Coal seam identification and correlation using this method requires comparison with wireline data, especially gamma ray and sonic. These tend to mis-represent coal seams by amalgamating several closely separated seams into one peak because they lack the resolution to determine thin seams.

The problems illustrated above mean that reliance on this method as a "stand alone" palynological tool is difficult without closely spaced cored well data, but it may be useful for "infill stratigraphy" once a target has been isolated, subsequently aiding reservoir management and development. The one point of note is the three palynologically highly distinctive seams occurring in all wells. The "+1" seam is immediately above the regionally correlateable Caister Sandstone and contains the last down hole occurrence of Westphalian B taxa. The "-1" seam, that is the coal immediately below the Caister Sandstone and hence the *Vanderbeckei* marine band, corresponds to the first down hole occurrence of *Schulzospora rara* which is the diagnostic taxa for uppermost Westphalian A sediments. The "-2" seam is equivalent to the first down hole occurrence of *Radiizonates aligerens* which is the diagnostic taxa for middle Westphalian A sediments. All of this supports the Smith and Butterworth

(1967) scheme and agrees with the whole rock palynological analysis, (section 2.5.4). The remainder of the zonation reflects a locally applicable refinement.

Chronostratigraphy				Palynostratigraphic Classification			
Sub-systems	Series	Lippolt <i>et al.</i> (1984) Hess & Lippolt (1986)	Stages	Zones	Sub-zones		
SILESIAN	WESTPHALIAN	306Ma	WESTPHALIAN D	W7	c		
		309Ma			BOLSOVIAN (WESTPHALIAN C)	W6	b
							a
		311Ma	DUCKMANTIAN (WESTPHALIAN B)	W5	b		
					a		
			LANGSETTIAN (WESTPHALIAN A)	W4	b		
					a		
		NAMURIAN	315Ma	YEADONIAN	N5	a	
				MARSDENIAN		c	
				KINDERSCOUTIAN	N4	b	
	a						
	319Ma			ALPORTIAN	N3	d	
			CHOKIERIAN	c			
				b			
	ARNSBERGIAN		N2	a			
				b			
	326Ma		PENDLEIAN	N1	a		
		BRIGANTIAN	b				
	DINAN-TIAN	VISÉAN				a	

Fig. 2.14 The palynological scheme of of the Industrial Palynology Unit at the University of Sheffield (after McLean and Turner 1990).

2.5.4 The palynological scheme used in this study for Quadrant 44

It is beyond the scope of this study to undertake independent palynological analysis to establish a scheme based on new data. Therefore, to establish a universally applicable palynological zonation scheme for Westphalian B sediments in Quadrant 44 an attempt has been made to synthesise all of the data available. This consisted of a review of the literature (see section 2.1) and an extensive study of the palynological count sheets and accompanying reports. Data quality is the controlling factor and good quality data (abundant and diverse taxa recognised; lack of reworking or downhole contamination; and; efficient sample spacing) allows the maximum number of taxa to be utilised. This allows for a palynological zonation based on primarily events such as extinctions and evolutionary inceptions to form the boundaries to zones. Each zone is then characterised by a particular assemblage with unique co-occurrences. These are described in section 2.5.4.1. It is necessary to understand the peculiar characteristics of the neighbouring Westphalian A and Westphalian C assemblages to recognise those of Westphalian B age, therefore a scheme (Fig. 2.15) from the middle of the Westphalian A to the middle of the Westphalian C is described here.

2.5.4.1 Uppermost Westphalian A - *Schulzospora rara* (SR) zone

The middle to upper Westphalian A is defined as the *Radiizonates aligerens* or RA subzone by Clayton et al. (1977) (Fig. 2.3), but it is separated into the *Radiizonates aligerens* (VI assemblage) and *Schulzospora rara* (VII assemblage) subzones by Smith and Butterworth (1967) (see section 2.2.3.2 for discussion). Owens (1991) suggests that where the subzonal indicator *Schulzospora rara* is found, considered rare by some workers in the United Kingdom and Netherlands, a *S. rara* subzone should be employed.

Throughout Quadrant 44 the taxon *Schulzospora rara* is seen to occur, consistently some 200' above the first downhole occurrence of the zonally diagnostic taxon *Radiizonates aligerens*. This concurs with the work of Smith and Butterworth (1967) and Van Wijhe and Bless (1974) (Fig. 2.8) who noted the absence of the latter taxa for several coal seams immediately below the *Vanderbeckei* marine band. Where the *Vanderbeckei* marine band can be identified by other means, (i.e. marine macrofauna) the first downhole occurrence of *S. rara* is immediately below, therefore it is appropriate to use *S. rara* to define a subzone from the Westphalian A/B boundary (*Vanderbeckei* marine band) to the first downhole occurrence of *Radiizonates*

aligerens. *Punctatosporites sinuatus* also has its first downhole occurrence at the Westphalian A/B boundary and may be used to define the subzone. Unfortunately this taxon is not found consistently in Quadrant 44 assemblages.

Additionally several typical Westphalian B taxa have their last downhole occurrences immediately above the boundary and therefore assist in delineation. These include *Endosporites globiformis*, *Vestispora pseudoreticulata*, *Radiizonates tenuis*, *Cristatosporites indignabundus*, *Microreticulatisporites nobilis* and *Florinites junior*. The latter is one of the index species for the NJ zone of Clayton et al. (1977), but it is infrequent in Quadrant 44 assemblages.

The recognition of a combination of last downhole occurrences of Westphalian B taxa and the first downhole occurrence of *S. rara* allows the Westphalian A/B boundary to be well constrained by palynology even in data reliant on cuttings.

2.5.4.2 Lower Westphalian B - *Dictyotriletes bireticulatus* (DB) zone

The Westphalian B has been split by various workers into one, two or three zones, (see section 2.4 and Fig. 2.4). However, in terms of palynological events there are two clear zones, based largely on Smith and Butterworth (1967) (Fig. 2.6). A lower Westphalian B *Dictyotriletes bireticulatus* zone and an upper Westphalian B *Vestispora magna* (*Triquitrites sculptilis*) zone.

The lower Westphalian B *D. bireticulatus* zone has its base at the extinction (first downhole occurrence) of *Schulzospora rara* and evolutionary inception of the group of taxa mentioned in section 2.5.4.1, that coincides with *Vanderbeckei* marine band defining the Westphalian A/B boundary. A typical assemblage includes elements of *Ahrensisporites guerickei*, *Camptotriletes bucculentus*, *Cingulizonates loricatus*, *Cirratriradites saturni*, *Crassispora kosankei*, *Cristatosporites connexus*, *C. indignabundus*, abundant *Dictyotriletes bireticulatus*, *Endosporites globiformis*, *Grumosisporites varioreticulatus*, *Knoxisporites stephanephorus*, *Mooreisporites fustis*, *Planisporites granifer*, *Radiizonates tenuis*, *Raistrickia fulva*, *R. striatus*, *Savitrissporites nux*, *Vestispora cancellata* *V. costata*, *V. pseudoreticulata*, *V. tortuosa*. as well as representatives of the genera *Densosporites*, *Laevigatosporites*, *Lycospora* and *Florinites*.

The top of the zone is marked by the drastic decrease in frequency of the genus *Dictyotriletes*, as indicated by the BGS (section 2.5.3.4), and includes *D. bireticulatus*,

D. castaneaeiformis and *D. muricatus* and a decrease in the cingulate miospores *Cingulizonates loricatus*, *Cristatosporites indignabundus*, *Densosporites annulatus*, *D. pseudoannulatus* and *D. sphaerotriangularis*. There is also a comparative reduction in the *Vestispora costata / tortuosa* group in favour of *Vestispora pseudoreticulata*.

There is some suggestion that this frequency change occurs in coal seams some distance beneath the upper/lower Westphalian boundary marine band, the Maltby marine band (see section 2.5.3.3). Although this may be the case frequency changes can also be difficult to identify in the wellbore due to local facies variations or drilling conditions. However, from a study of Westphalian B sediments in Quadrant 44 this downhole frequency increase is clearly evident even in poor quality data and therefore it can be used stratigraphically, despite the fact that it does appear to occur some way beneath the Maltby marine band. The top of the zone is marked by the extinctions of *Ahrensisporites guerickei*, *Grumosporites varioreticulatus* and *Mooreisporites fustis*, and the inception of upper Westphalian C taxa. However, these may only be recognised with good quality data which in some cases forces reliance on the downhole frequency increases, which are not accurate stratigraphic markers.

2.5.4.3 Upper Westphalian B - *Vestispora magna* (*Triquitrites sculptilis*) (VM) zone.

The base of the *Vestispora magna* (*Triquitrites sculptilis*)(VM) zone is marked by the extinctions of lower Westphalian B taxa as mentioned in section 2.5.4.2 which occur some way above the distinctive downhole frequency increase of *Dictyotriletes bireticulatus* and associated taxa (also discussed in section 2.5.4.2). The extinctions correspond to the inception or last downhole occurrence of typical upper Westphalian B to lower Westphalian C taxa *Vestispora magna*, *Triquitrites sculptilis* and *Cristatosporites solaris*. However, it has been noted that these taxa are rare to very rare in the assemblages immediately above the upper/lower Westphalian B Maltby marine band, hence the reason why Clayton et al. (1977) did not use them as zonal indicators. It makes accurate assessment of the position of this particular marine band and the boundary of the two zones difficult.

In Quadrant 44 it appears that *Triquitrites sculptilis* especially, is identified in sediments a short distance above the Maltby marine band. This taxa may be more important than the usual index species *V. magna*, therefore in Quadrant 44 it may be more useful to refer to a *T. sculptilis* zone as Kmiecik (1986) (Fig. 2.9) suggests. In exceptional cases this extends to the Maltby marine band, but more commonly it ceases

in sediments a few tens of feet above. If any of the three species are present they are important indicators.

The zone differs from the underlying *Dictyotriletes bireticulatus* zone as described in section 2.5.4.3 in the reduction in a number of key taxa. *Endosporites globiformis* and *Florinites mediapudens*, however, become more significant, as does *Vestispora pseudoreticulata* at the expense of the *Vestispora costata / tortuosa* group. The taxon *Alatisporites hoffmeisterii* is noted to range from coal seams just beneath the Maltby marine band upwards (Smith and Butterworth 1967) and is a common component of *V. magna* assemblages. It is also a good zonal indicator.

The top boundary of the *V. magna* or upper Westphalian B zone is marked by the extinction of *Savitrissporites nux*, a taxon that has a high frequency in Westphalian B assemblages. Its first downhole occurrence is therefore seen as a prominent pulse that is easily identifiable. Smith and Butterworth (1967) and Van Wijhe and Bless (1974) consider the extinction of *Dictyotriletes bireticulatus* to be at this point, but by this time the taxon is numerically insignificant and therefore largely redundant in boundary definition. *Camptotriletes bucculentus* may assist in boundary definition as it is identified in good quality data assemblages and dies out at this boundary. There is a further perceptible reduction in the number of spores of the *Densosporites* group. These factors correspond to the evolutionary inception (last downhole occurrence) of typical Westphalian C taxa (see section 2.5.4.4).

2.5.4.4 Lower Westphalian C - *Vestispora fenestrata* (VF) zone

Typical Westphalian C taxa (Fig. 2.5) have their evolutionary inception (last downhole occurrence) at or slightly above the Westphalian C/B boundary, marked by the *Aegiranum* marine band, in particular *Vestispora fenestrata* and *Punctatosporites granifer*. The former of these, *Vestispora fenestrata*, is commonly identified in Quadrant 44 well data and combined with the extinction (first downhole occurrence) of Westphalian B taxa it therefore is important in delineating Westphalian C sediments. The exact position of the Westphalian B/C boundary is often difficult to locate as the sedimentary facies are dominantly upper delta plain/alluvial plain passing to "red beds". Miospores are not in sufficient quantity and diversity, and compounding this is sample spacing which is often poor in the upper Westphalian B to lower Westphalian C, with little coring. Westphalian sediments of this age are more commonly oxidised and their miospores destroyed due to proximity to the Sub-Permian unconformity and the impending onset of Westphalian C well drained alluvial sediments.

Despite these unfavourable conditions *Vestispora fenestrata*, which marks the Westphalian B/C boundary, appears consistently and is useful in terms of correlation.

The SL miozone of Clayton et al. (1977) (Fig. 2.3) corresponds to this *V. fenestrata* zone, with its base corresponding to the Westphalian B/C boundary. However, many workers rely on a major faunal influx midway between the *Aegiranum* and *Cambriense* marine bands to form the base of a Westphalian C assemblage. This includes the appearance (last downhole occurrence) of the genus *Torispora*, striate bisaccates and two important members of the *Triquitrites* genus (*T. bransonii*, *T. tribullatus*). This is coupled with the demise (first downhole occurrence) of typical Westphalian B taxa *Cingulizonates loricatus*, *Raistrickia fulva* and *Grumosisporites maculatus*, as well as an increase in numbers (downhole frequency decrease) of members of the *Punctatosporites* spp (including *Punctatosporites granifer*) and *Triquitrites* spp.

A typical assemblage for this zone yields *Cirratriradites saturni*, *Crassispora kosankei*, *Cristatosporites indignabundus*, *C. connexus*, *C. solaris*, *Densosporites sphaerotriangularis*, *Florinites junior*, *Laevigatosporites minimus*, *Reticulatisporites polygonalis*, *Savitrissporites concavus*, *Triquitrites sculptilis*, *T. bransonii*, *T. tribullatus*, *Vestispora fenestrata*, *V. magna*, *V. pseudoreticulata*, and *V. tortuosa*.

The *Vestispora fenestrata* zone is equivalent to the SL miozone of Clayton et al. (1977). This is identified using the *V. fenestrata* palynoevent at the Westphalian B/C boundary, which is usually sufficient to delineate the zone. However, if this species is not present the distinctive palynoevent of the *Torispora/Triquitrites* genera between the *Aegiranum* and *Cambriense* marine bands assists in stratigraphic awareness. Representatives of this zone are the stratigraphically highest in the region.

2.5.5 Conclusions

The Westphalian A to C interval can be satisfactorily subdivided using palynological taxa. This is achieved by maximising the number of significantly available and useful taxa to develop a methodology that incorporates all of the stratigraphically important data which enables the upper Westphalian A to lower Westphalian C to be divided into 5 zones (Fig. 2.15). These are taken from existing published correlations, where all the palynoevents that these are based on are compared. Those events which appear most frequently and those events which occur in sediments nearest to the study area are preferentially utilised. As a consequence this scheme bears most resemblance to that of Smith and Butterworth (1967) and Van Wijhe and Bless (1974). Where points of these

schemes are shown to inaccurate by Owens (1990) and Clayton et al. (1977) such as the range of *Vestispora fenestrata*, these changes are adopted in this study. These latter two schemes cover too large an area and generally lack the resolution to be adopted in full. The 5 zones defined in this study are consistent and reliable, and lack the subjectivity of individual contractors appraisals (section 2.5.4.1 to 2.5.4.6). The zones are palynologically distinct, easily recognisable and are based on a combination of onshore schemes from which they take the best points to maximise the resolution of the correlation attainable. This Chapter together with Chapter 6 demonstrate that these zones can be used on a Quadrant wide spectrum, to subdivide Quadrant 44 well intervals, which subsequently ties into the onshore British and Dutch Westphalian succession.

It has been shown by this study that the Westphalian B assemblages conform to the work of Smith and Butterworth (1967), in that although most of the taxa are simply Westphalian B specific, distinct lower Westphalian B and upper Westphalian B assemblages can be ascertained that compare favourably to the assemblages described for the British Coalfields. Thus, it is possible where good quality data is available to subdivide the Westphalian B into two zones. However, where data quality is inferior it is necessary to infer a "negative" zone (cf. GAPS, section 2.5.4.3; SHELL (UK) EXPRO section 2.5.4.4) that occurs between the two palynologically distinct zones. This is due to the lack of overlap of taxa, or the occurrence of a significant interval between associated inception and extinction of the significant zone-defining taxa. In this case the Maltby marine band cannot be palynologically constrained and other methods are required to identify the marine band and therefore the boundaries of the two zones concerned.

The limitations of the proposed scheme are data quality, which varies markedly. Good data quality requires the recognition of diverse and abundant assemblages, lack of reworking and downhole contamination and clearly defined tops and bottoms to taxa ranges. Whereas poor quality data only allows for a broad or coarse stratigraphic subdivision. Nevertheless, by maximising the number of taxa utilised this problem can be circumvented in some instances. In other instances a simple Westphalian B assemblage may be the only interpretation proposed. The coarseness of the scheme, is a further limitation in that only a two or three fold division for the Westphalian B is applicable. This in itself is not of sufficient resolution to satisfy the needs of development and appraisal drilling programmes. However, the scheme produces a chronological control on which to base further more detailed work (Chapter 3 to Chapter 6).

Chapter 3

Westphalian B marine bands

3.1 Introduction

The Silesian sediments of North West Europe consist predominantly of upper delta plain/coastal alluvial plain shales, siltstones, sandstones and coals. The lateral facies variations common to these depositional environments (Chapter 4) and the repeated stacking of these facies in a subsiding basin (Chapter 5) make lithostratigraphic correlation difficult if not impossible. Chapter 2 demonstrates that palynological analysis can achieve a stratigraphic subdivision, with 6 broad zones encompassing the upper Westphalian A to the lower Westphalian C (Fig. 2.15). The recent increases in exploration interest in the Carboniferous of the Southern North Sea requires a higher definition of zone boundaries and an increase in zone frequency to more accurately constrain reservoir successions. Within the largely non-marine Westphalian succession there are 19 (Ramsbottom 1978) relatively short lived marine incursions preserved as distinct marine horizons or marine bands (Fig. 3.1). Typically these are thin shale beds distinguishable from other shales in the Carboniferous by their marine fauna (Calver 1968a). Ramsbottom (1978) describes marine bands as geographically widespread (occurring throughout Europe) and according to Leeder and Maynard (1990) they represent regional marine flooding events when a regional eustatic rise in sea level drowns the low lying upper delta plain/coastal alluvial plain slightly influenced by palaeotopography.

The extreme consistency and widespread geographic distribution (the *Vanderbeckeri* marine band is reported to be traceable from Ireland to the Urals in Russia) of individual marine bands with their short duration, regular occurrence throughout the succession and characteristic, unique faunal populations makes marine bands universally acceptable as regional chronostratigraphic markers (Ramsbottom 1978; Besly 1990). The Silesian coincided with a phase of rapid goniatite evolution with most of the major marine bands containing distinctive, age diagnostic goniatite populations. A sequential inception of goniatite taxa enables marine bands to be named and correlated regionally and allows them to be used by Carboniferous stratigraphers (Ramsbottom 1978; Besly 1990) to subdivide the Westphalian (Fig. 3.1). Marine events are restricted (Ramsbottom 1978) to the lower to middle Coal Measures (up to the top of the *similis - pulchra* non-marine bivalve chronozone which is equivalent to

the lower Westphalian C) (Fig. 3.1) and define the primary chronostratigraphic framework (Ramsbottom 1978; Besly 1990) on which the palynozones described in chapter 2 are based. Recent work by Leeder et al. (1988) suggests that the marine transgressions responsible for the marine horizons are probably of glacio-eustatic origin (Hecek 1986; Veevers and Powell 1987; Leeder 1988) and if correct, it provides an even more reliable degree of correlation, assuming diagnostic goniatites can be identified.

SUB-SYSTEM	SERIES	STAGE	SPORES		MARINE BANDS (Ramsbottom et al. 1978)	LITHO-DIVISIONS	
			(Owens et al. 1977)	(Clayton et al. 1977)			
SILESIAN	WESTPHALIAN	WESTPHALIAN C	Torispora securis X	Torispora securis Torispora laevigata SL	CAMBRIENSE SHAFTON EDMONDIA AEGIRANUM SUTTON HAUGHTON CLOWNE MALTBY	MIDDLE COAL MEASURES	
			Vestispora magna IX				
			Dictyotriletes bireticulatus VIII	Microreticulatisporites nobilis Florinites junior NT			
		WESTPHALIAN B	Schulzospora rara VII	Radiizonates aligerens RA	VANDERBECKEI BURTON JOYCE LANGLEY AMALIAE MEADOWFARM PARKHOUSE LISTERI HONLEY SPRINGWOOD HOLBROOK SUBCRENATUM		LOWER COAL MEASURES
			Radiizonates aligerens VI				
			Triquitrites sinani Cirratriadites saturni V	Triquitrites sinani Cirratriadites saturni SS			
		WESTPHALIAN A					

Fig. 3.1 Subdivision of the Westphalian B illustrating the relative stratigraphic position of marine bands compared with established zonations. Adapted from Ramsbottom (1978) and Besly (1990).

3.1.1 Marine bands and the Southern North Sea

Onshore, marine bands are readily recognised as "time lines" or tie points on which to subdivide the Westphalian. This allows the marine bands to be equated to the palynological assemblages to enhance correlation, based on the identification of the diagnostic goniatite fauna. However, in the offshore realm the recognition of marine bands directly relies on extensive coring or accurate side wall coring as these are the only methods by which marine macrofauna can be returned to the surface. Both these processes have until recently been used primarily for sandstone reservoir analysis with the result that there is a paucity of material from which goniatites might be extracted, thus making alternative methods of marine band identification a necessity.

3.2 Marine Band Macrofauna

"Analysis of side wall cores from ARCO well 43/24 - 2 revealed the presence of goniatites and microgastropods". (ARCO British, pers. comm.)

The report of goniatites in the wellbore is a rare event within the cored or side wall cored material, though it is becoming more common due to the increased realisation of the usefulness of marine bands. This leads to more coring programmes geared to finding marine bands with the ultimate aim of establishing a workable correlation scheme based on marine bands for the Westphalian of the Southern North Sea (ARCO well 44/18-3; section 6.2.1). The above extract is the only report of distinguishable diagnostic goniatites located within or near the study area, whereby the identity of the marine band can be unequivocally established. Thus other methods of determining the position and identity of marine bands are required. It has been established that the diagnostic goniatites that are used to verify the identity of marine bands in the onshore are very rare and therefore cannot be relied on to pinpoint marine bands. However, as Calver (1968a) noted there are other marine and brackish water fauna that are associated with marine bands. These fauna tend to be more common (wells 44/28-2, 44/23-5, 44/24-2, 44/18-3) as they extend over a greater thickness, suggesting there were initially more of them and they are more resistant to post depositional disturbance. Although not containing diagnostic goniatites, the faunal assemblage itself can be used to separate marine bands and if not, they are crucial in simply identifying the presence of a marine horizon and may have sequence stratigraphic implications (Chapter 5).

3.2.1. Marine band faunal phases

Many workers in Britain (Calver 1968a; Wignall 1987) and Europe (Bless 1976) recognised 3 faunal cycles (Fig. 3.2) within the relatively thin marine horizons: an advance (transgressive); acme and retreat (regressive). These cycles were characterised by particular suites of micro- and macrofauna, and were termed faunal phases. Calver (1968a) noted that the nature of the faunal phase at the acme of the marine incursion gave details of the environmental conditions prevalent at the time of maximum development (transgression) of the marine band. This method characterises the individual marine bands in terms (Fig. 3.3) of the maximum extent of transgression, and thus separating the less geographically widespread or "more marginal" marine bands. The individual faunal phases are characterised by paralic faunal assemblages by which they are designated. (Calver 1968a; Wignall 1987). The regressive episode with its characteristic faunal phase is often similar to that of the advance but it is commonly more drawn out, illustrating the asymmetry of the eustatic base level rise and fall (cf. Maynard and Leeder 1992) where the withdrawal of marine conditions was generally less rapid than the advance (Calver 1968a).

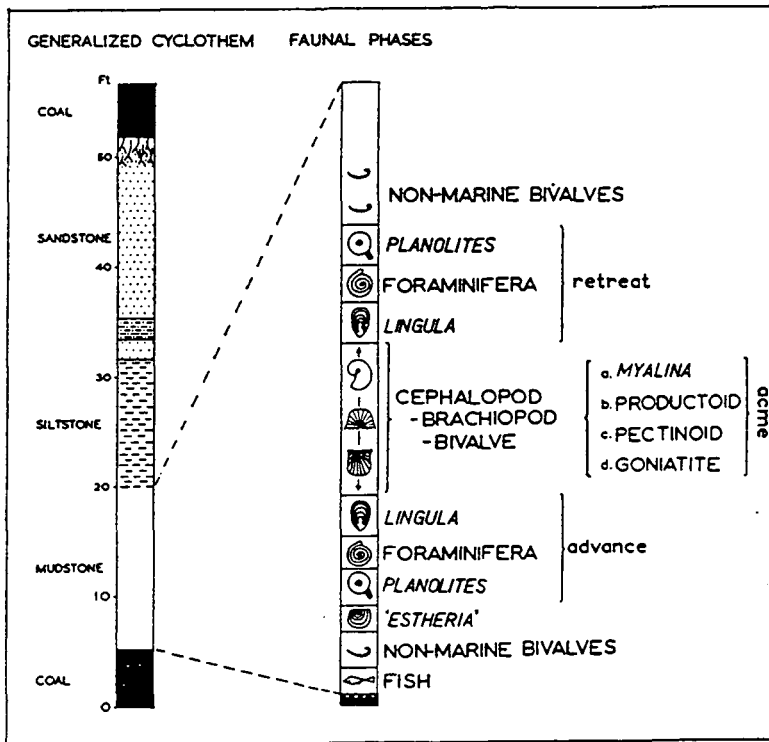


Fig. 3.2 Faunal cycles within Westphalian B marine bands. After Calver (1968a).

The extent in the British onshore of each Silesian marine incursion was documented by Calver (1968a) in terms of faunal phases, with the most effective results obtained in the East Midlands. He noted that the development and distribution of British Silesian marine bands closely reflected the palaeogeographic changes that occurred throughout the Silesian sub-system. Namurian marine bands, for instance, in all but very marginal situations develop fully marine faunal phases despite the trough and block palaeotopography and they have extensive goniatite acme phases with well developed diagnostic fauna. The Coal Measures in its upper delta plain/coastal alluvial plain setting experienced a reduction in the number of marine events upwards through the succession (Fig. 3.1). Ten marine bands are present in the Westphalian A, five in the Westphalian B and four in the Westphalian C. However, the distribution is not uniform throughout the succession with a concentration in the lower Westphalian A and another in the upper Westphalian B / lower Westphalian C. This latter cluster of marine bands is generally more marine in aspect and tends to have a wider geographic distribution than those in the Westphalian A. Clearly this coastal alluvial plain had a sufficiently low relief to allow 4th order (see Chapter 6) eustatic sea level changes to affect the whole region.

The identification of faunal phases within marine bands allows an appreciation of the extent to which true marine conditions were established for particular marine bands. The work of Calver (1968a) gave an indication of the possible geographic extent of these phases (Fig. 3.4). This characterisation of the faunal phases within marine bands assists in correlation, as it allows primary identification of marine bands, as in well 44/28-2 where an *Orbiculoidea* brachiopod, in core material, which identifies the *Cambriense* marine band. When it could be confused with the Shafton or Edmondia due to inaccurate palynology and unequivocal wireline recognition (section 3.3). However, the latter two are not known to have reached the *Orbiculoidea* faunal phase (Fig. 3.3) thus distinguishing the *Cambriense*. Secondly the determination of the conditions at the acme of a marine band may indicate the possible uranium concentration that may be expected from that marine band. This appreciation of possible uranium concentration allows individual marine bands to be identified by spectral gamma ray logs (section 3.3).

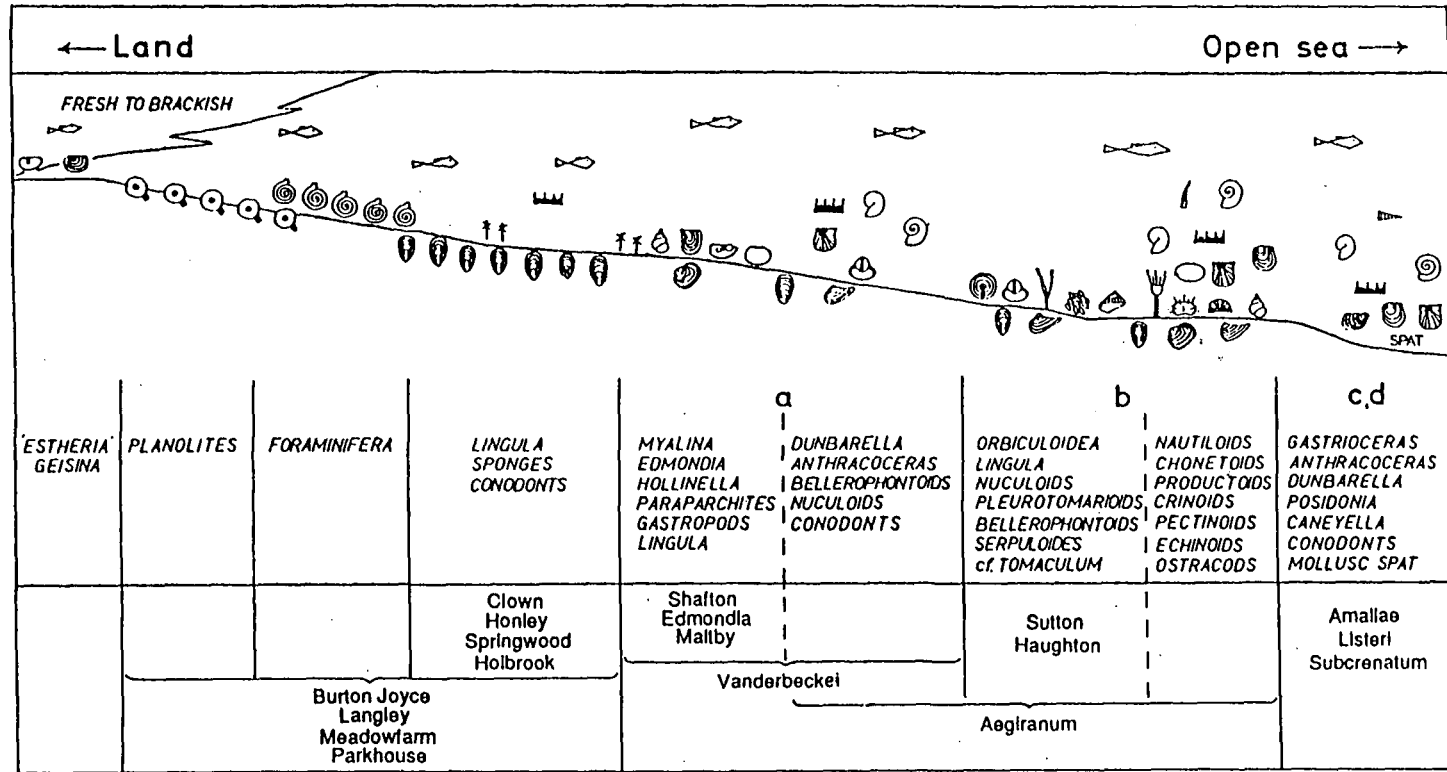
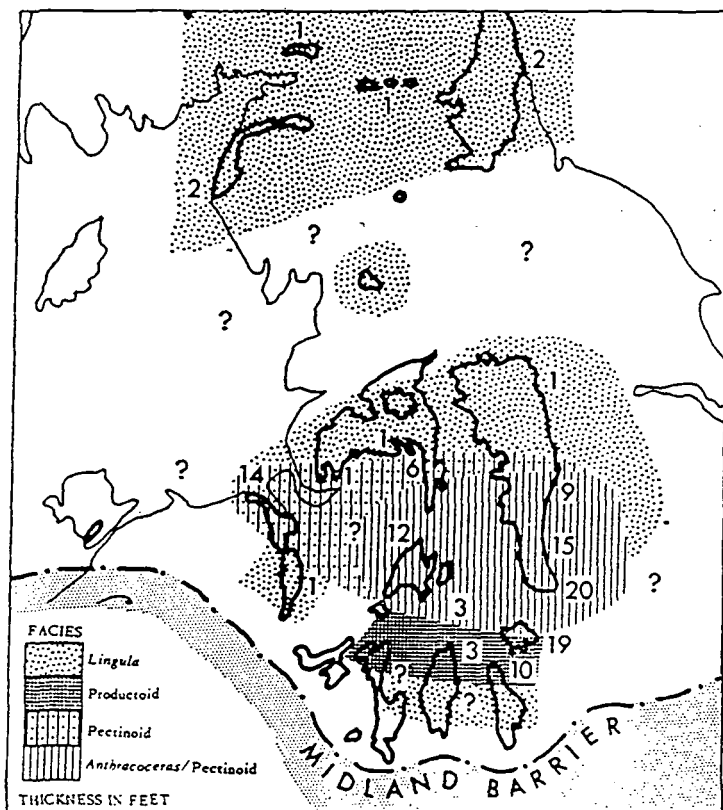


Fig. 3.3 Idealised relationship of facies belts and their typical faunas for Westphalian marine bands. Adapted from Calver (1968a).



	Thickness (to nearest foot)	Foraminifera	Sponge spicules	Paraconularia	Serpuloides	Crinoids	Lingula	Obiculoides	Levypuzosia	'Spirifer'	Heterophonoids	Gastropods (spired/turreted)	Aviculopecten	Dunbarella	F. Anonina	Myalina	Nuculoids	Schirodus	Orthoceras nautiloids	Coiled nautiloids	Anthracoceras	Hollinella	Paraparchites	Lystracambus	Conodonts
Canobie	1						*																		
Midgeholme	1						*																		
Nthumb-Darham	2	*	*				*	?														*		*	
Cumberland	2	*	*				*																		
Ingleton	-						*																		
Lancs.	1	*	*				*							*	?										
N. Staffs.	12	*	*	*			*					*	*	*	*	*	*	*	*	*	*	*	*	*	*
Yorks.	1						*																		
E. Midlands	15	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
S. Derby.	-						*	*	?	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Lolcs.	19	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Warwick.	10	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
S. Staffs.	3	*	*	*	*	*	*	*	*	*	*	*	*	*	?	*	*	*	*	*	*	*	*	*	*
Coalbrookdale	-						*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Deanbigh.	1						*				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
Fliat.	14						*				*	*	*	*	*	*	*	*	*	*	*	*	*	*	*

Fig. 3.4 Faunal phase distribution illustrated by the *Vanderbeckei* marine band. Adapted from Calver (1968a).

3.2.2 Non-marine bivalves

Non-marine bivalves are contained within the faunal advance (transgressive) and retreat (regressive) phases of marine bands, and occur in separate coal seam drowning surfaces throughout the Westphalian B Coal Measures. These distinctive and persistent units can sometimes be traced for significant distances comparable to marine bands e.g. Blackhall *Estheria* Bed (Smith and Francis 1967; Riley 1994). Trueman and Weir (1948) demonstrated that the Westphalian B could be subdivided using these non-marine bivalves (Fig. 2.1). However, these units, like marine macrofauna, have limited stratigraphic use in the offshore due to: The lack of stratigraphic reports containing data upon on specific non-marine bivalve taxa; the difficulties in species recognition with these similar looking long ranging taxa and; the lack of any distinctive wireline expression (Chapter 4) allowing independent verification. These factors contrive to make correlation using this data difficult in many wells. Nevertheless they should be taken advantage of where available as a back up or verification technique. The exceptions are wells such as 44/18-3 and 44/28-2 where extensive sections have been cored throughout the Westphalian B to establish stratigraphy. The drilling of these wells was not planned on reservoir assessment alone as in most in the region, but specifically to increase stratigraphic awareness, and thus there was no bias to sampling reservoir sands only. The complete Westphalian B interval was cored. This is essential for the identification of these fauna as they occur in non-marine shale drowning surfaces (section 5.3.2) to coal seams and interdistributary bay areas (Chapter 4). Consequently thick sections of non reservoir material are required for sampling and zonation. Detailed macropalaeontological analysis, as for example by Riley (1994), in well 44/18-3 is subsequently required to identify the bivalve species and its significance, which can then be compared to the established non-marine bivalve stratigraphy in Durham (Smith and Francis 1967), East Midlands (Smith et al. 1973) and Yorkshire (Eden et al. 1957).

3.3 Marine band recognition

3.3.1 Introduction to geochemical theory

Detailed "wet chemical" research by Knowles (1964) on known stratigraphic sections at outcrop in Yorkshire confirmed that certain marine bands have higher radioactivity than the associated non-marine sediments. Subsequent identification of marine bands in the subsurface using the standard gamma log became a widely practised technique in many United Kingdom onshore boreholes, particularly in the central Pennine Province. The marine band was identified from its abnormally high total gamma response and its presence was used to solve correlation problems (Howitt and Brunstrom 1970; Downing and Howitt 1969; Whittaker et al. 1985).

However, in the offshore realm reliance on the total gamma log alone is insufficient for confident marine band identification, due to the inability of the standard gamma log to rule out other sources of high radiation within Carboniferous sediments, such as feldspar or mica-rich non-marine shales, tuffs, tonsteins, zones of mineralisation and concentrations of feldspar and heavy minerals in sandstones. When this is coupled with the variations in downhole conditions and the distance removed from stratigraphically well known onshore sections, unlike those of the East Midlands boreholes, no confident marine band identification can be achieved. A higher than background total gamma signature due to an abundance of any one of the radioactive elements can lead to miscorrelation of a uranium peak in one well with a potassium peak in another.

3.3.2 Uranium enrichment in marine bands

Knowles' (1964) research supported the ideas of Adams and Weaver (1958) who demonstrated that uranium and thorium concentrations are good indicators of environment of deposition (Fig. 3.5). They noted that marine black shales contain higher levels of uranium than continental shales and attributed this to the fact that in an oxidising environment uranium forms highly soluble uranyl ions, whereas thorium is effectively insoluble in water and thus behaves purely as a detrital mineral. Consequently, in a terrestrial environment uranium is more readily leached from the sediment than thorium. In an anoxic restricted marine environment, uranium is actively

removed from solution, a solution in which uranium is believed to be 5000 times more concentrated than thorium (i.e. 0.0002 thorium : uranium of Adams and Weaver 1958). Thus, sediments deposited in anoxic marine environments would concentrate more uranium than their continental counterparts. The processes that bring this about are thought to be complex with a large amount of the uranium concentrated possibly in phosphatic, carbonaceous or bituminous factions (Ponsford 1955; Knowles 1964; Spears 1964). Organic matter appears to play an active role in extracting uranium from the solution in anoxic environments (Kochenov et al. 1977) and can be fixed in sediment by oxidating and reducing reactions following "sorption" of uranium ions by humic acids (Borovec et al. 1979). They are produced by the decay of organic matter and lead to the adsorption on to the surface of plant fragments, the substitution of ions in clay and phosphate minerals and the precipitation in the presence of hydrogen sulphide (H₂S).

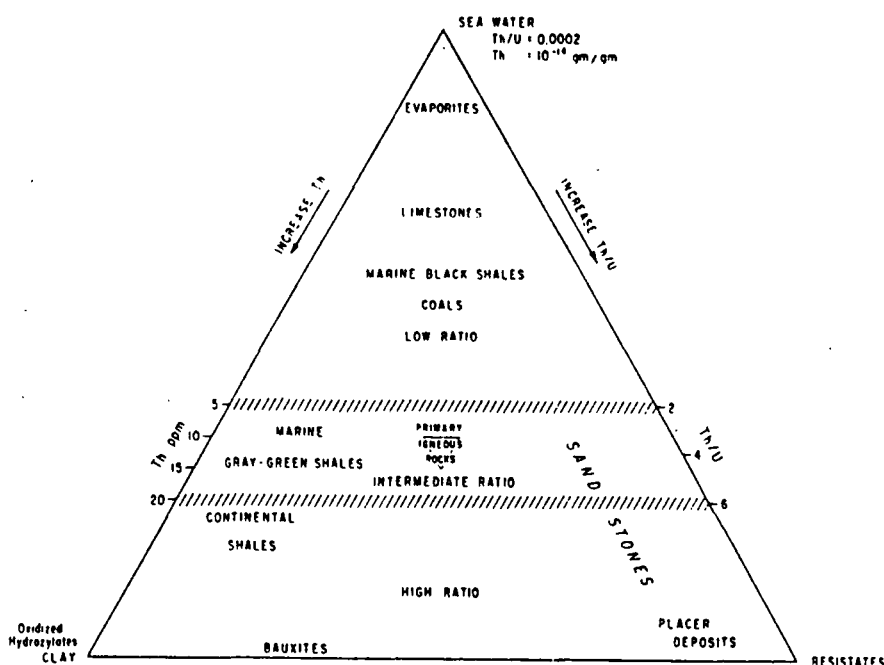


Fig. 3.5 Distribution of thorium and uranium in sediments. After Adams and Weaver (1958).

3.3.3 Development of Wireline log response recognition

The research work summarised above concerned marine sediments and their associated uranium concentrations and was chemically based. Archard and Trice (1990), however, investigated the Westphalian/Namurian boundary marine band, *Gastrioceras subcrenatum*, and the Namurian marine bands, *Gastrioceras cumbriense* and *G. cancellatum*, from type sections in Yorkshire and demonstrated that the uranium anomaly could be detected using standard wireline techniques (Fig. 3.6) by using a hand held spectrometer tool. These results were supported by Leeder et al. (1990) who also worked largely on the Namurian section and reached similar conclusions on outcrop sections. However, Leeder et al. (1990) utilised the development of downhole natural gamma spectrometry (NGS) logs capable of distinguishing the gamma ray contributions of radioactive potassium, uranium and thorium for a subsurface Namurian to Westphalian A section in well 48/3-3 in the Southern North Sea, to isolate zones of high uranium within the wellbore thereby highlighting possible marine bands. Leeder et al. (1990) note that caution must be exercised in extending such correlations into areas remote from cored boreholes or outcrops where biostratigraphic control is lacking. For example Whittaker et al. (1985) state that the *Gastrioceras listeri* marine band in the East Midlands and Central Pennines is usually highly radioactive, but in other areas and even in many recently drilled wells within the area, the horizon may not be distinguished on gamma ray logs. This causes problems in extending correlations to an area as remote as the Southern North Sea from the onshore, especially as well spacing is relatively poor.

Other points of discussion from Leeder et al. (1990) are that significant authigenic uranium content usually occurs only where black, fissile, pyritous, shaley mudrocks are developed. These contain climax fauna of the marine band and are dominated by pelagic groups such as goniatites and pectinoid bivalves. They are noted by an absent benthos (Calver 1968a) and are presumed to occur due to the development of de-oxygenated conditions. Leeder et al. (1990) add that increased levels of radioactivity due to the concentrations of authigenic uranium may be related to a slow rate of sedimentation under anoxic bottom waters and the fixation of uranium by organic tissues (reviewed by Bell 1978). Thus there is a strong positive correlation between uranium and the presence of phosphatic and carbonaceous materials (Knowles 1964). In the light of the faunal evidence cited, and recent advances in the understanding of the genesis of black shales in other parts of the geological record (Myers and Wignall 1988), it was considered likely by Leeder et al. (1990) that the greatly enhanced

uranium contents are mostly authigenic and that they are directly related to the deposition of slowly sedimented organic rich anoxic marine mudrocks. They state that it follows that the development of such uraniferous black shales will be related to local or to regional bathymetric conditions during Silesian marine transgressions and that the absence of anoxic bottom waters will lead to "normal" (oxygenated) marine mudrocks with a benthonic faunal development without uranium enrichment. No gamma log anomaly is thus expected from such marine horizons and hence the authors predict that uranium content of marine shales will vary widely.

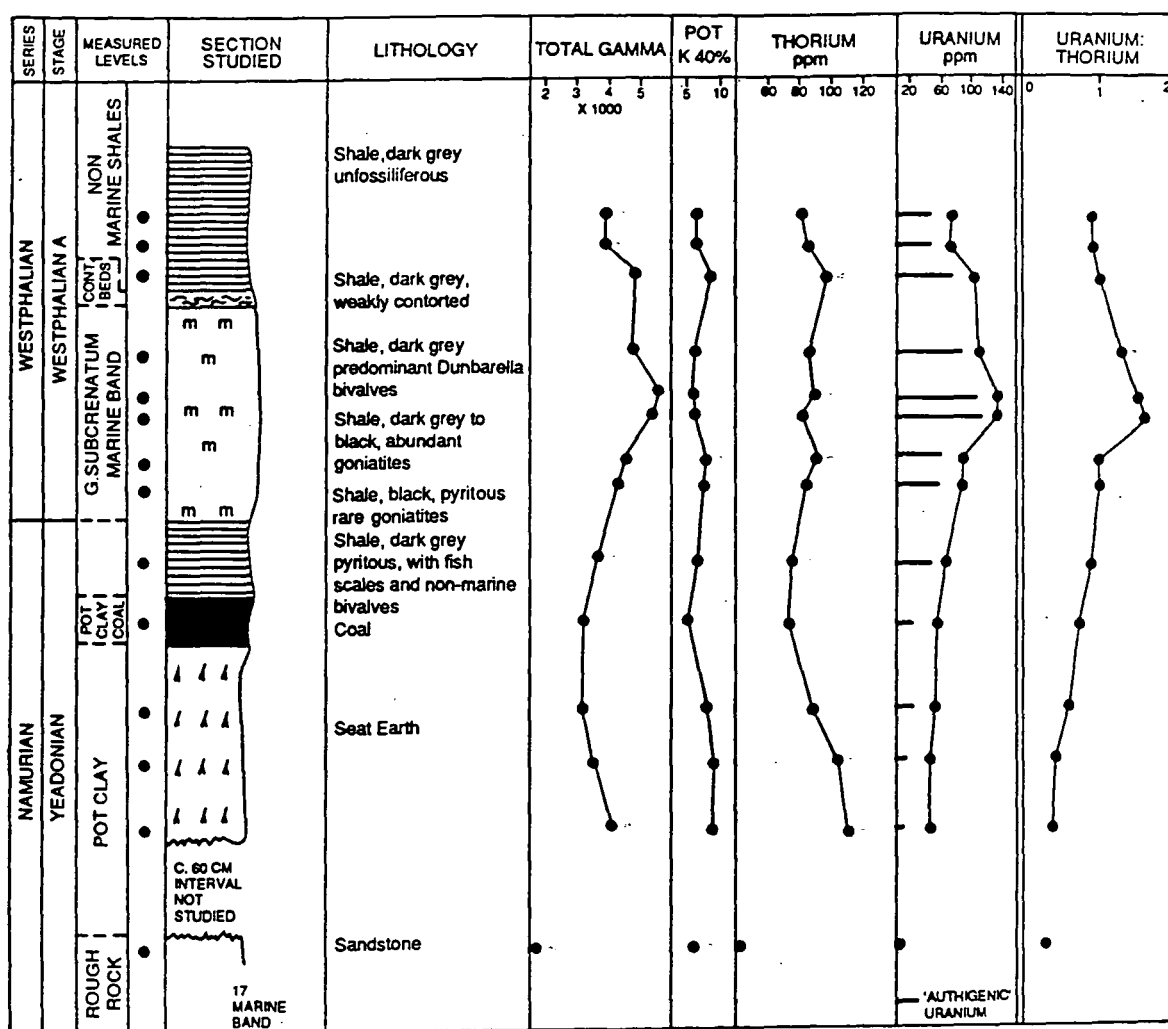


Fig. 3.6 Spectral gamma radiation over the *G. subcrenatum* marine band measured in the field by a hand held spectrometer. After Archard and Trice (1990).

The regional development of goniatite-bearing black shale facies in the most widespread onshore Silesian marine bands has been shown by Calver (1968a) to be closely related to regional patterns of subsidence, as derived from isopachs of strata between marine bands (Fig. 3.7). The isopachs describe a "bull's eye" pattern centred around the major depocentres in Lancashire and Yorkshire, and a similar situation is believed to have occurred in the Southern North Sea where a major depocentre occurs in block 44/26 and to the south. This important correlation clearly establishes that anoxism could only develop after the acme of the marine transgression in an area where Silesian subsidence was at a maximum. The failure of anoxic conditions to develop may be due to local or to regional slow subsidence, probably reflecting proximity to areas of high sediment influx and thus to contemporary palaeogeography. This latter point will include the important unknown controlling parameter, the slope of the coastal plain. Upslope areas with progressive water shallowing will inhibit the development of anoxia during marine transgressions, even when subsidence is still high (Leeder 1988).

It must be noted that these workers were largely looking at Namurian marine bands, which differ from their Westphalian counterparts in that they were fully developed marine bands in a lower delta plain setting. They had prominent pelagic phases that developed high organic contents and hence uranium enrichments, far in excess of the background. Since they formed in deep water where true anoxic conditions developed. The topography across this Namurian delta plain was probably more marked than that in Westphalian times when the coastal alluvial plain had a low relief due to slower more consistent subsidence (Leeder 1988) hence the Namurian palaeobathymetric variations were more noticeable and uranium concentrations may have been more variable.

It has become evident from this study that Westphalian B and C marine bands quite clearly have high uranium signatures (Section 3.5) based on an analysis of the natural gamma spectrometry (NGS) logs in Quadrant 44 wells and the relative stratigraphic position determined by palynology (Maltby marine band). A notable exception is the *Vanderbeckeri* marine band which is most often identified from marine fauna because of its proximity to the major Caister Sandstone (Chapter 4) (also seen in the Pennine Basin, Maynard and Church pers. com.). However, if we followed the arguments presented above then Westphalian B marine bands should not be significantly enriched in uranium as they do not contain abundant, thick, black, pyritous shales with extensive

pelagic fauna as required by Leeder et al. (1990) for significant enrichment. Regional palaeogeographic reconstructions of the Westphalian B describe a low relief coastal alluvial plain, where transgressive marine bands would have a decreased relative water depth compared with Namurian marine bands, as reflected in the predominance of benthonic faunal phases within marine bands, and the rare development of goniatitic black shales. Marine bands in the Westphalian B are commonly indicated by acmes in productoid, pectenoid and *Myalina* phases (Fig. 3.3) with rare *Linguloid* phases (Calver 1968a). Consequently the area is more proximal (as indicated by shallower water faunal phases) to sediment influx and spent less time at maximum water depth and possible anoxia. Intuitively then one might expect the uranium ppm to decrease (cf. Leeder et al. 1990), whereas in fact the opposite appears to be the case. This suggests the possibility of either very significant changes in eustatic water level to produce anoxic black shales of a Namurian type, forming under conditions of high water depths, high levels of anoxia, slow rates of sedimentation and abundant marine organic matter. This should produce short lived but highly uraniferous horizons, a situation refuted by the palaeontological evidence, (Fig. 3.3). Alternatively there may have been other controls on Westphalian B marine band uranium enrichment, as discussed below.

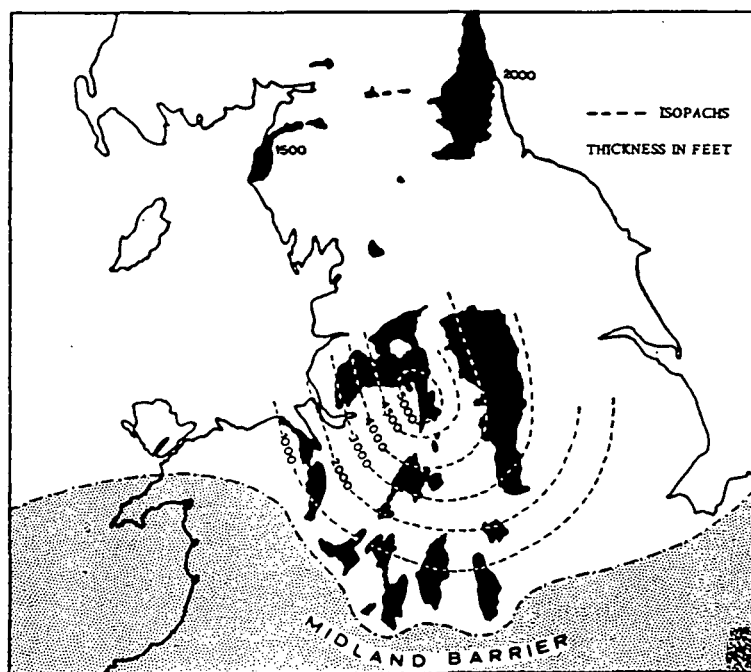


Fig. 3.7 Generalised isopachs of the combined lower and middle Coal Measures of the southern part of the Pennine Basin, illustrating the "bull's eye" pattern. After Calver (1968a).

3.3.4 Controls on uranium enrichment

De Voto (1978) suggests that favourable conditions for uranium enrichment in sediments are:

- 1) marine or lacustrine slow rates of sedimentation
- 2) abundant preserved land plant debris
- 3) strongly reducing environments
- 4) paucity of terrigenous, non-organic sediment
- 5) availability of phosphate

Quite clearly the Namurian marine bands satisfy many of the above criteria, especially the slow rates of sedimentation, strongly reducing environments and paucity of terrigenous input, where uranium is fixed by algae that thrive in this environment. However, despite the Westphalian B and C marine bands being different in character, in that they are more marginal, as reflected in their faunal phases (Calver 1968a). They have highly enriched uranium responses and therefore must satisfy different criteria or the same criteria in different ways, than their Namurian equivalents. Figure 3.8 illustrates how uranium may be fixed within sediment. The Westphalian marine bands when compared with their Namurian counterparts would, because of their more marginal setting, have a higher proportion of source area material, but included in this terrigenous input would be a significant amount of land plant debris derived from the low lying well vegetated humic coastal alluvial plain. The concentration initially increases offshore to an optimum distance where plant derived detritus is at a maximum before gradually decreasing offshore (Fig. 3.9). Plant debris of this nature in humid climatic conditions at low latitudes such as the Westphalian would provide abundant sites for uranium adsorption and thus the uranium concentration should mirror that of the abundance of land plant debris. The terrigenous portion of this land derived sediment would be at a minimum as erosion would be shifted landward by the relative base level high designated by the marine band. The relatively elevated nature of the coastal alluvial plain compared to the Namurian delta system suggests that the transgression would be approaching its landward limit, though the waters would be sufficiently saline from its marine provenance to contain a higher uranium concentration (cf. Section 3.3.1) than the surrounding lacustrine environments. The marginal marine setting allows the presence of abundant *Lingula* which Swanson, (1960) suggests preferentially concentrates uranium within its phosphatic test (Fig. 3.8).

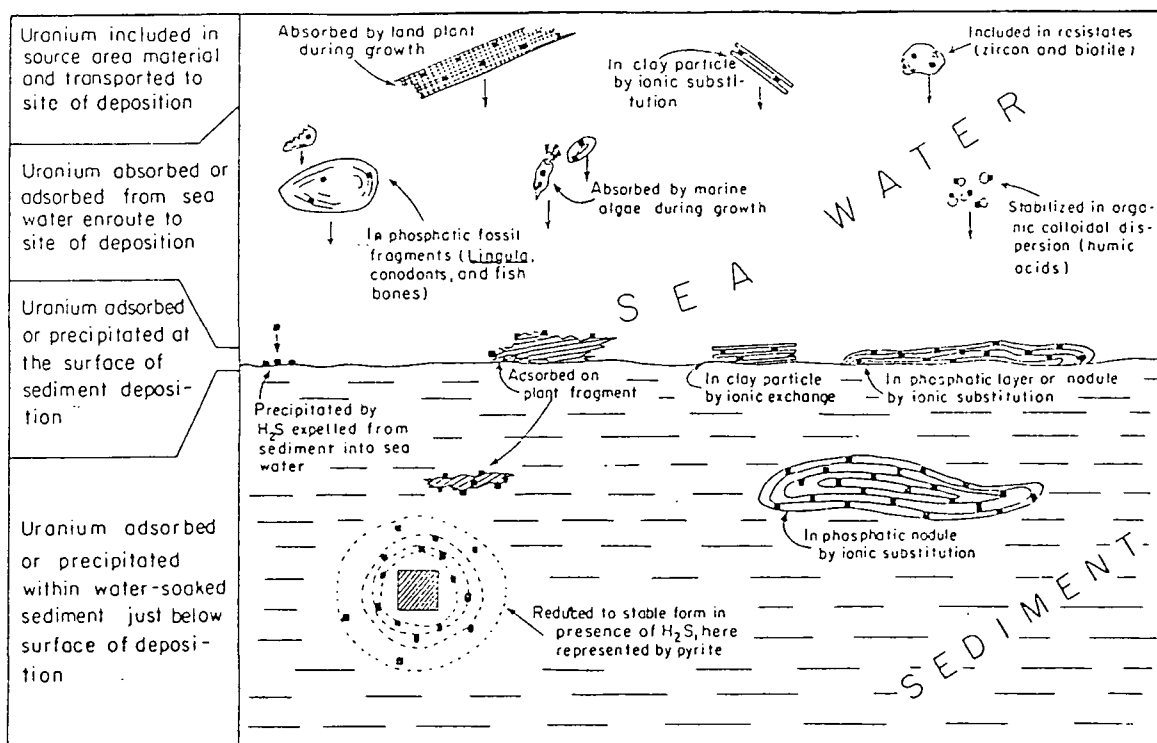


Fig. 3.8 Sites for Uranium fixing within black shales. After Swanson (1960).

In conclusion there does not appear to be a simple direct correlation between water depth and uranium concentration (Fig. 3.9) as Leeder et al. (1990) and Archard and Trice (1990) postulated. I believe the relationship is more complicated and may result in rapid lateral variations in the uranium response of marine bands over their geographic extent due to the interaction of several interrelated factors. This allows for a possible four fold division of marine bands.

- 1) Namurian marine bands are marine anoxic black shale events, with thick goniatitic acme phases, that concentrate uranium as outlined by Leeder et al. (1990) and summarised in section 3.3.3.
- 2) *Vanderbeckei* type marine bands have poorly developed anoxia, thin goniatitic acme phases and abundant benthos, resulting from shallower water depth (cf. Namurian

marine bands) and consequently negligible uranium enrichment. They contain a low proportion of humic material from land derived organics (cf. Westphalian B/C marine bands) as the distance to contemporary shoreline was greater (Fig. 3.9).

- 3) Westphalian B/C marine bands are more marginal, but have an abundance of land plant derived fragments with absorbed uranium, as well as uranium entrapped within the phosphatic tests of *Lingula* which are more abundant in these types of marine bands and consequently have high levels of uranium enrichment.
- 4) Brackish water *Lingula* beds with high proportions of terrigenous input, and negligible uranium response.

The variety of marine bands types described above supplements the ideas of previous workers and attempts to explain the differing uranium responses for different types of marine band and within the same marine band encountered within Westphalian B sediments as described in section 3.5.1. Most probably there is a transition from offshore Namurian type, through *Vanderbeckei* type to marginal type (Westphalian B/C) marine bands due to an interrelationship between anoxia, organic land-derived detritus, sediment supply and marginality (water depth and faunal content), leading to the perceived variation of uranium concentrations even within individual marine bands, as noted in the *Listeri* marine band by Leeder et al. (1990). All share, and are aided in their uranium concentration, by the intracratonic relatively shallow nature of the basin with restricted access and subsequent restricted circulation leading to the prevalence of reducing conditions.

Confusing this situation further are the high background levels of uranium in Westphalian environments due to the abundance of land plant debris which adsorbs uranium and the reducing conditions due to the high water table, favouring the formation of siderite. Lacustrine environments are common throughout Westphalian B facies associations and appear to be sites of uranium enrichment. Conceivably they may be anoxic (stratified) with poor current mixing leading to highly reducing bottom waters, combined with land plant debris, and they may have uranium levels approaching those of some marine bands. However, their waters were initially less enriched in uranium, and the terrigenous input is high. Thus marine bands particularly enriched in uranium can still be distinguished. Difficulties arise with marine bands of the *Vanderbeckei* type which are not significantly enriched above the non marine lacustrine background and in view of the abundance of such environments within the Westphalian B succession, extreme care is required.

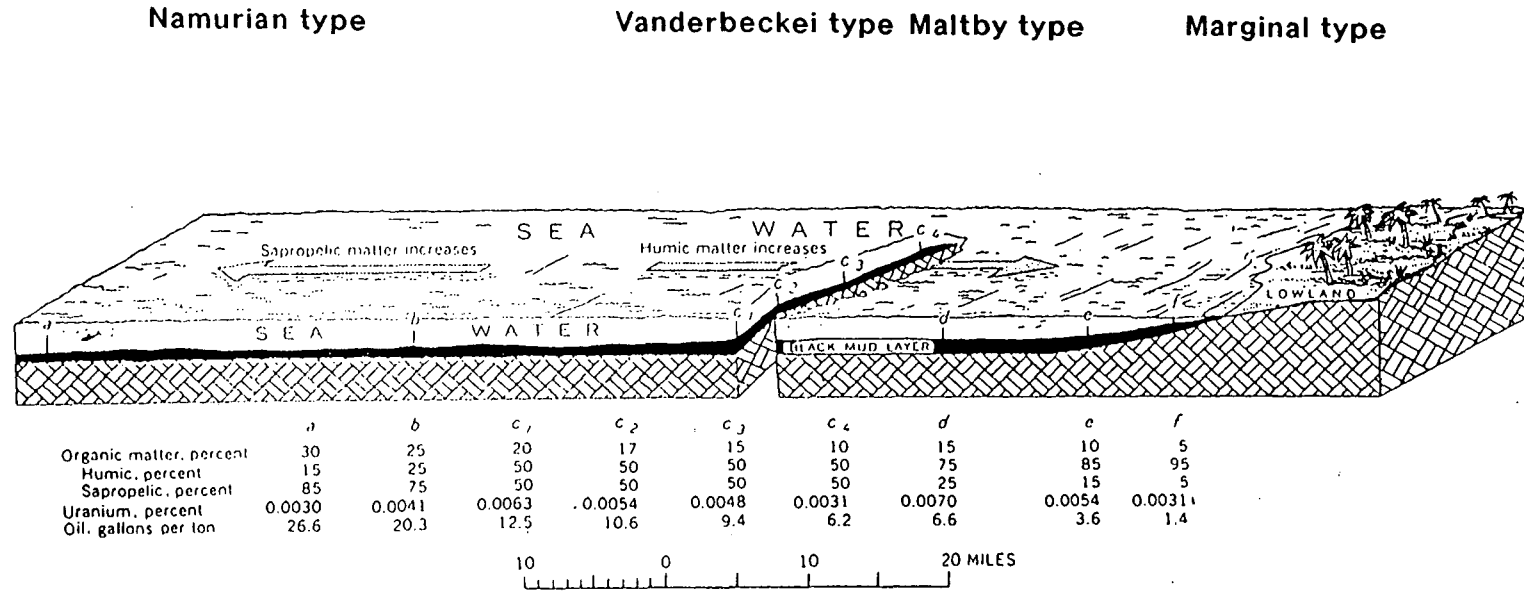


Fig. 3.9 Distribution of humic and sapropelic materials in a shallow sea in which black muds are accumulating, and estimated uranium concentration. After Swanson (1960).

3.4 Methodology of marine band identification in the subsurface

3.4.1. Introduction

Marine band identification is essentially a qualitative exercise and as discussed in section 3.3 the most important element for marine band recognition is uranium. In many subsurface well sections the uranium and thorium levels can be measured directly using the Natural Gamma Spectrometry Log (NGS of Schlumberger, Spectralog of Western Atlas Wireline). Modern tools have the ability to measure the spectrum ranging from 0-3 MeV which takes into account both high and low radiations. A recent research exercise by the Dutch Geological Survey on a late Carboniferous well section in the Joppe 1 borehole displayed high uranium and U:Th values at exactly the same interval as the Houghton marine band which was confirmed by marine fossils. (Fig. 3.10).

High uranium levels are not exclusively restricted to marine bands. Other possible causes of high uranium concentrations in Westphalian sediments are:

- 1) detrital heavy minerals such as zircon and magnetite (containing uranium) in sandstones;
- 2) tonsteins;
- 3) tuffaceous material and;
- 4) zones of mineralisation.

