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Variations in tectonic style and setting in British coalfields

by

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Top

ABSTRACT

British Carboniferous coalfield datasets are used for mapping, analysis, and modelling of depositional and structural patterns, through a significant stratigraphical range and across a variety of tectonic settings.

Westphalian depositional patterns are re-interpreted using channel axis orientations. Major flows were northeasterly into northeast Britain, westerly into the Pennine Basin, and southwesterly through South Wales. Most systems prograded into freshwater lakes. Tectonic depocentres had little effect on channel pathways, but significant effects on net depositional thicknesses, and sandstone and coal connectivity patterns. Varying depositional controls are evaluated, and a complex model is proposed, integrating these; simple sequence stratigraphical interpretations are inappropriate. Many sulphur variations in the coals reflect the channel inflows rather than marine invasions, which were only occasionally important, and were moderated by many local effects..

Structural and sedimentological criteria are proposed for the identification of syn-depositional faulting. Except in Scotland, few syn-depositional movements on specific faults are identifiable from the sedimentary record; some inherited structures continued to grow, as sub-basin bounding faults. These, and large post-depositional structures, generated mosaics of crustal compartments within which fault patterns and jointing orientations demonstrate varied block responses to tectonic events. Coal jointing orientations are considered to record Variscan near, far, and distant field stress, progressively north from South Wales, across central/northern England, and into Scotland.

Recent data on Carboniferous igneous activity are described and interpreted in the Scottish Midland Valley. The Westphalian igneous provinces of the southern Pennine Basin and Oxfordshire are discussed and recommended for further research.

Two case studies illustrate ways in which detailed coalfield data may be used for regional tectonic analysis, namely the evolution of the Kincardine Basin and Ochil Fault in Scotland, and the identification of a specific Variscan thrusting style in Kent.

CONTENTS

PREFACE

This thesis has been written at a time of many changes in the the British coal mining industry. During nationalisation (1947-1995), an industry-wide geological service was built up by the National Coal Board (NCB, latterly British Coal Corporation, BCC); understandings of coalfield geology grew rapidly from a combination of detailed underground data, the drilling of numerous boreholes, and advances in geophysics. Specialisms developed, reflecting local needs: in Durham and Nottinghamshire, sedimentological modelling was in use by the 1960's. But while many advances were made, little was published by NCB geologists. Recently, there has been a number of publications by external workers, but without detailed reference to available data. The NCB geological service built up both experience and a very large data set, and it is appropriate to attempt an "insider" account (the author having worked in the deep mines geological service in various coalfields over a number of years), in which particular aspects are described and further researched, in a contemporary geological style, while remaining compatible with massed mining data. Probably only an insider could do much of this, given the required familiarity with data characteristics.

The main chapters represent areas of interest that the author has taken forward from industry-background material, and developed into largely "stand-alone" accounts, so that readers can access specific themes. These chapters are accompanied by subsidiary accounts (Chapters 1, 3 and 8) in which coalfield data are reviewed, with some pointers provided for future research, beyond the scope of the present work. It is hoped that duplication which results from this structure has been minimised. Chapters 2, 3, and 4 deal mainly with sedimentology; Chapter 5, on syn-depositional movements and structures, links the sedimentological and structural parts of the thesis; Chapters 6 and 7 develop various structural ideas, and Chapter 8 briefly reviews some developments in igneous geology; Chapters 9 and 10 present regional case studies, from two contrasting areas that require modern mining detail, and a combination of sedimentology and structural geology, for their interpretation. The thesis does not include mining, engineering geology or hydrogeology, which have been of key importance to all NCB geologists. However, many site-specific problems in these specialised areas require understanding of spatial variations in both sediments and structures, and it is hoped that the author's colleagues will not regard this thesis as too academic. A theme that has not been fully addressed here is correlation. This is a major subject, and it is hoped to develop this in a separate publication.

Day-to-day pressures in active mining can promote a merely tactical approach to geological forecasting, but this works for only so long. Context is necessary, and best local forecasting presupposes best regional understanding. Forecasts are usually verified (or otherwise) fairly quickly, and this tends to concentrate the mind. Any academic readers should note that the culture of mine planning is a much sharper tool for encouraging robust geological interpretation than any literature peer review; in the thesis, where industry validation is mentioned, this is the background thought. It is a reflection of the present economic scene that readers are likely to be either academic geologists, or those involved in hydrocarbon evaluations, rather than mining geologists. But remaining UK coal resources are large by European standards, and usually suitable for mining. Extensive resources remain unexploited, especially around the margins of the Pennine Basin, in Oxfordshire, and in parts of Wales and Scotland. Continuing mining, and other exploitation methods, are to be expected and is hoped that this account will be of some value to future coalfield work.

ACKNOWLEDGEMENTS

This thesis obviously builds on the work of others, many now unknown, particularly mining surveyors who recorded most of the structural data. However, many colleagues in mining geology and geophysics have been personally involved in work that lies behind this account. Special mention should be made of R.E. (Dick) Elliott, formerly NCB Chief Geologist, who insisted on combining best current theory with ground truth. Dick's understanding of coalfield geology was exceptional; he would have liked to have been involved in all the work presented here. In the academic world, the author is particularly appreciative of working with R.A.Gayer (Cardiff), P.D.Guion (Oxford Brookes), D.A.Spears (Sheffield), J. Watterson and J. Walsh (Liverpool), B. Smart (Heriot-Watt) and, at Keele, B. Besly, W.A. Read and R.G. Park. Apart from his geological insights, Graham Park is also thanked for encouraging and supervising the project. The British Coal Corporation kindly provided funding for this research, and access to data; W.E. Hindmarsh is thanked particularly, as is the author's present employer, International Mining Consultants Ltd. Much of the work has been developed while working with colleagues in the Scottish Coal Company Ltd., especially at Longannet mine, and many thanks are due to Ramsay Dow and his staff. ARCO British Ltd. is thanked for approval to use some interpretations from recent consultancies. Much of the material presented here has now been published, mainly in the Transactions of the Institution of Mining Engineers, the Proceedings of the Yorkshire Geological Society, the Journal of the Geological Society of London, and the Geological Magazine; thanks are due to the relevant organisations for approval to use published material. Kevin Pickup, for the Coal Authority, has kindly reviewed and approved the contents. The opinions expressed are those of the author, and not necessarily of any other person or organisation. All the content should be regarded as interpretation, and figures as approximate in scale, and for illustrative purposes only. While many colleagues have contributed to the geological background, the development and research of this thesis is mainly the work of the author, with the exception of important contributions by R.G. Park and W.A. Read to Chapter 9, and by R.A.Gayer to Chapter 10. Matthew Rippon is thanked for help with word processing. All figures are by the author except where specified.

CHAPTER 1

INTRODUCTION

Abstract: *This introduction outlines selected aspects of the coalfields' geological evolution; some are developed in detail in later chapters, while certain issues in burial history are included here. Regarding data sets, the reader is referred to individual thematic chapters, as data requirements vary with investigative requirements; reviews of previous work are also covered separately.*

1.1 Background

The British Carboniferous coalfields are amongst the most intensively described anywhere, with numerous detailed and regional accounts from all branches of the geological sciences. These are found not only in the geological literature, but also in mining, fuel technology, and other specialist publications. A full literature review is well beyond the present account; later thematic chapters include details of previous relevant work. But despite the wealth of publications, there are few that relate the massed high quality geological and geophysical data of the National Coal Board (NCB, latterly British Coal Corporation, BCC) to modern accounts of regional depositional and structural geology. It is hoped that the following, with subsequent chapters, will rectify this. Figures 1.1 and 1.2 illustrate the main geographical and stratigraphical ranges of the Carboniferous coalfields, including concealed extensions; they occupy a considerable area of Great Britain, and original depositional extents would have been much greater (Chapter 2).

It is suitable to comment here on the possibility of the existence of certain onshore coalfields not fully identified by the NCB's exploration programmes. As now known from published seismic data (Chadwick *et al.* 1995), there is a probable coalfield within a prominent sub-basin lying between the margins of the West Cumberland field, near Carlisle, northeast to the known Canonbie field (Picken 1988). The Cumberland field probably also extends southeast along the Vale of Eden. In central England, the possibility of Westphalian A-C coal sequences lying within the (Triassic) Knowle Basin, east of Birmingham, was noted by Chadwick & Smith (1988) and by internal NCB studies. The potential for later Westphalian coals lying within the Worcester Basin is indicated by Peace & Besly (1997). Across the Wales-Brabant High (Fig. 1.3) there is some gravity and seismic evidence for restricted later Westphalian inliers, analogous to the wider Oxfordshire field. In eastern England, the concealed coalfield on the Norfolk coast is a link ultimately to the major Westphalian successions of the Southern North Sea. South from the high, the Westphalian A-C succession re-appears not only in South Wales, Somerset, and Kent, but also in Berkshire (Foster *et al.* 1989), where the southern limits are not well known, and are probably very disturbed, in a foreland basin context. Practical coalfield extents within the preserved Westphalian are also limited by progressive regional interdigitation with red beds through time. Across the Pennine Basin's southern margin, red beds occur in early Westphalian B sequences, becoming widespread later. The onset of these has been related by Besly (1988) to uplift patterns, perhaps representing Variscan compressional pulses; red beds also characterise the later Westphalian in Scotland, and perhaps an overall climate change is recorded, as well as tectonic events.

The Carboniferous successions occur approximately midway through Phanerozoic times, and gross geological structure frequently perpetuates earlier geological trends, as well as recording the effects of many later events. Figure 1.3 shows the coalfields related to regional tectonic provinces; Figure 1.4 summarises the overall history of events which have contributed to coalfield structure.

1.2 Depositional settings

Most of the coal-bearing sequences appear to have been deposited on very extensive plains with extremely low gradients (Guion *et al.* 1995). Chapters 2 and 3 expand on this, particularly for the Westphalian A-C successions. These have traditionally been described as "paralic", implying an overall coastal plain setting but (see Rippon 1996) this is misleading for the greater part of the Westphalian, during which most sediment accumulated in essentially freshwater settings, at considerable distances from any contemporary marine environment. The term "delta plain", used in much of the existing literature, needs to be understood in this context. However, Dinantian and Namurian successions of northern England and Scotland were obviously more integrated with marine conditions, with common marine-related lithofacies and fauna. The Scremerston Coal Group (Dinantian) of northeast England is the most marine-influenced sequence that is significantly coal-bearing, and is characterised by many inferior, sulphurous coals (Chapter 4), marine limestones and calcareous claystones. Westphalian geography (Chapter 2) would have been dominated by coal-forming forested mires and large lakes, punctuated by large river systems, in an ever-wet tropical climate, low marginal uplands contributing local alluvial fans. However, the overall depositional area extended across tectonic boundaries, and distinct differences in formation thicknesses and the connectivity of (particularly) sandstones and coals reflect these changing structural settings, as the sedimentation responded to different balances between external sediment supply controls, and any local basin subsidence (Chapter 3). On a regional scale, it is interesting to note that many features, including the stratigraphical incidence of major coal groups and marine bands, and the general lithofacies relationships, are similar across very different tectonic settings, such as the Scottish Midland Valley, the Pennine Basin, and South Wales (Chapters 2, 3, 6, 9 and 10). Very gentle gradients are thought to have characterised the topography even across main tectonic depocentres. Regarding subsidence rates for these, recent conference presentations (W.A.Read, pers. comm. 1997) suggest that the Dinantian/Namurian boundary (Fig.1.2) may be as young as 317Ma, requiring rapid subsidence, especially for the Pennine Basin Namurian (not considered here).

1.3 Correlation and diachronism

The correlation of the coal-bearing Carboniferous is well-established across all coalfields, with particular horizons being correlatable internationally. Coals, although involved in repeated splittings and re-unions, can often be correlated to a precision better than that of the traditional cycle (see 5.3.2) across 100's, or even 1000's km^2. The reasons for this are: 1, the density of high quality data; 2, the availability of many different correlation features (Fig. 1.5); and 3, the influence of external base level control, which determined coal concentrations at particular stratigraphical levels (although with local effects imposed by invading channel belts: Chapter 2; Fig. 2.3).

Practical correlation for mining requires not only correlation of the coals, but also that of the sand bodies, so that the adverse effects of channel systems on coal thickness, continuity, and quality can be forecast accurately by correct linkages. This is often straightforward where data density is good, but sandstones, like the coals, may also be partly diachronous (see below), and many local characteristics may need assessing; Chapter 3 gives some guidelines. Correlation for mining is therefore seen as something more than the biostratigraphical definition of stages and zones and more than the simple correlation of coals lying at similar horizons. Such correlation precision has been achieved not by the use of any particular high-definition technique but rather by the use of varied features revealed by very closely spaced data. Because of the rate of sedimentological change and the possibility of data points being inadequate, correlation depends upon a package of features that are locally and regionally reliable, and are in known stratigraphical order, although not all may be represented in each case.

One of the simplest and most effective methods of correlation, involving both individual features and packages, is by cross-plotting a significant stratigraphical range, normally hundreds of metres, at two locations (usually boreholes). Any variation from a 45^o plot will have geological significance, and such cross-plots may be used for both correlation, and identification of structural and depositional variations; examples are illustrated in Chapters 5 and 6. In the more marine-influenced Scottish Namurian, the scatter on these cross-plots that can be ascribed to fluvial variations is very low; this is true even for the sandstone-dominated Passage Formation (Fig.1.2). In the English Westphalian, there is often a more measurable scatter (see Odell 1976), although taken alone, the more marine horizons maintain very simple cross-plots. The correlation resolution achievable by cross-plotting, where the data are good, is dependent merely on the adopted scale; faults with throws as small as 5m are detectable, and correlation resolved to the traditional cycle. The method is, in principle, usable throughout fields which share the same balance between external and internal controls on sedimentation (Chapters 3 and 5), while a less refined inter-basin correlation can be achieved by use of marine bands and major coal groupings.

Regarding diachronism, coals and the main sandstones are particularly interesting. Both can often be shown to be diachronous (the coals from standard correlation diagrams) but there are two key differences: coals are normally considered to represent much longer periods of depositional time (but see Chapter 2 on the longevities of some sandstone channel belts), and they record significant compaction. With excellent correlation resolution, seam-top diachronism can be demonstrated to a scale of centimetres (post-compaction); Rippon (1984) illustrates a case, based on progressive flooding of a coal in the Pennine Basin.

1.4 Some aspects of burial history

Various aspects of coalfield geology may usefully be considered under this broad heading; an account of deformation phases is considered in detail in Chapter 6.

1.4.1 Coal ranking

Coalification is a complicated subject with a very extensive literature, much of which is in non-geological publications. Varied classification systems have been developed to cater for particular industrial and marketing applications, and are not covered here; British Carboniferous hard coals range from low rank (virtually sub-bituminous in some classifications) along parts of the Pennine Basin's southern margin, to the prime anthracites of western South Wales. (It should be noted here that the various coalfield rank maps published by the NCB from the 1950's to the 1980's, see Chapter 4, are not all constructed on the same basis. Some (e.g. South Wales) do represent regional geological variations, being mapped for specific horizons, but others reflect marketed output, and show no straightforward geological pattern.) The present account is concerned only with the main geological processes, some of which are still debated.

Depth of burial is a factor which will have been common to all fields. Elliott (1985) investigated the compaction of clean (<15% ash) coals in the eastern Pennine Basin, deducing compactional phases from forest loading to sediment loading in the immediate post-coal cycle, followed by progressive loading by the later sedimentary column. This sequence modified the peat to lignite. A pronounced coalification jump to bituminous coal, at a peat:coal compaction ratio around 14:1, depended more on heat at depth, rather than pressure. Maximum burial depths during coalfield evolution are difficult to assess, many fields having been uplifted, and some reburied. Frequently, the later Carboniferous is eroded. The varied effects of burial and reburial, particularly with respect to gas generation, and loss/retention, are discussed by Creedy (1988). The residual Westphalian is around 3km thick in parts of South Wales; there have been various estimates, up to 6km, for the full Upper Carboniferous depositional thickness there (see White 1991 for discussion). In the

Pennine Basin fields, Walsh & Watterson (1988) considered that the post-Carboniferous, pre-Permian (i.e. pre-earliest Permian strata) fault sets were characteristic of faulting initiated and developed at depths up to 3km. Chapter 7 discusses burial depths in relation to jointing.

Compression by crustal shortening might be considered a potential ranking process. Across the southern fields in the immediate Variscan foreland, coals were still relatively young at the time of main deformation, and it might be argued that at least some of Elliott's (1985) post-lignite coalification should have been achieved by horizontal stress, as well as vertical. However, White (1991) showed that ranking patterns across South Wales are modified by Variscan folding and thrusting; this compression does not seem to have been a noticeable factor in South Wales, and therefore is unlikely to have been important elsewhere.

Igneous processes are well-known factors in ranking, operating on mainly local scales (see Chapters 8 and 9). The rank pattern of South Wales (White 1991, Gayer *et al.* 1992) is one of the most pronounced in the British coalfields, with a well-defined anthracite area centred near Ammanford (E.260000, N. 210000). The possibilities of this resulting from a pluton at depth have been discounted by recent geophysical interpretations, although the depth to crystalline basement coincident with the prime anthracite area is reduced from around 6km in the wider coalfield to only 3km (Gayer 1992). Depth to basement alone is not a factor of any importance across central England, where Precambrian and Lower Palaeozoic rocks lie locally within 100m of high-volatile bituminous coals, suggesting that other factors are involved in the Ammanford area (see below). A basement effect is found in the northern Pennines, where vitrinite reflectances, in Dinantian coals, record rapid up-ranking above the Wensleydale Granite (late Caledonian); Creaney (1982) thought this resulted from post-emplacement heat flow. Regarding sills and dykes, the former, lying (sub)-parallel to bedding, have a wider effect on coals. In general, the contemporaneous sills of the Scottish Namurian, and the small Westphalian sills of the southern Pennine Basin margin, have little effect; many were intruded into shallow, and only partly dewatered and compacted sediments, and are difficult to distinguish from lavas (Chapter 8). By contrast, the thick widespread quartz dolerite Midland Valley Sill (late Carboniferous) generated a regional and multi-seam up-ranking.

Up-ranking by regional hot geothermal fluids was proposed by Gayer *et al.* (1991) for the South Wales anthracitisation. They envisaged hydrothermal fluids driven by a combination of gravity flow from Variscan uplift, and by expulsion from sediments in thrust sheets, the fluids being able to permeate the coalfield along early faults and cleats. From this model, high ranks around the Ammanford anthracite centre perhaps reflect major thrusting of the shallow crystalline basement, providing a window for permeation of Westphalian strata. Chapter 7 develops this model.

1.4.2 Some other features

The geochemistry of coal, and coal-bearing strata, is not straightforward, a result of many syn- and post-depositional effects, and the nature of coal itself. Assays of British coals have produced a large data set. Most individual reports detail the sulphur and chlorine contents, as these are of immediate marketing concern, as well as the major elements in the ash; many analyses also detail the trace elements. The ash itself is normally a function of the depositional environment; in a basin development context, both sulphur and chlorine are interesting, and regional differences must be explained before an overall understanding of their geological controls can be established.

Sulphur in coals is mainly a function of the depositional environment; Chapter 4 discusses this at length. The key regional difference is the higher background total sulphur content across the Pennine Basin Westphalian (1.5% by weight), compared with South Wales, and especially Scotland (0.5%). One explanation for this is inflow water chemistry, with the higher Pennine Basin background resulting from elevated sulphates in waters flowing from the west (Rippon 1996).

Chlorine in coals is widespread, but only locally concentrated, notably in parts of Staffordshire and Nottinghamshire. There is some evidence that chlorine content reflects detailed petrography, especially the presence of fusain, and that there is an indirect relationship with rank, that is, chlorine decreases as increasing rank reduces the available pore surface area. In lower rank fields, chlorine is sometimes thought to increase with depth, although the pattern is usually too large-scale for unambiguous interpretation. However, where compartmentalising faults of, say, 100's metres throw are involved, it is advantageous to contour each fault block separately for chlorine. This suggests research possibilities regarding sealing properties of faults over geological time. The importance of coal chlorine to burial history is the relationship with connate brines.

Connate brines are characteristic of many coalfields at depth, especially within and adjacent to the Pennine Basin, with sometimes extremely saline waters held largely in the sandstones. Salinity often increases with depth, reduces rapidly towards the surface, and usually towards the sub-Permian unconformity (Chapter 6), although local high coal chlorine values are found subjacent to early Permian dune sands. High chlorine coals are localised within fields with pervasive brines. All these factors were discussed in detail by Skipsey (1974). The geological origins of the brines have been variously ascribed to Namurian and Westphalian marine invasions, or to the Permian Zechstein transgression. The topic was extensively reviewed in the context of metalliferous prospectivity across the Pennine Basin, by Plant & Jones (1989). One of the models proposed in that study involved Dinantian limestones hosting metal sulphides carried by brines expelled from Namurian shales by overpressuring during Westphalian sedimentation. Especially in the Pennine Basin, Westphalian coals usually have carbonate-mineralised cleats with metal sulphides, and suggest parallels with the Derbyshire metalliferous field (Chapter 7). Given this model, the rarity of both brines and high chlorine coals in South Wales is interesting. This field had one of the thickest Westphalian successions, but the Namurian is very thin (and there were no late Caledonian intrusions at depth). However, the mountain front model of Gayer *et al.* (1991) suggests that brines could be driven into the basin during advance of the Variscan nappe front. Perhaps the South Wales field was, at some stage, sufficiently uplifted for freshening by meteoric waters, unless the "Variscan" fluids were, anyway, low in chlorine.

Cementation of sandstones may be noted here. Again, there are broad but significant regional differences, which may be generalised as: 1, often relatively poor cementation through the main Namurian and Westphalian sequences of the Scottish Midland Valley, and to some extent in the Northeast field of England; 2, generally well cemented in the Pennine Basin; and 3, often very well cemented in South Wales. The petrography of the sandstones has received relatively little attention recently (Rippon 1996), and it is inappropriate to draw definitive conclusions, but these regional differences must reflect both original sediment grade (Chapter 2) and post-depositional history. It may be that frequently coarser grain sizes in Scotland and the Northeast, and the lesser regional subsidence (compared with the Pennine Basin) promoted poorer cementation; and some silica redistribution in South Wales may reflect Variscan ranking processes.

1.5 Conclusions

In an introduction to such a diverse topic as coalfield geology, it is impossible to address all major themes. Those referred to here, and those detailed later, are particularly relevant to tectonic settings. Both Namurian and Westphalian coal-bearing sequences show many depositional similarities, but they were laid down across areas with quite varied settings; it is the interplay between depositional successions, and regional and local structural evolution, that is the underlying subject of the following chapters.

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1.7 Figure captions

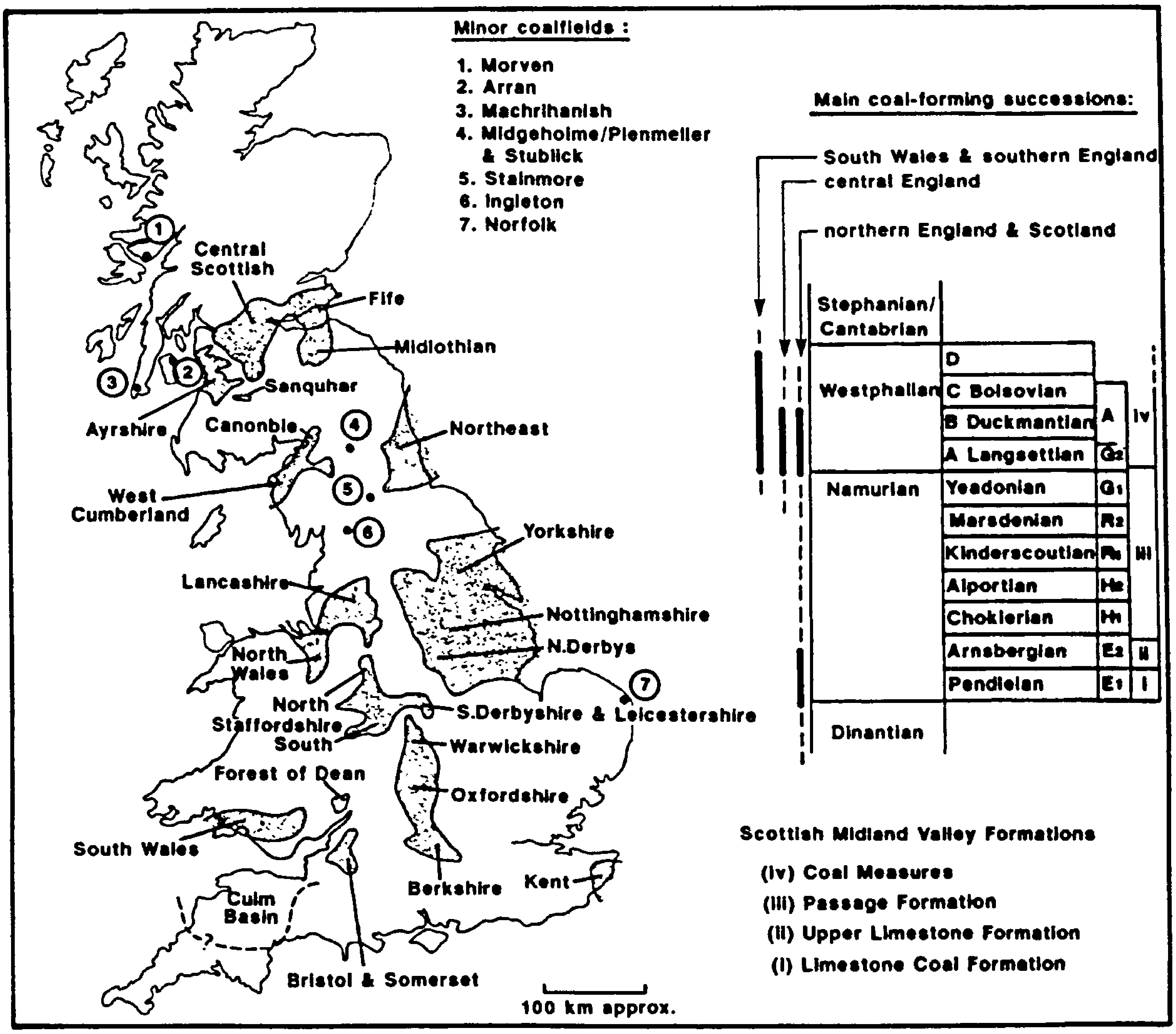
Figure 1.1 Coalfield locations and stratigraphical ranges. Coalfield extents are generalised, and include poorly-proved concealed extensions down-dip from mined and explored areas.

Figure 1.2 Chronostratigraphy of the Silesian (Upper Carboniferous).

Figure 1.3 General tectonic settings of the coalfields. The extent of coal-bearing Westphalian strata south of the Variscan Deformation Front is uncertain.

Figure 1.4 Selected tectonic events relevant to Carboniferous coalfields. Details particular to the Carboniferous are mainly from Clark *et al.* (1993), Guion *et al.* (1995), and Peace & Besly (1997).

Figure 1.5 British Silesian coalfields; summary of features with correlation value.



Location and stratigraphical summary of the Upper Carboniferous coalfields

Fig.1.1

Series	Stage	Zone	Radiometric age, Ma	Scottish Midland Valley Formations	Selected Marine Horizons
STEPHANIAN	C		300		
	B		303		
	A				
CANTABRIAN			305		
WESTPHALIAN	D		308		
	C Bolsovian		311	UCMS	C
	B Duckmantian	A		MCMS	A
	A Langsettian	G_2	315	LCMS	V S
NAMURIAN	Yeadonian	G_1		PF	
	Marsdenian	R_2			
	Kinderscoutian	R_1	319		3 MB
	Alportian	H_2			
	Chokierian	H_1			2 MB
	Arnsbergian	E_2		ULF	CCL OL
	Pendleian	E_1	326	LCF	IL THL
VISEAN	Brigantian			LLF	

series/stages based on Ramsbottom *et al.* (1978) and Guion *et al.* (1995)

Radiometric ages based on Guion *et al.* (1995)

Midland Valley Formations (British Geological Survey, 1993)

UCMS, MCMS, LCMS : Upper, Middle, Lower Coal Measures (Scotland)
PF : Passage Formation
ULF : Upper Limestone Formation
LCF : Limestone Coal Formation
LLF : Lower Limestone Formation

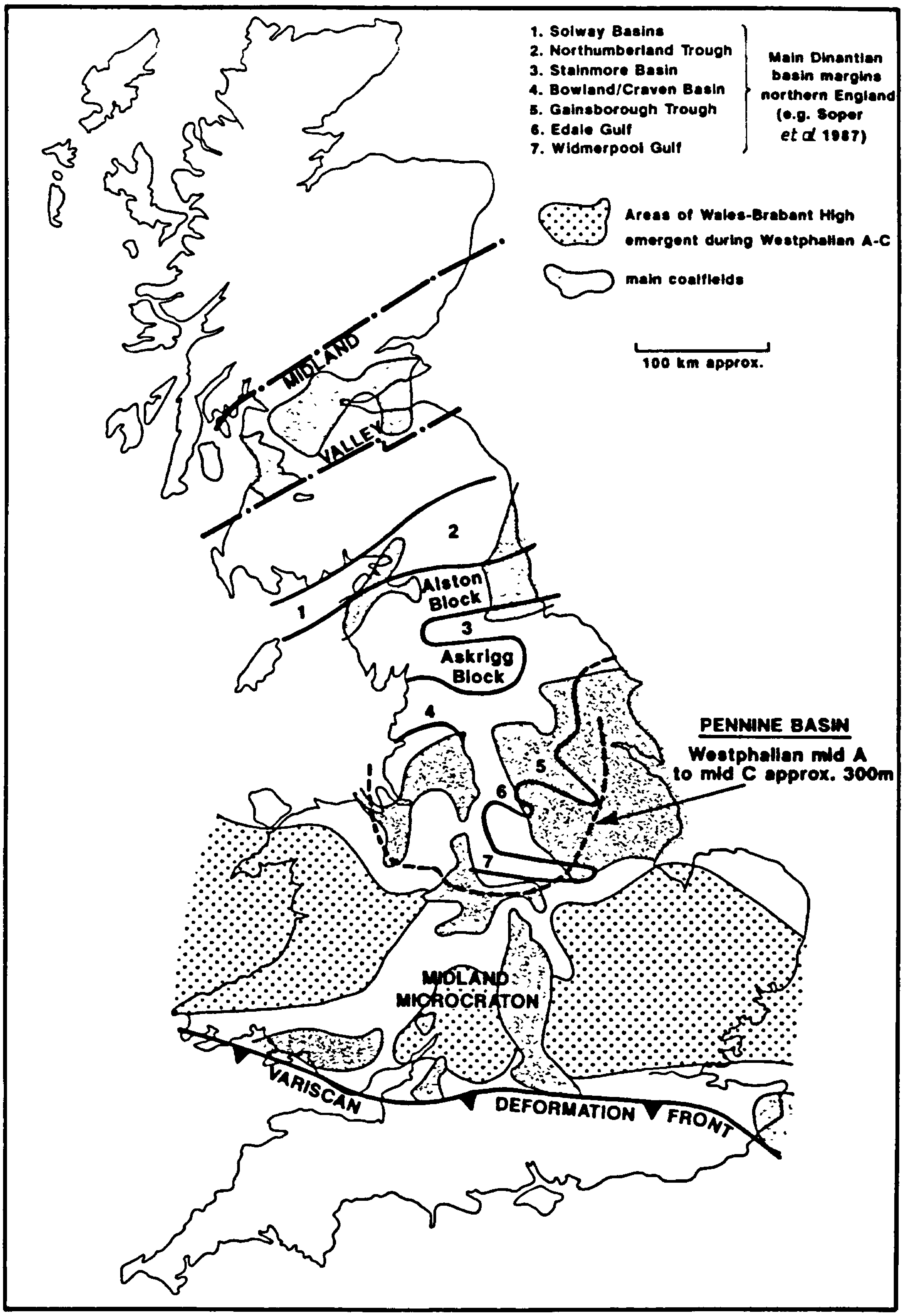
Horizons

C : Cambriense Marine Band
A : Aegiranum Marine Band
V : Vanderbeckei Marine Band
S : Subcrenatum Marine Band

3 MB, 2 MB : Marine bands in Passage Formation
CCL : Castlecary Limestone
OL : Orchard Limestone
IL : Index Limestone
THL : Top Hosie Limestone

CHRONOSTRATIGRAPHY OF THE BRITISH SILESIAN (UPPER CARBONIFEROUS)

Fig.1.2



Tectonic framework of the main Upper Carboniferous coalfields

Fig.1.3

SELECTED TECTONIC EVENTS RELEVANT TO CARBONIFEROUS COALFIELDS

Fig.1.4

BRITISH SILESIAN COALFIELDS

Summary of features with correlation value

Fig.1.5

CHAPTER 2

SAND BODY ORIENTATION, PALAEOFLOW ANALYSIS, AND BASIN FILL IMPLICATIONS IN THE WESTPHALIAN A-C OF GREAT BRITAIN

***Abstract*:** *Channel orientation and palaeoflow analyses across British Westphalian coalfields show that three main inflow directions dominated the palaeogeography from the mid-A to mid-C Westphalian. The depositional area included discrete tectonic depocentres, notably the Pennine Basin, which was traversed directly and tangentially by westerly-sourced major channel belts. These depocentres were incidental to main channel pathways, but sand body characteristics vary according to basin location. A new depositional model for the post-rift Pennine Basin is proposed, relating sand concentrations and connectivities to depositional and tectonic setting. Dominant SW to NE flow across South Wales through much of Westphalian A and B times implies similar channel/depocentre relationships to those described for the Pennine Basin.*

2.1 Introduction; data sets

The British Westphalian successions are mainly coal-bearing, and exploration and mining has generated a data set that is excellent in terms of geographical extent, stratigraphical range and precision, and the detail and quality of the geological records. Ongoing mine workings in most coalfields continue to add to the data (Fig. 2.1). The present account, based on Rippon (1996) is concerned primarily with the succession from the mid-A to mid-C Westphalian (Fig. 2.2), which is the main mined sequence and has the greatest wealth of geological data. It is also a part of the British Carboniferous that is less known in modern literature. Natural surface exposures are poor, being generally low lying, frequently masked by superficial deposits, and commonly urbanised. Westphalian sand bodies have therefore been described relatively infrequently from outcrop compared with those in the Namurian. Also, differences in horizon nomenclature and recording methods between coalfields create interpretational difficulties.

Perhaps reflecting these problems, recent overviews have tended to extrapolate from the detail of earlier studies, or build on models, both sedimentological and tectonic, derived from other geological settings. Neither of these approaches is necessarily compatible with modern coalfield data. One area where recent interpretations can be considerably modified is that of palaeochannel orientations and their relationships to the fill of the basins. In this account the eastern Pennine Basin coalfield provides the impetus for discussion on basin fill and sand body characteristics, and leads to a reappraisal of the spatial relationships and connectivities of the sand bodies. The interpretations raise sedimentological and palaeogeographical issues requiring further study.

The account draws on existing published material including detail from British Geological Survey (BGS) $25km^2$ Quarter Sheets, abandonment plans of mine workings available as public records, unpublished theses supported by the National Coal Board (NCB), later the British Coal Corporation (BCC), internal NCB/BCC reports, and recent mapping by the author. The eastern Pennine Basin and the Northeast coalfields provide the best data sets for sedimentological analysis, having a generally even scatter of good borehole data (often >50 boreholes per $25km^2$), a well-established stratigraphy with high correlation precision (see below), and especially the wide geographical extent needed for regional mapping. The Westphalian age coalfields of Scotland have a generally good data set, but are geographically restricted. The West Cumberland and North Wales coalfields are also geographically restricted, and are mainly characterised by old and less accessible mining data. The coalfields of the western and southern parts of the Pennine Basin are generally small and individually isolated, with data sets of varying quality and accessibility. The South Wales coalfield has a large but rather clustered data set; other coalfields of southern Britain, notably Somerset and Kent, are mainly later Westphalian C/D age. The term "orientation" is used here without any implied flow direction; "direction" is used when the flow sense is considered. Abbreviations N, NW, etc are used for channel trends.

2.2 Review of previous work

2.2.1 Background

Channel systems affect the economic mining of coal in various ways. These include erosion of coal ("washouts"), bank collapse rotational slips, differential compaction faults, variations in coal quality, coal seam splits, and geotechnical problems such as stress retention from limited sandstone fracturing, and the ability to retain and transmit water via sandstone joints (e.g. Fulton *et al.* 1995). The recording of washouts has a long history, and although many early records are not geologically described, the more prominent are outlined on the BGS Quarter Sheets. A few descriptions are known from the years prior to the nationalisation of the British coal industry in 1947, and published in either the mining or geological literature. The paper by Coke (1888) on the "Dumb Fault" of Derbyshire, re-described by Guion *et al.* (1995a) is one of the few that can be used for a regional channel orientation study. More systematic geological work followed nationalisation, with mining interest in most coalfields extending to previously unexploited areas and seams, while the advance in mechanisation necessitated an ever more refined geological description of the mining environment. However, with more work being undertaken internally within the NCB, there were progressively fewer external and published studies. NCB sedimentological interpretation was practised in all coalfields from the 1970's, especially in Nottinghamshire and northeast Derbyshire, where generally thinner coals are prone to variations in the underlying ("floor") and overlying ("roof") clastics. However, thinner coal also means that a greater thickness of roof strata is exposed during mining, and numerous exposures, complemented by many boreholes, allowed systematic recording, interpretation, and the development of depositional models. The following review is limited to references applicable to channel orientations. There are no significant publications detailing channel orientations in Kent or in Bristol and Somerset.

2.2.2 Scotland and the north of England

In Scotland, little is published relevant to palaeochannel mapping. Good surface exposures of Westphalian sandstones are restricted largely to the Fife coast, where the sequence is mainly of Westphalian C age. Read (1988) reported that channel sandstones in Ayrshire entered the coalfield from a variety of directions from E through to NW. In general, the Westphalian A and B successions in Scotland are sandstone-rich in the eastern coalfields of Fife and Midlothian, and relatively sandstone-poor in the western coalfields of Ayrshire. Whether this reflects a genuine regional trend, or merely unrepresentative "snapshots" resulting from the limited coalfield extents, is uncertain, but is compatible with an overall N/NE provenance for the eastern coalfields similar to that for the Northeast coalfield of England, discussed later.

The Northeast coalfield is comparable to the eastern Pennine Basin, in terms of sensitivity of the coals to sedimentological variations, and washouts are very common. A series of regional maps produced for coal quality attributes, published by the NCB (1957, 1959a, 1961) showed major washouts in the Busty and Harvey/Beaumont coals (Westphalian A) and to a lesser extent in the Hutton coal (Westphalian B). The Busty washouts (at the base of the Modiolaris Zone, Fig. 2.2) are very extensive and strongly oriented in a N-S belt over at least 80km. Using detailed mine records, Clarke (1963) mapped washouts in part of the Durham coalfield in a number of coals, mainly with a N-S or NNW-SSE trend. The BGS Tynemouth Memoir (Land 1974) contains palaeochannel maps, based mainly on washouts and sandstone thicknesses, for many horizons through Westphalian A and B successions. These show a strong overall N-S orientation, with some flow directions based on foreset azimuths. Two Westphalian B channels were recorded flowing from the N, and also a pair flowing from the E. The latter were also investigated by Haszeldine (1983), and B. Turner (pers. comm.1996) has described unusually coarse and feldspathic grains in these sandstones. Haszeldine & Anderton (1980) and Haszeldine (1981) produced a model for Westphalian B sedimentation, and concluded that much could be interpreted as a braidplain, with variable channel directions. Fielding (1982, 1984a, b, 1986) interpreted large palaeochannel systems, many kilometres wide, extending across the coalfield generally from the N and E, with the regional flow direction assessed from foreset data and mapped channel bifurcations. The overall directions from N to S and NE/E to W interpreted by these studies are compatible with trends implied by other BGS memoirs dealing with the coalfield (Smith & Francis 1954; Mills & Hull 1976; Smith 1994) and by the generality of mining industry mapping.