All of the above may exhibit higher uranium values than general background. To eliminate these potential causes of high uranium it is important to accurately establish lithology, as marine bands almost exclusively occur in shales, as drowning surfaces to coal seams. The application of depth matched gamma, lithodensity, sonic and any cuttings information usually proves satisfactory in eliminating these non shale anomalies. Once lithology has been determined, comparison with the spectral gamma log allows uranium peaks to be highlighted. Leeder (1970) suggests a threshold for significant enrichment of 6ppm, although this is borehole dependant (section 3.4.2). The next step is to calculate thorium uranium ratios (Th:U) and according to Adams and Weaver (1958) values of less than 2 are diagnostic of marine depositional environments. Hollywood and Whorlow (1993) propose a slightly higher cut off of 3 (Fig. 3.11) to account for variations in log quality and what they call variations in the

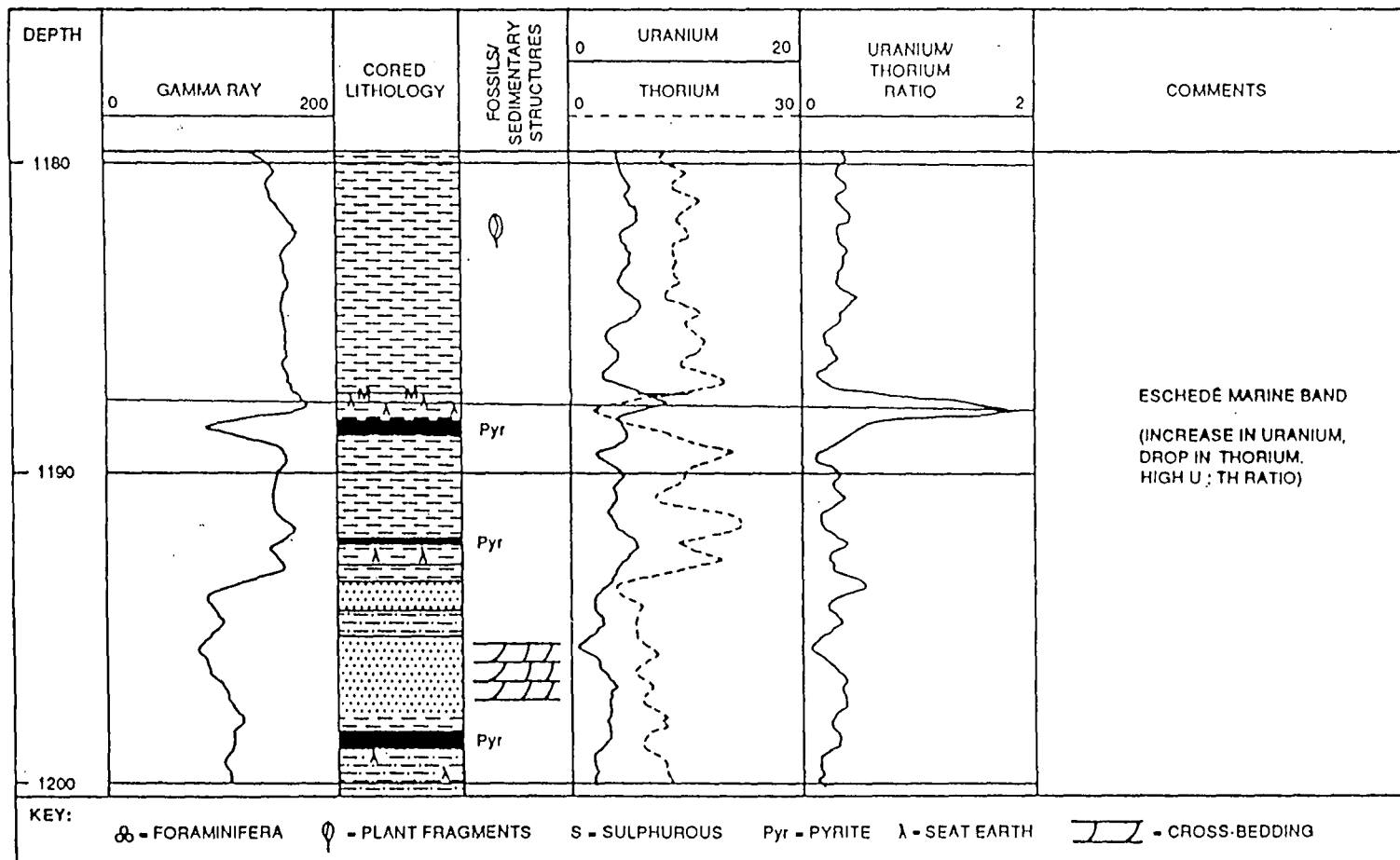


Fig. 3.10 Spectral gamma response in a section containing Eschede (Haughton) Marine Band, from Joppe 1 borehole, onshore Netherlands. After ECL (1989).

extent to which fully marine conditions are established in different areas (section 3.3.4). Most importantly, appreciation of the individual borehole conditions is required.

3.4.2 The effects of borehole conditions on uranium concentration

Excessive rugosity or hole roughness can cause severe interpretational problems and it is essential to evaluate hole conditions by reference to the caliper log. Wells 44/22-6z and 44/21-3 illustrate the problem where gamma peaks occur as the tool sticks during connections if wireline is run on drill pipe. Oil based mud systems tend to yield good uranium capture. Running speed of the tool can also significantly affect the uranium concentrations recorded, and increased tool recovery rates above recommended speeds severely reduces uranium levels, so that anomalies do not appear significantly higher than background levels.

The borehole variations mentioned above preclude the use of any absolute values. When picking marine bands from spectral gamma ray data, a background non marine shale uranium and thorium:uranium level can be established, although this may not be constant throughout the wellbore. Frequently the high uranium values experienced with marine bands are accompanied by either a constant thorium, or a drop in the thorium levels, both produce a pronounced "kick" in the Th:U ratio. Positive uranium anomalies accompanied by collective positive thorium and potassium are more likely to represent tool sticking events (check cable tension) though uranium peaks with just thorium peaks may still be caused by marine bands if the thorium peak is relatively insignificant. Distinct corresponding uranium and thorium peaks are most probably tonsteins (section 3.4.3).

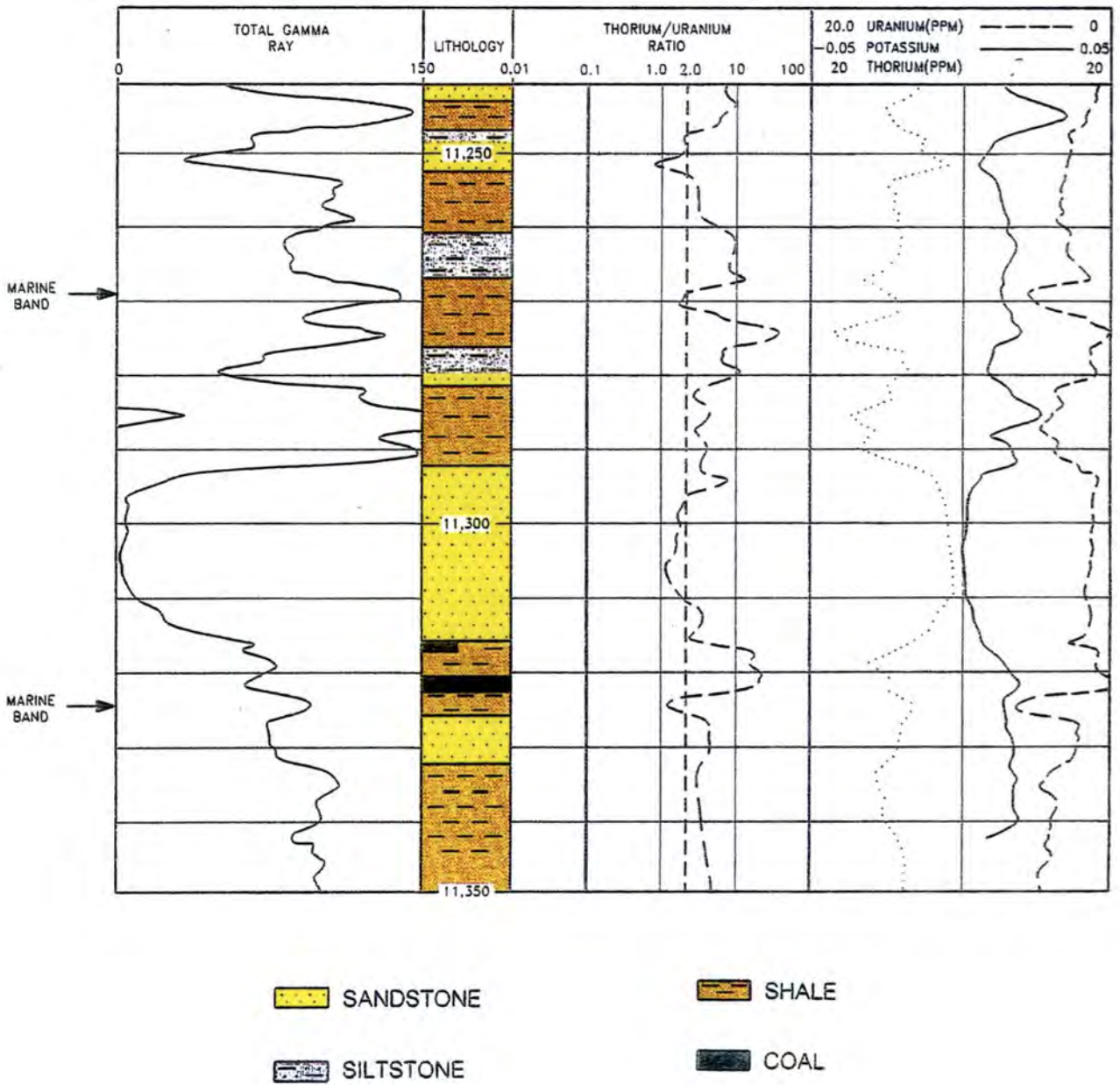


Fig. 3.11 Marine band identification from spectral gamma ray logs. After Hollywood and Whorlow (1993).

The processes outlined above aim to isolate uranium peaks that correspond to marine bands with high uranium levels and low thorium uranium ratios. With Quadrant 44 wellbores this requires elimination of much of the scatter experienced on the standard thorium uranium ratio log, where uranium readings at potential marine horizons need enhancing and anomalous thorium uranium ratio values that can occur in some channel lags in sandstones and in some coal seams need elimination. Sonic log identification of coals and accurate depth matching of the gamma log helps eliminate this, which is particularly important as marine bands frequently overlie coal seams, so any mismatching will result in the event not being identified. In rare cases where coals have either an anomalously high uranium level or a marked reduction in thorium so that the thorium uranium ratio appears low, careful appreciation of the sonic is required especially as marine black shales often show a broad low sonic peak. Channel sandstones are usually identified using the total gamma log (Chapter 4) which can distinguish the channel relatively easily based on generally consistent low gamma response. Distinct gamma peaks that then occur within the designated channel are then attributed to channel lags. This has been checked by calibration of wireline response using cored sections of channels compared to the total gamma log (Chapter 4).

3.4.3 The Sub-Clowne tonstein

Most tonsteins as discussed in section 3.4.1 have high uranium levels which may be far in excess of background levels. This usually corresponds to a distinct thorium peak which allows them to be distinguished from marine bands. However, these laterally extensive, kaolinitic-rich clays are commonly no thicker than 20mm and it is unlikely that with standard running speeds the spectral gamma log could resolve these beds. However, there are 2 tonsteins within the Westphalian B to lower Westphalian C succession (Fig. 3.12), one of which-the Sub-Clowne tonstein-has been described by Rippon and Spears (1989) as having considerable thickness. It is associated with the Clowne marine band in the late Westphalian B and (Fig. 3.13) it displays a very high total gamma reading comparable to marine bands (+150 API) and greatly in excess of background which is composed of both uranium and thorium (cf. marine bands). Due to its extensive geographic distribution it may be used as an additional correlateable horizon. It has a particularly distinctive gamma response that can be used as a "time line" independent of palynology, making this horizon (where identifiable) of great importance.

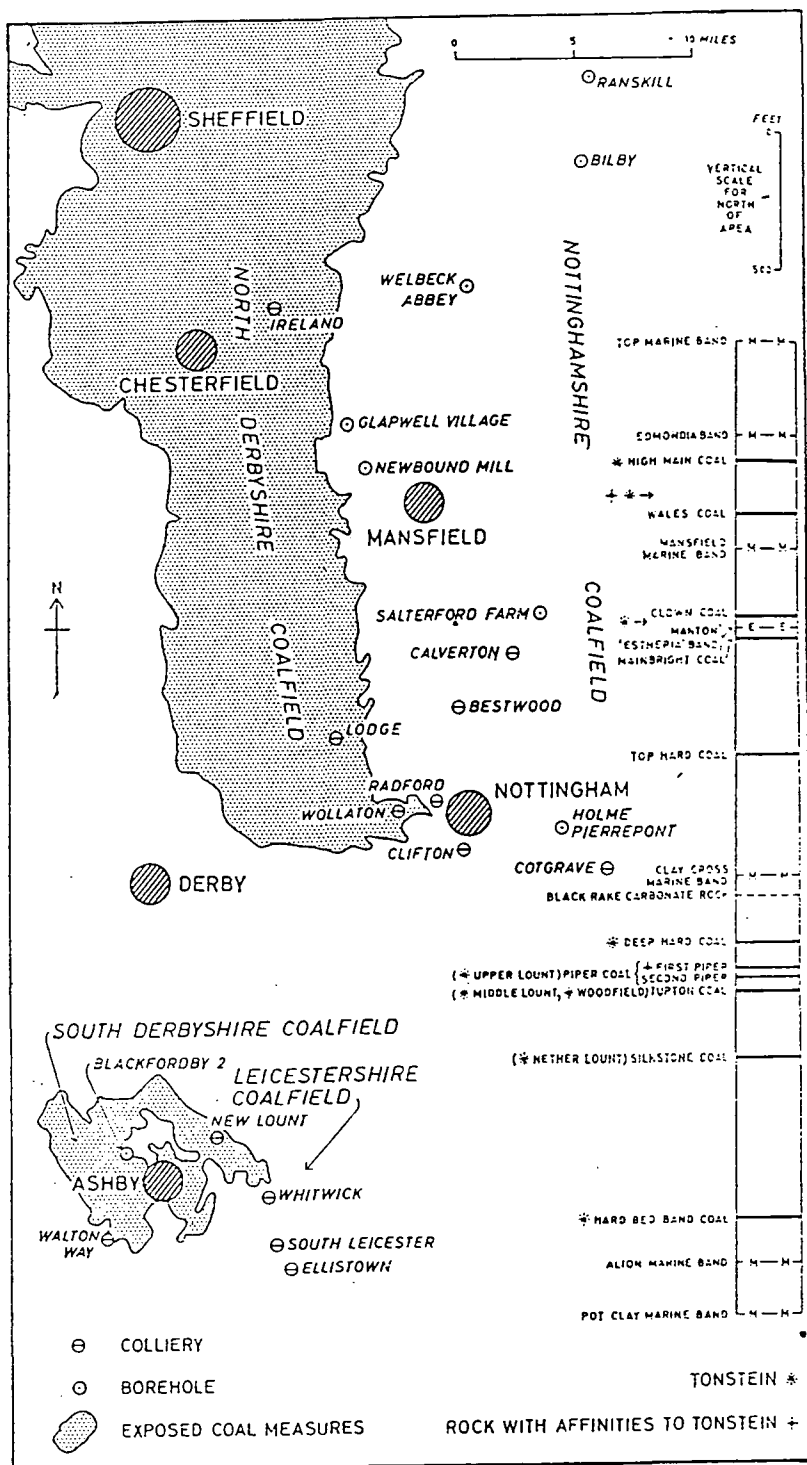


Fig. 3.12 Tonstein bands in the United Kingdom. After Eden et al. (1963). The spelling of "Clown" on this diagram differs from the accepted spelling of "Clowne", Rippon and Spears (1989).

The Sub-Clowne tonstein which is interpreted as a volcanic ash fall with acid igneous affinities (Spears and Kanaris-Sotiriou 1979), occurs within a palaeosol below the Clowne coal seam (Fig. 3.12 and 3.13) which is in turn overlain by the Clowne marine band. It is brown (of all shades), grey and green, and consists of a thin (<5 cm) "tough" mudstone within varied palaeosol lithologies including carbonate and ankerite. It corresponds to a gamma peak on the logs that may affect up to 4 or 5 m of section superimposed on various lithologies and seatearths, although never extending through the Clowne seam. It has been described by various workers throughout the Nottinghamshire, Derbyshire and Yorkshire Coalfield (Eden et al. 1963).

The tonstein of altered acid volcanic ash cannot be attributed to either a local or indeed a United Kingdom source. The original ash composition, however, is thought to be comparable with a tonstein in the French and German coalfields (Fig. 3.14) and a common source is envisaged (Spears and Kanaris-Sotiriou 1979). Based on lateral variations in thickness Bowoz (1967) proposed that French and German tonsteins were sourced from an area such as the Black Forest or the Vosges. The tonsteins in the UK are thought to be more distal equivalents of these European counterparts, an interpretation consistent with the reduced thickness and fewer records. In the Southern North Sea the sediments are nearer source and possibly thicker and more readily identifiable. The tonstein is a useful stratigraphic marker due to its gamma ray profile which Spears (1989) describes as the most prominent peak in the Westphalian (with the exception of the *G. listeri* marine band). He states that where the tonstein is recorded in core in geophysically logged boreholes, there is always a gamma anomaly present. The extension of the anomaly through up to 5 m of sediment is attributed by Spears (1989) to ash reworking and dispersal. Thickness variations of the tonstein and hence the anomaly may be due to differential compaction of the mudstone and also the rates of sedimentation and current activity variation across the district.

The gamma ray profile is particularly distinctive as the uranium and thorium peaks occur in the seatearth beneath a distinct gamma low that represents the Clowne seam, corresponding with a sonic peak. Subsequently enhanced radioactivity above the coal is attributed to the Clowne marine band (Rippon 1984) and not the Sub-Clowne tonstein, as reflected in the enrichment of uranium and not thorium. Thus, the gamma profile includes a peak corresponding to the Sub-Clowne tonstein, a low gamma high sonic equating to the coal seam, with a high gamma drowning surface above representing the Clowne marine band. This double gamma peak / coal is particularly distinctive and easily recognisable as a unique time line within the upper Westphalian B

succession. It compares to marine bands which usually occur as drowning surfaces to coal seam (i.e above coals) and are usually composed of uranium peaks only, associated with a broad sonic low.

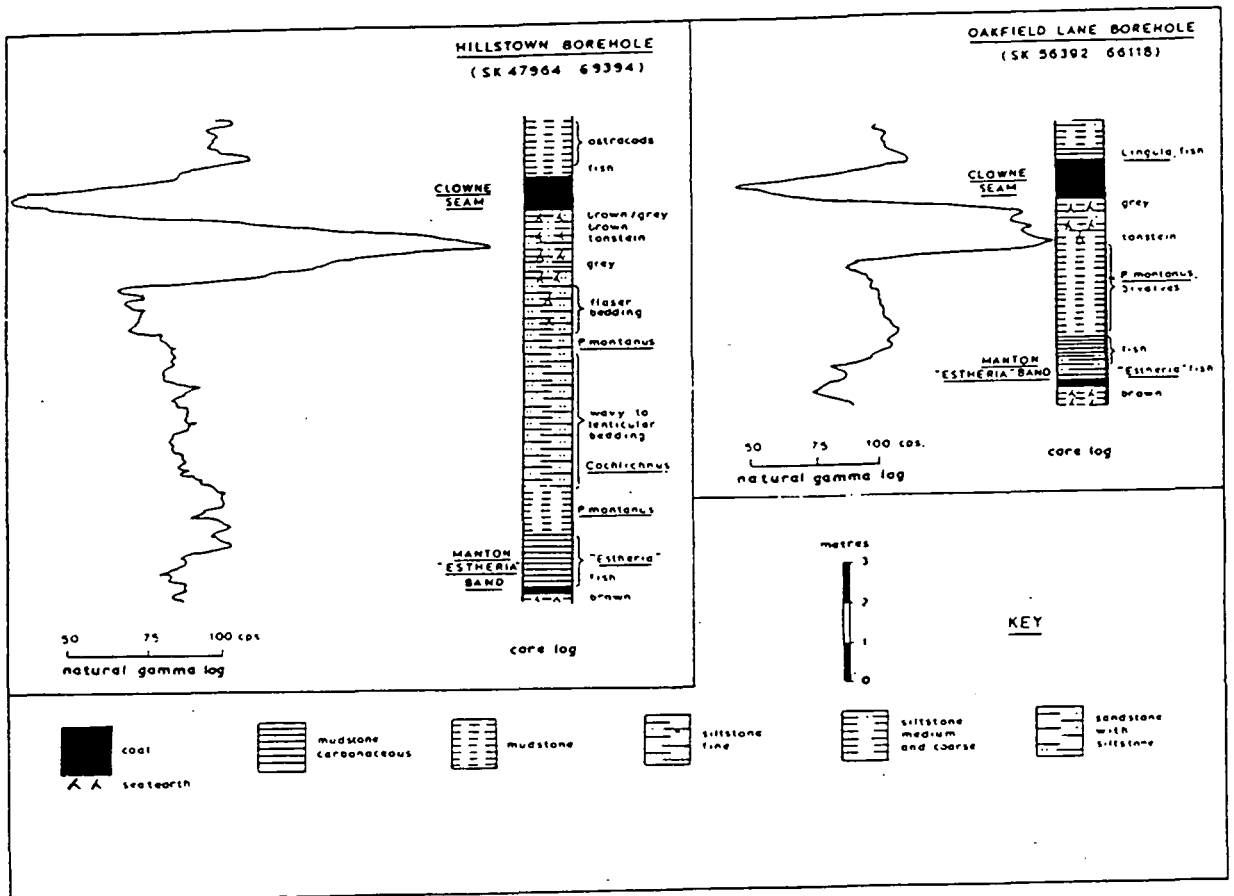


Fig. 3.13 The characteristics of the Sub-Clowne cycle and gamma ray response. After Rippon and Spears (1989).

A further tonstein is recorded in the literature. It occurs beneath the High Main seam of the East Midlands, between the *Edmondia* and *Aegiranum* marine bands (Fig. 3.12) and it is considered to be much thinner (up to 1cm thick) than the Sub-Clowne tonstein. Also it does not have the documented high gamma response as with the Sub-Clowne. Although modern wireline tools may not be capable of resolving this unit, which can be equated to those in France and Germany, it may be thicker in the more proximal Southern North Sea, and as such identifiable from logs. Admittedly its response may not be as distinctive as the Sub-Clowne as it is not known to be closely

associated with a coal or marine band (cf. Sub-Clowne tonstein) but its high thorium as well as uranium may be distinctive.

In the upper Westphalian A Eden et al. (1963) (Fig. 3.12) describe several tonsteins which may be the gamma signature that ECL (1989) describe as their marine band WA3, which has no onshore equivalent. It may in fact be a tonstein, but it lies well below the *Vanderbeckei* marine band and is not important for this study.

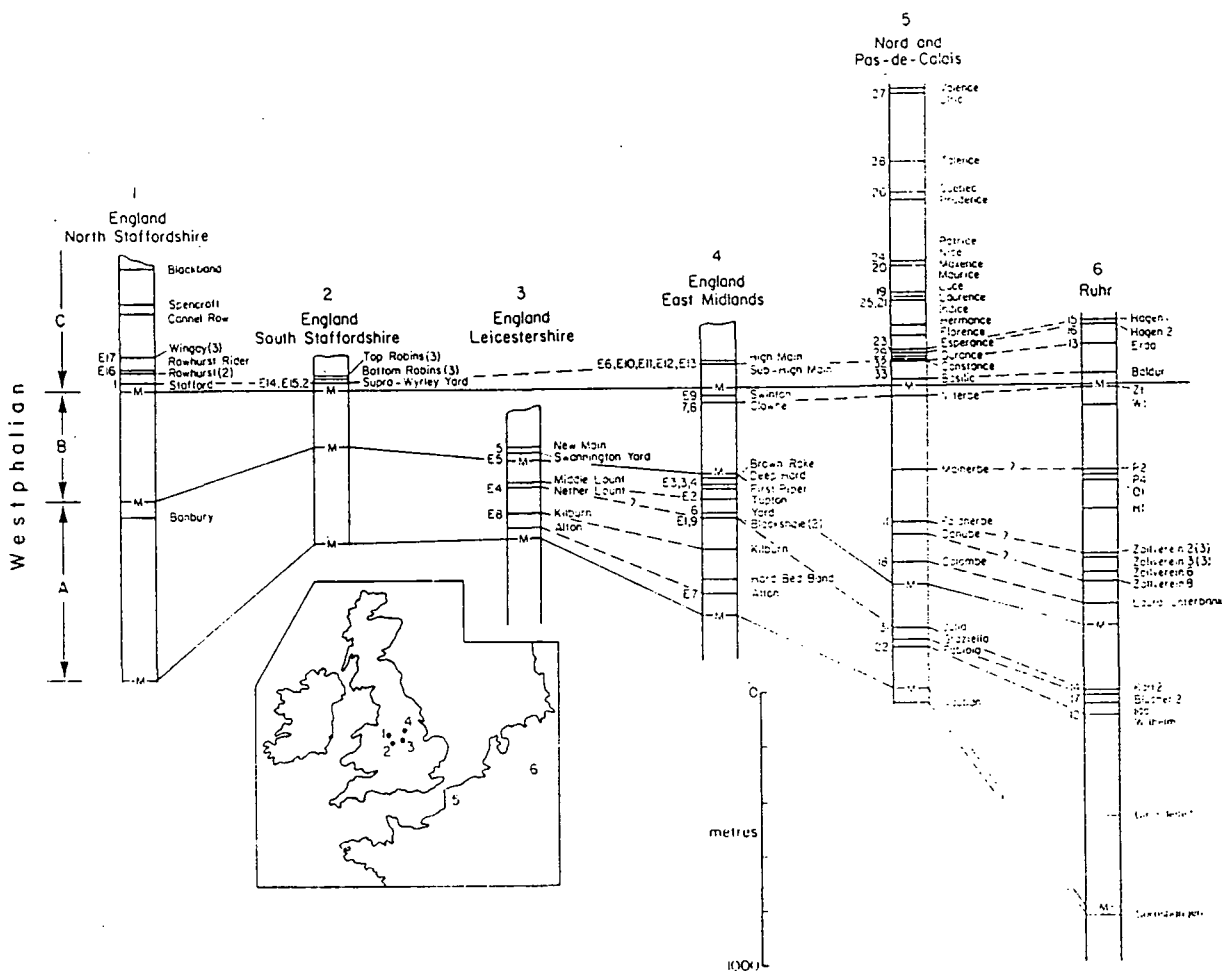


Fig. 3.14 Stratigraphic distribution of tonsteins from Britain and Europe. From Spears and Kanaris-Sotiriou (1979).

3.5 Incorporating marine bands into the palynostratigraphy

In order to effectively utilise marine bands to resolve subsurface stratigraphic problems, the identified marine bands need to be incorporated within the biostratigraphic framework (discussed in Chapter 2) based on palynological assemblages. The assemblages described from data obtained from offshore wells are compared to those established for the onshore (Chapter 2) thereby allowing comparison with the non-marine bivalve zonation of Trueman and Weir (1946) and the major chronostratigraphic marine bands (Ramsbottom 1978).

The stage-defining *Aegiranum* and *Vanderbeckei* marine bands may be picked out effectively by distinct faunal changeovers that occur across the marine band. The position of the *Vanderbeckei* marine band, for instance, can be accurately determined by faunal inceptions (last down hole occurrence) of zonally diagnostic taxa above and corresponding to extinctions (first down hole occurrences) or even slightly overlapping ranges (Fig. 3.15). Unfortunately the *Vanderbeckei* marine band is widely known (Maynard and Church pers. comm.) from the Pennine Basin not to have a significant uranium signature, so reliance on palynology and other parameters (Chapter 4) is necessary, as illustrated in well 44/18-3 where the *Vanderbeckei* marine band is identified by crinoid ossicles, but does not correspond to a distinct gamma (uranium) peak. The *Aegiranum* marine band despite the poor faunal recovery in Westphalian C sediments, can usually be identified by the last down hole occurrence of the common Westphalian C taxa *Vestispora fenestrata* and the first down hole occurrence of several Westphalian B taxa including *Savitrisorites nux*. Within the interval between these two tie points is a gamma peak composed predominantly of uranium (well 44/28-2) which can confidently be attributed to the *Aegiranum* marine band. Providing sufficient quality data is available the middle Westphalian B Maltby marine band and the lower Westphalian C *Cambriense* marine band can both be defined by this method.

Problems arise where several marine bands occur within one palynological zone as is the case with the upper Westphalian B, where 3 marine bands occur within the *Vestispora magna* sub-miozone between the Maltby and *Aegiranum* marker marine bands. In this case the Sub-Clowne tonstein / marine band is particularly useful as it provides a distinctive double gamma ray peak that is easily distinguished. The unique

nature of this double peak signature clearly identifies it as the Sub-Clowne tonstein / marine band thus providing an independently established "time line". This allows the position of the Sutton and Haughton marine bands to be inferred from peaks on the uranium concentration curve determined from the spectral gamma ray logs between the Sub-Clowne tonstein and the *Aegiranum* marine band. Comparison of the geographic development and extent to which each marine band develops marine conditions (Calver 1968a) will indicate the magnitude of the uranium response, thus enabling the relative stratigraphic position to be determined. Comparison with log response assigned a facies association (Chapter 5) increases confidence of these picks. If palynological data quality is poor the Maltby marine band also may require definition in this way although confidence in the pick is obviously reduced.

3.5.1 A review of upper Westphalian A to lower Westphalian C marine bands

Throughout this chapter the argument revolves around whether only fully marine representatives show high uranium signatures or whether nearshore or brackish water flooding equivalents also exhibit high uranium values, both are potentially widespread geographic markers so this does not hamper a multiwell correlation, if the actual flooding surface is recognised. It does, however, impede accurate identification of the individual marine bands.

ECL / SSI (1989) suggest that in the offshore area Westphalian deposits were in a more basinal setting or provided a pathway for marine incursions. They note that many of the marine bands that do not reach the "Dunbarella" faunal phase and true marine conditions onshore, such as the Maltby, Burton Joyce, Shafton and Edmondia marine bands are recognised by high uranium responses offshore. They attribute this to a greater "marineness". However, this suggestion is fraught with difficulties, as discussed in section 3.3.5 as there is no direct correlation between water depth and uranium concentration, and more marginal conditions may lead to high uranium values. The facies associations (Chapter 4) suggest the Westphalian B sediments in Quadrant 44 of the Southern North Sea compare to those in the Northumberland Basin, which are attributed to more marginal palaeogeographic conditions from the contained marine bands and facies characteristics. This view is supported by the development of the thick Caister Sandstone in the Quadrant 44 region (Chapter 4), which is thought to be located in a proximal setting adjacent to a topographically high area and therefore more marginal.

SHELL 44/28 - 2

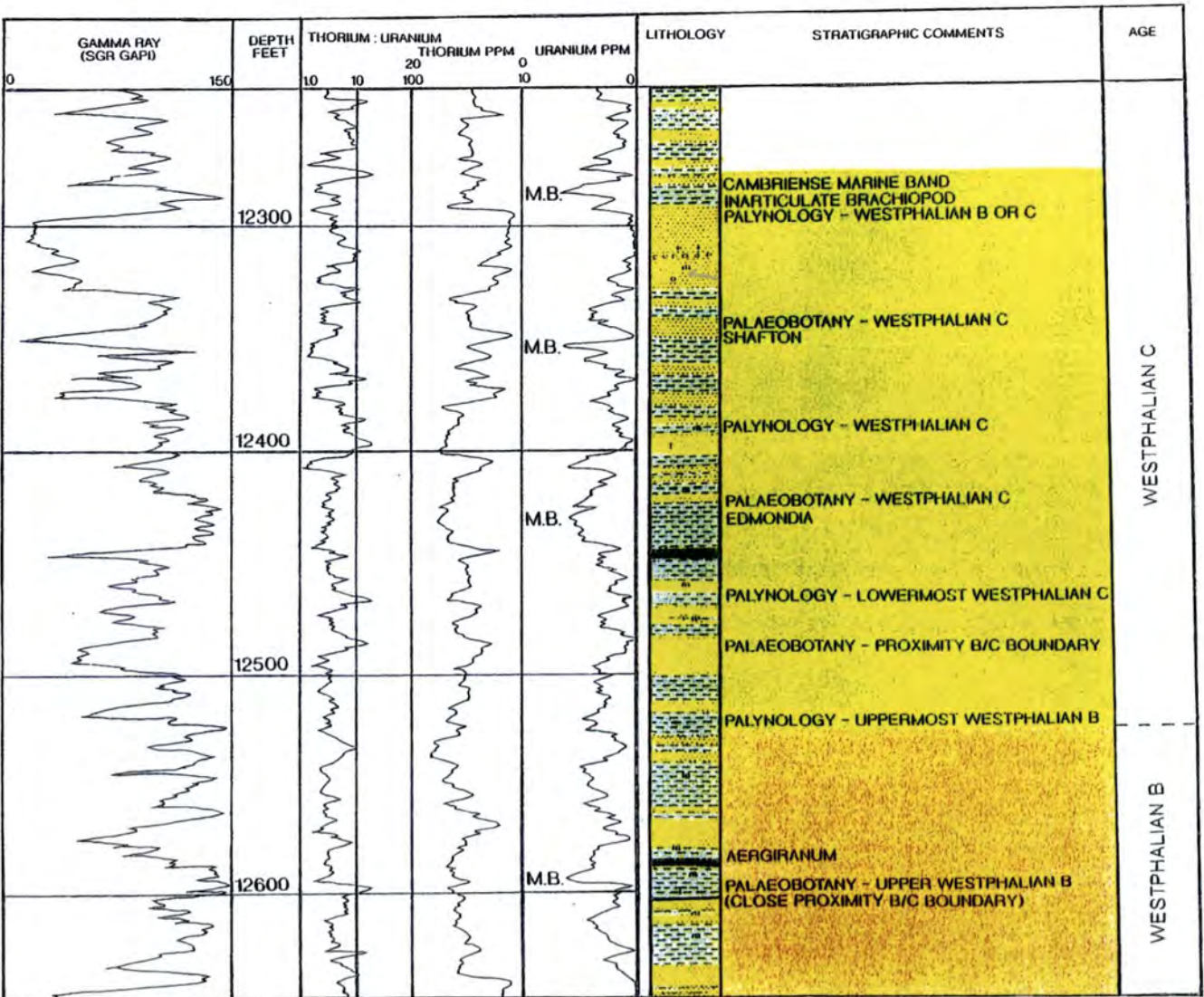


Fig. 3.15 Integration of the palynological data with the spectral gamma ray data for lower Westphalian C marine bands, allowing identification of the individual marine bands.

Nevertheless gamma ray markers and uranium spikes attributed to marine bands are identified from the spectral gamma ray logs and with careful integration into the palynologically based biostratigraphic scheme. Together with any additional information such as marine macrofauna, a detailed zonation scheme is possible for the late Westphalian A to early Westphalian C in Quadrant 44. Obviously this relies on good quality palynological data and spectral gamma ray logs being run, which is not always the case.

3.5.1.1 Cambriense, Shafton and *Edmondia* marine bands

Three marine bands occur within the lower Westphalian C (Fig. 3.1) above the *Aegiranum* marine band, although there are few wells that penetrate the section as it has usually been stripped off by the Sub-Permian unconformity. A further complication is that the onset of "red bed" sedimentation (well drained alluvial plain conditions) appears to be diachronous as noted by Besly et al. (1993) in the Staffordshire / Warwickshire Coalfield and the Southern North Sea (Fig. 3.16). This diachronaity in the onset of "red beds" is illustrated in the north of Quadrant 44 where an interdigitation of these red and grey facies (Besly et al. 1993) occurs, as in Block 44/21 (section 6.2.3). This appears to be a complex transition zone (cf wells 44/21-3 and 44/21-7) where the marine bands may be recognised in some wells but not in others. This is followed by a more permanent establishment of red bed facies in the lower Westphalian C (Chapter 4) as in wells 44/18-1 and 44/19-3. As a result these marine bands were not established due to the elevated well drained topographic nature of the floodplain at this time as the transgressions were not of sufficient magnitude to flood these areas.

Conversely in the south of Quadrant 44 in blocks 44/26, 44/27 and 44/28 the sediments remained waterlogged in a lower lying, more distal poorly drained alluvial plain situation, and as such were more susceptible to marine incursions into the lower Westphalian C, as evidenced by the presence of these marine bands. They can be identified from uranium signatures which are verified by the exceptional case of well 44/28-2 where an *Orbiculoidea* brachiopod is found: this is assigned to the *Cambriense* marine band and corresponds to a high uranium signature on the spectral gamma ray logs. This proves that high uranium signatures correspond to marine bands, even of a restricted marginal nature, in the lower Westphalian C, although this is an very unusual occurrence due to the paucity of cored data in this section which reflects the lack of reservoir objectives. A further complication is that these marine bands may have subsequently been overprinted by extensive Sub-Permian oxidation that formed

secondary red beds. Whilst this may not remove the gamma signature it destroys all the palynological information on which to base the chronostratigraphy and as they occur higher in the section there is a greater possibility of being affected by this post depositional reddening.

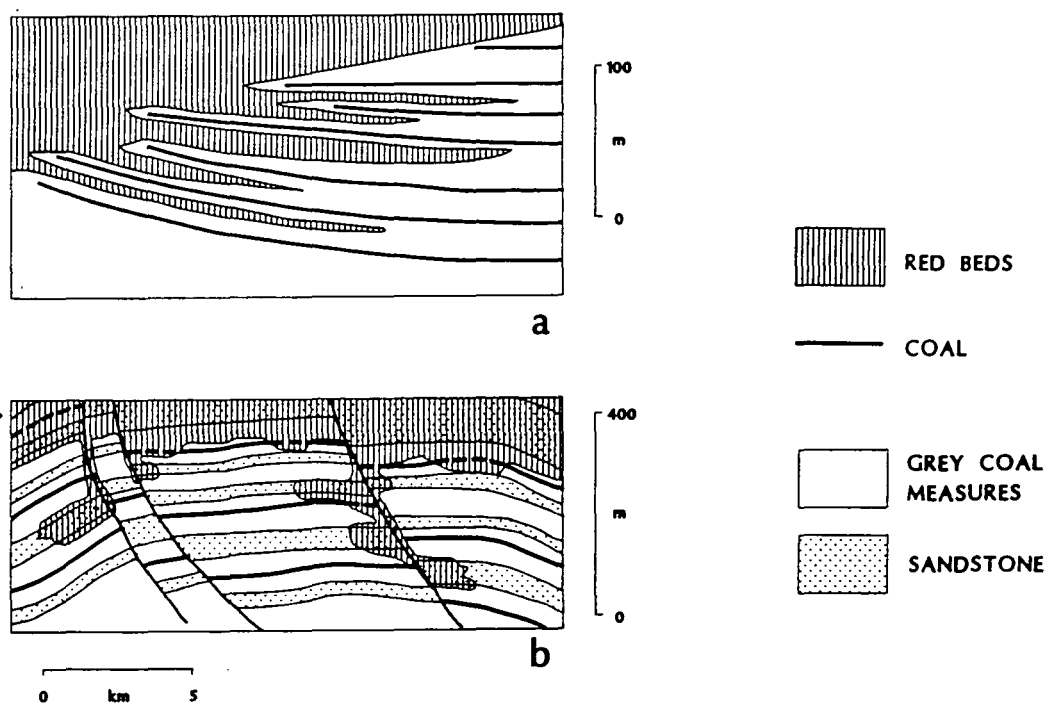


Fig. 3.16 Stratigraphic patterns of "red bed" occurrence in the UK onshore area. From Besly et al. (1993). a) syn-depositionally formed red beds interdigitated with coal-bearing sediments. b) unconformity-related reddening beneath the Permian.

3.5.1.2 *Aegiranum* marine band

The *Aegiranum* marine band coincides with the Westphalian B/C boundary and is one of the most geographically widespread of the Silesian marine bands. It displays a uniformity of conditions over a large part of North West Europe and has both abundant benthos and numerous free swimming fauna. In some parts of Staffordshire and the East Midlands it reaches 23' (Calver 1968a) and it is marked in the subsurface

by a distinctive gamma and uranium response. It is constrained palynologically by Westphalian C taxa above and Westphalian B taxa below.

3.5.1.3 Sutton and Haughton marine bands

These two marine bands occur in the late Westphalian B section. The Haughton marine band has a varied fauna and is thought to be a major marine episode strongly represented in most of the Pennine Coalfields (Calver 1968a), although it rapidly passes into a more brackish fauna to the north (Northumberland). Riley pers. comm. (via ARCO) suggests that it compares to the *Vanderbeckei* marine band in many respects (section 3.3.5 and 3.5.1.6), in that it contains abundant crinoid ossicles, and thus does not have a high uranium signature. ECL / SSI (1989) conversely believe it has a high uranium response, based on the Joppe 1 borehole (section 3.4.1) where marine fossils are found associated with a gamma high (Fig. 3.10). Calver (1968a) notes rapid faunal phase changes associated with the Haughton marine band and thus the uranium concentration may well vary accordingly. Confident identification of this horizon is difficult and ECL / SSI (1989) appear to confuse this band with the Sub-Clowne tonstein, which has a high gamma signature but which may be more consistent.

The Sutton marine band is only known from the central part of the basin and in Northumberland, where the thickest succession is found (Calver 1968a). It is considered a *Lingula* band with rare obiculoidea. Its spasmodic nature suggests that where present it may only exhibit a uranium value slightly above background. Both marine bands may be inferred by relative stratigraphic position between the palynologically defined *Aegiranum* marine band and the distinctive Sub-Clowne tonstein.

3.5.1.4 Sub-Clowne tonstein / Clowne marine band

The distinctive double gamma peak signal which is discussed in detail in section 3.4.3, produces an important stratigraphic marker (Fig. 3.13) that is geographically widespread and not affected by the regional facies changes that affect other marine bands, where present. Although thickness variations will occur, it nevertheless has a distinct uranium signature. The marine band overlying the intervening coal seam is the least widespread of the Westphalian B - lower Westphalian C marine bands and limited to a *Lingula* phase only. Its uranium signature is not significantly above the non marine shale background.

3.5.1.5 Maltby marine band

The Maltby marine band marks the boundary between the upper and lower Westphalian B. It represents the onset of more marine influenced upper Westphalian B and lower Westphalian C conditions. Faunally it is characterised by an acme of *Myalina*, which reflects water depth and a high uranium response, due to the interaction of the factors mentioned in section 3.4.1. Thus the Maltby marine band is represented by a high uranium response (cf. *Vanderbeckei* marine band types, section 3.4.1). With good quality palynological data enabling upper and lower Westphalian B assemblages to be recognised, the Maltby marine band may be constrained by faunal extinctions and inceptions (Chapter 2). Where good quality data is unavailable the position of the Maltby marine band must be inferred from the Sub-Clowne tonstein and the uranium signature alone, which obviously reduces confidence in the pick.

3.5.1.6 *Vanderbeckei* marine band

The *Vanderbeckei* marine band is an important stratigraphic event marking the Westphalian A/B boundary that can be traced throughout onshore Britain and into Europe, extending some 1000 kilometres east - west and 650 kilometres in a north - south direction. Calver (1968a) remarks that its value lies in providing a precise marker horizon in a thick coal bearing succession. Its acme is noted by a goniatite-pectinoid phase in the central Pennine Basin but predominantly it is dominated by a varied benthos passing into a *Lingula* band in Northumberland. Despite its widespread distribution the *Vanderbeckei* is associated with a relatively low uranium response (well 44/18-3) as noted by Whittaker (1985). This appears to be a feature of the marine band over most of its range. Slight variations in bathymetry may occur where isolated pockets of deeper water are located, (central Pennine Basin) and as a consequence, some variations in uranium response may occur throughout the distribution of the marine band. Palynological assemblages can usually constrain the marine band accurately so that the smooth gamma signal above a coal seam can give an indication of position.

3.6 Conclusions

Marine bands can be recognised from goniatites and associated marine macrofaunal phases. This recognition is extremely difficult in the subsurface, due to the lack of data but nevertheless it is crucial for the calibration of log response.

The uranium response of marine bands is seen to vary markedly suggesting that the controls (section 3.3.5) on uranium enrichment are complicated, which leads to variable response characteristics. This necessitates a four fold division of marine bands.

1) Namurian marine bands which are marine anoxic black shale events with thick goniatitic acme phases, concentrate uranium as outlined by Leeder et al. (1990).

2) *Vanderbeckeri* type marine bands have poorly developed anoxia, thin goniatitic acme phases and abundant benthos, resulting from shallower water depth (cf. Namurian marine bands) and consequently negligible uranium enrichment. They contain a low proportion of humic material from land derived organics (cf. Westphalian B/C marine bands) as the distance to contemporary shoreline was greater (Fig. 3.9).

3) Westphalian B/C marine bands are more marginal, but have an abundance of land plant derived fragments with absorbed uranium. As well as uranium entrapped within the phosphatic tests of *Lingula* which are more abundant in these types of marine bands as a consequence they have high levels of uranium enrichment.

4) Brackish water *Lingula* beds with high proportions of terrigenous input, and negligible uranium response.

This classification of marine bands allows for prediction of the possible uranium response of individual marine bands within a new data set. It is thought to be indicative of the organic content and the degree of salinity of the individual marine bands

The Sub-Clowne tonstein has been successfully identified from Quadrant 44 wells and can be used as an additional, regionally important stratigraphic marker in the Southern North Sea. It has a particularly distinctive gamma response and is useful in determining relative stratigraphic position, without the need for precise palynology. This is

important in helping to identify marine bands in an otherwise problematical part of the succession.

Marine bands can be recognised and identified in the subsurface from their gamma ray and spectral gamma ray log response, and with accurate palynology they can be incorporated successfully into a regional stratigraphic scheme where they provide important tie lines and surfaces for correlation (Fig. 3.17).

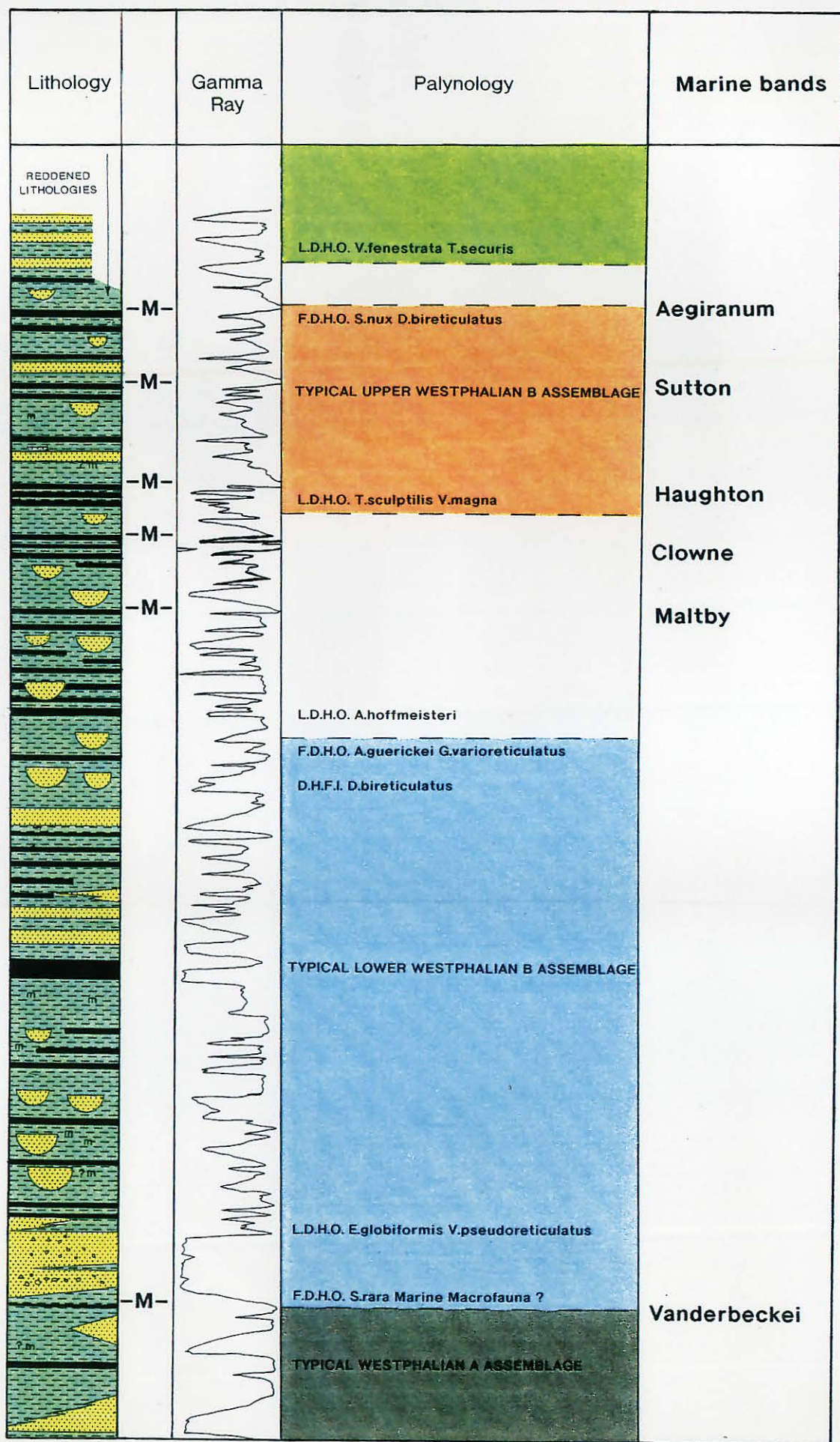


Fig. 3.17 Incorporation of Westphalian B marine bands with the palynological scheme developed for Quadrant 44.

Chapter 4

Westphalian B facies associations and facies

4.1 Introduction

Besly and Fielding (1989) suggest that there are four distinct facies associations recognisable in the Westphalian A-C fill of the Pennine Basin (section 1.3), which contains many of the coalfields of Northern England:

- 1) a lower delta plain association;
- 2) an upper delta plain association;
- 3) an alluvial plain association dominated by swamp deposits; and
- 4) an alluvial red bed association dominated by well drained overbank deposits

Figure 4.1 summarises the interpretation of the various facies within these four facies associations of the sediments of the Westphalian A-C in Central England and the resulting lithostratigraphic diagram (Fig. 4.2) illustrates how these facies associations vary spatially and temporally across the basin. This shows that the Westphalian B consists predominantly of the upper delta plain facies association with minor diachronous gradation into a better drained alluvial facies association and a well drained alluvial "red beds" association which subsequently dominates the Westphalian C. All four facies associations are coal-bearing, so the Pennine Basin has a large areal extent of coal-bearing Westphalian strata with numerous occurrences of laterally extensive coal seams, suggesting the apparent dominance of terrestrial conditions with only minor marine influence (Chapter 3). The facies present are all characteristic of an upper delta plain environment. The Coal Measures in the Pennine Basin have been interpreted in the same manner (Elliot 1969; Guion 1978; Scott 1978; Haszeldine 1981; Guion and Fielding 1988). Although similar deposits have been interpreted as coastal plain (Bagnaz et al. 1975) consequently the Westphalian B sediments described here are termed upper delta plain/coastal alluvial plain. Detailed facies analysis and facies descriptions were carried out for the Durham and Northumberland Coal Measures by Fielding (1982, 1984a,b, 1986) and Haszeldine (1981, 1984). The facies described for the Durham and Northumberland coalfield are comparable to facies elsewhere in the Pennine Basin and these descriptions are considered by Besly and Fielding (1989) to be representative of the whole basin. Besly (1988) recognised that a restricted assemblage of comparable facies was present in the alluvial coal-bearing deposits of Central England.

MAJOR FACIES ASSOCIATION				
	LOWER DELTA PLAIN	UPPER DELTA PLAIN	ALLUVIAL PLAIN	WELL DRAINED ALLUVIAL PLAIN
Principle facies	Marine band Prodelta Delta front Distributary channel Interdistributary bay / marsh	Distributary channel Interdistributary bay / swamp (Rare Marine band)	Alluvial channel Overbank lake Floodbasin swamp	Alluvial channel Levee and well drained floodplain (Floodbasin swamp) Marginal conglomeratic fans
Age	Basal Westphalian A	Mid Westphalian A to Upper Westphalian B	Westphalian A to Mid Westphalian C	Westphalian A to Late Westphalian C

Fig. 4.1 Summary of interpretations of facies and facies associations in coal-bearing sediments in Westphalian A-C, Central England. Table I of Besly and Fielding (1989).

4.1.1 Lower delta plain association

This facies association is restricted to the lower Westphalian A succession (Fig. 4.2) and consequently will not be discussed fully. It was described by Guion and Fielding (1988) and Besly and Fielding (1989) as consisting of shallow water deltas with distributary channels in a lower delta plain environment. The deltas prograded into interdistributary bays, which were extensive bodies of shallow, brackish to fully marine water as indicated by the frequently occurring marine incursions. There appears no single point in the stratigraphic record of the Westphalian A where it can be said that lower delta plain environments gave way to upper delta plain conditions. Thus the change is gradational and to some extent diachronous. The succession is characterised by coarsening-upward packages, reflecting the infilling of the extensive interdistributary areas by progradation of minor delta systems and mouth bars, with distributary channels, interspersed throughout. Brackish water fauna are common indicating that the interdistributary bays were partially marine influenced and extensive standing water bodies. Thin, infrequent, coals with underlying rootleted horizons cap the coarsening-upward packages and indicate the infilling of the interdistributary area and subsequent temporary emergence of the floodplain.

4.1.2 Upper delta plain association

The upper delta plain association, described in detail in section 4.2.1, contains the "productive" Coal Measures succession of mid Westphalian A to Westphalian B age, with only sporadic fully marine conditions, and predominantly non-marine faunas. The sediments are interpreted by Fielding (1982; 1984a,b; 1986) and Haszeldine (1981;1984) as the deposits of enclosed fresh water lakes separated by distributary channels of various magnitudes and types (Fig. 4.4). The interdistributary areas were filled by various overbank and crevasse splay derived sediments that resulted in mainly coarsening-upward packages which, where complete, allow lake depths of up to eight metres to be estimated. The complete infilling of these lakes provided sites for the formation of coal swamps at or slightly below the water surface in depths of around one metre of water. Such swamps produced the numerous coal seams up to 4 metres thick that characterise the succession. They may be laterally extensive and continuous over thousands of square kilometres (Besly and Fielding 1989). The upper delta plain / coastal alluvial plain environment diachronously passes to better drained environments in the late Westphalian B or lower Westphalian C. Marine bands again become common in the late Westphalian B, in basinal areas, reflecting a delicate balance between rate of subsidence and sedimentation. The facies identified do not return to the lower delta plain facies association of the Westphalian A, but the relief on the plain was probably less or sediment supply had reduced. In contrast to this, in more marginal areas during the upper Westphalian B there is a



gradual increase in the occurrence of better drained alluvial sediments reflecting the early onset of red beds (Besly 1988; Besly et al.1993).

4.1.3 Alluvial association

Besly and Fielding (1989) suggest that sediments of this association occur throughout the Westphalian A to Westphalian C interval in areas along the southern margin of the Pennine basin adjacent to the northern flanks of the London Brabant high. The distribution then extends to other areas throughout the basin from late Westphalian B to early Westphalian C times onwards (Fig. 4.2). Besly and Fielding (1989) suggest this association records the sedimentological transition both laterally and vertically between upper delta plain deposits of the "productive" Coal Measures to the red beds of the Etruria formation. A similar transition may occur on the southern flanks of the Mid North Sea High mirroring the succession on the northern flanks of the London/Brabant massif, (Wells 44/21-3, 44/18-1). However, in the Southern North Sea this facies association thins to the south.

This association, described by Besly and Fielding (1989) in the West Midlands is characterised by the extreme monotony of the constituent facies, consisting of silty and muddy palaeosols, interbedded with fining-upward overbank sheet-sands and fining-up channel fill sandbodies, the result of meandering distributary channels. However, in the more proximal reaches of the Southern North Sea, these sheet-sands may be sharply-based and conglomeratic. The distributary channel fill sandbodies are blocky, suggesting a low sinuosity and braided origin. Coals are infrequent and laterally impersistent. Minor well-laminated shales, containing fresh-water bivalves, ostracods, crustaceans and annelids, are present as drowning surfaces to the coals. In some areas large parts of the succession consist exclusively of palaeosols and this, together with the fresh-water fauna, implies a purely alluvial origin with the palaeosol types present indicative of predominantly waterlogged overbank areas.

4.1.4 Well drained alluvial "red bed" association

This association is believed by Besly et al. (1993) to be largely restricted to the Westphalian C (Fig. 4.2), although the lack of reliable dating methods makes this assertion unreliable and an early onset of true "red beds" in wells in a more marginal position (44/18-1; sections 6.2.3 and 6.2.4.) cannot be discounted. Accentuating this problem is the fact that it is also difficult to distinguish between primary, well drained oxidised conditions, and secondary reddening in many cases, especially as secondary reddening can occur due to pervasive oxidation at the Sub-Permian unconformity. Besly and Fielding (1989) describe the association as consisting predominantly of red coloured mudstones and silty mudstones with common root bioturbation

and colour mottling. Sedimentary packages form coarsening-upward units from mudstones to evolved palaeosols with thin sand-sheets and small isolated fining-upward channel fills in interdistributary areas, interspersed with rare erosively-based channelised sandbodies which transported most of the sediment.

These sediments are interpreted by Besly and Fielding (1989) as alluvial deposits. The larger sandbodies are attributed to meandering channels, but evidence from wireline log and core data in Quadrant 44 (section 4.3.3.6 and 4.3.3.7) suggests that the channels were straighter and braided in the southern North Sea area. The varied finer-grained sediments are interpreted by Besly and Fielding (1989) to result from the interdigitation of overbank levees, crevasse channel and splay, floodplain sediments and palaeosols, reflecting a distal to proximal relationship to the feeder channels. The red coloration, with mature and evolved palaeosols indicate that the sediments were deposited on a predominantly well drained alluvial plain. Red colouration should not be used as the diagnostic factor when identifying these strata, as it may result from the oxidation of previously poorly drained (grey) sediments (Besly et al. 1993). The identification of evolved well-drained palaeosols is a more reliable tool for recognising alluvial plain sediments.

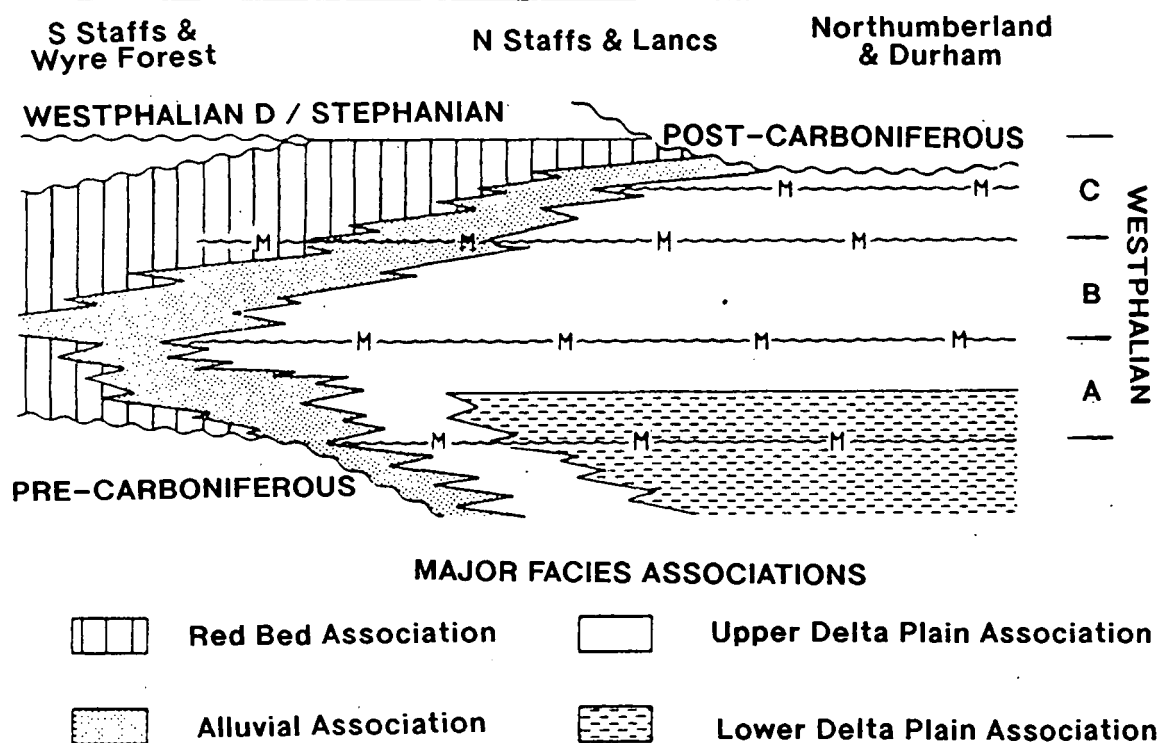


Fig. 4.2 Schematic lithostratigraphy of Westphalian A-C of Central and Northern England, based on occurrence of sedimentary facies associations. Fig. 2 of Besly and Fielding (1989).

4.2 Facies associations

Of the facies associations mentioned in section 4.1 only those directly applicable to Westphalian B sediments in Quadrant 44 wellbores will be described in detail. The lower delta plain conditions developed in the Westphalian A will not be dealt with further. Also the "red beds" or well drained alluvial sediments that predominate in the Westphalian C will only be referred to briefly. The majority of the Westphalian B sediments in Quadrant 44 wells are of the upper delta plain / coastal alluvial plain association and consequently will be discussed in detail. The transitional alluvial association is discussed in section 4.2.2 and is thought to typify Westphalian B sediments in more marginal areas, to the north of Quadrant 44 (44/18-1).

4.2.1 Upper delta plain / coastal alluvial plain association

4.2.1.1 Introduction

The depositional models that have been proposed for the upper delta plain / coastal alluvial plain, that characterises much of the Westphalian B are outlined in this Section. They have been synthesised from a review of the literature (Fielding 1984a,b, 1986; Haszeldine 1981, 1983a,b, 1984; Guion and Fielding 1988; Besly and Fielding 1989) on Carboniferous environments and data derived from the Westphalian B outcrop on the Northumberland coast between Tynemouth and Seaton Sluice. This is then compared to the reports from Quadrant 44 wells. In concurrence with Collinson et al. (1993) and Besly (1990) the Westphalian B Coal Measures encountered in offshore boreholes in the Southern North Sea are considered to closely resemble those in Northumberland in the lower Westphalian B and those in the East Midlands in the upper Westphalian B and this is verified by studies of core reports for Quadrant 44 wells (section 4.3.3).

It was beyond the scope of this study, because of time constraints, to undertake detailed facies analysis of the Westphalian B sediments in order to erect an independent facies scheme. As a result based on the analogues described in great detail in the literature, a scheme (Fig. 4.3) was developed from the above workers assessments, in order to refine correlation of the Westphalian B sediments in Quadrant 44. This ubiquitous facies characterisation scheme is then applied to Quadrant 44 core material to enable facies interpretations to be made, based on core material and wireline log response (section 4.3.3). Thus the distribution of the facies (Fig. 4.4) can be established allowing for palaeogeographic reconstructions. Based on detailed

facies analysis for the Westphalian A and B of the Pennine Basin Guion and Fielding (1988) suggested that the "productive" Coal Measures were deposited on an upper delta plain isolated from marine processes. Within this environment distributary channels (section 4.2.1.11, 4.2.1.12) of variable sinuosity were the main pathways of sediment dispersal. The major distributary channels formed sandy channel belts up to 5 km wide as they crossed the delta plain (Fielding 1986). They may have exhibited patterns of regular switching (Fielding 1986) or may have occupied a particular belt over a relatively long period, causing several successive seams to be absent, due to washouts, where the channel belt persisted (Guion 1978) and providing stacked channel systems.

Between these channel belts lay enclosed freshwater lakes (Haszeldine 1984) which were up to 10 m deep with wave fetches of the order of 20 km estimated by Fielding (1984a) from regional palaeogeographic reconstructions and wave ripple parameters (Guion 1978; Fielding 1982, 1984b). The lakes were infilled by various processes (sections 4.2.1.3 to 4.2.1.8) of crevasse splays / minor delta deposition and overbank sedimentation culminating in the formation of peat forming swamps (Guion 1978, 1984; Fielding 1984a,b) leading to repeated episodes of coal development. These abundant coals (section 4.2.1.10) are up to 4 m thick and laterally continuous, reflecting long term and extensive development of coal-forming swamp conditions. Rare marine incursions caused drowning of the upper delta plain and resulted in deposition of marine bands which, as discussed in Chapter 3, are of regional importance and geographic extent. Conditions were essentially similar across the entire Pennine Basin (section 1.3) and into the Netherlands, with thicker successions near the basin depocentres displaying a "bull's eye" isopach pattern composed of a greater number of lake infill packages rather than thicker individual packages (Duff and Walton 1964; Elliott 1969). Thus the network of distributary channels was able to keep the sedimentary basin "topped up" and deeper water successions were unable to develop. The palaeocurrents of these low gradient channel systems are highly variable, reflecting frequent crevassing and overbank flooding, filling the surrounding lacustrine environments. The exception is Northumberland and Durham where the predominant direction of sediment transport was southerly directed, suggesting a more proximal situation with more consistent channel orientations feeding sediment to the south. Guion and Fielding (1989) suggest that crevasse channels, minor distributary channels and sheet floods conducted sediment from the major distributary channels and fairways to minor crevasse splay deltas that prograded out into the surrounding lacustrine environments.

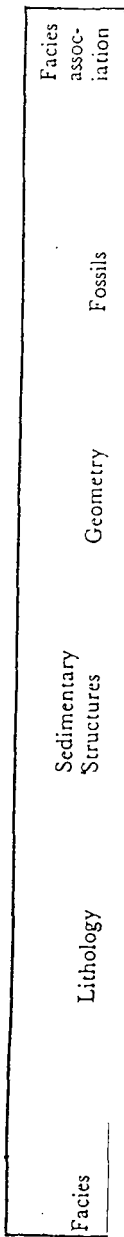


Fig. 4.3 Major facies represented in the upper delta plain facies associations of the Westphalian A and B of the Pennine Basin. Based on Fielding (1984a, 1986) and Guion and Fielding (1988). Note term clarification. Siltstone-dominated overbank deposits are termed Fine-grained overbank facies, Suboxic lake / bay floor are termed Anoxic lake facies, Passive lake / bay margin are termed Lake margin facies in this study. Minor crevasse channel deposits are not recognised as a separate facies in this study.

4.2.1.2 Durham / Northumberland Coalfield

Coal Measure sediments in this coalfield exhibit facies associations (Fig. 4.3) very similar to those in lower Westphalian B sediments penetrated in Quadrant 44 wells in the Southern North Sea (Fielding 1984a,b, 1986; Haszeldine 1981, 1984 and Guion and Fielding 1989). They display evidence of lateral variability and consist of interbedded claystone, siltstone, sandstone and intraformational conglomerates, with abundant coals up to 4 m thick. The facies components of the succession, were described from natural exposures on the Northumberland Coast, open-cast coal sites, brickwork quarries and other excavations (Fielding 1984a,b, 1986; Haszeldine 1981, 1984; Guion and Fielding 1989) and an exhaustive quantity of variable quality subsurface data (Haszeldine 1981). Fourteen facies (Fig. 4.3) were recognised and assigned to a lacustrine and fluvio-lacustrine facies association and a channel facies association by Fielding (1984a, 1986) based on processes of deposition, according to whether, they were deposited by overbank flooding, crevasse splay supplied delta systems or channel systems.

4.2.1.3 Coarse grained overbank facies.

Description: This facies, as described by Fielding (1984a) and Haszeldine (1984), comprises thinly bedded carbonaceous claystone, siltstone and sandstone arranged in packages up to 10 m thick. The sandstones are predominantly fine-grained and approximately 20 cm thick, and internally structured mainly by ripple cross-lamination and flat lamination, and locally developed soft-sediment deformation structures. They overlie sharp, locally loaded-bases and are interbedded with mainly structureless or poorly-laminated mudstone and siltstone containing occasional non-marine bivalves. Numerous types of trace fossils occur, including burrows and resting traces of bivalves (*Pelecypodichnus*) which occur on the underside of the sharply-based sandstone units, together with abundant plant debris which lie parallel to bedding planes. This facies was found by Fielding (1984a) to occur in elongate belts up to 2 km wide bordering major, or in some cases minor distributary channels. The grain size, frequency and thickness of individual sandstone units and the overall facies thickness reach a maximum close to the channel margin where they may pass into heavily rootlet penetrated sandstones which gradually decrease away from the channel.

Interpretation: Based on their geometry (Fig. 4.4) these sediments were interpreted by Fielding (1984a) as levees and coarse-grained overbank sheet-flows of sediment laden waters during flood events adjacent to active channels with thicker units representing more prolonged minor crevassing or exceptional floods. The fine-grained material settled out of suspension during quieter periods. The absence of roots suggests subaqueous deposition, with only the channel margins having sufficient potential relief for plant colonisation, hence the intense rootleted bed.

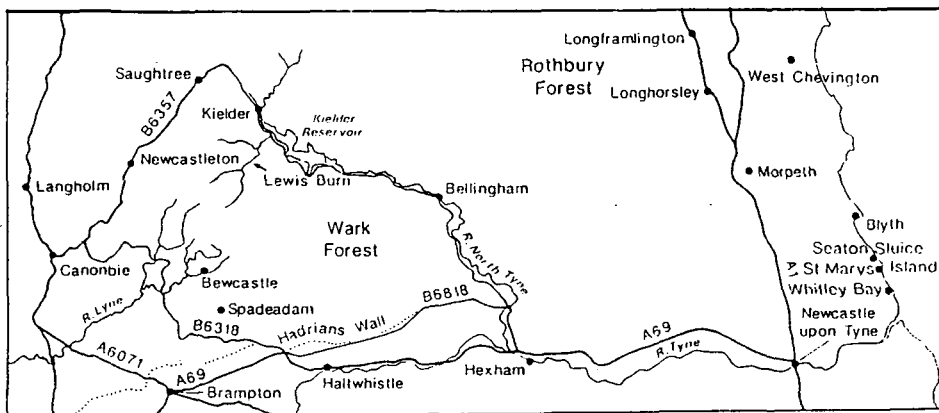
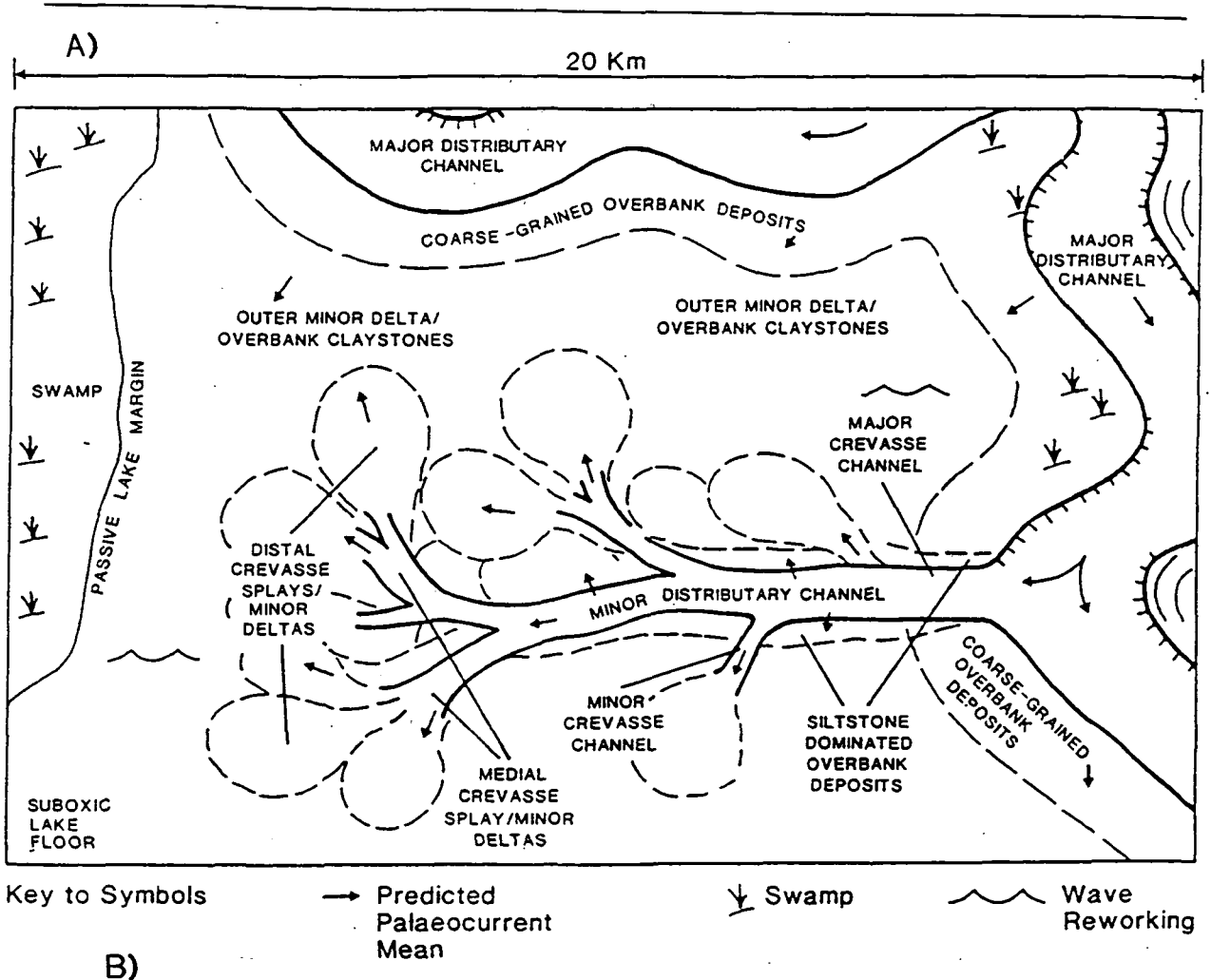


Fig. 4.4 a) Schematic plan reconstruction of a Coal Measure lake in the Quadrant 44 area, showing areal relationships between the various lithofacies and the controlling influence that crevasses in major channel banks have on lacustrine sedimentation. Adapted from Fig. 14 of Fielding (1984a) based on the Durham area.

Fig. 4.4 b) Location map showing positions of outcrops referred to in Chapter 4.

4.2.1.4 Fine grained overbank facies

Description: Flat-laminated massive siltstone with occasional sharply-based or load-casted sandstones up to 50 cm thick, are separated by thin claystone layers. Within the claystone layers are abundant siderite nodules and concretions confined to distinct horizons, scattered throughout the siltstone and sandstone units. These latter units have abundant well preserved plant stems and foliage. The facies occupies elongate belts parallel to minor distributary channels and attain thicknesses up to 10 m adjacent to the channel, but they thin and fine distally away from the channel.

Interpretation: Fielding (1984a) attributes fine-grained overbank sediments to flooding of minor distributary channels and deposition from turbulent suspensions, with the sharp-based sandstones being minor crevasses from the parent channel (Fig. 4.4). The presence of *in situ* and well preserved drifted plant foliage implies rapid though gentle deposition. The deposits described here may pass laterally into those described in section 4.2.1.3 and form under similar conditions adjacent to channels. Differences between them are mainly related to the nature of the sediment load carried by the respective parent channels, which is controlled largely by the magnitude of the channels.

4.2.1.5 Proximal major crevasse channel facies

Description: This facies comprises sharply-based, fining-upward fine- to coarse-grained sandstone (predominantly medium-coarse) up to 7 m thick with occasional silty partings, capped by a siltstone or claystone. The sandstones are dominated by trough cross-bedding and scour surfaces up to 2 m deep overlain by cross-stratified beds, which rapidly fine-up into rippled cross-laminated fine-sand. Fielding (1984a) notes that some troughs are partially or completely filled by siltstone or massive discordant sand, with abundant intraformational clasts. From outcrop studies in Durham, Fielding (1984a) describes how this facies progressively cuts down into the floodplain deposits of mixed lithologies on which they frequently sit. They fine and thin distally into crevasse splay deposits and up current pass into minor (section 4.2.1.12) or major distributary channels (section 4.2.1.13). They are thought to be deposited by highly erosive unidirectional flows and rapid deposition.

Interpretation: This facies owes its origin to breaching of distributary channels (Fig. 4.4) during flood stage (Fielding 1984a) via proximal crevasse channels, which maybe plugged almost immediately or were more prolonged sediment transport conduits, acting as feeder channels to crevasse splay delta systems. There appears to be a transition between distributary channels and proximal crevasse channels with a variation in the sizes of sediment transport avenues. Their fining-upward nature suggests a waning flow which occurs in the down current direction also. Abandonment is marked by siltstone horizons, which maybe rooted or rippled

and comparable with similar floodplain deposits, capped by a coal. This may reflect a complete infill of the lacustrine area or a autocyclic switching of channel or crevasse activity.

4.2.1.6 Medial crevasse splay / minor delta facies

Description: This facies consists of several lithologies organised into a variety of packages, up to 10 m thick. It consists of interbedded fine- to medium-grained sandstone, siltstone and claystone with individual beds up to 2 m thick, although often of considerable lateral extent (Fielding 1984a) and variable thickness. They are arranged in predominantly gross coarsening-upward packages composed of small-scale fining-upward sandstone units that increase in frequency and thickness upwards. The sandstones that form the bulk of the unit are fine- to medium-grained, and generally fine-upward. They contain abundant small scale trough-cross beds, ripple cross-lamination, soft-sediment deformation structures and rare internal erosion surfaces with associated sole marks. Upwards they contain occasional wave ripples, rare non-marine bivalves, common resting traces and burrows, and pass up to siltstone with *in situ* plants and rootlets. Root penetration also increases upward. Interbedded with these coarsening-upward vertically stacked units are channelised fining-upward packages that occupy irregular areas that pass proximally into crevasse channels and distally into crevasse splays; the coarsening-upward packages occasionally culminate in a fining-upward element.

Interpretation: This facies was deposited under various hydrodynamic conditions from quiet water suspension fall out to high energy flows and turbiditic underflows (Fielding 1984a). Current traction is mostly due to sheet-flows interspersed with periods of suspension fall out. The interbedded nature of the lithologies and sharp-topped, coarsening-upward profile suggests that the facies represents deposition via progressively more powerful currents, which culminate in an abrupt cessation in current activity. Where the unit terminates via a fining-upward unit a gradual waning in current activity is suggested.

The fining-upward units that cap some of the coarsening-upward packages reflect the development of feeder channels (minor distributary channels or crevasse channels passing across the minor delta top as the lacustrine area is infilled by progradation of minor delta systems (Fig. 4.4). These may pass into minor mouth bars and crevasse splays down current which form the bulk of the coarsening-upward packages. Conversely the unchannelised fining-up elements may simply reflect the gradual switching of the sediment source for the minor delta system, thus producing a fining-upward package of stacked fining-upward sandstones that gradually decrease in thickness and frequency. These sediments lie down current from the major crevasse channel or distributary channel feeder system in a medial setting on the minor crevasse splay delta system that infills interdistributary lacustrine areas. Hence the mixed confined and unconfined depositional processes.

4.1.2.7 Distal crevasse splay / minor delta facies

Description: This facies is represented by a single coarsening-upward package or by stacked packages composing claystone to siltstone and fine-grained sandstone, commonly up to 10 m thick. These fine-grained sandstones are ripple cross-laminated and form beds of 1-2 m with occasional wave ripples and muddy laminae; they may display occasional trough cross-bedding and overlie a loaded base. The uppermost parts are characterised by abundant root penetration and abundant drifted and broken plant fragments with trace fossils, and extensively bioturbated beds, that often have sharp-tops, capped by either coals or lacustrine mudstones, or less commonly channel deposits. Fielding (1984a) believes this facies to be lobe shaped (Fig. 4.4) with dimensions hundreds of metres wide and 1-2 km long; the maximum thickness being found in the centre which tapers and thins outwards. They have a moderate spread of palaeocurrents. The sediments are seen to occur down current from the medial crevasse deposit where they gradually fine and pass into lacustrine dominated sediment (section 4.2.1.8 to 4.2.1.10).

Interpretation: This facies was considered by Fielding (1984a) to have been deposited by hybrid underflows which gradually became more powerful, indicating progradation and subsequent shallowing concomitant with the gradual infilling of the interdistributary lacustrine areas. Fielding (1984a) suggests that the lobe shape indicates that the sediment was unconfined whilst the presence of abundant syn-sedimentary deformation features implies that the sediment surface was prone to liquefaction. The facies records the deposition of minor mouth bars and crevasse splays on the distal parts of the minor delta systems (Fig. 4.4) with the characteristic coarsening-upward log motif produced by progradation of mouth bars and crevasse splays at the front of a minor delta system, fed from the more proximal systems described in sections 4.2.1.5 to 4.2.1.6. These mouth bars and crevasse splays coalesced to form platforms or delta tops across which the systems described in section 4.2.1.6 flowed. Where single coarsening-upward units were deposited as part of lake-fill packages, they may be regarded as the distal expression of these larger splays.

4.2.1.8 Outer minor delta / overbank facies

Description: This facies is characterised by grey to dark grey claystones that are massive to flat-laminated, with occasional siltstone and sandstone laminae. These are thin bands of rippled or massive fine-grained sandstone less than 10 cm thick, with sharp often loaded-bases, which have a sheet-like geometry and pass up current into distal crevasse splay deposits. Abundant nodules, lenses and layers of siderite, with less common calcite and dolomite occur throughout in addition to flattened drifted plant fragments on bedding planes. *In situ* and broken shell

fragments may occur in distinct bands often associated with siderite nodules, and traces of such shells may occur in the sandstone units. Deposits of this facies may occupy the entire intercoal interval with the uppermost part becoming increasingly penetrated by rootlets. Commonly they pass into rhythmically bedded dark and pale grey depositional couplets (Haszeldine 1984), where the bases of the dark layers are erosive and may erode through the lighter, less erosive layers. These dark layers contain abundant plant fragments and both couplets show fine internal laminae and small loads. Spears (1980) demonstrates that the dark layers are coarser and contain siderite and ironstone. Macrofossils are limited to the rare inclusion of non-marine bivalves within diagenetic ironstone nodules. Trace fossils however, are common, especially near the base of such rhythmites, and they are largely filled by the dark sediment. The couplets may become thicker and coarser upward (Haszeldine 1984) and become separated between sandstone streaks accompanied by an increase in escape burrows in the dark layers.

Interpretation: This facies is interpreted as the deposits from suspension fallout (Fielding 1984a) as indicated by the presence of *in situ* and drifted bivalve shells which are typical in the lower part of the facies, suggesting that sedimentation rates were slow at first. An increasing sediment supply is reflected in a decreasing bivalve content and concomitant colour change from dark to light grey. The presence of unoxidised organic fragments and siderite indicates a reducing subsurface environment (Fielding 1984a). These deposits are thought by Fielding (1984a) to be laid down beyond the influence of crevasse splay delta systems (Fig. 4.4) by settling out from a sediment laden water column. Initial slow rates of sedimentation increased in response to distal crevasse and overbank activity that introduced large quantities of fine-grained sediment into the water column as the system prograded into the lacustrine interdistributary areas. Occasional sandstones are the distal expressions of such crevasse splay delta systems and their increasing frequency upwards reflects progradation of the system, prior to the facies grading into the distal crevasse splay minor delta subfacies via the couplets which are the deposits of fine-grained turbid underflows entering a body of fresh-water. The laminae are produced by a dynamic sorting mechanism (Haszeldine 1984) and are similar to clastic rhythmites in modern lakes after floods on feeder rivers. (Lambert and Hsu 1979; Ludlow 1979; Yuretich 1979). The light layers with abundant burrow traces, formed by worms and bivalve feet, suggest that the slowly sedimented organic rich dark layer was succeeded by a catastrophic light layer with burrows formed by escaping organisms. Fielding (1984a) also notes that this facies occurs in thin layers incorporated within channel sandstone units where it is interpreted as resulting from channel abandonment.

4.2.1.9 Anoxic lake facies

Description: Fissile "crackly" (Haszeldine 1984) grey to black claystones are ubiquitous throughout this facies which is pyrite-rich and highly organic (up 18% organic carbon) with abundant flattened, drifted, though delicate plant fragments and coaly traces. No current generated structures are seen. This facies predominantly overlies coal seams and may display an intermediate canneloid coal or clay (plant spore material) layer between the underlying coal seam and a basal thin kaolinitic claystone. This basal unit has abundant compressed ostracods, drifted bivalve fragments and fish debris and although seldom more than 1 m thick it is usually laterally persistent over several kms or tens of kms. These then grade into dark grey to grey mudstones with abundant non-marine bivalves. Where isolated the bivalve tests are usually dissolved and are preserved as molds, often in life position. However, where they form layers, preferential early diagenetic (Curtis 1978) siderite and ironstone development led to preservation of the tests. Although abundant, species and genera diversity was low.

Interpretation: The high proportion of preserved organic detritus, with associated canneloid claystone indicates an extremely slow rate of sedimentation. Furthermore shell fragments fell sideways and separated after death (Haszeldine 1984) and this together with the presence of pyrite and lack of benthos suggests a predominantly anoxic environment. The facies formed in lakes (Fig. 4.4), as indicated by the non-marine fauna (Calver 1968a), after the drowning of Coal Measures swamps (section 4.2.1.11) thus creating euxinic lake floors (Fielding 1984a). The very slow rain of fine-grained plant detritus out of suspension in largely standing water, lead to stratification of the water body and strongly reducing bottom waters. Although, anathema to benthic fauna, fish, ostracod and bivalves could live in the upper waters, which would have remained oxic, thus forming the beds above the canneloid intervals. The sediment remained undisturbed and cannel peats developed from the accumulation of organic matter, due to the lack of clastic input and the isolation of the area from clastic supply. The passage of dark grey to grey coloration indicates that the organic matter concentration decreased upward, corresponding to an increase in bivalve occurrences, although bottom waters remained poorly oxygenated and were only able to support a benthos of worms and filter feeding bivalves which lived on or semi-submerged in the sediment (Broadhurst 1958, 1964). The sediment itself continued to be anoxic as it preserved organic matter and remained largely unbioturbated.

4.2.1.10 Lake margin facies

Description: Well laminated grey claystone and siltstone, with occasional thin sandstones characterise this facies, which is capped by palaeosols and coals. Rootlets and siderite nodules are ubiquitous, and destroy all original sedimentary structures although occasional non-marine

bivalves are preserved. The facies which occupies narrow elongate wedges, may pass laterally into anoxic lake facies (Fig. 4.4), reflecting a more marginal lacustrine environment, or into coal swamps. It characterises seam splits or is a common component of channel abandonment facies.

Interpretation: The processes of deposition are largely similar to those discussed in section 4.2.1.9, that is, suspension fallout with distant floods in largely quiet water conditions. However, the co-occurrence of abundant plant rootlets and non-marine bivalves suggests a fluctuating but shallow lacustrine environment. This interpretation is supported by its association (Fig. 4.4) with the anoxic lake facies indicating a transition into deeper water. The association with coal swamps suggest shallower water, with abundant peat swamp development. This facies will frequently occur in channel abandonment and the shallow lakes that occupy oxbow type situations.

4.2.1.11 Coal swamp facies

Description: The presence of bituminous and shaley coals define the swamp facies, which consists of seams up to 2.5 m or exceptionally up to 4 m. They are composed of up to 90% organic matter representing compressed and metamorphosed plant remains from *in situ* peat and occasional clastic "bands" of claystone, siltstone or plastic clays. The reader is referred to McCabe (1984, 1987, 1991) and Haszeldine (1989) for detailed discussion of coal depositional environments, which are beyond the scope of this Thesis. Invariably the coals are underlain by palaeosols, siltstones and claystones containing abundant roots, sand-filled stigmara casts, and sideritic ironstone nodules and layers. They indicate a waterlogged environment co-existing with some overbank sedimentation and largely anoxic soil conditions a short distance beneath the sediment surface. Fielding (1984a) suggests that the coals in the Durham Coalfield are persistent over several hundreds of kilometres, and have a sheet-like geometry, although they exhibit numerous seam splits, especially toward the basin depocentre. They also exhibit thickness variations due to lateral facies changes as the swamp passes into a deeper water lacustrine environment or a shallower water palaeosol equivalent in addition to compositional changes due to variations in the maceral make up of the individual seams. Further complications in the lateral continuity of coal seams may result from washouts by distributary channel and crevasse splay sandbodies

Interpretation: The facies results from the largely authochthonous deposition of the organic detritus of peat swamps (Fig. 4.4) which developed from the prolific growth of hydromorphic vegetation on shallowly submerged (approximately 1 m deep) abandoned surfaces of lake infills and channels systems. Swamp vegetation acted as a sediment filter system so consequently only thin clastic layers form. Fielding (1984a) suggests that coals with clay interbeds were formed in a greater water depth or under conditions of greater subsidence

allowing clastic material from suspension fall out to mix with decaying organic matter. Peat accumulation was generally terminated by high rates of subsidence.

4.2.1.12 Minor distributary channel facies

Description: Fielding (1986) describes minor distributary channels as elongate and in some cases sinuous. They are a few kilometres long and several hundred metres wide, with bankfull depths and consequently thicknesses of up to 6 m (Fielding 1986). The channel fills are variably interbedded fine- to medium-grained sandstones, with finer-grained siltstones and mudstones. Typically they display a distinct fining-upward tendency with basal sandstones of up to 2 m thick, displaying various sedimentary features, overlain by finer-grained material, which decreases upward and grades into the surrounding interfluvial sediments. Other channel fills types may be composed of a single lithology, which may be structureless, or flat-laminated siltstones and mudstones. Epsilon cross-bedding (planar or asymptotic) is seen to occur in approximately 50% of examples (Haszeldine 1984; Fielding 1986). Where alternating sandstone and silty mudstone unit define the individual epsilon foresets. These units fine-upward and are aligned perpendicular to palaeoflow in outcrop and form cosets of up to 4 m dipping 5-15 ° towards the channel axis (Fielding 1986). Abundant ripple cross-lamination and small-scale trough cross-lamination are superimposed on the epsilon foresets and are aligned parallel or slightly oblique to the strike of the epsilon surface (Fielding 1986). Rarely trough cross-laminated sets occupy irregular erosion surfaces within the epsilon cross-bedded sets indicating more complex channel filling processes.

The minor distributary channel fills that do not display epsilon cross-stratification are generally coarser (Fielding 1986) comprising medium- to fine-grained sandstones with small-scale cross-bedded sets, passing rapidly upwards into ripple cross-laminated and flat irregularly-laminated fine-grained silty sandstones and silty mudstones. Abundant drifted plant fragments and stems and bivalve resting traces occur. Palaeocurrent indicators show a low to moderate dispersion with a unidirectional trend.

Interpretation: Fielding (1984a, 1986) suggests that the minor distributary channels form from prolonged crevassing (channel bank breach) of major distributary channels, (Fig. 4.4) whereby the initial crevasse channel conduits pass into minor distributary channels resulting from prolonged sediment transport. Such channels transport sediment across interdistributary areas over previously deposited medial and proximal crevasse splay minor delta systems to the delta front. Minor distributary channels show evidence of high sinuosity, indicated by the lateral accretion of point bars (epsilon cross-stratification), and the repeated channel fills of meandering stream system (Allen 1965), alternatively they are of low to moderate sinuosity (coarser-grained, dominated by trough cross-bedding) and are possibly the distal expression of major distributary channels (section 4.2.1.13). Palaeocurrent data from such channels show

less dispersion. The interbedded nature of channel sandstone types and their channel morphology suggests that the discharge of such perennial channels was not constant. Some incision may occur at the base of such channels which are seen to erode into the underlying interfluvial and crevasse splay deposits, resulting in washouts of the coal seam or several coal seams beneath. They are considered to be the result of single-story channel fills.

4.2.1.13 Major distributary channel facies

Description: Major distributary channels are described from the Westphalian B of Northumberland by Haszeldine (1983a,b) and from Durham by Fielding (1986). They occur in elongate belts a few tens of kilometres long and up to 5 kilometres wide, although exceptionally they may be up to 10 to 20 km wide. They average 10 to 20 m in thickness, consistent with bankfull depths of 10 to 12 m and they are composed predominantly of medium- to coarse-grained sandstone, with locally developed intraformational conglomerate in the basal part. Finer-grained intercalations occur throughout the sandstone especially toward the top. Intraformational conglomerates are clast or more commonly matrix supported (clast content 30 - 50%) with clasts composed of mudstone intraclasts, quartz pebbles and granules, sandstone filled (rolled) plant and root debris and compressed, rafted coalified clasts. They occur as isolated layers up to 50 cm thick overlying the basal erosive surfaces of channel sandbodies or on a smaller-scale overlying laterally impersistent internal erosion surfaces. They occur in largely massive units which may show some clast imbrication or crudely defined cross-lamination. The remainder of the channel sandbody consists of medium to coarse, or less commonly fine-grained sandstone which is poorly sorted, and predominantly trough cross-bedded in sets up to 50 cm thick. These occur singly or are grouped into cosets up to 3 m thick, although large-scale planar cross-bedded sets up to 2 m thick may occur in some channel sandstones. The trough cross-bedded cosets may pass up into minor planar-bedded units (Haszeldine 1983a) and irregular shaped trough cross-bedded sets of decreased coset size which subsequently pass upward into ripple-laminated and flat-laminated fine to medium-grained sandstone. These smaller-scale structures may be superimposed on the larger ones containing claystone and siltstone drapes, that increase in abundance upwards. Eventually the channel sandstone passes into an abandonment facies represented by rippled and flat-laminated silty mudstone with occasional bivalve resting traces, and sediments of the lake margin facies. The channel fill successions, although complex, have been shown by Haszeldine (1983b) at one locality to be downcurrent descending and segregated into distinctive depositional units bounded by erosive surfaces of a number of types. Palaeocurrents show a moderate dispersion about a vector mean for a single locality, but it is uncertain how representative this work is of the overall succession in Northumberland.

Interpretation: Fielding (1986) describes major distributary channel fills as broad elongate bodies (Fig. 4.4) that occur in belts up to 5 km wide which have a multi-storey channel fill nature (Haszeldine 1983a). They may be distinguished from minor distributary channels by their multi-storied nature, grain-size, thickness and predominantly low sinuosity, with concomitant straight geometry. Clast supported conglomerates are interpreted to be channel floor lags, (log jams) and bar surface accumulations (Fielding 1986) whereas matrix supported conglomerates and chaotic units are considered to be bank collapse structures (Fielding 1986). The majority of the fills of these channels are bank attached or medial bars according to Haszeldine (1983a) which may coalesce into platforms (large planar cross-beds) in these low sinuosity channels. Waning of flow is indicated by increased interfluvial deposits (clay and silt intercalations) and gradual decrease in grain size prior to rapid abandonment by interfluvial floodplain sediments.

4.2.1.14 Major stacked fluvial systems

Description: This facies is not seen to have an outcrop expression in the Durham/Northumberland Coalfield, but it may occur in the subsurface, where there is vague reference to unusually thick channel sandbodies (Land 1974). However, it occurs as a major reservoir horizon within Westphalian B sediments in Quadrant 44 where it forms a sheet-like unit deposited in a low sinuosity multi-channel (braided) system that SPM Geos (1993) attribute to a braidplain over 30 km in lateral extent. This major stacked fluvial system is distinguished from major distributary channels by its thickness which reaches a maximum of 40 m, and the predominance of conglomerates and coarse, pebbly and granular sandstones. Conglomerates and pebbly sandstones dominate the basal portion of the channel fills, where they overlie a sharp base. These are similar to those in the major distributary channels in that they are clast or matrix supported and show many of the features described in section 4.2.1.13. They are also seen to occur above frequent internal erosion surfaces which occur throughout the sandbody. These basal conglomerates pass into pebble supported polymictic conglomerates with coarse to medium-grained sand matrix. The pebbles are rounded and composed predominantly of vein quartz or mudstone rip up clasts. They commonly occur in massive units, 50 cm thick, where the cross-bedding is crudely defined by clast imbrication, by finer-grained granules on foresets or by discontinuous claystone drapes. These pebbly units fine into coarse-grained sandstone units that are moderate to poorly-sorted, with poorly defined trough cross-bedding occurring in sets up to 1 m and in cosets up to 5 m. Gradually the pebbly and coarse-grained sandstone becomes medium grained and moderately-sorted with scattered granules forming stacked cross-stratified sets and cosets. SPM Geos (1993) describe various styles and dips of cross-stratification, ranging from small-scale sets of trough cross-stratification with curved lower bounding surfaces and divergent dips (set size 10-20cm) to

larger sets of planar tabular cross-stratified units with localised angular discordances or reactivation surfaces (set size 30-75cm). Low-angled cross-stratification is less commonly developed. Carbonaceous drapes occur on some foresets and are locally concentrated along the lower bounding surface of cosets where they maybe associated with localised intraformational conglomerates.

Above the basal units the stacked major fluvial systems comprise fine-grained, moderately well sorted sandstones characterised by more abundant claystone and micaceous drapes. These define a moderately low-angle stratification which gradually increases in dip. This is organised into sets of 5-50 cm thick and probably represent trough cross-stratified units. Increasingly abundant upward throughout the facies are thin, dark, micaceous and variably carbonaceous siltstone and mudstone intercalations. They typically contain thin, rippled or parallel-laminated fine-grained sandstone laminae.

Interpretation: The conglomerates are high energy upper flow regime deposits (cf. section 4.2.1.13) interpreted as channel floor lags and bank collapse deposits, and those deposits resulting from erosion of the surrounding floodplain. They are abundant in the basal portion of the sandstone suggesting several phases of very high energy flow, which waned gradually during the evolution of the channel system. The coarse-grained deposits above, with their crude bedding suggest continued high energy flows and deposition in the form of channel bars and lags. The crudely developed bars increased in size as flow waned and conditions became more favourable for their preservation as erosion and reworking of previous bars decreased concomitant with decreased current strength. Further evidence for gradual waning flow throughout the life of the channel system is the gradual decreasing grain size. These pebbly bars pass into trough cross-bedded coarse-grained sandstones, that represent migrating bars and subaqueous dunes, under moderate energy flow conditions. Occasional coalescing of these dunes led to the formation of a platform characterised by large-scale planar-cross bedded sets. Periodic reactivation of the bar-forms by higher energy flows led to the deposition of granules on the foresets. Lower flow-stages resulted in the claystone and siltstone drapes that increase in frequency upward, recording temporary channel abandonment and deposition of low-stage fines consistent with a gradual waning of flow. The low-angled cross-lamination at the top of the sandbody records the migration of small subaqueous dunes or megaripples under low energy flow conditions superimposed on the larger bedforms, with the abundant drapes indicating periods of inactivity and waning and shallowing of the flow across channel bar-tops. This culminated in abandonment fines of various interfluvial floodplain lithologies deposited on top of the channel sandstone and at various stages in the upper to middle portion of the channel sandstone. Although little information is available about the geometry and extent of these sandbodies. I envisage a broad straight channel similar to major distributary channels (section 4.2.1.13) but of a larger scale (Fig 4.4).

4.2.2 Coal-bearing alluvial plain association

4.2.2.1 Introduction

This facies association was introduced in section 4.1.3 and is briefly summarised here based on the work of Besly (1988), Besly and Fielding (1988) and Besly et al. (1993). This facies association records the sedimentological transition both laterally and vertically between the poorly drained upper delta plain / coastal alluvial plain deposits of the "productive" Coal Measures (Fig 4.2) and the well drained alluvial "red beds" of the Etruria formation (Besly and Fielding 1988), which are the United Kingdom onshore equivalent to "red beds" described from the offshore (Besly et al. 1993). In studies from the onshore United Kingdom by Besly and Fielding (1989) this association is restricted to the northern flanks of the Wales-London-Brabant massif during the Westphalian A and B but becomes more widespread in the late Westphalian B to early Westphalian C. Besly and Turner (1983) describe an interdigitation of this association (Fig. 3.16) with the lower poorly drained Coal Measures, which become increasingly better drained toward the Westphalian C, with units tapering to the north (basinward) and passing into poorly drained sediments. This complex relationship suggests that in marginal areas the onset of better drained conditions will be earlier and that in transitional areas there will be periods of well drained and poorly drained conditions possibly controlled by base level fluctuations and thus sediments that reflect this. Conversely in the basin depocentres poorly drained Coal Measures may well be the lateral facies equivalents of these facies.

The late Westphalian B and early Westphalian C sediments in the Southern North Sea appear to mirror the effects noted on the flanks of the Wales-London-Brabant massif by Besly and Turner (1983) with the onset of the better drained alluvial association occurring at an earlier time (late Westphalian B) in well 44/18-1 (section 6.2.4) according to palynological and marine band evidence. A gradual improvement in drainage conditions occurs that eventually leads to the establishment of prolonged well drained conditions. In well 44/21-3 (section 6.2.3) well drained sediments overlie poorly drained Coal Measures although poorly drained intercalations occur within this predominantly well drained association, thus producing a complex relationship similar to that noted by Besly and Turner (1983) (Fig. 4.5) in the United Kingdom onshore. Coeval with these deposits are those in well 44/28-2 in which poorly drained Coal Measure deposits continue up until the early Westphalian C, (Fig. 4.2) as confirmed by the positive identification of the *Cambriense* marine band. Well 44/28-2 and closely associated wells (section 6.2.2) are the thickest in Quadrant 44, being more marginal and close to a major depocentre (Collinson et al. 1993) with the result that subsidence and

relative base level was at a maximum and conditions remained waterlogged up to the lower Westphalian C.

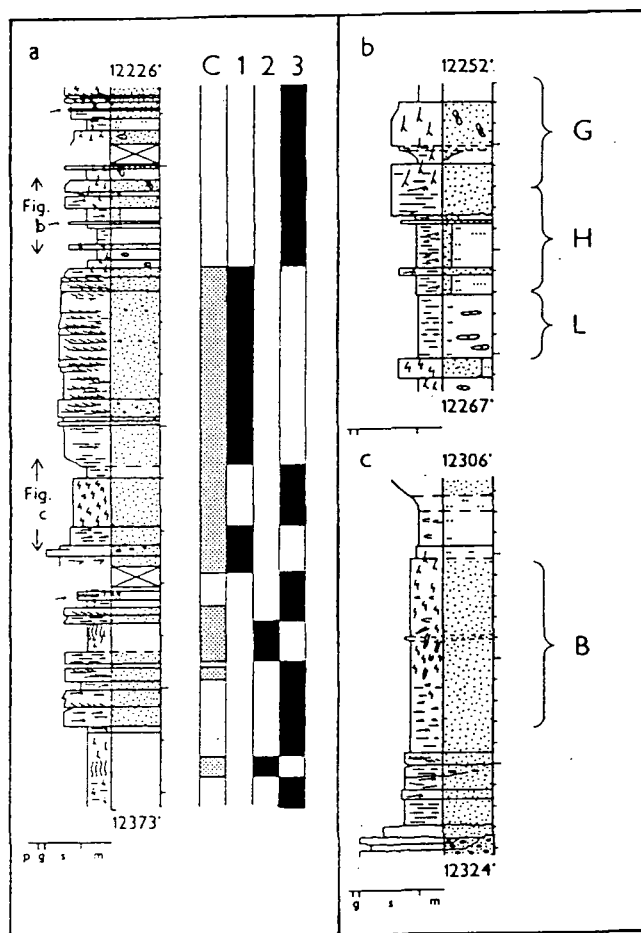


Fig. 4.5 Sedimentological log extract : UK Well 44/28-2 After Besly et al. (1993). Stippled pattern in column C indicates distribution of red pigment. 1: channel and mouth-bar; 2: well-drained floodplain with evolved palaeosol; 3: initially waterlogged floodbasin, penetratively oxidised. Red pigment is associated with major sandstone units. Abbreviations are as follows. G: gley palaeosol; H; interlaminated, rippled sandstone and siltstone; L: laminated shale with *Orbiculoidea*; B: intensely bioturbated sandstone.

The broad coastal alluvial plain may have had a more significant palaeotopographic variation at this time, allowing more marked facies association variation to occur. This was not the case

during the lower / middle Westphalian B when conditions were essentially similar across the entire plain. Topographic variation may have resulted from slight tilting of the palaeoslope due to reactivation of Caledonian fault trends during late stage Variscan tectonics. Westphalian C sediments support this hypothesis as they are characterised in the Southern North Sea by alluvial fans prograding from uplifted highs (ARCO pers. comm.) which are considered to be a continuation of this tilting process and closely allied to granite cored blocks. Simple filling of the Variscan foredeep depocentres, under conditions of decreased subsidence but continued sediment supply would lead to better drained conditions being established, concentrated around areas of high sediment input such as terminal fans. This provides a lobate topography as described by Besly (1988) in the Warwickshire/Staffordshire coalfield where well drained intercalations are associated with the underlying terminal fans, due to the elevated topography. This would occur primarily on the margins of the basin and only after continued infill and gradual aridification will well drained conditions reach the basin centres. Highs appear to be associated with the Mid North Sea High (Fig. 1.3) and adjacent areas (Elbow Spit High) where the increased elevation results in better drained conditions (44/18-1).

4.2.2.2 Coal-bearing alluvial plain facies

This facies association contains most (Fig 4.1) of the facies described in the upper delta plain/coastal alluvial plain association and only the palaeosols which are poorly represented in the upper delta plain/coastal alluvial plain are described here. Where there is evidence for a different emphasis in the relative abundance of facies within this predominantly better drained facies association, this is also discussed.

The facies are alluvial sediments and gley palaeosols (Besly and Fielding 1989) that were deposited on a continuously emergent or semi-emergent floodplain, where sedimentation rates matched subsidence. The floodplain was characterised by the consistent formation of swampy waterlogged palaeosols, where the depositional surface is very close to watertable and only rarely is accommodation space adequate for the formation of thin coals. This lack of accommodation space, as subsidence no longer outpaces sediment supply, results in the lack of extensive, deep lacustrine environments (cf section 4.2.1) and facies. A bi-product of this lack of lacustrine environments is the lack of prograding minor crevasse splay delta systems since the space was no longer available for them to fill. Instead crevasse deposits are characterised by proximal crevasse channel deposits and coarse-grained overbank sheet-floods, largely comprising fining-upward sharply-based sandstones, that maybe very coarse to fine-grained; their sheet-like geometry reflects the lack of accommodation space on the floodplain whilst their coarse-grained nature results from the lack of lacustrine floodplain fines available for entrainment and reworking. The parent channels sourcing these floods are

typified by low sinuosity major distributary channels, transporting coarse-grained bedload sediment as dune bedforms producing trough cross-stratified channel fills. In the United Kingdom onshore succession, Besly (1988) identifies upward-fining, laterally accreted sandstones deposited by northly flowing meandering channels. However, the situation in the Southern North Sea is different in that the channels were derived from a source to the north or northwest (ARCO pers. com.). They carried a coarser grained sediment load and occupied a more proximal position than the poorly drained Coal Measures. Thus, they were of a lower sinuosity and the lack of fining-upward minor distributary channel sandstones attributed to high sinuosity channels, is reflected in the lack of minor lacustrine crevasse splay delta systems of which they formed the main feeder channels. The floodplain areas are characterised by the monotonous development of palaeosols (Besly and Fielding 1989). These overlie rare lacustrine flooding surfaces and contain infrequent coals, which reflect a high stand in relative base level and may equate to marine bands in basinal areas. Large parts of the succession consist of stacked palaeosols of various stages of evolution, possibly reflecting local relative base level changes.

4.2.2.3 Palaeosols

The waterlogged nature of the Westphalian B upper delta / coastal alluvial plain led to a predominance of organic soils, alluvial soils and hydromorphic gleys (Besly and Fielding 1989). Towards the late Westphalian B to early Westphalian C partial or temporary drainage occurred resulting in a wider variety of profile types and palaeosol features (Besly and Fielding 1989). Five types of palaeosol have been recognised in these coal bearing associations and are described in detail by Besly and Fielding (1989). The characteristics of the palaeosols, based Besly and Fielding (1989), are summarised in Fig. 4.6.

The palaeosols preserved within the upper delta plain / coastal alluvial plain are mostly isolated in occurrence, although most commonly they show a vertical transition from alluvial soils upward through gley, into organic (coal) palaeosol types. The process accounts for the majority of the coal seams within the Pennine Basin, where coals occur above a seatearth (gley palaeosol), although rarely they may occur above an alluvial palaeosol. Besly and Fielding (1989) suggest a genetic relationship whereby peat swamps only develop after the establishment of plant communities and gley soil formation.

Interpretation	Colour	Horizonation/ profile thickness	Organic remains	Iron	Other remarks
<i>Immature palaeosols</i> Grey alluvial soils	Grey to white	None; palaeosol features developed over several m	Carb. rootlets, roots; <i>Stigmaria</i> ; <i>Calamites</i>	Sporadic siderite concretions	<i>Calamites</i> predates <i>Stigmaria</i> in some sections; roots terminate at different levels in profile
<i>True hydromorphic palaeosols</i> Reduced gley soils	Grey/white, rare brown/ochre mottle	Rare colour mottle in topmost part of profile only; carbonate nodules conc. in same zone; profiles mostly 1.00-1.50 m	Carb. rootlets, roots; <i>Stigmaria</i> ; various plant debris	Siderite and other carbonate concen- trations and disseminated cement throughout	
<i>Organic hydromorphic palaeosols</i> Eutrophic peats	Black	Compositional banding; profiles mainly up to 2 m thick, exceptionally up to 8 m	Dominant; mainly vitrinite; minor exinite/inertinite; clastic component; inertinite-rich layer at base of some seams; lenses of fusinite	Disseminated and nodular pyrite (< 5%)	Preserved as coal seams; clastic component disseminated or as thin partings
<i>Partly drained palaeosols</i> Low humic gley and semi-gley soils	Grey to white; brown/cream/red or mottled upper zone	Upper, oxidised, coloured zone — Go; lower reduced zone — Gr; profiles up to 2 m; thicker profiles usually stacked	Carb. rootlets and roots; in places as oxidised traces	Nodular and dissem. siderite and sphsids nodules commonly vert. orientated, around root traces; vert. zonation of sphsid	Desiccation cracks
<i>Well drained palaeosols</i> ? Podzolic soils	White upper layer; cream/brown/red lower layer	Upper quartz-arenite unit; lower clay-enriched layer; profiles 0.5 — 2.00 m	Carb. rootlets and root traces	Rare sphsid	Various micromorpho- logical features; quartz arenite layer partly relic sedi- mentary feature

Fig. 4.6 Characteristics of palaeosols developed in coal-bearing facies associations, Westphalian A-C, Central and Northern England. Table II of Besly and Fielding (1989).

In alluvial coal bearing sediments low-humic gley and semi-gley palaeosols are the more common, and palaeosols of this group are interpreted by Besly and Fielding (1989) to have formed as a result of lowering of the watertable (relative base level). Consequently overlying the lower waterlogged part of these profiles, the soil shows evidence of increasing desiccation and oxidation upward. Profiles of this type, from well 44/28-1 (Fig. 4.7) are up to 2 m thick and may form thick stacked sets that characterise the majority of the late Westphalian B sediments. They are composed of grey to white silty clays, siltstones and thin, fine sandstones becoming mottled brown and red upward, with abundant carbonaceous roots and rootlets, which form oxidised traces upward through the profile. Vertical orientated nodular and disseminated siderite and vertically zoned sphaerosideritic nodules commonly occur around root traces. Occasional desiccation cracks occur in the upper zones of these profiles.

4.2.3 Well drained "red bed" alluvial facies

Besly et al. (1993) consider most of the red bed succession encountered in wells in the United Kingdom sector to be of Westphalian C age (Fig. 4.2) based on palynological analysis. They note that a lateral facies transition occurs between red beds and the underlying Coal Measures in the Westphalian C, but as argued in section 4.2.2.2 they used wells 44/28-1 and 44/21-3 to demonstrate that the onset of alluvial coal-bearing strata began earlier in 44/21-3. This is also seen in 44/18-1, where the onset of alluvial coal-bearing strata is late Westphalian B in age. Taking this argument further, if the onset of transitional coal-bearing alluvial sediments is earlier as shown by well 44/18-1, then it is likely that the onset of true red beds may be earlier also. The sediments of potential red bed association, of Westphalian B age, resemble those encountered in the extensively cored section of red beds in 44/28-1 which are dominantly fluvial, containing single- and multi-storey braided channel deposits assigned to major distributary channels facies and stacked major fluvial systems facies. They are interbedded with intensely root penetrated overbank sediments, similar to those described in section 4.2.2.3, but contain increasingly more mature, oxidised and leached ferruginous palaeosols. These form profiles up to 3 metres thick, which are superimposed to form complex units up to 8 metres thick (Besly 1988). Coals are very rare, if not absent.

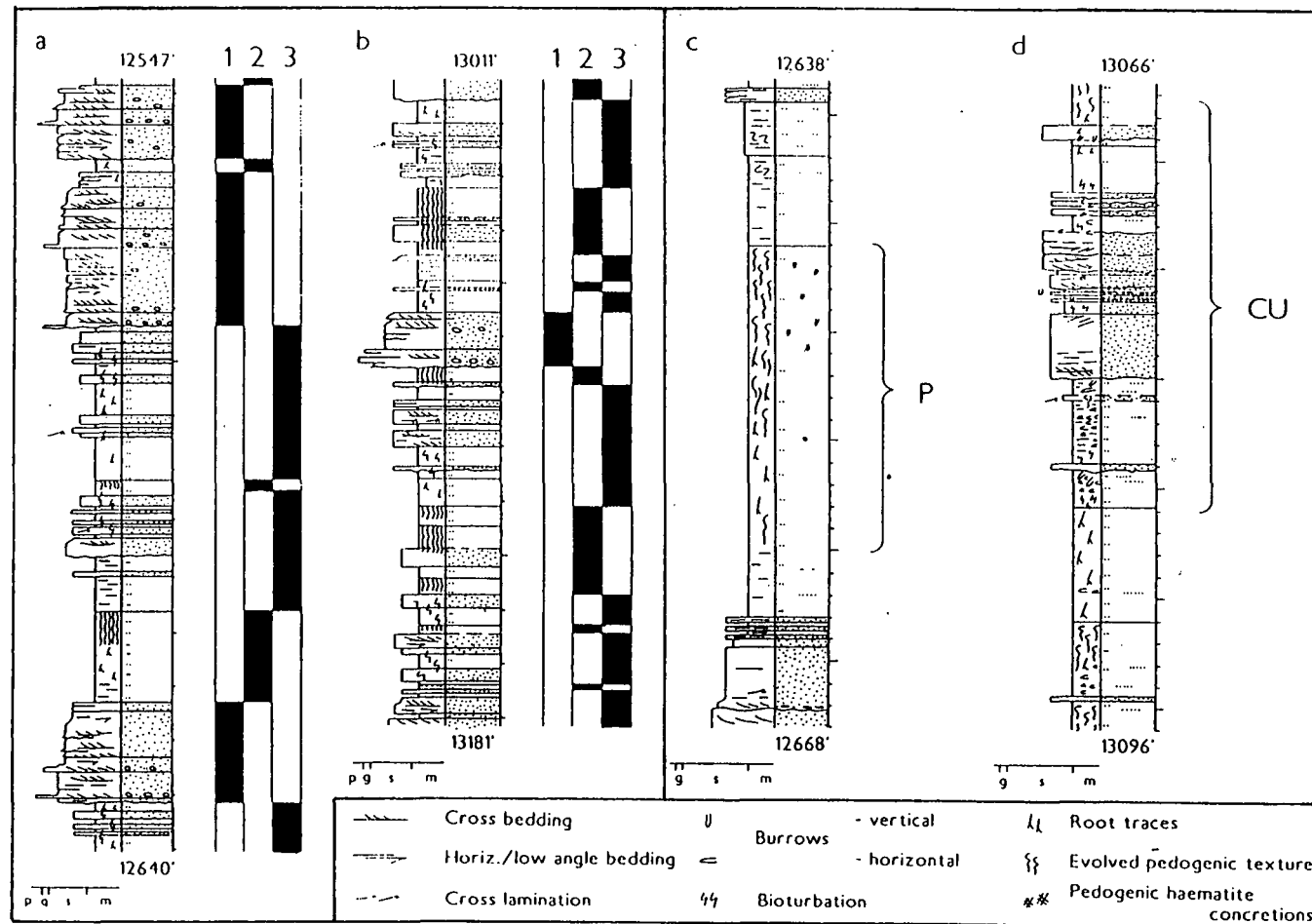


Fig. 4.7 Sedimentological log extracts : UK Well 44/28-1 After Besly et al. (1993). Facies interpretation in Figs 7a and 7b is as follows. 1: major alluvial channel; 2: well-drained floodplain with evolved palaeosol; 3: initially waterlogged floodplain, penetratively oxidised. Abbreviations in Figs 7c and 7d are as follows. P: evolved palaeosol; CU: coarsening- / shallowing- upward pattern in floodplain lake fill package.

4.3 Quadrant 44 Facies Identification Scheme

4.3.1 Introduction

The facies associations described in detail in section 4.1.1 for Westphalian B sediments, were used to establish a workable facies identification scheme which would enable the common Westphalian B facies (Fig 4.3) to be easily identified in core material. This can then be calibrated with typical wireline log response to give a ubiquitous facies identification scheme that allows eight major wireline log facies associations (Fig. 4.8) or WILFS (Leeder et al. 1990) to be identified. This enabled the facies distribution to be established and thus provides the basis for palaeogeographic reconstructions, depositional modelling and identification of sequence boundaries within the succession. This in turn enables the major flooding surfaces and systems tracts to be determined from facies stacking patterns, thereby allowing for a sequence stratigraphic framework to be established.

As wireline logs can only essentially be used to define lithologies, the relative proportions of the individual lithologies within the facies are the controlling factor for facies determination. Wireline logs are thus incapable of discriminating between small-scale lithological and therefore facies contrasts and changes. Consequently the identification of individual facies that reflect subtle variations in depositional environments is difficult, even in core material, due the lack of lateral constraint. This is especially true of facies that require geometrical dimensions to be assessed (e.g. levees), plan views (e.g. sheet-floods), or the relative facies variations and positions to be established (e.g. distal / medial crevasse splays) and which are indistinguishable in core material due to the limited diameter of the core material. This also includes many of the overbank and lacustrine deposits described in section 4.2.1 where lithologies and sedimentary structures are very similar. Also the various crevasse splay deposits which require their relative position on the minor crevasse splay delta system to be established, are composed of sands of similar grain size and structures and are indistinguishable in core material. Minor distributary channels can also be problematical as they grade into distal feeder channels on top of crevasse splay deltas and may look very similar in core to crevasse channels. As a result it was necessary to group the closely related facies on a lithological basis, thereby simplifying the lithofacies scheme into distinctive wireline log facies associations (WILFS) similar to Leeder et al. (1990), working on a Namurian section in well 48/3-3, and Church and Gawthorpe (1994) working on a Namurian well database in the East Midlands. Thus clearly identifiable and distinctive WILFS are identified, both in core and subsequent wireline response. They then can

then be assigned typical wireline log response characteristics so that facies analysis can be undertaken on intervals where there is no cored data, only wireline response data.

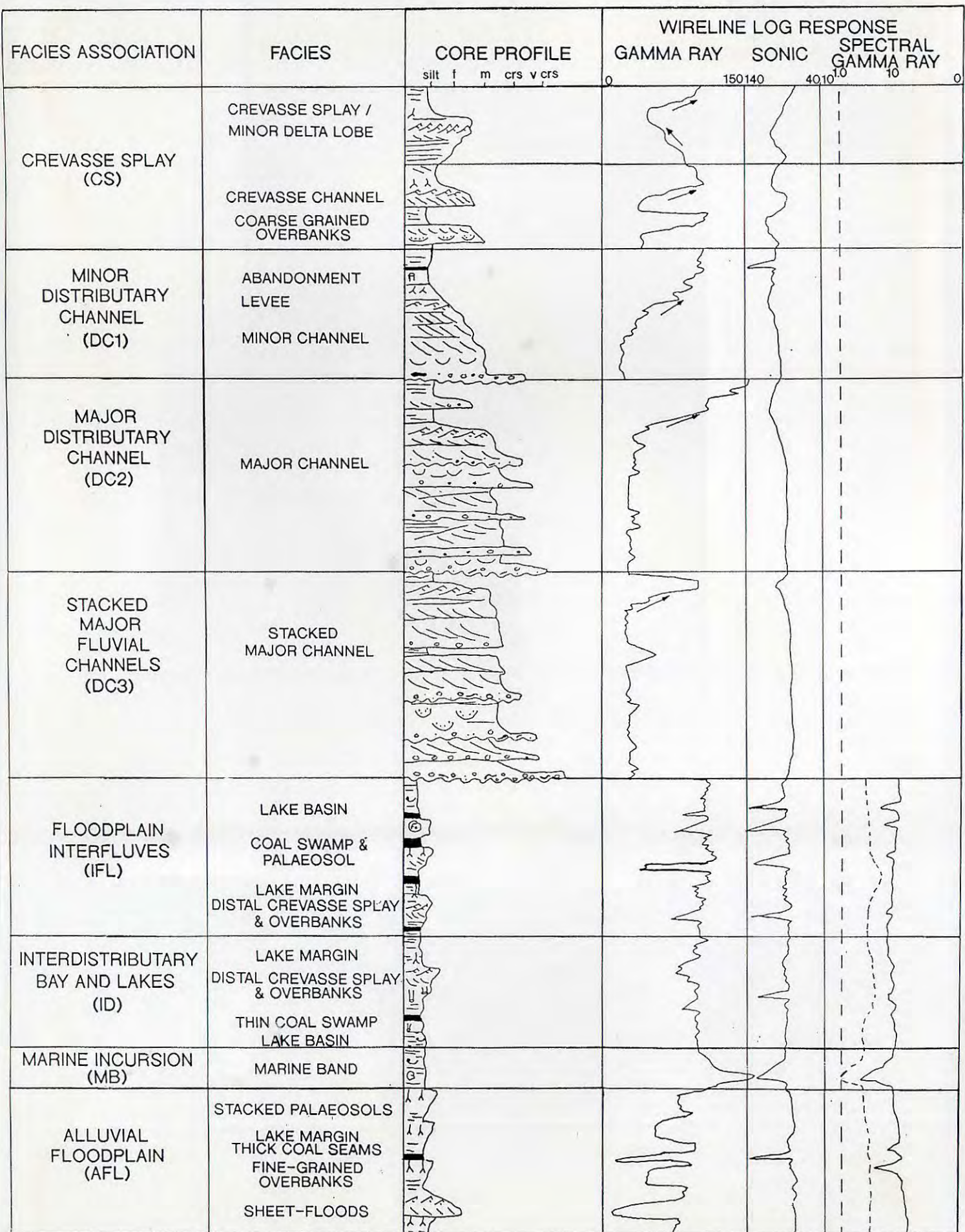


Fig. 4.8 Summary of Westphalian B Wireline log facies associations (WILFS).

4.3.2 Geophysical logs

Geophysical logs typically run on Quadrant 44 wells include gamma ray, natural gamma ray spectrometry (NGS), sonic, density, resistivity and caliper. The responses of these logs run across the complete spectrum of Westphalian B facies in cored intervals allowed facies assigned core to be equated (calibrated) to the distinctive responses of the logs. The closely associated facies grouping are thus identified as WILFS (Leeder et al. 1990).

4.3.3. Wireline log facies associations (WILFS)

4.3.3.1 Crevasse splay WILF (C/S)

Within this facies association are all the crevasse splay and crevasse channel facies described in section 4.2.1.5 to 4.2.1.7. The crevasse splay WILF (Fig. 4.9) is characterised by high frequency interbeds of clean to argillaceous, coarse to fine-grained sandstones, interbedded with siltstones and mudstones (Fig. 4.10). It ranges in depositional environment from distal crevasse splay silty mudstones to proximal crevasse channel, that may be dominated by intraformational conglomerate and coarse-grained sandstone. Indistinguishable on log response alone are levee sediments which are predominantly coarse-grained overbank deposits (including sheet-floods) characterised by thin sandstones, siltstones and mudstones. Palaeosols may also be included within this log association, especially where they are not overlain by coals. If a palaeosol occurs at the top of a coarsening-upward crevasse splay delta system that is subsequently drowned, no distinct lithological change has taken place allowing for any unequivocal identification. The sandstone content throughout the facies association is generally high, although the sandstone beds themselves are thin, predominantly fine- to medium- grained and often dirty (argillaceous), as indicated on log response. Where they taper to the distal end of crevasse splay delta systems they may grade into the floodplain WILFs.

4.3.3.1a Crevasse channels and associated subfacies

The proximal crevasse channel facies is the only facies within this WILF that may be distinguished on log response alone. It has a very characteristic log motif (Fig. 4.9) but is included within this WILFS because of its obvious close association with the other facies within the WILF. In cases where crevasse channels reach exceptional thicknesses they may grade into minor distributary channels. However, as the conditions of deposition of the two facies on top of the minor crevasse splay delta systems are very similar in this case, it is not a significant problem.

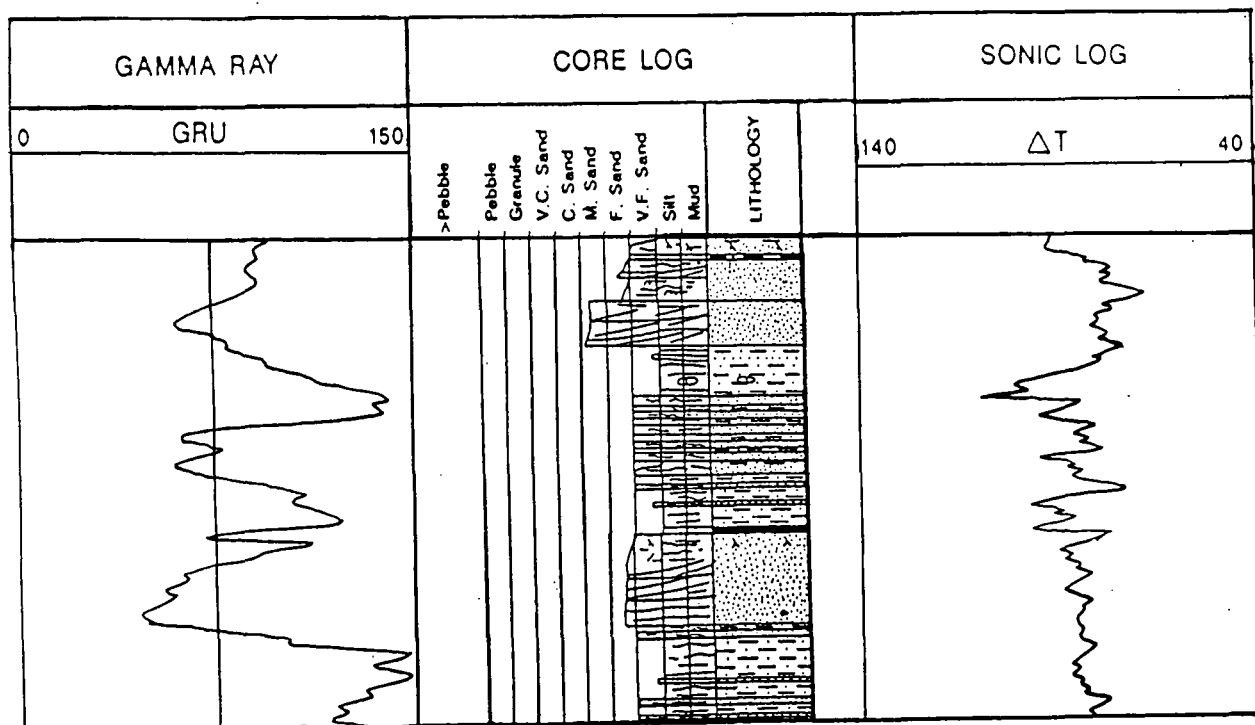


Fig. 4.9 Synthesised core profile and typical wireline log response of the crevasse splay WILF illustrating crevasse splay sandstones from several wells in Quadrant 44. These consist of predominantly fine grained sandstone, interbedded with mudstones, siltstones and occasional medium to coarse grained sandstone organised into coarsening-upward packages, often repeated, representing crevasse splay lobes. Alternatively they consist of crevasse channel sandstones, comprising medium-grained sandstone that fines-upward from a sharp base. Log response reflects this variety, showing upward-increasing or upward-decreasing profiles of moderate gamma and sonic response. Scale 1cm = 10'.