The sedimentology of the West Cumberland field has rarely been investigated. Kirk (1983) considered that some sands were derived from the E, based mainly on sand thicknesses. Jones (1992), using mainly opencast (surface) mine data, studied six major sand body horizons, and concluded that overall directions were mainly from the SW, W, and NW, based on foreset data, mapped bifurcations, and crevasse splay attributes; one sand body was considered to have been sourced from the NE, but this was based on less data.

2.2.3 The Pennine Basin

The western Pennine Basin includes North Wales, Lancashire, and North Staffordshire. There is very little published information on palaeochannels in these coalfields apart from the BGS Quarter Sheets. In North Wales, BGS memoirs for Wrexham (Wedd *et al.* 1928) and for Flint, Hawarden and Caergwrle (Wedd & King 1924) described various washout trends with a generally N-S orientation, locally geographically superimposed, and sub-parallel to intervening intra-coalfield anticlines. The convergence of these structures to the south led these authors to consider that the flow was from the S; supporting evidence was seen in the distribution of the bivalve *Carbonicola*, which the authors believed to have near-marine affinities (this setting would not be interpreted for *Carbonicola* today). In Lancashire, the NCB published various regional coal quality maps; that for the Trencherbone coal (Westphalian A) (NCB 1959b) included areas of extensive washout related to the overlying Trencherbone Rock. Broadhurst & Simpson (1983) described the NW-SE trending split of the Union coal (lower Westphalian A), and interpreted structural control for its orientation (see Chapter 5 for comments). This split defines the northeasterly margin of the Bullion Mine sand body, and was also mapped over 17km by the BGS using coal industry data. Elliott (1970) mapped the orientation of a channel over some 15km roughly N-S above the Bullhurst coal (Westphalian A) in North Staffordshire, based on washout trends; Corfield (1991) mapped isopachs there which suggested channel orientations similar to the main syn-depositional structures which lie generally SSW-NNE. Other washout trends, including N-S and E-W, are shown on BGS Quarter Sheets. The limited geographical extent of the North Staffordshire coalfield makes any overall assessment of orientation difficult. Little mapping of channels in the west of the basin was undertaken by the NCB, mainly because the key geological concern was structural, but also because washouts seem to be less common than in the eastern and southern parts of the basin; this is discussed later.

The eastern Pennine Basin is effectively a single coalfield, dipping generally eastwards from outcrop beneath the Permian and Mesozoic cover rocks across Nottinghamshire and Yorkshire. In the earlier-mined outcrop areas of Yorkshire and Derbyshire, the existence of large sand bodies was well-known from the beginning of the century, and some of the earliest descriptions of washouts and other channel-related features are from this coalfield. In Yorkshire, for example, Kendall (1918) described various coal splitting features, and illustrated NNW-SSE oriented channels in the Middleton Main coal (Westphalian A). Some memoirs of the BGS, especially Edwards *et al.* (1940), Mitchell *et al.* (1947) and Eden *et al.* (1957) illustrate sandstone development at various Westphalian A and B horizons, mainly by gross sandstone isopachs. Wilcockson (1947) considered that sandstones were well developed in the area subsequently described by Kent (1985) as the Gainsborough Trough.

The eastern coalfields proved ideal for the development of a sedimentological understanding of the coal-bearing Westphalian because of the economic imperative, good underground exposures, and an excellent borehole data set. Elliott (1965, 1968, 1969, 1970) set up a scheme of routine underground recording and interpretation of the lithofacies based on sedimentological modelling, partly using the Mississippi Delta as an analogue for the clastic lithofacies. This scheme has been validated through more than 25 years of mining geology, mainly in Nottinghamshire and northeast Derbyshire, with sedimentological detail used for the forecasting of channel features down to a scale of 10's of metres where data allow. By the mid 1980's, detailed sedimentological maps were available to the NCB for all principal coals (>0.9m) on a regional (1: 25,000) scale. Elliott (1970) included an orientation diagram for massed channel data, showing a dominant SW-NE trend. The same area was studied by Fatoma (1980) and Guion (1978, 1984, 1987a, b). The latter author investigated a variety of Westphalian channel systems and showed minor channel directions from the W/NW above the Threequarters coal (Westphalian A), from the SW above the High Hazles coal (Westphalian B) and a W-E orientation for a short length of a channel above the Top Hard (Westphalian B). Subsequent work on the major Silkstone Rock (Westphalian A) sand body of south Yorkshire (Guion *et al.* 1995b) showed that the overall direction was from the W, based on foresets at outcrop, together with mapped palaeogeography requiring flow away from the main channel belt by crevassing to the SE above the Threequarters horizon. Guion *et al.* (1995a) re-described the channel features of Coke (1888) that overlie and locally replace the Deep Hard coal of Derbyshire (Westphalian A). This channel is recorded as flowing from the SSW towards the NNE, as is also a parallel channel above the slightly later Deep Soft. Rippon & Spears (1989) described the detailed sedimentology of the sub-Clowne cycle (Westphalian B) in Derbyshire, including the mapped extent, nearly 20km, of a SSW-NNE "swilley" representing a channel abandonment. This feature was mantled by the Clowne precursor peat, and is known from mine plans as a belt of thicker coal along the watercourse, with thinner coals over levee flanks.

The outcrops of the earliest Westphalian A sandstones have also been investigated for palaeoflow direction by foreset mapping and by provenance studies. Microcline has been proposed as a provenance indicator, with Smith *et al.* (1967) suggesting continuation of late Namurian trends. Chisholm (1990) derived palaeoflows at three main horizons throughout the Pennine Basin: an overall flow from the W was deduced for two channel belts, and a more tentative flow from the E for a third. A fourth horizon, limited to northern outcrops, suggested termination thereabouts of a flow from the N. The sand bodies interpreted as flowing from the W were discriminated by a prominent chlorite content, giving the rocks a greenish field character. In the Bradford area of Yorkshire, Chisholm *et al.* (1996) have recognised flows ultimately from the N, with a "granitic" source area, interdigitating in the lower Westphalian A with flows from the W, in which chrome-spinel, together with chlorites (Chisholm 1990) are characteristic. The isotope work of Glover *et al.* (1996) supports this. The overall picture from early Westphalian outcrops suggests a Namurian-style N/NE source competing with a progressively more dominant W source. The varied source areas proposed for the lowest Westphalian were reviewed by McLean (1995), who preferred derivation from the south of the basin for reworked Lower Palaeozoic acritarchs in the Greenmoor Rock of the Sheffield district.

The southern Pennine Basin includes the coalfields of South Staffordshire, Warwickshire, Leicestershire, and southeastern Derbyshire. These coalfields, largely separated structurally, have some of the least usable records, many areas having been mined and abandoned before modern description. As will be discussed later, it is also a key area for wider interpretation. Although these coalfields lie towards the contemporary basin margin, channel systems were obviously quite prominent, evidenced by many presumed washouts (some may be tectonic faults) shown on mine abandonment plans. Apart from the washouts recorded on BGS Quarter Sheets and in the accompanying memoirs, there are few published details. Barnsley (1964) illustrated depositional trends and washout orientations for a variety of coals in South Staffordshire, with most channel orientations lying W-E to NW-SE. Elliott (1970) showed a NW-SE oriented channel above the Main coal (late Westphalian A) across 10km in Leicestershire and South Derbyshire, and a NW-SE oriented channel extending some 20km above the Warwickshire Thick coal (Westphalian B), which was also described by P.D. Guion & I.M. Fulton (pers. comm. 1986); their localised but detailed work on bedforms suggested flow from the NW. The same flow direction was reported for two late Westphalian A channels by Jones *et al.* (1995) northwest of Leicester.

The grey coal-bearing facies of the southern Pennine Basin coalfields gradually change upwards and interdigitate with red beds towards the basin margin. Besly (1988) suggested interdigitation of locally-derived material from the S with more regional sand input from the N. Towards the basin margin west of Birmingham, Glover & O'Beirne (1994) described a Westphalian C lacustrine delta with minor channel flows from the S into the basin.

2.2.4 South Wales

Depositional trends in the South Wales coalfield have been reported in the geological literature from the earliest years of interest in sedimentology, helped by coalfield-wide correlations established in the 1950's by the NCB and the Geological Survey. Bluck & Kelling (1963) described a pattern, from the earlier Westphalian A succession, of small channels oriented generally normal to the basin-form isopachs (Owen 1964), with centripetal flow into the basin mainly from the N and S, based on foresets. A similar pattern was proposed by Bluck & Kelling (1963) for later Westphalian A and B channels, although direction was not specified. Westphalian C/D channels were envisaged as having flowed predominantly from the developing Variscides in the south. Kelling (1974) later extended this work and included provenance data, confirming earlier interpretations for the lowest Westphalian, and for the Westphalian C/D. Subsequent work by Jones (1989a, b) further confirmed the later C/D direction. The main mined Westphalian A and B sequence in the coalfield downdip from outcrop was not investigated in any detail.

The NCB (1959c, 1962) published regional coal quality maps for the Five Feet/Gellideg (Westphalian A) and for the Nine Feet (Westphalian B) coals. Large washouts with prominent SW-NE orientations were shown at the Gellideg horizon, parallel to the overall basin axis. These divided to the NE, suggesting a flow from the SW if these are deltaic bifurcations. Woodland & Evans (1964) noted that these SW-NE trends lie roughly normal to the progressively-reducing basin-form isopachs. Individual washout lengths of at least 20km were recorded, with the width of the barren zone in the coal sometimes being around 1.5km, representing a substantial channel belt within the subsurface coalfield. This was not centripetally-disposed to the basin form as were the earlier features described by Bluck & Kelling (1963). Trends in the Nine Feet were more variable, but showed prominent washouts lying at high angles to the assumed eastern margin of the basin. Mine plans of washouts show the SW-NE orientation at various horizons, particularly for large features, including a major erosion of the Four Feet coal (Westphalian B) south of Merthyr.

The coal-mapping thesis of Parry (1966) is a detailed regional study of the subsurface coalfield, describing basin development as reflecting the SW-NE structural trends of the Neath Disturbance and the Usk Axis. Parry (1966) showed many inter-seam isopachs to be oriented subparallel to this structural trend. Inasmuch as these represent the lithofacies envelopes of invading channel systems, this work confirmed that the regional orientation of the major channel belts was SW-NE. This implies that the centripetal pattern of Bluck & Kelling (1963) may have been an earlier feature, as all their mapped horizons predate those with regional subsurface mining data. The directions derived by Bluck & Kelling (1963) for the later Westphalian A and B may then represent the varied trends of lesser distributaries, branching from Parry's (1966) major trends.

2.2.5 The Culm Basin of southwest England

The Culm Basin lies south of the South Wales coalfield, and the succession includes largely non-coal-bearing rocks of Westphalian A, B, and early C age of the Bude and Bideford Formations. The depositional and post-depositional relationships of this basin to that of South Wales, as discussed in the literature, are considered uncertain; Thomas (1988) gives an overview and Freshney *et al.* (1979) provide local detail. An extensive review of the Culm Basin Westphalian succession is beyond the scope of this paper; however, the Bideford Formation appears to be largely delta-top facies, while turbidites characterise the Bude Formation. Of the various issues which have thrown doubt on a straightforward relationship with South Wales, that of an accepted northerly provenance for many of the sandstones (e.g. Thomas 1988; *Cope et al.* 1992) is pertinent to a study of Westphalian palaeoflows, and is discussed later.

2.3 The Westphalian A-C depositional area

The Westphalian A to mid C sequence is thought to have been deposited as coal-bearing facies over much of Great Britain and the surrounding area, as described by Guion & Fielding (1988), by Guion *et al.* (1995c) for the Pennine Basin, and by Cope *et al.* (1992) who mapped a Westphalian A depositional interpretation across Britain. There are no recent published UK-wide interpretations for Westphalian B, and those for late Westphalian successions are beyond the scope of this account. However, from basin-form isopachs and established channel trends, it is suggested that Westphalian B sediments originally extended over a much greater area than those of Westphalian A age, and progressive overlap through the Westphalian is inferred in most coalfields.

2.3.1 Tectonic setting

Substantial areas of Westphalian deposition lay across and locally between four major structural provinces. Three of these lay north of the relatively shallow, undeformed Precambrian and Lower Palaeozoic of the Wales-Brabant High (WBH) (Guion & Fielding 1988; Guion *et al.* 1995c). These three, the Midland Valley of Scotland, Solway and Northumberland Basins, and the Pennine Basin are all considered by many authors to have had a varied pre-Westphalian history, with prominent rifting in the Lower Carboniferous or earlier. The sequence described here lies within the post-rift megasequence of Fraser & Gawthorpe (1990) and Corfield *et al.* (1996). In general there is progressively thicker mantling of the older sediments into the existing basins, but without the prominent and widespread syn-tectonic relationships often described for Dinantian and Namurian times. Active fold and fault movement can be interpreted in the mid-A to mid-C Westphalian in most coalfields, but on a very local scale with subdued effects (see Chapter 5). Glover *et al.* (1991) considered that the more readily-recognised syn-tectonism was to be seen towards the basin margins. Syn-tectonism is most prominent in the sub-basins of the Midland Valley of Scotland, where the sequences are much thicker compared with the intervening highs. The

Solway/Northumberland Basin of much of the literature (e.g. Chadwick *et al.* 1995) includes large areas without readily-definable depocentres, i.e. showing little variation in formation isopachs, although the Solway Basin, comprising the Canonbie coalfield north of Carlisle, and its southwestern extension towards West Cumberland shows a well-defined sub-basin form. Deposition during the later B and early C Westphalian may have been continuous across the entire region. The Pennine Basin is, overall, a circular feature as illustrated by the various basin-form isopach maps of Wills (1956); symmetry is interrupted locally by thickening into sub-basins inherited from the Dinantian (Kent 1985). Hierarchically-organised channel systems (Fig. 2.3) are typical of the described succession throughout the Pennine Basin.

The Pennine Basin is separated from the immediate Variscan foreland of southern Britain by the WBH. The South Wales coalfield is the best-known area. Basin-form isopachs (Owen 1964; Thomas 1974) for the Westphalian A and B show a WSW-ENE basin axis, with the local depocentre in the Swansea area, and suggesting a possible basin margin some 10's kilometres north and east of present outcrops. Subsidiary intra-basin folds reflect the developing Variscan orogeny, and were considered by Jones (1989a, b) to have affected sedimentation and channel pathways. The approach to a major uplift towards the Usk Axis shows some basin margin trends within the coalfield, especially uniting coal seams, giving substantial composite thicknesses. The tectonic setting of the Culm Basin is uncertain (Cope *et al.* 1992); it may represent a thrust sheet top basin above the major Bristol Channel thrust system (R.A.Gayer pers. comm. 1996).

2.3.2 Basin margins and uplands

Within the wider depositional area, definitive basin margins are rare, and are mainly confined to the WBH, which has been mapped in outline by Guion & Fielding (1988) and by Cope *et al.* (1992). Other emergent highs have been interpreted by extrapolating the pattern of basin-form isopach trends across areas now eroded. Given that some of the larger coalfields include sub-basins and "sub-highs" which are known to give prominent intra-coalfield thickness changes, this may not be a simple indication of the limits of deposition. Indeed it remains possible that some areas that have been considered as sourcing highs, particularly the Scottish Highlands (where

Carboniferous remnants together with more extensive areas offshore suggest a formerly more extensive cover) may have been characterised by attenuated, shelf-like sequences, across which channels may have dispersed sediment. In southern Scotland, the Sanquhar outlier coalfield implies a former greater extent of Westphalian deposits in the Southern Uplands area.

Definitive basin margin characteristics are well documented on the northern side of the WBH (Fulton & Williams 1988), and include the following features. 1.The overall sequence is condensed, with progressive onlap and some interdigitation with red beds (Besly 1988). 2. The individual coals tend to thin towards the margin, but this is accompanied by progressive seam unions giving composite thick seams (Fig. 2.3). Further towards the basin margin the thick coals pass laterally into palaeosols (Fulton & Williams 1988). Fulton (1987) has described detailed mire facies changes. 3. The clastic sediments tend to become progressively finer grained south towards the margin, with claystones dominating. Brown-tinted palaeosols become more common, indicating increased emergence and oxidation in the depositional environment (Elliott 1968). Marine bands are reduced from their faunal acme (Calver 1968) with only the most prominent marine horizons persisting into the marginal zone.

These features across the English Midlands may also have characterised North Wales. Within this overall basin-marginal setting, sand body dispositions are varied, and this will be discussed later. The northern margin of the WBH is significantly interrupted west and east of Birmingham (Wills 1956; Fulton & Williams 1988; Cope *et al.* 1992). To the west, Wills (1956) defined the "Hereford Straits" as a possible connection to South Wales, on the basis of remnant Westphalian strata (these include some red bed facies) in the Clee Hills, and by consideration of macrofaunal similarities suggested by Trueman (1947). East of Birmingham, exploration in Warwickshire and south into Oxfordshire and Berkshire proved Westphalian A and B strata through a corridor (Fulton & Williams 1988) well to the south of the previously accepted margin, with the implication of a connection through to the southern province in Berkshire (Foster *et al.* 1989).

The northern margin of the WBH west of the Hereford Straits is extrapolated across North Wales, and the southern margin through Wales is also speculative. Apart from basin-form isopach trends, there are no indications along most of the northern part of the South Wales coalfield of any depositional margin. It is possible that there was a thin Westphalian cover over parts of mid-Wales especially in downfaulted areas. The southern margin of the WBH across southern England is inferred from scattered boreholes.

2.3.3 Depositional continuity between coalfields

A generalised continuity of deposition between most British coalfields is suggested by various similarities. There is a gross tripartite pattern through the stratigraphy: coal-poor with many marine bands in the lower Westphalian A sequences; coal-rich with very limited marine influence through the later A to the mid-B; and relatively coal-poor, with further marine bands from mid-B to mid-C (Guion *et al.* 1995c). This pattern is known in all of the major coalfields, together with the onset of prominent coals at roughly the same horizon, and coal concentrations within close stratigraphical limits. These overall similarities suggest some extra-basinal control across a variety of tectonic settings. However, subtleties in the macrofauna (e.g. Trueman 1947; Forsyth & Brand 1986) indicate at least some compartmentalisation between the main basins. In summary, the overall picture indicates widespread deposition, especially from Westphalian B times, both north and south of the WBH and locally across it, and possibly across other palaeo-highs north through Scotland. The overall depositional area included evolving tectonic basins, inter-basin "shelf" areas, and zones marginal to emergent highs.

2.4 Sedimentological summary of the coal-bearing Westphalian

2.4.1 Regional setting

The overall and detailed sedimentology has been described by various authors e.g. Guion & Fielding (1988) and Guion *et al.* (1995c). An environment analogous to a lower delta plain in the lowest Westphalian was envisaged, covering much of central and eastern Britain. This included the Pennine Basin, with large low sinuosity channel belts flowing from the N and NE. In detail, some major channels were interpreted by these authors as entering the central Pennine Basin from the E via the inherited Dinantian sub-basins of Kent (1985), and perpetuating a trend that characterised many major sand bodies in the Namurian (e.g. Collinson 1988). For the later

Westphalian A/B, Guion & Fielding (1988) showed similar gross palaeoflows, with smaller and more sinuous distributary systems in an upper delta plain association. This latter setting was generally considered to have persisted, but with progressively more marine incursions, through to the Cambriense Marine Band (Westphalian C) which is commonly succeeded by a more arenaceous sequence, with large sand bodies characterising most coalfields where preserved. Transition into red beds (Besly 1988) during the later Westphalian has already been noted. A new model for the Pennine Basin's Westphalian fill is proposed later.

2.4.2 Cyclicity and sequence stratigraphy

The cyclicity of the coal-bearing Westphalian has long been recognised, as has the common deviation from the "ideal" cycle. The relative importances of autocyclic and allocyclic controls have been widely discussed, and recently focused by sequence stratigraphical and orbital forcing considerations; climatic variations in both source and depositional areas also need evaluation (Chapter 3). As noted, there are inter-coalfield similarities, particularly the gross stratigraphical distributions of the coal groups and marine bands, which strongly suggest some external controls. However, a simple sequence stratigraphical interpretation appears inappropriate, at least from the mid-A to mid-C Westphalian, as discussed below.

Erosional characteristics: potential for valley fills. The deepest erosional down-cuttings that can normally be demonstrated by detailed geological observations in mineworkings are around 5m, and exceptionally up to 8m. However, these are invariably very local over-deepenings from a more regional sandstone base. A sandstone base itself is often seen to have been constrained by the lithological control of a peat surface when the sand body lies in the immediate roof of a coal (see below). These over-deepenings (elongated 10's -100's metres sub-parallel to the channel axis) are most easily explained as scours initiated by basal turbulence, or perhaps by simple floating away of higher peat following any rupturing of its surface. The erosion of peat to form a washout depends largely on the relative position of the channel in the post-coal interval, most over-deepenings affecting only claystones. The main thicknesses of these channel sand bodies lie above their "regional" sandstone base, and may best be interpreted in terms of net aggradation above an initiation level, basal erosion being represented mainly by local over-deepenings. The aggradation is reflected by a pattern of lateral facies development, comprising a suite of lithofacies representing channel, channel margin, and overbank environments. These lithofacies patterns have been used extensively and successfully within the mining industry for channel proximity mapping. In many cases, the smaller channels lie at the horizon of a single seam split, and are represented by coal often within 2km of the channel axis. Major sand bodies can often be shown to be laterally equivalent to coals which are otherwise regionally developed (Guion *et al.* 1995b).

The well-defined regional sandstone bases, together with the lateral facies, leave little scope for significant low stand erosions and valley-fills. Further, extensive areas of deep weathering, with only thin coals, that should characterise any major interfluves, are not found. Brown-tinted palaeosols (indicating some oxidation) are found at some horizons, locally >2m thick and underying thinner coal areas, reflecting the detailed topography of abandonments (Rippon & Spears 1989), while Elliott (1968) noted more common brown palaeosols towards a basin margin. The palaeosol preceding the Aegiranum Marine Band has widespread oxidation tints, and may warrant detailed study but in general, no candidate features for significant interfluves are known. There may, of course, be large valley fills and complementary interfluves in different but contemporaneous settings elsewhere.

Base level and sequence boundary issues. A "regional" sandstone base as described above (i.e. not a local over-deepening) can often be shown to lie at a consistent stratigraphical level (e.g. a particular faunal horizon, or a coal), over many kilometres along a channel belt length, sometimes reflecting the importance of local pre-channel lithologies in controlling erosional down-cutting, especially peat surfaces. (These seem to have been highly cohesive and generally difficult to erode, except when channel initiation was early post-peat, in which case the peat surface would have been less cohesive.) This characterises the major sand bodies as well as the lesser features.

Where a depositional area, and its present preserved extent, are of sufficient size for analysis (e.g. the eastern Pennine Basin and the Northeast coalfield) the distribution of larger sand bodies is seen to be relatively evenly spaced temporally and spatially (except locally near basin margins, see later) such that at most horizons there is usually a large channel system somewhere.

Concentration of sand bodies at particular horizons is rare, if present. Further, the longevity of the large channel systems, lateral to two or sometimes more regionally-developed coals, may have been of the order of 10^4 years. Such considerations make it difficult to assign particular channel bases to significant sequence boundaries, as these would have to be inferred virtually throughout the described succession. The difficulties of a sequence stratigraphical interpretation are very evident when the lateral equivalence of thicker coals (related to development towards a maximum flooding surface) with major sand bodies (implying a significant low stand) can be demonstrated.

Regarding base levels, coastline locations need consideration. As discussed later, the author does not consider that the bulk of the succession had any direct marine influence, and it is probable that large channels prograded into very extensive areas of essentially fresh water. (Chapter 3 discusses the nature of internal and external controls, and their interactions.) In this connection, the propositions by Leeder & Stewart (1996), on the upstream circumstances that might moderate the effects of a marine base level fall, may be relevant and could be investigated further in Westphalian successions. Of particular interest are those intervals that are rarely bridged by diachronous/splitting coals, as these are more likely to relate to an external event.

The main differences between the depositional system described here, and those proposed by a sequence stratigraphical model (Flint *et al.* 1995) may be summarised as follows. 1. Sequence boundaries, evidenced by widespread contemporaneous erosions by major channels throughout a depositional area, are not found. 2. Channel downcuttings are limited to local over-deepenings. 3. Sandstones are vertically stacked only in particular circumstances, and aggradational patterns are normal. 4. Most major channel belts prograded into fresh water, remote from marine influence. Particularly regarding the Pennine Basin, the proposition by Flint *et al.* (1995), that Westphalian A times were dominated throughout by regional stacked fluvial deposits, is not supported by coalfield data; neither is the upwards transition to smaller-scale systems. Throughout the succession, there does not seem to have been a significant change in the number and disposition of large systems until after Cambriense Marine Band times.

2.4.3 Lithofacies, biofacies, and correlation

The palaeontology has been extensively described and referenced in the memoirs of the Geological Survey, and environmental interpretation is given in the papers of Elliott (1968, 1969) and Guion *et al.* (1995c). The environments represented by the coals have been interpreted by (e.g.) Smith & Butterworth (1967) and Fulton (1987). The key issue for channel system mapping is the degree to which the lithologies and their contained fauna and flora can be used for detailed correlation, providing a well-defined framework for precise horizon discrimination. An introduction to correlation precision for various palaeontological, lithological, and geochemical features is given in Elliott *et al.* (1984). For the channel mapping described here, correlation resolution better than that defining the traditional cycle is sometimes required.

Sandstone petrography is obviously of particular interest. In the Pennine Basin, the great majority of channel sandstones are fine grained, with occasional medium and coarse grained layers (Fatoma 1980). Most are mature, off-white orthoquartzites, with cross-stratification picked out by mica and carbonaceous debris. Intra-formational breccio-conglomerates, usually consisting of siderite nodules eroded from palaeosols, or of bank-collapse material, are common in many channel sandstones. Such sandstones are so typical that variants are easily noted, for example the coarse grained Woolley Edge Rock (Westphalian B) of Yorkshire (e.g. Mitchell *et al.* 1947, 71-73) and its coarse, feldspathic correlatives derived from the E in Nottinghamshire (Fig. 2. 5, channel axis 9A). The differences between the usual orthoquartzites of the mid-A to mid-C Westphalian, and the coarse feldspathic NE-derived Namurian sandstones are pronounced.

In the Northeast coalfield and Scotland, coarser grain sizes are much more common, and poor sorting and angular grains are frequently found (Land 1974). Again, unusual lithologies stand out, notably the Seaton Sluice Sandstone (Westphalian B) (Land 1974) which is also coarse, feldspathic, and was transported by a well-defined local flow from the E. The sandstones in South Wales are less well known, especially in the subsurface. These differ markedly from their counterparts in the Pennine Basin and beyond, often being dark grey, sometimes approaching black, with lithic fragments and more carbonaceous material, coupled with some recrystallisation and silica cementation. This makes underground sedimentological mapping much more difficult, with less easy colour differentiation between the clastics, and with often obscure bedforms. Unusually coarse sands known locally as Cockshot Rocks are typical of parts of the mid-Westphalian B succession in South Wales.

The relative abundance of sandstone is known to vary broadly across the coalfields, but the actual detail of this has not yet been addressed by analysis of modern coal exploration data. As broad generalisations, the Northeast and eastern Scottish coalfields frequently have locations where the sandstone content is greater than 50%. In the more central parts of the Pennine Basin, overall sandstone content is rarely greater than 30% at any one location, although higher concentrations may be found in some basin-marginal areas, see later. Sand-poor lacustrine and interdistributary environments show progressive fining towards the WBH in the south. As a consequence of the clustering pattern of data in South Wales, the sandstone proportion there is poorly known, but evidence from the numerous opencast mines suggest it is less than 20% (R.A.Gayer, pers. comm. 1996). Overall, it is possible to group the sandstones of the main coalfields into three petrographical provinces. 1: *Northern*. Eastern Scotland and the Northeast coalfield of England, characterised by relatively poor sorting, higher angularity, coarser grain size, and a higher proportion of sandstone in the succession; in the Northeast coalfield, a well-defined derivation from the N/NE for most channels. 2: *Central*. The Pennine Basin and probably the northwest of England, with better sorting and more rounding; dominantly fine grain size; a generally lower proportion of sandstone; main channel directions from the SW, W, and NW (see below). 3: *Southwestern*. South Wales, frequently including dark grey sandstones with variable grain size and more common lithic fragments; main channels from the SW.

2.4.4 Channel system mapping

Channel mapping requirements vary greatly according to end-usage; greatest precision is needed by deep mining, where safety and efficiency are sensitive to the heterogeneities presented by sand bodies and their lateral lithofacies. Channel systems have been mapped for deep mining in considerable detail in the eastern Pennine Basin, and the methods used there are briefly reviewed so that the difficulties of unambiguous mapping in areas with poor data may be appreciated.

The key to unambiguous mapping is correlation precision; this ideally needs to be below the resolution of the traditional cycle, as channels of varying ages and fill characteristics may have very different orientations within a given cycle. Such precision requires cored borehole control of at least one location per km^2, when distant from the detail provided by mineworkings. Without this correlation control, channel linkages become progressively more tenuous and ambiguous with decreasing sand body width. Channel proximity mapping for mining purposes uses various lithofacies criteria, particularly bedforms, sand/silt proportions, numbers of minor erosion surfaces, faunal and floral changes, etc. Lithofacies schemes are particularly relevant where a channel and its associated marginal facies were developed soon after termination of peat accumulation, resulting in better exposure at mined horizons. Given that most horizons have individualities, and that not all data sets are of modern sedimentological quality, local lithofacies schemes may be necessary. Inter-seam isopachyte mapping is a valuable tool for channel mapping. An interval between successive coals is generally expanded where channel sediments are present. A high-interval corridor largely defines the overall width of a channel and its marginal facies. As only the preserved sedimentary rocks and structures are available for interpretation, simple isopach maps need to be used with care, as very low values may characterise the central axis, reflecting a final unplugged abandonment. Axial areas may also have a low interval because of persistent erosion of the river's own bed; the highest intervals are usually in the overbank areas, where preserved.

The identification of coal quality and splitting trends is related to lithofacies mapping. Many, but not all seam splits are demonstrably associated with channel proximity, and their mapping is a fundamental tool for sand body investigation. Multiple splits towards a contemporary channel are invariably preceded by a progressive ash percentage increase, as recorded for example by Guion *et al.* (1995b, figure 8). The sulphur percentage of coals may also be used, with specific high values at horizons known regionally to be prone to splitting. Such highs probably represent overbank floodwater extents into the mire beyond the limits of mappable claystone deposition.

2.4.5 Channel hierarchies

A range of channels and channel belt sizes occurs throughout the coal-bearing Westphalian. Widths, with marginal facies, range from < 0.5km to >10km, and thicknesses from < 5m to >30m. However, width and thickness alone are not necessarily a guide to relative importance, as longevity of the channel system also needs consideration. Some major sand bodies span the stratigraphical interval represented by two, or more, regional coals, as reported by Guion *et al.* (1995b). Such features were major elements of the depositional geography through the lives of many subsidiary channels, and persistent erosion of the channel bed must have limited the preserved sandstone thickness. In addition channel fill may be of various lithologies, including coals (especially cannels), claystones, and palaeosols. Elliott (1968) described a linear belt of higher-ash coal which may have represented slow regional drainage within the peat. An overall channel system hierarchy is proposed as follows. First order, major multicycle channel belts, usually >5km wide; second, major single cycle channel belts, usually >5km wide; third, other multicycle channel belts, <5km wide; fourth, single cycle channel belts <5km wide; and fifth, minor single cycle individual channels, <0.5km wide. The quoted width categories are subjective, as there is a continuous size range. The first order belts, which are individual because of their size and longevity, are not always mapped for mining purposes, as they are frequently accompanied by widespread deterioration and absence of coal. The intermediate size channels are the best known and mapped, whereas some minor sandstone-filled channels escape even the best data sets. Figure 2.3 includes a schematic map of a distributive hierarchy, showing branching from a first order multicyclic channel belt, the progressively lesser features becoming more stratigraphically restricted downstream. The orientation diversity of real channels, see below, means that many crossing trends may be expected, compared with the simple illustrated pattern.

2.4.6 Channel orientation assessment

The orientation of any individual channel or belt will be partly a function of its hierarchical position. A major distributary branch will often maintain a consistent orientation over many km, whereas lower order features will deviate more from the regional, with individual lengths reflecting meanders, crevasse channels, and any local syn-tectonic or compactional controls. NCB mapping indicates that unambiguous interpretation of the "regional" orientation of channel belts over 1km wide needs a minimum of 10km, and preferably 20km of control, in order to account for such local trend variations (and indeed to ensure correct linkages where several discrete channels are present at the same horizon). In areas of limited data, much lesser lengths become significant only where most trends are subparallel, when they may be treated essentially as a population.

Mining data indicate that structural control on channel orientation has been considerably exaggerated in the literature (see Chapter 5 for detailed discussions). The great majority of definable channel lengths are unrelated to any specific fault, fold, or structural trend. Given the number of sand bodies and their diverse orientation potential, it is necessary to be prescriptive about the criteria for recognising local syn-tectonic control, especially where vertical stacking may have occurred. These are: 1, coincidence of detailed structural and sedimentological trend at each sand body horizon preferably over several kilometres; 2, good data control for several kilometres lateral to a candidate structure, for context and the reduction of linkage ambiguities; 3, correlation to at least the resolution of the traditional cycle; and 4, ideally other evidence that a particular structural trend has been active syn-depositionally. In general, less equivocal evidence for tectonic controls on sedimentation comes from claystones, and especially coals, rather than sandstones, i.e. representing those environments which are more sensitive to water table change. Compactional control on sedimentation at a local scale is usually difficult to prove or model even with good data, and the channels are often narrower than spatial variations in substrate lithofacies. The main parameter is peat/coal compaction (Elliott 1985), and the peats that ultimately became coals of mineable thickness would probably have dominated underlying heterogeneities. Crossing trends for minor channels are common through successive cycles in the main parts of the Pennine Basin, reflecting the orientation diversity implicit in smaller distributary watercourses. Structural and compactional controls are more readily detected on the regional scale, as described later.

Palaeoflow direction assessment is rarely straightforward. Good directional data over a sufficiently wide area are not always available, and different categories of information need to be assessed carefully for compatibility with both the data spread and with the mapping objective.

Published outcrop studies of bedforms are rare, and away from the coast are largely confined to lower Westphalian A sandstones (e.g. Bluck & Kelling 1963; Chisholm 1990). Dune foresets were frequently recorded underground by NCB geologists, especially in Nottinghamshire and northeast Derbyshire, although mining exposure limitations can lead to ambiguities, from difficulty in obtaining true depositional dip from linguoid bedforms, and potential confusion with lateral accretion surfaces. Local palaeoflow assessment from ripple bedforms has also been used where data have allowed, with feeder channel alignment inferred from splay bedforms. Foreset data are potentially misleading where the data density is insufficient for the investigative scale, and where correlation resolution is poor. Individual dipmeter logs are not a good guide to regional palaeoflow, unless consistent over a significant sequence. Foreset orientation to azimuth/azimuth+180^0 can be achieved on cores by reference to any regional joint/cleat system in the coal clasts. Channel sandstones can lie immediately above a coal over wide areas, mineworkings providing extensive views of the underside, allowing mapping of flutes, tool and crescent marks, as well as the orientation of small-scale flow-parallel scours ("rolls").

As noted, existing provenance studies are largely confined to lower Westphalian A outcrops. Apart from distinctive mineralogies, regional variations in grain texture also need consideration, as these may provide supporting data on channel system longevity and length from source. The overall differences in maturity between typical Pennine Basin sandstones and those of the Northern province described above, while not diagnostic, may suggest a different provenance, unless the latter province is directly up-system of the former; however, only some 60km separate the two. Obviously, detailed petrographic studies are required. With sufficient and well-correlated data, regional mapping is considered to be the least ambiguous method of determining regional palaeoflow. Within a distributary system, the high definition mapping of bifurcations and terminations, especially of first order channel belts, should be definitive. Isolated small coalfields of only a few 100's km^2 are unlikely to provide unambiguous regional direction maps unless they lie in areas where the channel orientations are essentially sub-parallel; this is discussed later.

2.5 Regional analysis of the data

2.5.1 Scotland

Palaeoflow orientations in the Scottish Westphalian successions remain poorly understood, partly because of restricted geographies and separated outcrops, but the following points are noteworthy. Regarding the depositional area, this must have extended well beyond the present outcrops, as implied by various regional trends, including those of known washouts. For example, a washout of the Kirkconnel Splint (late Westphalian A) trends SW-NE across the Sanquhar outlier. Also, a multicycle channel belt at Coalsnaughton Main and Alloa Splint horizons (Westphalian A, Central Scottish coalfield) is oriented NNW-SSE almost normal to the Ochil Fault in its hangingwall, and <2km to it (see Chapter 9). This feature continues several kilometres to the S and SE, suggesting that the depositional area extended across this large and long-lived structure which bounds the preserved coalfield. Coal seam splits often show no particular relation to geometries of the remnant synclines or their depositional precursor sub-basins, again implying an originally greater extent of the depositional area. Sandstone proportions also aid interpretation in Scotland. Sandstone is more prominent in the eastern fields than in Ayrshire, showing various similarities with the Northeast coalfield of England; Ayrshire and other western fields may be compared with Canonbie and the Solway Basin/West Cumberland.

2.5.2 Northern England

The work by Land (1974), Fielding (1982, 1984a, b, 1986) and others in the Northeast, and by Jones (1992) in West Cumberland suggests that different channel orientations characterised these two coalfields, although they were part of one depositional area. These orientations are from the SW/W/NW in West Cumberland, and from the N/NE/E in the Northeast. Minor branches may have extended across the intervening area, for example the E-W oriented washout of the Craignook seam (Westphalian A) in the Midgeholme outlier lies roughly halfway between the two main coalfields. The N/NE source for the Northeast field conforms to existing models for a main flow from FennoScandia; indeed it is partly data from the Northeast that have led to this trend being extrapolated south across the Pennine Basin in the existing literature. However a different source area is implied by the West Cumberland directions of Jones (1992).

2.5.3 Pennine Basin

Eastern Pennine Basin (Figs. 2.4, 2.5, 2.6, 2.7).The axes shown on Figures 2.4 and 2.5 for orientation are chosen not for their place in the depositional hierarchy, but because their lengths are particularly well-mapped; a considerable range of channel importances is therefore shown. Mapped channels for which direction is unknown and for which mapping is less well-constrained are included, together with the better records, collectively in Figures 2.6 and 2.7; here, a variety of orientations is obvious, but the principal trends from Figures 2.4 and 2.5 are well represented.

Apart from the lower Westphalian A, the only common and well-documented directions are in the eastern part of the basin where, with only one exception, flow is recorded either from the SW or the W. The exception is a mid-Westphalian B sandstone in Nottinghamshire/Derbyshire lying at the horizon of the Woolley Edge Rock, and annotated 9A on Figure 2.5. This is a coarse feldspathic sandstone in the roof of the Main Bright coal, a horizon which commonly contains evidence for penecontemporaneous deformation, considered by Shirley (1955) to be seismically induced; prominent crevassing, especially at a slightly lower horizon (i.e. contemporaneous with the Main Bright coal) may imply the same triggering mechanism. Taken together, these observations suggest a specific source area event. The Crawshaw Sandstone (early Westphalian A) was reported by Guion & Fielding (1988) to be similarly coarse grained and from the NE.

Given channel orientation alone, it would be possible to deduce a continuation of the "FennoScandian" trend described for the Northeast coalfield. However, well-established SW to NE directions for some channels suggest that these represent the majority on that orientation. The overall W-E directions shown e.g. by the Silkstone Rock (Guion *et al.* 1995b) and its correlatives require flow across the depocentre, while the SW-NE directions necessitate flow obliquely across the basin's southeastern parts. No particular structural control is evident, beyond the observation that two major channel belts at Silkstone Rock and Parkgate Rock horizons (5B, 8A of Fig. 2.4) turn to occupy one segment of the Gainsborough Trough. This is not necessarily causal, given the wide range of orientations available, and the high-angle crossings of the similar Widmerpool Gulf at various horizons further south. Overall, a pronounced flow from the W and SW is indicated. This may have been preceded by centripetal flow into the main basin during lower Westphalian A times, including flow to the W along the Gainsborough Trough (Guion & Fielding 1988).