In the better drained late Westphalian B to lower Westphalian C succession (44/18-1) sheet-floods are more important than crevasse splay delta systems, and as these have a very similar log motif to proximal crevasse channel systems they are included within this WILF.

Wireline log response. This shows a sharp-basal inflexion on gamma ray, indicating an influx of coarse to medium-grained generally clean sandstone (occasionally intraformational conglomerate), and within 3 m or exceptionally 5 m it fines-up through a serrate or bell shaped log response. It may unusually have a smooth, very low gamma with rapid top inflexion

(abandonment) indicating a possible sheet-flood origin. The thickness generally distinguishes this subfacies from channel deposits (Fig. 4.9).

4.3.3.1b Crevasse Splay and associated subfacies

The crevasse splay facies and the associated levee and palaeosol deposits that cannot be distinguished on wireline response are typified by an upward-coarsening, sand-rich core profile (Fig. 4.9). This is characterised by an upward-decreasing mudstone and siltstone content and concomitant increase in sandstone content and grain-size. The scale of sedimentary structures is also seen to increase upward, from flat-laminated to rippled, and even cross-bedded sets, and abundant soft-sediment deformation features. The top of the coarsening-upward package is marked by bioturbation and occasionally abundant rootlets (cf palaeosols) occurring within ripple cross-laminated sandstone. This surface may be capped by a coal or the succession may be capped by a minor distributary channel. Included are the proximal and medial crevasse splay deposits of Fielding (1984a) which consist largely of thin sandstones of various grain-sizes that coarsen-upward or consist of bulk coarsening-upward packages composed of stacked minor fining-upward beds (<1 m thick). Producing small-scale complex sandbodies 1 to 5 m thick, this coarsening-upward profile reflects the progradation of the minor crevasse splay delta systems into lacustrine environments. The supply of sediment to these lacustrine delta systems may be shut off gradually where the core profile is seen to gradually fine-upward (Fig. 4.9) via stacked coarsening-upward packages, or it is shut off abruptly leading to intense rootlet horizons and seatearths with coals. These occur above bioturbated horizons overlain by lacustrine mudstones above, showing that the supply was shut off before the system had time to reach emergence. These various processes are reflected in wireline log response. Minor coarse-grained overbank deposits are small-scale, thin, fining-upward, argillaceous sandstones and may have similar responses.

Wireline log response. The wide variety of rapidly interbedded lithologies and variations of package components, with both coarsening-upward and fining-upward trends mean that this WILF is characterised by a very "ratty" log response. Where thin, dirty sandstones show predominantly coarsening- and cleaning-upward trends. They display an erratic, upwardly decreasing gamma ray that produces a funnel-shaped response, 1 to 10 m thick, consisting of thin serrate bodies (sand beds) that smooth-upward (Fig. 4.11) as they become more proximal. This may have a mirrored (although usually thinner) fining-upward response above, which reflects the gradual waning of sediment supply, or alternatively it may be cut off rapidly by a gamma low and sonic peak induced by a coal seam capping the minor delta system (Fig. 4.9). Conversely a sharp-based fining-upward package may indicate a minor distributary channel. The distal expressions of these crevasse splay systems interbedded with high gamma lacustrine mudstones produces a very serrated gamma profile with little overall trend.



Fig. 4.10 Photograph of coastal exposure of crevasse splay sandstones interbedded with lacustrine mudstones at St Mary's Island (NZ353755). For location see Fig. 4.4b

4.3.3.2 Interfluvial Floodplain WILF (IFL)

The interfluvial floodplain wireline facies association consists of a variety of floodplain facies (Fig. 4.3) that cannot be successfully distinguished from other facies on wireline response alone. It comprises the lacustrine facies, overbank fines and the swamp facies, all of which are composed of similar lithologies in various proportions, predominantly mudstones and siltstones with thin fine-grained sandstones and abundant thick coal seams. The relative proportion of these different lithologies and the facies that they represent helps to distinguish this wireline facies association from all others, especially the interdistributary bay and lake WILF and the alluvial floodplain WILF, with which they show the closest similarity (Fig. 4.8). The frequency and thickness of coal seams is at a maximum in this facies, and is the distinguishing feature (cf interdistributary bay and lake WILF and alluvial floodplain WILF). The coal seams generally (Fig. 4.11) are between 0.5 and 4 m thick and are drowned by lacustrine flooding surfaces containing occasional non-marine bivalves. These are thin bands which quickly pass into lake margin silty mudstones, or distal minor crevasse splay deposits

composed of thin fine-grained sandstones, siltstones and mudstones, two facies which can only be distinguished in cored material. Frequently these pass into crevasse splay WILF deposits that are subsequently capped by palaeosols and fine-grained overbank deposits located beneath the succeeding coal seam. Alternatively, complete intercoal intervals may be made up of silty distal crevasse and overbank deposits (Fig. 4.12) infilling lakes. Coal seams, overbank siltstones and palaeosols frequently occur in abandonment sites associated with fluvial facies which are part of the interfluvial floodplain WILF.

The interfluvial floodplain WILF contains all constituents of the swamp deposits, including all the coaly lithologies and the poorly drained palaeosols described by Besly and Fielding (1989), and the various lithologies contained within the palaeosol facies. The abundance of coals and palaeosols suggest that the relative stand in base level of this WILF is higher than alluvial floodplain WILFS and lower than interdistributary lake and bay WILF. Fielding (1984a) describes a number of lake facies : suboxic (anoxic), passive (lake margin) and outer minor delta overbank deposits. These different lake facies reflect variations in the relative base level stand. Suboxic lakes, hereafter referred to as anoxic lakes, represent the deepest most extensive lakes and consequently, have the highest gamma ray response. These are often found in the interfluvial floodplain WILF occurring above coal seams as flooding surfaces, although they are much more common in the interdistributary bay and lake WILF (Fig. 4.8) and appear to have an inverse relationship to coal seam thickness and abundance. Conversely in the alluvial floodplain WILF (Fig. 4.8), these deposits are rare and represent only sporadic flooding of the floodplain.

Wireline log response. It is typified by moderate to high gamma response (Fig. 4.13) that generally decreases and cleans-upward from a high to moderately high gamma drowning surface above a coal seam, to moderate, serrated response indicating increasing silt content, often culminating in a major coarsening-upward crevasse splay WILF. Intermittent sharp "spikey" low gamma high sonic peaks indicate frequent thick coal seams, with a marked "kick" on the caliper neutron density and resistivity. Also, they generally have very low thorium and uranium levels on natural gamma spectrometry. Seatearths or palaeosols beneath the coals are often enriched in potassium and thorium due to increased organic and clay content and thus often have a higher gamma response than the crevasse splay sandstones they sit on. Intercoal intervals may be completely composed of lake or lake margin deposits and palaeosols, giving a moderately high but "ratty" log response. Fluvial abandonment, typified by lithofacies of the interfluvial floodplain WILF is marked by distinctive high gamma responses or coal spikes within or above fluvial channel systems.



Fig. 4.11 Photograph of coastal exposure of interbedded interfluvial floodplain sediments, lacustrine mudstones, palaeosol and a coal seam at St Mary's Island (NZ353755).



Fig. 4.12 Photograph of coastal exposure of interbedded interfluvial floodplain sediments, lacustrine mudstones and distal crevasse splay sandstones at St Marys Island (NZ353755).

4.3.3.3 Interdistributary Bay and Lake WILF (I/D) ;

As discussed in section 4.3.3.2 this WILF reflects a higher relative base level stand than the Interfluvial floodplain WILF (Fig. 4.8) and includes a predominance of lacustrine facies as described by Fielding (1984a) and Haszeldine (1984), and summarised in section 4.2.1.8 to 4.2.1.10. The lakes were deeper and more laterally extensive than those in the interfluvial floodplain WILF, as evidenced by the predominance of anoxic dark grey shales and abundant lacustrine fauna (non-marine bivalves) which are commonly seen in cored material (Fig. 4.14). These lakes were initially distant from active crevasse splay delta systems and distributary channels, and thus have a paucity of clastic input. This clastic content gradually increases upward as the lakes were infilled, primarily by distal crevasse splays consisting of siltstones and fine-grained sandstones prior to invasion by major prograding crevasse splay lobes (crevasse splay WILF). These are often characterised by subsequent drowning before emergence, and as a result they have a bioturbated top instead of a coal seam. This is further evidence that the lakes were initially deeper environments. Thin coal seams are present, including cannel coals and carbonaceous claystones, both of which show similar wireline response characteristics. However, many of the thin coal seams may be under represented, because they are too thin to be resolved by modern logging tools. Some intergradation may occur between the interfluvial floodplain WILF and the interdistributary lake and bay WILF (Fig. 4.8) reflecting the possibility of a complete spectrum of relative base level stands that control these facies associations.

Wireline log response. The distinguishing feature of the interdistributary bay and lake WILF are the predominance of high gamma lacustrine mudstones seen in the core as dark grey mudstones containing abundant non-marine bivalves (Fig. 4.14). The high gamma signature (Fig. 4.15) may be due to a high uranium concentration, determined from the spectral gamma ray logs, which may correspond to a high broad sonic peak. The lacustrine mudstones characteristically occur above coal seams and are characterised by a continued smooth high gamma signature which stays roughly consistent. This distinguishes this WILF from others, thereby reflecting the considerable time period necessary for crevasse splay delta systems and minor distributary channels to prograde into these lakes. These high gamma lake packages may be 20 m thick or occupy complete intercoal intervals. Generally they then coarsen- and clean- upwards in to the crevasse splay WILF. Repeated stacking of sediments of the interdistributary bay and lake WILF and the crevasse splay WILF produce a succession typified by high gamma lake facies and thin coal seams which are characterised by moderately low gamma and high spiky sonic. Alternatively they pass from high gamma deep lakes into a lower gamma interfluvial floodplain WILF reflecting a gradual decreasing base level.

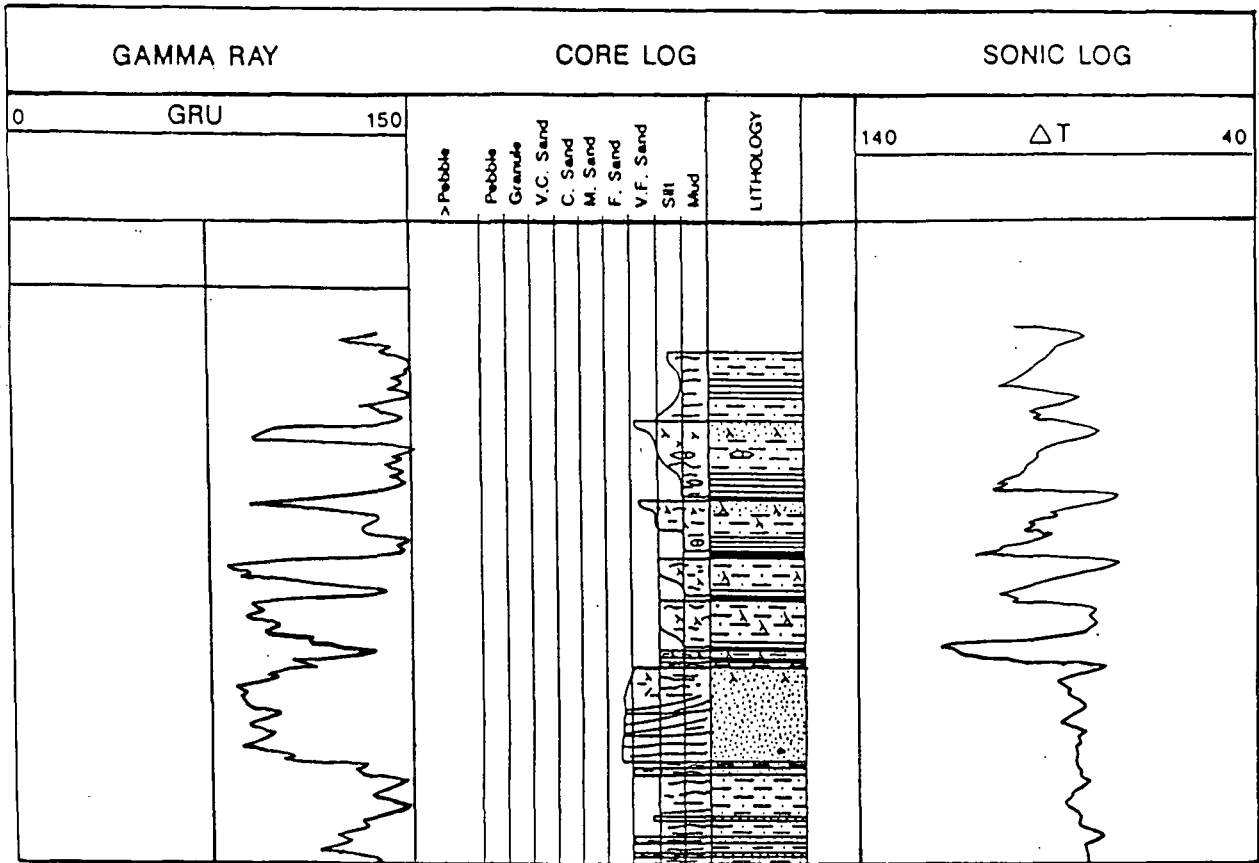


Fig. 4.13 Synthesised core profile and typical wireline log response of the interfluvial floodplain WILF generated from several Quadrant 44 wells. This consists of a series of interbedded mudstones, siltstones and very fine grained sandstones and abundant coals forming coarsening-upward packages representing the infilling of floodplain lakes. Log response: relatively high gamma response in upper part of increasing-upwards profiles, relatively low sonic response. Lake deposits have relatively high gamma and high sonic. Scale 1cm = 10'.

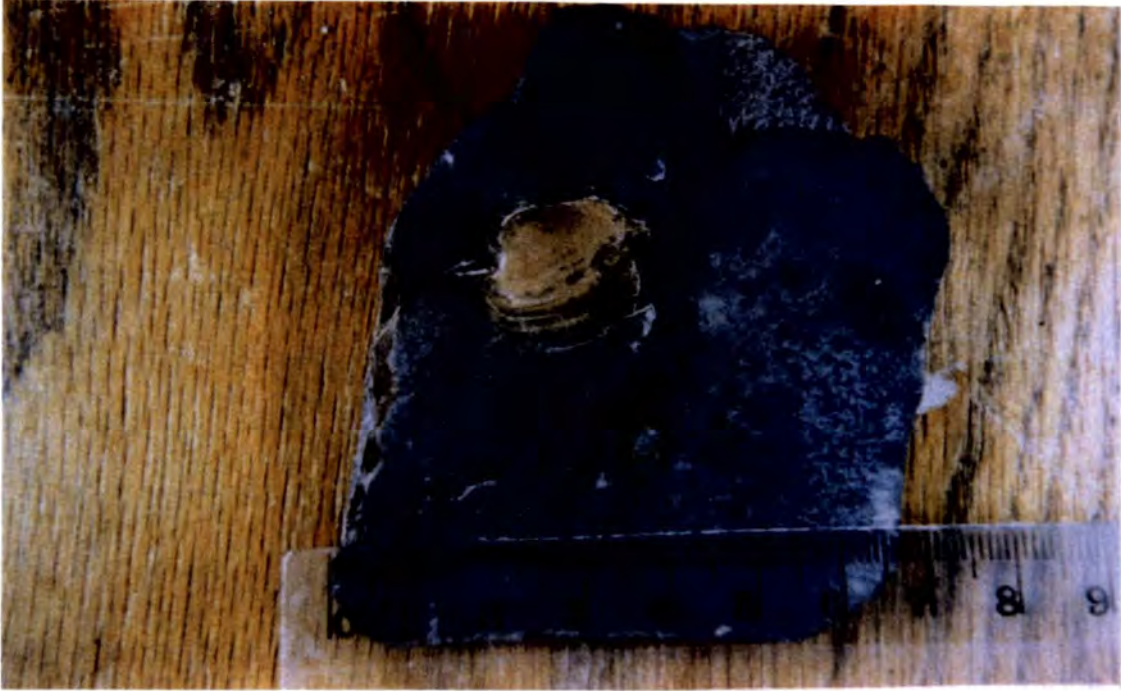


Fig. 4.14 a) Photograph of a non-marine bivalve from the Low Main Mussel band, outcropping at Hartley Bay (NZ344758).



Fig. 4.14 b) Photograph of typical inter-distributary lake deposits immediately above the upper Seaton Sluice Sandstone (Turner and O'Mara 1995) at Crag Point (NZ342761).

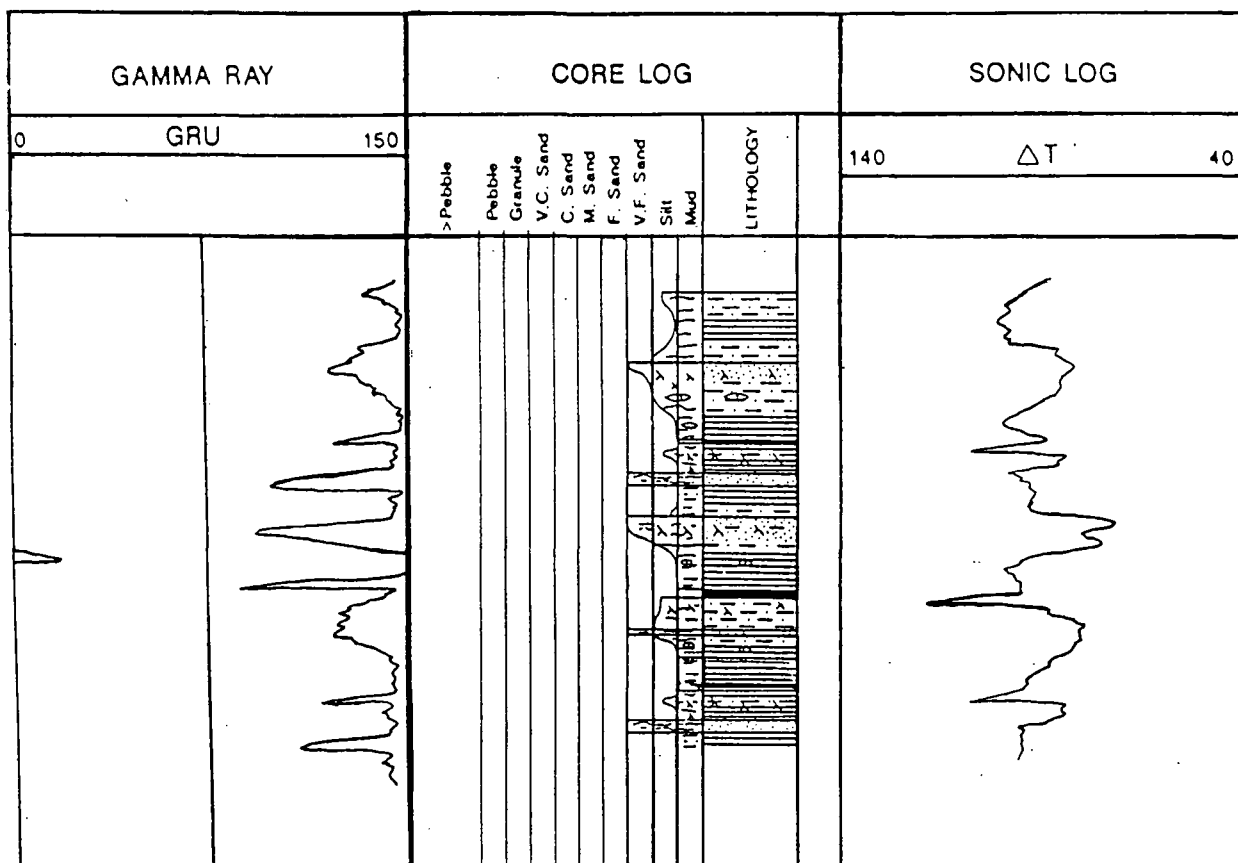


Fig. 4.15 Synthesised core profile and typical wireline log response of the interdistributary bay and lake WILF generated from several Quadrant 44 wells. This consists of packages of predominantly dark grey mudstones, with subordinate siltstones, fine grained sandstones and thin coals. Showing a small-scale upward-coarsening core motif. Log response: high to very high gamma response with upward decreasing profiles, interspersed with low gamma thin coals and distal crevasse splay sandstones. Scale 1cm = 10'

4.3.3.4 Marine Band WILF (MB) ;

This facies association has been dealt with in detail in Chapter 3. It has a very distinctive lithofacies and faunal content that necessitates a separate wireline log facies. The distinctive wireline log response summarised in Fig. 4.8 was also discussed in detail in Chapter 3 and the reader is referred to this chapter for discussion.

4.3.3.5 Minor distributary channel WILF (DC1)

The channel sandbodies which are distinguished on grain-size and thickness compared to core and log profile, reflect deposits of channel systems of different sizes and sinuosities.

Minor distributary channel WILFS (Fig. 4.16) are comprised of predominantly one facies, the minor distributary channel facies with minor amounts of interfluvial floodplain abandonment facies. In some cases they are indistinguishable from proximal crevasse channels and feeder channels on top of minor crevasse splay delta systems, although this distinction is largely arbitrary in this situation as all are acting as conduits for the transport of crevasse splay delta system sediment. As discussed in section 4.2.1.12 they are largely of sinuous origin and marked by lateral accretion surfaces that are difficult to distinguish in cored material (Fig. 4.16), although they contain considerable concentrations of argillaceous material, especially on these lateral accretion surfaces. Generally they have a maximum thickness of 20-25 m.

Wireline log response. The gamma response is characterised by a sharp-based gamma ray and sonic log inflexion, although this may be negated if the channel forms the top of a coarsening-upward crevasse splay delta system, thereby eroding into low gamma fine-grained sandstone. The channels are typified by low to moderate gamma response, reflecting their medium- to fine-grain size, which forms a generally serrated bell shape or thin cylinder. This gradually fines- (becomes more "dirty" argillaceous) upward (Fig. 4.16) in response to a gradual waning of flow or channel migration. Alternatively the upper contact is sharp, due to rapid cessation of flow, resulting in abandonment facies typified by interfluvial floodplain WILF deposits. Occasionally these minor distributary channels may have a lower blocky portion to their log motif (thin cylinder) possibly suggesting a temporary straighter geometry and often coarser-grained nature. These are the distal expressions of major distributary channels.

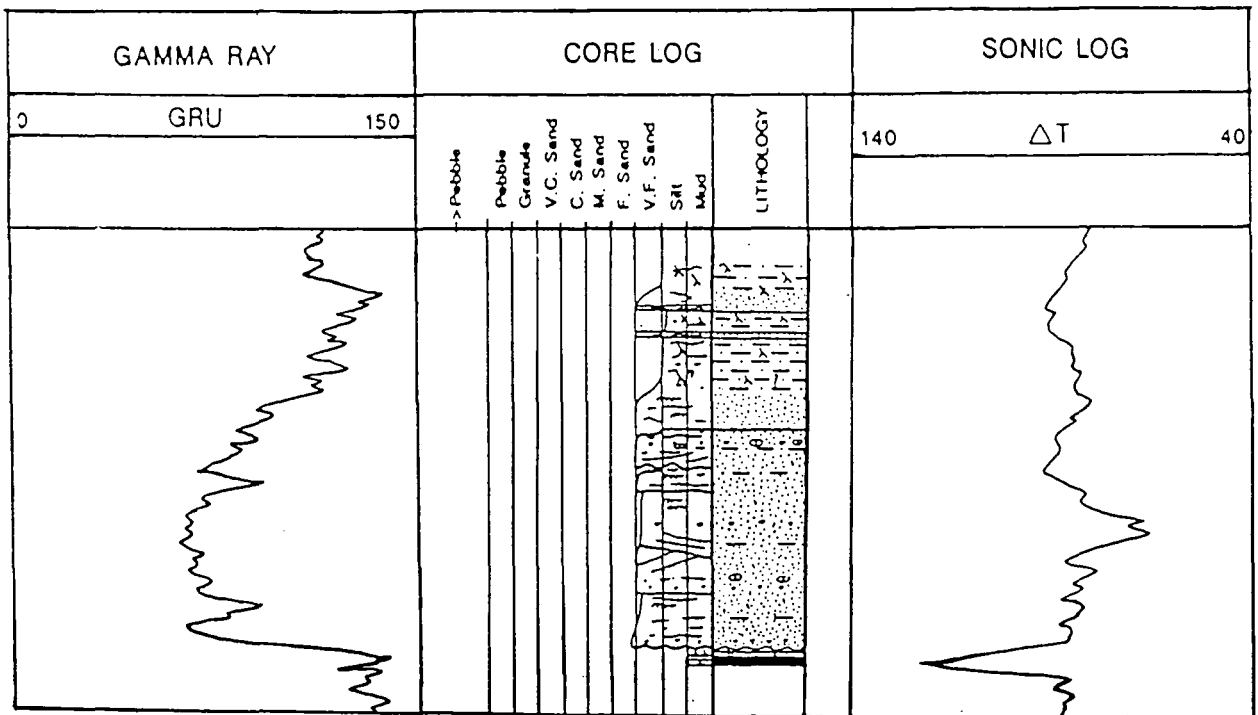


Fig. 4.16 Synthesised core profile and typical wireline response of the minor distributary channel WILF generated from several Quadrant 44 wells. Scale 1cm = 5'

4.3.3.6 Major Distributary Channel WILF (DC2)

Major distributary channels consist almost entirely of the facies described in section 4.2.1.13, with only minor development of abandonment fines characteristic of the interfluvial floodplain WILF. They can be distinguished at outcrop (Fig. 4.17) by their medium to coarse-grain size, thickness (up to 20 m) and stacking characteristics relative to minor distributary channels. They are typified (Fig. 4.17) by trough cross-bedded sandstones, organised into stacked cosets overlying internal scour surfaces and representing larger-scale bar forms (Haszeldine 1983a,b). They overlie sharp and often erosive bases (Fig. 4.18) that may show significant incision into the adjacent floodplain deposits. Their basal portion is characterised by intraformational conglomerate with abundant rip up clasts commonly composed of floodplain mudstones. The major distributary channel sandbodies display minor fining-upward trends in both outcrop and core profile (Fig. 4.19) prior to rapid abandonment fining in their uppermost section.



Fig. 4.17 Photograph of the upper Seaton Sluice Sandstone at Crag Point (NZ343761) showing sandbody characteristics of major distributary channel WILF.



Fig. 4.18 Photograph of the basal surface of the upper Seaton Sluice sandstone (Turner and O'Mara 1995) at Seaton Sluice (NZ338769) showing coalified clasts, pebbles and drifted logs. Major distributary channel WILF.

Wireline log response. The log motif reflects the core profile (Fig. 4.19) which is a relatively clean medium to coarse-grained sandstone, characterised by a smooth or slightly serrate "cylinder". Where marked internal scour surfaces and slight fining-up cosets are noted in core they define a bell shaped gamma ray. A low to very low response occurs in a sandbody seen to be 10 to 20 m thick, marked by a sharp basal inflexion. However, the basal part may contain small-scale gamma peaks due to the abundance of mudstone rip up clasts, coalified fragments and detrital heavy minerals that may yield high uranium counts overlying erosion surfaces. Slight fining-up trends may be discerned towards the top of the major distributary channel sandbodies as bedform scale begins to decrease, concomitant with waning flow. However, abandonment is usually rapid and marked by a sharp-top inflexion on the gamma ray.

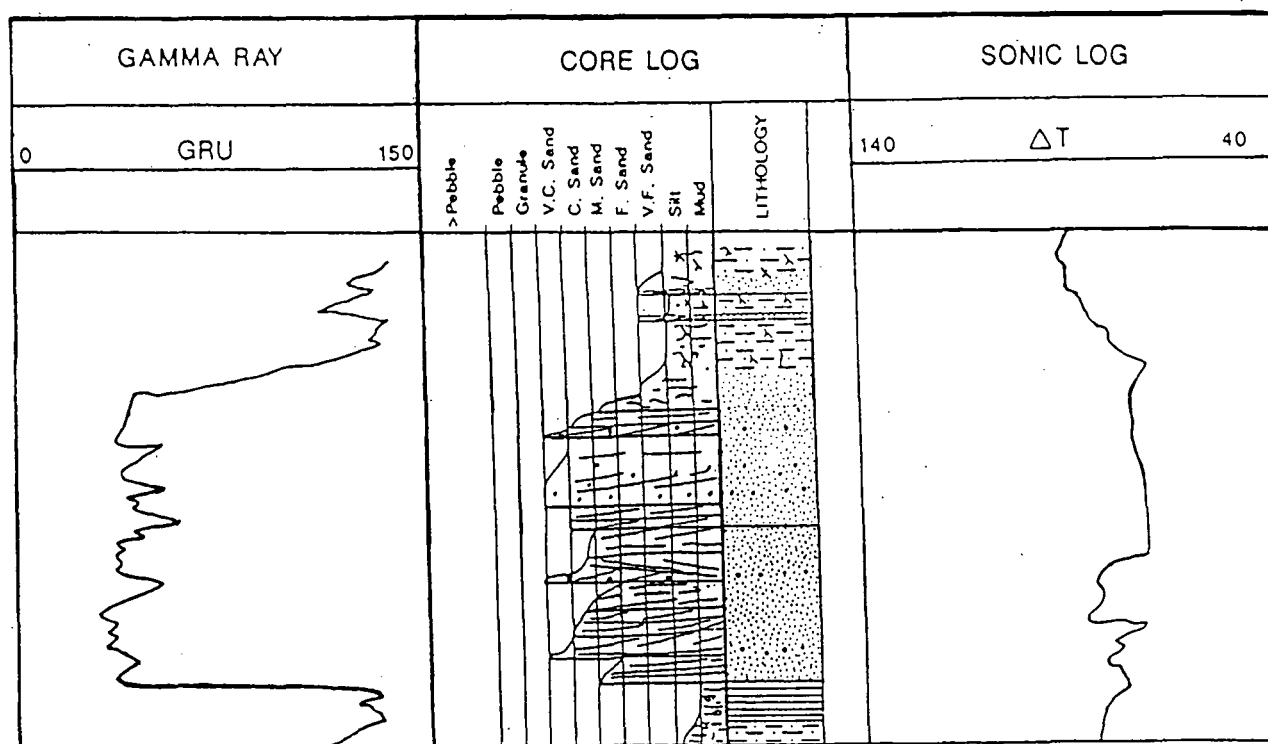


Fig. 4.19 Synthesised core profile and typical wireline response of the major distributary channel WILF generated from several Quadrant 44 wells. Scale 1cm = 10'.

4.3.3.7 Major Stacked Fluvial Systems WILF (DC3)

Major stacked fluvial systems are considerably thicker and predominantly consist of coarser-grained sandstone than major distributary channels. They are characterised by abundant intraformational conglomerate and pebbly sandstone in massive basal units up to 20 m thick that overlie an erosive surface. They are distinguished from major distributary channels by their thickness, which is up to 50 m (Fig. 4.20), and general coarser grain size. The stacked nature is indicated by frequent internal scour surfaces that separate fining-up cosets with occasional temporary abandonment fine-grained material intervening. These vary in position and frequency within sandbodies of this WILF when closely spaced well comparisons are made. The upper part of the sandbody generally has a smoother core profile with a more consistent medium to coarse-grained sandstone with pebbly layers, due to the lack of marked internal erosive surfaces and the mudstone rip up clasts and detrital heavy minerals normally associated with them. Abandonment is rapid, marked by mudstones, siltstones and thin coals of the interfluvial floodplain. This may be pre-empted by slight upward- fining of the sandbody prior to this abandonment.

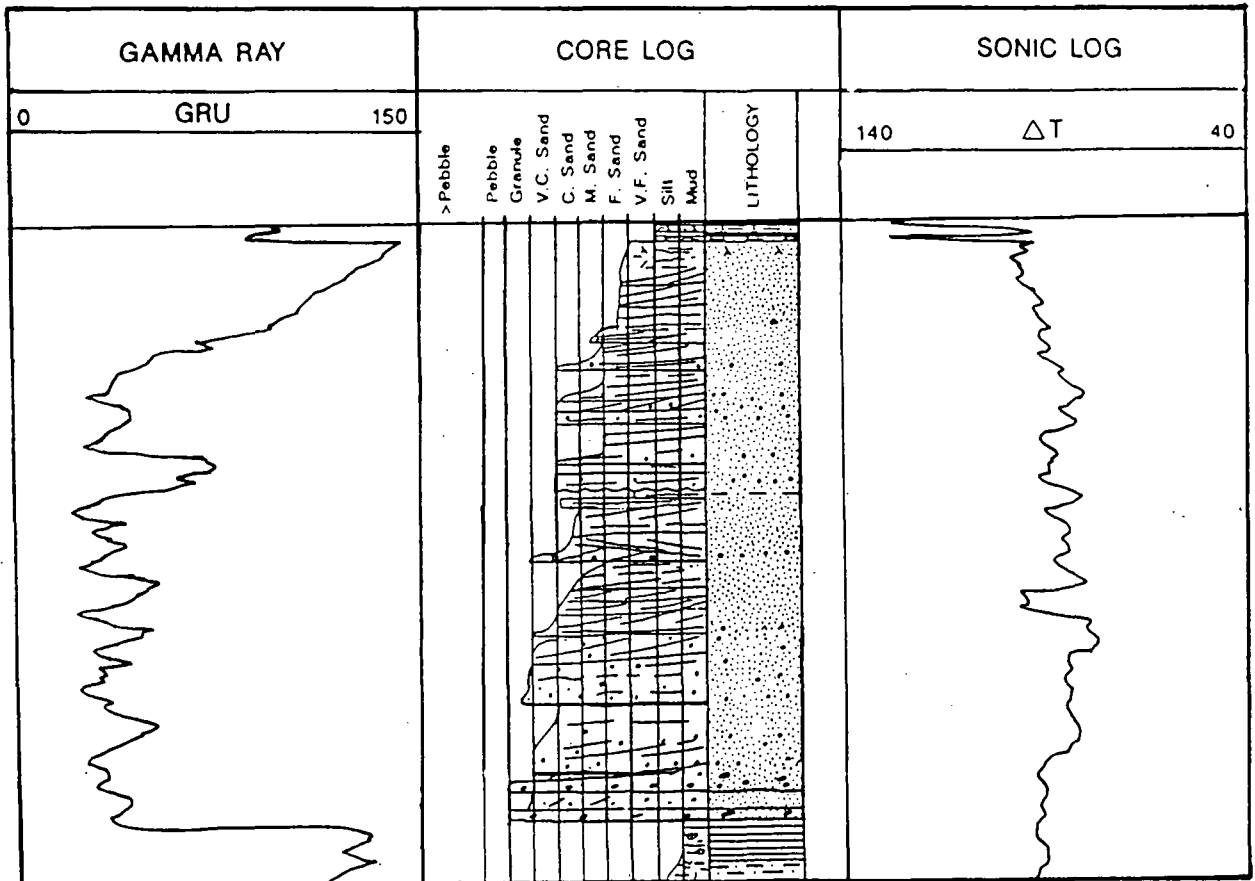


Fig. 4.20 Synthesised core profile and wireline log response of the major stacked fluvial system WILF generated from several Quadrant 44 wells. Scale 1cm = 10'

Wireline log response. This is similar in character to the major distributary channel WILF (Fig. 4.19) although thicker (over 20 m) and coarser (conglomerate to medium-grained sandstone) (Fig. 4.20). It is characterised by a sharp-basal inflexion on the gamma ray, and thick massive basal section, with low but erratic gamma due to the abundance of reworked mudstone clasts, conglomeratic material including detrital heavy minerals, particularly in lower portion of the major stacked fluvial systems. This occasionally produces an artificially high gamma response. Above the basal portion the sandbody is typified by a very low to low gamma response, with a smooth, blocky or serrate cylinder; serrations mark internal erosive surfaces and temporary abandonment. The upper portion is marked by a very smooth log response with very slight upward-increase of the gamma and upward-dirtying of the sandstone prior to rapid abandonment marked by a sharp top inflexion point.

4.3.3.8 Alluvial Floodplain WILF (AFL)

The alluvial floodplain WILF is treated separately as it reflects the onset of better drained conditions in the more marginal areas of the Coal Measures basin and is thus not strictly part of the upper delta plain/coastal alluvial plain facies association.

The alluvial floodplain WILF contains some of the facies described for the interfluvial floodplain WILF, although in different proportions. It contains less abundant lacustrine facies, restricted to thin flooding surfaces above coal seams, which are also more infrequent, although often thick. The wireline log facies association consists of interbedded siltstones and mudstones impregnated with roots and rootlets that indicate stacked palaeosols at various stages of evolution (core 44/28-1; Fig. 4.7). The WILF characteristically is interbedded with fining-upward crevasse channel/sheet-floods and braided river channel sandbodies of major distributary channel and major stacked fluvial systems. The succession is typified by coal seams drowned by short-lived, thin, lake mudstones which rapidly pass into silty palaeosols. The palaeosols may coarsen- and become less waterlogged upward, although more subtle variations in base level may cause more complex palaeosol evolutionary trends.

Wireline log response. The gamma ray response associated with the alluvial floodplain WILF (Fig. 4.21) is closely allied to the interdistributary bay and lake WILF to interfluvial floodplain WILF transition where further increased elevation, and better drainage of the floodplain leads to less frequent major drowning and less major high gamma lake mudstones (cf interdistributary bay and lake WILF) which only occur as thin bands. Coal seams with their associated low gamma, high sonic have an equally reduced abundance, (cf interfluvial floodplain WILF) although seam thickness generally does not decrease. This indicates that the water table is rarely sufficiently high for coal swamps to become established, although when it is coal seams will develop to thicknesses comparable to the interfluvial floodplain WILF. The

watertable appears to remain close to the sediment surface to allow prolonged palaeosol development, with slight variations leading to variations in the oxidation state of the soil, and the state of evolution of the soil profiles. This is reflected in the gamma response, where poorly drained soils tend to have a slightly higher organic and gamma content, compared to the better drained, slightly coarser-grained, less organic more evolved palaeosols which have less gamma response. Overall the gamma ray is moderate with variations to low/ moderate to moderately high.

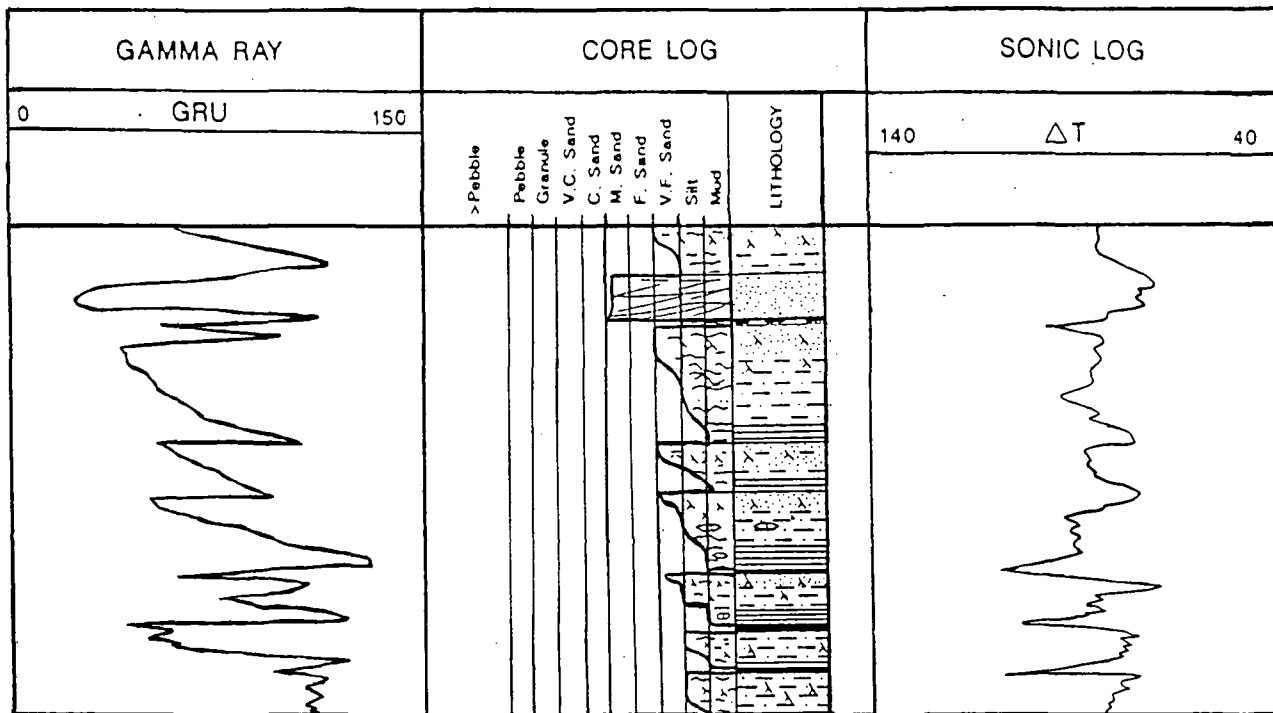


Fig. 4.21 Synthesised core profile and typical wireline log response of the alluvial floodplain WILF generated from several Quadrant 44 wells. Scale 1cm = 10'.

4.4 Conclusions

Eleven of the facies described by Fielding (1984a, 1986) and Guion and Fielding (1988) for the Northumberland/Durham Coal Measures and a further palaeosol facies from Besly and Fielding (1989) described from the Pennine Basin, have been recognised in core material for Quadrant 44 wells. An additional channel facies, peculiar to the Southern North Sea (SPM Geos 1993; Ritchie and Pratsides 1993) is also defined here. These make up a total of thirteen lithofacies identifiable in Westphalian B facies associations in Quadrant 44. Where these individual facies are recognised they can be utilised for sequence stratigraphic analysis as they allow for interpretation of the relative stratigraphic base level position and its variation within the sediments encountered in the well. However, as core material in Quadrant 44 wells is rare and lateral facies variations inherent to the depositional systems are marked, these individual lithofacies have limited use in all but interpreting singular wells, as they can not usually be traced between wells with any confidence.

From this core facies analysis, and using the thirteen facies outlined in section 4.2.1, it was possible to establish eight wireline log facies associations (WILF's). These include closely associated facies that are not sufficiently different in character to allow unequivocal identification in wireline response alone. They include three interfluvial wireline log facies associations which are characterised on the degree of palaeosol development and also coal seam thickness and frequency, which displays an inverse relationship to the development of lacustrine facies. These factors are interpreted to relate to the relative stand in stratigraphic base level. The crevasse splay WILF contains all of the sand-rich overbank deposits and consists predominantly of thin sandstones of varying grain size. Crevasse channels may be distinguished from the crevasse splay WILF as they have a distinctive wireline signature, thereby allowing the definition of a crevasse channel sub-WILF that may be utilised to enhance the wireline log facies association interpretation in some cases, they are grouped with the crevasse splays because of their obvious close depositional association. The channel sandstone WILF's are subdivided on wireline log response which reflects channel thickness, grain size and internal characteristics to allow appreciation of channel geometry.

Recognition of these eight WILF's permits reliable facies analysis to be carried out on intervals where no core information was available, allowing the coding of the wells in terms of these Westphalian B facies associations. The distribution of such WILF's provides a basis for

appreciation of the relative stratigraphic base level stand, with the aim of producing palaeogeographic reconstructions. It permits the identification of important surfaces such as sequence boundaries and maximum flooding surfaces thereby allowing establishment of a sequence stratigraphic scheme for the Westphalian B sediments in Quadrant 44.

Chapter 5

Westphalian B sequence stratigraphy

5.1 Introduction

The previous Chapters detailed the Westphalian B facies associations and showed that the Westphalian B sediments were deposited on an upper delta plain/coastal alluvial plain to alluvial plain environments in marginal areas of the depositional basin. This only sporadically underwent short-lived marine influence as reflected by widespread faunal concentrates (condensed horizons) or marine bands. These are regarded (Flint et al. 1995) as flooding surfaces, with several being good candidates for maximum flooding surfaces. The remainder of the succession is characterised by the continental facies comprising distributary channel sandbodies, swamps and lacustrine environments of various depths and extents. Large parts of the sedimentary fill of the Pennine Basin are arranged into coarsening-upward coal-bearing deltaic "cyclothem" (Hampson 1995), termed here intercoal intervals. The identification and integration of the marine bands with the biostratigraphy allowed preliminary correlation of the Westphalian B sediments in Quadrant 44. However, the spacing of marine bands and lack of definition available for the palynostratigraphic zonation means that these methods only provide a coarse chronostratigraphic framework. Modern exploration and development drilling needs a higher resolution correlation than is attainable using these methods. Sequence stratigraphy is a technique that has allowed high resolution correlation in many marine and some non-marine environments. It emphasises the allocyclic controls on sedimentary successions which are tectonism, climate and eustasy (Shanley and McCabe 1994), and it has led to an improved understanding of the controls on deposition and sedimentary systems (Flint et al. 1995). Sequence stratigraphic principles allow for improvements of the coarse chronologically constrained stratigraphic subdivision recognised to date and these have direct implications for development drilling in ascertaining facies stacking patterns and the areal distribution of some of the genetic facies within the facies associations.

5.2 Non-marine sequence stratigraphy: concepts and applications

5.2.1 Stratigraphic base Level

Shanley and McCabe (1994) suggest that stratigraphic base level in continental strata determines accommodation space (Fig. 5.1), although they note that this concept has a more complex relationship in non-marine strata compared to the marine realm, where stratigraphic base level can be considered to equate to relative sea level as well. Stratigraphic base level in continental strata takes various forms, such as the graded profile for fluvial strata (Makin 1948), the ground water table for swamp environments and the lake level for various lake facies; it equates to the "bayline" (Shanley and McCabe 1994) in tidal or marginal sediments. Shanley and McCabe (1994) further note that sediment supply is generally a more complex variable in continental strata due to the proximity of the source area, and the influence of climate and tectonism which can often be clearly seen. Although these factors are independent, a change in one parameter will most likely be reflected in others. Accentuating this problem is the fact that non-marine depositional systems respond to autocyclic processes as well as allocyclic processes, such as channel avulsion and differential compaction. Thus Shanley and McCabe (1994) recommend exercising caution when suggesting stratigraphic base level control for strata deposited over a short period of time where allocyclic processes may be indistinguishable from autocyclic processes.

Shanley and McCabe (1994) on behalf of the NUNA Conference Working Group on high resolution sequence stratigraphy suggest that the challenge in continental strata is to discriminate between depositional patterns that reflect autocyclic changes from those that are of more regional significance and allocyclic in nature. These allocyclic changes explain the widespread geographic nature of the Westphalian B marine bands, and although they may be of variable magnitude and frequency they affect accommodation space and may be utilised to help understand continental stratigraphic relations. Consideration of the autocyclic processes which are of a smaller scale and local importance is necessary when assessing continental successions in terms of stratigraphic base level changes. Where these small-scale, localised and often high frequency changes are superimposed on the potentially high magnitude, regional scale, low frequency allocyclic changes, a complex relative base level curve results, affecting stratal arrangements (Fig. 5.2). Critical to assessments of continental sequence stratigraphy are those situations where continental strata are traced laterally into the marine realm, thus verifying the stratigraphic base level changes. Shanley and McCabe (1994) suggest that it is

much less clear how sequence stratigraphic concepts could or should be applied to thick successions of continental strata where facies juxtapositions with marine strata are not present. Initial attempts to extend these sequence stratigraphic concepts inland to continental rocks have focused on fluvial strata located near to coeval marine deposits. This is why the Westphalian B marine bands are so important in understanding the succession as they reflect the most significant changes in stratigraphic base level across the entire floodplain.

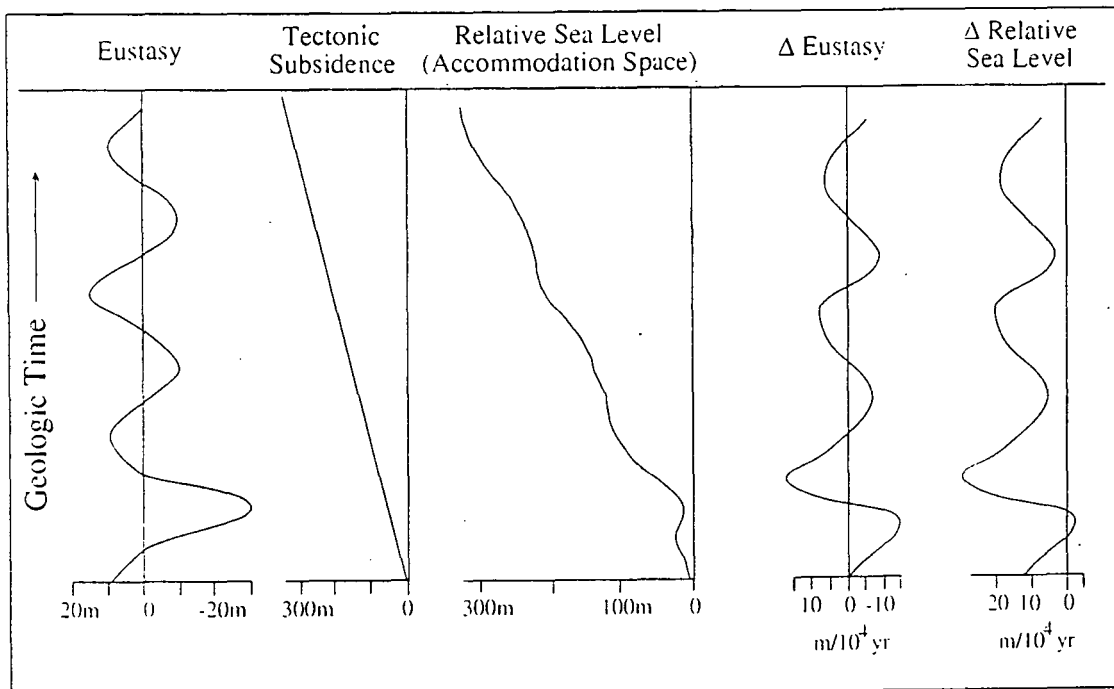


Fig. 5.1 Accommodation space is the space available for the potential sediment accumulation and is described by the convolution of tectonic subsidence and eustasy.

From Shanley and McCabe (1994) Fig. 1, modified from Posamentier et al. (1988).

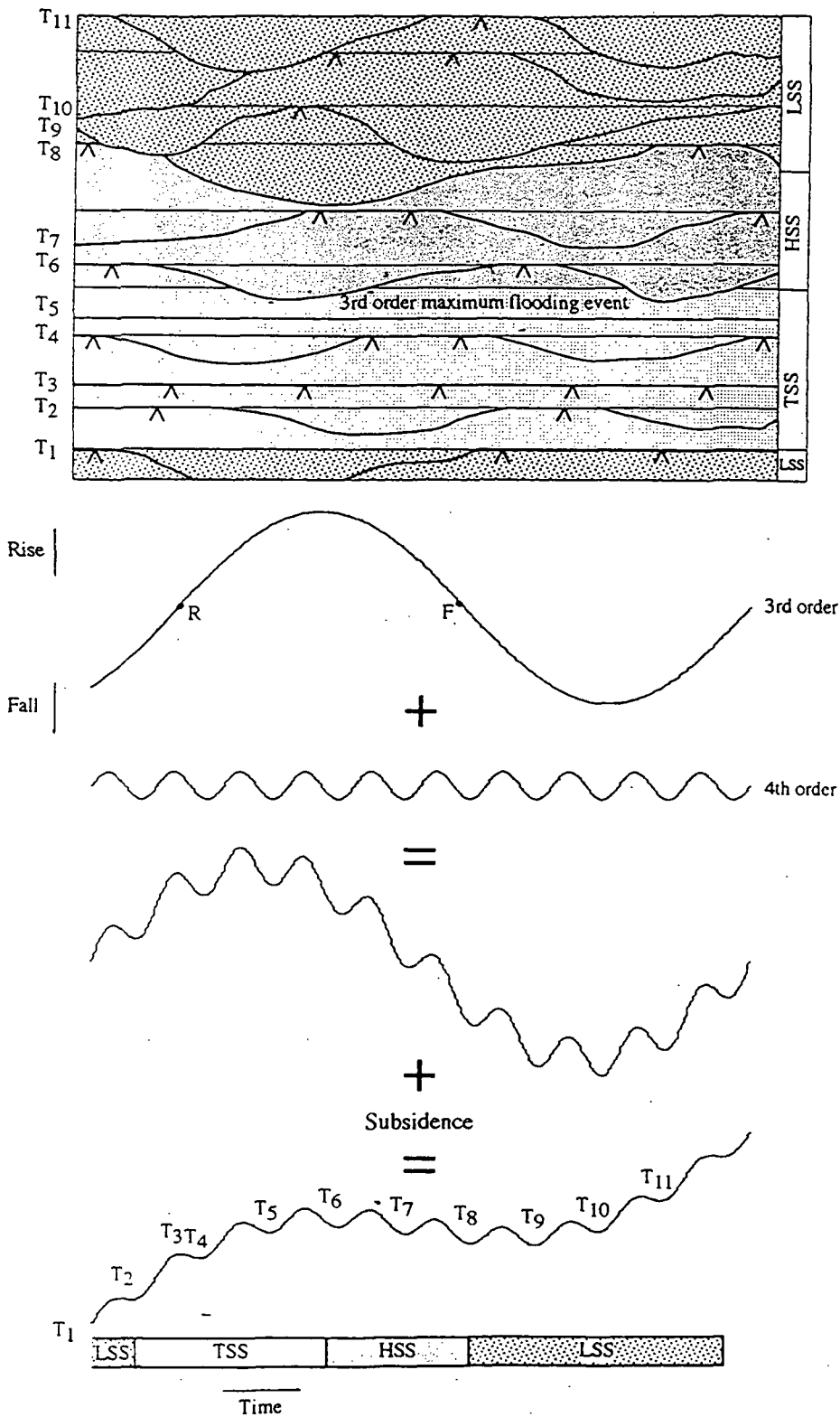


Fig. 5.2 Cartoon from Aitken and Flint (1993) to illustrate the development of sequence sets in relation to the 3rd- and 4th-order sea level curves with time.

5.2.2 Sequence stratigraphic terminology

The term sequence adopted here was outlined by the EXXON Group and is illustrated in Figure 5.3. The term is described at length in AAPG Memoir 26 (Payton 1977), SEPM Special Publication 42 (Wilgus et al. 1988) and AAPG methods in exploration 7 (Van Waggoner et al. 1990), and the reader is referred to these works for a more detailed discussion. A sequence is a stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their correlative conformities (Mitchum et al. 1977). These bounding unconformities and their correlative conformities are referred to as sequence boundaries, and are interpreted to reflect a depositional hiatus during a fall in relative stratigraphic base level or perhaps a change in the rates of relative stratigraphic base level rise. Shanley and McCabe (1994) suggest that an understanding of sequences and sequence stratigraphy is important because systematic, predictive facies assemblages appear to be developed within sequences. In continental successions, however, sequence boundaries may be controlled by climate and/or tectonic processes in the source area rather than base level fall (cf. Caister Sandstone, section 5.3.3), although the concept that they everywhere separate younger rocks above from older below (Van Waggoner et al. 1990) still holds true.

A sequence hierarchy (Fig. 5.4) has been recognised by Mitchum and Van Waggoner (1991) where sequences are seen to commonly span time periods ranging from a few thousand to millions of years, so that higher order short-time scale fluctuations in stratigraphic base level may be superimposed on longer scale lower-order base level cycles. Thus a nesting of sequences occurs, and consequently the term sequence does not imply any particular length of geological time. This superposition necessitates the term sequence set, which describes a set of sequences of high order arranged in a distinctive stacking pattern that may be progradational, aggradational or retrogradational. Thus a third order sequence of Mitchum and Van Waggoner (1991) may be made up of several fourth order sequences (cf. Church and Gawthorpe 1994; Flint and Aitken 1993) (Fig. 5.2).

The building blocks of a sequence are parasequences (Van Waggoner et al. 1988) and progradation, aggradation and retrogradation stacking patterns within parasequences relate to stratigraphic base level change (Fig 5.5), although in non-marine settings stacking patterns are significantly affected by conditions controlling sediment supply (Shanley and McCabe 1994). Thus even though parasequences are recognised in near shore environments, it is considerably more difficult to recognise and correlate them in continental settings. At a larger scale, discussions of architecture deal with the systematic variations in processes that occur throughout a sequence and the evolution of the depositional environments, such as that from

coarse-grained braided to fine-grained meandering river deposits (cf. Westphalian B) which reflects a rising stratigraphic base level. This evolution of stratigraphic architecture at the scale of the depositional sequence is governed by the rates at which accommodation space is created or destroyed, as well as the sedimentary processes inherent to the depositional system (Shanley and McCabe 1994).

5.2.3 Accommodation space and base level control

Accommodation space is described by Jervey (1988) as the "space made available for potential sediment accumulation", where "in order for sediments to be preserved, there must be space available below stratigraphic base level (the level above which erosion will occur)". Thus accommodation space is a volume whose shape is continually modified throughout geological time (Shanley and McCabe 1994) and is therefore dynamic (Fig. 5.5). In continental settings it may be considered to be the space available beneath a lake level, the level of the water table or base level that soils and coals may build (McCabe 1987), and the bankfull depths of channels. In general when accommodation space is positive, stratigraphic architecture is heavily influenced by processes responsible for sediment supply. Progradation (of shorelines or minor crevasse splay delta systems) will occur if sediment supply exceeds the rate at which accommodation space is created whereas aggradation will occur when rates of sediment supply and creation of accommodation space are balanced. Retrogradation will occur when the rate of sediment supply is exceeded by the rate of creation of accommodation space (Van Waggoner et al. 1988) (cf. coal seam flooding surfaces and minor crevasse splay delta systems). Where accommodation space is zero sediment by-passing will occur and where accommodation space is negative erosion and incision are likely to occur (Fig 5.5). Thus, the stratigraphic base level and consequently accommodation space beneath it, is the surface toward which external forces strive and it can be regarded as an undulating surface of equilibrium that variously intersects the Earth's surface. It may, for example, cross the varied topography of a floodplain to produce a range of environments which fluctuate spatially and temporarily with stratigraphic base level. This fluctuation is the combined function of tectonic subsidence, eustasy, sediment supply, discharge and climate, and the environmental response to this change in stratigraphic base level determines the stratigraphic architecture at the depositional sequence scale.

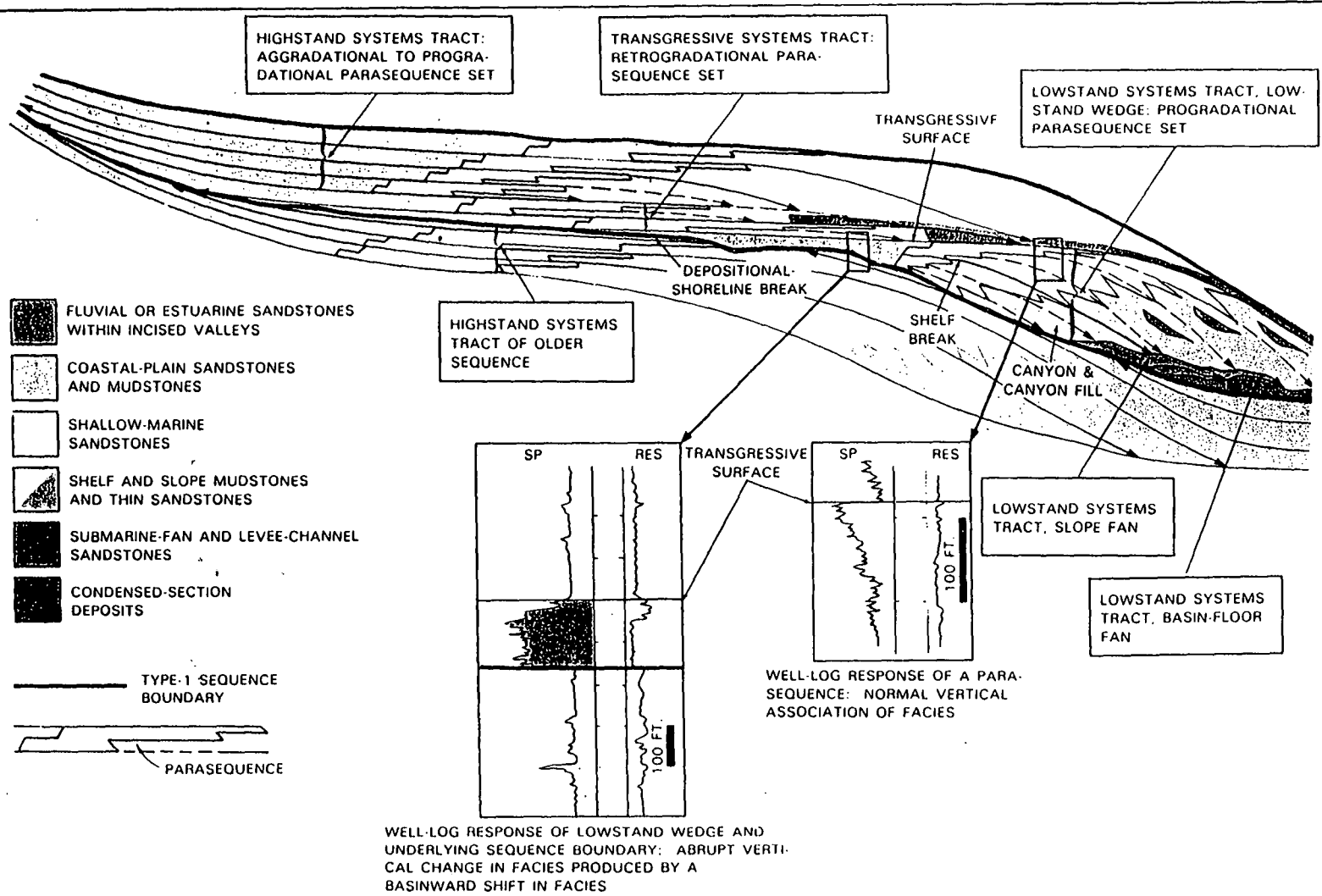


Fig. 5.3 Basic accommodation envelope or "slug model" of an unconformity bounded sequence, showing systems tracts and predicted progradational, retrogradational and aggradational stacking patterns of clastic sediments. From Van Waggoner et al. (1990 after Vail et al. 1977).

Scale	Duration	Comment
First order	50+ Ma	Too prolonged to have a notable effect at outcrop
Second order	5-50 Ma	Typically c. 10 Ma; as above but may effect background)
Third Order	1-5 Ma	Typical scale of seismic sequence
Fourth Order	0.1 - 1 Ma	Produces high frequency sequences or parasequences depending upon conditions Sub-seismic
Fifth Order	0.01 - 0.1 Ma	May produce parasequences

Fig. 5.4 Sequence Hierarchy (after Mitchum and Van Waggoner 1991).

5.2.4 Base level and stratigraphic architecture in a coastal plain setting

There is a diversity of opinion concerning the impact that changes in relative stratigraphic base level have in continental settings. However, on such a low relief coastal alluvial plain/upper delta plain as that in Northumberland and in the Southern North Sea the concept of the graded river profile (Makin 1948) is most commonly used to approximate an equilibrium surface. This controls erosion and sediment preservation (Shanley and McCabe 1994) and thus approximates a stratigraphic base level surface. The graded stream was described by Makin (1948) as one which "over a period of years, delicately adjusts its slope to provide, with available discharge and with prevailing channel characteristics, just the velocity required for the transportation of the load supplied from the drainage basin." The graded stream is a system in equilibrium. Shanley and McCabe (1994) describe its diagnostic characteristic as being one in which a change in any of the controlling factors, will cause a displacement of the equilibrium profile in a direction that will tend to adsorb the effect of the change. Thus, a change in relative sea level would lead to a change in slope and in turn elevation of the profile and the position to which the river system grades. Fisk (1944, 1947) demonstrated that changes in fluvial architecture in the Mississippi River related to changes in slope and consequently the position of the "bayline" (see below), which are in turn controlled by changes in relative base level.