Western Pennine Basin (Fig. 2.8). Here, poorer data indicate trends compatible with the eastern area, inasmuch as a generalised flow across the depocentre, and also tangential to it from NW to SE, can be inferred. The only major sand body to have been regionally mapped is the Trencherbone Rock (Westphalian A, a possible correlative of the Silkstone Rock of the eastern area). Evidence from mineworkings and boreholes in Lancashire and in North Wales suggests two major inflow directions, one from the NW across Lancashire, and a second from the W across the northern margins of North Wales. Assuming this, the pronounced N-S orientations in North Wales (Wedd & King 1924; Wedd *et al.* 1928) may represent south-flowing branches from first-order channel belts, rather than flows north off the WBH.

Southern Pennine Basin (Fig. 2.9). The NW-SE and W-E orientations that may be interpreted from Figure 2.8 are perpetuated into the Stafford area where further data, largely from Barnsley (1964) indicate a slight swing more to WNW-ESE. East from Lichfield, this is assumed to change to generally W-E before the strong alignment from the SW is gained between Leicester and Nottingham. The large washouts of the Staffordshire and Warwickshire Thick seams (annotated 9 on Fig. 2.9) approach the WBH margin at high angles, entering salients defined by formation isopachs (Fulton & Williams 1988). In a similar manner to the North Wales washouts, these may either represent flows off the WBH or major branchings from a channel system lying further north. The latter interpretation is preferred: in the case of the Warwickshire Thick, a flow from the NW is supported by palaeocurrent assessments. Moreover, the WBH does not appear large enough to source channel features of these dimensions (see, e.g., the model for Westphalian C alluvial fans illustrated by Glover & O'Beirne (1994, figure 12). However, there is scope for further work on petrography that might characterise a WBH source. Structural control is evident, with the Thick coal washouts and implied embayments lying along inherited Caledonide trends parallelling the northwest and northeast margins of the Midland Microcraton (Corfield *et al.* 1996). For the overall

Pennine Basin therefore, gross palaeoflow from the W and NW is indicated; main sand body dimensions and mature compositions suggest source areas many 100's kilometres distant.

2.5.4 South Wales (Figs. 2.10, 2.11)

Directional data are only known from the earliest Westphalian A, i.e. the centripetal flow pattern of Bluck & Kelling (1963) and Kelling (1974), and the later Westphalian C/D southerly Variscan source of Bluck & Kelling (1963), Kelling (1974) and Jones (1989a, b), based largely on outcrops. However, the overwhelming subsurface evidence for the main coal-bearing sequence is for major channels to have entered the area from the SW along the basin-axial trend, and flowing to the NE across successively reducing basin-form isopachs. The alternative, that channels of a size compatible with the large and extensive washouts known within the coalfield, flowed from the NE away from the rather small and probably low-relief WBH along the Hereford Straits (Fig. 2.12), is unlikely. Prominent flow through South Wales from the SW would also be compatible with northerly-derived Bude and Bideford Formation sandstones in the Culm Basin: a first order system may be envisaged as having flowed towards both basins from the W, branching NE across the coal-forming plain in South Wales, and SE into the deeper Culm Basin. Perhaps such a major branch could reflect noding on a structural high on the line of the Cowbridge-Cardiff Axis, or possibly on an uplift in the development of the Bristol Channel thrust system (R.A.Gayer, pers. comm. 1996). This interpretation does not necessitate the "Bristol Channel Landmass" of previous authors (reviewed in Cope *et al.* 1992) nor the major strike slip movement suggested (Higgs 1986) to account for apparent palaeoflow inconsistencies between South Wales and the Culm Basin.

Channel orientations are unknown in the other coalfields south of the WBH; the succession in Kent does not appear very sandstone-rich, and a location distant from major channel belts is assumed. As with the Pennine Basin, the new analysis for South Wales indicates gross principal flow from the W. However, the apparently less mature sandstones may suggest a less distant source, or possibly a different source composition.

2.5.5 Flows across the Wales-Brabant High ?

The parallelism of the SW-NE channel axes of South Wales and some in the southern and southeastern Pennine Basin is striking (Figs. 2.9, 2.10, 2.11, 2.12). Further, both sets are aligned with the intervening Hereford Straits. Channel throughways from South Wales into the Pennine Basin are however, considered unlikely. Firstly, many of the South Wales sandstones in the discussed sequence are distinctive in their dark grey colour. Secondly, although channels crossing basin-form isopachs are common, it seems very unlikely that the South Wales channels, some of which show evidence of terminating within that basin, would have continued a further 100km northeastwards. Thirdly, there is evidence (Besly 1988; Glover & O'Beirne 1995) for red bed alluvial fans and local fluvial systems flowing into the Pennine Basin off the WBH, including some within the basinwards extension of the Hereford Straits. It is therefore concluded that terminating distributary branches from both South Wales and from the Pennine Basin invaded the Hereford Straits, and interdigitated there with locally-sourced alluvial red beds.

2.6 Palaeogeographical reconstruction

2.6.1 Palaeoflow provinces

Three palaeoflow provinces, together with inferred basin and highland geographies are illustrated by Figure 2.12. It is concluded that these three provinces operated across Great Britain from at least mid-Westphalian A times, after a possible earlier centripetal palaeoflow in the Pennine and South Wales Basins, or (alternatively) after Namurian patterns had retreated. These dominated the sedimentation, with subordinate contribution from local sources (e.g. the WBH). It is assumed from limited data in the Pennine Basin that the described patterns persisted there through Westphalian B, and some C, times. Suggestions on the basin fill implications that follow from this analysis are discussed later. It is appropriate firstly to consider wider palaeogeographies, particularly regarding source areas and the ultimate destinations of the distributary waters.

2.6.2 Source areas

Major inflow to the northern province, off FennoScandia and highlands to the north, is compatible with the published and mining data in terms of channel orientations, flow directions, and sediment maturity. A distant westerly source for the central province is much more speculative. Accurate palaeogeographical reconstructions across Ireland and further west are inhibited by the scattered Irish and offshore data, such that detailed discrimination of depositional areas, tectonic basins, and possible areas of non-deposition, such as the Galway-Mayo High (Cope *et al.* 1992) is difficult, although Mitchell & Owens (1990) defined a local northwesterly Westphalian margin in western Northern Ireland. Using the described British Westphalian as an analogy, an extensive "shelf-like" depositional area to the west may be inferred, with highs onlapped progressively.

Some pre-Atlantic reconstructions (e.g. Haszeldine & Russell 1987; Dore & Gage 1987) would place Carboniferous coalfields of northeastern North America within close proximity to upstream equivalents of the large and mature-grained sand bodies of the Pennine Basin. Channel directions across the Canadian Maritimes basins based on mining detail (Forgeron *et al.*1986, and references included) are frequently directed from the SW towards the British Isles, although most of these horizons are probably later than those described here. This overall direction has also been reported from outcrop studies by various authors, including Gibling *et al.* (1991) who described it as typical from the late Westphalian A to the early Permian, resulting from flow off the Appalachians northeastwards along the structural grain of the older Acadian highlands. Haszeldine (1984) and Haszeldine & Russell (1987) also suggested an intervening early Atlantic rift system, with lateral highs providing potential source areas, and inferring a flow off these towards Britain; the Appalachian sourcing is considered more likely. The existence of more southwesterly and possibly closer source areas for South Wales sandstones is speculative, requiring detailed analysis of Variscan geography between the British Isles and Iberia, and areas to the west.

Throughout the A to mid-C Westphalian, relatively small flows off the WBH and similar emergent areas interdigitated with the main incoming systems. In the southern province, earlier inflows from the developing Variscan highlands are a further potential source area, although these seem to have been minor through most of this period.

2.6.3 Palaeoflow destinations

Hitherto, the depocentres have themselves been envisaged as terminations for major channel belts, but given the evidence presented here this does not appear tenable. Further, consideration of flow destination inevitably requires discussion of marine shorelines. The coal-bearing depositional systems described here suggest that even large channel belt terminations were prograding into a non-marine environment, with the well-documented marine horizons being the products of extra-basinal events that introduced temporary environments and lithologies, essentially alien to the overall system. Areas where much of the Westphalian was always, or often, marine in a European context include parts of Iberia, the Boreal Ocean between Laurentia and FennoScandia, and east from the Ukraine (Haszeldine 1984; Wagner *et al.* 1979; Dore & Gage 1987). Marine band detail in some of the coalfields, suggesting marine invasions from differing directions, could reflect these various potential connections. However, the overall palaeontological evidence suggests that the most likely seaway into the British coalfields was through eastern Europe, with the foreland basins ahead of the Variscan nappe front aiding the westwards transfer of marine transgressions (N. Riley, pers. comm. 1996). For most of the sequence being discussed, the overall non-marine sediment dispersal system followed trends (across very low gradients) which may have operated somewhat independently of any varying marine invasion directions.

The gross W-E palaeoflow inferred for much of England and Wales indicates that any waters flowing across the Pennine Basin may have entered the southern North Sea area, interacting there with systems flowing from the N (e.g. Leeder 1988) and possibly from the S. However, "paralic" style settings comparable to the Pennine Basin extend east across northern central Europe without intervening contemporaneous marine basins. Widespread, essentially freshwater, environments with extensive mires dominated most of this area, and there would have been no clear-cut connection through to the very distant marine areas of Russia (Wagner *et al.* 1979).

2.7 Implications for the fill of the Pennine Basin

The Pennine Basin has been described here as a post-rift tectonic feature with regional palaeoflow largely across it, and with some channel outflows to the E and S away from the depocentre (Fig. 2.12). Figures 2.13 and 2.14 summarise varying depositional characteristics across the basin.

2.7.1 Depocentre

Just to the east of Manchester, the depositional thickness of the combined Westphalian A and B exceeds 2000m across a circular area about 30km in diameter. A distinction needs to be made between the fill characteristics of the Westphalian, when the Pennine Basin was at a late sag stage, and the more active earlier phases, when rapid basin subsidence may well have attracted centripetal flow as possibly in the lowest Westphalian A. The deposits of the Westphalian depocentre are now partially eroded, but some aspects of its fill can be deduced from channel, mire and lacustrine trends within the coalfields, and from analyses of sub-basins (e.g. the Gainsborough Trough). Coalfield evidence suggests that increasing fill thickness towards the depocentre comprised largely claystones and coals (Fig. 2.3), rather than sandstones; the main channel systems crossed or bypassed it.

2.7.2 Channel trajectories

Known channel orientations and locations, together with sandstone concentration patterns to the west of the depocentre, suggest that channel belts entering the Pennine Basin area were constrained within two main loci, one along the North Wales coast and another more from the northwest. These loci represent the "entrance zones" shown on Figures 2.13 and 2.14, although it is recognised that, where mapped, they are already within the Pennine Basin. The controls on these entrance zones were beyond the limits of the British coalfields, but they are assumed to reflect either upstream tectonics or palaeogeography. Channel trajectories across the main basinal area would have been partly pre-set by these loci, with trend diversity able to increase to the E and SE. Major branches that flowed directly across the depocentre crossed basin-form isopachs at a high angle, whereas those that passed the depocentre tangentially, and approached a basin margin obliquely, flowed subparallel to that margin for considerable distances. This strongly tangential system, leading to the prominent flows from the SW across the eastern basin, suggests that the NW-SE zone across Lancashire may have dominated, giving pre-set trajectories southeastwards towards Stafford with a swing on approaching the basin margin. The channel systems lost water and sediment within the central part of the basin, but some flow continued beyond, and it seems likely that there were also major sediment pathways here, notably the southwards breaches through the WBH, and zones to the east, including (at some horizons) the Gainsborough Trough; these are the "exit zones" of Figures 2.13 and 2.14. Inadequate data density to the east makes it difficult to know the extent to which the exit zones persisted through intervals spanning more than three cycles; however, locations are known where substantial proportions of the later A and earlier B Westphalian are composite sand bodies. Interestingly, Read (1989) essentially described entrance and exit zones, with tangential flow past the depocentre, for channels in the Namurian Kincardine Basin, although the scale is much smaller.

2.7.3 Sandstone concentrations

Within the entrance and exit zones, sand bodies may coalesce, with a significant proportion of the succession represented by multi-storey sand bodies, or by crossing/eroding channel belts. A condensed sandy channel succession would be generated by continued channel bed erosion. In such zones, sandstone connectivity is high. Further, several first order channel belts show wide areal extents (see Fig. 2.14) towards their exit zones. Elliott (1968) showed the Tupton Rock (Westphalian A) was a SW to NE flowing channel belt around 4km across near Nottingham, widening downstream to the NE. Recent re-mapping shows that the lateral spread of sandstone is nearly 30km wide further to the north and northeast, with one preferred exit to the NE. This laterally extensive sand may represent a distributive delta system, as suggested by large areas of channel and rippled sandstones, known from mineworkings. The Silkstone Rock (Westphalian A) near Sheffield, recently mapped by Guion *et al.* (1995b) has a width near its outcrop of around 15 kilometres, and may well represent a similar feature. Such patterns of sand dispersal appear to lie where the regional palaeoslope conflicts with the local subsidence slope of the Pennine Basin's eastern side (Fig. 2.13) giving downstream slope reductions. In general, sand bodies are fairly evenly spread, in terms of hierarchy, stratigraphy, and geography, in the central areas of the basin, and concentrated only in the entrance and exit zones.

2.7.4 Erosion features

Erosion, notably of coal, is more common away from the depocentre. For example, there are significantly fewer washouts in the thicker Lancashire sequence when compared with Nottinghamshire. Erosion at channel bases will in any case cut further down within a given stratigraphical interval where the sequence is condensed, especially with channel bed erosion limiting cumulative sand thickness. Hence individually thick sandstones may be expected in the basin centre where subsidence (due both to thermal subsidence, and compaction of thicker underlying coals and mudstones) keeps pace with sand deposition. The thicker composite sand bodies towards the entrance or exit zones will tend to be multicyclic features in which persistent channel bed erosion was particularly significant.

2.7.5 Bathymetry

The bathymetry of the basin during marine and non-marine periods may be considered briefly. During marine transgressions, especially of the Pennine Basin, bathymetry has been considered using macrofaunal evidence (Calver 1968) and magnitudes of glacio-eustatic sea-level changes (Maynard & Leeder 1992). However, actual bathymetries remain uncertain. Brand (1977) for example considered that the more fully-marine fauna of the Vanderbeckei (Queenslie) Marine Band in Scotland did not necessarily coincide with depocentres, and the converse (e.g. that the brackish *Lingula* phase can be found towards the Pennine Basin depocentre in the Vanderbeckei Marine Band) has been observed; of course, depth and salinity may not have been related. Some depth quantification for a minor marine flooding event, the Clowne Marine Band (Westphalian B) can be derived from the work of Rippon (1984) who showed that the near-marine, *Lingula*-bearing high-gamma, dark carbonaceous claystones were the lateral equivalent of around 0.2m of bituminous coal (i.e. the compacted equivalent of some 3m of peat). In this example, in which the marine shoreline across northeast Derbyshire has been mapped to the detail of 10's and 100's metres, it is unlikely that overall water depths were much more than 5m. Minimal gradients are implied by widespread marine floodings at other horizons.

There was probably also a minimal difference in elevation across the main parts of the basin during non-marine times. Lacustrine lithofacies do not appear to be significantly different when traced using borehole detail across the eastern Pennine Basin, nor do they show any significant changes in the analogous preserved sub-basins, other than greater thickness representing enhanced subsidence. A minimum water depth of 5m is probably needed for the grey lacustrine claystones to have remained below oxidation level. Elliott (1985) considered that typical levee heights were 7m above their surroundings in the coal-bearing Westphalian.

2.8 Conclusions

The Westphalian depositional area across the British Isles is considered to have been much more extensive than the present coalfields, and the various tectonic depocentres were discrete features within it. Overall channel flow into the area appears to have been in three provinces, with flows from the N/NE in northeast England and eastern Scotland, from the W in the Pennine Basin, and also from the W in southwestern Britain, branching to the NE across South Wales, and to the SE into the Culm Basin. A new model is described for the Westphalian fill of the Pennine Basin (with parallels for South Wales) in which sand bodies are largely incidental to the claystone-dominated tectonic depocentre and in which channel trajectories, longevities, and sandstone connectivity characteristics are determined by their particular basin setting. Sand dispersal patterns are notably affected where gross palaeoslope, considered to have been W to E across the Pennine Basin area, was in local conflict with the subsidence pattern. Some questions on palaeogeography and basin fill are raised here, as well as answered. However, this study of Westphalian sequences, regionally based but using very detailed data, may have relevance to other basin settings.

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2.10 Figure captions

Figure 2.1 Location of the Westphalian coalfields. The Culm Basin is marginally coal-bearing.

Figure 2.2 Stratigraphical summary of the coal-bearing Westphalian A-C, with North Sea stratigraphy for comparison. Named coal horizons are from the eastern Pennine Basin.

Figure 2.3 Some basin fill relationships. **(a)** Schematic map showing a hierarchical channel system with progressive downstream branchings through time. The 1st. order multicyclic channel belt has a persistent locus in the W, dispersing water and sediment eastwards, with the 5th. order single cycle channels showing a gradual northwards migration with time. Low order channels are frequently mapped for mining purposes. Sandstone B is contemporary with a coal, and an idealised seam split is shown for this horizon. **(b)** Schematic section showing progressive basinwards coal splitting. Regionally, coals tend to thicken individually into the basin, reflecting increased subsidence. Thinning towards the margin is accompanied by seam unions, giving thick composite coals which themselves pass laterally into palaeosols. The number of cycles in the eastern Pennine Basin correlates with total succession thickness (Duff & Walton 1964).

Figure 2.4 Westphalian A channel orientations, eastern Pennine Basin. Horizon 1A data from Chisholm (1990); 7 = Tupton Rock just west of Nottingham, from Elliott (1968); flow direction of 10, above Deep Hard around E.442 N.350, from Guion *et al.* (1995c). For channel axis selection, see text. By mid-A, the typical Westphalian pattern of flow from the W or SW was well-established; the inherited sub-basins had little influence on channel trajectories with the occasional exception of the Gainsborough Trough. Correlation details not shown.

Figure 2.5 Westphalian B and early C channel orientations, eastern Pennine Basin. Horizon 6 = High Hazles, just east of Nottingham, directional data from Guion (1987a); 11 = Oaks Rock, directional data from Mc.Mahon (1990). For channel axis selection, see text. The overall flow pattern from the W and SW continued through from Westphalian A, with the SW trend becoming dominant at many horizons. Correlation details not shown.

Figure 2.6 Channel orientations, northeast Derbyshire. The roses incorporate data from all well-constrained channel mapping undertaken for mining purposes, and include the axes shown in Figures 2.4 & 2.5. To cater for short mapped lengths and sinuosities, channel axis orientations have been counted by 1km lengths. Only dominant trends are significant to a regional study.

Figure 2.7 Channel orientations, southern Nottinghamshire. See caption for Figure 2.6.

Figure 2.8 Westphalian A-C channel orientations, western Pennine Basin. Horizon 2 data from Chisholm (1990); horizon 5 = Bullhurst, near Stoke, from Elliott (1970). Some North Wales correlations are uncertain. For selection of channel axes, see text. There are few good records of washouts in the western Pennine Basin, see text and Figure 2.14; the generalised extent of the Trencherbone Rock is specifically mapped here because of this deficit. The poor data, compared with the eastern Pennine Basin, suggest a NW-SE trend from Preston towards the depocentre. Consideration of areas of massed sandstones (known from deep mining data along the North Wales coast) together with areas with very few (known from exploration boreholes) suggests a corridor of channels extending W-E either just south of Liverpool, or just south of Chester; the latter interpretation is preferred. See text for discussion. Correlation details not shown.

Figure 2.9 Westphalian A and B channel orientations, southern Pennine Basin. Horizon 1 data from Chisholm (1990); data between Stafford and Lichfield largely from Barnsley (1964); 5 = Smoile south of Derby from Jones *et al.* (1995); directional data at horizon 9 = Warwickshire Thick, from P.D. Guion & I. M. Fulton (pers. comm. 1986); see also Figures 2.4 & 2.5. The limited information suggests a prominent flow tangentially around the southerly basin margin, with most channels adopting the prominent SW to NE direction on entering the eastern Pennine Basin near Nottingham, while others (especially at horizon 9) branch S into salients in the Wales-Brabant High. Correlation details not shown.

Figure 2.10 Later Westphalian A channel orientations, South Wales. Channel axes from mining data, including NCB (1962). The linear seam split axes, derived from Parry (1966), represent channels invading contemporary mires; the channels themselves have not been mapped, and the axes shown here are therefore an approximation based on the mid points between sub-parallel seam splits. The orientations of Bluck & Kelling (1963) are all below the horizons mapped here, and their centripetal flow was superseded by the late Westphalian A by a dominant SW-NE flow across the coalfield's basin-form isopachs, sub-parallel to the Neath Disturbance and the Usk Axis. Correlation details not shown: the channels lie at varying horizons within annotated intervals.

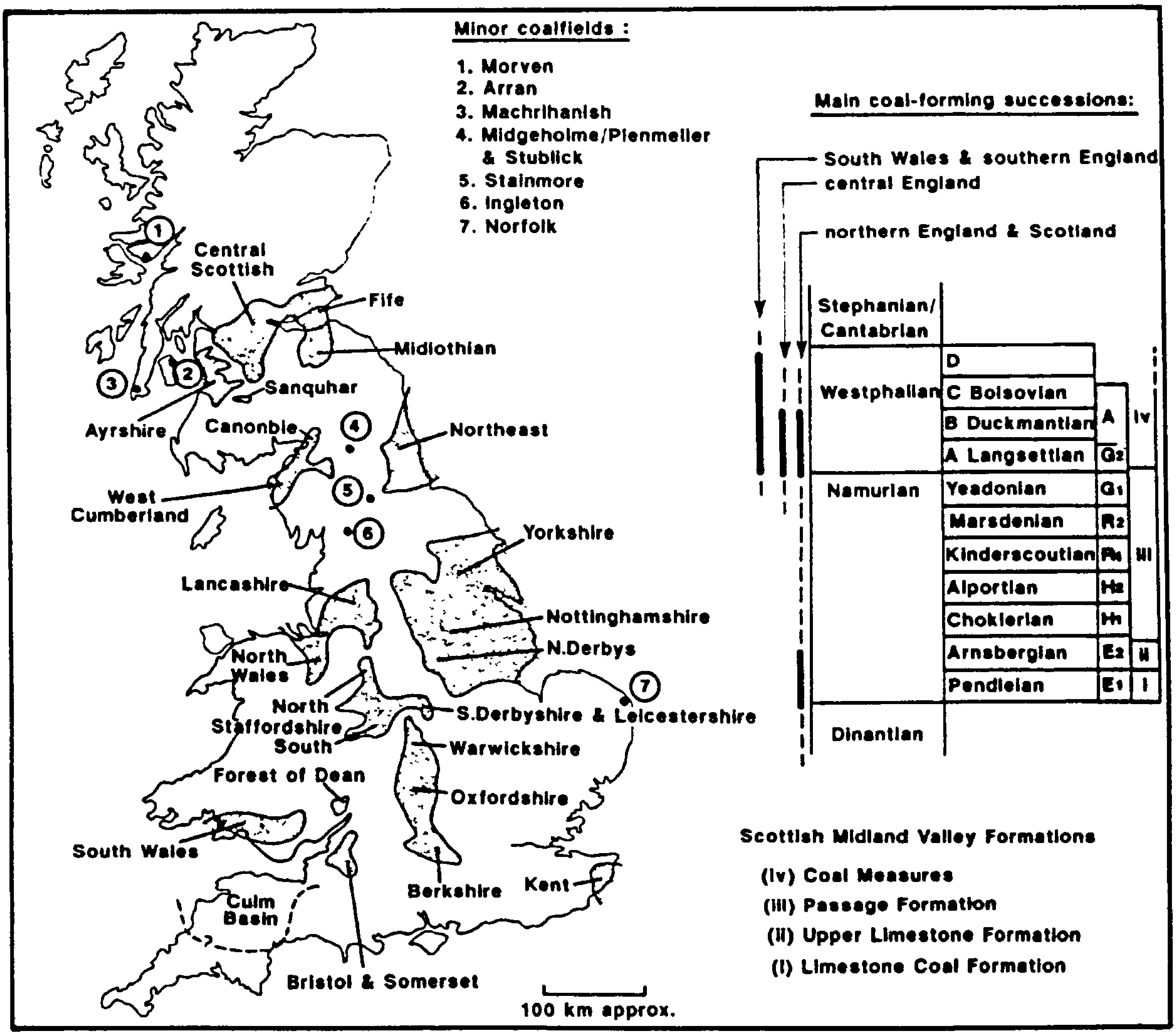
Figure 2.11 Westphalian B channel orientations, South Wales. Channel axes from mining data, including NCB (1959c). Parry's (1966) data: see Figure 2.10 caption. The overall SW-NE orientation continues through from Westphalian B patterns.

Figure 2.12 Generalised Westphalian A/B palaeogeography, showing principal inflow directions schematically; local flows off the Wales-Brabant High and other uplands not shown. The three provinces are defined by main inflow directions and sandstone character.

Figure 2.13 Depositional model for the post-rift Pennine Basin. See text and Figure 2.14.

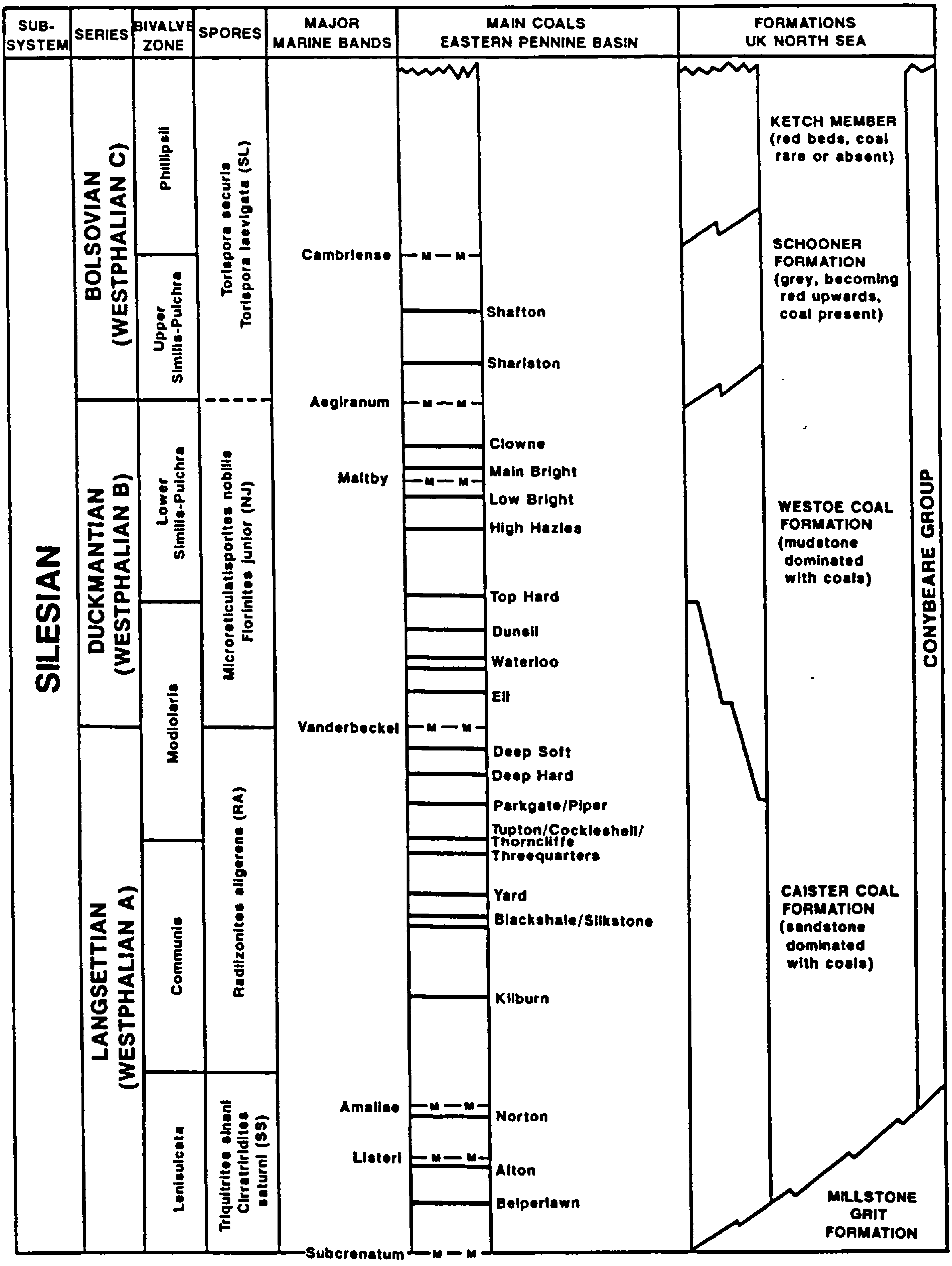
(a) Summary map showing the development of differing sand body characteristics according to basin location. **(b)** Schematic section showing cross-basin relationships. Multicyclic sand bodies characterise entrance and exit zones, with low net sand deposition because of lesser subsidence and persistent channel bed erosion. By contrast, within the main part of the basin, net sand deposition is higher, with sand bodies achieving greater individual thicknesses. Main basin fill lithologies are claystones and coals. In the eastern part of the basin, flows are retarded where the gross regional slope is moderated by the basin subsidence pattern: slackening gradient encourages lateral dispersal of sand, and termination of some channel belts in large lacustrine deltas. The exit zones are preferred loci for some channels that persist beyond these areas.

Figure 2.14 Depositional model for the Westphalian post-rift Pennine Basin: a summary of the main variations shown schematically in Figure 2.13. Basin fill characteristics vary considerably according to location, but, on the basin scale, may be organised as shown here. Inflow/outflow margins: basin margins that are crossed at high angles by the regional palaeoflow; a standard basin margin lies lateral to the gross palaeoslope. Entrance and exit zones: corridors with main inflow and outflow channels, possibly reflecting some structural control; the adjacent passive areas attract few channels. Auto-erosion: continued erosion of the channel's own bed.



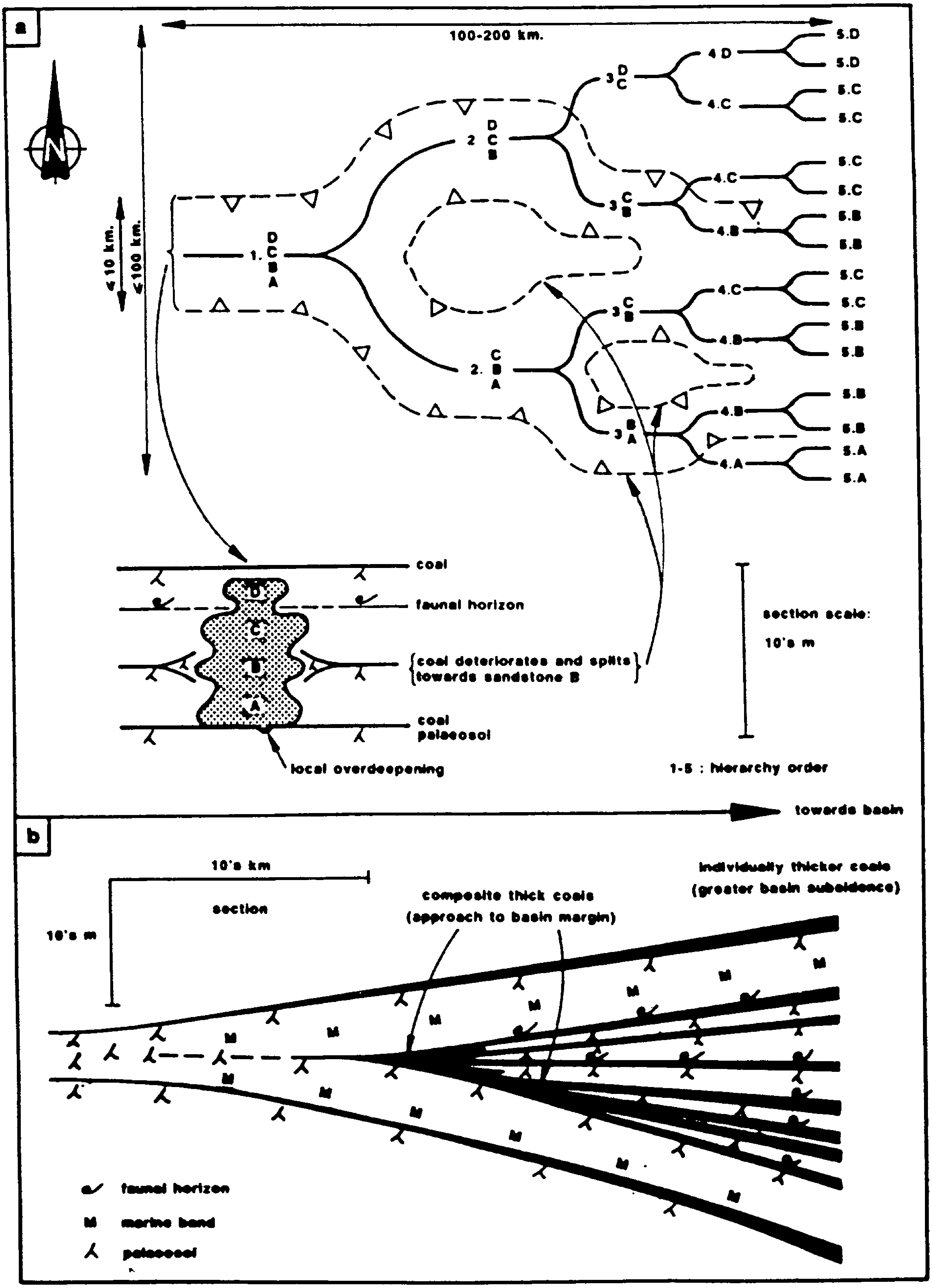
Location and stratigraphical summary of the Upper Carboniferous coalfields

Fig.2.1



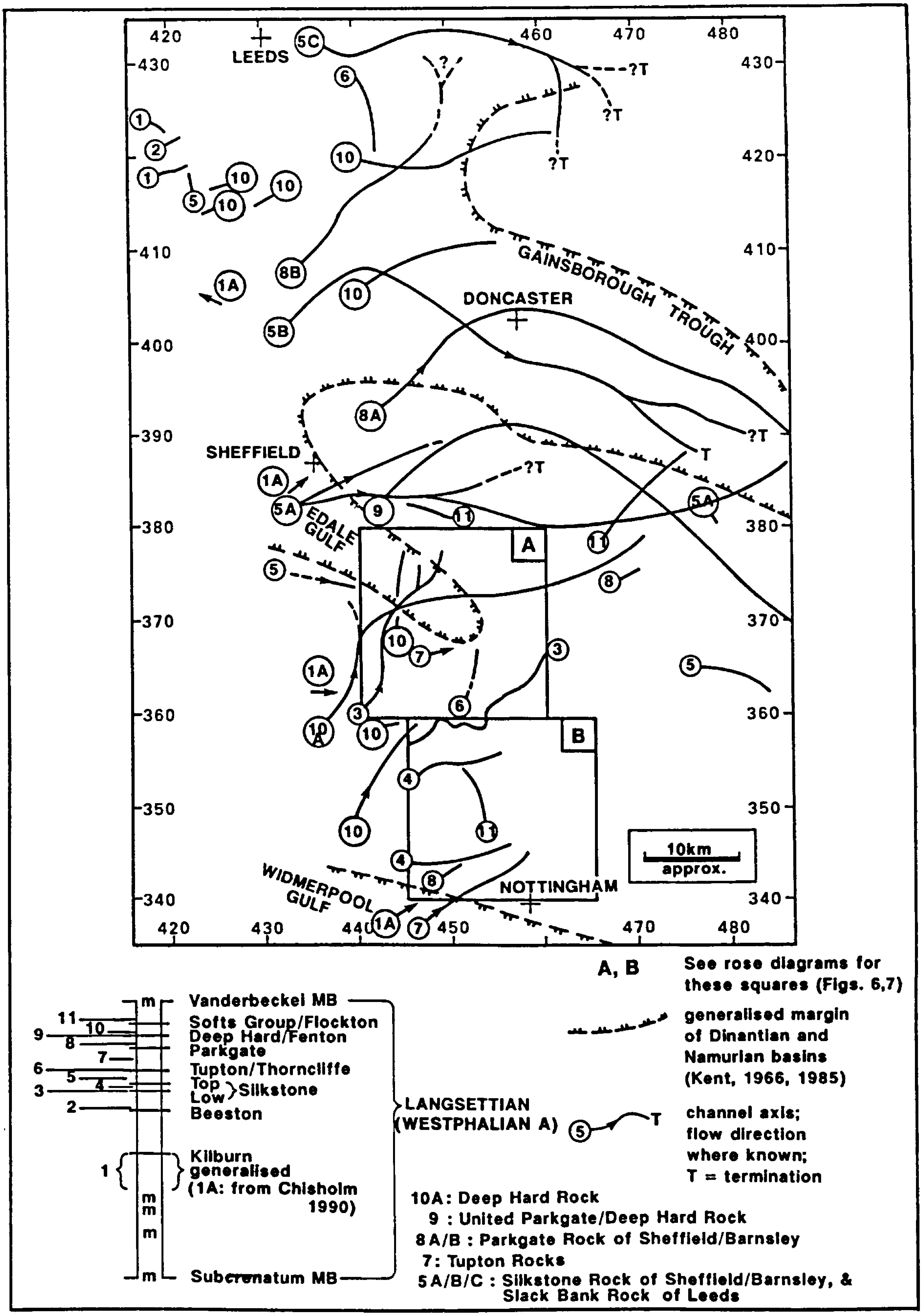
STRATIGRAPHICAL SUMMARY OF THE UK COAL-BEARING WESTPHALIAN A-C

Fig. 2.2



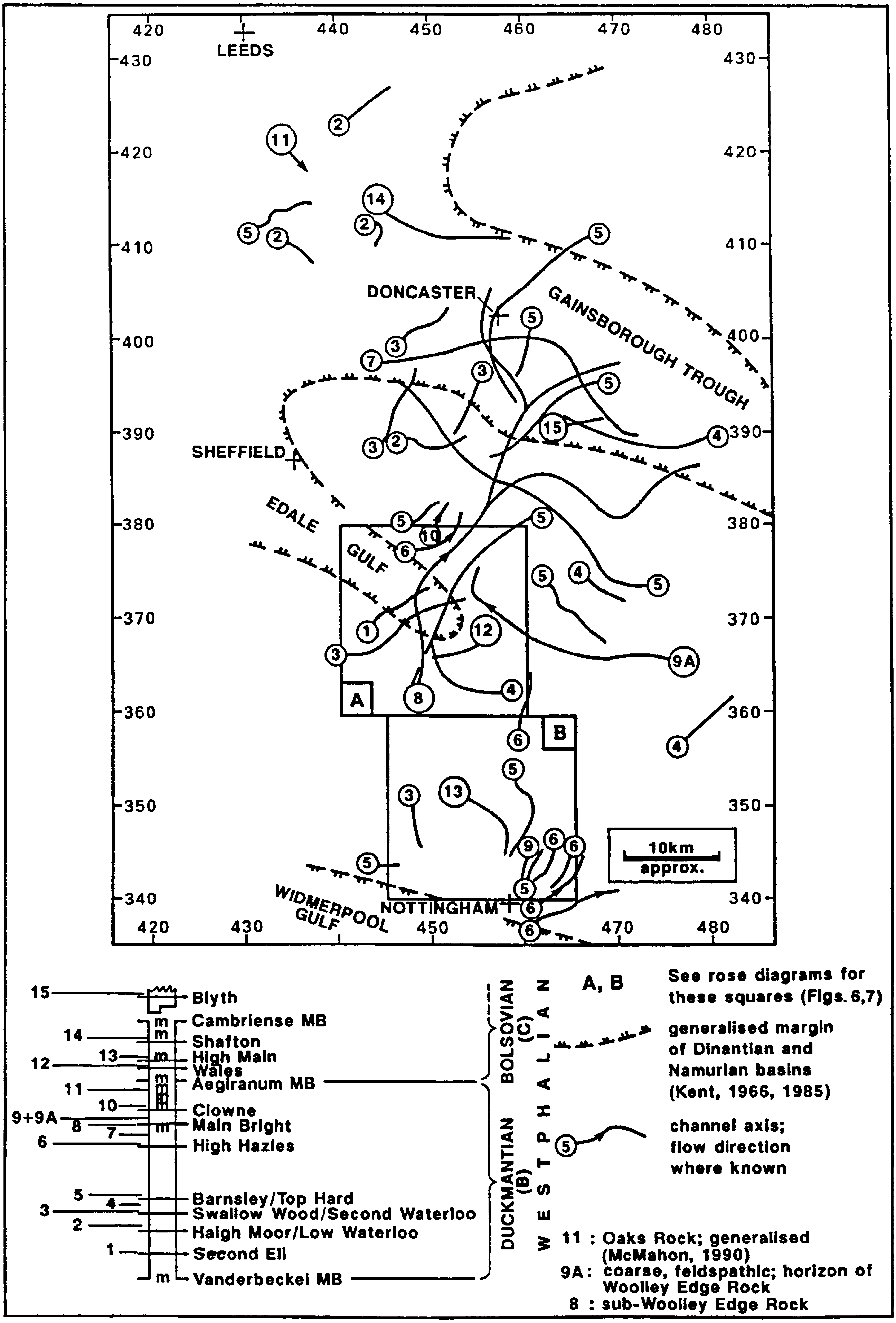
WESTPHALIAN A-C DEPOSITION : SOME BASIN - FILL RELATIONSHIPS

Fig.2.3



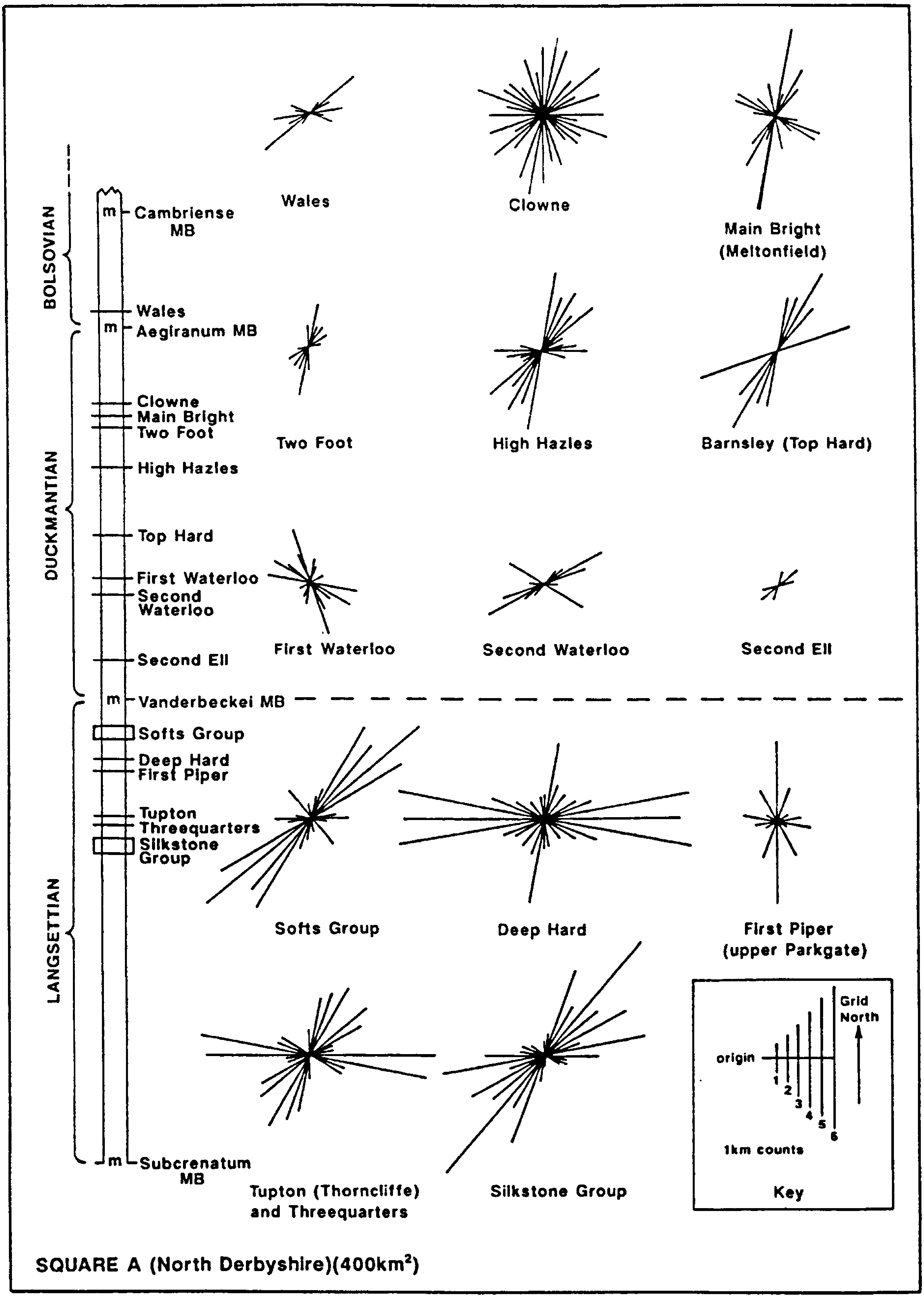
WESTPHALIAN A CHANNEL ORIENTATIONS, EASTERN PENNINE BASIN

Fig.2.4



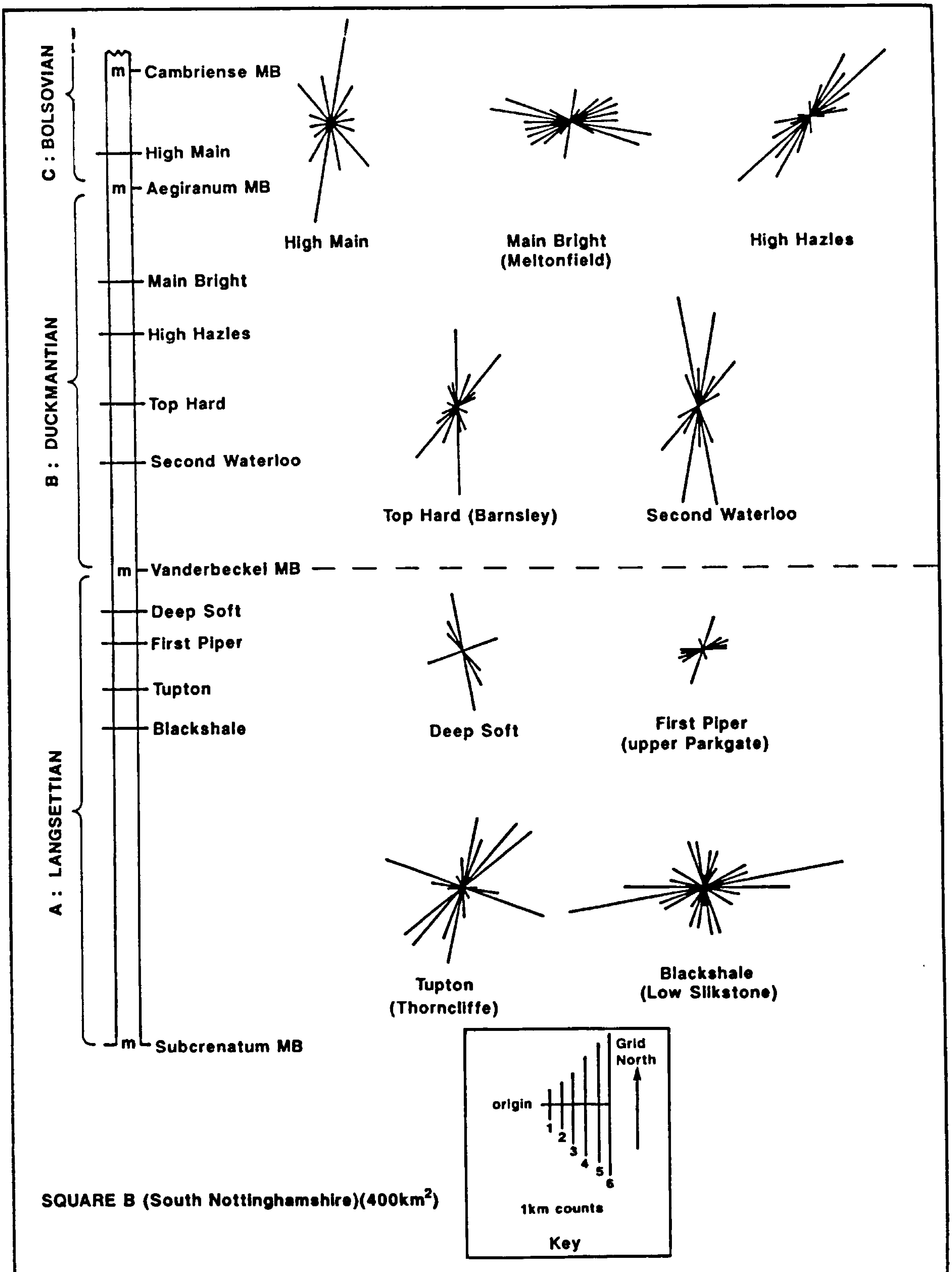
WESTPHALIAN B to mid-C CHANNEL ORIENTATIONS, EASTERN PENNINE BASIN

Fig.2.5



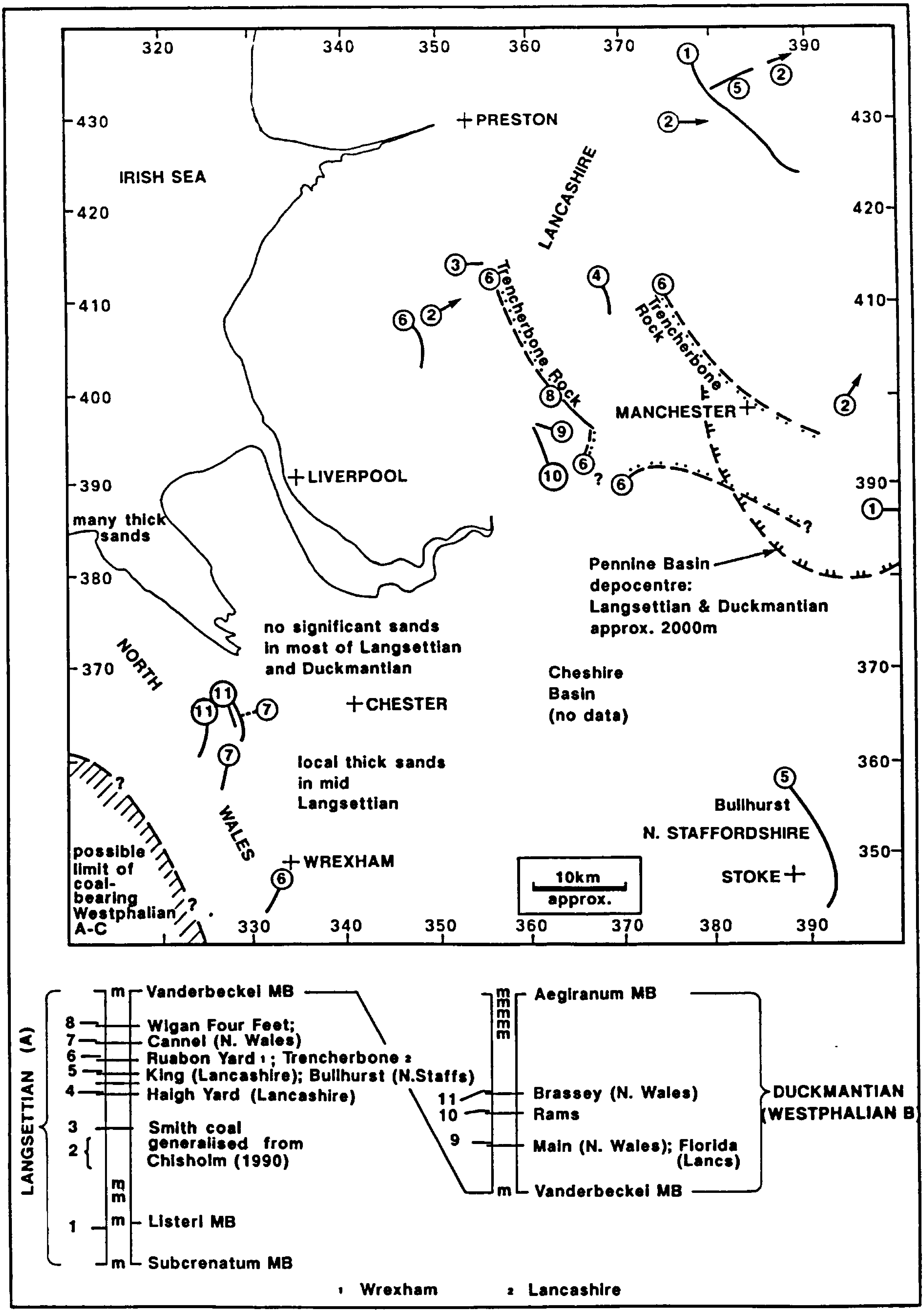
SQUARE A (North Derbyshire)(400km^2)

Fig. 2.6



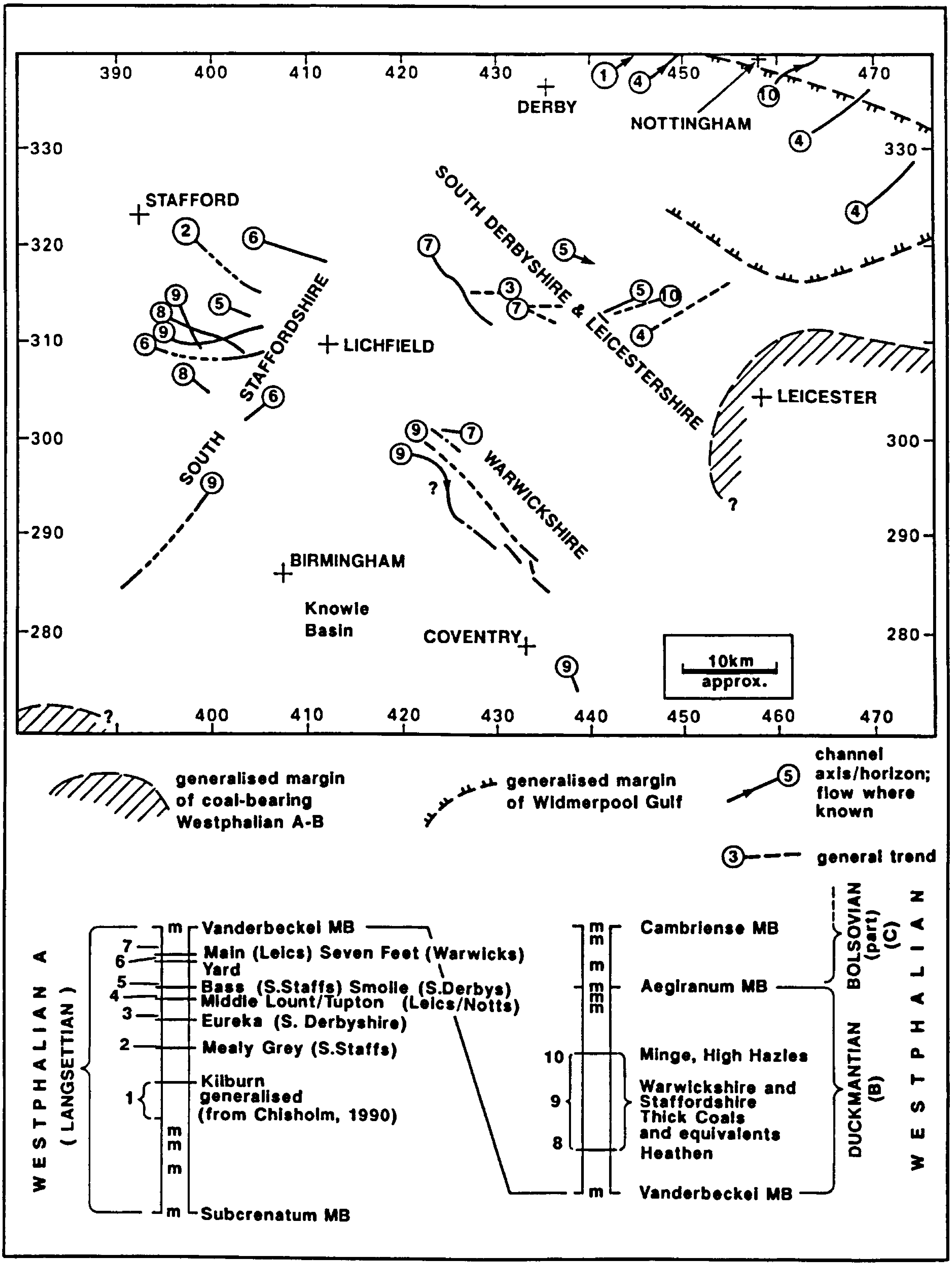
WESTPHALIAN CHANNEL ORIENTATIONS, SOUTH NOTTINGHAMSHIRE

Fig.2.7



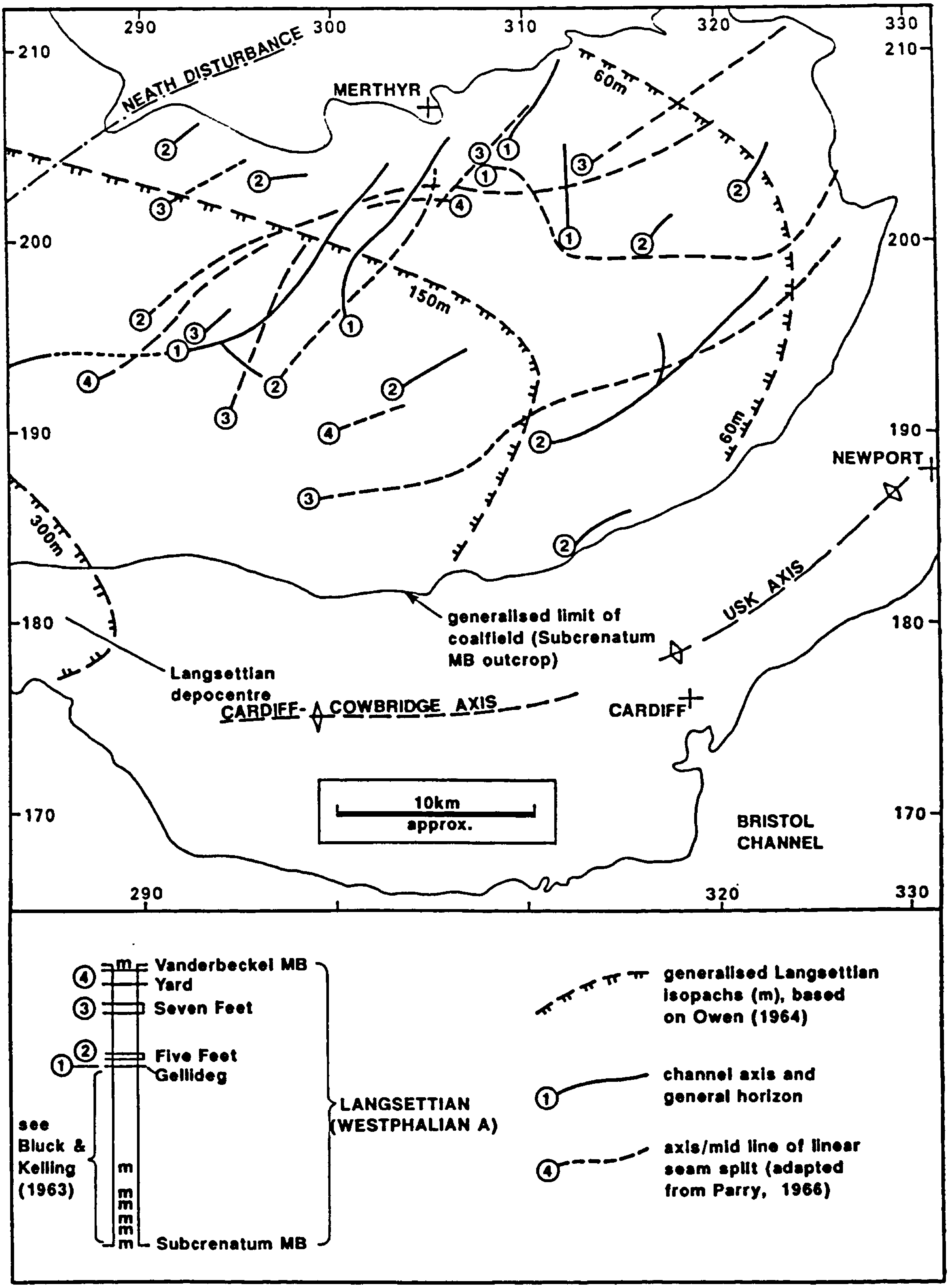
WESTPHALIAN A-C CHANNEL ORIENTATIONS, WESTERN PENNINE BASIN

Fig.2.8



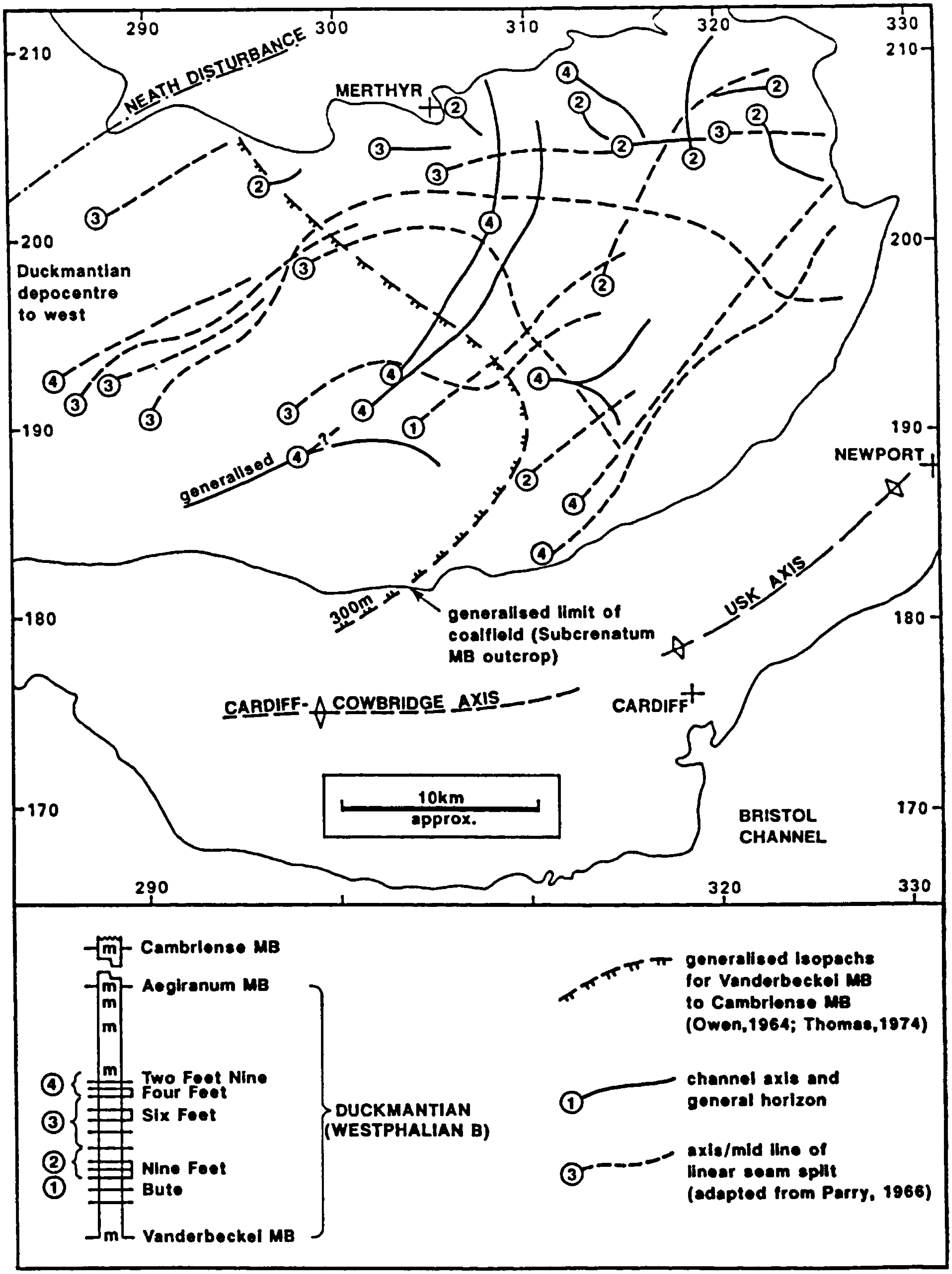
WESTPHALIAN A AND B CHANNEL ORIENTATIONS, SOUTHERN PENNINE BASIN

Fig.2.9



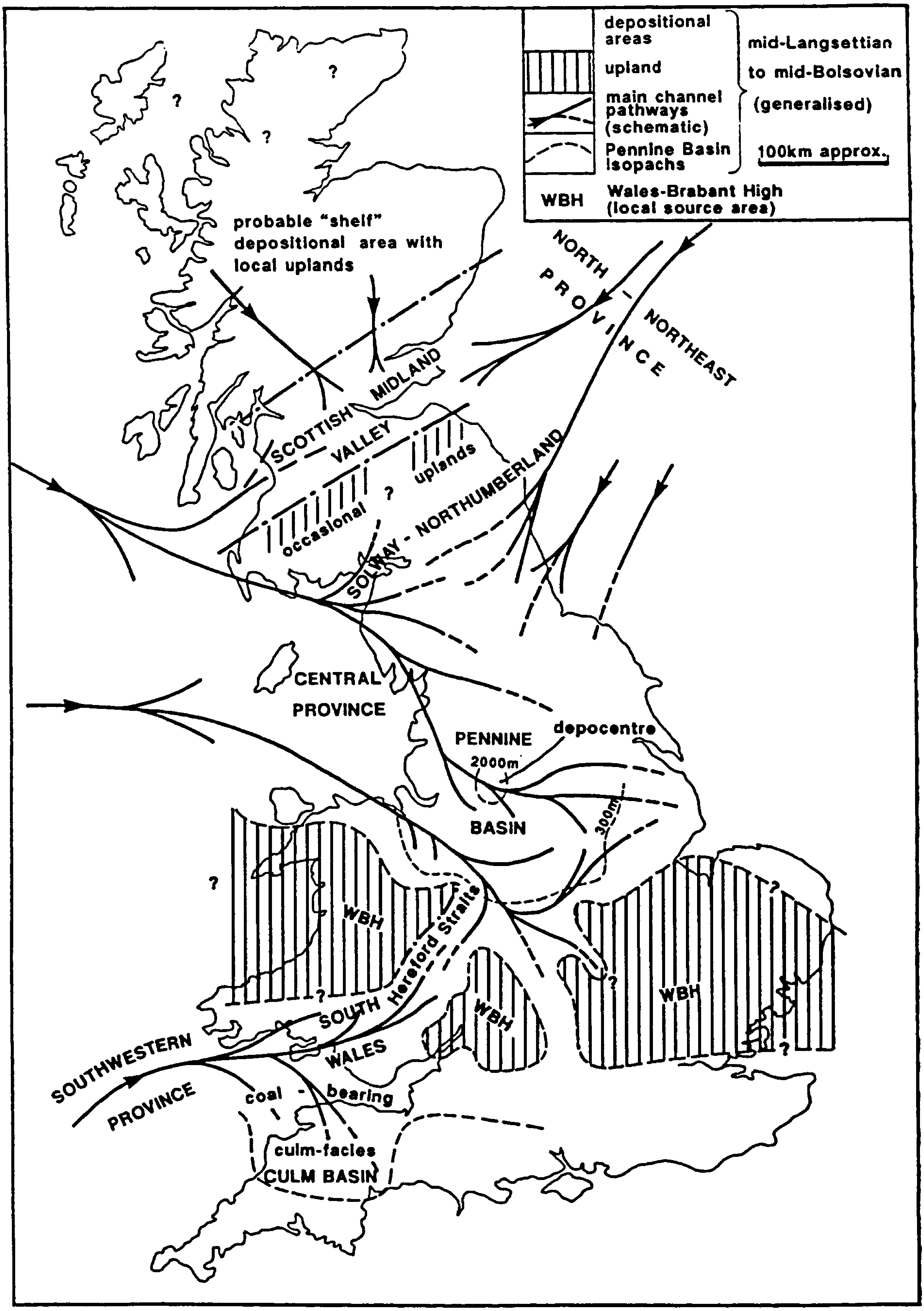
WESTPHALIAN A CHANNEL ORIENTATIONS, SOUTH WALES

Fig.2.10



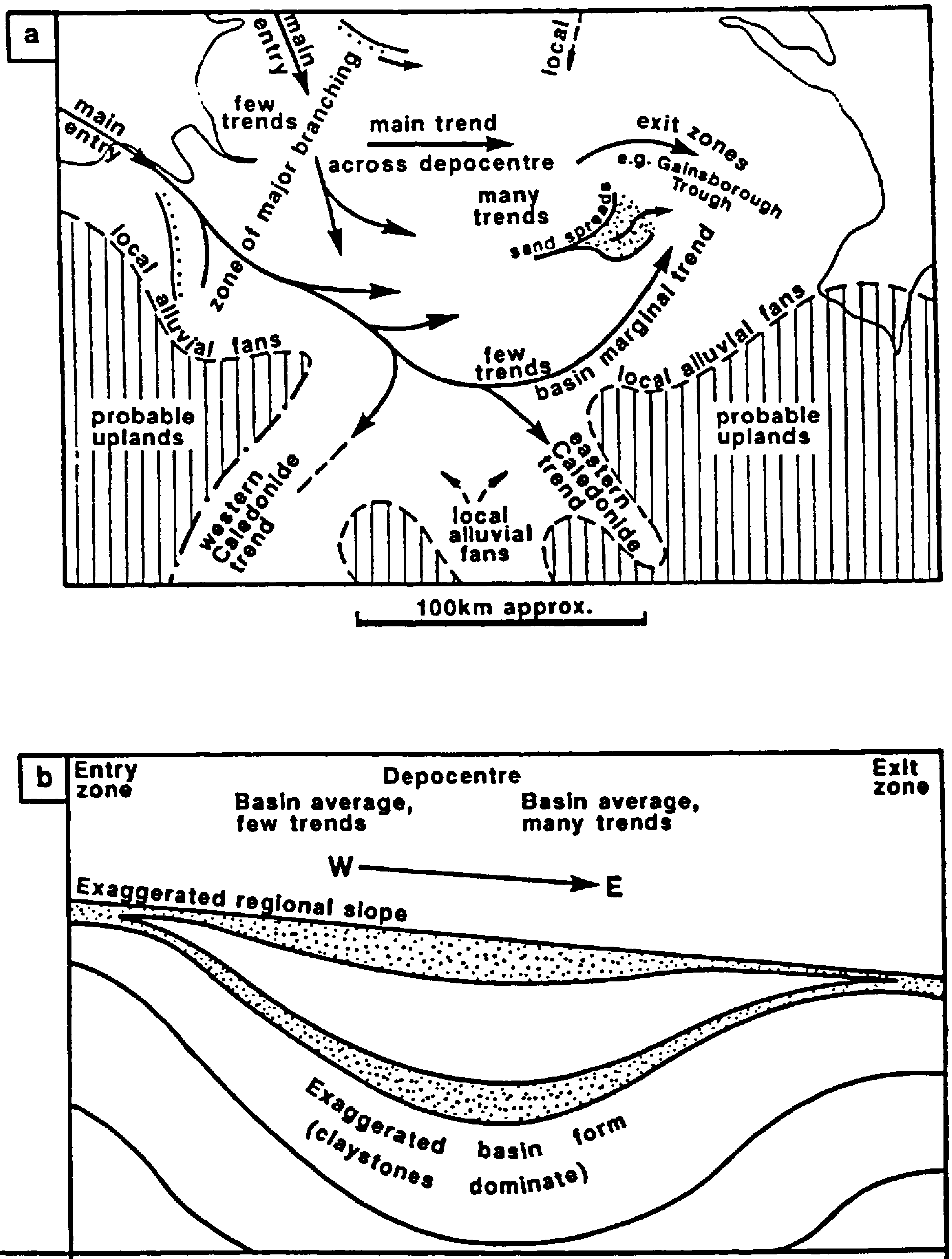
WESTPHALIAN B CHANNEL ORIENTATIONS, SOUTH WALES

Fig.2.11



GENERALISED WESTPHALIAN A-MID C PALAEOGOEGRAPHY OF GREAT BRITAIN

Fig.2.12



Slope	regional	regional plus basin subsidence		regional minus basin subsidence	regional
net sand deposition	very low		relatively high		very low
Sand body character	thicker, composite sands	thinner	thicker, individual sands	thinner, wide spreads of sand (slackening gradient)	thicker, composite sands

A DEPOSITIONAL MODEL FOR THE MID-A TO MID-C WESTPHALIAN OF THE PENNINE BASIN

Fig.2.13

	INFLOW MARGIN		MAIN PARTS OF TECTONIC BASIN			OUTFLOW MARGIN		STANDARD BASIN MARGIN		
	1. Passive areas	*2.* Entrance zones	*3.* Inflow-side average	*4.* Depocentre	*5.* Outflow-side average	*6.* Exit zones	*7.* Passive areas	*8.* Approach zone (coal-bearing)	*9.* Passive areas	*10.* Alluvial fan etc.
A. Formation isopachs (regional)	may reflect local structure	modified by major channel activities	essentially tectonic basin form; regional subsidence masking local structural and depositional controls			modified by major channel activities and local structure	may reflect local structure	modified by compaction of thick coals, and local structure	may reflect local structure	local patterns only
B. Formation sand %	< 20	locally > 50	20 - 30	20 - 30	20 - 30	locally > 50	< 20	very variable		high
C. Major sand body orientations	minor channels only	constrained (one quadrant) →	diverging (two quadrants) →	many trends	many trends with major sand spreads	constrained by local structure and basin margin	minor channels only	sub-parallel to local basin margin	local trends	
D. Channel erosions	very local	common erosion of coals; common auto-erosion	some erosion of coals; main erosions in overlying (thicker) claystones			common erosion of coals; common auto-erosion	very local	local erosion of coals in condensed sequence	local features	
E. Suspension sediments	claystones generally silty; the dominant lithology	claystones silty; a subordinate lithology	claystones are the dominant lithology thickening →	maximum thickness	thickening ←	claystones (silty) are a subordinate lithology	claystones (generally not silty) are a dominant lithology	claystones (generally not silty) are the dominant lithology		claystones very subordinate
F. Coals	very varied thickness and splitting patterns		thickening →	maximum thickness	thickening ←	very varied thickness and splitting patterns		condensed sequence with coal seam unions	hinterland:- grade into thick palaeosols	local, not often preserved
G. Emergence (oxidation zone)	local		very rare			local		more frequent	common	typical

DEPOSITIONAL MODEL FOR THE MID-A TO MID-C WESTPHALIAN PENNINE BASIN : SUMMARY OF MAIN VARIATION

Figure 2.14

CHAPTER 3

CONCEPTUAL MODELLING OF BRITISH WESTPHALIAN COAL-BEARING SUCCESSIONS

Abstract: *Paralic coal-bearing successions have long been modelled in attempts to rationalise intricate geological patterns, and to serve as tools for coal and, more recently, hydrocarbon appraisals. Models for clastic lithofacies distributions have been used since the 1960's; more recently, there have been attempts to introduce sequence stratigraphical models. This chapter reviews all these, following new basin fill interpretations, and proposes a complex model (particularly for the Pennine Basin), integrating external controls with basin subsidence.*

3.1 Background

The Westphalian of Great Britain is mainly coal-bearing, and the preserved coalfields are found in various tectonic settings (Chapter 6). Most Scottish fields lie within the Midland Valley, initiated as a Devonian rift, and those of central England occupy the Pennine Basin, a large extensional province with rifting through the Dinantian and earlier Namurian. Westphalian A to mid-C sedimentation in these is mainly post-rift (Chapter 2); intervening more stable areas were in depositional continuity with the basins. These northern areas were separated from the immediate Variscan foreland province of South Wales and southern England by the contemporary uplands of the Wales-Brabant High, which were overstepped by Westphalian C/D formations. A review of the depositional setting of the main coalfields is given by Rippon (1996), who interpreted three dominant mid-A to mid-C Westphalian inflow regimes (Fig. 3.1 and Chapter 2). Despite differing settings, the stratigraphical groupings of coals (and occasional marine invasions) are similar across all coalfields, indicating some external controls on the development and preservation of mires which were long-lived, and sensitive to water table change (Chapter 5). Depositionally "passive" mire and lacustrine environments represented a continuum across which the channel belts imposed local variations, and the resulting interactions produced the very intricate depositional patterns that are so characteristic of these sequences.

Apart from mining interest, coalfield data have analogue value for hydrocarbon reservoir descriptions of fluvial sandstones, including Carboniferous sand bodies of the Southern North Sea.

Excellent data sets allow regional mapping at many horizons. However, to progress from coalfield mapping to conceptual, and thence perhaps to numerical modelling, data details must be honoured, and the conceptual model must be compatible with the tectonic setting. This account provides initial guidelines for valid modelling of the British Westphalian itself, especially for the Pennine Basin. The term "basin" is used here only in the context of a tectonic depocentre: overall depositional areas included more stable regions with inter-basin, "shelf-like" settings.

3.2 Depositional models; a brief review

Depositional models have been used to interpret the British Westphalian since the 1960's. Elliott (e.g.1970) developed a model for the Pennine Basin clastic rocks based on the Mississippi Delta. This is still used successfully for forecasting mining interceptions of channel-related disturbances. Regarding palaeoflows, most authors (e.g. Guion & Fielding 1988) inferred flow as essentially into depocentres, either on the basis of extrapolation from particular Westphalian data, or by assuming that Namurian trends continued; main flows into the Pennine Basin were assumed to be from FennoScandia, or from the east and south. These interpretations were compatible with only some mining detail. For discussion of these and other contributions, see Chapter 2, and Rippon (1996), who considered that most Pennine Basin inflows were from the west. The sedimentological interest in channel systems developed somewhat separately from work on other aspects of basin evolution, especially faunal compartmentalisation, coal development, and the construction of formation isopach maps. This partly reflected the differing interests of authors, but also pointed to fundamental problems in reconciling palaeoflow and sand body data with basin form, and with the uncertain geography of marine invasions. A key discussion on the importance of marine-related base level to the cyclicity of the coal-bearing sequences, and to the stratigraphical incidences of major coal groups and marine incursions was provided by Ramsbottom (1979).

In the 1990's, sequence stratigraphical interpretations have been proposed, notably by Hartley (1993) and Flint *et al.* (1995). These developed the views of, e.g., Ramsbottom (1979), suggesting alternative ways of interpreting the system, in which sea level change was the dominant control on depositional patterns, affecting sand body stacking patterns and regional coal thickness variations.

A coal-prone phase was seen as typical of a transgressive systems tract, leading to a maximum flooding surface, whereas large sand bodies occupied incised valleys as a result of sea level fall.