The models outlined above suggest that generation of significant alluvial accommodation space during slowly rising base level requires seaward migration of the "bayline", defined by Shanley and McCabe (1994) as being located at the junction of the upward sloping alluvial profile and low-lying coastal alluvial plain (Fig. 5.6 and 5.7). This is at or near relative sea

level and thus equates to stratigraphic base level. Allen and Truilhe (1988) have shown in the Gironde Estuary in France that the bayline occurs at the landward limit of tides during high river flow in tide dominated river mouths, and it is marked by an abrupt facies change from fluvial gravel and coarse-grained sand to tide dominated point bars of muddy sand. Allen (1991) suggests that in the Carboniferous the bayline is marked by the facies and grain-size transition which delimits the palaeogeographic boundary between the alluvial and the paralic Coal Measure deposits. As stratigraphic base level rises the bayline migrates landward and as it falls it migrates basinward.

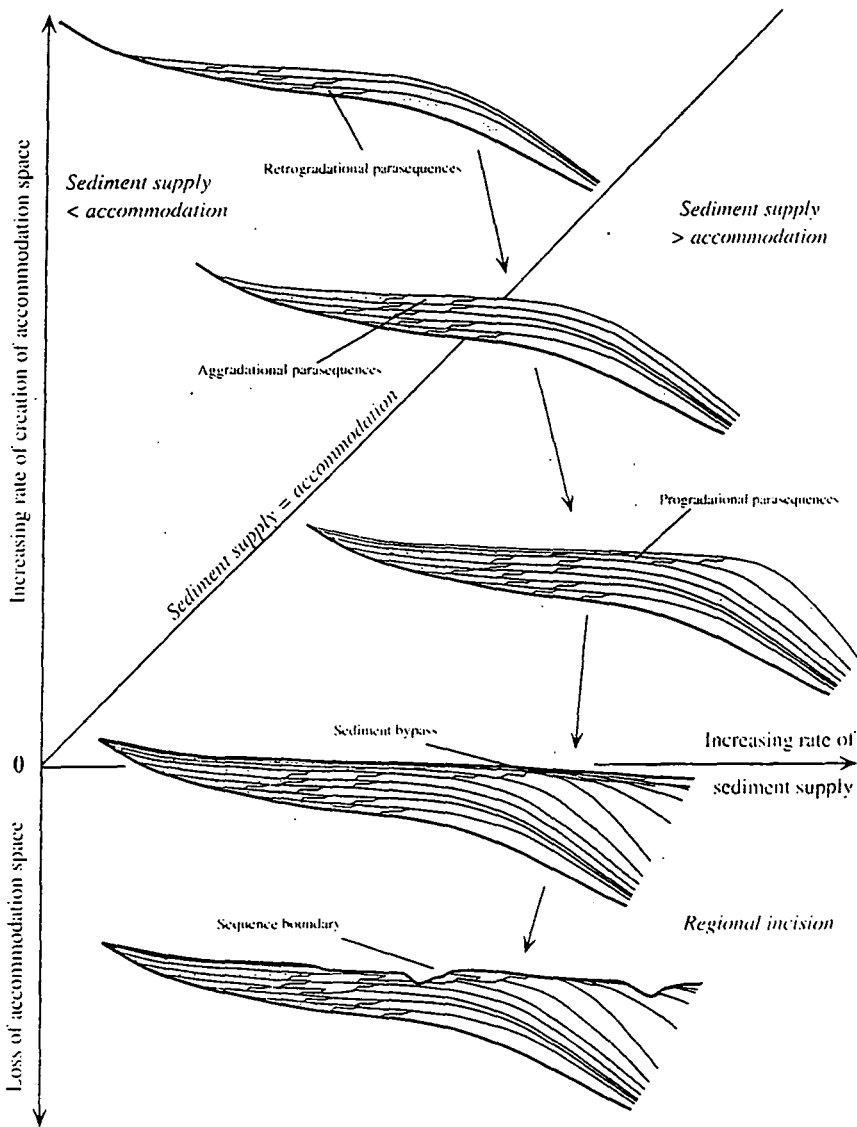


Fig. 5.5 The interplay between accommodation space and sediment supply and the resulting stratigraphic stacking pattern, illustrated in a plot of accommodation space vs. sediment supply. From Shanley and McCabe (1994).

The lower coastal plain/upper delta plain or paralic Coal Measures environments are obviously susceptible to changes in relative sea level, as demonstrated by the occasional presence of marine bands. Thus, relative sea level fluctuations will be the major factor controlling stratigraphic base level for depositional systems, especially as on this low-lying coastal plain, ground water table and lake levels determine facies in all the environments in Westphalian B facies associations. The ground water table will have a direct influence on swamp facies in so far as it determines how waterlogged they are and consequently the distribution of well drained and poorly drained palaeosols. Stratigraphic base level will also affect lake levels which in turn control lake facies. Shanley and McCabe (1994) suggest that the effects of change in relative sea level become diminished further inland and factors such as climate and source area uplift become more important controls on stratigraphic base level. Significant stratigraphic base level lowering will not only affect the bayline, but will subsequently rejuvenate drainage systems (Shanley and McCabe 1994) and set in motion a complex series of events that may ultimately increase sediment supply as drainage basins are captured by the landward migration of knick points. However, rapid stratigraphic base level rise precludes significant fluvial aggradation as a large volume of accommodation space is available, shifting the stream profile rapidly in a landward direction, until the rate of rise decreases. This allows the fluvial system to readjust to grade, so that when the rate of rise decreases the stream profile is transferred basinward (Posamentier and Vail 1988; Posamentier et al. 1988; Shanley and McCabe 1993, 1994).

In the fluvio-lacustrine setting of the Westphalian B Coal Measures environments changes in lake level will affect lake stratigraphy as lake levels control accommodation space and the distribution of physical energies within lakes (Shanley and McCabe 1994). Thus lake levels will exert a fundamental control on the lake facies and adjacent fluvial stratigraphy, in much the same manner that marine and coastal plain environments respond to changes in relative sea level (Van Waggoner et al. 1990). The lake level will determine the area of water exposed to the effects of wind-generated waves and the degree to which density stratification and/or mixing occurs within the water column (Sly 1978; Allen and Collinson 1986). Thus, as Shanley and McCabe (1994) suggest, lake strata will reflect the interplay of change in accommodation space driven by changes in stratigraphic base level (consequently lake levels) and sediment supply rates. The type of sediment input systems will in turn be controlled to a certain extent by sediment supply rates and accommodation space available, determined by lake levels (cf. interfluvial floodplain WLF and alluvial floodplain WLF). As a result fluvial incision and aggradation near the lake shore may well correspond to either a fall or rise in lake level. The lake level also determines the type of crevasse splay system, since it determines the volume of accommodation space available, thereby controlling whether the crevasse splay system progrades, forming minor crevasse splay delta systems during high lake levels or

alternatively forming crevasse splay systems that spread laterally and are dominated by sheet-floods. Thus, the stratigraphic base level across these low lying floodplains will take the form of lake levels, ground watertable or bayline, and changes in these levels will partly control the distribution of the Westphalian B facies.

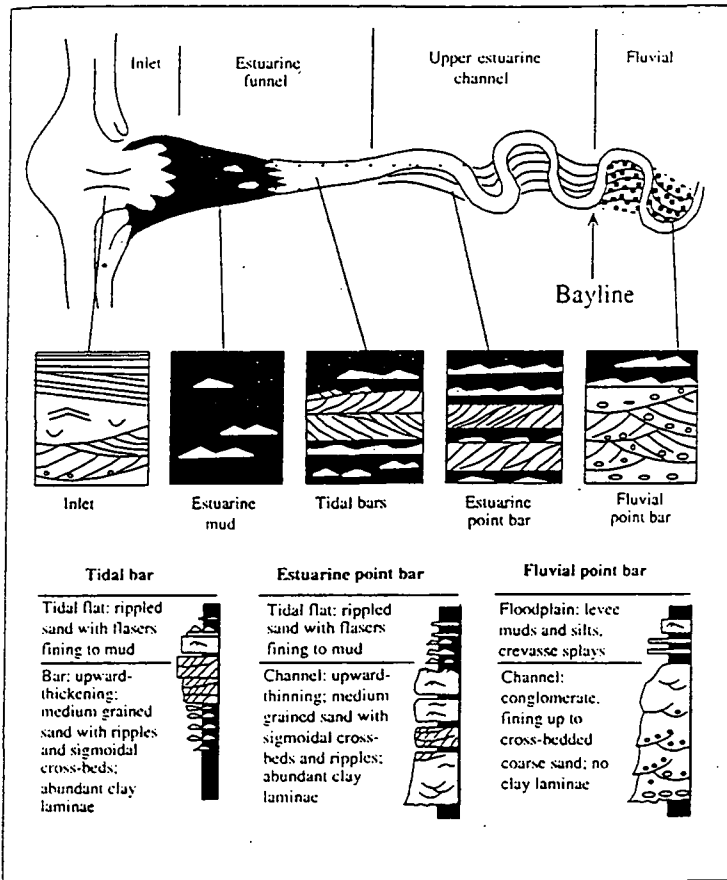


Fig. 5.6 Schematic illustration of the longitudinal facies within a Gironde-type macrotidal estuary. Each morphological zone is represented by a characteristic facies type indicating a downstream evolution from fluvial to estuarine channels and bars. From Shanley and McCabe (1994, after Allen 1991).

5.2.5 Sequence boundary recognition in a coastal plain setting

Shanley and McCabe (1994) suggest that the juxtaposition of braided river deposits on to marine or lacustrine sediments allows for unconformity identification, provided it is possible to discriminate regionally extensive surfaces driven by allocyclic phenomena to confirm this. These surfaces reflect allocyclic forcing and signify an abrupt change in the rate at which accommodation space is created which in turn affects stratal geometry. Shanley and McCabe (1994) note that these braided river deposits are multilateral, multi-storey channel sandstone units, and similar sandbodies are recognised by Aitken and Flint (1993a,b), Van Waggoner et al. (1990); Davies et al. (1992) and Gibling and Bird (1994). These units are typified by high net to gross (sandstone : mudstone ratios) that are thought to represent low rates of stratigraphic base level rise. The widespread lateral amalgamation and lack of interfluvial fines suggests significant cannibalism and reworking of the floodplain has taken place due to the low rate of accommodation space creation. Typically these sandbodies pass into increasingly isolated meander belt sandbodies (Fig. 5.8) suggesting an increasing proportion of mudstone. This fluvial geometry motif is interpreted to reflect an increasing rate at which accommodation space is created. This is a relationship that is clearly visible in the Westphalian B succession of Quadrant 44 (section 5.3.4).

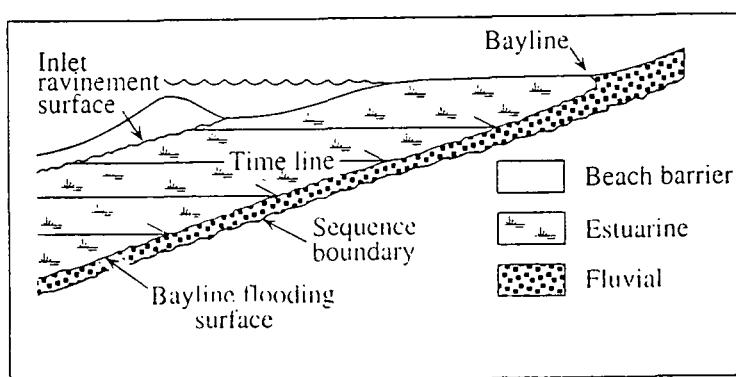


Fig. 5.7 Schematic longitudinal section along the axis of the Gironde incised valley illustrating the facies and stratigraphic patterns of the transgressive fill. From Shanley and McCabe (1994 after Allen and Posamentier 1993).

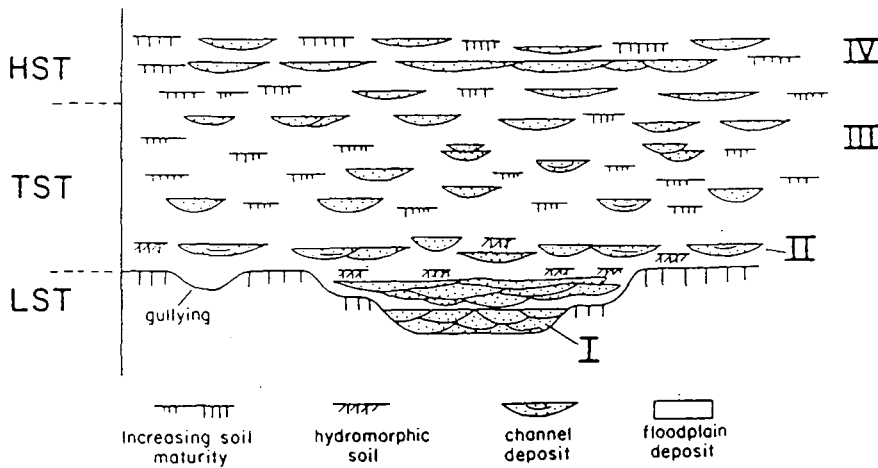


Fig. 5.8 Proposed simple architectural/pedogenic model for a fluvial sequence during a third-order scale base-level fall-rise (type 1 sequence of Posamentier and Vail 1988). From Wright and Marriott (1993). LST= lowstand systems tract; TST= transgressive systems tract; HST= highstand systems tract.

5.2.6 Relative base level fall and incised valleys in a coastal plain setting

Interpretation of regionally extensive sequence boundaries is often made on the basis of alluvial incision (Shanley and McCabe 1994). However, not all instances of relative stratigraphic base level fall are characterised by fluvial rejuvenation and valley incision (Posamentier and James 1993). In reality incision is quite a common feature in the sedimentary rock record and has been demonstrated in the Carboniferous by Fielding (1984a,b, 1986) to occur in response to autocyclic channel switching. In general Posamentier and James (1993) suggest there are several reasons for potential valley incision (Fig 5.9):

- (1) relative base level fall, exposing a land surface steeper than the graded fluvial equilibrium profile;
- (2) relative base level remains constant or slowly rises, but stream discharge increases;
- (3) relative base level remains constant or slowly rises, stream discharge remains unchanged, but stream load decreases significantly (loses competency); and
- (4) relative base level remains constant or slowly rises, but tectonic uplift occurs in the non-marine source area;

Shanley and McCabe (1994) based on Posamentier et al. (1992) suggest that valley incision in the continental realm, due to stratigraphic base level fall, is influenced by a difference in slope between the shallow marine shelf or, in this case, the low-lying coastal alluvial plain and the well drained alluvial plain (Fig. 5.9). Where the low lying coastal alluvial plain or shallow marine shelf has a gradient steeper than the adjacent alluvial plain which occurs in marginal positions in the north of Quadrant 44 a significant lowering of stratigraphic base level will lead to incision (Miall 1991) due to the significant gradient change affecting the hydrodynamics of the system. However, in a low relief, extensive ramp setting, (Fig. 5.9) where the fluvial profile near the coastline has a similar bathymetric profile to that of the coastal alluvial plain to shallow marine shelf, lowering of the stratigraphic base level will cause only minor fluvial incision, and fluvial profiles are simply extended. As a consequence (Fig. 5.9) fluvial facies shift basinward, perhaps with a change in fluvial channel pattern (Wescott 1993) as no significant gradient change occurs. In a setting where the shallow marine shelf or low lying coastal alluvial plain has a gradient less than the adjacent fluvial profile, stratigraphic base level lowering may be accompanied by deposition and no incision (Shanley and McCabe 1994) as accommodation space is still available (Fig. 5.9). Thus relief is critical in influencing fluvial styles and the amount of incision that occurs with significant stratigraphic base level fall. The Westphalian B coastal alluvial plain is thought to lie somewhere between the latter two scenarios, an extensive ramp setting with possible slight variations in gradient between this and the marginal alluvial areas. Consequently a lowering of stratigraphic base level leads to extension of the fluvial profile and shifting of fluvial facies tracts basinward, with little incision but quite significant deposition, at the time of stratigraphic base level fall in a situation characterised by subsequent slowly rising stratigraphic base level (section 5.3.4).

5.2.7 Type 1 versus type 2 sequence boundaries

Type one and type two sequence boundary unconformities were defined by Vail and Todd (1981) based on observations from seismic data. These definitions were subsequently refined by Posamentier and Vail (1988). A type one sequence boundary "develops an unconformity in response to relative base level fall and is associated with a abrupt basinward shift of facies tracts and coastal onlap characterised by forced regressions and in some cases fluvial incision". A type two sequence boundary "develops unconformities in response to decelerating and then accelerating relative base level rise, in this case no relative base fall occurs because the maximum rate of eustatic fall never quite attains the rate of subsidence". Between potential incised valley fills the correlative unconformity, due to exposure of the floodplain as base level is lowered, will be marked by facies characterised by low rates of accommodation space creation. These may be over-thickened, well-drained, mature palaeosols, or in some cases

thick laterally extensive coal seams. With type two sequence boundaries, the intervening sedimentary facies may reflect the low rates of accommodation space creation.

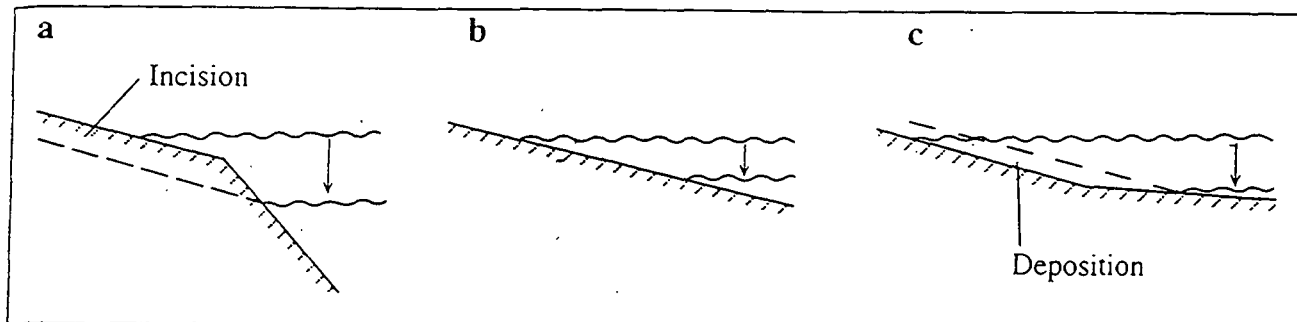


Fig. 5.9 Fluvial response to a base level fall is largely dependent on the slope of the marine shelf vs. that of the fluvial system itself. Where a steep sloping surface is exposed (a) incision is likely. Where a slope approximates the equilibrium gradient (b) little incision is likely and where the shelf slope is significantly less than the equilibrium profile (c) fluvial profiles may be extended resulting in deposition. From Posamentier et al. (1992).

5.2.8 Recognition of maximum flooding surfaces within alluvial strata

Maximum flooding surfaces represent the most landward point of transgression, which generally correspond to the deepest water facies marked by a condensed section (Shanley and McCabe 1994). In the Westphalian they are marked by the entire drowning of the floodplain, when marine waters containing abundant marine fossils invaded the Pennine Basin. Their widespread nature, as evidenced by the *Vanderbeckeri* marine band (Chapter 3) suggests that base level, or in this case relative sea level, was significantly high enough to drown the entire floodplain. Alternatively the influx of marine water was volumetrically too great for dilution by fresh water discharge of the fluvial systems. These periods of maximum flooding were short lived, suggesting that the sea level was not above the level of the floodplain for a considerable duration and subsequently the basin was rapidly desalinated by fluvial discharge. A base level rise of this magnitude will concomitantly raise ground water levels and lake levels in the more marginal areas producing lacustrine flooding surfaces and poorly drained swamp conditions in usually well drained environments.

5.2.9 Genetic sequence stratigraphy

In many data sets, especially those in the subsurface, the maximum flooding surface is more readily identifiable than the sequence boundary unconformity (Shanley and McCabe 1994). Thus it may be more applicable to use "genetic stratigraphy" (as defined by Galloway 1989a,b) as opposed to sequence stratigraphy. The approach taken by Galloway (1989a,b) was to subdivide the stratigraphic succession on the condensed sections (CS) or maximum flooding surfaces (terminology of Posamentier and Vail 1988). In many situations, as in the Westphalian B sediments in the Southern North Sea, it is easier to recognise condensed sections than it is to recognise sequence boundaries. Condensed sections are distinctively thin, marine stratigraphic units (marine bands) consisting of pelagic sediments that have a widespread nearly uniform distribution. Sequence boundary unconformities on the other hand can have a variety of expressions characterised by a sharp erosional contact and/or incised valleys (Harms 1966; Weimer 1983, 1984; Posamentier and Vail 1988; Van Waggoner et al. 1990). Further varieties in sequence boundary expression are in interfluvial areas where the unconformity may be characterised by a shale to shale contact or palaeosols, which can be difficult to identify or recognise as important sequence bounding surfaces. In a ramp margin setting the physiography precludes the formation and/or preservation of incised valleys (Posamentier et al. 1992). The unconformable portion of sequence boundaries in this case are expressed as E/T surfaces (erosional truncation) as defined by Plint et al. (1987) and Posamentier and Chamberlain (1991), overlain by extensive sheet-like sandbodies. In contrast condensed section (Galloway 1989a,b) recognition appears more straightforward as they are initially more recognisable on cores and wireline logs.

Posamentier and James (1993) argue that in spite of these difficulties it is both philosophically and economically more important to identify stratigraphic successions punctuated by unconformities. Although they suggest that in working a new data set it is common sequence stratigraphic practise to initially identify the condensed sections (maximum flooding surfaces) as they are easier to identify, and thus represent a starting point. Once this step has been taken, sequence boundaries can be inferred to occur between successive condensed sections (maximum flooding surfaces). These are potentially more difficult but more important surfaces to identify. An approach similar to this has been taken to study the Westphalian B succession in Quadrant 44.

5.2.10 System tracts and alluvial strata

Systems tracts as defined by Van Waggoner et al. (1988) are contemporaneous depositional systems defined objectively on the basis of bounding surfaces, position within a sequence and parasequence stacking patterns (Fig. 5.3). Thus it is necessary to identify sequence boundaries and maximum flooding surfaces or their alluvial equivalents before systems tracts can be ascertained. Systems tract identification in alluvial strata is of considerable interest and uncertainty (Shanley and McCabe 1994). There are few outcrop studies described that clearly demonstrate how changes in fluvial sedimentology and geometry correlate to systems tracts that have been ascertained in coeval marine and near shore sediments. Such situations are important as they verify the alluvial systems tracts identification, and allow a higher resolution framework to be established, than that based purely on identifying major stratal surfaces. Parasequences, the stratal building blocks in the systems tracts of marine successions, have not been reliably identified as yet and may well be impossible to identify in the non-marine realm as Shanley and McCabe (1994) suggest they may be strongly influenced by sediment supply and need not directly reflect allocyclic control on sediment distribution. Thus allocyclic fluctuations may not be distinguished from autocyclic ones. Nevertheless, the identification of systems tracts has been achieved in alluvial strata with coeval marine strata, as demonstrated by Shanley and McCabe (1991a,b, 1993) from the Kaiporowits Plateau, southern Utah. Here alluvial strata can be traced into coeval marine units. Transgressive systems tract (Van Waggoner et al. 1988) and highstand systems tract (Van Waggoner et al. 1988) are thus identified on geometry and sedimentology, and based on these criteria are subsequently traced into the coeval marine strata. They note that sequence boundaries are overlain by laterally-amalgamated, fluvial, sheet-sandstones (Fig. 5.10 and 5.9) that have a high relative proportion of interconnected coarse-grained channel-fill deposits (cf. major stacked fluvial systems).

Subsequent corroboration of the regional extent of such bodies and facies architecture allowed Shanley and McCabe (1994) to define them as part of an alluvial transgressive systems tract. Other workers (Posamentier and Vail 1988; Posamentier et al. 1988; Van Waggoner et al. 1990) suggest that the transgressive systems tract *sensu stricto* would be bounded by flooding surfaces (Fig. 5.3), and thus stacked amalgamated channel sandbodies would be assigned to the lowstand systems tract (Van Waggoner et al. 1990). However, application of this definition requires considerable knowledge of the stratal relationships and Shanley and McCabe (1994) suggest that the initial flooding surface would onlap in a landward direction such that "true" lowstand deposits are absent. Thus, amalgamated fluvial sheet-sands similar to those in the Kaiporowits Plateau are assigned to the transgressive systems tract (Shanley et al. 1992; Shanley and McCabe 1993) even though they overlie the sequence boundary. Evidence for subsequent gradual rising rate of base level rise, which increases upward, typifies the

transgressive systems tract, and results in vertically stacked and amalgamated sandbodies which grade vertically upward into thin isolated channel deposits (Fig. 5.10 and 5.9). These are interbedded with fine grained alluvium (Shanley and McCabe 1994) reflecting increased accommodation space and sediment preservation. Highstand deposits were described from the interior drainage basins of Argentina (Mancilla et al. 1991; Legarreta and Guilsano 1989; Kokogian 1989; Legarreta and Uliana 1991) which displayed a similar amalgamated alluvial transgressive systems tract (Fig. 5.10) to the Kaipiorowits Plateau, passing up to isolated meander-belt channel sandbodies as accommodation space creation increases. The highstand deposits were characterised by suspended load floodplain deposits, with a greater occurrence of soil profiles, suggesting limited accommodation space creation. A similar situation is envisaged for the transition from amalgamated major stacked fluvial systems to isolated minor and major distributary channel sandstones seen in Westphalian B sediments in Quadrant 44 of the Southern North Sea.

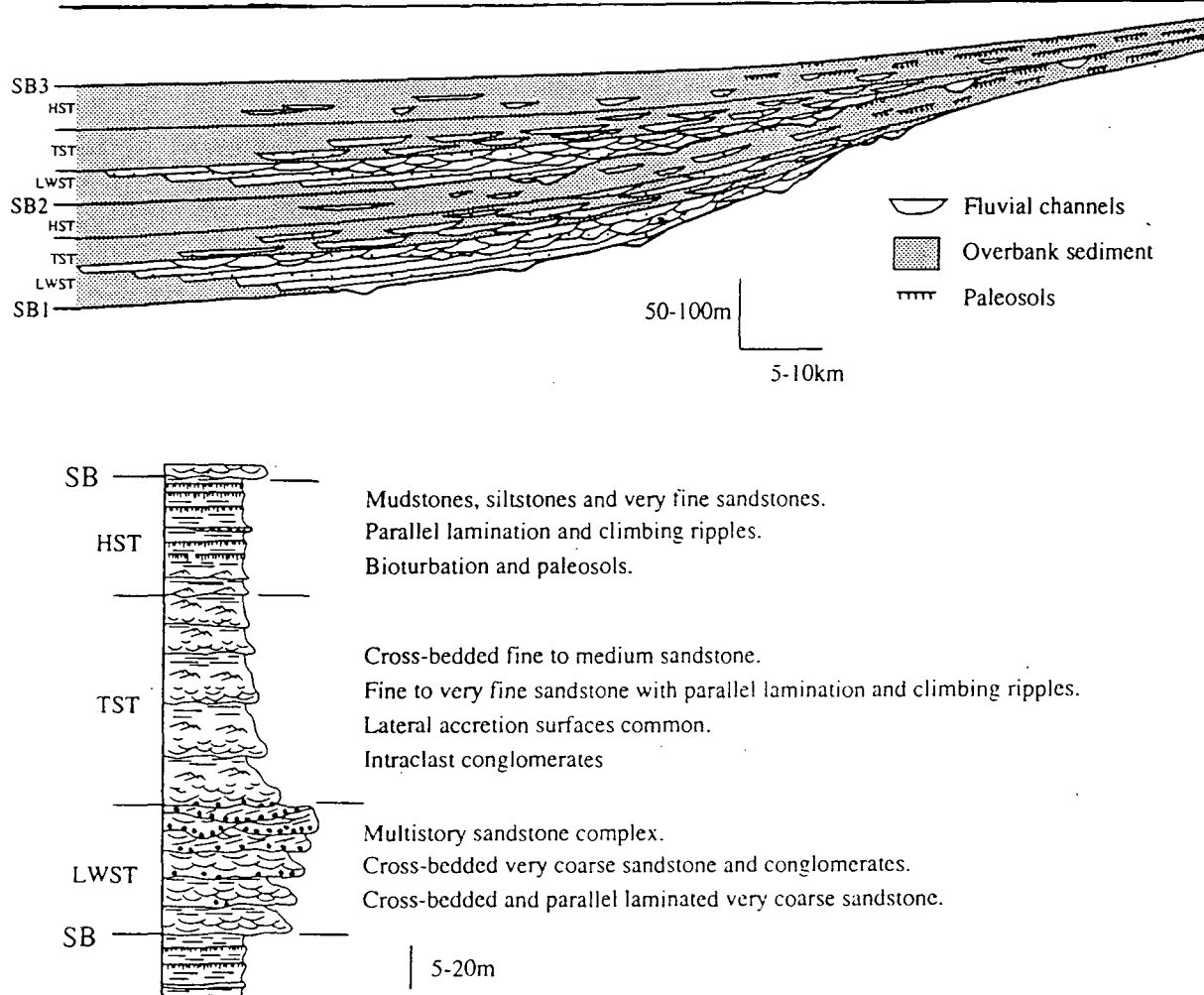


Fig. 5.10 Schematic cross section and columnar section of alluvial depositional sequences based on studies of Mesozoic strata of Argentina. Adapted from Shanley and McCabe (1994 based on figure supplied from Uliana and Legarreta).

5.3 Sequence stratigraphy for coastal-alluvial plain environments

5.3.1 Coal Seam Distribution

The facies associations for the Westphalian B Coal Measures discussed in Chapter 4 show peat accumulation occurred in close proximity to active, clastic depositional systems, typical of low-relief, coastal alluvial floodplains (Gersib and McCabe 1991), in interdistributary bay areas and on levees in deltaic settings (Baganz et al. 1975). The properties of coal such as thickness, ash content and maceral type are controlled by the type of vegetation, humification rates, sediment supply rates and rates of stratigraphic base level change. These are in turn controlled by eustasy, climate and tectonics, which define the sequence stratigraphic architecture. Flint et al. (1995) suggest that good economic quality, potentially coal-forming peat swamps are unlikely to develop in such areas because of the regular introduction of overbank siliciclastic material, but evidence from the stratigraphic record shows that they do. Although the formation of raised mires (McCabe 1984) may deflect siliciclastic-bearing currents, and help to explain this apparent discrepancy, most of the mires on the Westphalian floodplain are considered to be low-lying (McCabe 1984, 1987; Haszeldine 1989), draping and infilling the underlying topography. The inherent filtering of siliciclastic-bearing currents by plants and their ability to reduce current activity and trap sediment allows coal swamps to become established. The preferential control of channels by fault-controlled depressions (Haszeldine 1981; Fielding 1984b, 1986) with a localised expression allows coal-forming swamps to form over a longer period of time.

The rapid facies variations in the low-lying, coastal alluvial plain environments of the Westphalian B, and consequent slight topographic variations, are controlled by sediment supply rates and fault-controlled depressions. Thus produces numerous, rapidly changing areas for coal swamp development. Thus, lateral continuity and synchronicity is unlikely and most coal seams will be characterised by thickness variations across the floodplain reflecting this underlying topography. Concurrent with these coal forming environments there is abundant evidence for large amounts of siliciclastic input in the form of crevasse splay/minor delta systems and minor distributary channels, which provide the sediment for the lake infilling packages discussed in Chapter 4. Thus, sediment supply cannot be shut off across the whole or large parts of the floodplain to allow for the formation of extensive coal seams as Flint et al. (1995) claim, unless a rapid rise in stratigraphic base level causes a landward shift in fluvial sediment supply systems. It is argued that this would result in thin seams that were rapidly

drowned by base level rising too rapidly (section 5.3.2), and in general coal seams will occupy areas of the floodplain spatially similar to the other facies, although they preferentially occur at the top of lake-infilling crevasse splay delta lobes and abandoned channel areas. Certain combinations of conditions may allow more extensive seams as documented in section 5.3.4.

Flint et al. (1995) suggest that humification rates (decay of organic material within the peat profile) limit coal seam thickness to about 3m, with static ground water table (Clymo 1987) or in this case stratigraphic base level. Although most coals in the Pennine Basin are not more than 3m thick, it is argued that the preservation of coals of this thickness is dependant on rising stratigraphic base level as otherwise the swamp will be destroyed by oxidation. The majority of roof rocks to coal seams are lake mudstones, indicative of increased accommodation space, and this is best achieved by a rising stratigraphic base level (McCabe and Parrish 1992).

5.3.2 Flooding surface hierarchy

The first step for sequence stratigraphic analysis of a new data set is the location of the maximum flooding surfaces, or initial flooding surfaces of low order sequences (3rd order). The Westphalian B throughout Great Britain and Europe is delineated by the *Vanderbeckeri* marine band at its base and the *Aegiranum* marine band at the top. These two marine bands develop fully marine conditions over much of their areal extent (Calver 1968a) and together with the Westphalian/Namurian boundary marine band, the *Gastrioceras subcrenatum*, are regarded as the most geographically widespread. They also record the greatest water depth of the 19 Westphalian marine bands, and are thus considered to be 3rd order maximum flooding surfaces (cf. Flint et al. 1995). However, within a 3rd order depositional sequence, which is composed of a 4th order sequence set (Fig. 5.11) (cf. Aitken and Flint 1993), there are several other major flooding surfaces, such as 4th order maximum flooding surfaces (Fig. 5.12).

The most readily identifiable flooding surfaces in the Coal Measures environment generally occur overlying coal seams. Stratigraphic base level in a mire is that surface or water level above which humification exceeds organic supply (Flint et al. 1995) and the level to which a swamp could build (McCabe 1984, 1987). Mires develop in conditions of rising stratigraphic base level, and maintain themselves in this way for thousands of years, in water depths of approximately 1m (Fielding 1984a) which is possibly an optimum water depth for swamp growth. Reducing stratigraphic base level will result in oxidation and destruction of the organic matter and ultimately the swamp gives way to better drained conditions. Under these conditions no coal is preserved, only over-thickened palaeosols. Rising stratigraphic base level

at the same rate as organic matter production will lead to thick coal seams in excess of 3m, although this is very rare in the Westphalian B.

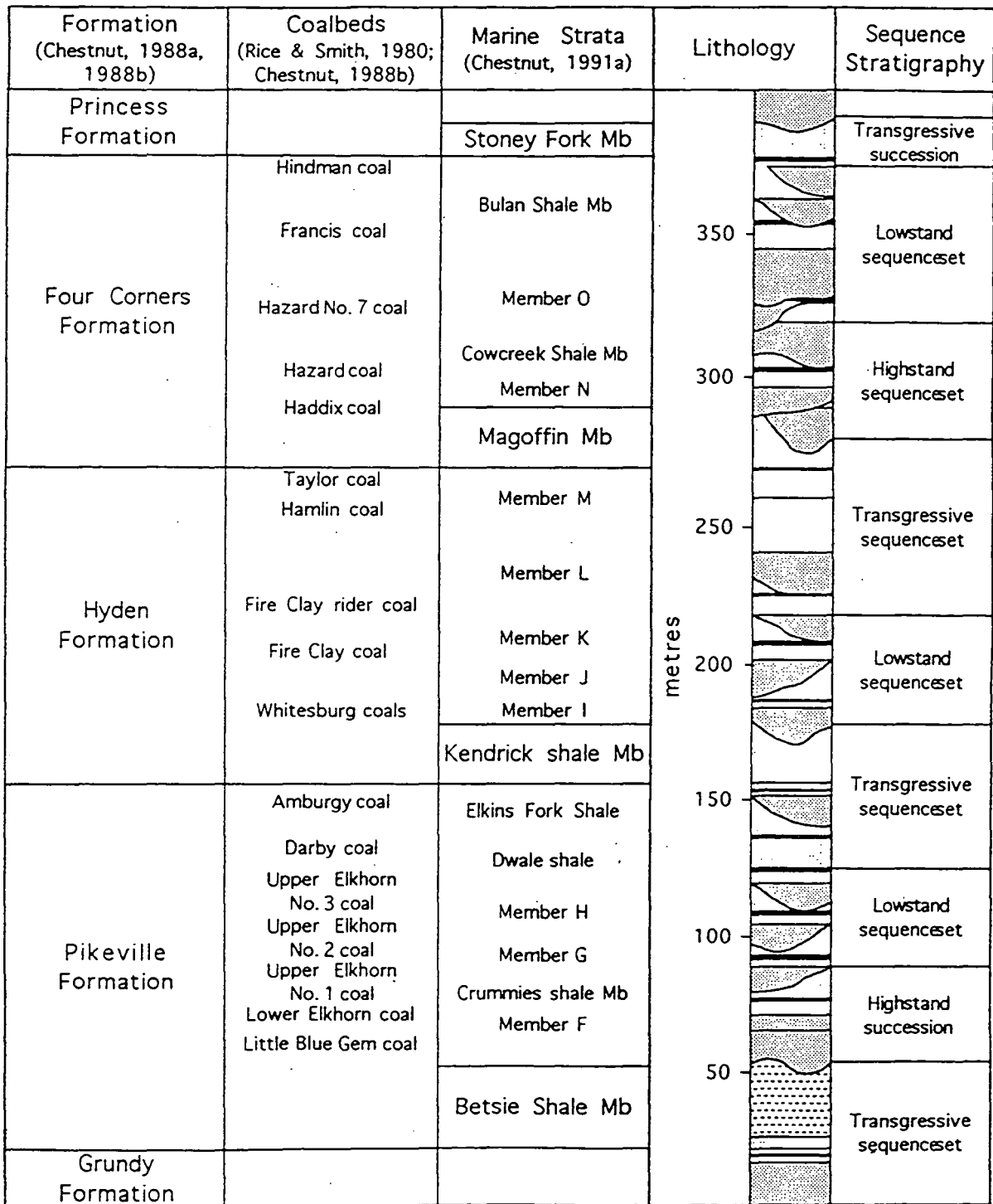


Fig. 5.11 Lithostratigraphy and sequence sets from the Breathitt Group, Eastern Kentucky. From Aitken and Flint (1993).

The majority of swamps although initiated by rising stratigraphic base level are also destroyed by this factor (Haszeldine 1989) if and when the rate of stratigraphic base level rise increases above the rate of organic matter production. As a result water depth or accommodation space creation is too high for coal formation. Thus, as described by Fielding (1984a) increased clay content indicates increased water depth in coal swamps, ultimately giving rise to channelised coals and carbonaceous mudstones, and culminating in lake or marine mudstones depending on the relative rate of stratigraphic base level rise (Fig. 5.12). Increasing base level rise may ultimately mean that coal swamp formation may shift diachronously into previously elevated areas of the floodplain, concomitant with a shift in the graded fluvial profile with sediment supply and erosion, migrating in a landward direction. Under these conditions coal swamps may give the appearance of a greater geographic extent, although their occurrence is diachronous. Where this stratigraphic base level rise is rapid, large parts of the floodplain will almost instantaneously become flooded, drowning the entire suite of Westphalian B facies. This leads to the drowning of active channels, crevasse splays and deepening existing lake and swamp environments. In contrast minor flooding events may be areally restricted to individual interdistributary lake or bay areas. Thus, the magnitude and rate of stratigraphic base level rise controls the type of flooding surface as (Fig. 5.12), summarised below.

(1) Differential compaction and switching of minor crevasse splay delta systems or minor distributary channels will result in localised small-scale stratigraphic base level rises. This comprises a peat swamp flooded by a lacustrine environment with mudstones of the interfluvial floodplain lake facies association. It occurs in the interdistributary areas, and does not flood universally across the floodplain. These are autocyclic processes.

(2) Cyclic stratigraphic base level fluctuation on various periodicities discussed by Maynard and Leeder (1992) reflect stratigraphic base level changes in the Carboniferous that are responsible for "cyclothem" and have been described by Church and Gawthorpe (1994) for the Namurian. These are short 4th order periods and will cause small scale 4th order flooding of the entire, or large parts of the floodplain, resulting in the non-marine shell beds that can be mapped across coalfields. Poorly developed marine bands (Maltby marine band) may be attributed to such changes.

(3) Third order maximum flooding surfaces that flood the entire basin with marine environments, reflect high magnitude stratigraphic base level changes.

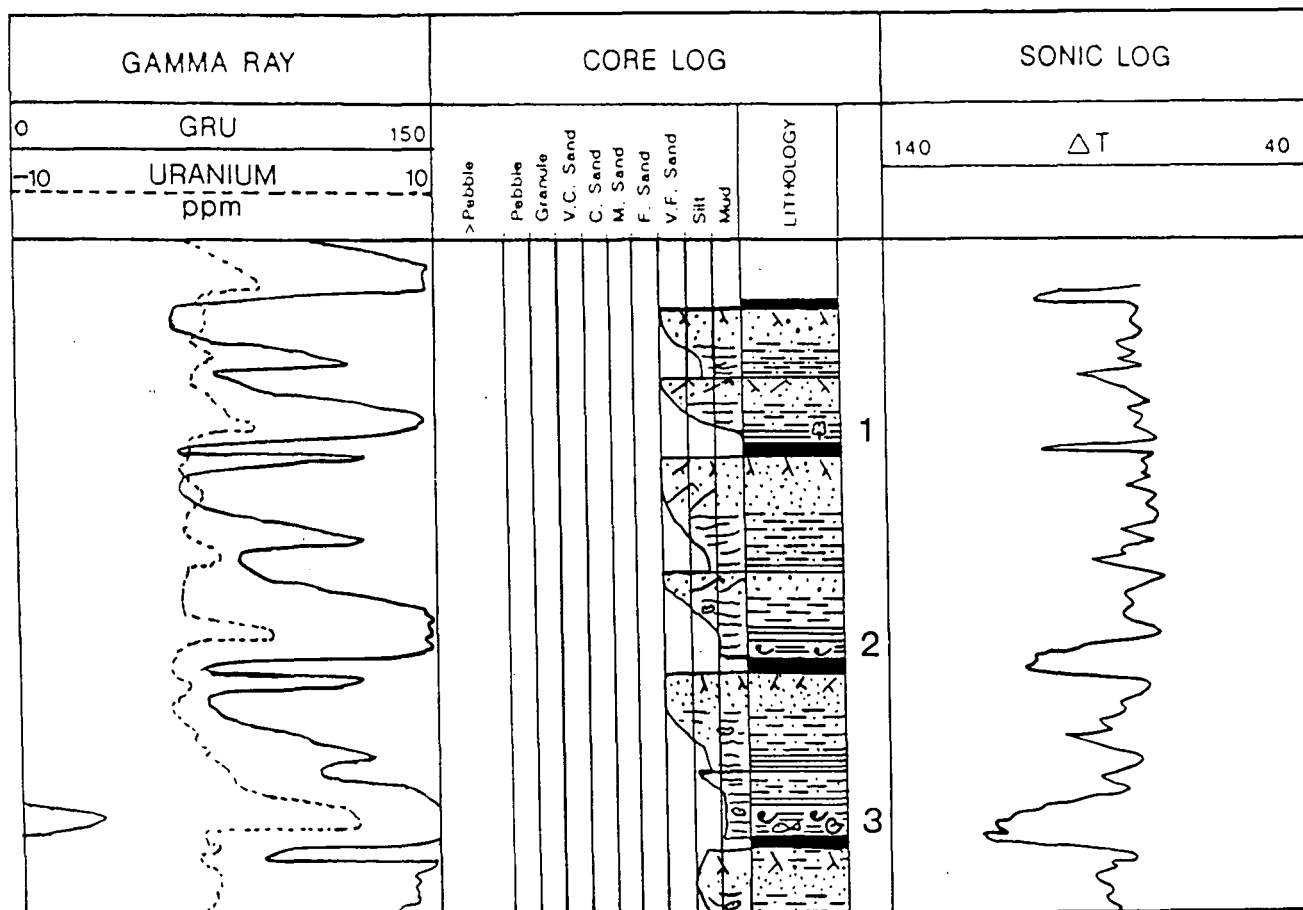


Fig. 5.12 Schematic Flooding surface hierarchy for the Westphalian B Coal Measures: 1) Coal seam flooding surface with thin lake mudstone interbeds above, abundant drifted plant fragments and moderate gamma ray, cannot be regionally correlated, 2) 4th order flooding surface with non-marine bivalves (occasionally will contain marine fossils), high to moderately high gamma signature, with moderately high to high uranium and low broad sonic peak, sub-regional to regionally correlatable, 3) 3rd order maximum flooding surface, abundant marine fossils, with non-marine bivalves above, thick smooth gamma lake mudstone package, containing high gamma and uranium (not in the case of the *Vanderbeckei* marine band) with extensive sonic low. Scale 1cm = 10'

The 4th order flooding surfaces are either characterised by non-marine bivalve beds or by marine bands depending on their position on the overall background stratigraphic base level trend, equating to that portion of the 3rd order sequence they are superimposed on. Approaching the 3rd order maximum flooding surface, at the *Aegiranum* marine band, the background stratigraphic base level is relatively high, so the associated 4th order flooding surfaces (Fig. 5.13) are typified by marine bands (Sutton and Haughton marine bands). However, in that part of the 3rd order stratigraphic base level curve that reflects a low stratigraphic base level stand, the flooding surfaces are characterised by non-marine bivalve beds (Land 1974). Thus the initiation and termination of coal forming mires is related to groundwater fluctuations controlled by stratigraphic base level changes, and changes in rates of change in accommodation space.

5.3.3 Sequence boundary recognition

Flint et al. (1995) suggest that where stratigraphic base level drops below the depositional surface in the lowstand portion of base level fluctuation, incision will occur across the exposed floodplain, and incised valleys will be cut and partially filled, with the associated unconformity defining the sequence boundary (Fig. 5.9). The rationale is not argued here, apart from stressing that this situation does not occur in the British Coal Measures. Incised valley fills *sensu stricto* have not been described from the British Coal Measures, contrary to the claims of Flint et al. (1995) who base their assumption on studies from the chronostratigraphically equivalent Pennsylvanian Breathitt Group of eastern Kentucky (Aitken and Flint 1993a,b) (Fig. 5.11). They observe, at a number of stratigraphic levels, medium- to coarse-grained, multi-storey, channel-fill sandstones with basal pebble lag conglomerates. These are demonstrably incised into marine and floodplain deposits and consequently interpreted as part of a lowstand incised valley fill complex that overlies a sequence boundary. When studying alluvial sediments, incision and subsequent apparent basinward shift in facies tract can be confused with more localised channel scour. Thus a series of criteria have to be met for verification of sequence boundary identification, as summarised below (Aitken and Flint 1993b):

- (1) degree of facies tract dislocation, referred to as an abrupt increase in vertical amalgamation of sandbodies;
- (2) marked contrast in grain size and/or petrographic composition;
- (3) degree of incision;
- (4) contrast in depth of individual channel fills (maximum of c. 3-4m) in relation to the total depth of incision (15-20m); and

(5) the regional, mappable extent of the surfaces that indicate fluvial incision, relating to significant fall in base level, (occurs at many places at the same time) rather than normal switching or progradation phenomena.

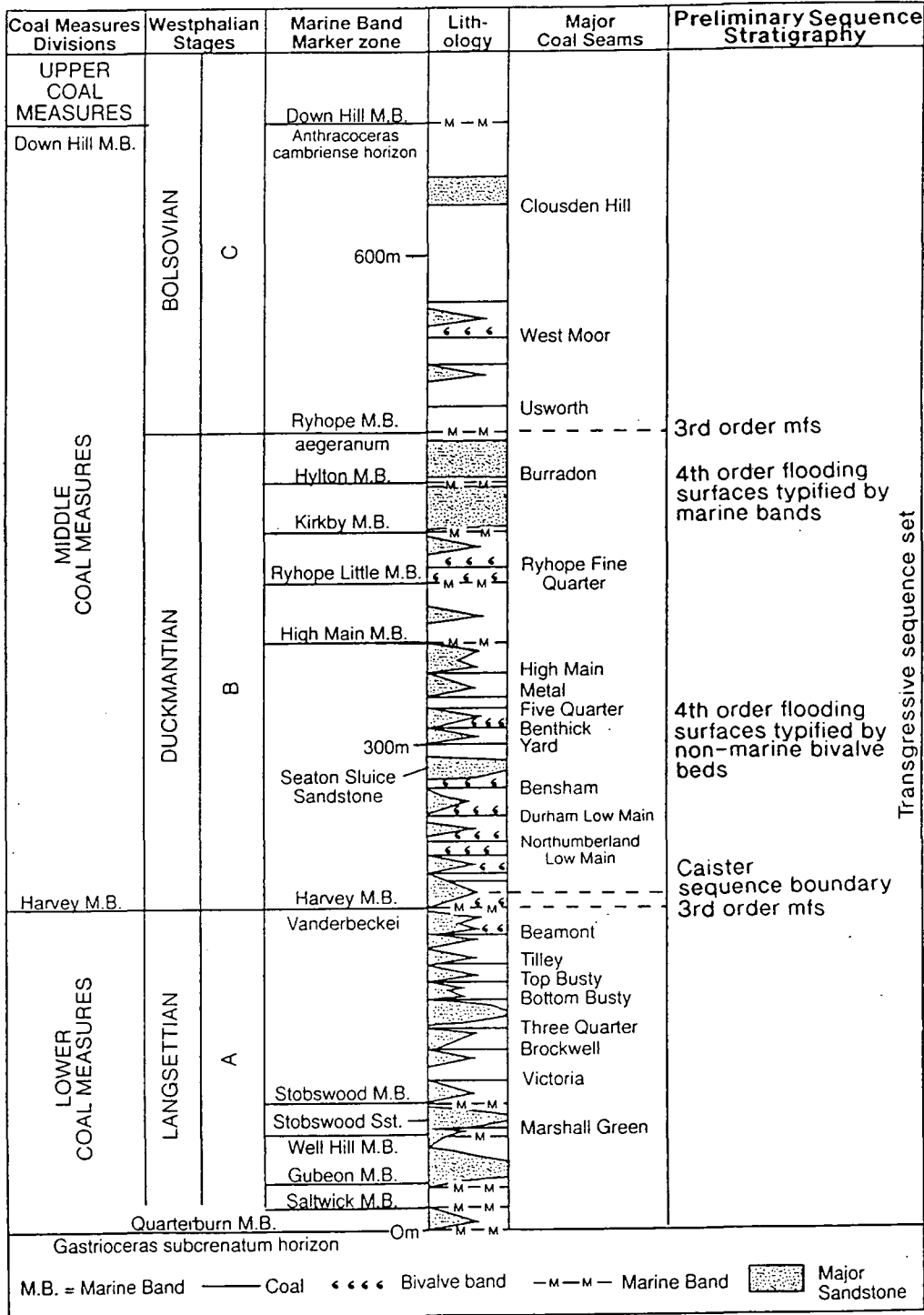


Fig. 5.13 Generalised lithostratigraphy of the Westphalian A-C of the Northumberland Coalfield, with the sequence stratigraphic interpretation used in this study. (Adapted from Land 1974; Turner and O'Mara 1995). Used as a basis for the Southern North Sea.

In the Breathitt Group sequence boundaries and overlying incised valley fills (Fig. 5.11) are represented by major stacked fluvial bodies (Aitken and Flint 1993a,b) and interpreted as such due to the marked change in hydrodynamic conditions that allows entrainment of such a coarse sediment load. This creates a major facies tract dislocation with a sharp base and subsequent change in fluvial style and architecture. The major stacked fluvial sandbodies described by Aitken and Flint (1993a,b) from eastern Kentucky share many features in common with major stacked fluvial systems (DC3 WILF) in Quadrant 44, and to the Seaton Sluice Sandstone on the Northumberland Coast described by Haszeldine (1983a,b) and more recently by Turner and O'Mara (1995). All three sandbodies are thought to be products of low sinuosity braided channels, and form multi-storey, multilateral sandbodies. Aitken and Flint (1993a,b) consider the sandbodies from Kentucky to have a dendritic to sheet-like geometry and to be considerably incised. They have a similar magnitude, areal extent, and individual channel unit thickness to the major stacked fluvial systems (section 4.3.3.7) described from Quadrant 44, and are attributed to the vertical accretion of channel fills. They represent low rates of stratigraphic base level rise as channels cannibalised and reworked the floodplains, giving rise to a high net to gross sandstone ratio. The sequence boundary at the base of such sandbodies (cf. Turner and O'Mara 1995) represents an abrupt change in the rate of accommodation space creation.

Members of the NUNA Working Group describe similar sandbodies overlying sequence boundaries and associate them with allocyclic phenomena (Shanley and McCabe 1989, 1991a, 1993; Van Waggoner et al. 1990; Davies et al. 1992; Gibling and Bird 1994). However, Turner and O'Mara (1995) have demonstrated that these sandbody types in the Westphalian B of the United Kingdom relate to tectonically induced stratigraphic base level fall, which produces sandstones that are atypical of the Westphalian B succession. They concur that the Westphalian B equivalents of major stacked fluvial sandbodies (Aitken and Flint 1993a,b) relate to significant stratigraphic base level fall, due to an allocyclic forcing function, which results in extending and changing the fluvial profile (Wescott 1993), but argue that the controlling factor is a tectonically induced uplift of intrabasinal areas. This led to increasing sediment supply and grain size, and shifted the graded fluvial profile landward. This in turn increases erosion and concomitantly shifts the bayline basinward with the result that sediments more typical of the well drained proximal alluvial plain overly floodplain deposits characterised by finer grained sediment and small-scale high-sinuosity channels. Turner and O'Mara (1995) also demonstrate that the areal extent and thickness of the fluvial system, depends on the magnitude of the tectonic uplift of the source area (cf. Seaton Sluice Sandstone and Caister Sandstone). Only uplift of a significant source area produces a basinwide tectonically induced sequence boundary with a regionally important sandstone above (Caister Sandstone). This occurs due to the significant tectonic lowering of relative stratigraphic base level, which is

superimposed on the background eustatic base level curve. The Seaton Sluice Sandstone in comparison reflects the effects associated with the uplift of a small-scale, intrabasinal source area, culminating in a localised unconformably based sandstone that does not overly a sequence boundary.

Turner and O'Mara (1995) demonstrate that significant incision is not associated with either the Seaton Sluice Sandstone or the more areally extensive Caister Sandstone, and suggest that the incision and washout in the underlying coal seam associated with the Seaton Sluice Sandstone is controlled by a fault controlled depression concentrating the erosive effects at the centre of the channel. Elsewhere little erosion at the base of the sandbody has occurred. This is also the case with the Caister Sandstone, which is seen to overly the *Vanderbeckei* marine band (Chapter 3) across the entire basin, with local erosion at the base not more than 2m. If considerable incision had occurred at the base of the sandbody, then it may reasonably be expected that the *Vanderbeckei* marine band would be frequently removed by erosion. The fact that the marine band is only rarely removed indicates that little incision occurred beneath the sandbody, and where it is missing the washout is attributed to a fault controlled depression (cf. Seaton Sluice Sandstone). Further evidence for the lack of incision associated with the Caister Sandstone comes from the seismic interpretation of Quirk (1993) who suggests that the Coal Measures lithological units have a remarkably consistent thickness and no unconformity is visible. This is supported by the Northumberland Coal Measures where intercoal intervals are said to have constant thicknesses over the extent of the coalfield (Land 1974). Aitken and Flint (1993a,b) suggest that the geometry of the major stacked fluvial bodies may be sheet-like, but still invoke an incised valley fill origin, although significant incision is unlikely to have occurred on such a scale. Shanley and McCabe (1994) suggest that in low relief ramp settings lowering of stratigraphic base level will not normally give rise to incision, although the fluvial style is radically altered due to abrupt reduction in accommodation space creation, combined with an increased sediment supply, thereby producing a marked facies shift. Consequently, fluvial channels normally seen in the proximal parts of the basin overlie coastal alluvial plain deposits as is the case with the Caister Sandstone. Quirk (1993) argues that sedimentation appears to have been uninterrupted during the entire Westphalian A to lower Westphalian C, and the fact that there were no unconformities indicates that subsidence always exceeded stratigraphic base level fall.

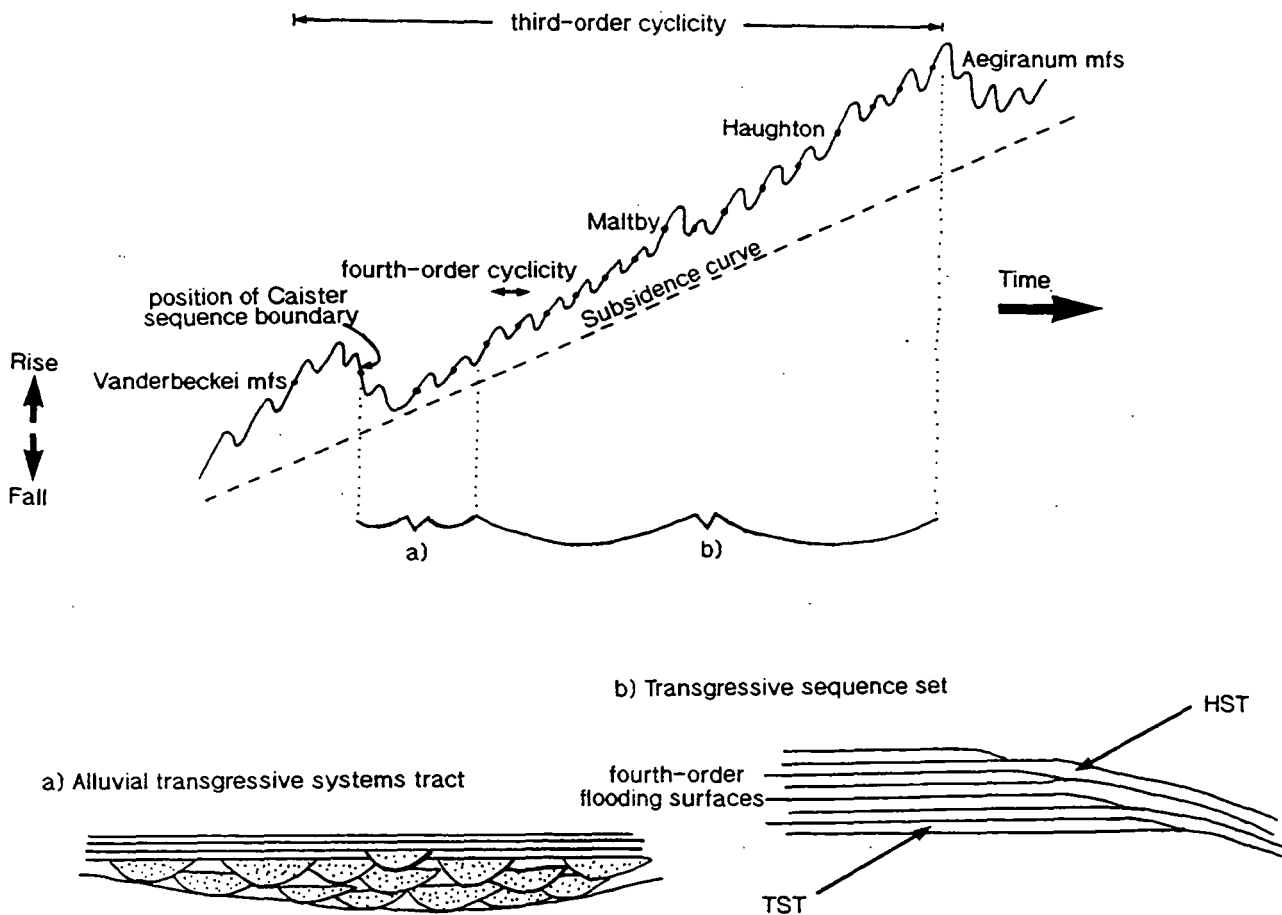


Fig. 5.14 Sketch illustrating how the observed sequence stacking patterns might fit a third- or fourth-order relative stratigraphic base-level curve allowing for subsidence.

5.3.4 A Westphalian B 3rd order sequence

Major stratal surfaces between the two regionally important 3rd order maximum flooding surfaces delineating the top and bottom of the Westphalian B can be identified in the Westphalian B succession. These maximum flooding surfaces record a maximum rate of stratigraphic base level rise and production of accommodation space. Conceptually there would be a point where stratigraphic base level is at a minimum and accommodation space creation is slow or even negative, producing a sequence boundary (Fig. 5.14). The fact that this point is interpreted to occur at the base of the regionally correlateable Caister Sandstone, and that no significant incision occurred, suggests that accommodation space was not actually negative, but created at a very slow rate (cf. Shanley and McCabe 1993). It also appears to occur at a point only slightly above the maximum stand in stratigraphic base level recorded by the *Vanderbeckei* marine band (Chapter 3) when normally it would occur in the middle of the two maximum flooding surfaces (Fig. 5.3). The asymmetry of this candidate sequence boundary position was cited as evidence for the tectonic inducement of this sequence boundary by Turner and O'Mara (1995). The occurrence of such a multi-storey multilateral sandstone with little evidence for incision overlying a regionally important surface that was produced during slow rates of accommodation space creation assigns this sandstone to part of an alluvial transgressive systems tract. Nonetheless, it still overlies a 3rd order sequence boundary, since it represents the lowest point on the stratigraphic base level curve between the two maximum flooding surfaces.

The remainder of the Westphalian B succession (Fig. 5.14) thus represents a gradual rise in stratigraphic base level from the low point, above the sequence boundary and beneath the Caister Sandstone, to the maximum flooding surface at the *Aegiranum* marine band. This equates to a 3rd order transgressive systems tract or sequence set (Fig. 5.13) This comprises a number of 4th order sequences that reflect high rates of accommodation space creation punctuated by 4th order fluctuations. The sediment supply rate always managed to keep pace with the high rates of subsidence, leading to rapid vertical aggradation and frequent emergent surfaces for coal seam establishment. Concomitant with this increasing rate of stratigraphic base level rise and accommodation space creation is a change in fluvial style from the multi-storey, multilateral transgressive sandstones of low-sinuosity braided channel origin to increasingly isolated channel sandstones of various sinuosities, which are thinner and finer grained. A similar progression is noted by various workers in Argentina (Mancilla et al. 1991; Legarreta and Guilsano 1989; Kokogian 1989; Legarreta and Uliana 1991) and Shanley and McCabe (1991a,b, 1993) in southern Utah.

From analysis of the facies associations described in Chapter 4 it appears that concurrent with this change in style of the fluvial systems is a change in coal seam thickness. The thickest coal seam development across the Murdoch / Caister Field and in wells (44/18-3, 44/23-8) (section 6.2.1) occurs above the alluvial transgressive systems tract sandstones that provide the reservoir for the fields. This series of thick and laterally extensive coal seams develop in the lower Westphalian B (Chapter 2) and can be traced at approximately the same stratigraphic level in Northumberland across Quadrant 44 based on wireline data, and corroborated by seismic data (ARCO pers. comm.), as they provide a distinctive seismic marker. The rate of base level rise at this time appears to have been at an optimum pace for coal swamp initiation and long-term maintenance. The thick coals that developed compare with thick coals described for transgressive systems tracts in other areas (Flint et al. 1995). As the rate of stratigraphic base level rise increases the coal seams become thinner and less frequent due to the fact that they are drowned more rapidly by the increasing rate of stratigraphic base level rise. It also takes more sediment and time to infill lakes of a deeper and more extensive nature, formed by this more rapid rate of rise, to allow emergent conditions to develop. Thus there is an inverse relationship of coal seam thickness to the thickness of high gamma-ray lacustrine facies, thereby, producing a gradual transition from the interfluvial floodplain WILF (section 4.3.3.2) with thick coals, to the interdistributary bay and lake WILF (section 4.3.3.3) with thick lacustrine mudstone packages and thin infrequent coals. The postulated increase in rate of stratigraphic base level rise and accommodation space creation is confirmed by comparison of the wireline log facies associations. The culmination of this process of increasing rate of stratigraphic base level rise is that by upper Westphalian B times, the coal seams are drowned by marine bands (section 5.3.2), indicating that the rate of stratigraphic base level rise is of such a magnitude that marine conditions prevail (Fig. 5.12). The first marine band in this part of the succession is the Maltby marine band. The marine bands (Fig. 5.13) then generally increase in the abundance of their marine fauna and become more marine in character up to the 3rd maximum flooding surface at the *Aegiranum* marine band (Chapter 3).