Simple sequence stratigraphical interpretations of the British Westphalian successions, particularly in the Pennine Basin, were considered inappropriate by Rippon (1996), as they did not cater for mining data, or mining-validated models; he considered that depocentres were incidental to channel pathways, but nonetheless significantly modified sand body attributes. In the Pennine Basin: 1, channel systems crossed the depocentre, or flowed past tangentially; 2, inflow and outflow loci were characterised by composite sandstones condensed by minimal basin subsidence and persistent channel bed erosion; 3, sandstones reached individual thickness maxima across the depocentre, where greater subsidence allowed higher net deposition; and 4, on the outflow (eastern) side of the basin, large lacustrine deltas developed where a slackening gradient may have resulted from interaction between the overall depositional slope and local basin subsidence. A hierarchical channel system was also described, in which channel longevity was important, as well as dimension; channel distribution within the main parts of the basin was largely uniform, both temporally and spatially. Figure 3.1 shows the general extents of the coalfields, together with the main inflow provinces of Rippon (1996).

3.3 Depositional controls: a discussion

The relative importance of allogenic and autogenic controls on coal-bearing successions has long been debated. However, combinations of controls will interact throughout a depositional system of the extent, and the duration, of the northern European Westphalian, especially where there are discrete depocentres. Some controls will be important throughout, others will be more localised. Table 3.1 summarises some differences between the various approaches, relevant to the Pennine Basin. The term "traditional" is used for pre-sequence stratigraphical interpretations, in which there were no unifying schemes that accomodated the main factors of basin subsidence control, externally-sourced sediment flux, or contemporary marine dispositions. The term "integrated" is used for the interpretations of Rippon (1996) as these factors are integrated in that account. The problems of applying a sequence stratigraphical interpretation to the Westphalian, particularly in the Pennine Basin (Flint *et al.* 1995; see Chapter 2) are as follows. 1. Sequence boundaries, evidenced by widespread contemporaneous erosion by major channels throughout a depositional area are not found. 2. Channel downcuttings are limited to over-deepenings; there are few or no significant interfluves (amplitudes, say, of >20m) within the main coal-bearing sequence. 3. Major sandstones are vertically stacked only in particular circumstances, and aggradational patterns are normal. 4. Most major channel belts prograded into fresh water, remote from marine influence. 5. There was no significant change in the number and disposition of large channel systems until mid-Westphalian C times. 6. Coal depositional patterns largely reflect basin subsidence. All this indicates that periodic sea level changes were not a major control on sand body dispositions, but a muted response may be interpreted from the stratigraphical groupings of the coals.

At this point, it is suitable briefly to note the Namurian coal-bearing sequences of Scotland, and particularly the Limestone Coal Formation (E_1), as this is as coal-rich as the Pennine Basin Westphalian, while also being much more marine-influenced (Chapter 1). Further, this formation is proved by a data density comparable to the best in the Pennine Basin coalfields, and has been extensively described by Read (e.g. 1995). In that paper, different distal (greater marine influence) and proximal (greater fluvial influence) depositional patterns were described; distal lithofacies associations were readily interpetable in sequence stratigraphical terms, whereas in proximal associations, fluvial processes tended to obscure background variations in sea level. Some comparisons between these Westphalian and Namurian successions (the latter entries provided by W.A. Read, pers. comm. 1997, mainly following Read 1995) are given in Table 3. 2.

3.4 Correlation considerations and data density requirements

Fundamental to all mapping, and therefore modelling, of fluvial systems is the degree to which regional correlation can be achieved. Coal industry data often allow correlation resolution better than that of the traditional cycle, the result of many decades of interdisciplinary work. Not only marine bands are widely correlated, but also many coals. Individual coalbeds are commonly mappable across areas up to 1000km^2, while correlation of coal groups is possible over greater areas, within and between basins, implying some external control.

It is beyond the scope of this account to detail the many coal correlation factors and techniques (Chapter 1; Fig. 1.5), but assuming that a researcher has detailed experience, coal correlation itself is relatively straightforward. Greater correlation difficulties are presented by channel sandstones, partly because they replace features of correlation value, and partly because some sandstones may lie at essentially the same stratigraphical level, although being of slightly different age. This is true both for the composite sandstones described for the inflow and outflow channel loci of Rippon (1996), where multicyclic sandstones may contribute to the same sand body, and also for basin-centre sandstones, where sandstones from one system may cross those of another. Criteria for assessing linkages between channel sandstones that lie at the same or similar horizons in more basin-central areas are summarised as: 1, the level of the regional sandstone base above the preceding marker horizon (usually a coal); 2, overall channel belt lithofacies and their distribution; 3, any petrographical characteristics; and 4, the implications of known palaeocurrent indicators and the overall spatial relationships of a distributary system.

Obviously, data density requirements for very detailed palaeoenvironmental mapping will be greater than those for more regional syntheses. Assuming that regional correlation is sufficiently established, it is possible to generalise the requirements for the chosen scale of investigation. The most detailed regional sedimentological mapping in the British coalfields is in the Westphalian A and B of the eastern Pennine Basin, where numerous channel lengths have been mapped for mining purposes. In general, these are smaller features, rather than major channel belts. Figure 3.2 defines a 400km^2 square within which channel patterns above fourteen different coals have been analysed for the robustness of their linkages. This necessarily subjective plot illustrates the high data density needed for unambiguous mapping of smaller channels. A simple up-scaling to an equivalent plot for the multicycle channel belts (widths up to about 15km) is not straightforward. Some major belts are known to have been very long-lived feeders for several generations of smaller channels: they probably need characterising separately, but there may be a simple numerical relationship that describes progressively smaller features. Figure 3.3 suggests data density requirements for varying widths within a hierarchical system, including the suggested 1 (cored) borehole/km^2 for definitive mapping of the small channels of Figure 3.2.

3.5 An integrated depositional model for the coal-bearing Westphalian

Following Rippon (1996), the combination of processes controlling the development of coals and claystones within a basin is considered to be different to that controlling sand body attributes. Cyclicity, and the relative thicknesses of coals, will depend partly on basin subsidence rates, and on any regionally important base level control, especially sea level change. By contrast, overall sediment influx will reflect many external controls.

External controls contributing to the depositional volumetrics of the Pennine Basin Westphalian may be summarised into: 1, sea level change (note that the distance to a contemporary marine bay line is relevant, as upstream migration of nick points may be significantly protracted); and 2, continental-scale contemporary geographical factors, particularly source area climate, general disposition of highlands, flow distances, etc., all of which contribute to channel pathway distribution, and to erosional and depositional capabilities on entry to the basin area. Internal controls will interact with these where there is an evolving tectonic depocentre, and are summarised as: 1, the phasing and varying subsidence rates of syn-rift and post-rift basin development; 2, the actual shape, size, and location of the basin with respect to major channel pathways (a sub-basin may conceivably not lie near these, and therefore be largely filled by claystones); 3, movement on specific structures (see Chapter 5); and 4, compaction. (Where a depositional area is "shelf-like", and there is no major depocentre, controls may be mainly external, with minor contribution from movement on specific active faults and from compaction.) Figure 3.4 illustrates these, as a graphic summary for an integrated model.

As noted, the sedimentary volume is a record of interaction between some essentially independent processes, summarised as: 1, continual, pervasive claystone and peat accumulation, largely reflecting basin subsidence; 2, continuous interruptions by channel belts which also provided the suspension sediment; and 3, rare marine invasions. However, assuming the marine invasions were alien to the general depositional system, it is important to note that exceptionally gentle gradients across much of the depositional area of northern Europe would have allowed regional base levels to exert some influence for considerable distances. To summarise, the integrated model for Westphalian deposition, proposed here, suggests different combinations of geological controls operating in different parts of the depositional area, resulting in a highly complex interplay between the main lithofacies. There is no simple scheme, and this model is really a logical combination of all relevant factors, compatible with the intricacies and patterns that have been validated by mining data sets and their interpretation.

Despite some quite fundamental problems (see above), the sequence stratigraphical approach can contribute to this integrated model. As noted, minimal gradients would have allowed some regional base level control, and this would have interacted with subsidence to produce basin-wide correlatable coals: not all cyclicity can be assigned to basin evolution. Further, there are a few intervals in the mid-A to mid-C Westphalian successions that rarely contain coals with significant diachronism (i.e. the intervals are rarely, if ever, "bridged" by seam splits and unions). And on any interpretation, marine invasions will represent a major eustatic change. Specific ways forward using sequence stratigraphy may include: 1, detailed examination of those restricted intervals in which the coal-accumulating continuum is significantly interrupted; and 2, study of those areas where there were no regional tectonic depocentres to complicate the depositional volume; in Great Britain, this includes much of the Durham area in the Northeast field, which lies on the eastern extension of the Alston Block (Chapter 5; Fig. 5.2).

3.6 Conclusions

The model described here is "integrated" because, although the separation of controls affecting channel pathways and energies from those applicable to coals and claystones is an essential conceptual step, it forms the basis for a realistic re-integration of the competing processes that produced the final very intricately-patterned depositional volume. No simple model should be imported into a particular geological setting without careful validation by available data, and this, of course, is also true for exporting the model suggested here. However, it is considered that the British Westphalian A to mid-C is now well-enough described and understood for novel analogue use in various hydrocarbon reservoirs. The Pennine Basin provides the most varied opportunities; it is now possible, using the basin-location variations of Rippon (1996), to quantify for channel belts: 1, dimensions throughout the hierarchy; 2, their varying sand body characteristics; and 3, geographical and stratigraphical distributions. Cyclicity and basin subsidence patterns might be interactively modelled with these.

3.7 References

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3.8 Table and figure captions

Table 3.1 Depositional models for the Westphalian A to mid-C of the Pennine Basin: some differences. The "traditional" column refers to the various pre-1990's approaches which did not achieve any integration between channel belt pathways and basin development. The sequence stratigraphical model is based on fluvial systems interacting with systematic sea level changes; this is considered inapplicable as the basin seems usually to have been very distant from persistently marine areas; this model also fails to account for tectonic basin subsidence patterns.

Table 3.2 Some comparisons between the Pennine Basin Westphalian (Rippon 1996) and the Limestone Coal Formation of the Midland Valley of Scotland (Read 1997, pers. comm.).

Figure 3.1 Generalised palaeogeography of the British Westphalian showing schematic inflow channel belt pathways, together with the extent of the main preserved coalfields.

Figure 3.2 Westphalian channels, eastern Pennine Basin: the exploration effort required for mapping channels with a width of about 0.5km, a subjective plot based on mining experience within the area shown.

Figure 3.3 Channel hierarchies and mapping requirements in the Pennine Basin Westphalian. Multcycle features divide progressively downstream into smaller and more stratigraphically-restricted channels. In the schematic map **(a)**, there is a progressive northwards migration of the lower-order channels with time. The plots **(b, c)** illustrate some typical width variations related to hierarchy, and suggest minimum data densities for differing mapping needs; mining requirements necessitate resolution to 5th order features.

Figure 3.4 The integrated model (developed from Rippon 1996) adopted here, describes a regionally-varying balance between the fluvial system, basin subsidence development, and marine floodings, resulting in the highly complex depositional patterns observed in the coalfields.

	"Traditional"	Sequence Stratigraphical (Flint *et al.* 1995)	"Integrated" (Rippon 1996)
palaeoflow and marine relationships	assumed progradation into depocentre; relationship of depocentre to marine geography not defined	marine progradation; relationship to depocentre not defined; marine geography not defined	progradation into fresh water; depocentre incidental to channel pathways; marine invasions alien to the main depositional system
sand body incidence	essentially undefined	major sand bodies concentrated at key horizons (sequence boundaries)	channel hierarchies, evenly distributed through time and space except in specific basin-margin settings
sand body character	related to delta plain setting	related to sequence boundaries	varies across the basin, reflecting differing combinations of external controls and basin subsidence
cyclicity and coal development	formation isopachs reflect depocentre shape; more cycles towards depocentre, coals thicken towards depocentre	related to sea-level variations; relationship to depocentre undefined	similar to "traditional"; varies across the basin, reflecting differing combinations of external controls and basin subsidence
sand body and peat/coal coexistence	accepted, relationships not defined	major coals and sand bodies not considered to be normally contemporaneous	coexistence whenever a channel belt extends across the basin during any period of coal formation

Table 3.1

DEPOSITIONAL MODELS FOR THE WESTPHALIAN A-MID C OF THE PENNINE BASIN
SOME COMPARISONS

Table 3.1

SOME QUESTIONS	PENNINE BASIN ENGLAND (mid A-mid C Westphalian)	MIDLAND VALLEY, SCOTLAND (E_1 -E_2 Namurian)
1. High stand and low stands		
i. Is there any relationship between marine and non-marine systems in the depositional record, i.e. are there any gradations? Are there any systematic geographical changes? (e.g. subparallel to a bay-line).	No significant relationship	Close relationship
ii. Are there any channel sand bodies that co-existed with marine claystones?	Yes, marine claystones may fail on approach to channel belts	No (but some sheet sandstones do)
iii. Are there any channel sand bodies that co-existed with regional coals?	Yes, common	Yes (proximal facies)
iv. Do major channels lie at similar horizons and grade to a common base; or are they random?	Random	Yes, not random
2. Valley fills and interfluves		
i. Are there observable valley sides? What is the topographic difference? How wide are the valley bases?	None identified	Channels incised to ≥20 m; widths 2-14 km
ii. Is the system commonly aggradational?	Yes	Pro/retrogradational
iii. Are there regional oxidation zones etc. which map like interfluves?	Yes, but with amplitudes <5 m, usually <2 m	Yes
3. Patterns		
i. Is there an identifiable marine direction? Is it compatible with progradation directions etc.?	Gross palaeoflows into lacustrine deltas, no obvious marine connection throughout the succession	Yes
ii. Do cycle isopachs subparallel a bay line, or do they reflect other controls?	No, basin subsidence is the main control	Not known
iii. Do thick coals accumulate subparallel to a bay line? If not, what patterns do they have?	No, they reflect intra-basin controls	Uncertain (small areas only)
4. Data density		
What minimum data density and quality is required for a regional sequence stratigraphic interpretation?	1 borehole per km^2 minimum data density	) uncertain (small area)
What is the minimum geographical area necessary for a valid interpretation? (i.e. how many sand bodies need identifying, for assessing any stacking, or stratigraphically-specific patterns?)	4000 km^2 minimum area (estimated as approximately half the area of the proved eastern Pennine Basin)	)
	mainly based on Rippon (1996)	from Read (1995) and Read (pers. comm. 1997)

Table 3.2

SEQUENCE STRATIGRAPHY APPLIED TO COAL-BEARING FORMATIONS IN THE BRITISH SILESIAN

Table 3.2

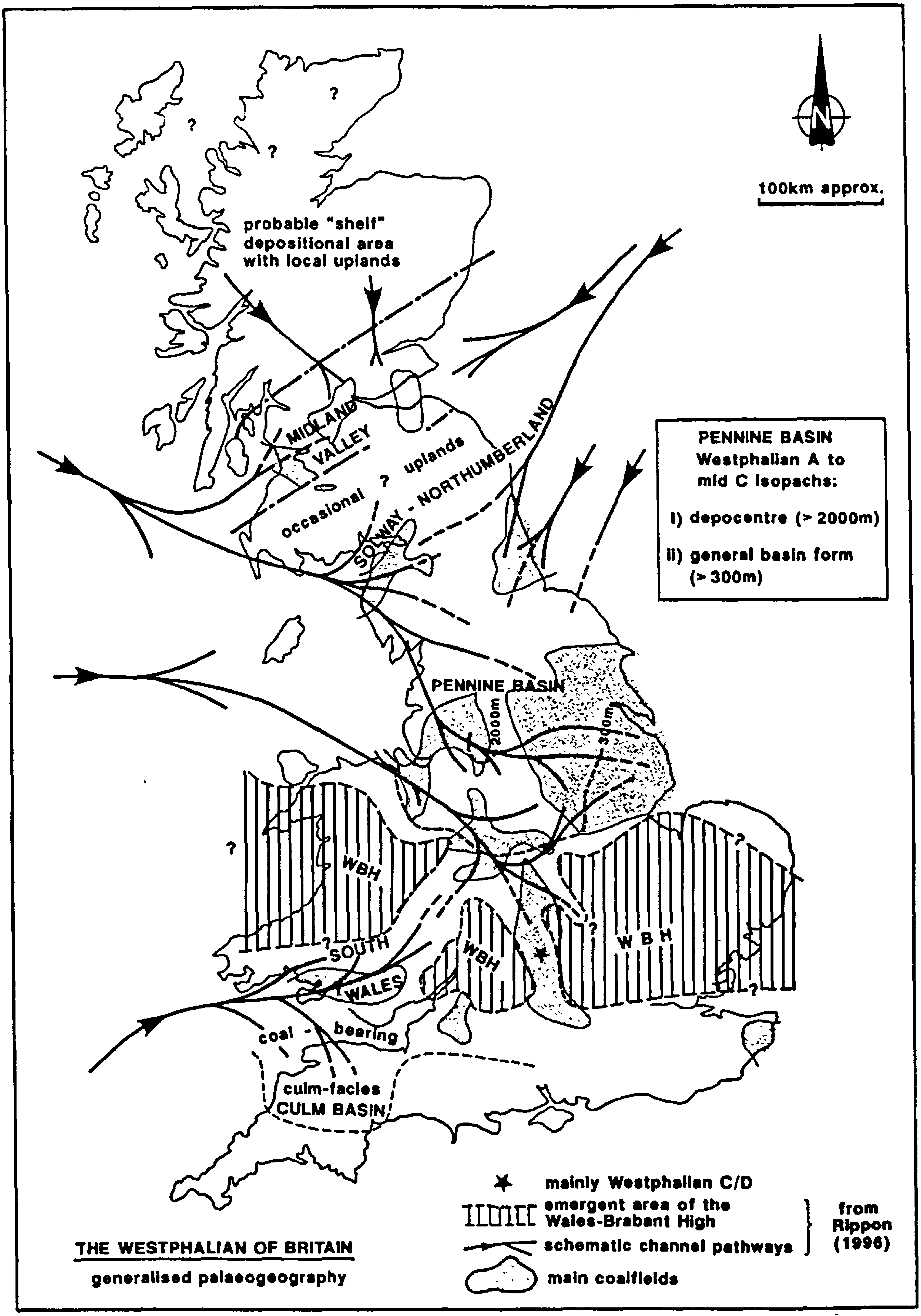
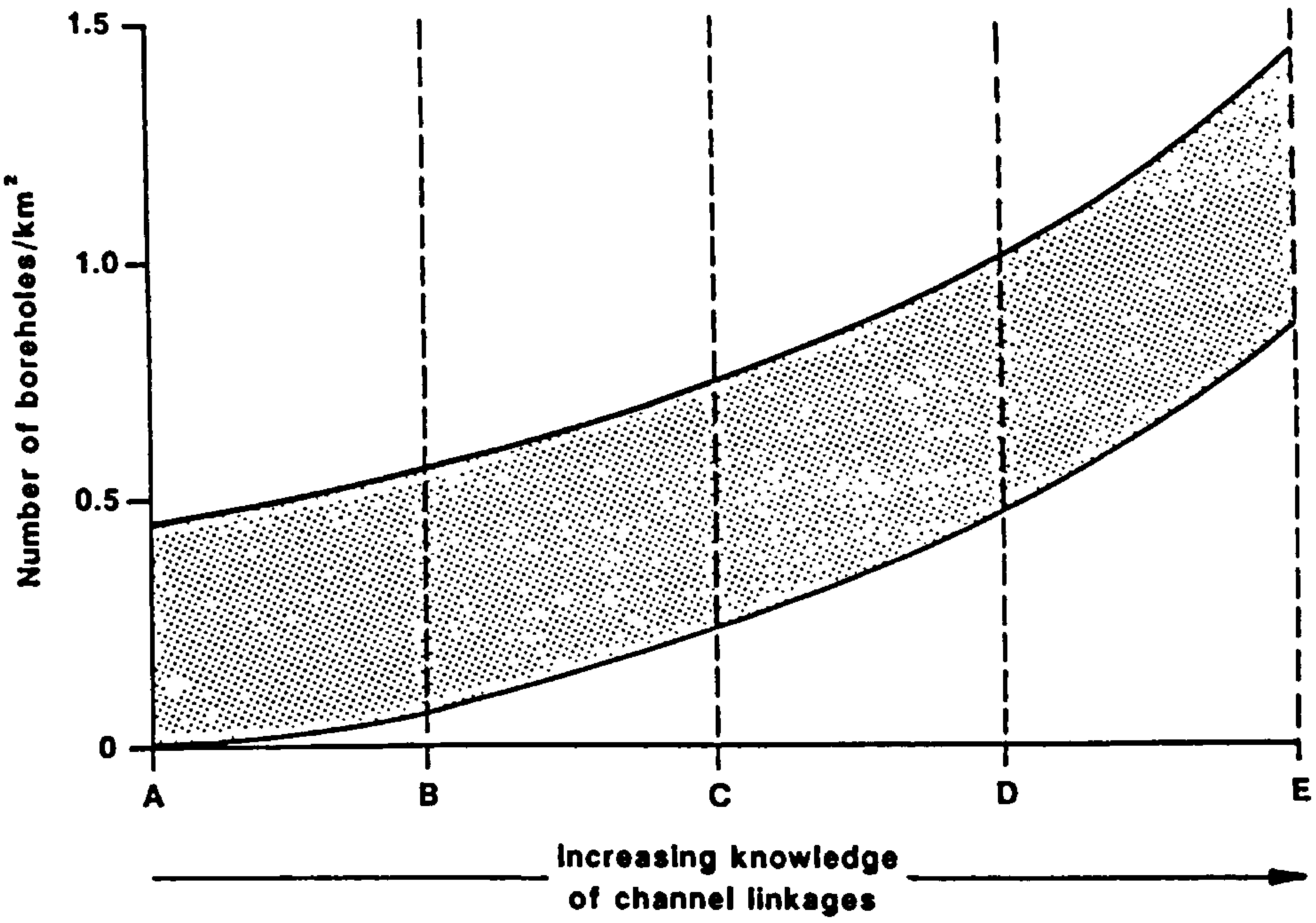

N
100km approx.
?
?
?
probable "shelf" depositional area with local uplands
PENNINE BASIN
Westphalian A to mid C Isopachs:
i) depocentre (> 2000m)
ii) general basin form (> 300m)
MIDLAND VALLEY
occasional ? uplands
SOLWAY - NORTHUMBERLAND
PENNINE BASIN
2000m
300m
?
WBH
WBH
W B H
?
?
?
?
SOUTH WALES
coal - bearing
culm-facies
CULM BASIN
mainly Westphalian C/D
emergent area of the Wales-Brabant High
schematic channel pathways
from Rippon (1996)
main coalfields
THE WESTPHALIAN OF BRITAIN
generalised palaeogeography

Fig.3.1



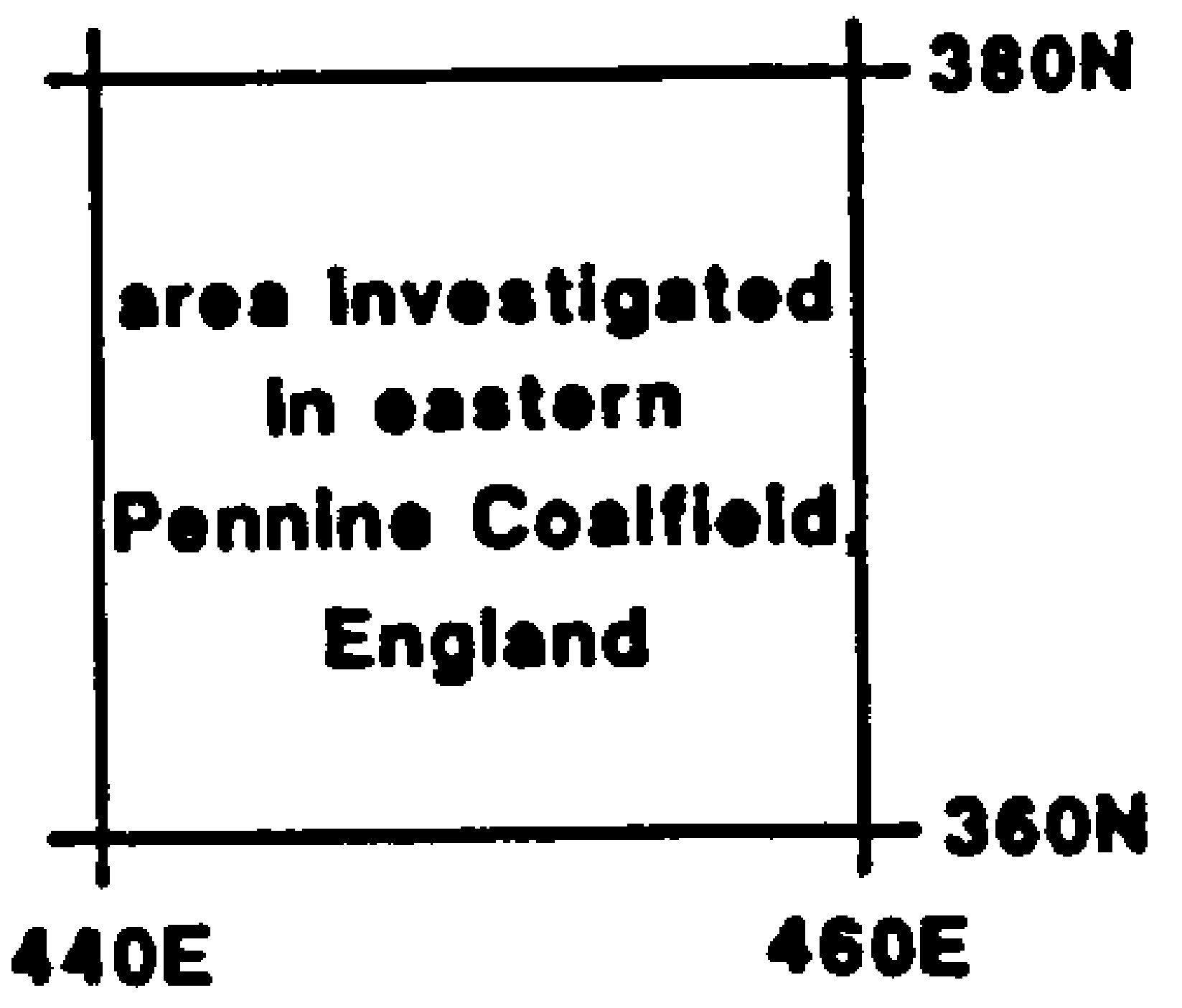
A. Unknown linkages: detailed stratigraphy in doubt.

B. Inferred linkages: known detailed stratigraphy.

C. Partly known linkages: some known, some inferred, some conjectural.

D. Mainly known linkages, some inferred.

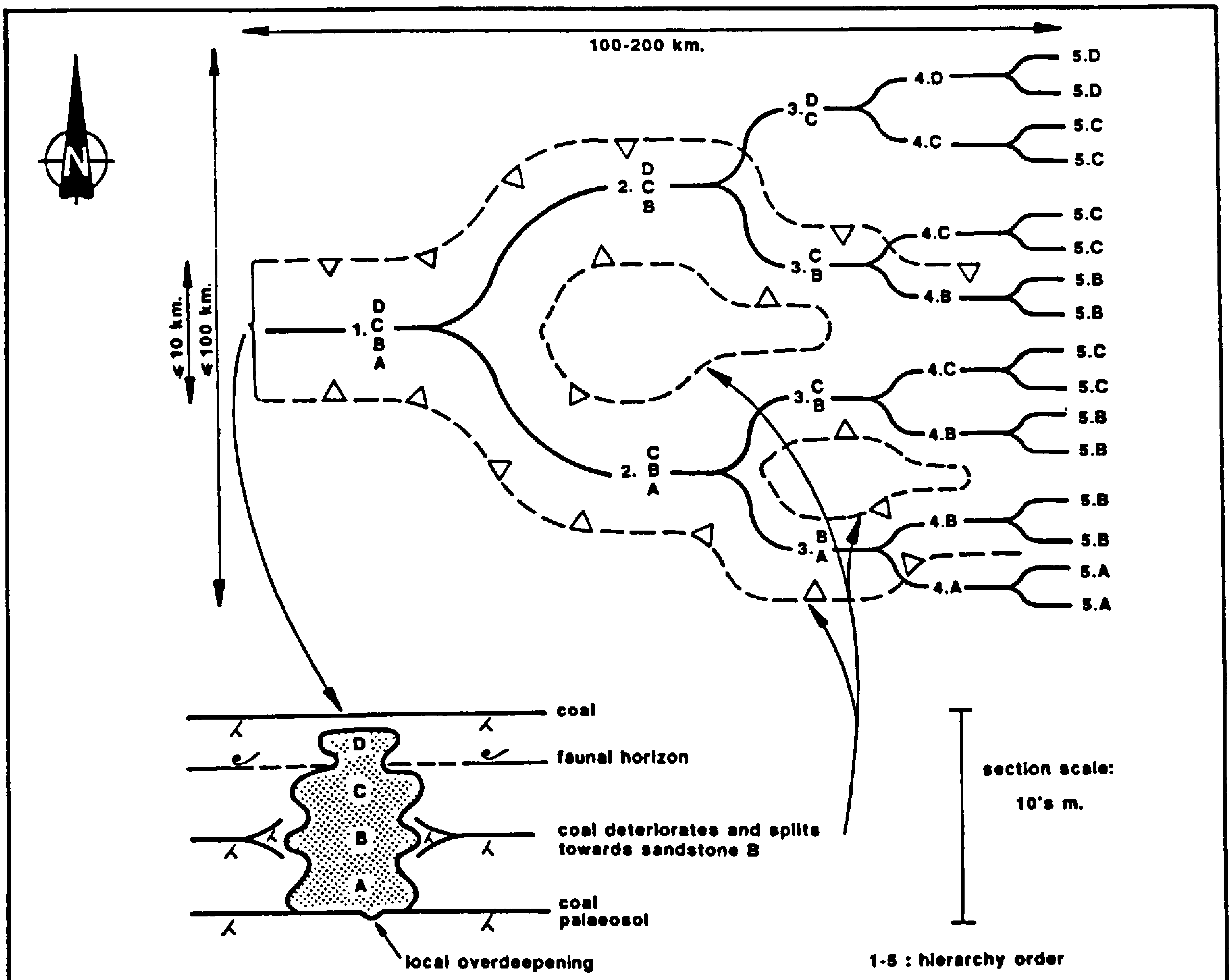
E. Pattern proved: all channels and linkages known.



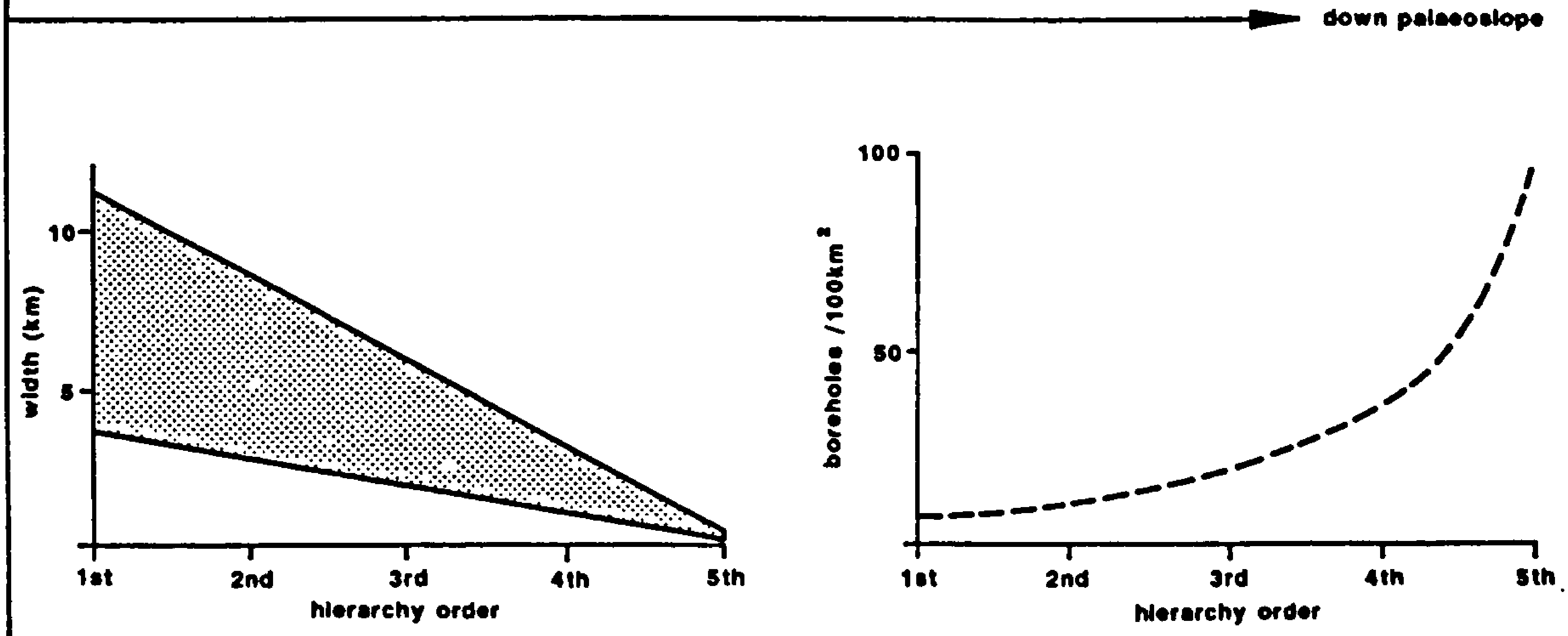
WESTPHALIAN CHANNELS, EASTERN PENNINE BASIN

Exploration effort required to prove linkages

Fig.3.2



a. Schematic map of a hierarchical channel system (based on Rippon 1996)



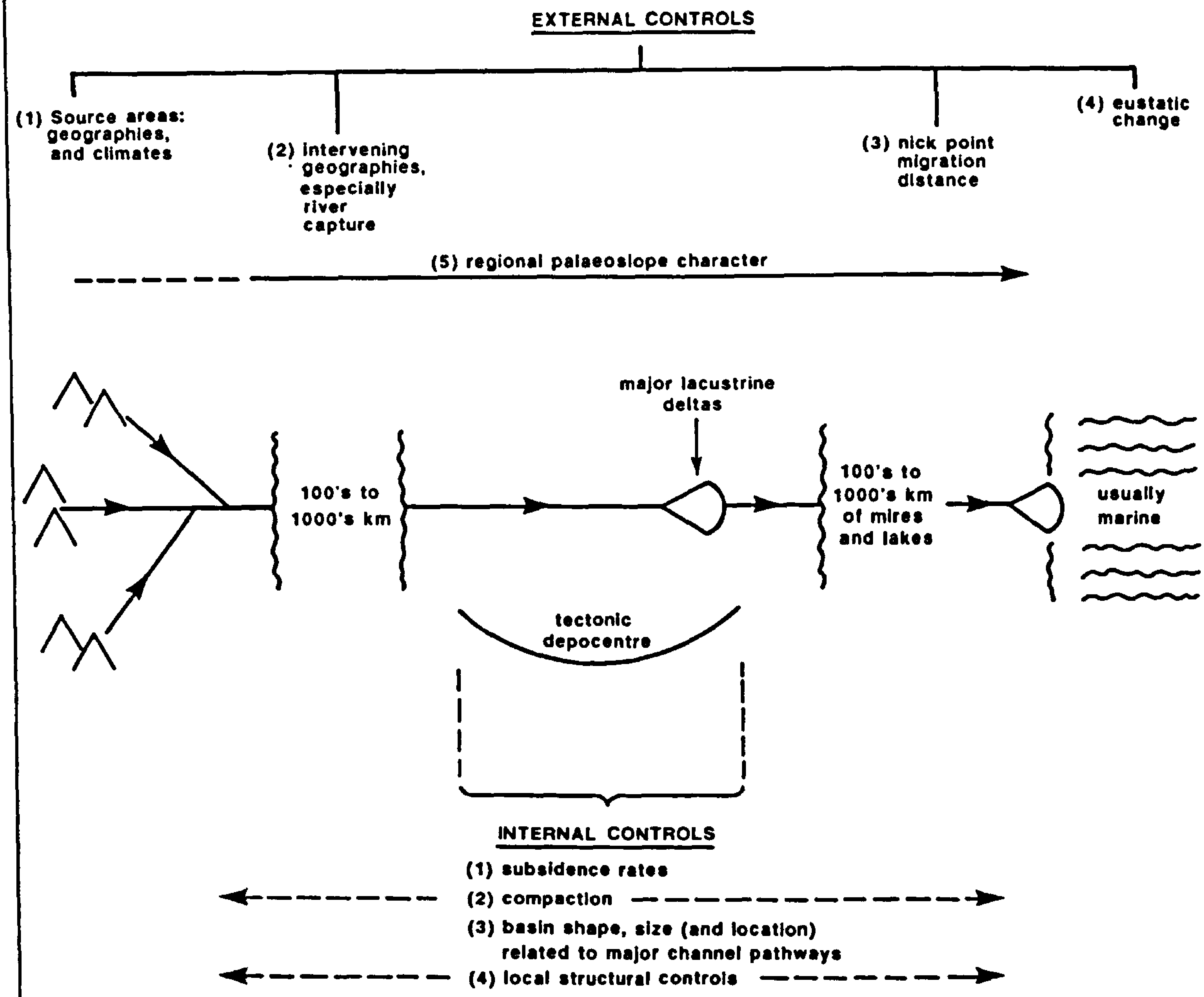
b. Typical widths within the channel belt hierarchy

c. Likely data density requirements for reasonable mapping

WESTPHALIAN CHANNEL HIERARCHIES, PENNINE BASIN.

Data density requirements for mapping

Fig.3.3



WESTPHALIAN A TO MID-C, PENNINE BASIN

AN INTEGRATED MODEL SHOWING

INTERACTION OF DEPOSITIONAL CONTROLS

Fig.3.4

CHAPTER 4

GEOLOGICAL CONTROLS ON SULPHUR DISTRIBUTION IN BRITISH CARBONIFEROUS COALS: A REAPPRAISAL

Abstract: *Little has been published on geological controls on sulphur distribution in British coals since the 1950's, since when most of the data set has been generated. International literature tends to build on earlier generalisations, or extrapolate from specific present-day peats into geologically more complex coals. This account interprets data on British Carboniferous coals, concluding that source area geochemistry was a significant control.*

4.1 Introduction

Sulphur is an impurity in many coals, presenting varied problems in utilisation, and therefore affecting mining economics. As a result, there is a very extensive literature on analytical methods, mineral preparation, and combustion. Geological contributions tend to be intermixed with those of other disciplines, and there are few publications that provide significant geological overviews, and very few that illustrate typical spatial variations in sulphur content. However, forecasting the sulphur distribution in a coal, or through a coal-bearing succession, is very much a geological matter, requiring knowledge of the depositional environment and other controls. An earlier summary by Wandless (1959) reviewed possible relationships between elevated sulphur contents and various geological factors. He considered (particularly in the context of organic sulphur) that current knowledge represented "a graveyard for promising generalisations". As will be seen, the most promising generalisation, that coals closely overlain by marine beds are higher in sulphur, is incorrect for many British examples. Since Wandless (1954, 1959), many authors have used the generalisation as a working model, particularly as studies on modern marine-marginal peats have supported it; these peats, however, are usually found in relatively simple "single issue" contexts.

Most of the British Carboniferous coal-bearing successions were deposited on extensive plains with very low gradients, in generally fresh water settings, although subject to some marine floodings (Rippon 1996). Combinations of external and internal depositional controls produced intricate patterns of fluvial, mire and lacustrine lithofacies distributions and coal sequence cyclicity.

Widespread low-latitude coal formation began in Scotland and northern England during the Dinantian, becoming common in the early Namurian; these earlier sequences in northern Britain were much more frequently invaded by sea water than succeeding Westphalian formations. These (broadly) delta plain settings characterised most areas until the mid Westphalian C, after which there were no further definitive marine invasions, and there was a progressive change to sandstone-dominated fluvial systems with different coal and other lithofacies distributions, and a general trend to red beds. The overall depositional setting is detailed in Chapter 2. The coal-bearing successions were deposited across varied tectonic settings, from late/post rift through northern Britain and the Pennine Basin, across the Wales-Brabant High to the south, to the incipient and developed Variscan foreland basins of southern Britain. Chapters 2, 5 and 6 summarise these settings, and Chapter 1 introduces some aspects of the varied burial histories that characterise the coalfields. Figure 4.1 illustrates the general extents of British coalfields, and Figure 4.2 their stratigraphical range, and the levels of the main coals mentioned in this account.

This account draws on some 45 years of intensive data collection and analysis by the National Coal Board (NCB, later the British Coal Corporation, BCC), together with NCB geological mapping of sulphur variations. Most of the material generated by that work has not been published, while the internal mapping, although usable for practical forecasting, has only rarely been interpreted in terms of geological controls. The intention here is therefore to concentrate on the NCB data set and the geological interpretations that may, or may not, be drawn from it. This account does not attempt significant reviews of industrial analytical methods, petrographical or geochemical work, or of the existing international literature; these may be accessed from the references. A brief description of the data and previous work is followed by a consideration of all potentially significant geological controls on sulphur distribution; and then by a review of these as exemplified by the British Carboniferous data, and a reappraisal of the controls.

4.2 Data

The British coalfields are geographically extensive, and intensively mined at many horizons. Coal sample analysis and reporting has used common procedures over several decades. Before nationalisation of the British coal industry in 1947, analyses for private operators were undertaken systematically by the Coal Survey, which was absorbed into the NCB as its Scientific Department. The great expansion in mined areas, and associated exploration, that followed nationalisation significantly added to the data. Data value is enhanced by close correlation control. Both organic and pyritic sulphur were frequently determined up to the mid-1960's after which it was normal to analyse for total sulphur only. Sulphate sulphur is neglible in unoxidised coals, and is not normally determined. NCB categories for S% are summarised below, and used in this account:

0.50 and under, very low; *0.51-1.00,* low; *1.01-1.50,* moderately low; *1.51-2.00,* moderate; *2.01-2.50,* moderately high; *2.51-4.00,* high; *4.01 and above,* very high.

It is common for seam analyses taken in mine workings to be spaced at a few hundreds of metres where quality has not been a concern, with data density rising where necessary. "Pillar" samples, involving a full column of coal, have been largely replaced by "horizon" samples cut out of fresh coal, since about 1975. Borehole data sets supplement underground sampling: multi-seam provings are common, often at least one good-quality borehole per km^2. Obviously the greatest number of analyses are at the most important mining horizons; however it has been standard practice in many coalfields to core and analyse many unworkable coals, as these are often split portions of seams that are mined elsewhere, and therefore help with correlation and mapping.

Where sulphur content is a significant concern, iso-sulphur lines have been mapped at both regional and local scales, the maps being constructed according to the subtleties of mined section and seam splits. The ash content of some coals closely reflects prominent nodular pyrite, but this is rare; most higher ash British coals indicate proximity to palaeochannels, and their suspension load. Iso-sulphur mapping requires attention to trends, rather than particular samples (especially those with very high sulphur content); this is largely because of variations in sampling methods, both between coalfields, and through time (especially the inclusion or exclusion of nodular pyrite).

4.3 A brief review of previous work

The following is a broad introduction only, particularly of the international literature, much of which is concerned with marine origins for sulphur in coals.

4.3.1 The Upper Carboniferous coalfields of Great Britain

Before coal industry nationalisation, there were few if any available regional maps, reflecting the localised ownership of the mines; it followed that there were no geological accounts of geographical or stratigraphical trends in sulphur content. This was rectified by the NCB, with a series of folios published between 1957 and 1965. These included text, whole-coalfield maps, and supporting tables for seams chosen to show regional trends in various quality parameters where well known from previous workings, for extrapolation across new reserve areas. Although now old, these remain the only published set of coalfield-scale maps of sulphur (and other properties); many sulphur variations described then remain valid; because of their unique status, they are listed and summarised in Table 4.1 and are referenced collectively here as NCB (1957-1965). Because of seam selection, values summarised in these should not necessarily be taken as typical for either a particular horizon or coalfield.

Two other important publications accompanied this work. The earlier summary on all the coalfields by Wandless (1959) recognised the relevance of differentiating organic from pyritic sulphur for some trend assessments, and reviewed sulphur distribution in the main producing seams at that time. The tendency for elevated sulphur subsections to lie near the top, base, or adjacent to a splitting horizon of a seam was noted, also the lower sulphurs of durains compared with bright coals; sulphur was not found to be rank-related on any inter-coalfield scale. Organic sulphur varied broadly between 0.5 and 0.9%, with a tendency to increase slightly with local increases in pyritic sulphur. The potential for higher sulphur coals close to marine horizons was highlighted, having previously been noted by Wandless (1954). On a wider scale, he identified gross stratigraphical variations, and also pronounced differences between some coalfields, especially the lower sulphur coals that typified eastern and central Scotland and many Westphalian A to mid-C coals of South Wales; other low sulphur coalfields were noted, but their stratigraphical and geographical extents were more restricted. One of his conclusions was that there were few if any relationships, at any scale, that were universal. The later publication associated with NCB (1957-1965) was that of Adams (1967), specific to South Wales, which noted the generally very low to low sulphur contents in the main Westphalian sequence, but also the change to generally higher values in the later Westphalian C/D, that is, the Pennant Series. High sulphur in seams close to the Vanderbeckei (Amman), Aegiranum (Cefn Coed) and Cambriense (Upper Cwmgorse) Marine Bands was also recognised, as were other mappable trends for which an immediate control was not obvious.

Since these earlier studies, there have been few published accounts. Rippon (1984), investigating the Clowne Seam (Westphalian B, eastern Pennine Basin) and its overlying claystones, showed that the superjacent Clowne Marine Band extended into the precursor peat in a pattern of small creeks and bays, being contemporaneous with the later peat, and in an onlap relationship to it (see 4.5.5). In this particular case, it was found that lower sulphur values in the coal characterised those areas overlain by the marine band, while enhanced sulphurs were in the marine material itself, a very carbonaceous claystone. Rippon (1984) also recognised the generally lower sulphur content of two regionally-correlatable durain bands in the Clowne Seam; Rippon & Spears (1989), investigating the relationship of the Clowne Seam to its underlying clastics, found no relationship between sulphur content and sub-seam sedimentological variations, which included varying oxidation and drainage patterns, and a volcanic ash fall. Investigating forms of post-depositional sulphur, Spears & Caswell (1986) studied cleat minerals and assessed pore fluid evolution, concluding that cleat sulphides formed early in burial history, perhaps deriving the sulphur from the hosting coals. More recently, Cavender (1995) described sulphur distribution patterns in the Parkgate Seam (Westphalian A, eastern Pennine Basin) concluding that the dominant control was within the depositional environment, perhaps channel floodings.

4.3.2 Other coal deposits

The following notes are designed only to introduce examples of the main geological factors that have been reported; a full review of the extensive literature is beyond the present scope.

Marine flooding is the most commonly inferred control, but with authors describing various factors that moderated its influence. Williams & Keith (1963; a paper cited by many later authors) had described Pennsylvanian coals in western Pennsylvania, and following the earlier pointer by Wandless (1954) concluded that enhanced sulphurs were largely the result of marine floodings at particular horizons; many subsequent papers on the North American Carboniferous coals have supported this. Gluskoter & Hopkins (1970) reported lower sulphurs where fluvial channels protected mires from seawater ingress. Westgate & Anderson (1984) described Desmoinsian coals, concluding that a key control promoting higher sulphur was bacterial reduction of dissolved sulphates from marine flooding after peat deposition. Gibling *et al.* (1989) described the Maritimes Basins coals (Pennsylvanian) of eastern Canada, concluding that high sulphurs reflected the source area geochemistry of inflowing channels, specifically Mississippian evaporites, rather than Pennsylvanian seawater, although this was not precluded. This was based on geological and isotopic work using a biogeochemical model from studies of sulphur isotopes in modern peats..

In Permian successions of eastern Australia, Hunt & Hobday (1984) considered that alluvial settings had lower sulphur coals than those in lower delta plains, and pyritic sulphur was increasingly important in the latter. In a wide-ranging paper on some Cretaceous coals of North America, Kalkreuth & Leckie (1989) described strandplain coals related to the Western Interior Seaway; generally very low sulphur contents were reported, and the lack of relationship to the marine influence, very evident throughout the successions, was ascribed to the time lapse (up to hundreds of thousands of years) between deposition of shoreline lithofacies and accumulation of peats. Palaeogene coals of Japan were found by Shimoyama (1984) to have higher sulphur coals where overlain by marine sandstones; enhanced organic and pyritic sulphurs were related to seawater sulphates, and the associated iron was derived from nearby laterites. This study was later developed by Shimoyama *et al.* (1990) by considering sulphur isotope composition. Recent mires have been widely studied for sulphur distribution patterns (Casagrande 1987). Most interpretations favour marine influence; thus, non-marine Okefenokee peats are lower sulphur, whereas marine-influenced Everglades peats are higher.

Apart from marine influence, various authors have described more specific relationships. Reidenouer *et al.* (1967) studied Pennsylvanian coals in palaeotopographic lows, and their correlatives, the former having relatively high sulphurs; this was ascribed to the availability of ferric iron in the more detrital fractions attracted into the hollows, this then combining with sulphides in the mire. Roberts (1988) reviewed some Permian coals in South Africa; sulphurs were higher in vitrinite macerals, reflecting a higher water table and lower Eh during peat accumulation, favouring bacterial reduction. Whateley & Tuncalli (1995) described Miocene lignites in Turkey, and considered that some higher sulphur coal resulted from contemporaneous igneous activity; basin-marginal geochemistry may also have influenced mire water character, and circulating sulphate-rich fluids may have precipitated late-stage cleat pyrite.

The international literature indicates that many factors may interact to produce varying sulphur contents in coals. Overall, the literature seems to suggest that the Carboniferous coals of the northern hemisphere are generally higher in sulphur than Gondwanan coals, and also higher than the extensive Cretaceous deposits of North America. However, this may partly be a function of reporting, on coals that are now considered suitable for exploitation.

4.4 Summary of potential geological controls

It is now useful to consider all factors (Fig. 4.3) that might have influenced sulphur distribution, including those potentially relevant to coals with complex burial histories.

Syn-depositionally, there would have been a continuing interaction between internal and external factors. Main external factors capable of importing sulphur into the depositional system include marine and fluvial flood-water hydrochemistry, and perhaps regionally-important, distant, volcanism. However, the local depositional setting itself would also contribute to sulphur content in various ways. Floras obviously varied through geological time, through palaeolatitude, and through the differing sedimentological settings in which mires can form, from tropical coastal plain to cold temperate uplands. In coalfields experiencing contemporaneous igneous activity, local effects would include discrete volcanic atmospheres, permeation of coal-bearing beds by gas-phase crypto-volcanism (Chapter 8) and the varied effects of intrusions.

Post-depositionally, a further range of factors may be relevant. It may be expected that the burial histories of coals as old as the Carboniferous, occupying the many different settings such as characterise the British coalfields, might well have produced significant regional differences. Igneous activity would have continued locally, in early post-depositional time. As burial history proceeded, mineralised connate waters would often have been available, with the heterogeneous lithologies combining with structural evolution to produce intricate pathways for migration, and eventual deposition of sulphides. These waters might have derived from intra-basin compaction of Upper Carboniferous successions, from expulsion in advance of Variscan compression, and perhaps from Zechstein flooding of the post-Carboniferous landscape (Chapters 1, 6 and 7).

As noted, the last overview of the geological controls on sulphur distributions throughout the British coalfields was by Wandless (1959), and some comment on the mass of 1960's-1990's mining data is timely; moreover, these data may now be viewed in the light of recent understandings of the depositional and tectonic settings in which the coals are found. It is well beyond the scope of this chapter to consider such a review seam by seam, and some selection is necessary. The selected examples are particularly useful for demonstrating positive, ambiguous, or negative relationships between high/low sulphur and various geological factors. The following sections now discuss the British Carboniferous data, firstly by considering examples in which mainly syn-depositional controls might apply, and then those which might illustrate mainly post-depositional controls. Case studies that aid discussion on marine influence are reviewed first, because of the prominence of this in the literature.

4.5 Some case studies: (i) marine influence

Marine influence is easily the most commonly cited factor regarding higher sulphur contents in coals, usually in the context of a closely-overlying marine bed. The British coals show this to be a significant over-generalisation. A general discussion on marine flooding follows this case history review, which is in stratigraphical order.

4.5.1 Dinantian coals of northern Britain

There are relatively few analyses of these coals, which are widespread across the Scottish Midland Valley at certain horizons, and also across much of northeast England, where they are generally thinner. Particular mention however may be made of the Scremerston Coal Group (Asbian) of northeast England. In many ways, this succession was a forerunner of many later coal-bearing sequences, being coal-rich, but in a setting which included large channel belts and many marine invasions; the latter are evidenced by abundant marine limestones and calcareous claystones. For the present discussion, it is interesting to note sulphur contents throughout are high to very high; these are known from 1980's prospecting for opencast coal at Allerdean and Unthank sites, southwest of Berwick upon Tweed. Most of the sulphur is pyritic. Repeated flooding by marine waters in a lower delta plain setting appears to be a straightforward explanation.

4.5.2 Pendleian coals of Scotland

Most coals in the Scottish Upper Carboniferous have low to very low total sulphur contents over wide areas; there are only very rare exceptions. This certainly applies to the Pendleian coals of the Limestone Coal Formation, which nonetheless shows overall delta plain characteristics, with prominent marine limestones and many subsidiary marine and brackish clayrock bands (e.g. Read 1995): the overall setting is significantly more marine-influenced than the coal-bearing Westphalian (see below). There are few published analyses beyond those found in NCB (1957-1965), in which the sulphur ranges were so small that the property was not mapped; in the generalised range 0.5 to 1.0% total sulphur, much was thought to be organic (analysed specifically for the Meiklehill Main coal). *Lingula* (brackish) horizons lie locally within the Bannockburn seam group, and also closely below the Wilsontown Main, both low sulphur coals (Table 4.1).

4.5.3 Arnsbergian coals of Scotland

The Upper Limestone Formation also shows many characteristics of a lower delta plain succession, with several marine limestones and many subsidiary marine and brackish clayrocks. It is therefore similar to the Limestone Coal Formation but differs in having some very thick sand bodies (including sheet sandstones) and a virtual absence of significant coals.

The Upper Hirst coal is a prominent exception, being 1m to 3m thick over wide areas with particular economic value in the Kincardine Basin (Francis *et al.* 1970). Here, a *Lingula* horizon lies close below, while the regionally important marine Calmy Limestone lies at varying heights above the coal, usually between 2m and 10m; between the coal and the limestone are varied claystones (some being calcareous with presumed marine affinities) and a very prominent high-gamma marine band, bearing pyritised *Edmondia punctatella*. Throughout the Kincardine Basin, hundreds of coal analyses of the Upper Hirst show a total sulphur content varying between 0.3 and 0.6%. There is no relationship between sulphur content and the thickness of clayrocks between the coal and the Calmy Limestone or the *Edmondia* band. Part of the area mapped by the BCC was illustrated by Cavender (1995), showing essentially random iso-sulphur contours with a very low rate of change; a few higher value areas are thought to relate largely to crypto-volcanism (see later). The Upper Hirst therefore lies within a distinctly marine-influenced sequence, but shows no sulphur enhancement. Within the Kincardine Basin, the seam itself is probably distant from any contemporary channel belt (see below), as there is only very minor seam splitting; thin sideritic beds within the seam are thought to represent occasional shallow lakes within the mire. For pyrite to form, of course, there must also be iron available, as well as sulphate, together with a reducing environment; the sideritic beds indicate that iron was readily available during peat accumulation.

The Plean 1 is another coal in the Upper Limestone Formation for which there are analyses, although fewer than for the Upper Hirst. This seam has a very similar setting, having a *Lingula* bed close below, and an overlying marine limestone, in this case directly above. However, the few analyses all give moderate to high total sulphurs, substantiated by unanalysed descriptions of "foul" or pyritic coal elsewhere. Obviously the Plean 1, which is an inferior coal with many clastic partings, presents a totally different picture to the Upper Hirst. This may be because these analyses lie close to sulphur-importing channels, or again maybe because of local igneous activity: the interval between the Upper Hirst and the Plean 1 contains numerous tuffs, including one very prominent horizon close below the latter coal (Francis *et al.* 1970). But given the regional descriptions, it is assumed that the main difference between the lower sulphur Upper Hirst and the higher Plean 1 was probably a minimal time interval between the final Plean peat and the marine invasion; perhaps the marine invasion was itself instrumental in drowning this peat.

4.5.4 Westphalian A coals

The various marine horizons of the lower Westphalian A only rarely overlie coals of mineable thickness, and there are consequently few analyses. The Lower Dysart of Fife, towards the base of the Westphalian succession, is another of the few Scottish coals with a moderate or higher sulphur content; it is overlain by a *Lingula* band. The Alton coal of Derbyshire, immediately below the Listeri Marine Band, has been mined in the eastern Pennine Basin, and the correlative Union Mine coal has been worked in the Burnley area in the northwest. The Alton is often a high to very high sulphur coal, with the impurity distributed generally through the seam, usually as very fine dispersed pyrite. The Kilburn Seam of Derbyshire has a local *Lingula*-bearing "roof", but the relation to sulphur variations in the coal are unknown.

The topmost Westphalian A coals, lying close below the Vanderbeckei Marine Band, are commonly reported as having higher sulphurs, and those in South Wales appear to have initiated recognition of a marine waters relationship (Wandless 1959, Adams 1967). In South Wales, the Amman Rider has a high sulphur content across the coalfield; underlying seams locally unite with this, and then the high sulphur profile extends down through these. Cope (1979) discussed the thickness interval needed, between the Amman Rider and underlying coals, to moderate the higher sulphurs in the latter seams, which are of mineable thickness. At a separation of around 0.75m, the underlying coals maintained a total sulphur content of <1.5%, compared with up to 3% where the seams converged with the Amman Rider. It should be remembered here that the interval needs to be considered not only as compacted/uncompacted thicknesses, but also in terms of the associated time interval. Higher sulphur coals at this horizon are also known from certain Pennine Basin coalfields, including the Seven Feet of Warwickshire and the Banbury of North Staffordshire (NCB 1957-1965), but relationships with the marine band are not well known; the Seven Feet has exceptionally high sulphur, but only locally.

4.5.5 Westphalian B and C coals

Although most marine band/high sulphur relationships have been identified where a coal is closely (say, <2m) overlain by marine beds there must be a possibility that an underlying marine horizon may affect the sulphur content of a succeeding coal (see 4.5.6). For example the Bute/Lower Nine Feet coals of South Wales are commonly higher in sulphur (NCB 1957-1965); these are the first coals above the Vanderbeckei Marine Band, but the separation is often several metres, even tens of metres. The Smithy coal of Warwickshire has a similar setting.

The later Westphalian B marine bands are more closely associated with mineable coals than most other horizons, and provide considerable detail. The Maltby Marine Band immediately overlies the Two Foot coal in Derbyshire, for which many analyses are available; where mined, this is a higher sulphur seam, but by contrast to the Alton (see above) the sulphur is concentrated in the topmost subsections, that is, in the upper 0.2m of the coal, often as prominent nodular pyrite. At a comparable horizon in the Northeast coalfield, the High Main seam tends to be the highest sulphur coal of that area, with values averaging 2.5%. The Maltby Marine Band lies close below the Main Bright/Meltonfield coal over much of Nottinghamshire, but there is no particular relationship with it, the Main Bright being normally a lower sulphur coal; however, there are prominent corridors of higher sulphur within this seam across Derbyshire and Yorkshire (see 4.6.2). The *Lingula*-bearing Clowne Marine Band directly overlies the Clowne coal where present; as noted earlier, Rippon (1984) found that low sulphur coal was present underneath the marine band, but with higher values lying in coal lateral and contemporary to it (Fig. 4.4). Coal/marine band relationships towards the late Westphalian B are less well known; however, the Wheatworth coal, lying very close to the Sutton Marine Band, has high and very high sulphur contents; it is uncertain whether this relates to the marine band, or to its proximity to the major Oaks Rock sand body (with which it is partly contemporaneous): this might have been a significant sulphate-importing channel system (4.6.1). Westphalian C coals closely overlain by marine beds are generally thinner and less frequently mined, with the prominent exceptions of the High Main (Nottinghamshire), the Shafton (Yorkshire), and the Rowhurst and Winghay coals (Staffordshire); the sulphur/marine band relationships of these coals remain to be investigated.

4.5.6 Marine influence: a discussion

It is appropriate here to consider the wider implications of marine flooding. Although a simple sequence stratigraphical model seems more appropriate to the Dinantian and Namurian coals of northern Britain, rather than to the greater part of the coal-bearing Westphalian (Chapters 2 and 3) the possibilities of muted marine influence throughout the coal-bearing successions are of interest because of the implications for floodwater chemistry.

Because Westphalian marine bands are usually lithologically and faunally discrete horizons, it is often assumed that marine influence did not begin earlier, or persist later, all the faunal zones of Calver (1968) being taken as included within a marine band (although some of his phases were brackish). The question therefore arises as to how such discrete bands relate to actual rises and falls in base level; a rapid onset fits well with marine band field relationships, but a lengthy wane period is more difficult to assess. The post-acme macrofaunal phases of Calver (1968) are some measure of this, but not all marine bands show this ideal sequence. An answer may lie in the co-existence of channel inflow waters with remnant seawater, giving a mixture that was insufficiently saline for marine fauna, but which nevertheless retained significant sulphates; some channels may well have continued flowing throughout more short-lived marine floodings, introducing local variations on the overall faunal zonations. It follows that subdued marine effects may be sought above a definitive marine band, up to the base of the first succeeding regional coal horizon. This may explain enhanced sulphurs in seams such as the Bute coal (post-Vanderbeckei Marine Band) of South Wales and its Pennine Basin correlatives; conversely a zero-effect on a post-marine band coal may simply result from channel-flow waters continuing to dilute the remnant seawater. It also follows, then, that there may be other horizons, not including definitive marine bands, in which an overall base level rise introduced sulphate-rich waters which were diluted by contemporary freshwater inflows. In such cases, the absence of a marine band, as such, necessitates use of indirect evidence. The following possibilities are suggested.

Lithologies. Known marine bands often include claystones that are noticeably different from typical lacustrine material, having a distinctive ragged surface on borehole cores, presumably reflecting clay mineralogy, and in which plant fragments may be pyritised. An approach to this lithological subtlety is sometimes found away from known marine bands, for example in the claystones above the Low Silkstone coal (Westphalian A, eastern Pennine Basin; this horizon may very locally contain *Lingula*); associated siltstones sometimes include isolated and apparently eroded sand ripples. The Low *"Estheria"* Band (see below) lies immediately above the coal in places, and the coal itself is relatively high in sulphur over wide areas. Rhythmites of inferred tidal origin have been described from the earlier Westphalian A by Broadhurst (1988).

Fauna. *"Estheria"* bands are found either associated with marine bands, or widespread on their own, when their typically high-carbonaceous claystones, regional extent, and positions just above coal seams all suggest similarities. It may be that the *"Estheria"* horizons represent failed marine invasions, while nonetheless providing extra sulphates. Also, some siltstone-dominated lithofacies in interdistributary bays may have been marine-influenced: some horizons show prominent increases in burrows, perhaps reflecting increased nutrition availability; all the Westphalian B marine bands commonly have very burrowed beds above them.

Non-coal intervals. Overall, the Westphalian coalfields show coal groups that split and rejoin through most of the succession, but there are certain horizons at which coal "bridgings" are rare or absent. The interval including the Vanderbeckei Marine Band is easily the most obvious of these, across all coalfields; however, there are others which can be traced across individual coalfields, although further work is necessary for inter-coalfield comparisons. Such intervals may well represent base level rises in which marine influence was subdued, but which nonetheless introduced sulphates into the depositional system.

4.6 Some case studies: (ii) other syn-depositional factors

Whereas marine flooding is undoubtably a major factor in introducing sulphates into coal-forming sequences, the dominant geochemical input into environments which were usually (especially in the Westphalian) well upslope from any marine lower delta plain would have been from inflowing channel systems. The effects of these, and other factors are now considered.

4.6.1 Palaeochannel water chemistry

Source area geochemistry has been suggested as contributing to higher sulphur contents in a few case histories (Gibling *et al.* 1989; Querol *et al.* 1991) but has not previously been considered for British Carboniferous coals. However, Rippon (1996; see Chapter 2) interpreted three main source areas for palaeochannel inflows during the Westphalian A to C (Fig. 4.5). Inflows to the Pennine Basin from the west were considered to be from particularly remote source areas, based on channel belt size and sediment maturity; flows into South Wales were largely from the west and southwest; while those into northeast England and eastern Scotland were from the north and northeast, off FennoScandia. Certainly this last source area may be expected to have made little sulphur contribution, from the generally granitic background. The distant westerly source area for the Pennine Basin must be assumed to have been more varied, while the long distance may have allowed some concentration of salts through evaporation, despite heavy low-latitude rainfall. Speculatively, the potential source areas for this western province might have included the Mississippian evaporites or their equivalents which are thought to have been the likely origin for enhanced sulphurs in the Canadian Maritimes coalfields (Gibling *et al.* 1989). These coal-bearing successions include coals of comparable age to those of the Pennine Basin, have generally higher sulphurs, and (following Rippon 1996) may well have lain up-depositional slope. Obviously, no specific conclusions can be drawn without more work on the palaeogeographical relationships between North America and northwest Europe during the later Carboniferous.

Figure 4.6 shows very generalised contouring of Wandless's (1959) organic and total sulphur data. Any explanation of sulphur variations in British coals must take account of the background differences between the Pennine Basin and other fields, especially Scotland, with its more strongly marine-influenced Namurian coals but nonetheless low sulphurs; these gross regional differences in background are compatible with the three inflow provinces of Rippon (1996).

4.6.2 Channel flooding

Rippon (1996; see Chapter 2) described a hierarchy of channel belts which were pervasive through most Westphalian A to mid-C sequences in the Pennine Basin. This hierarchy included small features only a few 10's metres wide to sand bodies locally >10km wide; apart from size, the longevity of a channel belt was also important, with some major sand bodies representing the time taken for the accumulation of at least two, and sometimes three significant regional coals and their intervening rocks. Such major channel belts may have been conducting water through a locality for some 10^4 years, flooding contemporary mires with their characteristic water chemistries. The Silkstone Rock (Westphalian A) of the eastern Pennine Basin is a good example of this, and has been described by Guion *et al.* (1995); in that paper, the ash of one regional coal was plotted against distance from the line of multiple splitting, beyond which the seam passes very rapidly into thin and inferior coal, through palaeosols, and into channel sands. For comparison, Figure 4.7 plots sulphur content against distance to continuing channel for the Main Bright coal (Westphalian B, eastern Pennine Basin). In both cases, the distance from channel margin into the mire to which flooding commonly extended is similar, between 2 to 3km, and it may be deduced from the sulphur plot that water flooding extended much further than any mappable clastic deposit. Figure 4.8 summarises the ash/distance plot of Guion *et al.* (1995), and adds the field for sulphur content. This shows a broader band for sulphurs compared with the Main Bright although the upper limiting line is very similar to that in Figure 4.7. The broader band may reflect sampling, with some coals being excluded, having already split away and beyond sampling height, or the slightly different setting: the sand body contemporary with the Main Bright coal lies in a very well-defined and relatively narrow channel corridor, whereas the Silkstone Rock in the mapped area is a wide channel belt in which the main distributive element will have varied in its distance from the mire margin. The regional increase in sulphur towards the Silkstone Rock was also illustrated by NCB (1957-1965), for the Threequarters coal.

These major channel floodings are known from mining detail to characterise most coal horizons. In the case of the Main Bright, it is known that the associated channel belt was initiated soon after the deposition of the Maltby Marine Band, and possibly there were remnant seawater sulphates available for redistribution. More minor channels also flooded mires, and these are well known from the "single-event" splitting that is characteristic of most British coals. Referring to the flooding distances deduced above, it is known from coal quality mapping that higher sulphur subsections often lie at horizons that develop elsewhere into seam splits, and this can be useful in correlation. Most coal mapping for sulphur content produces regional patterns that almost certainly reflect depositional systems, few if any structural features having any measurable effect.

Many channel features are not contemporaneous with the coal, but lie close below or above it. Where sand-filled, these will have been pathways for water migrations, but no geographically-specific relationships with enhanced sulphurs in the coals have ever been noted.

4.6.3 Mire variations and coal lithotypes

A detailed discussion on any relationships to variations in floral communities, preservation, and the resulting differences in coal lithotypes is beyond the scope of this account. There are no known British case studies that compare these to geographically-varying sulphur contents on a scale that could indicate a causal relationship.

4.6.4 Igneous features.

Apart from rare volcanogenic tonsteins, most British coalfields are largely devoid of igneous features, but there are prominent exceptions (Chapter 8). Scottish coalfields include a wide range of intrusions and volcanics of Carboniferous, Permian, and Tertiary ages; the Northeast coalfield of England is traversed by a number of end-Carboniferous dykes with sills at depth, and by some Tertiary dykes; coalfields along the northern margin of the Wales-Brabant High are characterised by vents and sills; and the later Westphalian C/D of Oxfordshire, lying across this high, includes significant lava flows and sills. The western Pennine Basin fields are traversed by occasional Tertiary dykes, and there are minor features elsewhere. Although some of these are significantly post-depositional, igneous features are dealt with here in a single discussion, as most relationships with sulphur in coals are likely to have been contemporaneous with coal sequence deposition.

The folio maps of NCB (1957-1965) show no regional relationship between sulphur variations and dykes, the more prominent of which are shown. Possible sill relationships are more ambiguous. Depending on intrusion level (Chapter 8), sills may be expected to have degassed either passively or violently; many penecontemporaneous sills in the Scottish coalfields and those marginal to the Wales-Brabant High are thought to have been intruded into largely unconsolidated sediment, and any sulphur-bearing gases may have passed passively through these. Further, because of their areal extent, sills may have imposed a sulphur background which could appear depositional. However, because of the widespread low and very low sulphur contents of the Scottish coals, penecontemporaneous sills are not thought to have been significant sulphur-importing features there, and therefore may reasonably be discounted elsewhere.

Volcanism can contribute sulphur on a very local, to intercontinental scale, via post-eruption acidified rains, and also through local gas-phase permeation of country rock. The volcanos of the Scottish Carboniferous were mainly small (Chapter 8) and correlation of their activity spans with specific coals is not always straightforward. There seems to be no general relationship with sulphur patterns in coal seams. However, the potential for a local volcanic overprint on the regional pattern is suggested strongly by an example from the Upper Hirst coal (Arnsbergian), commented on by Cavender (1995) and illustrated here by Figure 4.9. Tillicoultry borehole proves a vent which is assumed to have been active not long after the Upper Hirst cycle was deposited, being readily correlatable with thick tuffs which underlie the succeeding Plean coals. The Upper Hirst is steeply dipping and lies in strongly fractured ground; small sills and basalts lie close below and above, and thick agglomerates above. The sulphur content of the Upper Hirst in this borehole is 2.2%, compared with a regional background of around 0.5%, and may represent late gas-phase permeation (Barnett 1985). Other discrete sulphur highs on this scale may represent either similar crypto-volcanism, or merely sampling effects; further evidence for igneous activity should be sought prior to reaching any conclusions.

Direct evidence for major, distant volcanism is sparse, and effectively the acid-affinity tonsteins in the Westphalian described by Spears and Kanaris-Sotiriou (1979); only two are well-known in Great Britain, namely the sub-Clowne tonstein (Westphalian B, Pennine Basin, see Rippon & Spears 1989) and the Stafford/sub-High Main/Pentre tonstein (Westphalian C) of the Pennine Basin and South Wales. These lie below their named coals with the exception of the Pentre tonstein of South Wales, which commonly lies within the named seam; the sulphur characteristics of the Pentre coal require further study, but the other tonsteins are not relatable to any obvious sulphur enhancement in the succeeding coals. Major volcanism may be of more interest in later sequences, especially the Westphalian D coals of Oxfordshire, which are typically higher sulphur over wide areas. These coals are also associated with very large sand bodies that must be assumed, like their counterparts in South Wales (Jones 1991) to have derived from the developing Variscan orogen to the south. Acidified rain from distant volcanic sources, a sulphur-contributing fluvial source area, or a combination of these may have promoted the regionally high sulphurs of these coals; there is no known marine influence. Evidence for volcanogenic sulphur is lacking, but it is a potential factor in producing higher values in later Westphalian coals.

4.7 Discussion: possible post-depositional controls

The possible post-depositional contributions that might have been made by igneous activity were discussed, for convenience, above. It is now necessary to consider any other factors that might have operated during burial history. Bearing in mind the excellent data control on fault and fold patterns in British coalfields, identification of any obvious causal relationship between these and sulphur variations might appear straightforward, but this is rarely the case.

Structural controls that might be considered relevant to sulphur patterns in coal may be local, on the scale of an individual fault, or regional, including major folds and more widespread tectonic events. In practice, probably any structural control will be associated with the coal cleating; this is known to vary in intensity, direction, and mineralisation both within and between coalfields, and there are many anecdotal accounts of cleat variations adjacent to faults (Chapter 7).

No definitive examples of excess cleat pyrite contributing significantly to overall coal sulphur patterns are known, but must be assumed for the Pennine Basin, with its strongly mineralised character; in most cases, the likelihood is that the size of the structure and its adjacent strain (Chapter 6) will be too small for detection by the spread of coal analyses. In his studies on the Parkgate (Westphalian A) of the eastern Pennine Basin, Cavender (1995) found no mappable control related to structure, which included the Eakring Anticline and its associated faults. He also illustrated a zone of higher sulphur coal in the Warwickshire Thick (Westphalian B, southern Pennine Basin) that lies sub-parallel to the major Western Boundary Fault of Warwickshire, and it is possible to deduce a structural relationship here. However, a seam split line also parallels this structure, and it seems probable that control on sulphur distribution is more related to the depositional system, even if the detailed geography of this was determined by the structure. Some of the higher sulphur coals illustrated in NCB (1957-65) lie parallel to major fault zones, and within the likely extents of their associated strains (Chapter 6); thus some seams in North Staffordshire show increasing sulphur contents towards the major Red Rock Fault; but again, structural control, if present, might have been indirect, by variations imposed on the depositional system.

It is concluded that there probably is structural control on sulphur distribution, expressed through greater cleat intensities and corresponding increases in cleat mineralisation, including sulphides. This may be common, but for small faults, the effects are too localised for detection, while certain large structures may have moved syn-depositionally, resulting in an indirect relationship.

Connate brines would have been involved in cleat mineralistations; these are introduced in Chapter 1. As with structural controls, it is assumed that brines of whatever origin would have effects on sulphur deposition mainly from relationships with the cleats, which would have provided both pathways, and opportunities for sulphide deposition. The matter is discussed by Spears & Caswell (1986). There are no definitive studies relating connate brines to sulphur patterns in coals; given that brine chemistry is likely to have evolved through burial history, and that hosting cleat frequencies are likely to be very site specific, it is assumed that any relationship will only ever be inferred. A particular case might be made for coals in northeast England, closely overlain by late Zechstein marine beds (see Smith 1994, p.12).

4.8 Conclusions

As noted earlier, coals as old as the Carboniferous, with relatively complex and varied burial histories, might reasonably be expected to reveal various controls on sulphur distribution. In particular, these coals might also be expected to show clear differences between the few horizons that were definitely marine-influenced, and the many that were not. From the previous case study review, neither of these are straightforward conclusions. Firstly, it is clear that the dominant controls *were* syn-depositional, any complicating effects that significantly post-dated formation deposition produced only localised overprintings on that background. But secondly, the syn-depositional controls themselves were far from simple, with many interactions. Figure 4.10 summarises the inferred relative importance of various controls, relevant to main coalfield areas. Apart from the possibility of distant volcanism influencing sulphur contents in the later Westphalian coals of southern Britain, most factors, other than marine flooding and fluvial channel source waters, were of only local importance. The overall conclusion is that these two factors were the most important, but especially the latter. Specific conclusions on these are now summarised.

4.8.1 Marine influence

Marine influence is not a simple cause of elevated sulphur in coals. Although there are some very good examples, notably certain coals lying immediately below marine beds in the Westphalian of South Wales and the Pennine Basin, there are others that are at best ambigous, and, especially throughout the Scottish sequence, many that are exceptionally low in sulphur, despite strong stratigraphical relationships to marine beds. Factors that appear to have moderated marine influence include: 1, the thickness and lithologies of beds, and the time intervening between a peat and a marine horizon (see 4.5.3, 4.5.4); 2, the marine lithology itself may have had a greater affinity for sulphur than the underlying coal (Fig. 4.4); 3, some marine bands probably represent short-lived and shallow floodings, sometimes restricted by local topography (Rippon 1984); 4, some marine floodings will have interacted with waters delivered by fluvial channel systems (4.5.5), both during marine invasions, and residually, after marine retreat.

However, none of these, alone or combined, are adequate explanations of the low and very low sulphur contents that characterise most Scottish coals, especially in the strongly marine-influenced Namurian successions. The time-lapse factor of Kalkreuth & Leckie (1989) provides a partial explanation, especially if thinner, lower delta plain coals are discriminated from thicker upslope seams, giving more time/space distancing. The main problem for wider application of the time-lapse factor stems from the Scottish Westphalian coals. These are also generally low to very low in sulphur compared to their English equivalents, but demonstrate similar sedimentary geometries (although they do lie in the least marine-influenced Westphalian succession in Great Britain, definitive marine invasions are rare in all coalfields, see Chapters 2 and 3). An overall reason for this negative relationship throughout the Scottish Namurian and Westphalian is required, and this might then be important elsewhere. It is unlikely that Scottish mires were significantly different in their microbiological character, unless the mire waters themselves had significantly different chemistries. It may simply be that there was less iron available in the Scottish area, or that the fluvial system provided fewer sulphates and other salts. Either way, the likelihood is that low Scottish sulphur contents are ultimately reflecting source area geochemistry.

4.8.2 Influence of fluvial channel systems

Given that the bulk of the Westphalian A-C succession was deposited remote from marine influence (Rippon 1996; see Chapter 2), and that both specific (Figs. 4.7, 4.8) and general sulphur distribution patterns are readily explained by channel flooding, it is concluded that the dominant control through the Westphalian A-C was source area geochemistry, modified along the river systems by intervening geographical factors. Detailed patterns in coals reflect varying distances from contemporary flooding watercourses. Returning to Figure 4.6, this is the only overall control that can explain gross regional differences between Scotland and coalfields farther south. The three main inflow regimes Rippon (1996) generally match background sulphur variations; higher values for all coals in the Pennine Basin coincide with dominant westerly derivations.

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4.10 Table and Figure captions

Table 4.1 A summary of the sulphur data from NCB (1957-65). The analytical basis was air-dried; inferior coal has ash content >15%, "dirt" is any bed >40% ash.

Figure 4.1 The general extents and stratigraphical ranges of British Carboniferous coalfields.

Figure 4.2 The stratigraphy of the main coal-bearing Carboniferous, showing horizons of coals referred to in the text.

Figure 4.3 Summary of the potential controls on sulphur incorporation into coal-forming mires.

Figure 4.4 Relationships between the sulphur content in the Clowne Seam and various overlying beds, including the Clowne Marine Band (see text for discussion).

Figure 4.5 Main palaeoflow patterns in the Westphalian A-C, from Rippon (1996).

Figure 4.6 Generalised contouring of sulphur data from Wandless (1959). Note that the data presented by Wandless were based on the 1957 British coal output, and tabulated weighted average sulphur contents of seams worked, per cent. However, it is considered that these data represent a good summary of British coal sulphur variations by coalfield, both in 1957 and indeed in 1997. A full study, even of the data existing in 1957, is well beyond the present scope.

Figure 4.7 Sulphur and ash variations in the Main Bright coal (Westphalian B) related to distance to a contemporary channel belt.

Figure 4.8 Sulphur and ash variations in the Threequarters coal (Westphalian A) related to distance to the Silkstone Rock channel belt.

Figure 4.9 Sulphur content of the Upper Hirst coal (Arnsbergian); regional background and local high in the neighbourhood of a vent.