Superimposed on this stratigraphic base level curve is topography which reflects palaeoslope variations. These appear to become more marked in the upper Westphalian B, so that the onset of well-drained alluvial conditions normally associated with the Westphalian C (described by Besly et al. 1993) occurs in the upper Westphalian B in the northerly, probably more elevated areas of Quadrant 44. This apparent stratigraphic base level fall occurs concurrently with the relative stratigraphic base level rise in basinal areas, suggesting that the palaeoslope had a higher gradient or was tilted. This may be due to the onset of Variscan tectonics or possibly more localised source area uplifts (cf. Turner and O'Mara 1995). Concomitant with these uplifts is an increased sediment supply and grain size, leading to the formation of elevated and well drained alluvial areas (cf. terminal fans of Besly et al. 1993).

Poorly drained intercalations of grey Coal Measures facies within the predominantly well drained alluvial (red-bed) environment may well correlate to marine incursions and stratigraphic base level highs in the basinal areas (section 4.2.2).

5.3.5 High frequency 4th order sequences in the Westphalian B

Superimposed on this 3rd order transgressive sequence set are high frequency 4th order fluctuations on the stratigraphic base level curve (Fig. 5.14). The most readily identifiable surfaces are the 4th order maximum flooding surfaces within these sequences (discussed in section 5.3.2). Typically these are characterised by coarsening and shallowing upward packages of prograding minor crevasse splay delta systems (Fig. 5.15) that suggest accommodation space creation decreases upward. Thus, vertically accreted suspension fallout lake sediments pass into crevasse splays that prograde increasingly into the lacustrine areas concurrent with the reducing accommodation space. In the alluvial floodplain WILF (section 4.3.3.8) the low stratigraphic base level precludes any crevasse splay progradation as the accommodation space is simply not there to be filled. Thus, intercoal packages are characterised by palaeosols and overbank sheet floods that spread out laterally not vertically. The filling of the interdistributary area culminates in shallow water environments where palaeosols and ultimately coal seams form. Lateral facies equivalents to these environments will be minor high sinuosity distributary channels that commonly occur at the top of infilled lake packages into which they may incise, as stratigraphic base level is at its lowest in the 4th order sequence.

These idealised 4th order sequences are complicated by small scale autocyclic processes that affect stratigraphic base level and typically drown coal seams, such as differential compaction and channel switching, although the basinally important 4th order flooding surfaces can still be recognised by the high gamma peak responding lake facies with abundant non-marine bivalves. These 4th order sequences are equivalent to intercoal intervals, which in Northumberland (Land 1974) (Fig. 5.14) and the Southern North Sea (Quirk 1993) do not vary markedly in their thickness across the floodplain, only towards the basin depocentre, where subsidence is greater. Here there are more sequences of a smaller order, not thicker sequences, suggesting that sediment supply was always able to keep pace with rising stratigraphic base level, allowing coal seams to form as parts of the floodplain were frequently emergent. concomitant with lake filling. Consequently, down palaeoslope there are more coal seam flooding surfaces and intercoal intervals in the same time span. These are of some higher order, and may amalgamate into 4th order flooding surfaces up slope, or coal seams. Thus correlation across the palaeoslope is more reliable than up and down the palaeoslope.

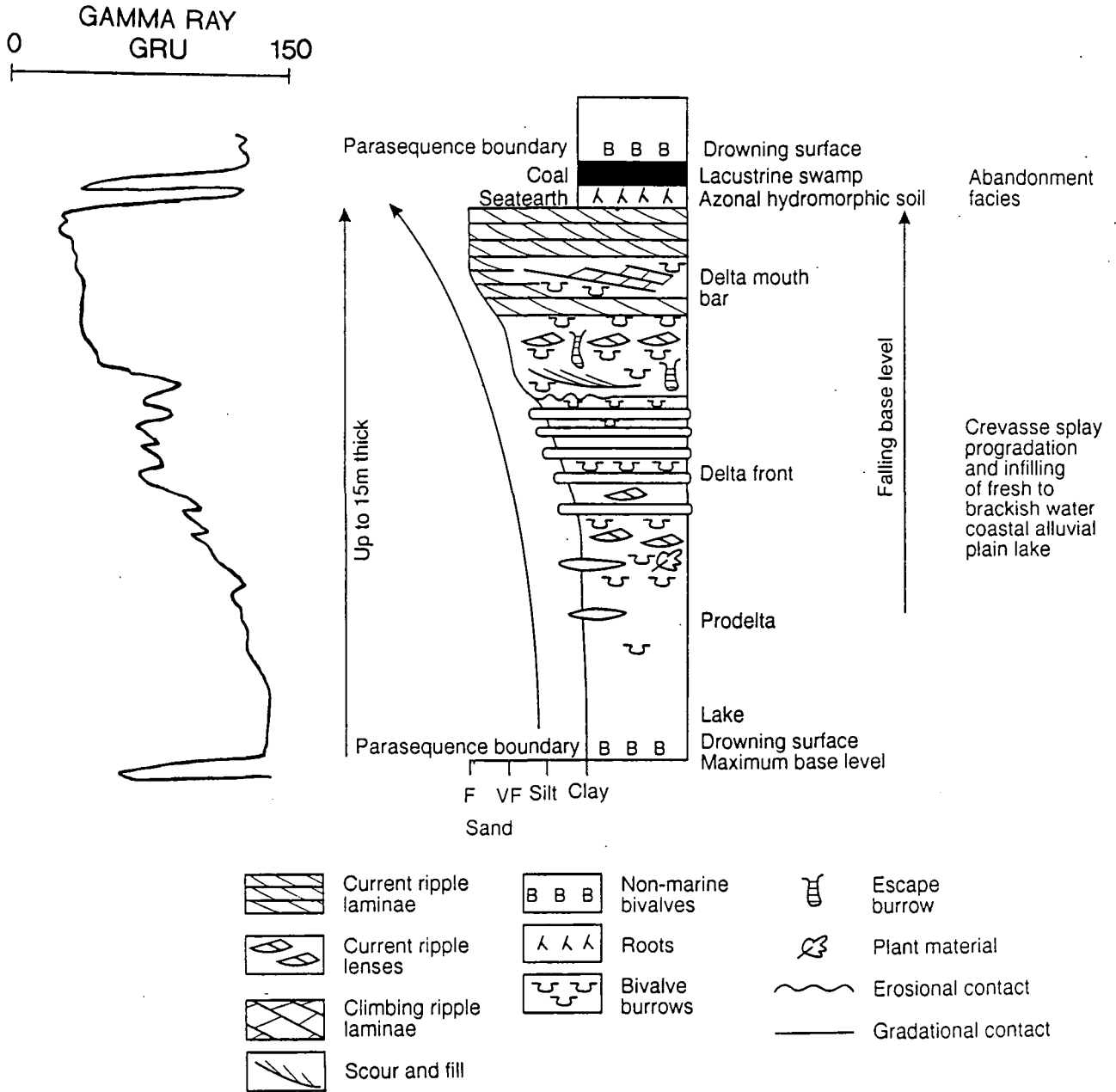


Fig. 5.15 Schematic core section through a 4th order coarsening- and shallowing-upward package from Quadrant 44 (adapted from Turner and O'Mara 1995).

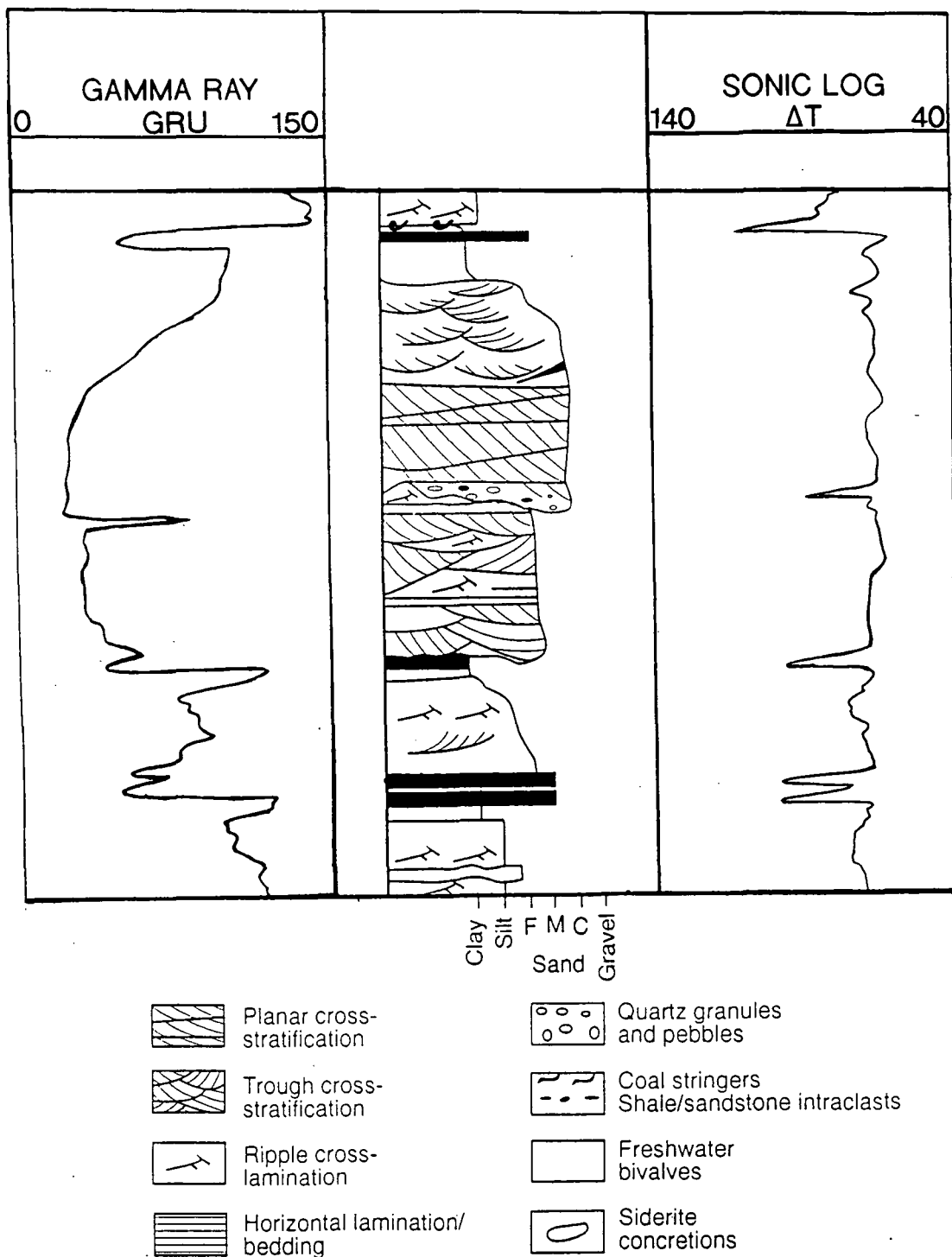


Fig. 5.16 Schematic core section through an intercoal interval, characterised by a distributary channel sandstone (adapted from Turner and O'Mara 1995).

Interspersed with these intercoal interval 4th order sequences are those dominated by sharp-based, blocky, multi-storey sandbodies (major distributary channel WILF) or those which are single-storey fining-upward sandbodies (minor distributary channel WILF) (Fig 5.16). These are the feeder channels that provide sediment for crevasse splay delta systems and overbank deposits, but how much stratigraphic base level controls their development is uncertain. It is thought that these sandbodies are the lateral facies equivalents of the various Westphalian B facies. The controlling factors on distribution, stacking and geometry are thought to be indistinguishable from autocyclic processes such as switching. 4th order base level falls conceivably could produce sandbodies of this type (Aitken and Flint 1993a,b) although due to the high rates of subsidence, the small-scale 4th order base level falls are thought, in the Westphalian B of Quadrant 44, to have little effect on the overall relative base level curve, and thus are not considered a likely mechanism for driving sandbody formation. Only gross changes in channel style, geometry and net sandstone to mudstone ratio will assist in stratigraphic base level curve interpretation. Thus they have limited use in a sequence stratigraphic interpretation. Stacking is thought to be controlled by autocyclic factors such as differential subsidence and fault controlled depressions (44/22-1).

5.4 Conclusions

It has been demonstrated in this chapter that Westphalian facies associations are susceptible to stratigraphic base level changes, both rises and falls, of various magnitudes. However, the changes may result in different responses across the floodplain reflecting the variety of facies inherent to the depositional system. The surface defined as stratigraphic base level approximates to either water table, lake level or bankfull depth depending on the facies. Two 3rd order maximum flooding surfaces are defined and identified in the Westphalian B succession of Quadrant 44, which correspond to the stage-defining *Vanderbeckei* marine band at the base and the *Aegiranum* marine band at the top. Representing a time when vast areas of the Westphalian foreland basin were flooded by a marine incursion, they result from high points on the stratigraphic base level curve.

A 3rd order sequence boundary can be recognised and although tectonically induced it still represents the lowest stand in stratigraphic base level and can be used to enhance correlation across Quadrant 44. It is directly overlain by a multilateral, multi-storey sandstone, the Caister Sandstone, which forms part of an alluvial transgressive systems tract (terminology of Shanley and McCabe 1994). This sandstone resulted from conditions of low rates of accommodation

space creation which immediately followed the maximum low point on the 3rd order stratigraphic base level curve defined by the two maximum flooding surfaces. Although accommodation space creation was slow, it was never negative (cf. incised valley formation).

Superimposed on this 3rd order stratigraphic base level curve are 4th order base level fluctuations, that are identifiable across the floodplain as base level rises that drown large areas of the floodplain but are of smaller magnitude than the 3rd order maximum flooding surfaces. These are recognised as having a regional to sub-regional extent, by which they can be used to distinguish them from localised autocyclicly driven flooding surfaces, thus defining a 4th order flooding surface hierarchy. Base level falls of this magnitude are indistinguishable from autocyclicly driven base level falls because of the high subsidence rates inherent in the system. Base level fall recognition requires a 3rd order magnitude fall, induced by tectonics (Caister Sandstone). From the relative position of the 3rd order maximum flooding surfaces and sequence boundary combined with the relatively high levels of stratigraphic base level stand (cf. Westphalian C) the Westphalian B succession is interpreted as a transgressive sequence set.

Chapter 6

Westphalian B correlation in Quadrant 44

6.1 Introduction

The previous Chapters detailed the techniques that have been used to provide a chronologically constrained sequence stratigraphic framework for Westphalian B sediments in Quadrant 44. This chapter details how these techniques were integrated to enable a high resolution zonation scheme to be developed to ascertain thickness variations relating to the regional south-southwesterly directed palaeoslope (section 1.3). Facies distribution and the marine band study provide evidence for the way in which 3rd, 4th and even 5th order base level fluctuations were reflected in Westphalian B sediments, and how these allowed for the definition of a 3rd order sequence boundary, and a 4th order transgressive sequence set. These culminate in the establishment of a flooding surface hierarchy (Fig. 6.7) that is the product of the superposition of the various magnitudes of base level fluctuation (Chapter 5). The detailed work described here allows for the identification of a number of regional and sub-regional important flooding surfaces, and an unconformity between the Westphalian C/D conglomeratic unit (cf. Besly et al. 1993) and the underlying conformable Westphalian B to C succession. It also confirms that in northern parts of Quadrant 44 the onset of well drained alluvial plain sediments was in the upper Westphalian B and not in the lower Westphalian C, as in the onshore (cf. Besly et al. 1993). This greatly enhances the understanding of Westphalian B depositional systems in Quadrant 44 and aids reservoir predictability. An outline of this high resolution scheme for Quadrant 44 wells is given in (Fig. 6.7).

6.2 A High resolution correlation scheme for Quadrant 44

6.2.1 Caister / Murdoch fields and the surrounding areas

Westphalian B correlation in Quadrant 44

The central southern area of Quadrant 44 (Fig. 6.2) has several major Westphalian B gas discoveries, within the lower Westphalian B Caister Sandstone (Ritchie and Pratsides 1993).

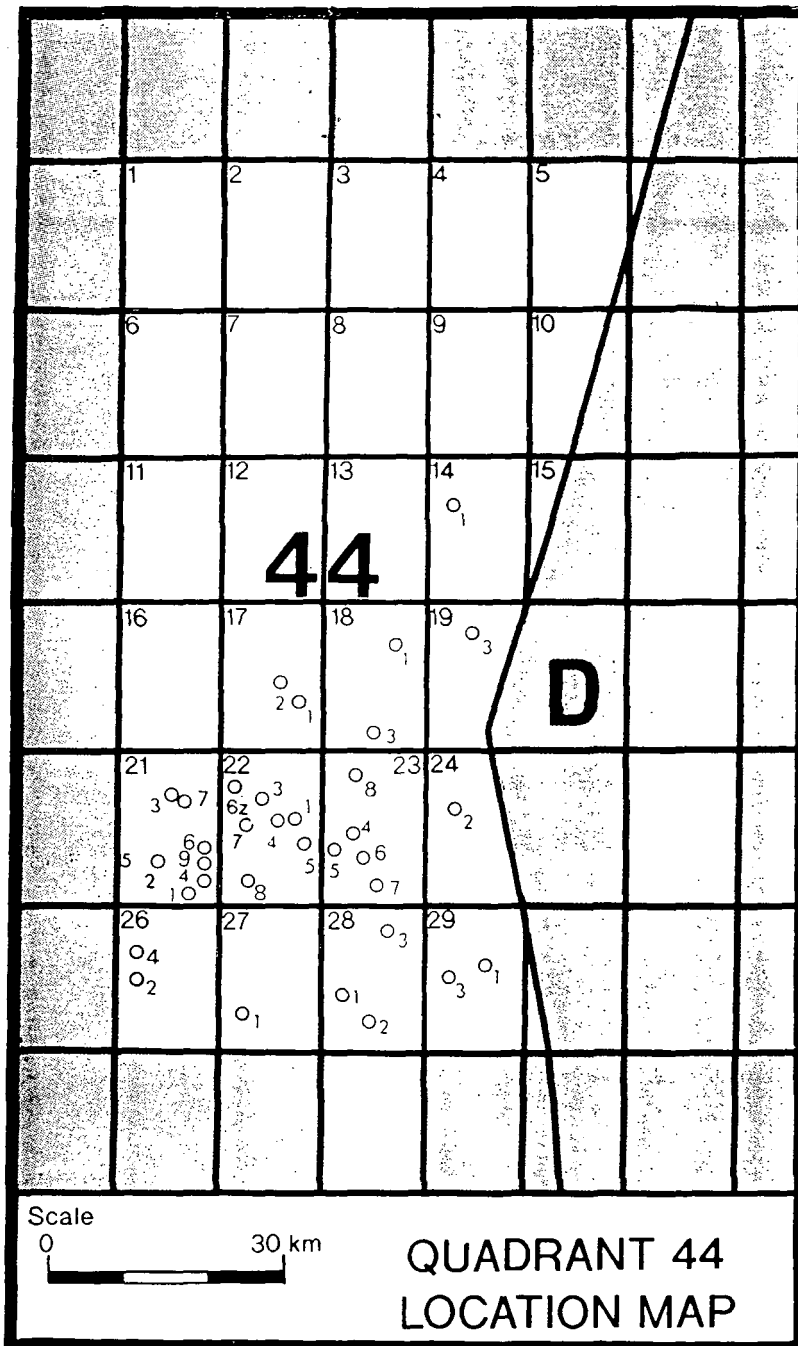


Fig. 6.1 Quadrant 44 location map showing the position of the wells used in this study.

It includes the important Caister (Ritchie and Pratsides 1993) and Murdoch fields, as well as more recent discoveries in 44/18-1 (ARCO pers. comm.). The exploration wells for the established fields were drilled in the early to late eighties and subsequent appraisal, delineation and development wells have led to a superior well coverage than most blocks in the Southern North Sea (Fig. 6.2). The availability of a large amount of palynological analysis, macropalaeontological reports and only wells with abundant core density, allow for a high degree of chronological control. This section includes wells in blocks 44/18, 44/21, 44/22, 44/23, 44/24, 44/28 and 44/29 and is ideal to develop a high resolution correlation scheme for the Westphalian B sediments in Quadrant 44 (Enclosure 1). It is based on the ideas of Turner and McLean (1990) and Riley (1994), and uses information from the sedimentological analysis by SPM Geos (1993) and Ritchie and Pratsides (1993), as well as numerous palynological and sedimentological reports for individual wells.

The wells 44/22-1 and 44/18-3 are important as they are almost entirely cored and yield a complete section through the lower Westphalian B. The report by Riley (1994) on the comparative stratigraphy of the Duckmantian interval in selected wells in Quadrant 44 attempts to identify the coal seams within the Westphalian B sediments and compare them with and assign equivalent names to the onshore coal seams (Fig. 6.3). This is achieved by identifying the associated non-marine bivalve beds, as discussed in section 6.2.1.2 and section 5.2.4. The important surfaces, which provide a sequence stratigraphic framework for the Westphalian B sediments, are not the coal seams as some workers suggest (Flint et al. 1995) but the overlying flooding surfaces. These are thought to represent regional and sub-regional (Fig. 6.3) stratigraphic base level highs, which flood the floodplain irrespective of the underlying facies, and thus are ubiquitous to the succession. The importance of the report by Riley (1994) is that he identifies the flooding surfaces (section 5.3.2) above the coals by the occurrence of non-marine bivalves and attempts to name the individual flooding surface (Fig. 6.3) by reference to a similar non-marine bivalve band onshore from the associated fauna. Using well 44/18-3 and similar cored intervals it is then possible to identify the non-marine bivalve flooding surface. The non-marine bivalve flooding surfaces (Fig. 6.4) are associated high gamma ray interdistributary lake and bay facies, and thus are easily recognisable. The recognition of such surfaces may then be extended to wells without the macropalaeontological evidence based on wireline response. These surfaces are then assigned the typical onshore names. The reader is referred to Enclosure 1 which summarizes the descriptive correlation of the Caister / Murdoch fields and surrounding areas.

6.2.1.1 Biostratigraphy

Generally the biostratigraphy of the Caister / Murdoch fields and surrounding areas is well understood because of the large numbers of wells available and proximity of the section to reservoir horizons, allowing core data to be examined. The top and bottom of the succession are the palynozone-bounding marine bands, the *Vanderbeckei* and the Maltby. The latter can be identified independently by spectral gamma ray logs and corroborated by the distinct faunal changeover associated with it. The presence of the *Vanderbeckei* is confirmed in a number of wells by the occurrence of marine macrofauna, the palynological zone changeover and in 44/18-3 by the non-marine bivalve sub-zone changeover associated with it (Riley 1994). The coring of the Westphalian B succession beneath the Sub-Permian unconformity in its entirety has led to the identification of diagnostic non-marine bivalves which further subdivide the succession. Thus the interval is split into 3 non-marine bivalve sub-zones (Trueman and Weir 1946), two of which are positively identified and a third inferred, by association. Comparison with equivalent onshore successions in Durham (Smith and Francis 1967; Riley 1994), Northumberland (Land 1974), Yorkshire (Eden et al. 1957) and the East Midlands (Smith et al. 1973) allows a number of important non-marine bivalve beds to be identified in Quadrant 44, which are thought to be equivalent to 4th order base level rises. These flood large parts of the floodplain and can be used to enhance the correlation. A secondary set of seams or groups of seams (Fig. 6.3 and 6.4) with occasional flooding surfaces are identified between these flooding surfaces and these are attributed to 5th order base level fluctuations (Mitchum and Van Waggoner 1991) or autocyclic processes. The use of these 5th order fluctuations is tested in the Caister / Murdoch fields and surrounding areas, where it is concluded that they are largely indistinguishable from autocyclic processes.

6.2.1.2 *Vanderbeckei* marine band to Hutton flooding surface

The base of the Westphalian B succession is marked in the Southern North Sea, as in the equivalent onshore section (Fig. 6.3), by the *Vanderbeckei* marine band defining the Westphalian A/B boundary. It is characterized by a shallow marine assemblage of calcareous brachiopods, pentamerid crinoidal debris, arenaceous forams, sponge spicules and *Lingula*. This assemblage is similar, though a little more marine, than the equivalent assemblage obtained from the *Vanderbeckei* marine band in the Durham Coalfield (Smith and Francis 1967; Riley 1994). GAPS (1994) describe a goniatite in 44/22-1 but this has not been substantiated by either the operator or other contracting companies that studied

the same section, thus the claim is ignored. On this evidence diagnostic goniatites have not been found. Nevertheless, the marine band is confirmed as the *Vanderbeckei* by the distinct palynological changeover (Turner and Mclean 1990) that occurs across it, whereby Westphalian B taxa occur above and Westphalian A taxa below. This is supported by the macropalaeontology in well 44/18-3 where Riley (1994) describes the non-marine bivalve *Anthracosphaerum dawsonii* below and *Anthracosia ovum* above, again defining the *Vanderbeckei* marine band by association. Marine fauna of any genera, with palynological corroboration thus positively identify the marine band in 44/22-1, 44/18-3, 44/22-5, 44/24-2 and 44/23-5.

Without macropalaeontological evidence the marine band can be identified by the distinct palynological changeover (Turner and McLean 1990) where a seam beneath the marine band contains the first down hole occurrence of the distinctive Westphalian A taxa *Schulzospora rara*, corroborated by the last down hole occurrence of Westphalian B taxa above. In core material calibrated to the spectral gamma ray signal the *Vanderbeckei* marine band is not seen to have an unusually high total gamma or uranium response. However, the smooth high to moderately high gamma response of an interdistributary lacustrine interval with corresponding dark grey mudstone lithofacies, combined with the palynological evidence identifies this interval as the *Vanderbeckei* marine band and can be correlated as such across the block, in all wells used for the study.

6.2.1.3 Caister Sandstone

In well 44/18-3 the major reservoir horizon, the Caister Sandstone, is clearly identified and it satisfies all the criteria for an alluvial transgressive systems tract. It is bounded at its base by a regional unconformity, marked by a major facies tract dislocation representing the low point on a relative stratigraphic base level curve. Interpreted to be a 3rd order sequence boundary named the Caister Sequence Boundary by Turner and O'Mara 1995. The alluvial sandstone is seen to sit directly upon floodplain deposits, with little basal erosion and occurs only 7' above the *Vanderbeckei* marine band (well 44/18-3). This relationship is repeated in all the Caister / Murdoch field and surrounding area wells, although the interval between the *Vanderbeckei* marine band and the sequence boundary appears to increase southwards, down the regional palaeoslope. This provides further evidence that the sandbody results from the progradation of an alluvial transgressive systems tract under conditions of slowly rising base level, and that it is not as part of an incised valley fill system.

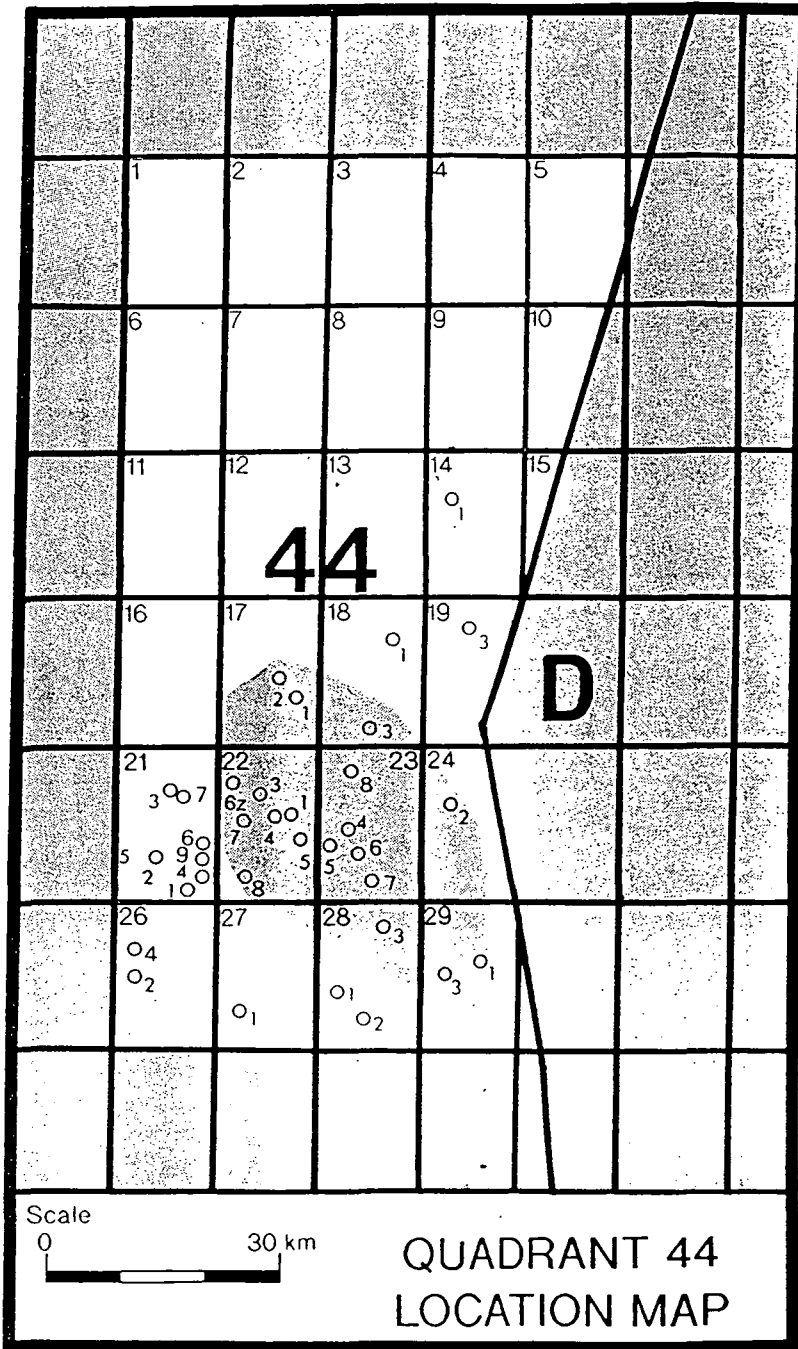


Fig. 6.2 The positions of the wells used in the Caister / Murdoch fields and surrounding area correlation (shown stippled, also including 44/21-9).

In most wells overlying this sequence boundary the Caister Sandstone is represented by a stacked, amalgamated coarse-grained (occasionally conglomeratic or alternatively medium-grained) low sinuosity braided distributary channel sandstone, with corresponding sharp-based, blocky gamma ray log response. Its maximum thickness is thought to correspond to central channel locations (Ritchie and Pratsides 1993) as in wells 44/22-1, 44/22-5, 44/18-3, 44/21-9 and 44/23-4 where it is up to 100' thick and retains its coarse grain-size and blocky log character up to final and rapid abandonment. Although the lower 50 to 60' consist of more massive conglomeratic sandstone the top section is predominantly trough cross-stratified coarse- to medium-grained sandstone.

In wells away from an axial position the sandbody is often seen to split, with a lower blocky portion up to 50' thick on the wireline log response always present (44/17-2, 44/22-8, 44/24-2). This correlates with the lower portion of conglomeratic and coarse-grained sandstones in the wells near the channel axes. It is terminated by an abandonment surface, which consists of facies which are part of the interfluvial floodplain wireline log facies. These include a thin coal seam, and suggest a rapid cessation of channel activity. This abandonment surface represents the encroachment of floodplain sediments concomitant with rising stratigraphic base level and the shifting of the fluvial facies tract landward. This may be temporary, so that fine- to medium-grained, often fining-upward minor distributary channel sandbodies occur above this abandonment surface, suggesting a return to high rates of sediment supply and a shifting of the fluvial facies tract basinward again. The channel style, which is fining upward and of higher sinuosity suggests that this shift of the fluvial facies tracts basinward was not as significant as the initial shift that resulted in the sequence boundary which produced channels of a blocky type. Perhaps the relative rate of rise of stratigraphic base level was slightly faster than that forming the lower blocky portion of the sandbody, although still slow. The abandonment surface may represent a 4th order stratigraphic base level rise causing temporary cessation of the prograding alluvial transgressive systems tract. Thus, the upper part of the sandbody may represent repeated tectonic uplift of the intrabasinal source area (cf. Turner and O'Mara 1995) thereby maintaining high rates of sediment supply and low stratigraphic base level. Thus, this is part of the upward transition to increasingly sinuous channels. Alternatively the abandonment of the lower blocky portion may be permanent (44/22-6z, 44/22-7, 44/23-6, 44/28-3, 44/29-1, 44/29-3) suggesting that the rising stratigraphic base level overprinted the increased uplift and sediment supply in all but near-channel areas.

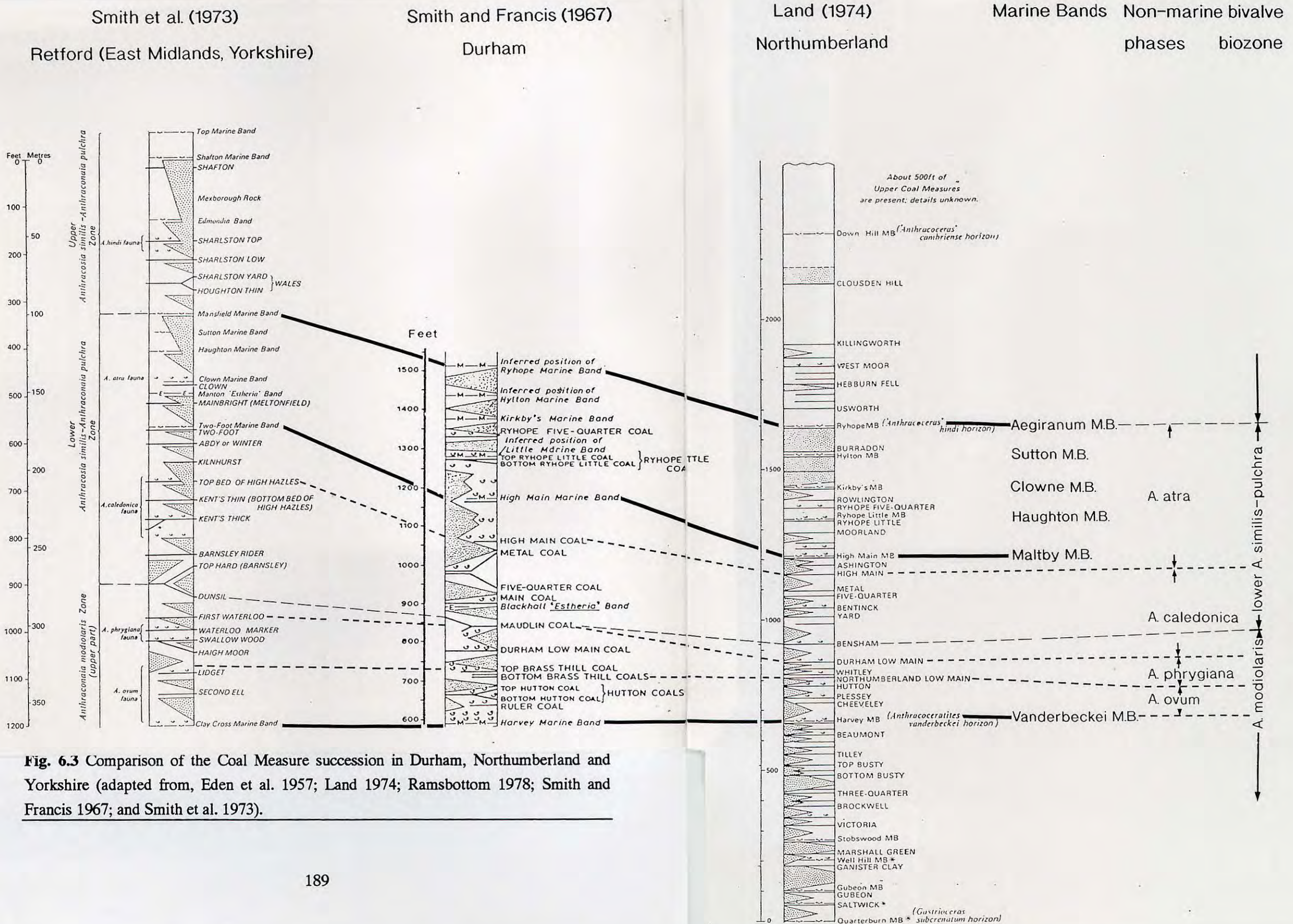


Fig. 6.3 Comparison of the Coal Measure succession in Durham, Northumberland and Yorkshire (adapted from, Eden et al. 1957; Land 1974; Ramsbottom 1978; Smith and Francis 1967; and Smith et al. 1973).

These active channels possibly became restricted to fault-controlled depressions, which concentrated the channel effects. Rising stratigraphic base level also meant that there was accommodation potential on the floodplain (Wright and Marriott 1993) and less reworking of the floodplain took place, hence channels could be filled without significant lateral amalgamation.

The thin coal contained within abandonment facies and interfluvial floodplain facies, where abandonment of the channel is permanent, is thought to equate to the Ruler seam (Riley 1994) of the Durham Coalfield (Smith and Francis 1967). The Ruler seam (Fig. 6.3) and shell bed associated with it is evidence of relative stratigraphic base level rise (Fig. 6.4). In axial positions where the sandbody is at its thickest interfluvial floodplain sediments including a thin coal occur above. The thin coal lies above the stratigraphic level of the Ruler seam which is evident in all axial wells and is thought to be the lowest of a succession of seams known as the Hutton seams (Fig. 6.3) of the Durham area (Smith and Francis 1967), defined by the shell bed above.

6.2.1.4 Caister Sandstone to Hutton flooding surface

The thin coal marking the abandonment of the reservoir sandstone is equivalent to the lowest of the Hutton seams of the onshore Durham area (Fig. 6.3)(Riley 1994). These are a succession of thin inconsistent seams which continually split and rejoin into several leaves across the Northumberland (Land 1974) and Durham Coalfields (Smith and Francis 1967). Each seam is capped by a minor flooding surface occasionally containing non-marine bivalves, with the uppermost seam, the Top Hutton, being drowned by a prominent shell bed with a distinctive non-marine bivalve fauna (Riley 1994).

The interval from the top of the Caister Sandstone is cored in its entirety in 44/18-3 and consists of a variety of interfluvial floodplain deposits, characterized by muddy and silty gley palaeosols (Besly and Fielding 1989), with extensively bioturbated small-scale crevasse splays, with frequent thin coal stringers and seams, capped by thin dark shales. The crevasse splays are seen to thin and fine vertically suggesting a waning flow concomitant with a rising stratigraphic base level. This rising stratigraphic base level culminates in the drowning of a thin coal by a thick interdistributary lake mudstone package. This coal seam drowning (Fig. 6.4) is noted initially by fish debris, including *Rhizodopsis sauroides* and other indeterminate fish debris, with the deeper more extensive lake in which a diverse benthos of non-marine bivalves was able to thrive, with both

shallow and deep burrowers. Riley (1994) identifies the zonal form of *A. ovum* which confirms the presence of the eponymous basal subzone of the Westphalian B, thus conclusively identifying this flooding surface as the Hutton flooding surface. Similar assemblages at this stratigraphic level are described in 44/24-2 (Riley 1994) where the non-marine bivalve horizon is noted by *Anthracosia cf lateralis* and *Anthracosia sp.* while in 44/23-7 disarticulated *Carbonicola* are noted above both the lower Hutton seam and the upper Hutton seam equivalents. Comparing the cored interval with wireline response allows a moderate high gamma ray surface above a succession of thin coal seams to be identified as the Hutton flooding surface (Fig. 6.4), as in wells 44/21-9, 44/22-3, 44/22-4, 44/22-6z, 44/22-7, 44/22-8, 44/23-5, 44/29-3 and 44/29-1.

The interval in well 44/22-1, which is cored, suggests that this part of the floodplain remained an area that preferentially concentrated channel activity, in that the intercoal intervals up to the Blackhall *Estheria* Bed are dominated by channel sandstones. They represent vertically stacked feeder channels, possibly resulting from fault controlled depressions concentrating channels, as noted in the Durham Coalfield by Fielding (1984b, 1986). The major distributary channel sandstones are characterized by sharp bases with a blocky lower log and core portion that subsequently fines upward to abandonment surfaces dominated by the interfluvial floodplain deposits (palaeosols, lake margin siltstones and thin coals). The stacking patterns of the channel sandstones show a fining- and thinning-upward trend, with a consequent increase in log rattiness upward indicative of an increased sinuosity. This reflects an increasing rate of stratigraphic base level rise and gradual decrease in sediment supply as the system returns to equilibrium after the tectonic episode that initiated the lowering of base level and increased sediment supply (Turner and O'Mara 1995). In this case the Hutton flooding surface is marked solely by the abandonment surface and the thin coal seam. The sandbodies may have eroded the mudstones above the coal seam that mark the flooding surface, the coal provides a barrier to further erosion or alternatively it may not have developed due to the possibly elevation of the floodplain above the sandbody, as a consequence of positive differential subsidence. The interval is dominated by channel sandstones in 44/22-5, 44/17-2, 44/23-5, 44/23-8 as well as 44/22-1.

In wells 44/17-1 and 44/23-6 no distinctive flooding surface occurs above a thick coal seam in this stratigraphic interval. In this case the rising stratigraphic base level is noted by the coal seam as the floodplain possibly was initially elevated and thus base level rise was insufficient to flood the plain at this location.

6.2.1.5 Hutton flooding surface to Brass Thill flooding surface

This intercoal interval is 55-70' thick and characterized in 44/18-3 and 44/22-6z by dark grey poorly laminated, heavily bioturbated interdistributary lake mudstones and siltstones containing thin crevasse splay sandstones. These are fine-grained with minor cross-stratification and ripple-cross lamination, interbedded with minor coal seams. They pass into heavily rooted beds typical of the interfluvial floodplain deposits, and are capped by a 3' thick coal seam. From a study of the wireline log response, many of the wells (44/17-2, 44-21-9, 44/23-5, 44/23-6, 44/23-7, 44/23-8 and 44/29-1) from the Caister / Murdoch fields and surrounding areas are typified by similar deposits, dominated by coarsening-upward crevasse splay lobes that subsequently fine-upward, and other interfluvial floodplain lithofacies.

The interval is capped by the Quadrant 44 equivalent (Fig. 6.4) of the extensive and prominent Brass Thill Shell Bed (Fig. 6.3) of the Durham Coalfield (Smith and Francis 1967; Riley 1994) cored in 44/18-3 where it is characterized by a "non-marine bivalve hash" (Riley 1994). The presence of an identifiable specimen of *Anthracosia disjuncta* is typical of the *Anthracosia phrygiana* non-marine bivalve subzone (Trueman and Weir 1948). The lower boundary is taken at the Brass Thill Shell Bed. This together with the presence of *Anthracosia ovum* in the flooding surface below, identifies this flooding surface as equivalent to the Brass Thill flooding surface (Fig. 6.4). This is suggested by the occurrence at a similar level in 44/24-2 by an ostracod, *Carbonita humilis* and other non-identifiable non-marine bivalve fragments, which although non-diagnostic, strongly suggest the Brass Thill flooding surface. Adjacent to this flooding surface on the wireline logs is a significant broad total gamma peak and corresponding broad uranium peak with a sonic low. This indicates that the Brass Thill flooding surface was the precursor to a laterally extensive and relatively deep interdistributary lacustrine environment that flooded much of the floodplain as indicated by the wide lateral extent of the flooding surface across Quadrant 44. It is evident in 44/17-2, 44/21-9, 44/22-4, 44/22-6z, 44/22-7, 44/23-4, 44/23-5, 44/23-6, 44/23-7, 44/23-8, 44/24-2 and 44/29-1. At a similar level in well 44/28-2 (Fig. 6.5) the diagnostic non-marine bivalve *Anthracosia phrygiana* has been identified confirming the identity of the flooding surface and verifying its lateral extent.

The comparable interval in 44/22-1 is again typified by a channel fill, part of the series of stacked major distributary channel fills discussed in section 6.2.2.3. The interval

concentrates channel activity due to the continued readjustment of the system back to grade. Wells 44/17-1, 44/22-3, 44/22-5, 44/22-8, 44/28-3 and 44/29-3 are all characterized by channel sandbodies in this interval. However, these wells still display the major flooding that is associated with the Brass Thill flooding surface, whereby the channels are rapidly abandoned by a high to moderately-high gamma ray interfluvial floodplain lacustrine mudstone flooding event. The exception is 44/22-1 where the base level rise is marked by abandonment of the underlying sandbody including a thin coal seam. No flooding surface occurs above the seam and the succeeding sandbody sits on it, probably due to limited erosion at the base of the sandbody removing the mudstones of the flooding surface.

6.2.1.6 Brass Thill flooding surface to Durham Low Main flooding surface

The Brass Thill flooding surface appears to be the precursor to an extensive lake, indicating a period of relative high base level stand across large areas of the floodplain. This led to the deposition of thick packages of moderately-high to high gamma ray interdistributary lake mudstones. In some wells (44/22-4, 44/22-8, 44/23-6) they occupy the complete intercoal interval up to the Durham Low Main seam (Fig. 6.3 and 6.4) and occasionally up to the Blackhall Estheria Bed equivalent flooding surface, as in 44/22-3, where the Durham Low Main seam and flooding surface is only marked by a lake deepening interpreted from the gamma ray response. A similar lake deepening is noted at the level of the Waterloo Marker seam (see below and Fig. 6.3) in between the Brass Thill seam and the Durham Low Main seam equivalents in 44/22-8. This latter seam is a prominent thick seam in the Durham Coalfield (Smith and Francis 1967; Riley 1994) that has been extensively worked, and from the relative stratigraphic position of the non-marine bivalve flooding surfaces (Riley 1994) in Quadrant 44 a thick seam is developed here also. In 44/18-3 a succession of thin seams overlies a single-storey minor distributary channel sandstone that occurs above the Brass Thill flooding surface. These thin seams pass into a thick palaeosol with a 6'6" coal seam above, thought to be equivalent to the Durham Low Main seam. From a study of the wireline logs at a similar stratigraphic level in 44/24-2 a prominent seam is seen to be present. This is not noted to have a prominent shell bed above it in the Durham Coalfield (Smith and Francis 1967) but it is seen, from its wireline log response in well 44/24-2, to have a high to moderately-high gamma ray interdistributary lake facies flooding the seam in Quadrant 44. This indicates that subsidence rates were higher, and consequently relative stratigraphic base level stand was

consistently higher, leading to the continued presence of lake environments. A similar situation occurs in 44/21-9 and 44/29-1 where a major crevasse splay lobe (section 4.3.3.1) fills the Brass Thill lake to allow a thin Durham Low Main seam equivalent to form.

Because of the accurate definition of the prominent Blackhall *Estheria* flooding surface many of the equivalent intercoal intervals in Quadrant 44 bear more resemblance to the equivalent onshore section in the Yorkshire (Eden et al. 1957) and East Midlands Coalfields (Smith et al. 1973) (Fig. 6.3) than they do to the Durham Coalfield section. The prominent non-marine bivalve bed above the Swallow Wood seam in Yorkshire (Eden et al. 1957) is equivalent to the Brass Thill Shell Bed (Ramsbottom 1978) identified in Durham and in Quadrant 44 (section 6.2.1.5) (Fig. 6.4). In Yorkshire (Eden et al. 1957; Smith et al. 1973) a further coal seam called the Waterloo Marker seam (Fig. 6.3) occurs slightly above this, called the Waterloo Marker, which also has a prominent shell bed associated with it (cf. Durham Coalfield). This suggests that the relative stand in stratigraphic base level was high at this time, and in areas of high subsidence rates like Yorkshire and Quadrant 44 a further coal seam formed with its important flooding surface. This is located between the Brass Thill flooding surface and the Durham Low Main flooding surface. This is equivalent to the First Waterloo seam in Yorkshire. In wells in Quadrant 44 this additional seam is a common feature of the succession although, it is not ubiquitous and only occurs in areas of high subsidence. Thus it is not considered a 4th order base level fluctuation but a smaller-scale base level rise attributed to a 5th order cycle, known as the Waterloo Marker flooding surface (Fig. 6.4).

This is illustrated in 44/17-1 and 44/17-2 where the Waterloo Marker seam equivalent occurs midway between the Brass Thill flooding surface and the thick Durham Low Main seam equivalent in an interval dominated by high to moderately high gamma ray interdistributary lake mudstones typical of a high stand in relative stratigraphic base level. In 44/23-4 the lakes are generally of lower overall gamma ray signature suggesting an interfluvial floodplain lake environment. In wells 44/22-5, 44/22-6z, 44/23-5, 44/23-7, 44/28-3 and 44/29-3 the Brass Thill lake is invaded by major crevasse splay lobes/minor delta systems with the Waterloo Marker seam capping the lobe. This was subsequently drowned by a Waterloo Marker flooding surface and a further interdistributary lake and crevasse splay system up to the Durham Low Main seam equivalent.

In 44/22-1 this interval is once again typified by a blocky, sharp-based major distributary channel sandstone (40' thick) with stacked proximal crevasse channels above. The intervening temporary abandonment phase is possibly equivalent to the Waterloo Marker flooding surface. The crevasse channels pass up into interfluvial floodplain deposits with a thin seam that could equate to the Durham Low Main seam.

6.2.1.7 Durham Low Main flooding surface to Blackhall *Estheria* Bed

In the Durham Coalfield the Durham Low Main seam (Fig. 6.3) has an impersistent shell bed above it (Smith and Francis 1967; Riley 1994) and consequently the underlying prominent Waterloo Marker flooding surface may in some cases be mis-correlated. The Blackhall *Estheria* Bed described from the former Blackhall Colliery (Smith and Francis 1967) is a shell bed that can be identified across the Durham and Northumberland Coalfields (Smith and Francis 1967; Land 1974) and into Yorkshire (Eden et al. 1957; Smith et al. 1973). It lies some distance above the Maudlin seam (Fig. 6.3) of Durham (Smith and Francis 1967) or Top Bensham of (Fig. 6.3) Northumberland (Land 1974) and is closely associated with the Main seam a short distance above (Ramsbottom 1978). In Northumberland (Land 1974) there is an additional seam between the Top Bensham and Durham Low Main, called the Bensham seam (Fig. 6.3). In Yorkshire (Smith et al. 1973) the Maudlin seam is equivalent to the Barnsley (Top Hard) seam (Fig. 6.3) with a rider leaf above known as the Barnsley Rider seam (Fig. 6.3). The Dunsil seam (Smith et al. 1973) occurs between the Barnsley (Top Hard) seam and the Durham Low Main seam equivalent (cf. Land 1974; Smith and Francis 1967). This variation is illustrated in Quadrant 44 (Fig. 6.4) where wells in the northern part are similar to the Durham Coalfield succession, whereas wells in the south have higher rates of subsidence and consequently develop all of the seams (Fig. 6.4 and 6.5).

The interval in 44/18-3, which is cored has a moderately high gamma-ray flooding surface to the Durham Low Main equivalent which is characterized by thin silty interfluvial floodplain lacustrine deposits that rapidly pass into coarsening-upward crevasse splay sandstones and interfluvial floodplain lithofacies including thin coal stringers. Bioturbation is common in the crevasse splay sandstones, palaeosols and sharp based sheetfloods. A thick coal seam consisting of several small leaves occurs above this interfluvial floodplain succession thought to be equivalent to the Maudlin seam. Ten feet above this, overlying a crevasse splay sandstone is a 7' thick dark grey interdistributary lake mudstone containing an ostracod indicative the Blackhall *Estheria* Bed (Fig. 6.3). Although no definitive taxa

are found the ostracod indicates an extensive lake environment and the high gamma ray adjacent to this allows corroboration of this lacustrine environment in wells 44/17-2, 44/24-2 and 44/23-8 which appear very similar to 44/18-3 on wireline response.

In well 44/23-6 the Blackhall *Estheria* Bed (Smith and Francis 1967) is positively identified in cored material by Riley (1994) although no data is forthcoming to substantiate this interpretation. The interval is characterized by smooth high gamma-ray interdistributary lake mudstones suggesting that base level remained high after the Brass Thill flooding surface (Fig. 6.3) and no intervening seams developed. The Blackhall *Estheria* Bed then occurs a short distance above a thin seam which is probably equivalent to the Maudlin (Smith and Francis 1967) or Barnsley Rider seam (Smith et al. 1973) equivalents. A similar situation occurs in 44/22-4 although the high gamma surface equivalent to the Blackhall *Estheria* Bed does not overly a thin seam, it is only represented by a lake deepening. A shell bed is noted at the top of a interdistributary lake mudstone package that continues from the Durham Low Main flooding surface in 44/22-1, although there is no faunal interpretation. In 44/23-4 and 44/23-5 the succession resembles that of Yorkshire (Eden et al. 1957; Smith et al. 1973) with thin coals above the Durham Low Main flooding Surface equating to the Dunsil Coal, above which lies a further thin seam, the Maudlin Seam. An acritarch (44/23-4) above this seam and included within a high gamma interdistributary lake package indicates the Blackhall *Estheria* Bed.

In well 44/29-1 the interval is marked by a series of thin coals, between the Maudlin seam equivalent and the Durham Low Main flooding surface, equating to the Dunsil seam. The Maudlin is then capped by a high gamma-ray lake mudstone flooding surface. In 44/29-3 no coals are present due to the proximity of the Sub-Permian unconformity but two prominent flooding surfaces occur (cf. 44/29-1). In wells 44/28-3, 44/21-9 and 44/22-8 two thick seams occur above the Durham Low Main flooding surface equating to the Dunsil and the Maudlin seams, both of which have high gamma ray flooding surfaces associated with them, prior to the Blackhall *Estheria* Bed which occurs as a separate flooding surface a short distance above the Maudlin seam equivalent (Fig. 6.3).

44/22-6z is characterized by a fine-grained major distributary channel sandstone which is blocky on wireline log, and makes up the whole interval from the Durham Low Main flooding surface to the Blackhall *Estheria* Bed (Fig. 6.4). No intervening seams are thus established. A similar situation occurs in 44/22-3 where the interval is dominated by a series of sandstone-rich crevasse splays and interfluvial floodplain deposits suggesting the

continued proximity to an active channel system. However, a thin seam, possibly equivalent to the Maudlin seam, occurs midway between the Durham Low Main flooding surface, and a high gamma surface, which occurs beneath the Sub-Permian unconformity and may be equivalent to the Blackhall *Estheria* Bed (cf. 44/22-6z).

6.2.1.8 Blackhall *Estheria* Bed to Metal flooding surface

The Blackhall *Estheria* Bed is closely associated with the Main seam (Fig. 6.3), equivalent to the Yard seam of Northumberland and Kents Thick seam of Yorkshire (Ramsbottom 1978). It is a thick seam evident in many wells, for example 44/21-9, 44/22-1, 44/22-6z, 44/22-8, 44/23-4, 44/23-5, 44/23-6, 44/23-6, 44/28-3 and 44/29-1 where it occurs a short distance above the Blackhall *Estheria* Bed. It is cored in 44/18-3 where it is a 1'6" seam. From the onshore section it is known to have a significant flooding surface associated with it, as does the next seam in the succession, the Bentick seam of Northumberland (Land 1974) which has no equivalent in Yorkshire (Eden et al. 1957; Smith et al. 1973) or Durham (Smith and Francis 1967). This seam occurs only a short distance above the Main seam in Northumberland. A further seam, the Five-Quarter seam, (Fig. 6.3) occurs in Northumberland (Land 1974) and Durham (Smith and Francis 1967), which is not known to have a shell bed and flooding surface above it. Thus, the next major flooding surface is defined as that associated with the Metal seam (Fig. 6.4) equivalent to the Kents Thin seam of Yorkshire (Eden et al. 1957; Smith et al. 1973). However, the problem with this interval is that the Metal flooding surface is not proved in any of the wells in Quadrant 44, and the problem is compounded by the lack of wells penetrating this section.

In the cored interval in 44/18-3 the sediments are typical of interfluvial floodplain deposits with small-scale fining-up minor distributary channel sandstones. A thin seam equates to the Bentick seam (Fig. 6.3) equivalent described from Northumberland (Land 1974), while a flooding surface at the top of a further minor distributary channel sandstone is thought to represent the Metal flooding surface. Similarly in 44/22-1 and 44/22-7 where the Metal Seam flooding surface equivalent (Fig. 6.4) equates to abandonment surfaces of initially blocky, then fining-up minor distributary channel sandstones, these abandonment surfaces include a thin seam with flooding surface above which maybe the Metal seam equivalent. However, in 44/22-1 a further sandbody above may have removed the flooding surface associated with it. The Metal flooding surface is also removed by a sandbody in 44/23-7 (cf. 44/22-1) where a seam at an intervening level may equate to the Bentick seam. Consistently, the flooding surface above the Metal seam appears as a moderately high

gamma drowning surface to a seam as in 44/23-4 and 44/23-5. However, 44/23-6, 44/29-1 and 44/29-3 display both Bentick and Metal seams as moderately high gamma ray flooding surfaces. In 44/23-6 the Five-Quarter flooding surface equivalent is also shown by the abandonment of a blocky, major distributary channel sandbody due to shifting of the fluvial facies tract landward. In 44/23-8 similar abandonment surfaces to channel sandstones occur at the Bentick seam level and the Metal seam flooding surface equivalent, but with no seams developed.

In the Murdoch wells (Block 44/22a) such as 44/22-4 and 44/22-7 the Main seam is clearly represented by a thick prominent seam. However, high gamma interdistributary lake mudstones continue from the Blackhall Estheria Bed to the Bentick seam equivalent in 44/22-3, and up to the High Main flooding surface (Fig. 6.4) equivalent in 44/22-6z. Interfluvial floodplain deposits dominate up to the Metal flooding surface equivalent in 44/22-3, which is described in core as being a very dark grey shale. However, no mention is made of shell debris within this core material. In the wells with a thicker Westphalian B succession the minor intervening seams like the Bentick seam and the Five-Quarter seam appear to be more significant and are associated with high gamma flooding surfaces above them as in 44/21-9, 44/22-8 and 44/28-3. This suggests that increased rates of subsidence allowed smaller-scale base level fluctuations to have greater effect, resulting in additional flooding surfaces when compared to the typical Caister / Murdoch fields and surrounding area successions (Fig. 6.4).

6.2.1.9 Metal flooding surface to High Main flooding surface

The Metal seam flooding surface is problematical because it is nowhere proved in core, a problem compounded by the fact that it is not always well developed as a flooding surface. Thus it provides a marker of only limited use. It may be more applicable to use an interval from the well defined Blackhall Estheria Bed to the flooding surface associated with the High Main seam. This is a prominent shell bed (Fig. 6.3) known from the Durham (Smith and Francis 1967) and Northumberland (Land 1974) Coalfields and equivalent to the High Hazles Shell Bed of Yorkshire (Eden et al. 1957; Smith et al. 1973) is described as being characterized by the abundant non-marine bivalve *Naiadites* sp. (Land 1974). It is proved in well 44/22-1 where abundant *Naiadites* sp. (Riley 1994), associated with a coal seam flooding surface, define this as the High Main flooding surface (Fig. 6.4) (cf. Riley 1994). Similar high to moderately-high gamma ray flooding surfaces are developed in most of the other wells that penetrate this section. In 44/22-1 the Metal to High Main interval is

High Main Shell bed although an intervening unnamed shell bed is described which occurs at the same stratigraphic level as the Ashington seam in Northumberland (Land 1974) and a similar unnamed shell bed in Yorkshire (Eden et al. 1957, Smith et al. 1973). Thus, it is conceivable that in areas of high subsidence like Quadrant 44 a coal seam and flooding surface could occur in a similar stratigraphic position as the Ashington seam: these are hereafter termed the Ashington seam and flooding surface (Fig. 6.4). The unnamed shell bed in Yorkshire (Eden et al. 1957; Smith et al. 1973) equivalent to the Ashington seam and flooding surface is described as occurring beneath a seam known as the Kilnhurst seam (Fig. 6.3). This is seen in some localities to have a shell bed associated with it. Consequently, a seam at the equivalent stratigraphic level may be identified in Quadrant 44 as the Kilnhurst flooding surface (Fig. 6.4). Between this flooding surface and the Maltby marine band in Yorkshire (Eden et al. 1957; Smith et al. 1973) is a succession of thin seams known as the Abdy or Winter seams (Fig. 6.3) with an occasional non-marine bivalve bed above. The Kilnhurst and Ashington flooding surfaces are interpreted to be 4th order events as they are clearly visible in the Caister / Murdoch fields and surrounding areas. However, the Abdy / Winter seam only develops a flooding surface (Fig. 6.4) in areas of higher subsidence and is interpreted as a 5th order flooding surface.

The interval is fully represented in well 44/28-3 where a very high uranium enriched flooding surface occurs above a coal seam. Palynological evidence constrains the flooding surface as the Maltby marine band (Fig. 6.3) and allows the marine band (Fig. 6.4) to be tied into the correlation of the Westphalian B in the southern part (Fig. 6.5) of Quadrant 44 (Enclosure 2). From analysis of the wireline log response, the interval is marked by a drowning surface of a crevasse splay lobe by high to moderately high gamma interdistributary lacustrine deposits a short distance above the High Main flooding surface (Enclosure 1). This equates to the Ashington flooding surface. Further crevasse splays and interfluvial floodplain deposits occur up to a doublet of seams, equivalent to the Kilnhurst seam, which has a significant flooding surface above it which marks the onset of a interdistributary lake package. A crevasse splay lobe fills this lake, allowing a succession of thin seams to develop, the Abdy seams, which are known from Yorkshire (Eden et al. 1957; Smith et al. 1973) to be a succession of thin seams. A similar situation is noted in Quadrant 44. The Maltby marine band then occurs a short distance above the seams.

The Maltby marine band which is also constrained by palynology in 44/21-9 by the last down hole occurrence of upper Westphalian B taxa corresponds to a coal seam drowning surface whose gamma ray is in excess of 225API. Similar drowning surfaces, although of

lower gamma ray response, correspond to coals equating to the Ashington and Kilnhurst flooding surfaces, and a short distance beneath the Maltby marine band is a flooding surface associated with the Abdy seams. The only Caister / Murdoch well to penetrate the complete section is 44/22-6z where a very high gamma surface occurs beneath the Sub-Permian unconformity. This is attributed to the Maltby marine band, although uranium enrichment associated with the Permian (Riley 1994) cannot be ruled out. Nevertheless, the High Main flooding surface is considered to be identified with confidence due to the similarity of this section with 44/22-1 where the High Main flooding surface is proved. Thus, two significant flooding surfaces occur above the High Main equivalent in 44/22-6z equating to the Ashington and Kilnhurst with a blocky major distributary channel sandbody above. This sandbody is drowned (abandoned) by a high gamma surface, the Maltby marine band. The Abdy seam equivalent is missing due to the presence of the sandbody. The lower part of the section is visible in 44/23-4 where the Ashington flooding surface is not developed due to sand-dominated crevasse splay deposits. However, the Kilnhurst flooding surface equivalent occurs above a thin seam above these deposits, immediately below the Sub-Permian unconformity (Enclosure 1).

In the expanded interval in 44/22-8 high rates of subsidence have resulted in two flooding surfaces separated by 20' a short distance above the High Main flooding surface. Both are characterized by high gamma flooding surfaces of their own and they equate to the Ashington flooding surface. One hundred feet above this is a further flooding surface associated with two thin coals equating to the Kilnhurst flooding surface. The Abdy coals then occur a further 70' above but 60' beneath the Maltby marine band. These extended intervals (cf. 44/28-3) suggest that the minor intervening seams begin, like the Abdy, to become important and even though they are considered 5th order base level rises they may be correlated across the southern part of Quadrant 44 as intercoal intervals.