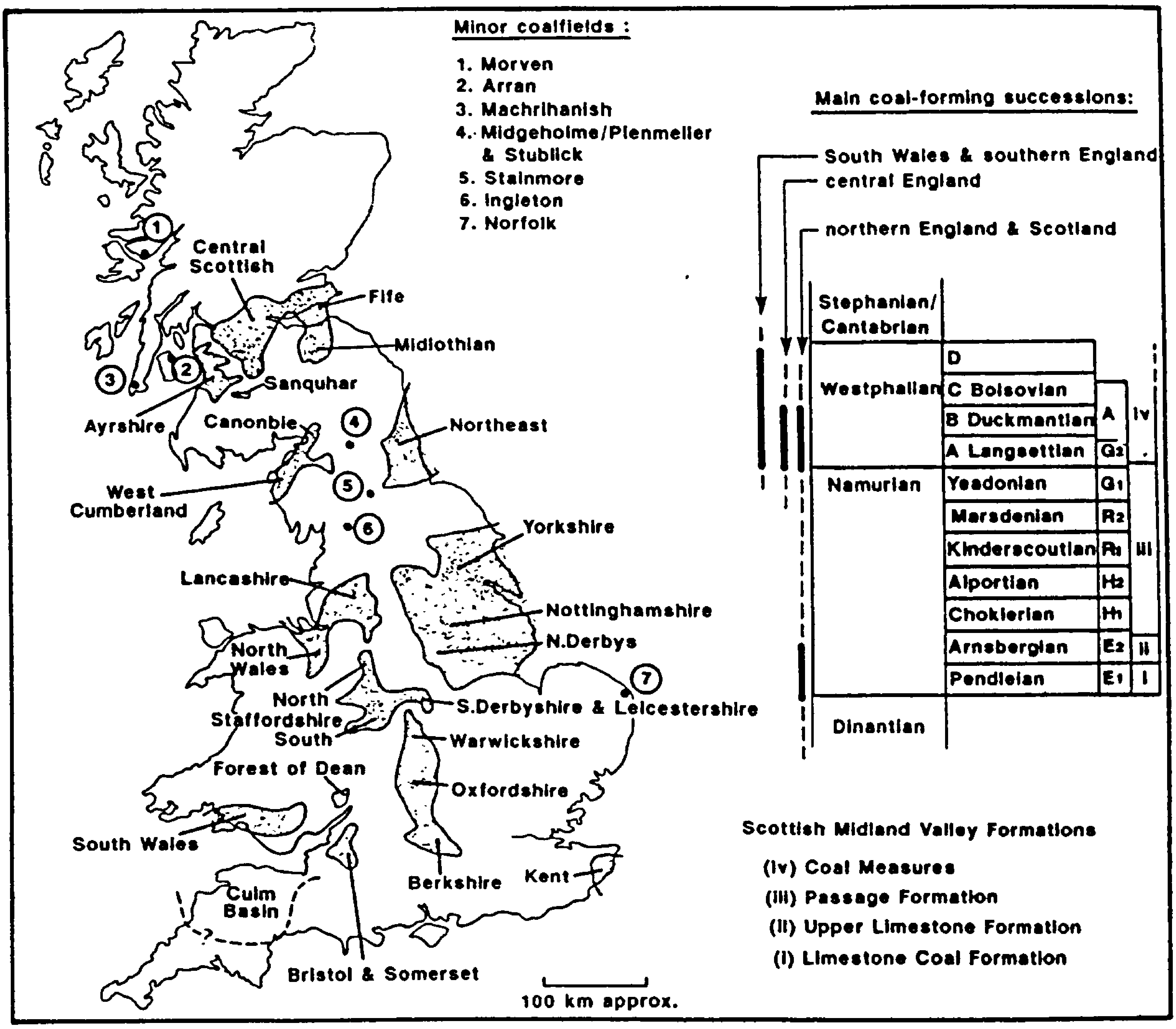
Figure 4.10 Summary of the likely relative importance of different sulphur distribution factors in the main British Upper Carboniferous coalfields.

Coalfield	Stratigraphy	Seam	Mapping basis ①	General S% range	Remarks ②	Reference
Scotland (Lothian Syncline)	Langsettian	Fifteen Foot	SLD / IC	< 1.0%	below 0.5% in syncline centre, general rise to western outcrop and the Pentland Fault	NCB 1964 (Coal Survey, Edinburgh)
Scotland (Kilsyth)	Pendleian, E1,	Meiklehill Main	?WS	< 1.0%	no regional trend, mainly organic sulphur	NCB 1960 (Coal Survey, Edinburgh)
Scotland (Central)	Pendleian, E1,	Wilsontown Main	SLD / IC	< 1.0%	little variation NB:- Lingula - horizon close below	NCB 1959 (Coal Survey, Edinburgh)
Scotland (Stirling)	Pendleian, E1,	Bannockburn Main group	SLD and SLD / IC	< 1.0%	some very low values <0.5%; little variation; N.B. Lingula horizon in roof of Bannockburn Lower Main	NCB 1964 (Coal Survey, Edinburgh)
Northeast England (Durham)	Duckmantian	Hutton	SLD / IC	Composite seam 1.0 - 2.5%; 0.8% - 1.3% organic	very variable trends across coalfield	NCB 1961 (Coal Survey, Newcastle)
Northeast England (Northumberland)	Langsettian	Beaumont (or Harvey)	?WS	< 1.0% to >3%	broad regional increase west to east	NCB 1957 (Coal Survey, Newcastle)
Northeast England (Northumberland)	Langsettian	Busty	SLD	0.5 - 1.0% locally >1.5%	no overall pattern	NCB 1961 (Coal Survey, Newcastle)
Northeast England (Durham)	Langsettian	Busty	SLD / IC	0.5% - 1.0% locally >1.0%	up to 1.5% in east and north, but no particular pattern	NCB 1959 (Coal Survey, Newcastle)
Pennine Basin (Lancashire)	Duckmantian	Crombouke	SLD	< 1.5 - 2.5%	increase W to >3.0%	NCB 1960 (Coal Survey, Chester)
Pennine Basin (Lancashire)	Duckmantian	Rams	SLD	< 1.0 - >2.5%	no particular pattern	NCB 1959 (Coal Survey, Chester)
Pennine Basin (Lancashire)	Langsettian	Trencherbone	SLD / IC	< 2.5%	prominent rise to >3.0% in west and north	NCB 1959 (Coal Survey, Chester)
Pennine Basin (Lancashire)	Langsettian	Peacock	SLD / IC	> 2.0%	often >3.0%; locally >4.0% on coalfield west and east margins	NCB 1959 (Coal Survey, Chester)
Pennine Basin (N.Staffordshire)	Duckmantian	Moss	SLD / IC	0.5 - 1.0%	mainly organic sulphur; slightly higher along NW boundary close to Red Rock Fault	NCB 1959 (Coal Survey, Birmingham)
Pennine Basin (N.Staffordshire)	Langsettian	Banbury	SLD / IC	1.0 - 2.0%	increases along NW boundary towards Red Rock Fault	NCB 1959 (Coal Survey, Birmingham)
Pennine Basin (Yorkshire)	Duckmantian	Meltonfield	SLD	1.0 - 4.0%, generally 2.0 - 3.0%	organic sulphur generally 0.9 - 1.2%; broad regional variations; N.B. close above Maltby M.B.	NCB 1965 (Coal Survey, Sheffield)
Pennine Basin (Yorkshire)	Langsettian	Fenton	SLD	1.5 - 3.0%, Low Fenton generally >3.0%	no obvious regional pattern	NCB 1959 (Coal Survey, Sheffield)
Pennine Basin (Yorkshire)	Langsettian	Parkgate	SLD	1.5 - 2.5	durains only 0.6% - 0 - 9%; no obvious regional pattern	NCB 1959 (Coal Survey, Sheffield)
Pennine Basin (Yorkshire)	Duckmantian	Thorncliffe	SLD, SLD / IC	durains 0.5-1.0% brights >1.5, sometimes >3.5%	broad regional variations	NCB 1964 (Coal Survey, Sheffield)
Pennine Basin (Nottinghamshire & N. Derbyshire)	Duckmantian	Threequarters	SLD	< 2%	prominent W - E regional zones with pronounced high along northern margins adjacent Silkstone Rock; and in south to N. and W. of Nottingham	NCB 1959 (Coal Survey, Nottingham)
Pennine Basin Southern Margin (Shropshire)	Duckmantian	Top	? WS	0.5 - 0.8%	essentially all organic sulphur	NCB 1965 (Coal Survey, Dudley)
Pennine Basin Southern Margin (Warwickshire)	Duckmantian	Two Yard	? WS	0.5 - 1.5%	general increase to SE	NCB 1957 (Coal Survey, Birmingham)
Pennine Basin Southern Margin (Warwickshire)	Langsettian	Seven Feet	SLD / IC	1.5 - over 5%	values 5.0 - 6.0% over wide areas, decreasing to 1.5% to N.E. and South; N.B. close below Vanderbeckei M.B.	NCB 1957 (Coal Survey, Birmingham)
Pennine Basin Southern Margin (Warwickshire)	Langsettian	Bench	? WS	0.5 - 1.5% (Top Bench, 2.0 - over 4.0%)	generall increase to NW and SE	NCB 1957 (Coal Survey, Birmingham)
Pennine Basin Southern Margin (Leicestershire)	Langsettian	Middle Lount	? WS	1.0 - 3.0%	increases SW towards Boothorpe Fault Zone	NCB 1959 (Coal Survey, Nottingham)
Pennine Basin Southern Margin (Leicestershire)	Langsettian	Yard	? WS	1.5 - 2.0%	increases towards western outcrop to >3.0%	NCB 1960 (Coal Survey, Nottingham)
South Wales	Duckmantian	Nine Feet Lower Nine Feet	SLD / IC SLD / IC	< 1% 0.8 - 1.5%	no obvious regional pattern higher, often >2.0% where combined with Bute (first significant coal above Vanderbeckei MB)	NCB 1959 (Coal Survey, Cardiff)
South Wales	Langsettian	Five Feet Gellideg	SLD SLD	0.5 - 1.0%	2.0 - 2.5% high area between Pontypridd and Hirwaun Gellideg is usually < 0.8% except where close to Lower Five Feet	NCB 1962 (Coal Survey, Cardiff)
Kent	Westphalian ?D	Kent 6 (Millyard)	SLD	1.0 - 1.5%	2.0 - 2.5% towards west	NCB 1959 (Coal Survey, Tilmanstone)

① SLD = seam - less - dirt
SLD/IC = seam - less - dirt and less inferior coal
WS - whole seam

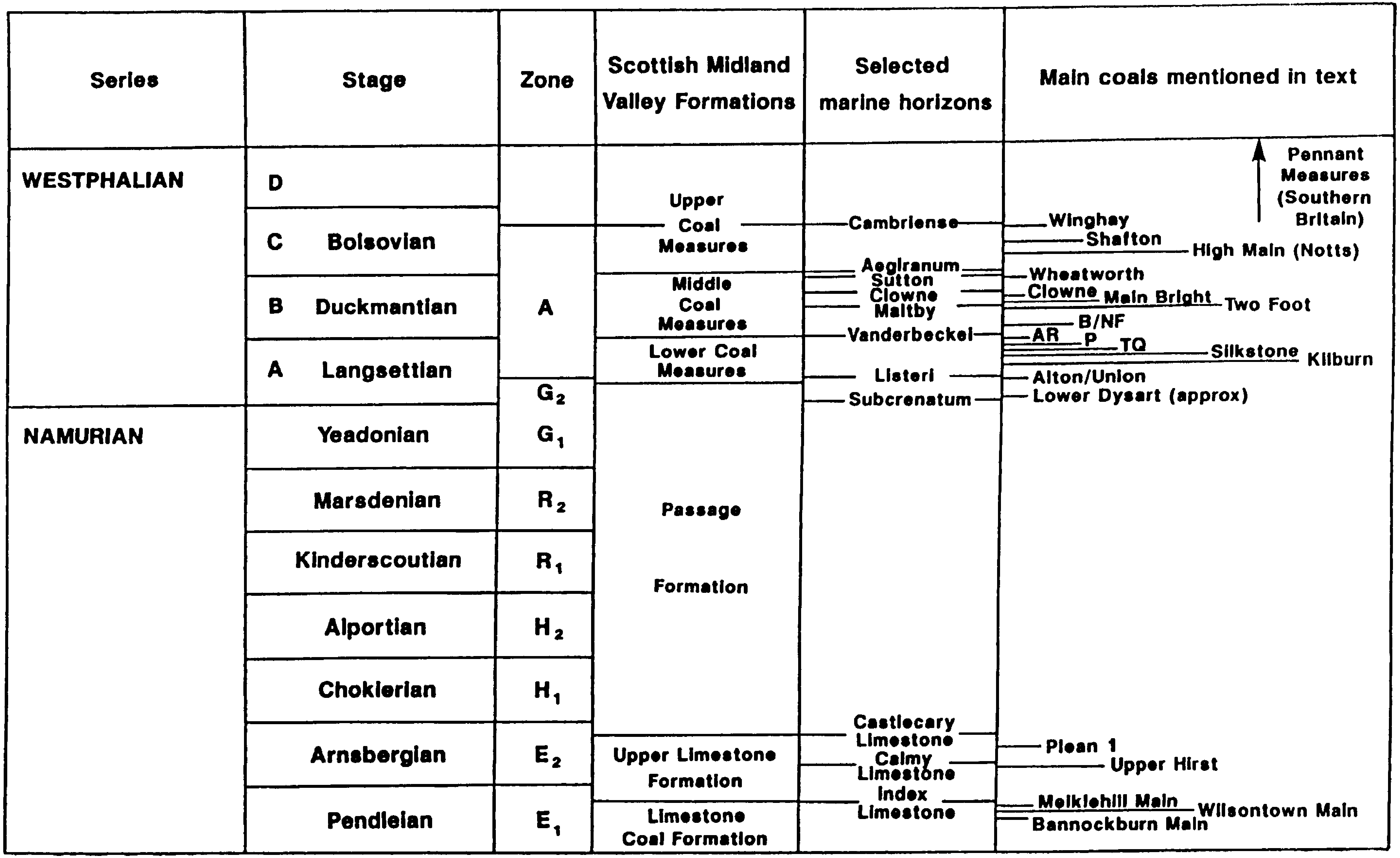
② Remarks are those of the present author

Table 4.1



Location and stratigraphical summary of the Upper Carboniferous coalfields

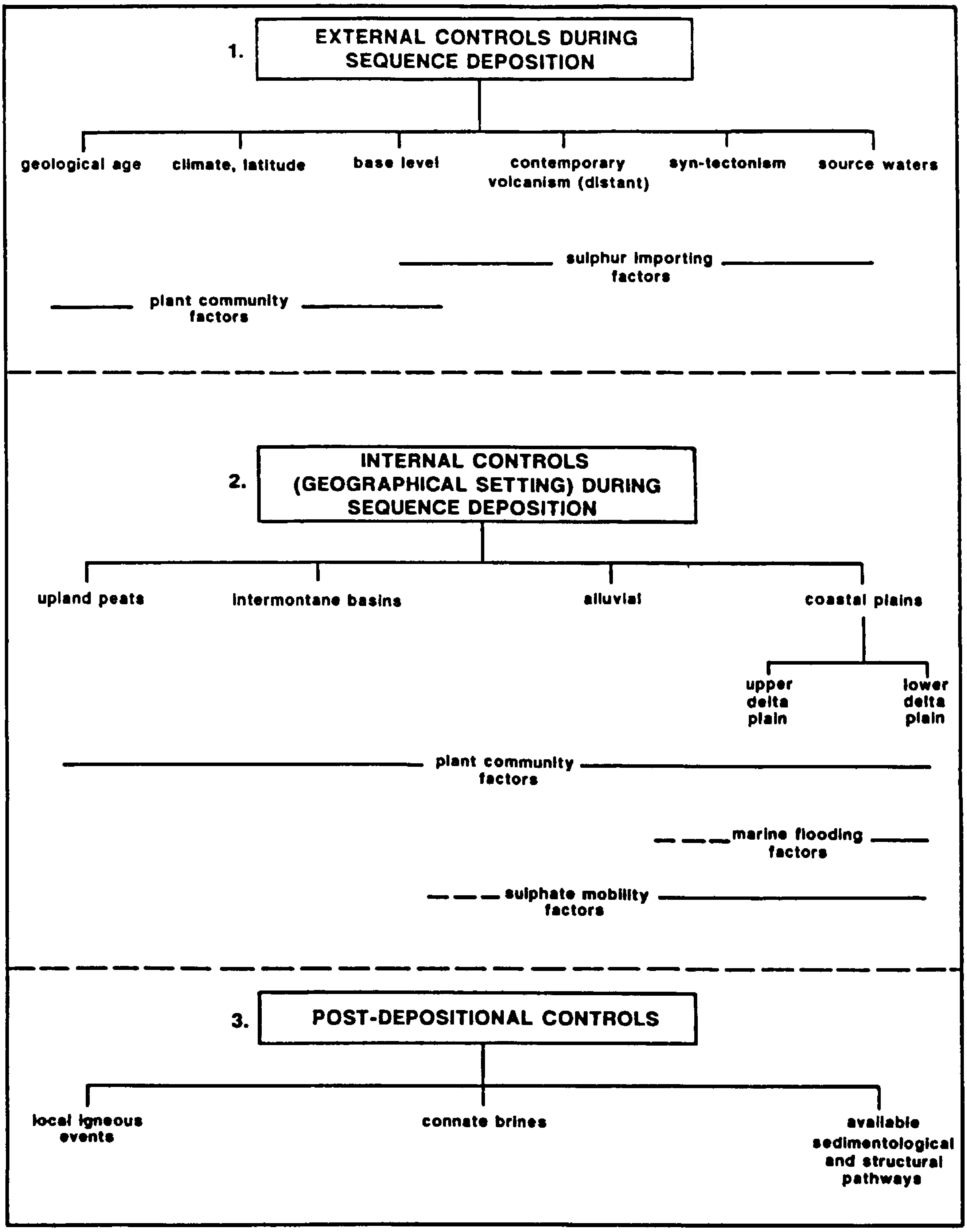
Fig.4.1



Abbreviations AR, Amman Rider; B/NF, Bute/Nine Feet; P, Parkgate; TQ, Threequarters

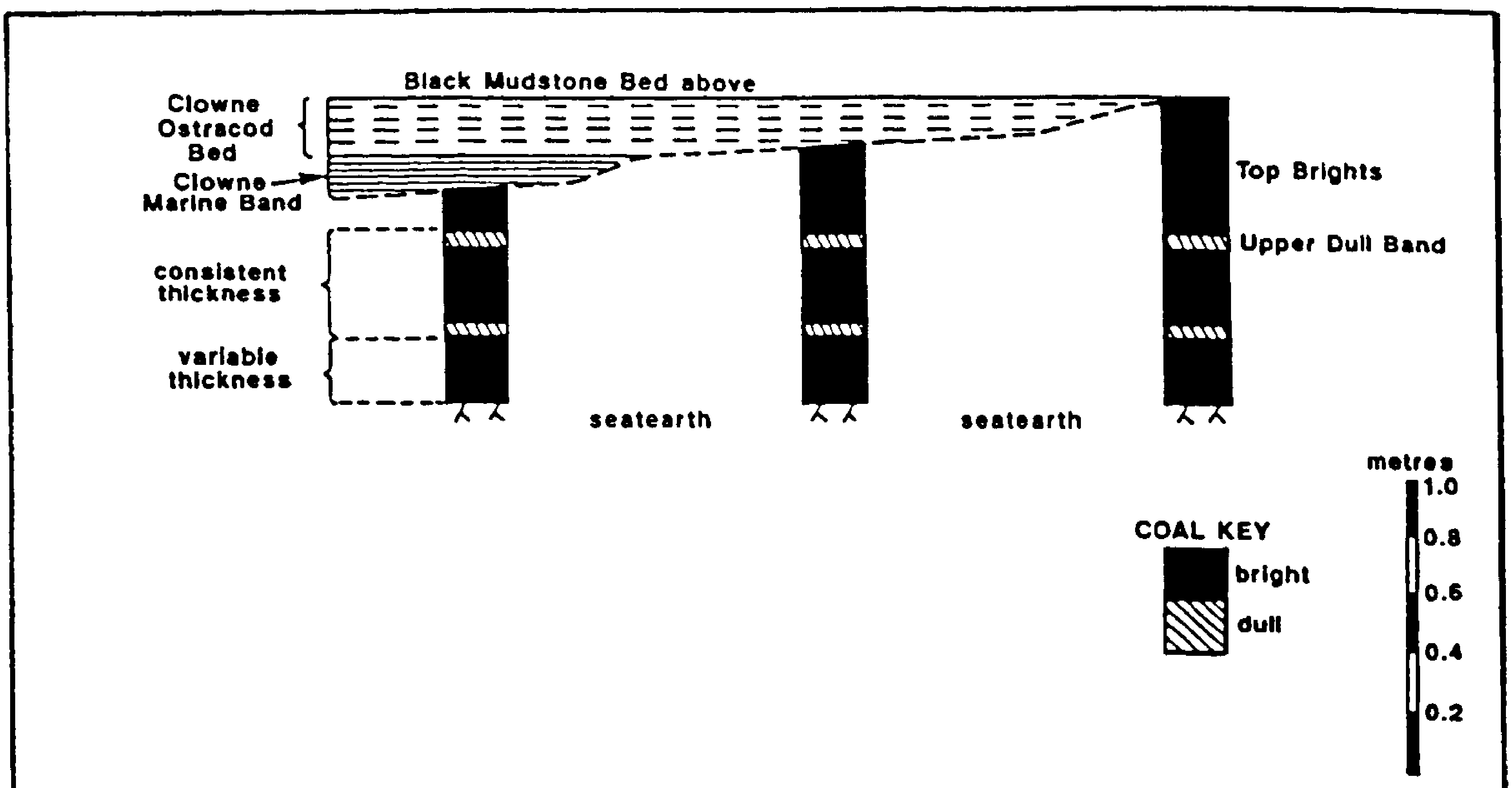
STRATIGRAPHICAL SUMMARY OF THE COAL-BEARING SILESIAN

Fig.4.2

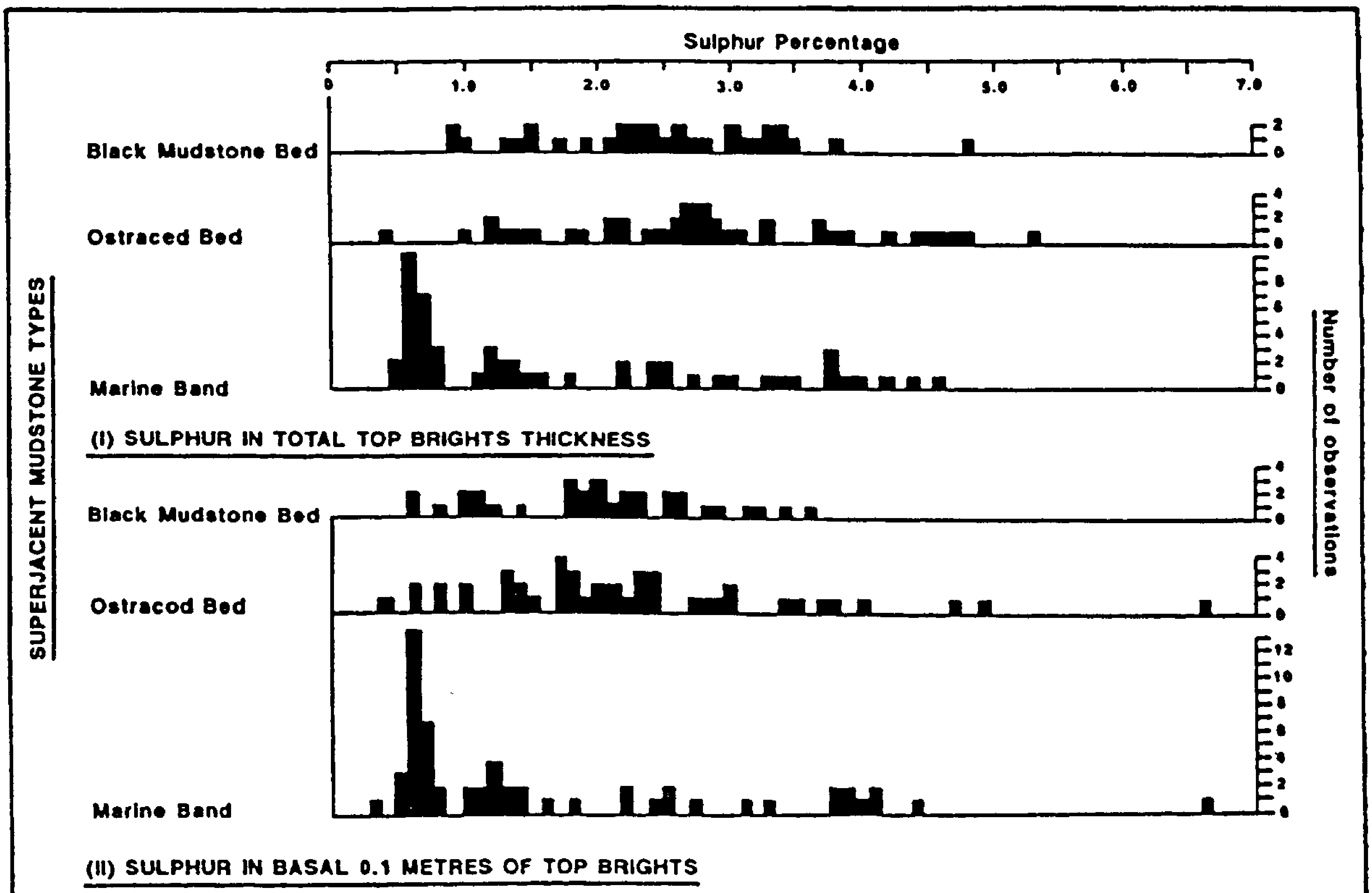


POSSIBLE FACTORS CONTRIBUTING TO THE DISTRIBUTION OF SULPHUR IN PEATS AND COALS

Figure 4.3



a. The relationship between thickness of the Top Brights coal and the overlying mudstones (diagrammatic)



b. Sulphur variations in the Top Bright coal related to superjacent mudstone type

SULPHUR DISTRIBUTION IN THE TOP BRIGHTS OF THE CLOWNE SEAM (WESTPHALIAN B)

RELATED TO THE CLOWNE MARINE BAND

based on Rippon (1984)

Fig.4.4

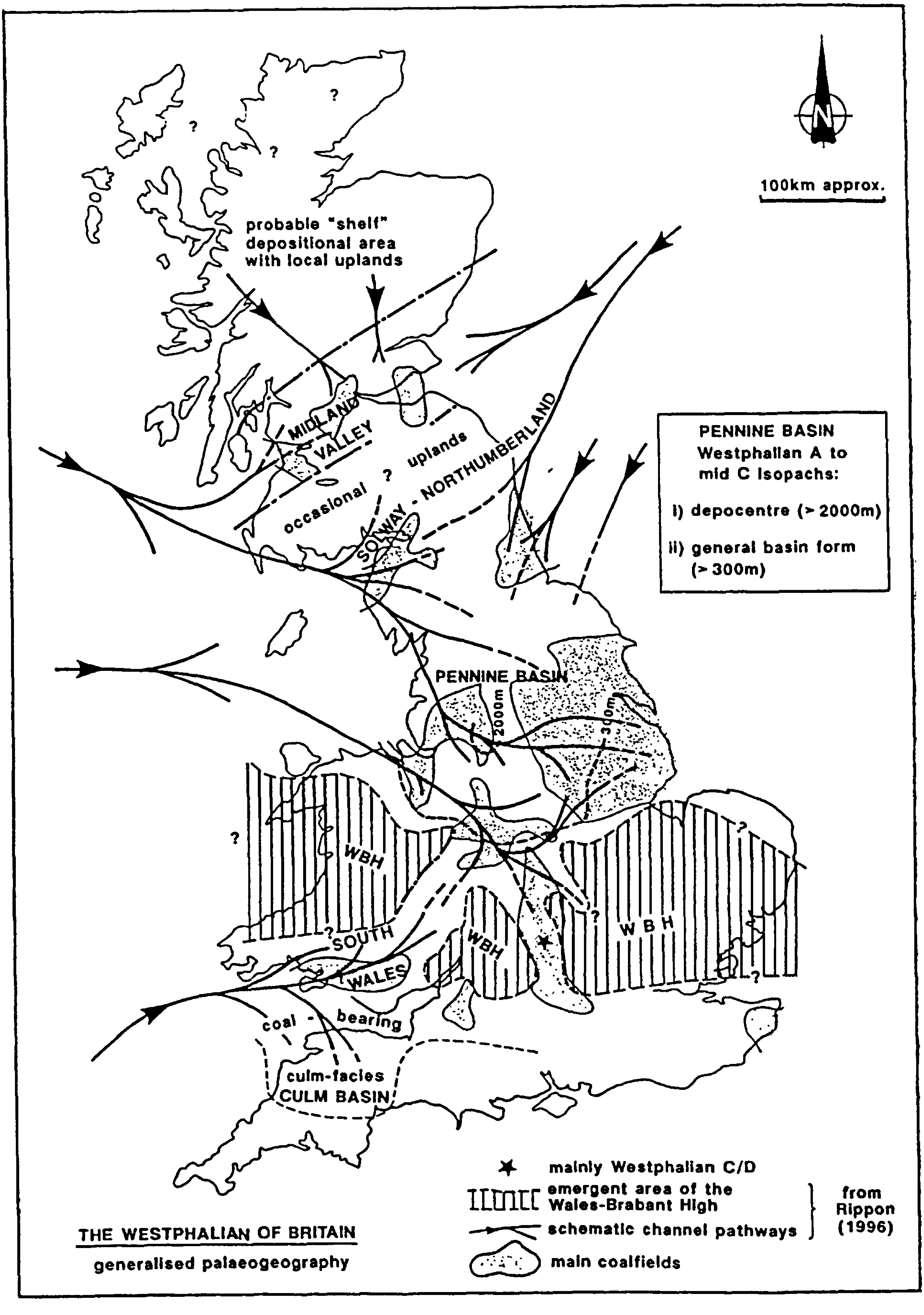
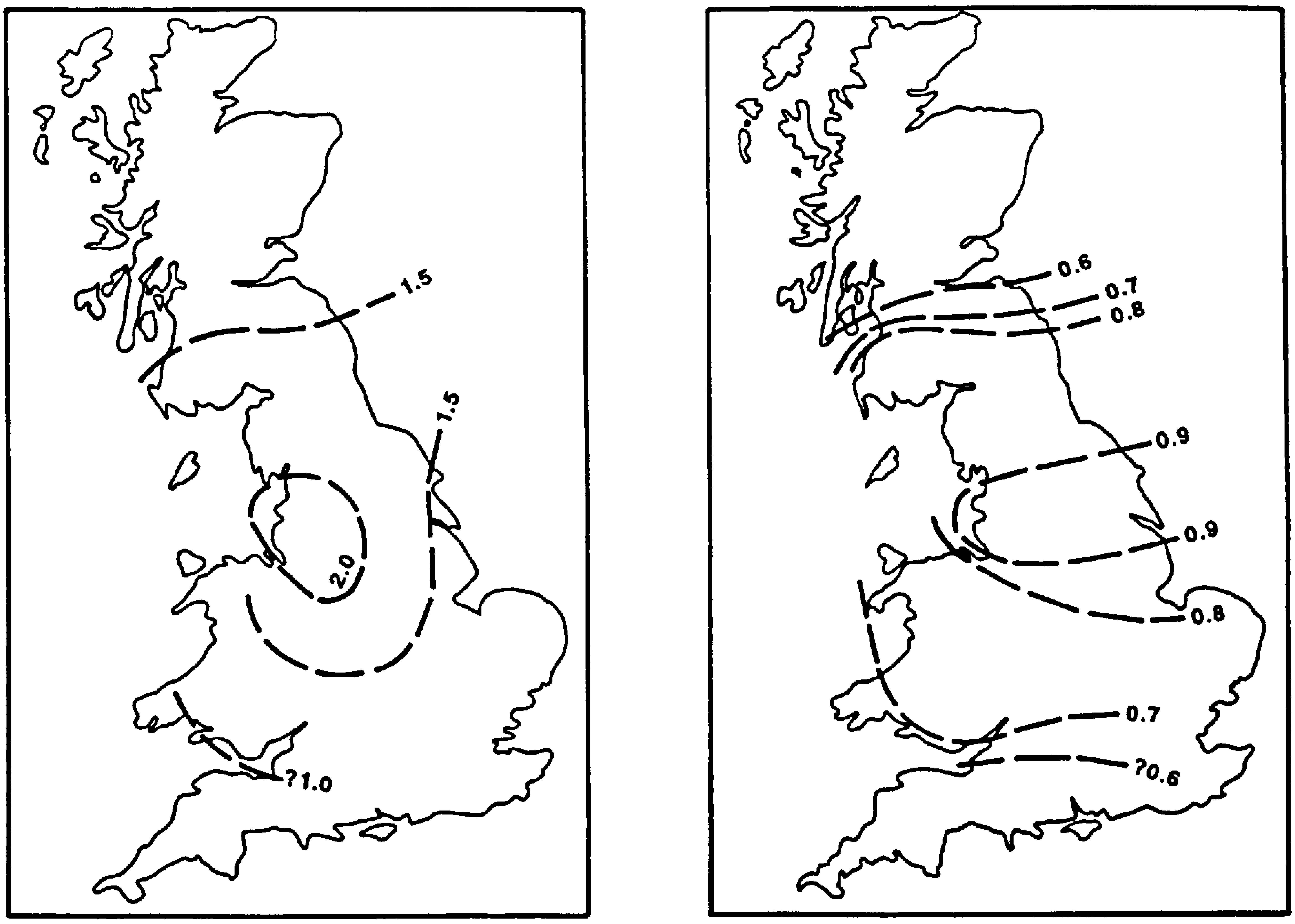

N
100km approx.
?
?
?
probable "shelf" depositional area with local uplands
MIDLAND VALLEY
occasional ? uplands
SOLWAY - NORTHUMBERLAND
PENNINE BASIN Westphalian A to mid C Isopachs:
i) depocentre (> 2000m)
ii) general basin form (> 300m)
PENNINE BASIN
2000m
300m
?
WBH
?
SOUTH WALES
WBH
W B H
?
?
?
coal - bearing
culm-facies
CULM BASIN
mainly Westphalian C/D
emergent area of the Wales-Brabant High
schematic channel pathways
from Rippon (1996)
main coalfields
THE WESTPHALIAN OF BRITAIN
generalised palaeogeography

Fig.4.5



A. Total sulphur %

B. Organic sulphur %

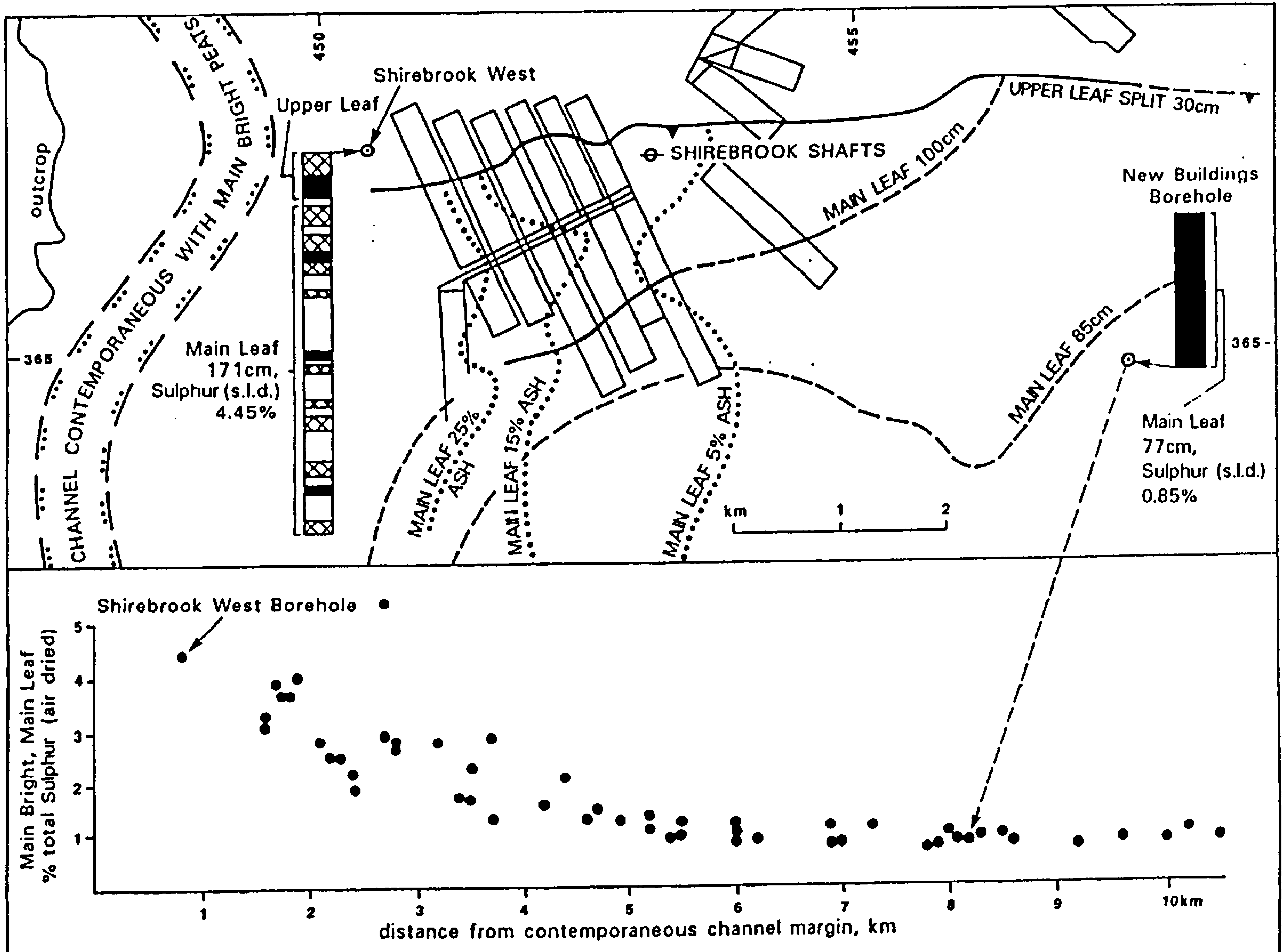
Generalised contouring of total and organic sulphur % from Wandless (1959):–

A. Based on coal outputs for 1957, excludes Bristol and Somerset, Forest of Dean and Kent (output in 1950's mainly from Westphalian D) and Warwickshire