6.2.1.11 Conclusions

Fig. 6.4 illustrates the flooding surface hierarchy established for the Caister / Murdoch fields and surrounding areas. Enclosure 1 illustrates how these flooding surfaces can be identified and used to enhance the correlation of the wells in this area. This flooding surface hierarchy can be used to assess thickness variations across the block including how the palaeoslope affects sedimentation. The thickness of the succession in the north of the area is only 81% of the thickness of that in the south. This extra thickness is accommodated by slightly increased thicknesses of intercoal intervals as well as the

increased significance of the fifth order base level changes. As a result intervening seams in the northern part of the area, attributed to minor base level fluctuations or autocyclic processes, take on extra importance in the south where they have well developed associated flooding surfaces. Thus they could be classed as intercoal intervals.

Some of the 4th order flooding surfaces may be missing. This may be attributed to either the fact that extensive lakes already existed in some parts of the floodplain and further stratigraphic base level rise simply led to a deepening of these lakes. This is only distinguishable on log response as thick packages of lacustrine mudstone with no distinct surface identifiable. However, in this case the deepest part of the lake represented by the highest gamma ray response can be used to represent the flooding surface. Alternatively the flooding surface may be missing due to it being washed out by an overlying sandbody. Erosion associated with the base of these sandbodies will easily remove the lacustrine deposits above a coal seam, although the seam itself may present a further barrier to erosion due to its inherent cohesion. The flooding surface may be equivalent to coal seams in some parts of the floodplain, especially if it is elevated, so that flooding is not significant enough to flood the more elevated areas. Sandbody abandonment may also be attributed to relative stratigraphic base level rise, drowning the fluvial system and transferring the facies tracts landward.

Above significant sandbodies the intercoal intervals may be reduced due to positive differential compaction, as sandbodies are less compactable than the surrounding interfluvial mudstones, siltstones and sandstones. This is illustrated in 44/22-7 which has a thin Caister Sandstone equivalent, with the two succeeding intercoal intervals having an increased thickness.

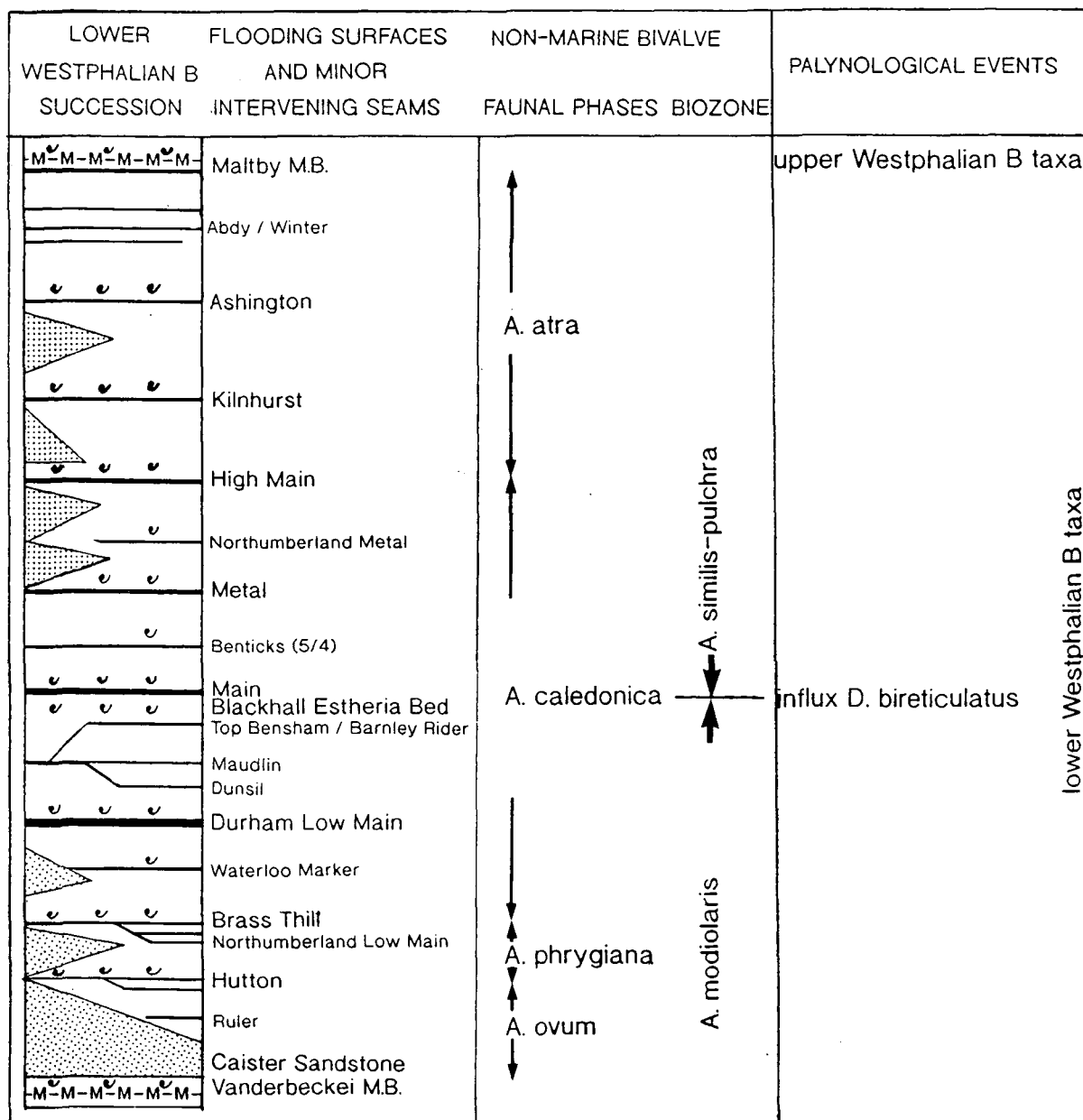


Fig. 6.4 Flooding surface hierarchy developed for the lower Westphalian B in the Caister / Murdoch and surrounding area correlation. Shows major coal seams and corresponding flooding surfaces which are depicted by shell symbol and correspond to flooding surfaces annotated on Enclosure 1.

6.2.2 The southern blocks : 44/26, 44/27, 44/28 and adjacent areas

6.2.2.1 Comparison of the southern blocks with the established flooding surface hierarchy

The correlation of the Caister / Murdoch fields and surrounding areas was undertaken in section 6.2.1 and produced a flooding surface hierarchy (Fig. 6.4) for the lower Westphalian B part of the succession, from the *Vanderbeckei* marine band to the Maltby marine band. This section has two aims: to verify the scheme developed in the Caister / Murdoch fields and surrounding areas, in wells that have a considerably thicker *Vanderbeckei* marine band to the Maltby marine band section than that in the Murdoch / Caister areas; and to establish a similar flooding surface hierarchy (Fig. 6.5) for the upper Westphalian B succession in Quadrant 44 from the Maltby marine band to the *Aegiranum* marine band. This is illustrated in Enclosure 2 to which the reader is referred. There are seven wells in this area (Fig. 6.6) with considerable sections of upper Westphalian B sediments and two wells (Enclosure 1) are included which were involved in the Caister / Murdoch correlation as a tie-in point or control.

In the composite flooding surface and coal seam succession defined in the Caister / Murdoch fields and surrounding areas (Fig. 6.4) it was noted that in wells with a thick section such as 44/22-9 and 44/28-3, additional flooding surfaces equivalent to the intervening seams seen in other wells were developed. This reflects the increased subsidence rates; an observation that is developed below. The high resolution correlation of the Caister / Murdoch wells led to an accurate total thickness determination of the interval between the *Vanderbeckei* marine band to Maltby marine band in 44/28-3 suggesting the presence of some 800' of section. However, a combination of 44/26-2 and 44/26-4 defined on palynology, with common tie-in points at the Maltby marine band and Sub-Clowne tonstein suggest that the thickest succession of Westphalian B sediments in Quadrant 44 occurs in 44/26 where the equivalent *Vanderbeckei* marine band to Maltby marine band section of the succession attains a thickness of some 1100', with the total Westphalian B succession being 2000' thick, considerably thicker than the equivalent onshore section (Land 1974; Eden et al. 1957; Smith et al. 1967). Each of the intercoal intervals that are recognised in the Caister / Murdoch fields and surrounding areas, and the major reservoir sandbody, the Caister Sandstone, are recognised in the 44/26 area. These intercoal intervals accommodate this extra thickness by each intervening minor seam (Fig. 6.7) which lack onshore flooding surface, assuming full intercoal interval status, characterized by major flooding surfaces. This suggests that each 4th order intercoal interval as defined in section 6.2.1 (Fig. 6.4) increases in thickness. However, but within this 4th order relative base level fluctuation are base level fluctuations of a higher 5th order (Mitchum and Van Waggoner 1991). These affect sedimentation styles and stacking patterns within these

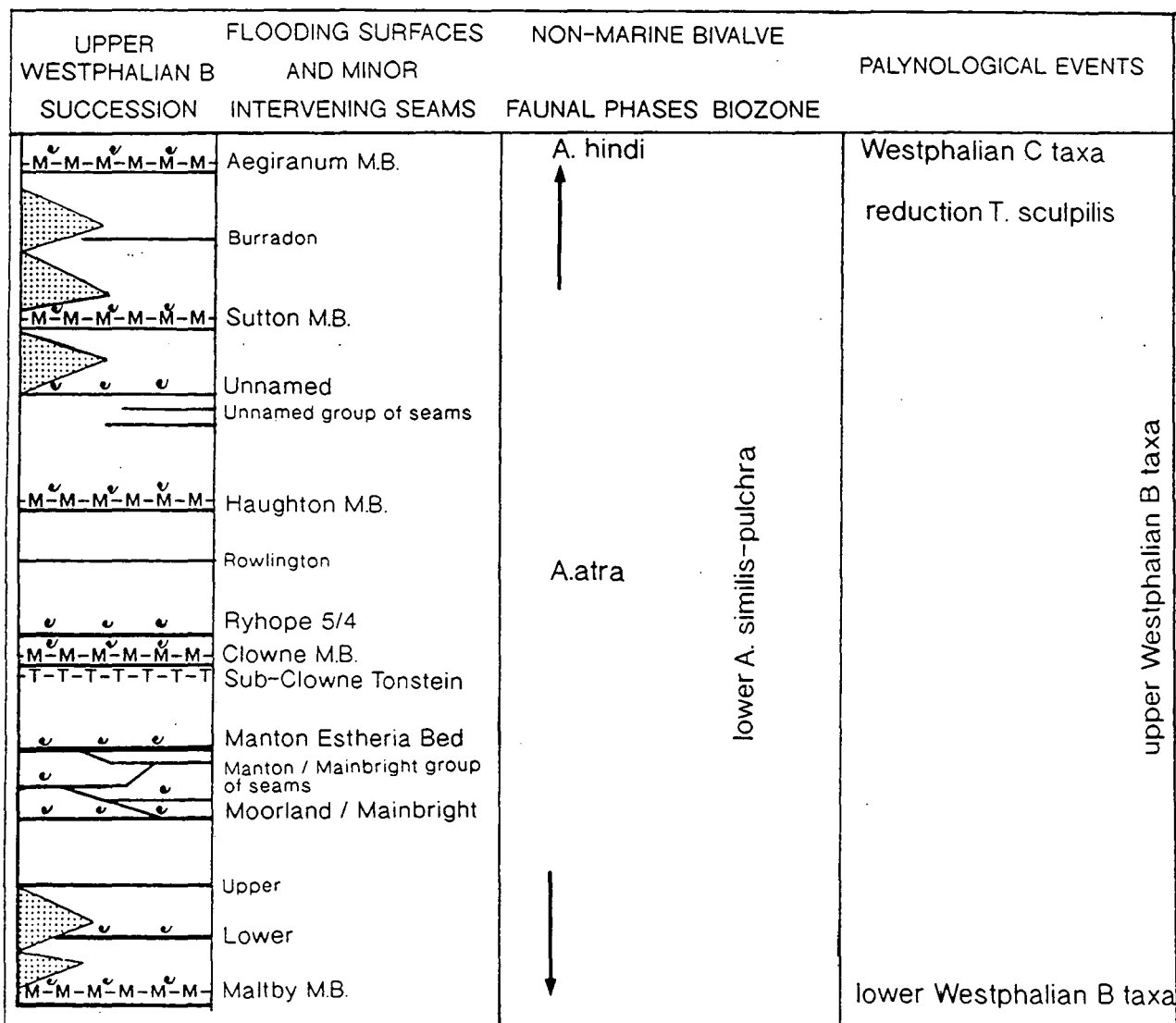


Fig. 6.5 Flooding surface hierarchy developed for the upper Westphalian B in the southern blocks (44/26, 44/27, 44/28) and adjacent area correlation.

4th order packages. Consequently there are small-scale base level highs that drown the distal and low-lying 44/26 to 44/28 region that pass up palaeoslope into the minor intervening coal seams and interfluvial floodplain deposits. Sediment supply rates appear to be capable of keeping up with the high rates of subsidence as the typical intercoal interval sediments are identical to those of the Caister / Murdoch fields and surrounding areas. However, the major coal seams and intervening seams appear to split into several leaves, more commonly separated by high gamma interdistributary lacustrine mudstones. This reflects the distal nature of these sediments whereby major river systems appear to have reduced significantly in terms of grain size and sinuosity (cf Caister Sandstone 44/26-4 and 44/22-1) although not necessarily in the total amount of sediment carried. The predominance of high gamma interdistributary lake mudstones reflects the high subsidence rates, causing abundant and widespread flooding of the floodplain. However, emergence of the floodplain is still common as coal seams are frequent and thick.

In the wells in the southern part of Quadrant 44, 15 flooding surfaces (Fig. 6.5) can be identified in the lower Westphalian B (Enclosure 2), 6 more than the Caister / Murdoch fields and surrounding areas. These represent higher 5th order fluctuations superimposed on the 4th order flooding surface hierarchy (Fig. 6.4) developed in section 6.2.1. They may be identified and subsequently used to develop a high resolution correlation for these Southern Wells (Enclosure 2). Well 44/28-2 confirms this correlation at the level of the Brass Thill Shell Bed as the presence of the diagnostic non-marine bivalve *Anthracosia phrygiana* is noted (Shell 1986), defining the flooding surface underneath as the Brass Thill, or at least part of the lower Brass Thill succession of thin seams (cf. Smith and Francis 1967). The palynostratigraphy of the interval in the southern area wells shows that a significant "negative" zone occurs between the base of upper Westphalian B taxa and the top of lower Westphalian B taxa and the Maltby marine band cannot be palynologically constrained. The flooding surface hierarchy (Fig. 6.7) is important then in assisting the correlation, although the Maltby marine band can usually be identified using the total and spectral gamma ray logs.

There are slight problems in the flooding surface correlation in the interval above the Blackhall *Estheria* Bed up to the Maltby marine band as the number of coal seams increase markedly in their frequency (cf. Fig. 6.4). The individual seams appear to split into several leaves in places separated by 20' to 30' of section. Thus, it is important to group these leaves together as part of the seam seen in other areas. The splitting of the seams is due to the continued high rates of subsidence and they are accommodating this increased subsidence by the development of very small-scale cycles, in response to base level rise equivalent to individual seams in other areas.

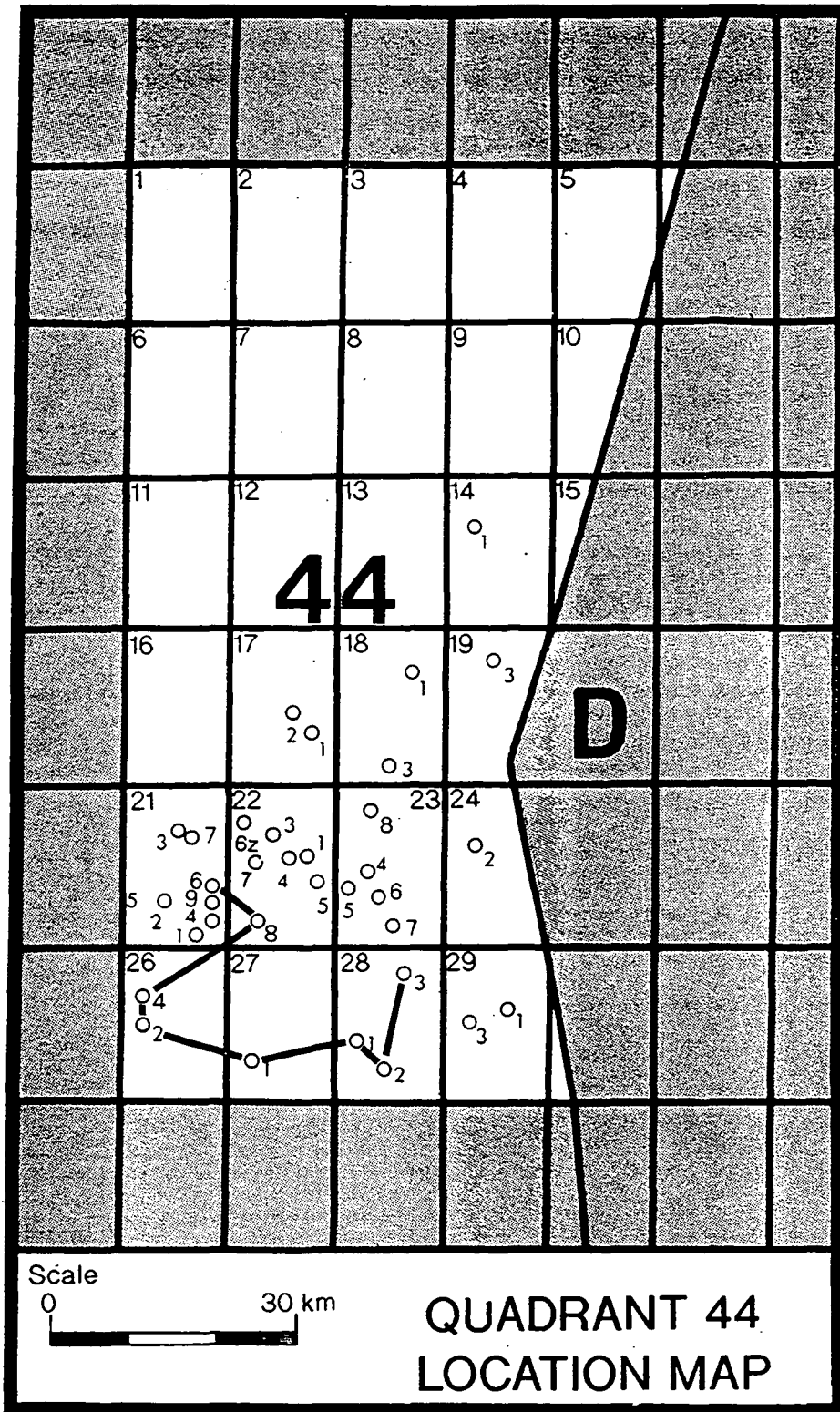


Fig. 6.6 The positions of the wells used in the southern blocks (44/26, 44/27, 44/28) and adjacent areas correlation.

Facies changes (Chapter 4) brought about in this manner will be indistinguishable from those derived from small scale autocyclic changes and as a consequence, the coal lithofacies will be of variable geographic extent and limited correlation potential with a complicated seam and flooding surface interaction. The top flooding surface to the individual groups of seams is thought to be the most important and equivalent to the 4th or 5th order flooding surface in other areas as it represents the major flooding of the floodplain.

6.2.2.2 Maltby marine band to *Aegiranum* marine band : Onshore succession

The seven wells described in this section (Fig. 6.6) have various amounts of this part of the succession available for study (Enclosure 2), although data quality and coverage is inferior to the Caister / Murdoch fields and surrounding areas for the lower Westphalian B. The palynostratigraphy (Chapter 2) yields a broad sub-division and allows the extension of a flooding surface hierarchy (Fig. 6.5) into the upper Westphalian B. The combination of the two areas then allows a flooding surface hierarchy to be developed for the complete Westphalian B succession (Fig. 6.7). The equivalent upper Westphalian B onshore succession (Fig. 6.3) is similar to that described in section 6.2.1 for the lower Westphalian B, although it is typified by flooding surfaces characterized by marine bands in addition to prominent on-marine bivalve shell beds, each with underlying coal seams. These are 4th order stratigraphic base level changes superimposed on a background rise in the 3rd order stratigraphic base level curve up to the *Aegiranum* marine band maximum flooding surface and all these 4th order base level rises have named equivalents in Quadrant 44 (cf. section 6.2.1).

In Durham (Smith and Francis 1967; Riley 1994), Northumberland (Land 1974) and Yorkshire (Eden et al. 1957; Smith et al. 1973) the typical succession of coal seams and non-marine bivalve or marine band flooding surfaces (Fig. 6.3) have a wide distribution. They can be traced across the coalfields and have identifiable equivalents in Quadrant 44 (Fig. 6.3 and 6.5). This is accomplished by integrating the palynostratigraphy (Chapter 2) and facies analysis (Chapter 4) data to identify the flooding surfaces. Additional important stratigraphic markers are the marine bands (Chapter 3), which have high to very high total gamma and uranium signature, and the Sub-Clowne tonstein, an independently established time line, with a marine band flooding surface above. As described in section 6.2.1 there are a number of 4th order flooding surfaces above coal seams with intervening minor seams. However, in the southern part of Quadrant 44 (Fig. 6.6) where subsidence rates are very high compared to the rest of the Quadrant and the onshore section, these intervening seams are typified by flooding surfaces of a smaller 5th order scale (Fig. 6.5). The high rates of subsidence also cause the seams to split with the result that the seams are characteristically marked by groups of thin

coal stringers or seams, over a 30' to 40' interval, each group being drowned by moderately-high gamma interdistributary lake deposits. The top seam is drowned by a high gamma flooding surface representing the regionally correlatable rise in stratigraphic base level. These allow thickness variations to be identified and are correlatable across blocks 26, 27, 28 and surrounding wells in blocks 44/21 and 44/22.

6.2.2.3 Maltby marine band to Lower seam flooding surface

In the Northumberland area (Land 1974) this interval is well represented compared to Durham (Smith and Francis 1967) and Yorkshire (Eden et al. 1957; Smith et al. 1973) which are dominated by major distributary channel sandstones and consequently coal seams and flooding surfaces are poorly established (Fig. 6.3). The Maltby marine band is typified by a very high total gamma and uranium response at the level of the faunal changeover of palynological assemblages from lower to upper Westphalian B taxa. The marine band occurs within a coal seam flooding surface described by Land (1974) as being 2' thick and part of a interdistributary lake mudstone package containing abundant non-marine bivalves which occupy strata up to 30' thick. A thin seam occurs at the top of this package, known in Northumberland (Land 1974) as the Lower seam (Fig. 6.3); it is also noted as having a "mussel" or non-marine bivalve bed above.

In Quadrant 44 the Maltby marine band (Fig. 6.5) is defined clearly in most wells by the total gamma response in excess of 150API. This is seen in 44/28-1, 44/28-2, 44/28-3 and 44/27-1 where the Maltby marine band and thick interdistributary lake mudstone package above continue up into a thin Lower seam equivalent (Fig. 6.5) with high gamma flooding surface. This compares well to the Northumberland section (Fig. 6.3) and indicates that stratigraphic base level remained at a relatively high level except in 44/28-1 where the Lower seam and flooding surface are washed out by a minor distributary channel sandbody. Well 44/26-4 shows the Lower seam flooding surface but not the Maltby marine band equivalent because of a similar minor distributary channel sandbody. The Lower seam and flooding surface is thought to occur above the sandbody abandonment surface. In well 44/22-8 the Maltby marine band is not typified by coal seam flooding but by abandonment of a minor distributary channel which passes rapidly into two thin coal stringers representing the Lower seam with flooding surface above. The interval in 44/26-2 is marked by a poor quality gamma ray signal approaching the Terminal Depth of the well, so assignation of the flooding surface hierarchy (Fig. 6.5) lacks confidence.

6.2.2.4 Lower seam flooding surface to Upper seam flooding surface

The Upper seam is part of a doublet of seams (Fig. 6.3) with the Lower seam in Northumberland (Land 1974). Both are characterized by non-marine bivalve beds above (Land 1974) and with high subsidence rates in Quadrant 44; each are assigned flooding surface status. In Northumberland these seams are noted for their inconsistency and frequent splitting, which also typifies these seams in Quadrant 44, as in 44/28-3 where the Upper seam (Fig. 6.5) splits into several thin leaves. High gamma drowning surfaces above equate to the non-marine bivalve beds above the seams. Similarly in 44/28-1 the Upper seam occurs as a doublet of seams, but in 44/27-1 it occurs as a single seam as it does in 44/22-8 where a single seam occurs with an overlying minor distributary channel sandbody eroding the flooding surface. In 44/26-4 the Upper seam occurs as part of an abandonment package to a minor distributary channel sandstone. No high gamma flooding surface is developed and this interval is also thicker than equivalent intervals in other wells. It is thought that positive differential compaction above the sandbody led to an elevated position and less flooding potential. An intervening seam is noted in well 44/26-2 which has no named equivalent, and may be a result of the very high subsidence rates in block 44/26.

6.2.2.5 Upper Seam flooding surface to Moorland flooding surface

This intercoal interval is consistent across the block with a flooding surface above the Upper seam passing into interfluvial floodplain deposits prior to the Moorland seam (Fig. 6.3 and 6.5) above seen in wells 44/22-8, 44/26-4, 44/27-1, 44/28-1, and 44/28-2. The exception is 44/28-3 which is typified by a blocky major distributary channel sandstone. This washes out both seam and flooding surface, and 44/26-2 which displays a minor intervening seam. This has no equivalent in the onshore section or in other wells and can be attributed to a minor lateral facies change or small scale autocyclic change in stratigraphic base level.

6.2.2.6 Moorland flooding surface to Manton Estheria Bed

This intercoal interval is characterized in Quadrant 44 by a succession of thin coal seams (Fig. 6.5) overlying a Moorland seam flooding surface (Land 1974) occupying the whole intercoal interval up to the Manton Estheria Bed (Fig. 6.8) (Rippon and Spears 1989). This closely approximates to the onshore (Fig. 6.3) where the Moorland seam of Northumberland (Land 1974) appears to split frequently as does its equivalent in Yorkshire the Mainbright (Eden et al. 1957; Smith et al. 1973); an observation confirmed by Rippon and Spears (1989) in their study of the Sub-Clowne cycle in East Midlands. The exceptional subsidence rates in Quadrant 44 multiply this splitting to encompass 50 to 110' of section and up to 8 thin seams (44/26-4),

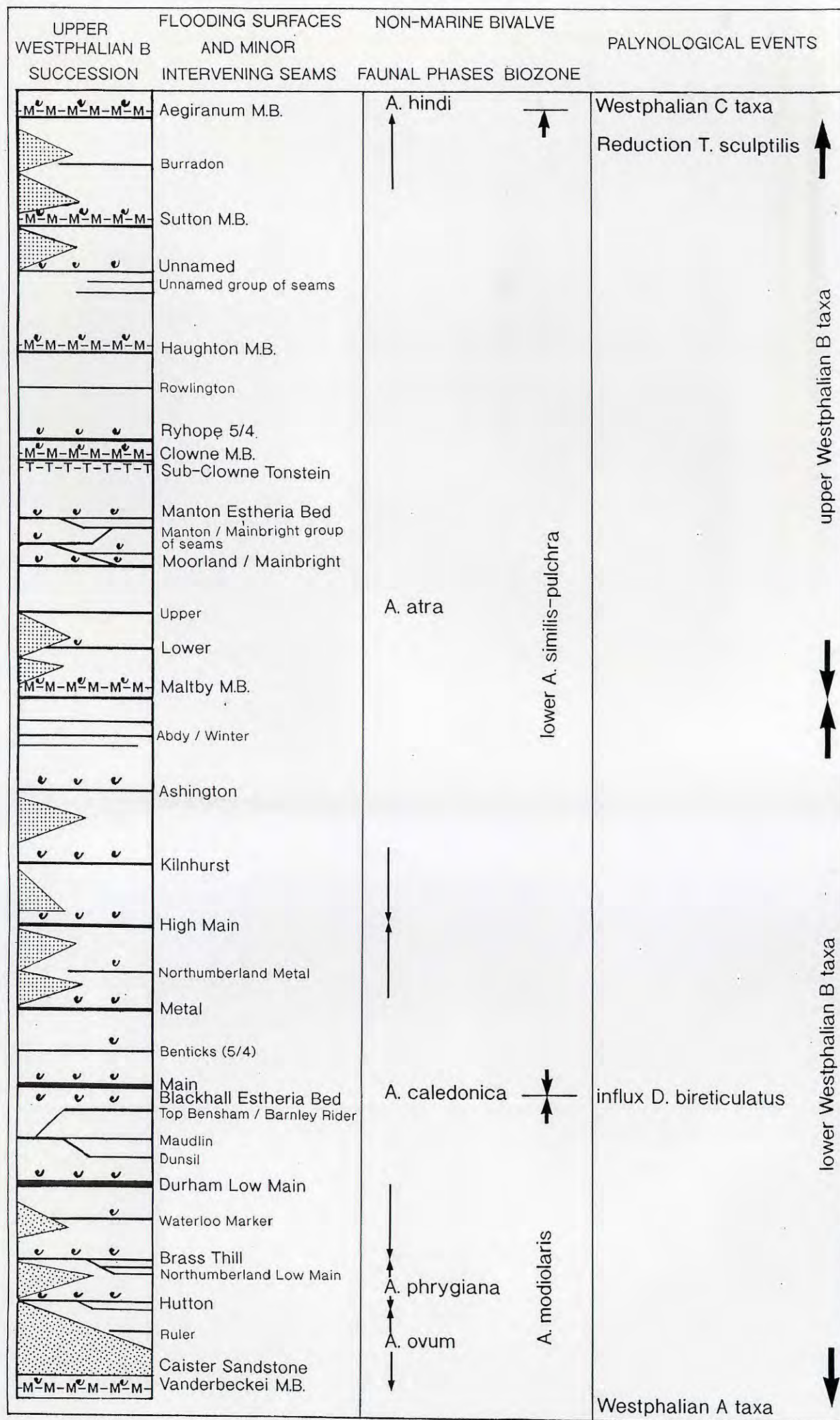
each of which is typified by a high to moderately-high gamma ray flooding surface and intervening interfluvial floodplain deposits. It is important to use the package of seams for correlation rather than individual seams, as these will be inconsistent, and it is necessary to appreciate that high gamma surfaces are common indicating that base level was relatively high throughout this part of the succession. The drowning surface at the top of the thin seams should equate to the Manton *Estheria* Bed (Eden et al. 1957; Smith et al. 1973). In well 44/27-1 the onset of this muddy, coal dominated environment appears to have been slightly earlier as 12 thin coal seams occur in 230' from the Upper seam to the Sub-Clowne tonstein.

6.2.2.7 Manton *Estheria* Bed to Clowne marine band

The Manton *Estheria* Bed (Fig. 6.3) was described by Smith et al (1973) as occurring at the base of the cycle immediately below the Clowne coal seam. Rippon and Spears (1989) describe (Fig. 6.8) it as being up to 2 m thick and having a widespread geographic distribution. It is thought to equate to a shell bed in Northumberland (Land 1974) of diverse "*estheria* fauna" above an unnamed intermediate seam (Manton seam equivalent) between the Moorland seam and Clowne seam equivalent (Land 1974). This shell bed appears to be the precursor to an extensive interdistributary lake which gradually shallows up to the Sub-Clowne tonstein, a palaeosol with volcanic debris which has a very high gamma signature as a consequence. The Manton *Estheria* Bed equivalent is evident in all of the Quadrant 44 wells (Fig 6.5) dealt with in this section and is typified by an unusually high gamma response for a non-marine bivalve flooding surface. It usually marks the onset of a high gamma interdistributary lake package that passes up into the Sub-Clowne tonstein (Fig. 6.8) the regionally correlatable gamma and time line marker. The tonstein is recognised easily in all of the wells except 44/28-3 where the Sub-Permian unconformity erodes to about the level of the Sub-Clowne tonstein (Fig. 6.5), with the result that recognition of the tonstein is uncertain.

In wells 44/26-2, 44/27-1, 44/28-1 and 44/28-2 a single coal seam or several thin seams may occur within the interval of the Manton *Estheria* Bed and Sub-Clowne tonstein. These seams result from minor facies changes or small-scale stratigraphic base level changes superimposed on a thick intercoal interval compared to the onshore succession, as a direct result of high subsidence rates in the southern part of Quadrant 44.

Fig. 6.7 Flooding surface hierarchy developed for the complete Westphalian B succession developed from the Caister / Murdoch and surrounding areas, and southern blocks (44/26, 44/27, 44/28) and adjacent areas correlations.



6.2.2.8 Clowne marine band to Haughton marine band

The Clowne marine band (Fig. 6.3) is described by Calver (1968a) as being an impersistent *Lingula* band. It is not proved in Quadrant 44 as the only cored interval coinciding with the Clowne marine band (Fig. 6.5) has a minor distributary channel sandbody immediately overlying the Clowne seam equivalent. In all other wells except 44/27-1, where a crevasse channel sandstone overlies the Clowne seam equivalent, the Clowne marine band is marked by a particularly high gamma response composed of uranium (cf. Sub-Clowne tonstein) above the Clowne seam equivalent and part of the particularly distinctive double gamma response described in section 3.4.2 (cf. Rippon and Spears 1989). Above the Clowne marine band equivalent in Northumberland (Land 1974) is the Ryhope Five-Quarter seam (Fig. 6.3). This splits into two leaves across Northumberland, each with corresponding flooding surfaces and associated non-marine bivalves. This is a continuation of the high frequency coal seams with abundant high gamma flooding surfaces described in the preceding section. In Quadrant 44 this interval is noted for a single coal seam and flooding surface in 44/22-8 and 44/26-4, while in 44/26-2 and 44/27-1 the Ryhope Five-Quarter splits into top and bottom leaves (cf. Land 1974). The bottom one is a seam with a high gamma flooding surface above, with the top leaf represented by either a coal seam in 44/27-1 with a moderately high gamma flooding surface, or a moderately high gamma-ray minor distributary channel abandonment surface with thin coal seam in 44/26-2. In 44/28-2 the interval is characterised by a blocky, major distributary channel sandstone although the upper leaf of the Ryhope Five-Quarter seam may explain the thin coal stringer contained within the abandonment facies of this sandbody. In 44/28-1 interfluvial floodplain deposits and a minor distributary channel sandstone mask any base level signature. Thus, in both wells the Ryhope Five-Quarter seams and flooding surface (Fig. 6.5) are not well developed.

Between the Ryhope Five-Quarter seams and Haughton marine band (Fig. 6.5) (Calver 1968a; Ramsbottom 1978) there is an intermediate seam called the Rowlington seam described from Northumberland (Fig. 6.3) by Land (1974) as having a non-marine bivalve bed above. This is represented in 44/28-1 and 44/26-4 as a moderately high gamma flooding surface above a coal seam. In 44/26-2 a moderately high gamma minor distributary channel abandonment surface is attributed to the stratigraphic base level rise associated with the Rowlington seam while in 44/28-2 and 44/27-1 the interval is characterised by sandstone dominated crevasse splays.

6.2.2.9 Haughton marine band to Unnamed seam flooding surface

As noted by Smith et al. (1973) in the eastern end of the Yorkshire Coalfield (Fig. 6.3) the Haughton marine band is characterised by a diverse faunal assemblage (cf. Calver 1968a) with a distinct gamma ray peak, identifying the Haughton marine band (Fig. 6.5) in Quadrant 44. It is noted from the wells that penetrate this section (44/26-2, 44/27-1, 44/28-1, 44/28-2) as being a high to very high gamma flooding surface to a thin underlying seam. It appears to be the precursor to a high gamma interdistributary lake package or what Fowler (1936) describes as "Blue shale with *Carbonicola* shells" which is up to 20' thick in Northumberland. It occurs prior to a prominent sandbody and an unnamed coal seam (Fig. 6.3), hereafter referred to as the Unnamed seam and flooding surface. In Northumberland the number of boreholes and collieries that penetrate this part of the succession is few and thus the details of this intercoal interval are poorly known.

In Quadrant 44 the Haughton marine band is also the precursor to a high gamma interdistributary lake package, as in 44/27-1 and 44/28-2. This passes into a succession of interfluvial floodplain deposits and crevasse splay sandstones prior to a number of thin seams equivalent to the Unnamed seam (Fig. 6.5). The lateral equivalent of this in 44/26-2 appears to be many thin seams separated by interdistributary lake mudstones, suggesting a gently rising but consistently high base level. A major crevasse splay lobe invades the extensive lacustrine environment in 44/28-1.

6.2.2.10 Unnamed seam flooding surface to Sutton marine band

No flooding surface is noted in Northumberland by Land (1974) above the Unnamed seam because in the few instances where it is proved a sandbody lies above and has eroded the roof rocks and flooding surface. In Quadrant 44, however, a flooding surface is noted (Fig. 6.5). The Unnamed seam in Quadrant 44 is represented by a series of thin seams as in 44/28-2, or single seams as in 44/28-1. Above the last of these seams is a high to moderately high gamma flooding surface which represents the Unnamed seam flooding surface. The four wells dealt with in this section that penetrate the interval between the Unnamed seam flooding surface and the Sutton marine band (Fig. 6.5) are characterized by sandstones. In 44/27-1, 44/28-1 and 44/28-2 these are stacked blocky major distributary channel sandstones abandoned in each case by high gamma interdistributary lake mudstones either with a coal as in 44/28-2 or, without a coal as in 44/28-1 and 44/27-1. In 44/26-2 the interval is dominated by a minor distributary channel sandstone that fines-upward and passes into stacked crevasse splay sandstones abandoned by a doublet of thin seams. The Sutton marine band is thought to be

represented by a high gamma flooding surface that occurs above the last seam in this succession of thin seams.

6.2.2.11 Sutton marine band to *Aegiranum* marine band

The Sutton marine band is the least well understood of the upper Westphalian B marine bands, due to the scarcity of data from the onshore section (Fig. 6.3). This reflects diminished coal seam frequency and as a consequence data from mining activity. Also much of the onshore equivalent of this strata is removed by the Sub-Permian unconformity. In Yorkshire (Eden et al. 1957; Smith et al. 1973) it contains a restricted marine assemblage comprising approximately 1-4' of black to grey mudstones, although in an offshore borehole in the extreme southeast of the Northumberland Coalfield it is around 4' thick and has a more diverse assemblage (Land 1974). The Sutton marine band has the lowest gamma and uranium signal of the upper Westphalian B marine bands. It is not significantly enriched above the background lacustrine deposits, as illustrated in the four wells (Fig. 6.5) described here where the flooding surface at the base of this interval, which is thought from its relative stratigraphic position to be the Sutton marine band, has no significant uranium enrichment or very high total gamma ray response (cf. Haughton marine band) associated with it.

The Sutton marine band to *Aegiranum* marine band interval in the Northumberland area (Fig. 6.3) comprises about 100' of strata (Land 1974) containing a thin intermediate seam known as the Burradon seam (Fig. 6.3). However, the interval is predominantly sandstone-dominated and as a consequence the Burradon flooding surface is missing. In Yorkshire the interval is marked by 40' of strata with no intervening coal seam but a shell bed is known to occur midway between the Sutton marine band and the *Aegiranum* marine band (Eden et al. 1957; Smith et al. 1973) which is thought to be equivalent to the Burradon seam in Northumberland resulting from a stratigraphic base level high.

Because of the high subsidence rates in Quadrant 44, the Sutton marine band to *Aegiranum* marine band (Fig. 6.5) interval is considered more like the Northumberland section than Yorkshire. Well 44/28-2 has the best constrained section, based on palaeobotanical analysis. Due the frailty of plant fragments it is thought that reworking of material at the time of deposition, and contamination of material at the time of drilling is much reduced compared to the palynological analysis. Thus the zonation based on plant material in well 44/28-2 is considered highly reliable. The limitations are that species tend to be long ranging and thus poor biostratigraphic markers. Nevertheless the palaeobotany suggests (Shell 1986) that the *Aegiranum* marine band occurs at a distinct coal seam flooding surface noted in core by abundant drifted plant fragments but no macrofossils of any type. It corresponds to a high

gamma ray and uranium peak similar to that noted in the East Midlands for the *Aegiranum* marine band in oil bores (Smith et al. 1973). The flooding surface identified in 44/28-2 is part of an 25' interdistributary lake mudstone package of dark grey mudstones. The magnitude of this flooding surface, considering the thick lake mudstone package above, suggests a major base level rise attributed to the *Aegiranum* marine band, which forms a mudstone package of similar thickness to that seen in the Northumberland (Land 1974) and Yorkshire (Eden et al. 1957; Smith et al. 1973) succession.

The intervening interval in 44/28-2 is characterized by a thin seam above the Sutton marine band equivalent and a further seam some 30' higher which represents the Burradon seam equivalent (Fig. 6.5). Above this is a ratty interval of high gamma-ray interdistributary lake surfaces and crevasse splay sandstones, verified in the core material. These indicate the presence of extensive and deep interdistributary lacustrine environments in which the crevasse splays never filled the lake to allow peat colonization of the depositional surface. This onset of high gamma interdistributary lakes is the precursor to the *Aegiranum* marine band maximum flooding surface (Fig. 6.5) that occurs above a thick seam. A thin seam occurs some 40' beneath the *Aegiranum* marine band flooding surface. This appears to have no onshore equivalent, although in core it is seen to have a minor flooding surface associated with it.

In well 44/28-1 above the Sutton marine band is a minor distributary channel sandstone with a possible thin seam above it, equating to the Burradon seam (Land 1974) equivalent, with interfluvial floodplain deposits above. A thick seam with a minor temporary high gamma flooding surface represents the *Aegiranum* marine band flooding surface. A minor distributary channel invades the lacustrine package that represents the flooding surface but this in turn is rapidly drowned by a smooth, 30' thick high gamma, interdistributary lake mudstone package and is thought to contain the *Aegiranum* marine band. The first down hole occurrence of Westphalian B palynological taxa occurs just above. The Sutton marine band in 44/27-1 has a high total gamma signature, but is not seen flooding a coal seam. It passes up into a major crevasse splay lobe with temporary abandonment about the level of the Burradon seam. A blocky major distributary channel sandstone occurs above this, and is in turn abandoned by two thick seams with no lateral equivalent onshore. The *Aegiranum* marine band occurs a short distance above this and is a marked coal seam flooding surface comprising a 20' interdistributary lake mudstone package, approaching 150 API on the gamma ray log. As in well 44/28-1 the first downhole occurrence of Westphalian B palynological taxa occurs just above. A similar situation occurs in 44/26-2 with a Burradon seam equivalent and major distributary channel sandstone above, although the seams seen in 44/27-1 are not evident. A thick package of interfluvial floodplain sediments with crevasse splay sandstones occurs up to a prominent coal seam flooding surface with high gamma interdistributary lake mudstones

representing the *Aegiranum* marine band flooding surface. The first down hole occurrence of Westphalian B taxa and last down hole occurrence of Westphalian C taxa correspond with this flooding surface. 44/26-2 is peculiar in that Westphalian C/D conglomerates overlie the marine band, which is evidence for an unconformity at the base of the Westphalian C/D conglomeratic unit (cf. Besly et al. 1993). As in other wells (4427/1) Coal Measure sediments of the lower Westphalian C overlie the *Aegiranum* marine band.

6.2.2.12 Conclusions.

The flooding surface hierarchy (Fig. 6.5) illustrates that a total of 9 major Flooding Surfaces can be identified in the upper Westphalian B of the southern part of Quadrant 44 in blocks 44/26, 44/27, 44/28 and surrounding areas. These are considered 4th order flooding surfaces and they correspond to non-marine bivalve bearing coal seam flooding surfaces in the equivalent onshore section (Fig. 6.3). The flooding surface hierarchy developed for the lower Westphalian B can then be amalgamated with that developed in this section to produce a flooding surface hierarchy for the complete Westphalian B succession (Fig. 6.7). The top of this flooding surface hierarchy corresponds to the 3rd order maximum flooding surface. Minor intervening seams occur in the lower Westphalian B identified in the Caister / Murdoch fields and surrounding areas, these correspond to 5th order flooding surfaces in the areas of high subsidence rates in the southern part of Quadrant 44. A similar situation occurs in the upper Westphalian B interval also. Consequently four intervening seams described from Durham, Northumberland and Yorkshire (Smith and Francis 1967; Land 1974; Eden et al. 1957; Smith et al. 1973) are seen to have flooding surfaces developed in the southern part of Quadrant 44. However, when comparing these data with a thinner more proximal setting these flooding surfaces may be only represented by coal seams. Due to the high subsidence rates in the southern part of Quadrant 44 the coal seams frequently split into minor leaves, and in some cases it is necessary to assume that groups of seams are equivalent to the onshore seam. The flooding surface at the top of the succession of thin seams is the point of final drowning of the floodplain and represents the point of maximum rate of rise of stratigraphic base level and as such is used as the correlation point. The minor intervening seams represent laterally impersistent facies changes that form over a considerable period of potential coal forming conditions.

The use of this flooding surface hierarchy (Fig. 6.7 and Enclosure 2) allows unequivocal proof of an unconformity at the base of the Westphalian C/D conglomerates, as it allows for a better understanding of the stratigraphy and thickness variations within it. The top of the Westphalian B succession in wells 44/27-1, 44/28-1 and 44/28-1 shows a gradual transition into Westphalian C Coal Measures and is characterized by similar environments. This

continues at least up to the level of the *Cambriense* marine band which is positively identified in 44/28-2 by a marine brachiopod. A gradual transition into well drained alluvial plain sediments is seen in such wells in the Westphalian C. However, in well 44/26-2 the top of the Westphalian B is overlain directly by Westphalian C/D conglomerates (cf. Besly et al. 1993). Thus the Westphalian C must have been removed before deposition of the Westphalian C/D conglomerates (cf. section 6.2.3.2).

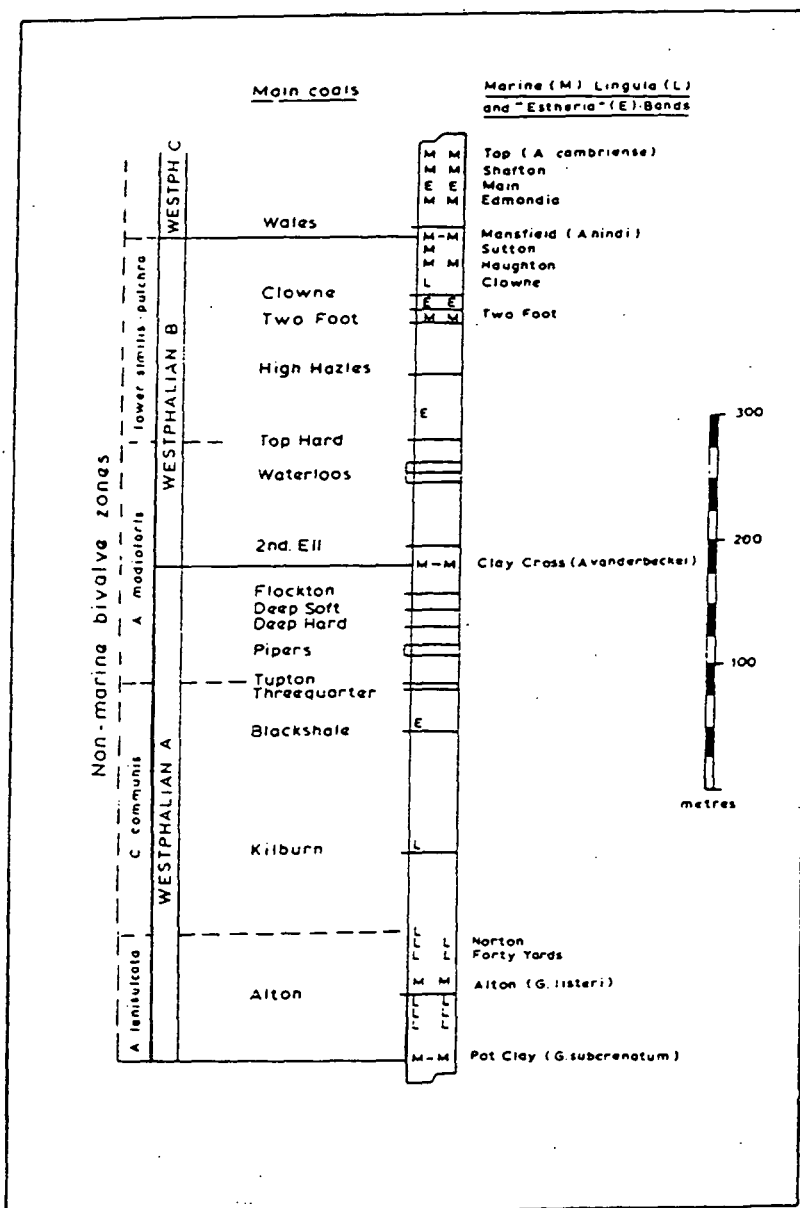


Fig. 6.8 Generalised succession of the Coal Measures of north-east Derbyshire. After Rippon and Spears (1989).

6.2.3 Correlation of block 44/21

6.2.3.1 Introduction

Block 44/21a lies to the west-southwest of the Caister / Murdoch fields area (Fig. 6.9) and includes 44/21-9 which was described in section 6.2.1 as part of the Murdoch / Caister fields and surrounding area high resolution study. It is palynologically well constrained and provides a control succession. The data for these wells is generally of poor quality as most of these wells are traded, so palynological or biostratigraphical reports are unavailable, except for released wells. This is also the case for spectral gamma ray logs. This section illustrates how the flooding surface hierarchy developed in sections 6.2.1 and 6.2.2 (Fig. 6.7) can be utilised to enhance the correlation of wells with such limited data quality, where in some cases, only the total gamma ray and sonic logs are available. It also illustrates the problems of the early onset of well drained alluvial environments. The well spacing is moderate (Fig. 6.9) with three wells (44/21-4, 44/21-6 and 44/21-9) in the south-southwest corner forming a 2.5 mile north-south line of section. Well 44/21-6, the northernmost one, then forms a triangle with 44/21-2 and two wells in the north-central part of the block (44/21-3 and 44/21-7 see Fig. 6.9). Additional wells are not available for this study and 44/21-1 has limited information as it was terminated on encountering Westphalian B sediments. The reader is referred to Enclosure 3 which accompanies this section.

6.2.3.2 Comparison of block 44/21 with the established flooding surface hierarchy

The flooding surface hierarchy in well 44/21-9 compares favorably with that developed in the Murdoch / Caister fields and surrounding area (Enclosure 1) in terms of thickness of individual intercoal intervals (Fig. 6.7) with intervening seams also developing flooding surfaces (cf. 44/28-3). It is palynologically well constrained (McLean 1994) in that the palynological changeover associated with the *Vanderbeckei* marine band is well defined. McLean (1994) also identifies the *Anthracosia ovum* shell bed which occurs as a flooding surface to the Hutton seam. The faunal changeover associated with the top flooding surface in the lower Westphalian B, the Maltby marine band, is also noted by overlapping ranges of lower and upper Westphalian B taxa associated with a very high gamma-ray coal seam flooding surface. This occurs immediately beneath the Sub-Permian unconformity in 44/21-9 and allows the lower Westphalian B sediments in the other wells to be directly compared to a well constrained succession.

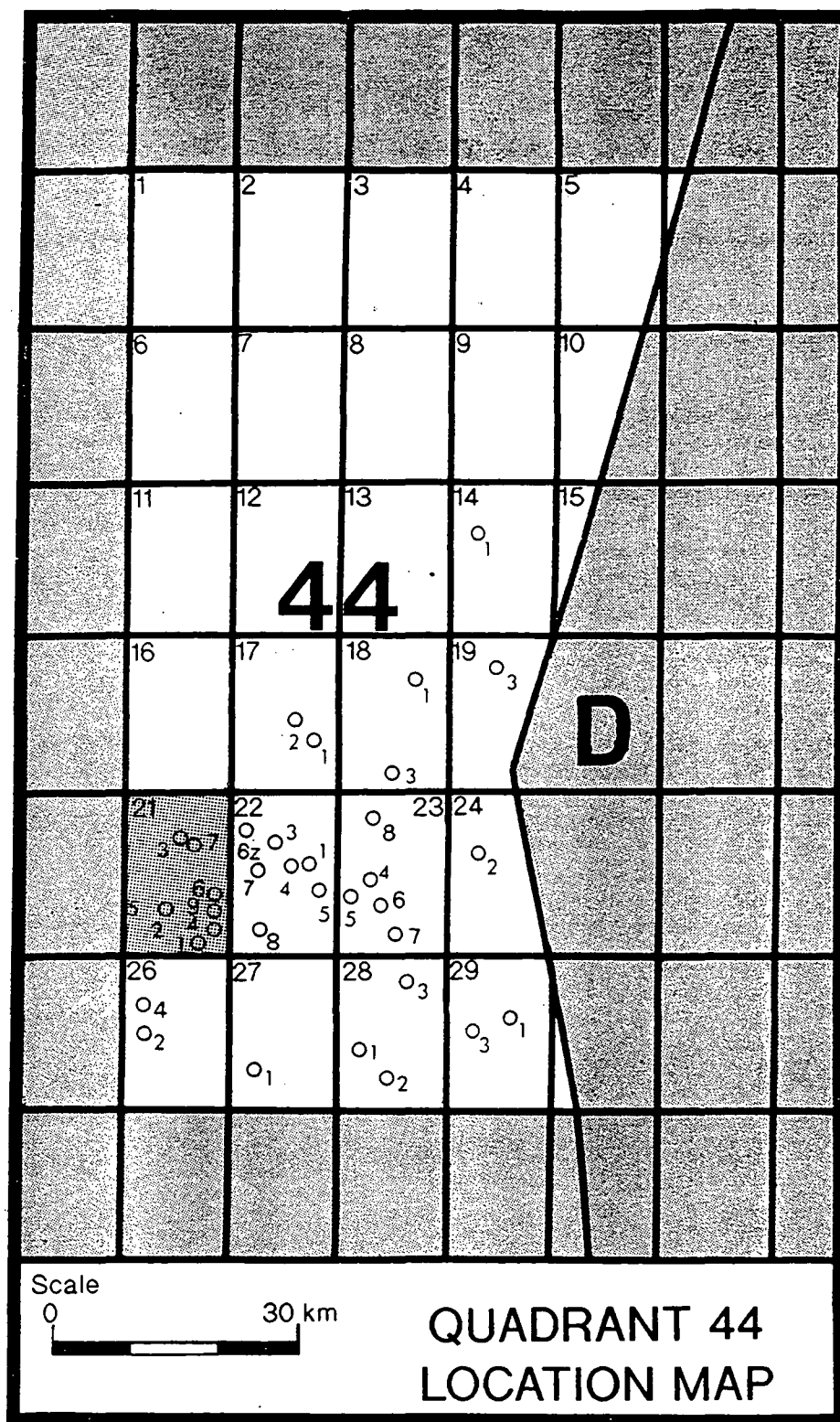


Fig. 6.9 The positions of the wells used in the correlation of block 44/21a and comparison with other block locations (shown stippled).

The details of the Westphalian B flooding surface hierarchy were discussed in sections 6.2.1 and 6.2.2 (Fig. 6.7) and will be dealt with only briefly here. The two wells in the north-south section in the south-southwest corner of the block (Fig. 6.9) are very similar to the control well in the centre of this section (44/21-9). The individual coal seam flooding surfaces (Fig. 6.7) can be traced between the wells up to the Sub-Permian unconformity in 44/21-4 that occurs at the level of the Metal seam flooding surface (Fig. 6.7) and at the level of the Maltby marine band in 44/21-9. However, in 44/21-6 the section appears to correspond to the control section up to the Maltby marine band, but above this level sharp-based conglomerates occur on the gamma ray log, suggesting the unconformable encroachment of the Westphalian C/D conglomeratic unit (Besly et al. 1993). This also requires a significant amount of section to be removed before this unit is deposited. This unit is chronologically poorly constrained (Besly et al. 1993) due to the lack of available dating methods and these workers also assume that the upper Westphalian B remained a Coal Measures depositional environment with sediments of this type deposited up to the lower Westphalian C (cf. well 44/21-3). This conglomeratic unit is thin (60' thick) in 44/21-6 and occurs up to the Sub-Permian unconformity.

Six miles to the north-northwest of 44/21-4 are two wells (44/21-3 and 44/21-7) 0.4 miles apart. The major flooding surfaces (Fig. 6.7) described in sections 6.2.1 and 6.2.2 are identified in 44/21-3 with intervening seams also developed. The individual intercoal intervals appear to be a little thinner than in 44/21-9, but this is attributed to the more northerly up-palaeoslope position. The flooding surfaces (Fig. 6.7) are identified up to the Maltby marine band, which is not constrained palynologically although its position is identified by a high total gamma peak flooding surface above a coal seam (cf. 44/21-9). This gamma peak is not as high as in other wells due to tension problems with the wireline tool. It does, however, equate to a very high gamma ray coal seam flooding surface in 44/21-7. The intervening lower Westphalian section in 44/21-7 can be equated to that in 44/21-3 and consequently the control well 44/21-9 despite slight thickness variations in intercoal intervals due to a major distributary channel sandbody above the Metal flooding surface and a thick high gamma interdistributary lacustrine package above the Hutton flooding surface. One hundred and sixty feet above the Maltby marine band in 44/21-7 is a very high gamma ray surface that occurs beneath a coal seam, attributed to the Sub-Clowne tonstein. The equivalent interval in 44/21-3 is characterized by a minor distributary channel sandstone in which case the Sub-Clowne tonstein will not be developed. The volcanic ash deposits that characterize the tonstein are reworked and dispersed by the channel activity (cf. Rippon and Spears 1989). The coal seam and abandonment surface associated with the channel may well equate to the base level rise associated with either the Clowne marine band or the Ryhope Five-Quarter flooding surface.

Above the Sub-Clowne tonstein in Well 44/21-7 the Westphalian B succession is seen to be similar to that in the Caister / Murdoch fields and surrounding areas and the southern blocks (Fig. 6.7; Enclosures 1 and 2) with high gamma flooding surfaces to coal seams up to what is considered the *Aegiranum* marine band. However, the lack of a control section and any biostratigraphic data place a low degree of confidence on this interpretation. A consistent thickness ratio for 44/21-7 is seen to occur within the total Westphalian B succession (Enclosure 2) when compared to that in the southern blocks, such that similar ratios occur for the lower Westphalian B thickness against the upper Westphalian B thickness in the southern blocks (Enclosure 2). However, in 44/21-3 the high gamma flooding surface associated with a minor distributary channel abandonment surface is thought to occur at the level of the Houghton marine band, the last major high gamma flooding surface and coal seam in the well. From the composite log the sandstones and associated mudstones above this level are described as red brown in colour with occasional grey intercalations, suggesting an early onset of red beds or well drained sediments in this well, with possible poorly drained intercalations. These are most probably still of Westphalian B age although is uncertain due to the lack of reliable dating methods. These well drained alluvial floodplain deposits are not dominated by conglomerates and are considered conformable with the underlying Coal Measures. They relate to improved drainage conditions rather than the unconformable relationship of the Westphalian C/D conglomeratic unit (Besly et al. 1993) seen in well 44/21-4. The transition to well drained environments appears to be gradual, as high to moderately-high gamma interfluvial floodplain deposits continue for about 150' above the Houghton marine band. This may reflect the continued high stratigraphic base level up to the *Aegiranum* marine band maximum flooding surface. This well drained unit is seen to be 500' thick and these sediments are thought to represent upper Westphalian B to lower Westphalian C well drained alluvial floodplain deposits equivalent to the Coal Measures in well 44/21-7 which are thought to occur up to the *Aegiranum* marine band. Above this level in well 44/21-7 well drained alluvial deposits considered equivalent to the lower Westphalian C appear and continue for 300' up to the unconformable onset of the Westphalian C/D conglomerates (Besly et al. 1993).

The onset of well drained sediments in the late Westphalian B suggested by well 44/21-3 is inconsistent as it occurs at different levels in closely spaced wells. It may relate to localised preferential elevation of the floodplain forming well drained areas, a relationship that appears conformable with the gradual transition into better drained conditions. However, an unconformity occurs at the base of the Westphalian C/D conglomeratic unit (cf 44/21-6 and 44/21-7) which has considerable relief on it, as large sections may be removed.

Six miles (Fig. 6.9) to the west of 44/21-6 is 44/21-2. The area is characterized by a thicker more basinal setting, whereas in the southern blocks (Enclosure 2) each intercoal interval is

slightly thicker and the intervening seams have well developed coal seam flooding surfaces (Fig. 6.7) and include the gamma marker of the Sub-Clowne tonstein. The coal seam flooding surface above this is thought to be the Haughton marine band, where a coal seam is flooded by a high gamma (150API) surface. This is the last coal seam in the succession and represents the onset of well drained alluvial conditions (cf. 44/21-3) above which the Westphalian B is typified by moderately-high to high gamma interfluvial floodplain deposits, sharp based crevasse channels and blocky major distributary channels, without coal seams. High gamma ray interdistributary lake intercalations occur at levels suggestive of the Sutton marine band and *Aegiranum* marine band flooding surfaces (Fig. 6.7), although there is no palynological corroboration. A smooth, high to moderately high gamma interdistributary lake package, 40' thick, may represent a stratigraphic base level high that allows poorly drained floodplain deposits to encroach on to the predominantly well drained environment. This stratigraphic level is equivalent to the *Aegiranum* marine band when compared to the southern wells (Enclosure 2).

Well 44/21-1 was drilled in 1965 when the Westphalian B was considered basement. Thus a terminal depth core was taken, providing 138' of section. It is useful in that it displays the Sub-Clowne tonstein, a very high gamma ray peak beneath a coal seam. This is the last coal seam in the well and the sediments rapidly pass into moderate gamma ray alluvial floodplain deposits, indicating that the well drained alluvial deposits occur at the level of the Sub-Clowne tonstein in well 44/21-1.

6.2.3.3 Conclusions

Block 44/21 (Fig. 6.9) illustrates that the onset of well drained alluvial floodplain sediments is variable (Enclosure 3), and controlled by tectonics, possibly due to localised increases in palaeoslope gradient, relating to intrabasinal source area uplift (cf. Turner and O'Mara 1995) or due to local elevation of the floodplain, possibly in response to terminal fans (Besly et al. 1993). This apparent base level rise contradicts the overall stratigraphic base curve which has its maximum flooding surface (highest base level stand) in this interval.

These wells also demonstrate that the Westphalian C/D conglomeratic unit (Besly et al. 1993) unconformably overlies the Westphalian B Coal Measures or well drained alluvial floodplain sediments of either Westphalian B or C age. It demonstrates the considerable relief associated with this unconformity, such that the conglomerates may erode down as far as the Maltby marine band.

6.2.4 Correlation of northern wells in blocks 44/18 and 44/19

6.2.4.1 Introduction

The wells in the northern part of Quadrant 44 (Fig. 6.10) at first glance are considered problematical in that they are spatially isolated from other wells, and from one another. Wells 44/18-1 and 44/19-3 are 6 miles apart along an east-northeast line of section, with 44/18-1 10 miles west-southwest of 44/17-2 and 9 miles north of 44/18-3 (Fig. 6.10). The thickness variation due their northerly position on the palaeoslope is established here. This is difficult considering that the palynological data is of very poor quality and core material is totally lacking. Compounding this is the fact that it is these wells that show a high channel sandstone content, possibly due to their more proximal nature. Thus, it requires careful integration of the palynology (Chapter 2), spectral gamma ray logs (Chapter 3) and established flooding surface hierarchy (Fig. 6.7) to incorporate them into any correlation scheme. It is important that this is undertaken from an economic point of view as both wells display gas discoveries, albeit in the Westphalian C/D conglomerate unit (ARCO pers. comm.). Nevertheless, consideration of the underlying Westphalian B is important for its source area potential or as a secondary reservoir target. The reader is referred to the illustration of this section in Enclosure 4.

6.2.4.2 Comparison of the northern wells with the established flooding surface hierarchy

The quality of the palynological data is poor in both wells because of the reliance on drill cutting data, and to understand these wells it is important to incorporate information from both wells. Well 44/18-1 has a well constrained Westphalian A/B boundary (Fig. 6.3 and 6.7) where the first down hole occurrence of Westphalian A taxa overlap over a 90' zone with the last down hole occurrence of Westphalian B taxa. Immediately above this interval is a 105' thick, sharp-based major sandbody, which has a blocky wireline log response, which is classed as a major stacked fluvial channel system. This compares with the Caister Sandstone in well 44/18-3, especially considering the proximity to the Westphalian A/B boundary zone. The *Vanderbeckei* marine band lacks a distinctive wireline signature and consequently it is thought to occur beneath the sandbody in a mudstone package of moderately-high gamma ray signature. However, due to the northerly position on the palaeoslope and the more proximal nature of the sandstone, the removal of the marine band associated with erosion at the base of the sandbody cannot be discounted. This sandbody is characterized by rapid abandonment, the precursor to a succession of thin seams. Above this level the palynological information is very poor, with the exception of the consistent occurrence of *Ahrensisporites guerickei* which indicates a lower Westphalian B age at least to a depth of 12990'.

Well 44/19-3 palynology poorly constrains the Westphalian A/B boundary, even though both Turner (1990) and the Geochem Group (1990) undertook palynological analysis of the Westphalian interval. Turner (1990) places the *Vanderbeckei* marine band in the interval 13670'-13780' although he does not indicate what criteria this is based upon and he also mentions that the palynological assemblages beneath this are poor due the reliance on drill cuttings. The Geochem Group (1990) count sheets suggest that the only evidence at this time is a down hole frequency decrease of *Endosporites globiformis* although this is tenuous as *E. globiformis* occurs in low levels down to 13995', where the Geochem Group (1990) place their Westphalian A/B boundary. The first down hole occurrence of Westphalian A taxa does not occur until 14440' where *Schulzospora rara* makes an appearance. These zonations are obviously unreliable. However, if Turner (1990) is assumed to be more reliable then the Westphalian A/B boundary potentially occurs at 13670'. Comparison with well 44/18-1 reveals a blocky 105' thick, sharply-based major sandbody at 13465'-13360'. which is interpreted as the Caister Sandstone equivalent. As in 44/18-1 and 44/18-3 the *Vanderbeckei* marine band is believed to occur beneath this, although there is no direct evidence. This occurs some distance above the first indication of Westphalian A taxa at 13670'-13780' and illustrates the problems of reliance on drill cuttings for palynological zonation.

Above the Caister Sandstone in well 44/19-3 the resolution of the stratigraphic zonation improves, on account of the distinctive gamma-ray marker, which is in excess of 225 API. This is composed of both uranium and thorium and occurs in a palaeosol horizon beneath a coal seam, identified as the Sub-Clowne tonstein, with the Clowne seam above. This occurs 677' above the base of the Caister Sandstone. One hundred and twelve feet beneath this is a similar high gamma peak, composed of uranium, which is thought to equate to the Maltby marine band. This peak is unusually well constrained palynologically, with the last down hole occurrence of the upper Westphalian B taxa *Vestispora magna* occurring only 10' above the peak. The palynological zonation of the Westphalian B/C boundary is difficult even in well 44/28-2 where data quality is good, and in 44/19-3 the identification of the boundary is problematical. The Geochem Group (1990) identify the boundary at 12380' on the basis of the single occurrence of *Triquitrites sculptilis*, even though this taxa is known to range down into the upper Westphalian B, and is used by many worker to indicate an age no older than the upper Westphalian B. Nevertheless, a downhole frequency decrease of *T. sculptilis* is thought to occur across the Westphalian B/C boundary and this is what may have been picked up in the otherwise poor quality assemblages. Coincidentally, or due to the abundance of miospore assemblages preserved within marine bands associated with the poorly oxygenated conditions, a high gamma peak with unusually broad low sonic peak occurs at 12389' which is considered to equate to the *Aegiranum* marine band.

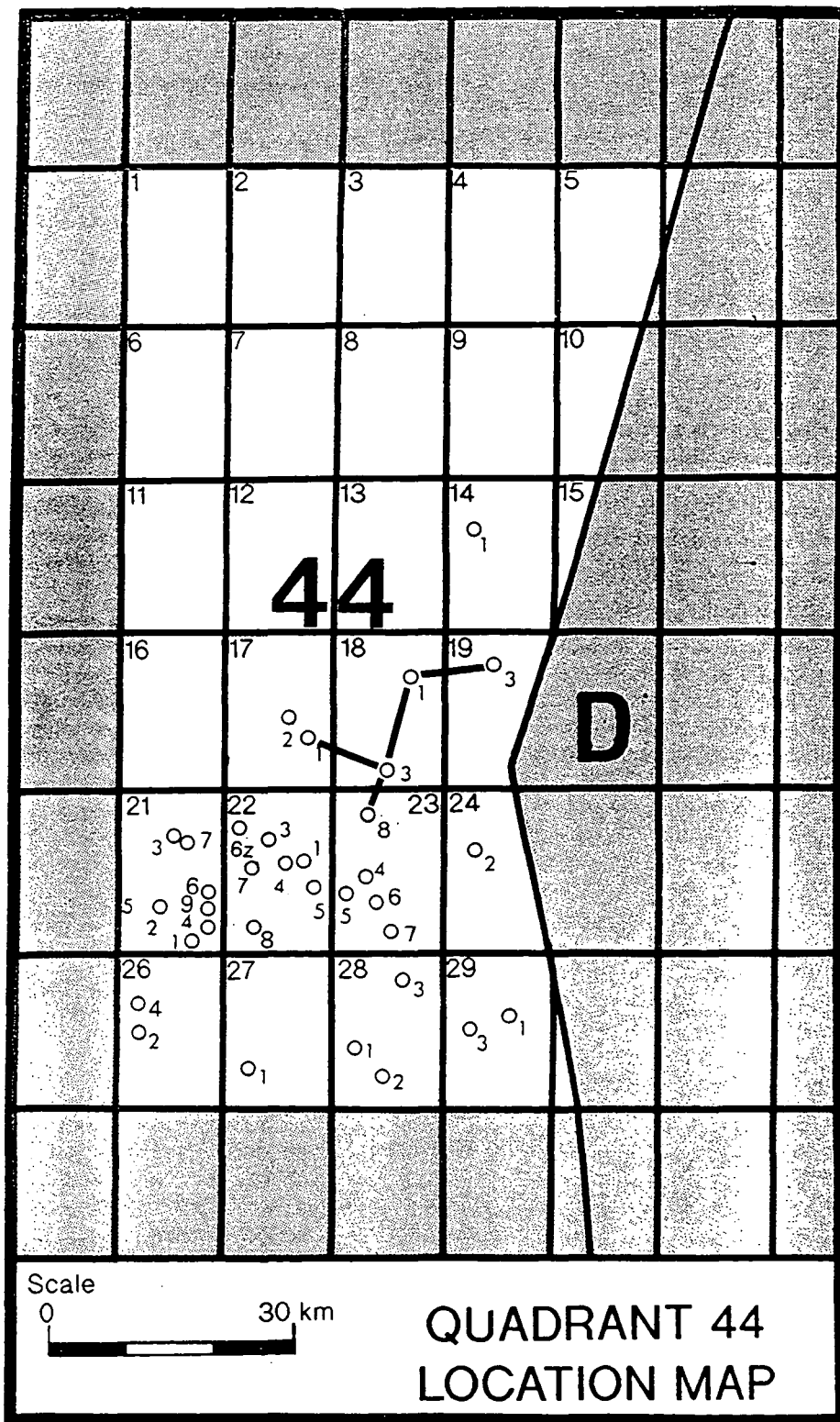


Fig. 6.10 The positions of the northern wells used in the correlation of blocks 44/18 and 44/19 and comparison with other block locations, showing key wells (also 44/17-1 and 44/23-8).

This marine band, because of its prominent marine nature, geographic extent and status as a maximum flooding surface is seen, to be associated with the thickest lake mudstone package of the upper Westphalian B to Westphalian C marine bands, and this interpretation is made with a high degree of confidence. It occurs as a flooding surface to a thin coal seam which in turn is underlain by a sandbody with a very high gamma peak contained within it. However, this is composed of both uranium and thorium and is believed to be a result of heavy mineral enrichment within the sandbody.

6.2.4.3 Stratigraphic details

The stratigraphic detail of the wells can be interpreted using a comparison of the gross Westphalian intervals in 44/19-3 i.e. Westphalian A/B boundary, mid Westphalian B boundary, and Westphalian B/C boundary, and the stratigraphic details in 44/18-3. As a consequence it is considered that 44/18-1 is similar to the Murdoch / Caister fields and surrounding area wells in many ways and conforms to the flooding surface hierarchy (Fig. 6.3, 6.4 and 6.7) established in this region. Owing to its northerly position on the palaeoslope the individual intercoal intervals are thinner and the intervening seams, although developed, do not have high gamma flooding surfaces associated with them. It is important to analyse the well in terms of coal seam flooding surfaces (Fig. 6.3, 6.4 and 6.7), but not just the coal seams themselves as these may be laterally impersistent facies variations. Using this method, as Enclosure 4 illustrates, the Brass Thill, Durham Low Main, Blackhall Estheria Bed (with overlying Main seam flooding surface), Metal, High Main and Ashington flooding surfaces defined in section 6.2.1 (Fig. 6.3, 6.4 and 6.7) can be recognised.

The Hutton to Brass Thill interval is characterized by a series of thin seams with no significant flooding surfaces. This is probably a result of the thick Caister Sandstone underneath forming an elevated area of the floodplain and preventing base level rises to flood these areas of the floodplain. Rises in base level in this case may result solely in coal seams. The Waterloo Marker flooding surface seen in some wells is characterized by an abandonment surface to a blocky major distributary channel sandstone. This in turn is overlain by a minor distributary channel capped by a thick prominent coal seam equivalent to that seen in 44/18-3 and attributed to the Durham Low Main seam equivalent. Two flooding surfaces overlying coal seams above this equate to the Blackhall Estheria Bed and closely associated Main seam and overlying flooding surface. Similar flooding surfaces are associated with the Metal and High Main seams with the intervening seams also present.

The Kilnhurst and Ashington seam equivalents are overlain by a minor distributary channel sandstone and a major distributary channel sandstone respectively, with intervening high to

moderate gamma ray interfluvial floodplain deposits. The latter of these two sandbodies is capped by a very high gamma abandonment surface which is thought to equate to the Maltby marine band. The Ashington seam is the last of the coal seams in the succession in 44/18-1. Above this the overbank sediments are typified by moderate gamma ray siltstones suggesting passage into the well or moderately drained alluvial floodplain sediments. Periodic poorly drained intercalations occur throughout these well-moderately drained sediments, marked by high gamma ray interfluvial floodplain sediments which are thought to equate to flooding surfaces in a more basinward setting. The Sub-Clowne tonstein is not evident in this well drained succession as it is characteristic of oxidising environments, and uranium will be react with the oxygen present to form soluble uranyl ions which will be removed in solution. However, the Clowne marine band, a result of a 4th order stratigraphic base level high, will be associated with wide-scale flooding of the floodplain in a basinward setting. This will cause poorly drained intercalations to occur in previously well to moderately drained floodplain deposits. It is believed to form the high gamma interdistributary lacustrine mudstone defining the Clowne marine band. There is then a series of blocky major conglomeratic distributary channel sandstones, which represent the Westphalian C/D conglomerates (Besly et al. 1993). In block 44/21 it was demonstrated that this unit had a considerable unconformity associated with it, accompanied by a large amount of erosion and consequent relief. This is also illustrated here.

However, well 44/19-3 appears in many ways more similar to 44/22-1 as many of the intercoal intervals are characterized by major distributary channel sandstones. These overly a thick package of high gamma ray interfluvial floodplain or interdistributary bay and lake deposits with frequent crevasse splays and crevasse channels but no coals. The reason for this is unclear but it may be that the overall stratigraphic base level was too high for coal development. Thus an extensive lake was established, which was frequently invaded by crevasse splays. This is the case in several intervals in the Caister / Murdoch fields and surrounding area where rises in base level only cause changes in lake level with no emergence of the floodplain to allow for coal seam development. The first of the major distributary channel sandstones occurs at about the level of the Durham Low Main seam and flooding surface in the equivalent section in 44/18-1. Above this four such channels occur and appear preferentially stacked in this region (cf. 44/22-1), separated by high to moderately high gamma abandonment surfaces that may be equivalent to flooding surfaces in 44/18-1. A thick coal seam occurs above the last of these major distributary channel sandstones with a high gamma ray drowning surface above. The last vestiges of the channel system are indicated by a minor distributary channel which is in turn drowned by a high gamma surface consisting of high uranium, and interpreted to represent the Maltby marine band. The rising base level associated with the marine band flooding surface causes shifting of the fluvial system landward allowing the floodplain to colonised initially by a

coal forming swamp with temporary encroachment of a minor distributary channel. Continued rise in base level caused flooding of the floodplain and formation of the Maltby marine band. This interpretation is corroborated by the last down hole occurrence of the upper Westphalian B palynomorph *Vestispora magna*.

The upper Westphalian B interval in 44/19-3 is similar to that seen in other wells in Quadrant 44 (Enclosures 1,2,3) with coal seam flooding surfaces overlying the Lower seam equivalent. Also the Manton to Mainbright intercoal interval is characterized by high gamma lacustrine mudstones including the Manton *Estheria* Bed and abundant thin seams. As described above, the Sub-Clowne tonstein is clearly identified in well 44/19-3; with the Clowne seam and marine band above. The Ryhope Five-Quarter seam occurs above and this appears to be the precursor to a high gamma ray interdistributary lake mudstone package with frequent coarsening-upward crevasse splay sandstones. These continue up to the Rowlington seam equivalent with its overlying flooding surface. Subsequently a very high gamma ray peak composed predominantly of uranium, indicates the Haughton marine band. The high gamma ray lake and interfluvial floodplain environments overlying the Haughton marine band are thought to contain the Unnamed seam and flooding surface equivalent, and continue up to a minor distributary channel sandstone capped by a high gamma ray and high uranium peak thought to equate to the Sutton marine band. The *Aegiranum* marine band occurs above this and is overlain a short distance above by the Sub-Permian Unconformity suggesting that there is no transition into well drained alluvial floodplain deposits and that no Westphalian C/D conglomerates (Besly et al. 1993) were developed in this well.

6.2.4.4 Conclusions

It is possible to incorporate these spatially isolated wells (Fig. 6.10) within the flooding surface hierarchy (Fig. 6.7) developed for other areas, to improve the correlation (Enclosure 4). These wells show a reduction in thickness of the Westphalian B interval consistent with palaeoslope variations. They illustrate that topographic variations were established during the Westphalian B, with some areas of the floodplain becoming better drained, although major base level changes are still recognisable within this well drained environment in the poorly drained intervals. The Westphalian C/D conglomeratic unit in these two wells is again shown to have considerable relief ranging from 0' to 375' associated with the unconformity that it overlies. This suggests that it is a laterally impersistent and highly variable unit, although where established it may have removed considerable thicknesses of the underlying succession.

Chapter 7

Summary and Conclusions

7.1 Palynostratigraphy

The Westphalian A to Westphalian C interval is shown in this study to compare favourably to the equivalent section onshore and that the interval may be biostratigraphically subdivided using palynological taxa. This is achieved by maximising the number of significantly available and useful taxa to develop a methodology that incorporates all of the stratigraphically important data (including any macropalaeontological and palaeobotanical data). This enables the upper Westphalian A to lower Westphalian C to be subdivided into 5 zones (Fig. 2.15). These zones, which are consistent, reliable, palynologically distinct and easily recognisable, are based on a combination of onshore schemes. By taking the best points from these schemes one is able to maximise the resolution of the correlation attainable. This study demonstrates that these zones can be used on a Quadrant wide basis, to subdivide Quadrant 44 well intervals, which can be used to relate the Westphalian B succession to the onshore British and Dutch Westphalian successions.

The Westphalian B palynological zones, and the assemblages that they are based on, conform predominantly to the work of Smith and Butterworth (1967) on the British Coalfields. However, there are slight but important variations in the upper Westphalian B to lower Westphalian C assemblages. Within this interval the upper Westphalian B zonal marker reflects the relative importance of *Triquitrites sculptilis* compared to *Vestispora magna* used by Smith and Butterworth (1967). The Westphalian B/C boundary is also shown to be constrained by a faunal changeover, which compares to the scheme of Clayton et al. (1977) and not that of Smith and Butterworth (1967). The majority of the taxa are Westphalian B specific, although distinct lower Westphalian B and upper Westphalian B assemblages can be ascertained. It can be demonstrated that there are marked faunal changeovers coinciding with stratigraphically important marine bands, and that the top and base of the Westphalian B and distinct Westphalian A and C assemblages were recognised in Quadrant 44 well assemblages.

It is possible where good quality data are available to subdivide the Westphalian B into two zones, except where data quality is inferior in which case it is necessary to infer a "negative" zone (cf. GAPS; SHELL (UK) EXPRO) between the two palynologically distinct zones. This is necessary due to the lack of overlap of taxa, and/or the

occurrence of a significant interval between associated inception and extinction of the significant zone-defining taxa. For example, the Maltby marine band cannot be palynologically constrained and other methods are required to identify the marine band and therefore the boundaries of the two zones concerned. The limitations of the proposed scheme are data quality, which varies markedly, with the result that poor quality data only allows for a broad or coarse stratigraphic subdivision. However, by maximising the number of taxa utilised this problem can be circumvented in some instances. In other instances, a simple Westphalian B assemblage may be the only interpretation possible.

7.2 Marine bands

The incorporation of the marine bands, recognised from the goniatites and associated marine macrofaunal phases, together with the palynological zonations allows a precise chronostratigraphic framework to be established for the equivalent onshore Westphalian succession. This is extremely difficult to recognise in the subsurface (offshore) as goniatites and marine macrofauna are rarely detected, due to the lack of data. Nevertheless, it is crucial to prove the presence of marine bands in the succession to allow accurate stratigraphic subdivision. This study demonstrates that marine bands can be recognised in the subsurface, independent of their faunal content, by their gamma ray and uranium response. Unfortunately the relationship between marine conditions and uranium enrichment proved inconsistent. As a consequence uranium response is seen to vary markedly, suggesting that the controls on uranium enrichment are complicated and produce variable response characteristics. This necessitates the definition of a four fold division of marine bands.

- 1) Namurian marine bands are marine anoxic black shale events, with thick goniatitic acme phases, which concentrate uranium as outlined by Leeder et al. (1990).
- 2) *Vanderbeckei* type marine bands have poorly developed anoxia, thin goniatitic acme phases and abundant benthos, resulting from shallower water depth (cf. Namurian marine bands) and consequently they have negligible uranium enrichment. They contain a low proportion of humic material from land derived organics (cf. Westphalian B/C marine bands) because the distance to the contemporary shoreline was greater (Fig. 3.9).
- 3) Westphalian B/C marine bands are more marginal, but have an abundance of land plant derived fragments with absorbed uranium as well as uranium entrapped within

the phosphatic tests of *Lingula* which are more abundant in these types of marine bands with restricted faunal assemblages.

4) Brackish water *Lingula* beds with high proportions of terrigenous input, and negligible uranium response.

This classification of marine bands defined in this study allows for the development of a model for the possible uranium response of individual marine bands to be expected in a new well and re-evaluation of an old data set. It is thought to be indicative of the organic content and the degree of salinity of the individual marine bands. An additional important stratigraphic marker, the Sub-Clowne tonstein, has been identified from Quadrant 44 wells. It has a particularly distinctive gamma response and is useful in determining relative stratigraphic position without the need for precise palynology, and is subsequently used as a time line for Quadrant 44 well correlation. This is important in helping to identify marine bands in an otherwise palynologically uncertain part of the succession.

The recognition of the marine bands in the subsurface from their gamma ray and spectral gamma ray log response, was demonstrated in this study. Despite uranium variations, when they are constrained by accurate biostratigraphy, this allows for successful incorporation into a regional chronostratigraphic framework (cf. Ramsbottom 1978). The marine bands provide important tie lines and surfaces for correlation (Fig. 3.17) to enable the offshore succession to be compared successfully to the equivalent onshore succession.

7.3 Facies associations and facies

Within the chronostratigraphic framework developed from biostratigraphy and marine band data detailed facies analysis was undertaken. This enabled twelve facies to be recognised in core material from Quadrant 44 wells, similar to those described by Fielding (1984a, 1986) for the Northumberland / Durham Coal Measures and by Guion and Fielding (1988) and Besly and Fielding (1989) from the Pennine Basin. An additional major stacked channel facies, peculiar to the Southern North Sea is also defined here, which is similar to that described by SPM Geos (1993) and Ritchie and Pratsides (1993) from the Southern North Sea. This makes a total of thirteen lithofacies identified in core material in this study for Westphalian B facies associations

in Quadrant 44. Where these individual facies are recognised they can be utilised for sequence stratigraphic analysis including base level change assessment and correlation for individual wells. However, as core material is rare in Quadrant 44 wells these facies have limited use, except in individual wells, as they can not usually be traced between wells.

From this core-based facies analysis and using the thirteen facies described in section 4.2.1, it proved possible to establish eight wireline log facies associations (WILF's). These include closely associated facies that are not sufficiently different in their sedimentological characteristics to allow unequivocal identification in wireline response. This allows reliable facies analysis to be carried out on all Quadrant 44 wells, including those intervals where no core information was available, and allows for the coding of the wells in terms of these Westphalian B facies association.

Recognition of these eight WILF's allows initial appreciation of the relative base level stand, and preliminary information about possible channel geometry, grain size and internal architecture. Furthermore it formed the basis for delineating facies distributions, thereby allowing subsequent palaeogeographic reconstructions and sequence stratigraphic analysis to be undertaken.

7.4 Sequence stratigraphy

The fundamental hierarchical facies component in the Westphalian is the facies association, which is demonstrably susceptible to stratigraphic base level changes, both rises and falls, of various magnitudes. However, it is shown that these base level changes cause different responses across the floodplain, which reflects the variety of facies inherent to the depositional system. This in turn has an effect on the wireline log facies associations (WILFS). The surface which controls the facies distribution is defined as stratigraphic base level and in this study it approximates to either the water table, lake level or bankfull depth depending on the facies. The stage defining *Vanderbeckeri* marine band at the base of the Westphalian B succession in Quadrant 44 and the *Aegiranum* marine band at the top are interpreted to represent two third order maximum flooding surfaces. These represent a time when vast areas of the Westphalian foreland basin were flooded by marine incursions and they result from high points on the stratigraphic base level curve.

The 3rd order sequence boundary described by Turner and O'Mara (1995) can be recognised, and although interpreted to be tectonically induced it still represents the lowest stand in stratigraphic base level and can be used to enhance correlation across Quadrant 44. It is directly overlain by a sharp-based multilateral, multi-storey sandstone, the Caister Sandstone, which forms part of an alluvial transgressive systems tract (terminology of Shanley and McCabe 1994). This sandstone, is argued to have resulted from conditions of low rates of creation of accommodation space which immediately followed the maximum low point on the 3rd order stratigraphic base level curve defined by the two maximum flooding surfaces. Although accommodation space creation was slow, it was never negative (cf. incised valley formation).

Superimposed on this 3rd order stratigraphic base level curve are 4th order base level fluctuations and small-scale fluctuations attributed to autocyclic switching and differential compaction. These proved to be identifiable across the floodplain and are interpreted to result from 4th order base level rises that drown large areas of the floodplain but are of a lesser magnitude than the 3rd order maximum flooding surfaces which cover the whole of the foreland basin. It is demonstrated that these have a regional to sub-regional extent which enables them to be distinguished from localised autocyclically driven flooding surfaces. Thus, three distinct magnitudes of flooding surface are defined which reflect differing rates of base level rise. These are used to identify and classify flooding surfaces to prevent mis-correlation of a 4th order flooding surface with a flooding surface produced by an autocyclically driven base level rise. Base level falls of a 4th order magnitude are shown to be indistinguishable from autocyclically driven base level falls because of the high subsidence rates inherent in the system. Base level fall recognition requires a 3rd order magnitude fall, induced by tectonics (Caister Sandstone). From the relative position of the 3rd order maximum flooding surfaces and sequence boundary, combined with the relatively high levels of stratigraphic base level stand (cf. Westphalian C), the Westphalian B succession is interpreted as a transgressive sequence set (cf. Aitken and Flint 1993).

7.5 Correlation

Based on an integration of the chronostratigraphically constrained facies analysis and sequence stratigraphic surfaces a flooding surface hierarchy (Fig. 6.7) can be established for the Westphalian B in Quadrant 44 where 4th order coal seam flooding

surfaces are recognised and traced across the Quadrant. This is a combination of : (1) a flooding surface hierarchy developed for the lower Westphalian B in the Caister / Murdoch and surrounding areas, which takes advantage of the good quality and abundant data; and (2) a similar flooding surface hierarchy developed for the upper Westphalian B in the southern blocks allowing the entire Westphalian B to be incorporated into one scheme. The top and basal flooding surfaces correspond to the 3rd order maximum flooding surfaces defined in Chapter 5. Between these two markers are 4th order flooding surfaces typified by non-marine bivalve beds or marginal marine bands. All of these have comparable expressions in the onshore succession and may be identified in all the intervals studied. In the Caister / Murdoch and surrounding areas, as in the onshore area, there are additional intervening seams between the 4th order events, although in the southern blocks where subsidence rates are high these intervening seams develop flooding surfaces, referred to here as 5th order flooding surfaces.

The flooding surface hierarchy is used to assess thickness variations across the block, including how palaeoslope effects sedimentation. In the southern blocks the Westphalian B succession is thicker than in the Caister / Murdoch areas and this extra thickness is accommodated by a slight increased thickness of each intercoal interval and an increased importance of each of the intervening 5th order seams and flooding surfaces. It provides evidence that the onset of well drained alluvial sediments, may be earlier in some areas, possibly due to topographic variations across the floodplain. This may be a result of intrabasinal uplift (Turner and O'Mara 1995) or terminal fans (Besly and Turner 1983) which created elevated areas where well drained sediments are deposited. It provides proof of the unconformity at the base of the Westphalian C/D conglomeratic unit. The development of an integrated correlation scheme based on a combination of techniques allows spatially isolated wells with poor data quality to be incorporated, enhancing the correlation and providing for accurate prediction of the succession thickness and the amount of succession removed by the Sub-Permian and Sub-Westphalian C/D unconformities. This considerably improves reservoir and source rock understanding.

7.6 Future work

Continued exploration in the Southern North Sea means that wells are drilled with increasing frequency and spacing, thereby providing an ever increasing data set which will only enhance the correlation and understanding of Westphalian B sediments in Quadrant 44. Particular areas of interest to enhance the correlation are outlined below.

- 1) Increased palynological resolution, based on assemblage characteristics, as undertaken by Turner and Mclean (1990) for the Murdoch area, but expanded to a greater area, will provide a tighter chronological control. A high priority should be placed on retrieving good quality palynological samples.
- 2) Non-marine bivalve stratigraphy is an underused technique in many Quadrant 44 wells. Re-studying of cored sections for important species will enhance the correlation and identification of flooding surfaces. New cored sections should be geared towards identification of individual flooding surfaces, combined with reservoir evaluation.
- 3) The uranium enrichment of Westphalian B marine bands is poorly understood. The response characteristics of each marine band could be catalogued to provide information on the likely response characteristics of individual marine bands.
- 4) The Sub-Clowne tonstein cored in well 44/26-4 could be analysed geochemically thereby proving it unequivocally.
- 5) The development of non-marine sequence stratigraphy is in its infancy. However, increased understanding of how coastal alluvial sediments respond to stratigraphic base level changes will allow distinction of allocyclic and autocyclic changes and thereby increase the awareness of facies distribution.

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Appendix well data

Well 44/14x-1 Operator Phillips Petroleum (UK) Limited

Completion date	Status	Log corrected cores	Biostratigraphy
29th July 1969	Released	No cores cut	Poor quality reports

Well 44/17-1 Operator Conoco (UK) Limited

Completion date	Status	Release date
22nd May 1990	Unreleased and confidential	23rd May 1995

Good quality palynological report.

Well 44/17-2 Operator Conoco (UK) Limited

Completion date	Status	Release date
10th January 1992	Unreleased and confidential	10 th January 1997

Well 44/18-1 Operator ARCO British Limited

Completion date	Status	Release date
21st January 1992	Unreleased and confidential	January 1997

Good quality palynological report

Well 44/18-3 Operator ARCO British Limited

Completion date	Status	Release date
4th July 1994	Unreleased and confidential	4th July 1999

Good quality biostratigraphic report

Well 44/19-3 Operator Sovereign Oil and Gas plc.

Completion date	Status	Log corrected cores	Biostratigraphy
5th February 1989	Released	Core # 1 12009' - 12082'	2 poor quality,

Appendix

Core # 2 12088' - 12178' conflicting reports.
Core # 3 12178' - 12298'
Core # 4 16263' - 16308'

Well 44/21-1 Operator Total Oil Marine Limited

Completion date	Status	Log corrected cores	Biostratigraphy
26th September 1965	Released	Core # 9 13784' - 13828' Core # 10 13828' - 13838' Core # 11 14100' - 14171'	Poor quality

Well 44/21-2 Operator British Petroleum

Completion date	Status	Log corrected cores	Biostratigraphy
02nd November 1984	Released	Core # 2 12739' - 13791' Core # 3 14652' - 14666' * no core report available	Poor quality, with no count sheets.

Well 44/21-3 Operator British Petroleum

Completion date	Status	Log corrected cores	Biostratigraphy
12th November 1986	Released	No information available	No reports.

Well 44/21-4 Operator British Petroleum

Scout data, untraded and unreleased. No biostratigraphic data.

Well 44/21-6 Operator British Petroleum

Scout data, untraded and unreleased. No biostratigraphic data.

Well 44/21-7 Operator British Petroleum

Scout data, untraded and unreleased. No biostratigraphic data.

Well 44/21-9 Operator Conoco (UK) Limited

Completion date	Status	Release date
22nd April 1993	Unreleased and confidential	23 May 1998

Good quality palynological report

Well 44/22-1 Operator Conoco (UK) Limited

Completion date	Status	Log corrected cores	Biostratigraphy
29th October 1984	Released	Core # 1 11352' - 11439' Core # 2 11440' - 11531' Core # 3 11533' - 11623' Core # 4 11623' - 11714' Core # 5 11714' - 11803' Core # 6 11803' - 11892' Core # 7 11893' - 11951' Core # 8 11954' - 12028' Core # 9 12028' - 12097' Core # 10 13412' - 13455' Core # 11 13974' - 13990'	Good quality reports.

Well 44/22-3 Operator Conoco (UK) Limited

Completion date	Status	Log corrected cores	Biostratigraphy
01st August 1985	Released	Core # 1 11360' - 11404' Core # 2 11684' - 11736' Core # 3 11784' - 11813' Core # 4 11813' - 11833' Core # 5 11837' - 11877' Core # 6 11956' - 12044'	Good quality reports.

Well 44/22-4 Operator Conoco (UK) Limited

Completion date	Status	Log corrected cores	Biostratigraphy
13th August 1987	Released	Core # 1 12039' - 12077' Core # 2 12083' - 12175' Core # 3 12175' - 12265'	Good quality reports.

Well 44/22-5 Operator Conoco (UK) Limited

Completion date	Status	Log corrected cores	Biostratigraphy
12th March 1988	Released	Core # 1 12010' - 12053' Core # 2 12053' - 12142' Core # 3 12142' - 12271'	Good quality reports.

Well 44/22-6z Operator Conoco (UK) Limited

Completion date	Status	Log corrected cores	Biostratigraphy
11th May 1988	Released	Core # 1 12233' - 12324' Core # 2 12324' - 12414' Core # 3 12414' - 12497' Core # 4 12497' - 12587' Core # 5 12587' - 12677'	Good quality reports.

Well 44/22-7 Operator Conoco (UK) Limited

Completion date	Status	Log corrected cores	Biostratigraphy
08th June 1988	Released	No cores cut	Good quality reports.

Well 44/22b-8 Operator Conoco (UK) Limited

Completion date	Status	Release date
30th May 1990	Unreleased and confidential	30th May 1995

No biostratigraphy available

Well 44/23-4 Texas Gas Exploration (UK) Corp.

Completion date	Status	Log corrected cores	Biostratigraphy
27th February 1985	Released	Core # 1 11517' - 11538' Core # 2 11636' - 11364'	Good quality reports.

Well 44/23-5 Texas Gas Exploration (UK) Corp.

Completion date	Status	Log corrected cores	Biostratigraphy
21st January 1986	Released	Core # 3 12415' - 12445' Core # 4 12445' - 12478' Core # 5 12478' - 12519' Core # 6 12519' - 12576'	Good quality reports

Well 44/23-6 Texas Gas Exploration (UK) Corp.

Completion date	Status	Log corrected cores	Biostratigraphy
16th August 1986	Released	Core # 1 12125' - 12167' Core # 2 12389' - 12415' Core # 3 12415' - 12468' Core # 4 12468' - 12500' Core # 5 12500' - 12507' Core # 6 12507' - 12591' Core # 7 12673' - 12680'	Good quality reports

Well 44/23-7 Texas Gas Exploration (UK) Corp.

Completion date	Status	Log corrected cores	Biostratigraphy
10th October 1986	Released	Core # 1 12040' - 12106' Core # 2 12106' - 12175' Core # 3 12175' - 12187' Core # 4 12187' - 12245'	Good quality reports

Well 44/23-8 Total Oil Marine plc.

Completion date	Status	Log corrected cores	Biostratigraphy
06th January 1989	Released	Core # 1 12787' - 12846' Core # 2 12847' - 12854' Core # 3 13108' - 13115' Core # 4 13117' - 13169'	Good quality reports

Well 44/24-2 Operator Hamilton Brothers Oil and Gas Limited

Completion date	Status	Log corrected cores	Biostratigraphy
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Appendix

18h November 1987 Released None available Good quality biostrat
report, no count sheets

Well 44/26-2 Shell / ESSO

Completion date	Status	Log corrected cores	Biostratigraphy
25th January 1987	Released	Core # 1 12453' - 12489'	No count sheets
		Core # 2 12489' - 12549'	poor quality
GAPS		Core # 3 12549' - 12640'	zonation

Well 44/26-4 Shell / ESSO

Completion date	Status	Log corrected cores	Biostratigraphy
11th February 1989	Released	Core # 1 12960' - 13050'	Good quality
		Core # 2 13050' - 13113'	reports with
		Core # 3 13862' - 13953'	count sheets
		Core # 4 14429' - 14491'	

Well 44/27-1 Lasmo

Completion date	Status	Log corrected cores	Biostratigraphy
17th February 1987	Released	Core # 1 13277' - 13299'	No count sheets
		Core # 2 13299' - 13334'	poor quality
GAPS		Core # 3 13334' - 13340'	zonation
		Core # 4 13352' - 13354'	
		Core # 5 13355' - 13384'	
		Core # 6 13384' - 13401'	
		Core # 7 13401' - 13461'	
		Core # 8 13461' - 13518'	
		Core # 9 14402' - 14452'	
		Core # 10 16332' - 16387'	

Appendix

Well 44/28-1 Shell / ESSO

Completion date	Status	Log corrected cores	Biostratigraphy
07th November 1984	Released	Core # 1 12553' - 12555'	No count sheets
		Core # 2 12555' - 12608'	poor quality Shell
		Core # 3 12608' - 12617'	zonation
		Core # 4 12617' - 12653'	
		Core # 5 12653' - 12688'	
		Core # 6 12688' - 12730'	
		Core # 7 12730' - 12771'	
		Core # 8 12771' - 12829'	
		Core # 9 13016' - 13085'	
		Core # 10 13076' - 13137'	
		Core # 11 13137' - 13666'	

Well 44/28-2 Shell / ESSO

Completion date	Status	Log corrected cores	Biostratigraphy
16th December 1985	Released	Core # 3 12052' - 12060'	No count sheets.
		Core # 4 12060' - 12112'	Good quality Shell
		Core # 5 no recovery	Biostrat report
		Core # 6 12108' - 12269'	
		Core # 7 12274' - 12354'	
		Core # 8 12354' - 12395'	
		Core # 9 12397' - 12487'	
		Core # 10 12487' - 12589'	
		Core # 11 13453' - 13540'	
		Core # 12 13425' - 14070'	
		Core # 13 14151' - 14192'	
		Core # 14 14253' - 14265'	
		Core # 11 14294' - 14302'	
		Core # 12 14302' - 14365'	
		Core # 13 14990' - 15048'	

Well 44/28-3 Shell / ESSO

Completion date	Status	Log corrected cores	Biostratigraphy
Not available	Released	Core # 1 12006' - 12039' Core # 2 12039' - 12119' Core # 3 12119' - 12187'	No reports

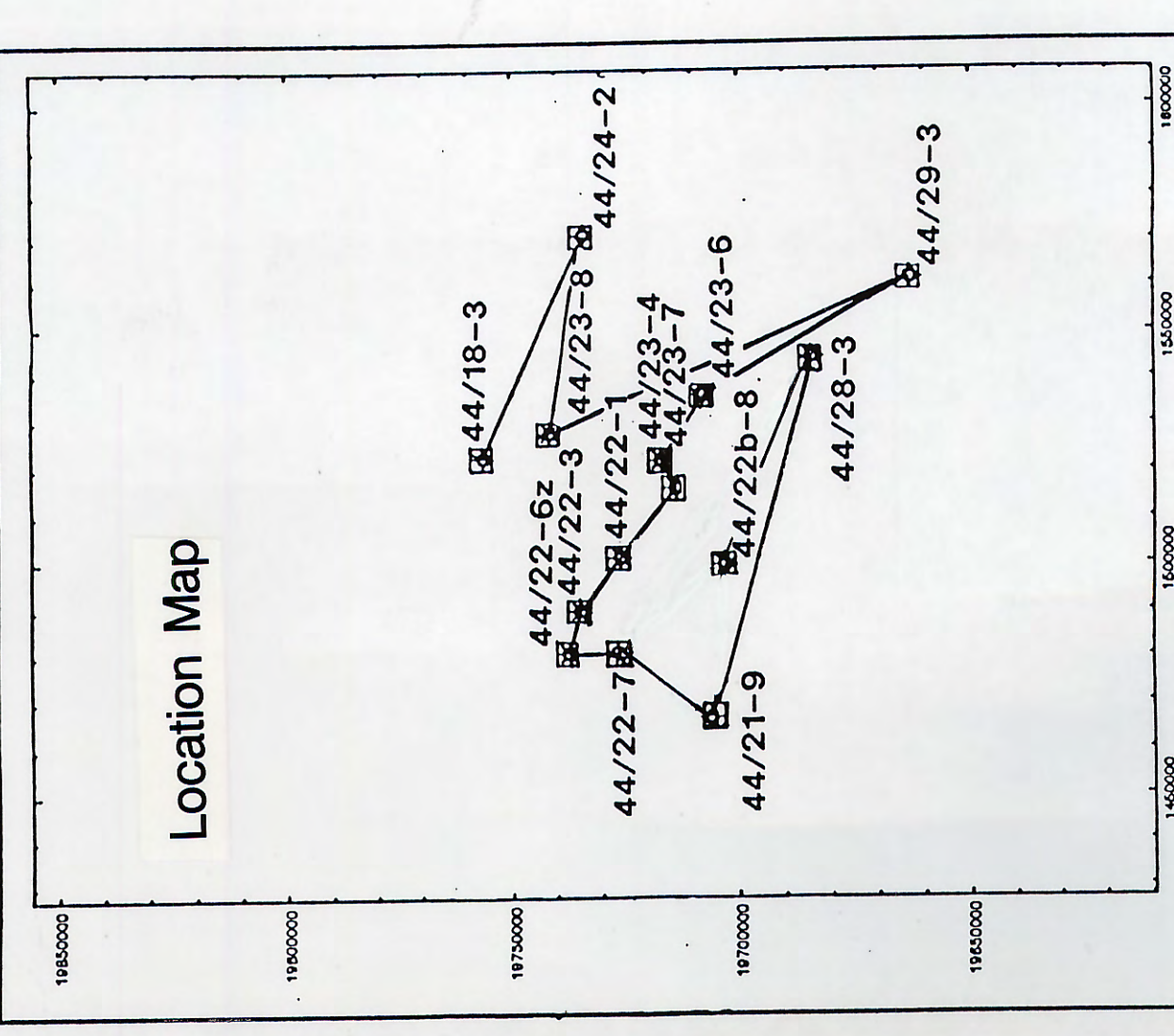
Well 44/29-1 Charterhouse Oil and Gas Limited

Completion date	Status	Log corrected cores	Biostratigraphy
11th July 1986	Released	Core # 2 12164' - 12223' Core # 3 13029' - 13088' Core # 4 14703' - 14785'	No count sheets, poor quality report

Well 44/29-3

Untraded well, part of GAPS (1994) report, no details available

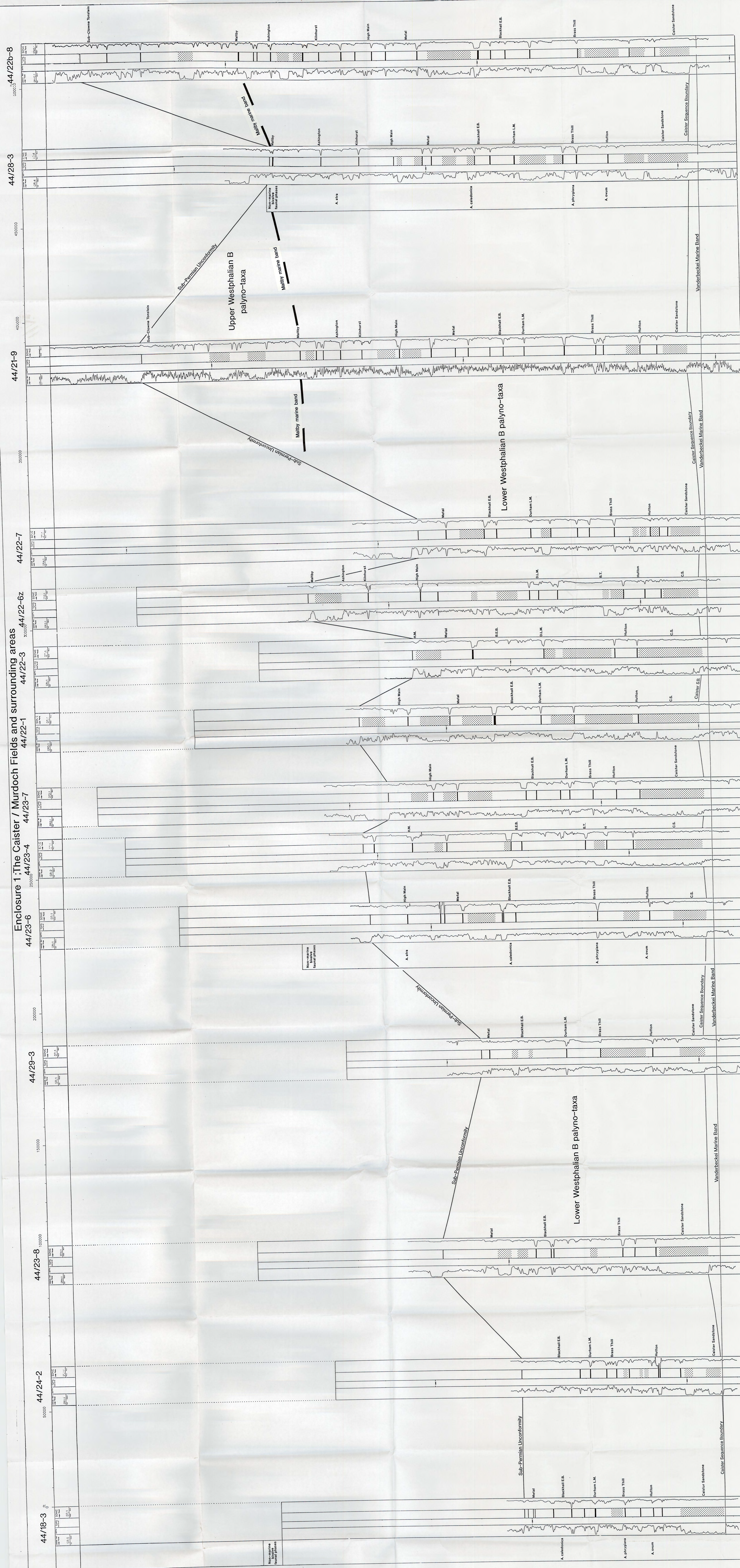




Key
 Coal seam
 Sandstone

Names above coal seams relate to flooding surfaces mentioned in the text

Enclosure 1 is hung off the Vanderbeckel marine band



Enclosure 1: The Caister / Murdoch Fields and surrounding areas

Well identifiers: 44/18-3, 44/23-6, 44/23-7, 44/23-8, 44/23-9, 44/24-2, 44/29-3, 44/29-8, 44/29-3, 44/21-9, 44/28-3, 44/22b-8

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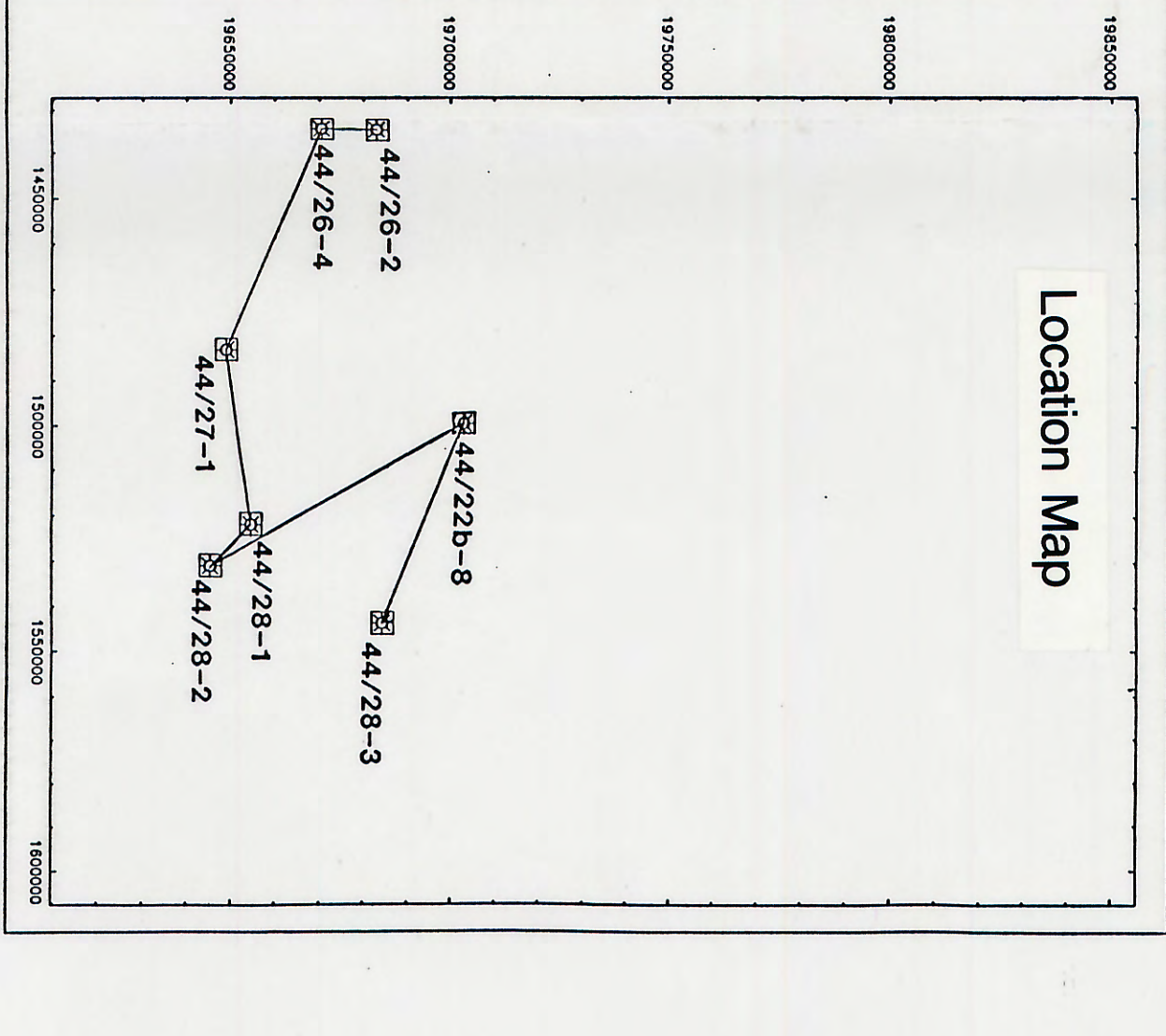
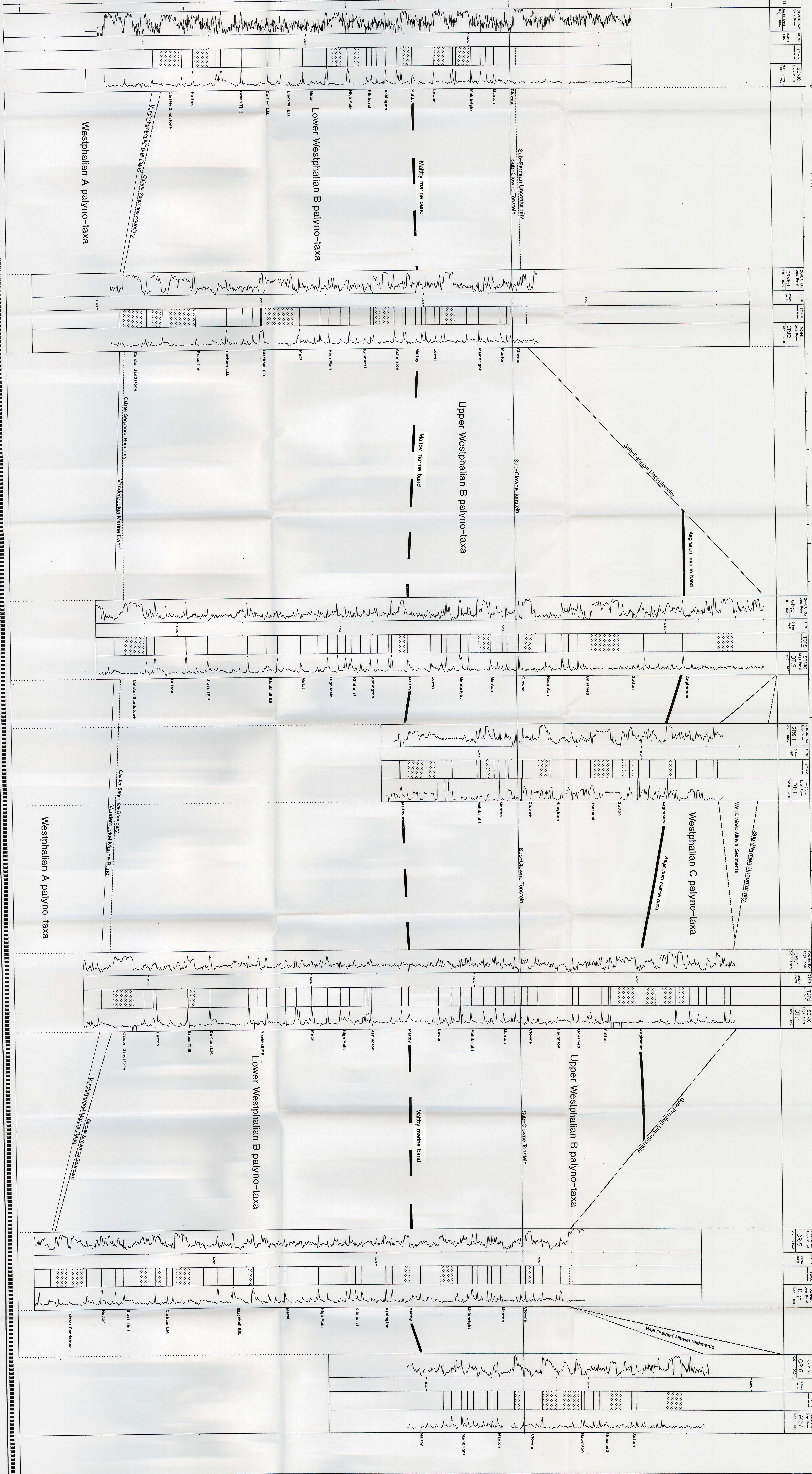
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Enclosure 2 : The Southern Wells (Blocks 44/26-44/28)

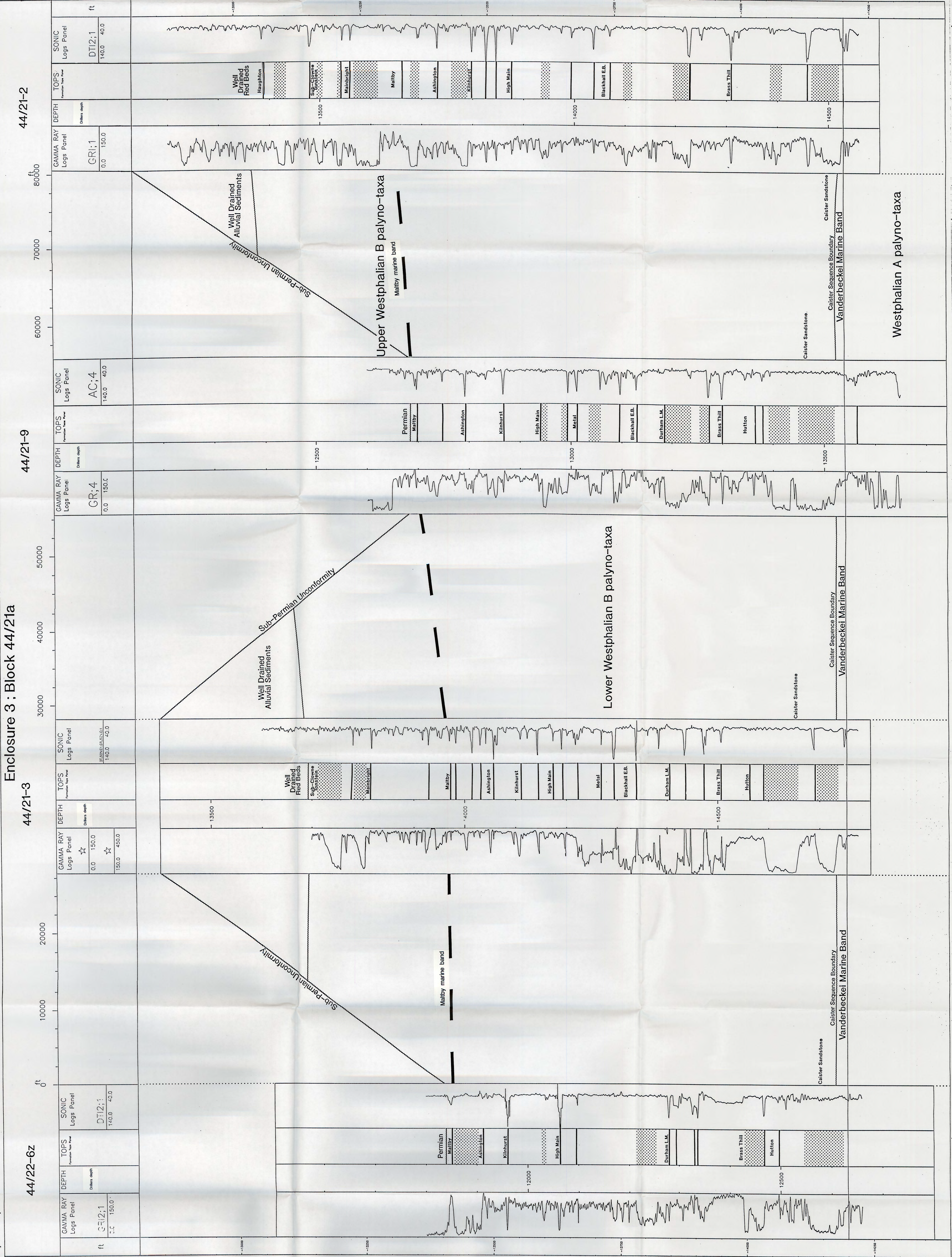


Key
 Coal seam
 Sandstone

Enclosure 2 is hung off the Sub-Clowrie Tonstain

Names above coal seams refer to footwall surfaces mentioned in the text

Enclosure 3 : Block 44/21a



Key

- Coal seam
- Sandstone

Enclosure 3 is hung off the Vanderbeckel marine band

Names above coal seams relate to flooding surfaces mentioned in the text

Enclosure 4; The Northern Wells

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44/18-1

44/18-3

44/23-8

44/28-3

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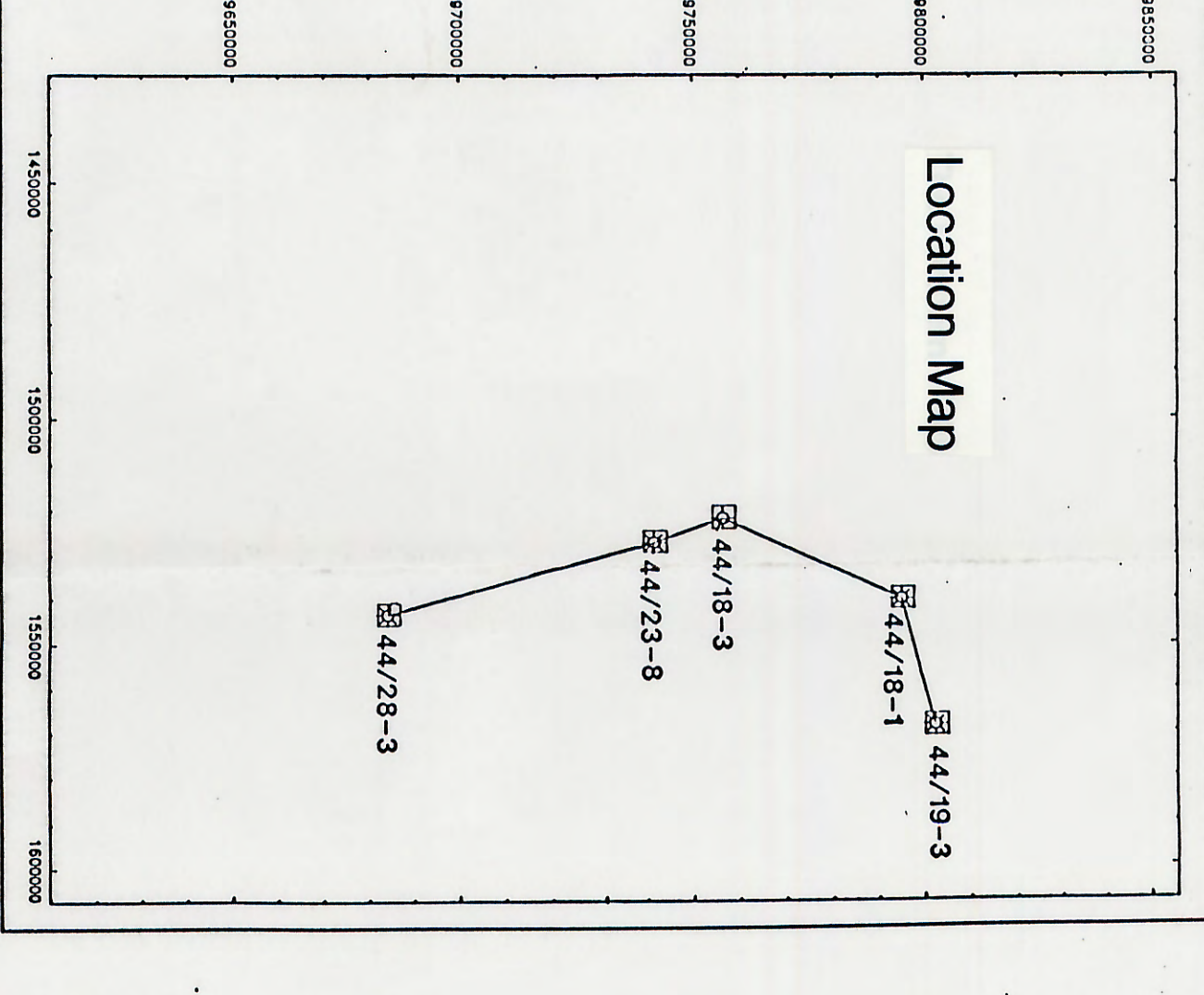
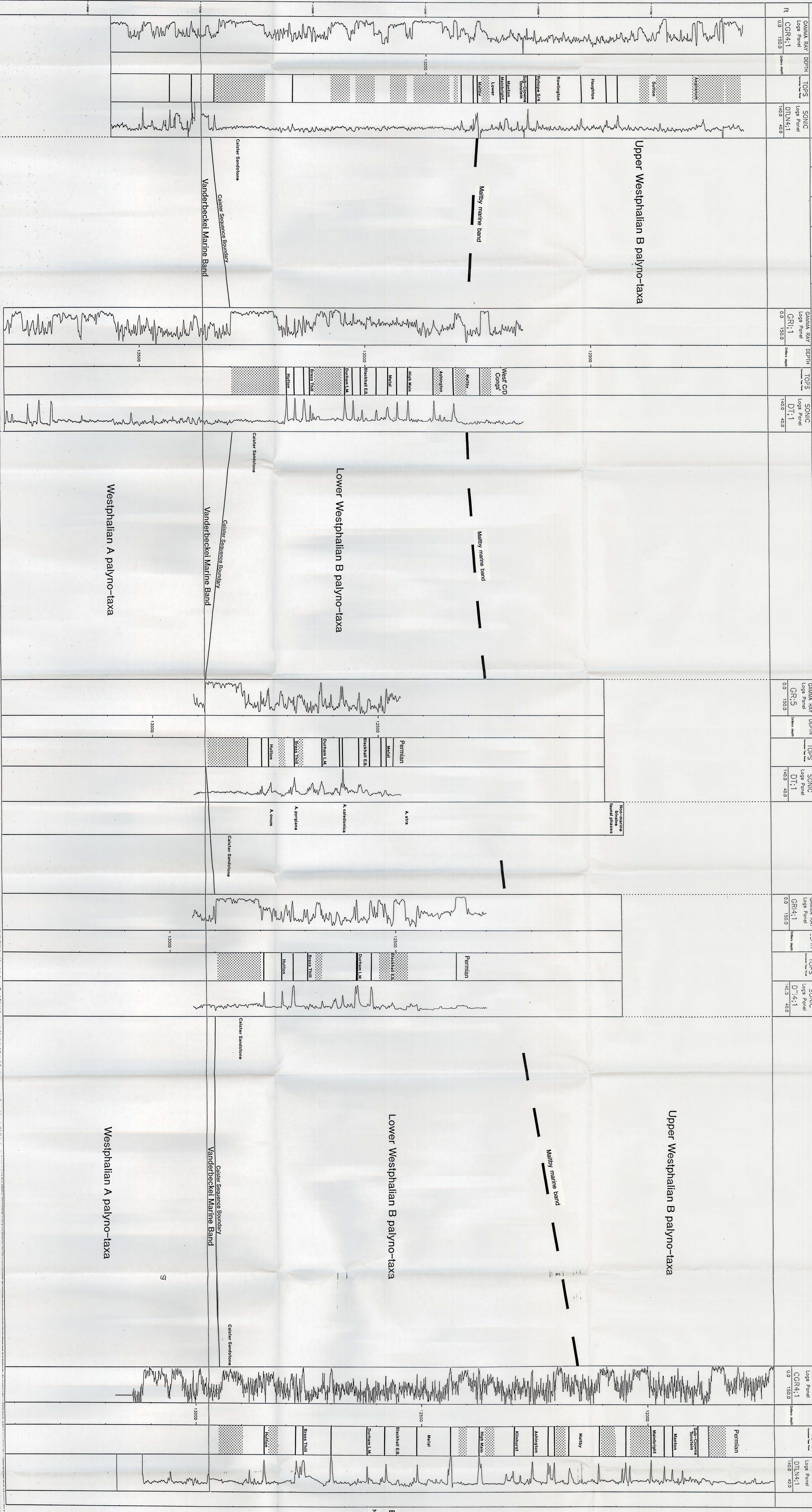
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Enclosure 4 is hung off the Vanderbeekel marine band
Names above coal seams refer to flooding surfaces mentioned in the text