B. Excludes Warwickshire; based on all organic S% determinations by the Coal Survey to 1959.

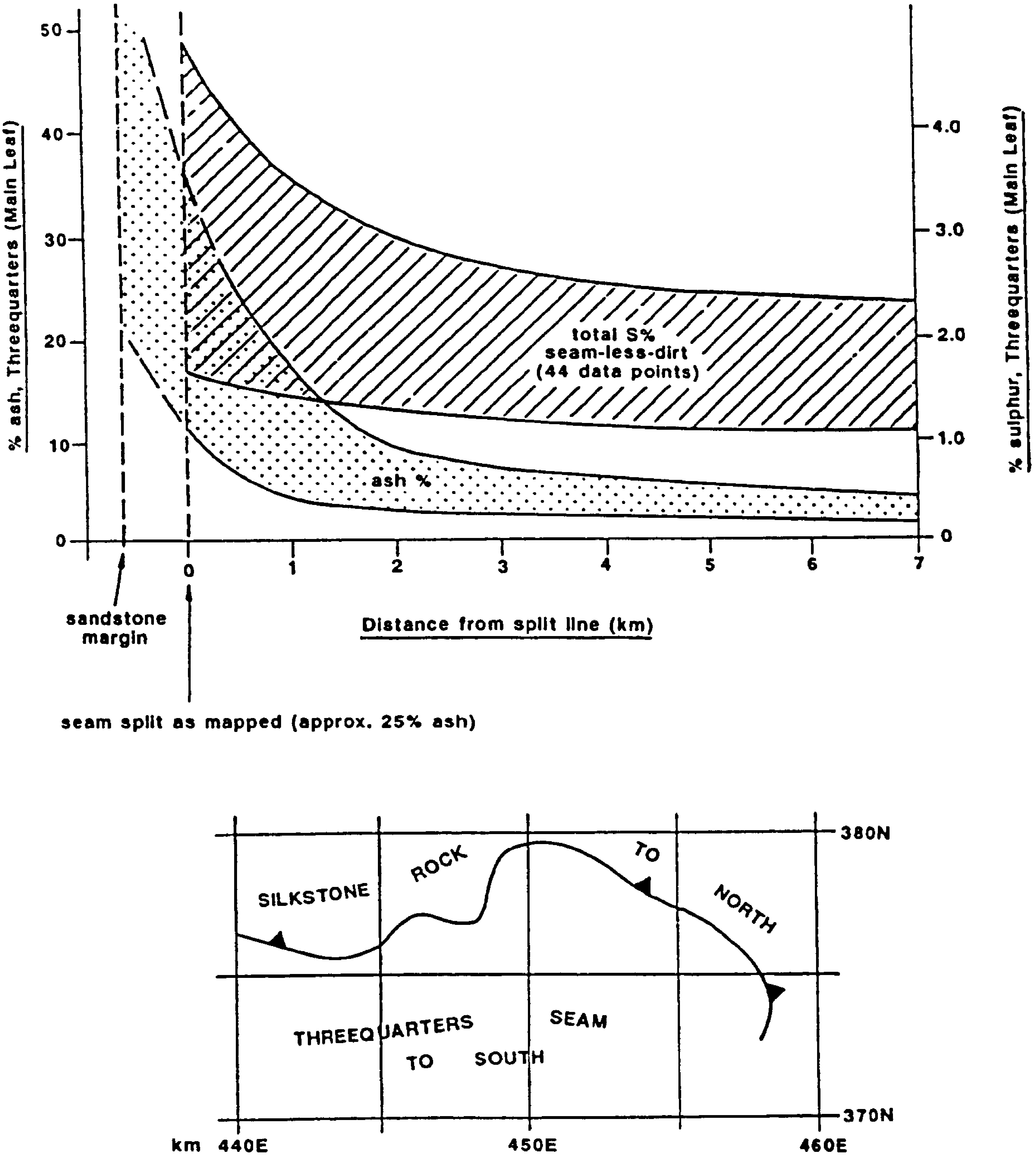
BACKGROUND SULPHUR CONTENTS OF BRITISH SILESIAN COALFIELDS

Figure 4.6



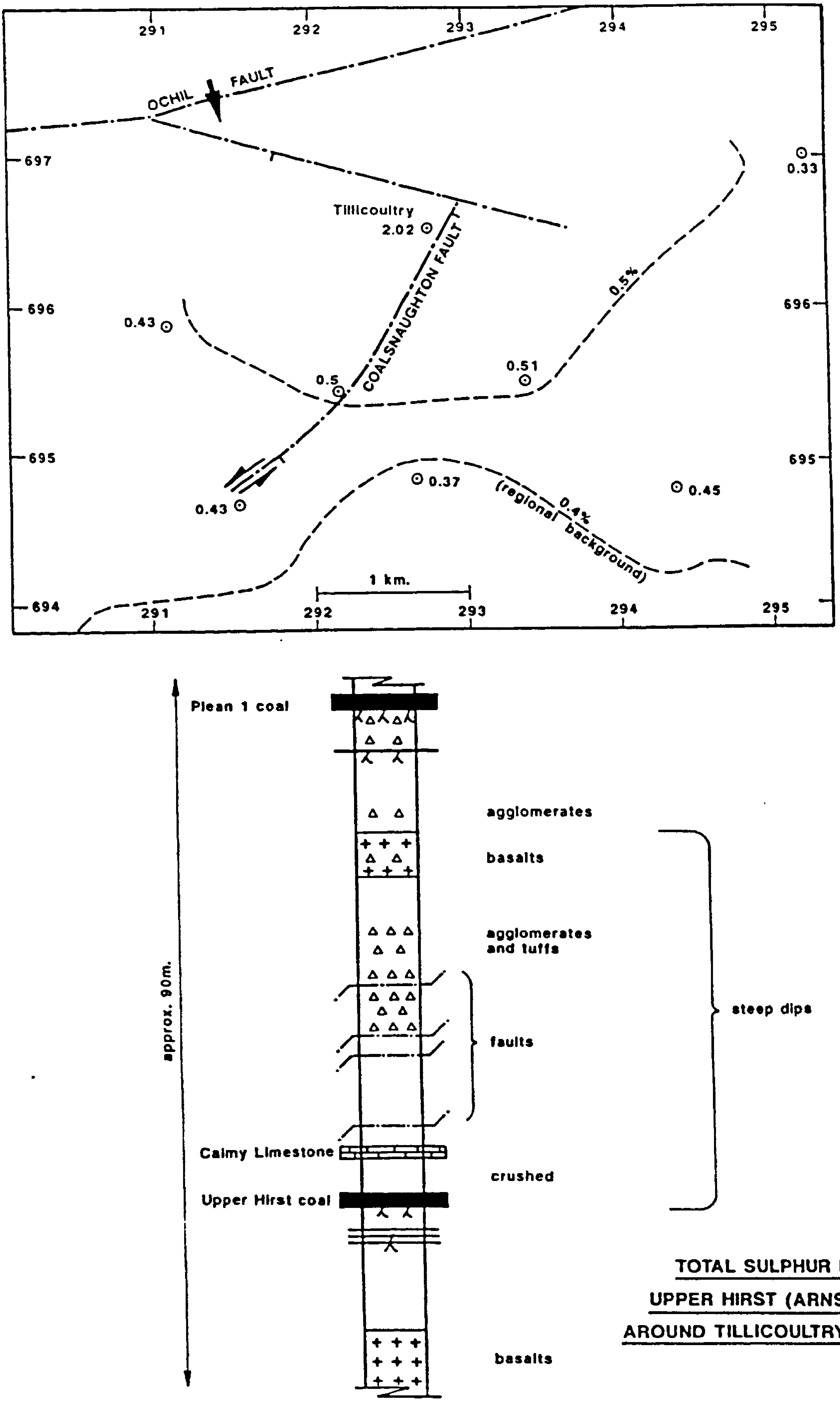
MAIN BRIGHT SEAM (WESTPHALIAN B) NORTHEAST DERBYSHIRE

Fig.4.7



MULTIPLE SPLITTING OF THE THREEQUARTERS SEAM TOWARDS THE SILKSTONE ROCK (LANGSETTIAN): ASH AND SULPHUR VARIATIONS

Fig.4.8



TOTAL SULPHUR IN THE UPPER HIRST (ARNSBERGIAN) AROUND TILLICOULTRY BOREHOLE

Fig.4.9

		Importance of contribution to total sulphur			
		South Wales	Pennine Basin		Scotland and Northern England
			general	basin margins	
A. Regional background	1. Source waters	lower	higher	very variable	lower
	2. Connate waters (regional)	lower	higher	variable	lower (E.Scotland) higher (NE. England)
	3. Volcanism (distant)	? higher in later Westphalian C/D ?			——
B. Local effects	1. Marine floodings	very high at several horizons	very high at several horizons	variable	high at a few horizons
	2. Structural control	probably very local and minor throughout			
	3. Igneous (local)	——	——	possibly local	local (Scotland)

SULPHUR DISTRIBUTION FACTORS IN THE SILESIAN COALFIELDS OF GREAT BRITIAN

SOME POSSIBLE VARIATIONS

Fig.4.10

CHAPTER 5

THE IDENTIFICATION OF SYN-DEPOSITIONALLY ACTIVE STRUCTURES IN THE COAL-BEARING CARBONIFEROUS OF GREAT BRITAIN

Abstract: *British coalfields occupy various tectonic settings, across which syn-depositional movements can be identified on a basin scale. However, with the exception of the Scottish Midland Valley, definitive evidence for movement on specific faults is rare, especially in the English Pennine Basin. This is indicated by a scarcity of detailed structural control on coal-depositional patterns. Precursor peats probably spanned around half the available time and space during Westphalian deposition across the Pennine Basin; rarity of local structural control on coal patterns is therefore firm evidence of rarity throughout. Referring mainly to the Pennine Basin and the Midland Valley, this account discusses some likely, and less likely syn-depositional features, and proposes structural and sedimentological critieria for systematic assessment.*

5.1 Introduction

Much of the British Carboniferous is coal-bearing, particularly the mid-A to mid-C Westphalian. Significant Dinantian and Namurian coals are found in northern Britain, while Westphalian D coals are present in the coalfields of southern England and South Wales (Fig. 5.1). The main sequences have been extensively explored and mined. Many publications describe regional geology, structural setting, and sedimentology, but there is little published on syn-depositional movements and associated structures, and the existing literature does not assess the prevalence, or rarity, of movement and its effects on deposition; naturally, authors have reported examples of likely movement, rather than its absence. Rippon (in press) is based on the following account.

Syn-depositional features on all scales may be considered, from individual fault segments through to overall basin development. Post-rift fill sequences (Fraser & Gawthorpe 1990) might involve less pronounced movement on specific faults than their syn-rift predecessors. However, successions in entirely conformable areas, contemporary with intra-Silesian unconformities (other than simple oversteps) elsewhere, may show more evidence of movement, as any local unconformities may relate to regional tectonic events. Structural effects should be more noticeable near basin margins, where there is thinner mantling of basement structures: Waters *et al.* (1994) concluded that in the Pennine Basin, growth folding was present in the thicker Westphalian sequences of the central basin areas, compared with the development of angular unconformities, associated with folding and faulting, towards the basin margin.

Some structural and sedimentological criteria required for detailed assessments of syn-depositional movement, in coal-bearing sequences, are described here; detail from mining data sets is used in discussion of some examples. This account deals mainly with features in the Pennine Basin (Westphalian) of northern England, and the Midland Valley of Scotland (Namurian - Westphalian successions). Basin scale movements are considered prior to those at the scale of specific structures. Syn-depositional movements in other areas have been inferred by various authors, particularly Fielding (1984), Haszeldine (1984) and Collier (1989) in the northeast of England; and Jones (1989) and Hartley & Gillespie (1990) in South Wales.

Key issues are: 1, the distinguishing characteristics of faults which are known to be products of the depositional environment alone; 2, the specific structural and sedimentological criteria that should be applied when assessing syn-depositional movement on tectonic faults; and 3, certain basin fill characteristics, particularly the geographical and stratigraphical ranges and depositional patterns of the coals, as these should provide the best data (see below).

5.2. Data sets and previous work

Figure 5.1 illustrates the locations and stratigraphical ranges of the main coalfields. Mining data sets are large: borehole data density is commonly >50 per National Grid Quarter Sheet (25km^2); many boreholes are extensively cored, described in sedimentological detail, and geophysically logged. There is high resolution seismic reflection coverage across many areas, commonly giving resolution of fault throws less than 5m, at several hundreds of metres depth. Seismic data can aid interpretation of syn-depositional movement, but only where there is other supportive information. This is because even the higher resolution data are not able to detect smaller-scale syn-depositional relationships (say, involving fault displacements up to 10m), while in the case of larger faults, there is potential for confusing fault-controlled depositional thickenings with simple post-depositional structural dilations in hangingwalls (see later). Plans of mine workings provide a wealth of spatial data, particularly on fault patterns. The density of underground sedimentological observations reflects the susceptibility of a mined seam to depositional variations. The generally thinner coals of Nottinghamshire and northeast Derbyshire have required sedimentological logging at spacings from 100 to 200m, as mining there is more sensitive to changes in the accompanying clastics. In these eastern fields, discrimination between structural and sedimentological disturbance is often easy, giving good understanding of the detailed variations that are found in sedimentary environments alone, in the absence of any specific structural contribution.

There is a long history of geological interpretation linking variations in deposition with structure. This might suggest that such links are common; however at least some earlier interpretations were made without knowledge of the features that could be produced entirely by sedimentological, or indeed entirely by structural processes. Some accounts have been published in mining, rather than in geological literature; there are various unpublished National Coal Board/British Coal Corporation (NCB/BCC) studies. The main references are incorporated into regional summaries below; there is no existing overview of this topic.

5.3 Tectonic and depositional settings

Although there are broad regional variations, Westphalian depositional patterns found in the main coalfields show many lithostratigraphical and biostratigraphical similarities, especially the discrete marine invasions, the overall development of non-marine bivalve fauna, and the stratigraphical levels of the main coal groups (and also the onset of significantly arenaceous sedimentation from the mid-Westphalian C). These similarities indicate persistent and important external depositional controls (Chapters 2 and 3) superimposed across a variety of tectonic settings (Fig. 5.2).

5.3.1 Tectonic settings

Most Scottish fields lie within the Midland Valley, initiated as a Devonian rift, and characterised by post-rift sedimentation through the Namurian and Westphalian (Rippon *et al.* 1996). Enhanced sedimentation rates typified discrete sub-basins, while the overall depositional area may have extended well beyond the rift itself, through most of the Carboniferous. In northern England, the West Cumberland and Northeast coalfields lie across specific tectonic depocentres, and also across intervening areas (Chadwick *et al.* 1995). The fields of central England and North Wales all lie within the Pennine Basin, a large extensional province initiated by Dinantian rifting and succeeded by post-rift sedimentation in the Namurian and Westphalian (Fraser & Gawthorpe 1990). The basin is some 200 kilometres across, and includes several sub-basins.

The Pennine Basin is limited to the south by a shallow Precambrian and Lower Palaeozoic massif, the Wales-Brabant High. During the main coal forming period (Westphalian mid-A to C), this was an area of low uplands, locally breached by broad valleys preserving attenuated sequences, with possible communication with basins to the south. The high was widely overstepped by coal-bearing arenaceous sequences of Westphalian D age; its southern margin approximates to the northern limit of main Variscan thrust deformation (Rippon *et al.* 1997).

In the immediate Variscan foreland south of the high, the South Wales, Bristol and Somerset, and Kent fields are the best known. In South Wales, the main depocentre was interpreted as a Variscan foreland basin by Kelling (1988), but it is uncertain whether this interpretation is entirely valid for Westphalian A and B coal-forming successions (see 6.6.1). The Culm Basin of southwest England is only marginally coal-bearing, and is not discussed further.

5.3.2 Depositional settings

Throughout these various tectonic settings, most coal-bearing sequences were deposited on extensive and very low-lying plains. The most common environments were coal-forming mires, and fresh water lakes characterised by claystone deposition; channel systems locally invaded both of these, introducing sandstone and siltstone lithofacies. Coals and claystones are particularly interesting because they represent much of the depositional duration, and record those environments which would have combined depositional continuity with sensitivity to slight ground movements. Sluggish watercourses, filled with allochthonous cannels and draining regional coal-forming mires would have been particularly sensitive, compared with large and more energetic channel belts. Examples of spatial variations in claystone and coal lithofacies are given in Elliott

(1969), Rippon (1984), Fulton (1987), Rippon & Spears (1989), and Guion *et al.* (1995a). Rippon (1996) gave an overview for Westphalian channel sand systems, interpreting three main fluvial inflow directions. Aggradational channel belts characterised most stratigraphical levels, and reflected a different set of depositional controls to those affecting coal development, which was seen as depending largely on basin subsidence. Marine invasions were inferred as essentially alien to the overall fluvial-deltaic system, which normally prograded into large lakes.

Coal-bearing sequences have traditionally been interpreted as cyclical, with coal succeeded in turn by faunal claystones, siltstones and fluvial sandstones, prior to palaeosol development and mantling by the next precursor-peat. In practice, the cyclicity is extremely complex, in terms of lithofacies variations, diachronism, and thicknesses, reflecting the interactions of basin subsidence with distributary systems and external depositional controls. For the present account, the important aspects of cyclicity are firstly, that it is a valid method of describing (and correlating) coal-bearing sequences; and secondly, that thicknesses of individual cycles rarely exceed 10m.

5.4 Basin-scale syn-depositional movement

When considering depositional characteristics, it is useful to distinguish those parts of the overall depositional area that extended across tectonic depocentres (basins, sub-basins), from those across more stable areas, where subsidence was slower and more uniform. Apart from much of the Northeast coalfield of England, lying across the eastern extension of the Alston Block (Fig. 5.2) most presently extensive fields developed mainly within tectonic depocentres.

5.4.1 Sub-basins, Midland Valley of Scotland (Dinantian to Westphalian)

It is beyond the scope of this account to comment fully on these which, together with their intervening palaeo-highs, are known to have profoundly influenced sedimentation, probably throughout the Carboniferous. Francis (1991a) and Read (1988) give many descriptions and interpretations, while Rippon *et al.* (1996) interpreted the evolution of one of these, the Kincardine Basin, in detail (Chapter 9). The following summarises main conclusions from the literature.

1. The sub-basins have complex geological histories, in which basin formation mechanisms are not always obvious, but usually referred to major faulting (sometimes unseen) in the Lower Carboniferous or earlier, in overall strike slip regimes. 2. Later Namurian and Westphalian fills are post-rift in most areas. 3. Isopach patterns suggest that some end-Carboniferous synclines are offset from depositional precursors. 4. Coals are significantly thicker in sub-basins. 5. Correlation within and between sub-basins is usually straightforward. 6. Differing subsidence rates applied to different periods within each sub-basin; each had its own overall rate. 7. Intervening highs may have greater fault densities, and many minor folds, and there may have been more venting (but because coal sequences are commonly eroded, there are fewer details from mining data).

Apart from the main sub-basins, smaller and more individual features are known. The union of seams forming the Quarrelton Thick (Dinantian) southwest of Glasgow reflects topographical variations across an igneous pile, whereas spectacular coal thicknesses in the Westfield Basin (Namurian to Westphalian) of Fife are more directly structurally controlled (Francis 1991a).

5.4.2 Sub-basins, northern England (Westphalian)

The West Cumberland and Northeast coalfields lie largely across inter-basin areas, but both also cross the major northerly-downthrow Maryport-Stublick-Ninety Fathom fault system which defines the northern margin of the Alston Block; a well-defined sub-basin extends northeast from West Cumberland into Canonbie, on the Scottish border (Chadwick *et al.* 1995). The Northeast field also crosses the continuation of the southern margin of the Alston Block, defined by the large Butterknowle Fault. Enhanced depositional rates may be deduced for these structural lows.

5.4.3 The Pennine Basin, and its sub-basins (Westphalian)

The overall form of the Pennine Basin in the Westphalian is illustrated by the isopach maps of Wills (1956). Aspects of the regional depositional setting are described by Fulton & Williams (1988), Guion *et al.* (1995a), Rippon (1996) and Waters *et al.* (1996). Subsidiary depocentres are known, tens of kilometres long, and a few kilometres wide, which perpetuated Dinantian rifting structures. Active structures might be less detectable towards the basin centre, with deep sediment mantling, than on the margins, and it is assumed that the overall basin has considerable internal compartmentalisation that will rarely be obvious in the depositional record (indeed much of which is now eroded). Care is necessary when considering the terms "basin" and "trough" in earlier literature (e.g. Edwards 1951) as these may refer only to post-Carboniferous structures; for example, the "Maltby Basin" and "Farnsfield Trough" probably have no syn-depositional relationships. It is however, interesting to note some earlier speculations on "lines of change" across the eastern coalfields, which were only poorly defined, if at all, by known structures. Some of these were anecdotal, others have been investigated geologically, but not using recent data (e.g. the "Holme Disturbance" of Bromehead *et al.* 1933, based on formation isopachs and coal variations). While presently unsupported by modern geological analysis, some of these may represent zones of real change across deep-seated, occasionally reactivated structural lines.

The Gainsborough Trough, Edale Gulf, and Widmerpool Gulf are sub-basins, defined by Namurian isopachs, and inherited from Dinantian rifting (Kent 1966). They lie within the overall Pennine Basin, trending WNW-ESE towards its eastern and southeastern margins. Their influence through at least Westphalian A and B times is revealed by re-entrants in formation isopachs (Rippon 1996): all three close eastwards. Their Westphalian development is best known from the Gainsborough Trough and Widmerpool Gulf.

The Gainsborough Trough (Kent 1966, 1985; Gaunt 1994; Corfield *et al.* 1996) occupies the hangingwall of a fault zone that trends NW-SE from the Craven faults of northwestern Yorkshire, and known through the coalfield as the Morley-Campsall/Askern-Spital zone. Its northeastern structural boundary is well defined by this zone, with formation isopachs swinging tightly along it. The southerly side is much less definite, although the boundary (Kent 1985) conforms well with Westphalian isopach patterns; the sub-basin includes within it a line of prominent W-E folds and faults (e.g. the Walkeringham-Gainsborough Anticlines) that may themselves mark another deep-seated structure (see 6.6.2). Figure 5.3 shows selected isopachs for the mid-A to top Westphalian B succession, and illustrates differences in the net depositional rate between the footwall high to the northeast, and the sub-basin, by cross-plotting depths to stratigraphical levels in suitable boreholes. Assuming no structural complications, a 45^{o} slope on this graph would indicate equal rates of subsidence in the two areas. An increase of 5^0 is equivalent to nearly 20% increase in interval, and the plot allows comparisons through the succession. The inset table shows the proportion of sandstone varying generally between 15 and 25% for the chosen boreholes. Many other local boreholes (not chosen because of faults, or uncored lengths) substantiate the conclusion that the proportion of sandstone does not increase noticeably within the sub-basin. The main thickening is in claystones and siltstones, and the overall picture is of a passive fill, with channel belts being generally incidental. It may have been that the sub-basin's Westphalian history was essentially compactional, with no large-scale or frequent active movement on the controlling fault zone, but some coal depositional patterns suggest growth anticlines in the footwall high (Edwards *et al.* 1940, Giles 1989). Also, Rippon (1996) noted that some channel belts lay within the trough while others crossed it, implying either that the hangingwall basin developed too slowly to influence the more energetic environments, or that movement was selective on certain segments, at certain times. The present structural character of the controlling fault zone suggests strike slip movement, assumed to be at least mainly post-depositional (Chapter 6; Table 6.1).

The Widmerpool Gulf is similar. Its northeasterly boundary is defined by the Cinderhill Fault near Nottingham, and its southerly boundary by the Hoton Fault (Fraser & Gawthorpe 1990). Mining data suggest that these faults and others on similar trends were pathways for some of the intra-Westphalian sills and lava flows that are found in the Nottingham area (Chapter 8; Burgess 1982), suggesting continuing extension. The Cinderhill Fault is considered to have moved occasionally during the Westphalian (Barnett *et al.* 1987, from pers. comms. by R.E.Elliott). The evidence communicated by Elliott included thickness changes across the fault, mainly in the Cinderhill Main coal (Westphalian B) which is thicker in the hangingwall. The fault dips 45^0 or less through a significant succession. Westphalian channel belts cross the sub-basin at high angles (Guion *et al.* 1995b; Rippon 1996); again, it is concluded that sub-basin sedimentation involved mainly claystones and siltstones, with little or no structural influence on channel belt loci.

In the western Pennine Basin, there are only smaller identifiable subsidiary depocentres, e.g. the North Staffordshire coalfield area, illustrated by the formation isopach patterns of Corfield (1991). In South Staffordshire, Barnsley (1964) identified the "Brinsford Axis", a small positive feature paralleling the local NNW structural trend, across which several Westphalian A and B sequences are attenuated. Waters *et al.* (1994) discussed relationships between Westphalian sequences and structures towards the southern basin margin in Staffordshire, and concluded that extensional and compressional regimes overlapped, with Variscan compression eventually becoming dominant. Some specific active faults were inferred from depositional patterns.

5.4.4 Southern Britain (Westphalian to Stephanian)

Formation isopachs for South Wales show a well-defined depocentre near Swansea, with some northwards migration (Jones 1989; see also Figs. 2.10, 2.11). Late Namurian/early Westphalian centripetal drainage (2.2.4) suggests basin-scale movement, although as noted, this may not necessarily indicate a definitive Variscan foreland basin during those times. In the absence of detailed coalfield data, depocentres across southern England are likely to remain poorly known.

5.5 Fault types, styles, and origins

Detection of sub-basin scale movement is relatively straightforward, but identification of more discrete syn-depositionally-active faults requires very detailed assessment, and it is necessary to consider firstly the many structural styles that are found in the coalfields. Varied origins and reactivation histories have given rise to significant differences in fault plane geometries and linkages; the mechanical attributes of the sediments also produce style differences, especially any gross lithological variations, and the degree of compaction prior to faulting. Figure 5.4 summarises main fault categories by origins. As will be seen, not all faults in coal-bearing sequences originated directly as part of the tectonic framework, and faults of different origins have quite different field characteristics. All faults may be associated with syn-depositional movement other than those which entirely post-date the sequence; however, it is possible to confuse some purely structural effects with those resulting from syn-depositional movement (see 5.6.1 and Fig. 5.7).

5.5.1 Faults resulting solely from sedimentation and compaction processes

These do not depend directly on tectonic setting, being expressions of local depositional slope, scours, abandonments, and compaction. Nonetheless, their locations may result from tectonic influence, with seismicity promoting failures in poorly consolidated sediments. All commonly have dips that are low relative to nearby fault planes of post-depositional tectonic origin, reflecting the mechanical properties of the sediments on initiation, and compaction flattening of the plane (Elliott 1985). Although not tectonic, their recognition is important, so that they are not unnecessarily confused with faults that are. (It may be noted here that Quaternary effects in the near-surface, locally >50m deep, from ice movement and periglaciation, also produced local faults and folds.) Structures that are solely the products of the depositional environment are now described. Some examples are illustrated by Elliott *et al.* (1984).

"Faultlets" is a term used in NCB records for millimetric-scale faults that are common in lithofacies associated with channel systems. They rarely extend more than a few tens of millimetres vertically or horizontally, or have displacements greater than a few millimetres. Some are known to dip towards contemporary minor scours. Faultlets are commonly pervasive in the unlaminated siltstones interpreted by Elliott (1969) as overbank deposits.

Compaction faults result from differential compaction of heterogeneous sediments during, or soon after, deposition of a cycle. These typically extend horizontally for tens to hundreds of metres, achieving displacements of several metres. The most compactable material was peat (Elliott 1985) and compaction faults originated along channel abandonments, filled with earlier peat prior to renewed regional mantling. Arrays of normal faults lie between the resulting thicker coal along the abandoned channel, and the thinner coals above lateral levees (Rippon & Spears 1989). Displacements reflect differing peat thicknesses available for compaction. Compaction faults also lie beneath and sub-parallel to any local over-deepenings of a channel, with sets of normal faults and shears intersecting to give prismatically-fractured ground below. As such over-deepenings are usually into siltstones and claystones, the differential compaction potential is much less than if peat were involved, and displacements are rarely greater than 1m.

Rotational slips are found along channel margins where bank erosion initiated mass movement into the channel. These are tens to hundreds of metres long, locally sinuous in plan, with listric fault plane cross sections. They sole out channel-wards usually in sub-channel claystones. Throws reflect channel/levee amplitudes (Elliott 1985) i.e. rarely greater than 7m, varying somewhat unsystematically along the channel margin: locally, the toe area includes small thrusts.

"Tilted blocks" is a mining industry term (Elliott *et al.* 1984) for large (1000's m^3) bodies of sediment which appear to have foundered through several metres of clay, usually being arrested at the next significant peat surface, but locally penetrating it. These are typically of channel or near-channel lithofacies, distinguished from rotational slips by generally lesser elongation, by local non-coincidence with a channel margin, and by coalfield-wide occurrence at particular stratigraphical levels. Internally, they may contain many "faultlets", and neighbouring claystones are intensely sheared. Typical examples were described above the Meltonfield Coal (Westphalian B) of Yorkshire by Shirley (1955), who deduced initiation by contemporaneous seismicity. Mining observations have shown these to characterise this horizon; also, crevassing is extensive, and there are local unusually coarse sandstones. The overall picture supports Shirley's interpretation (Rippon 1996). Tilted blocks are, however, also known from other horizons.

Other features that may be confused with tectonic faults include: 1, structures associated with compactional effects around large siderite masses (e.g. some sigillarian trunk infills); 2, diapiric emplacement of palaeosol material into peat, where erosion has removed the unlithified overburden; and 3, structures associated with peat de-gassing.

5.5.2 Faults resulting solely from syn-depositional igneous processes

Contemporaneous intrusive and extrusive rocks are common in the Scottish Dinantian and Namurian, and more localised in the Westphalian. Lavas, sills and small vents of Westphalian A to C age are found along the southern margin of the Wales-Brabant High (Waters *et al.* 1994); sills and lavas are found in the Westphalian C/D sequences of Oxfordshire, and in the earlier Westphalian of Berkshire (Poole 1977; Foster *et al.* 1989). Igneous features are known to have produced a range of associated fault styles, e.g. radial and ring patterns around vents; crypto-volcanic vents were interpreted by Bamett (1985). Usually, they can be distinguished from faults of obvious sedimentary, or directly tectonic origins by field relationships with known or suspected igneous bodies, and by their irregular traces and non-systematic throws, which are rarely greater than 5m. Vent locations can locally be related to specific faults, or to more regional structural features, e.g. the Bumtisland Anticline and Bo'ness Line in the Scottish Midland Valley (Francis 1991a; Rippon *et al.* 1996).

5.5.3 Gravity slides

These may or may not directly reflect tectonic movements. Gravity slides affecting up to hundreds of metres of sequence and many stratigraphical levels, and which are typically arcuate structures downthrowing to the progradation direction on major distributaries, have not been positively identified in the coal-bearing Carboniferous of Great Britain; they probably characterise more down-palaeoslope settings (Chisholm 1977). Large listric-geometry normal faults have however been described in South Wales. Typically, these have steep fault plane dips in their upper parts, flattening to bedding-parallel at depth, e.g. the Jubilee Slide faults detailed by Woodland & Evans (1964). These authors noted the possibility of syn-depositional origins, based on listric geometry, and the arrays of arcuate fault traces in the higher stratigraphical levels, attributes considered by Crans *et al.* (1980) to support a large-scale gravity slide interpretation. All authors (see Jones 1989 for a full bibliography) except Crans *et al.* (1980) considered a syn-depositional interpretation to be at best unproved; altemative explanations included their origins as Variscan thrusts modified by Mesozoic extension. The consensus is that there is little evidence for significant sedimentological variations across them, although syn-depositional initiation cannot be ruled out.

Although there is little or no evidence for such large scale gravity slides, there are many smaller scale examples, usually described from lacustrine environments; some coalfield examples are noted later. Some may have been triggered by distant seismicity and some may relate to specific faults growing to intersect the contemporary free surface. Others may have no direct tectonic relationship. Gravity slides therefore appear twice on Figure 5.4.

5.5.4 Faults that are purely tectonic in origin

These form the great majority, with displacements ranging from less than a metre to more than a kilometre, and including many styles of normal, strike slip, and thrust faults and their variants. Some, especially those representing inherited structural features (Chapter 6), were syn-depositionally active. The great majority are considered entirely post-depositional, based on their relationships at different stratigraphical levels and their general field attributes. The systematics of tectonic normal faults in the coalfields have been considered by (e.g.) Rippon (1985), Barnett *et al.* (1987) and Walsh & Watterson (1988a, b; 1989). Normal faults are those usually cited for syn-depositional movement, reflecting their extensional character in basin settings. However, large strike slip fault zones have also been described as contemporaneously active, especially in Scotland (Francis 1991a). Variscan thrusts deforming the coals of South Wales are post-depositional, but minor folds are thought to have been partly syn-depositional (Jones 1989).

5.6 Some criteria for assessing syn-depositional movement on tectonic faults

Before describing some examples, it is necessary to discuss criteria for assessing causal relationships; this has not previously been made for the coal-bearing Carboniferous sequences. Ideally, evidence for syn-depositional movement should come from both structural and depositional patterns. For British coalfields, structural patterns are usually evident from published maps or publicly-available mining plans. However, depositional patterns are accessible only in occasional publications, or in NCB documents; Guion *et al.* (1995a) provide generalisations on the geometries of main lithofacies, and Section 5.6.2 reflects NCB mapping experience.

5.6.1 Structural criteria

Given the range of fault styles, sizes, and multi-phase movements, it is impossible to detail all potential syn-depositional structural features here. This account attempts some generalisations, particularly relating to normal faults (Fig. 5.5). Figure 5.5 (1a) shows the throw contour pattern for an idealised blind normal fault with no syn-depositional history (Rippon 1985; Barnett *et al.* 1987). The fault grows radially from its initiation point, its pattern unrestricted (Nicol *et al.* 1996) by any other feature; its ultimate maximum throw results from compounding subsequent displacements at the centre. The elliptical tip line is a zero throw contour. The adjacent rock volume is necessarily strained, ideally to an ellipsoid (Barnett *et al.* 1987), with dilational strain in the upper hangingwall and lower footwall, and contractional strain in the lower hangingwall and upper footwall. Some normal faults can be contoured to a close-to-ideal shape in most coalfields, but modifications are general, usually resulting from proximity to other faults, from multi-phase movements, or from some strike slip component (see 6.6.2). Intersection of the free surface during fault growth will give different patterns (Fig. 5.5 (1b), redrawn from Nicol *et al.* 1996, again idealised): it will be less easy to identify this, given interaction with other faults, effects of gross lithological change, or simply erosion of the upper horizons (most good multi-horizon data will be in exposed coalfields).

Again considering fault systematics, another criterion may be the rate of change of throw across the fault surface. Where a fault is defined such that its maximum throw point, and at least one (upper or lower) tip line is known, then the vertical displacement gradient (that is, the rate at which the displacement reduces, up or down the fault plane from the maximum) can be determined. In the eastern Pennine Basin, vertical rate of change varies with maximum throw, ranging from 1 in 300 to around 1 in 50, more rapid attenuations characterising greater maximum throws (Fig. 5.6). This range is compatible with the displacement gradients of Huggins *et al.* (1995) and Nicol *et al.* (1996) who noted that greater rates are characteristic of relay zones, and also where there is significant lithological restriction. However, the attenuation rates of the larger "W-E" faults in the Kincardine Basin (Chapter 9) commonly achieve 1 in 5 or even 1 in 3. Figure 5.6 does not attempt to link all observations generically, and the Kincardine Basin plots, although possibly compatible with the field trend shown, may require an entirely different fault growth mechanism.

In this connection, it should be noted that some of these W-E faults were probably initiated during the Namurian, and evidence for this is summarised later (5.7.1). It follows that, while main displacement on the W-E set was largely end/post Carboniferous, the relevant faults were in existence along substantial proportions of their lengths, and through a significant vertical extent, during some periods of Namurian deposition. If the evidence for syn-depositional movement given, for example, for the Langfauld Fault (see 5.7.1, and Fig. 5.9) is valid, such Namurian fault extents must have been very similar to those seen now. This suggests that syn-depositional fault plane extents attained in the Namurian were large compared with contemporaneous throw maxima, approaching (at least laterally) the tip line limits reached post-depositionally. Such faults may have grown internally within these pre-fractured limits, with an implied inherited propagation pattern through Westphalian strata. Much of this is speculative, as comparisons need to be made with low-dip normal fault systems elsewhere, but for the present discussion, it is suggested that very high displacement gradients may be supporting evidence for syn-depositional initiation.

As implied by Barnett *et al.* (1987) and Gibson *et al.* (1989), hangingwall rollovers do not necessitate a listric fault geometry, nor a syn-depositional history. Careful assessment of fault growth is needed, particularly regarding hangingwall sedimentation. Figure 5.5 (3) shows cartoons to illustrate this. For some normal faults of >100m maximum throw, the adjacent hangingwall, and often footwall, ductile strain can be quite pronounced; upper hangingwalls might be misinterpreted as showing syn-depositional growth, because of the structural dilation, and the tendency for a fault plane dip to flatten towards the fault centre (Rippon 1985). Figure 5.7 shows the uneroded parts of the Clackmannan and Alloa Faults in the Kincardine Basin, related to an idealised blind normal fault. The cross section is well constrained by mining, borehole, and seismic reflection data (various shallow boreholes and mined levels are omitted for clarity), and is illustrated merely to demonstrate the degree of volumetric change that can be assigned to structural dilation (lower footwall) or contraction (lower hangingwall); see 6.5.1 for background and terminology. Here, corresponding upper hangingwall dilation could easily be misread as syn-depositional growth, particularly if only seismic data were available; for this fault, there is no supporting evidence for syn-depositional movement at the relevant scale, within the illustrated succession.

The fault plane dip cartoons of Figure 5.5 (4, 5) require little comment. Such variations are well known in the existing literature. It is only necessary to point out that there will be many variants, reflecting initiation setting, fault style, and subsequent geological history. The upper tip line cartoons of Figure 5.5 (6) follow from the structure illustrated later in Figure 5.12. Recognition of such features will depend largely on serendipity: frequently, the tip will have been overprinted by subsequent fault growth, removed by erosion, or not have been at an observed (mined) level. A monoclinal tip does not itself require a syn-depositional interpretation, the essential ingredient is associated soft-sediment deformation, and ideally a gravity slide. Cataclasis and drag details will vary with setting and geological history; the entries on Figure 5.5 (7) are simple examples.

5.6.2 Sedimentological criteria

Figure 5.8 shows representations of common depositional patterns found in British coalfields (no actual azimuths are intended by the drawings). The sand body orientation style of Fig. 5.8 (1a, b, c) is common in many coalfields, but does not necessitate any control by a specific structure. On a regional scale Rippon (1996) suggested that some dominant trends were pre-set by major distributary trajectories without identifiable reference to specific structures, while elsewhere, they may well reflect a regional structural trend. More locally, the channel branchings and sinuosities that characterise the lower orders of a distributive hierarchy will give frequent opportunity for correlation, justified or not, with varied fault patterns (1d). It is therefore useful to consider minimum lengths for relating depositional trends to specific structures, using the extensive and well documented eastern Pennine Basin as a basis. NCB mapping suggests that, at a single stratigraphical level, channel belts (those over, say, 1km wide), need to coincide with a candidate structure for a minimum of 10km for a causal relationship to be plausible, and this assumes that depositional environment mapping also extends many kilometres lateral to the structure, for sedimentological context. Related to this, of course, is the extent of a fault line that might be implicated in one movement event, as fault zones tend to grow by segments, and the duration of a seismic episode may be relevant to that of a depositional cycle. A lesser trend coincidence might be required where co-linearity persists through many depositional cycles, and there is only one structural trend. However even then, it is still not necessarily convincing that individual channels may be related to individual structures, as can be seen in Jones (1989, figure 5) where depositional thickenings only partly coincide with synclines.

Coal depositional patterns (Fig. 5.8: 2a, 2b) offer another way of describing channel orientation patterns using different sedimentary environments, and as noted, these environments will have been more susceptible to structurally-initiated changes in elevation. Also, according to Broadhurst

& France (1986) the coals represent a very large proportion of depositional time (around 50%, estimated by R.E. Elliott, pers. comm. 1980, for the mid A/mid B Westphalian of the Pennine Basin) and therefore likely to have dominated contemporary geography. And again, it is the coals that, because of mining, provide most data. The interpretative value of the coals is only diminished if their own stratigraphical incidence reflects tectonically quiescent periods. However, the regional coal groups of mid-A to mid-C Westphalian age are correlatable over many thousands of square kilometres, and (apart from a few specific horizons) there are repeated splittings and re-unions between these main groupings. This means that a series of environmental snapshots would show continually changing patterns of widespread mire, lacustrine, and channel environments. Such geographical patterns would indicate that the coals did not represent particularly quiescent periods compared with related clastics. Hence, widespread absence of obvious structural control on coal depositional patterns will be good evidence for its rarity throughout the sequence.

Again, it is useful to consider some minimum requirements for trend coincidences. With coal splitting patterns, the degree of intricacy of a mapped split line will itself be significant. In British coalfields, the isopach used to define a seam split for mining purposes has commonly been 0.3m. Below this, patterns are largely random. In most coalfields, the 1m isopach normally gives a definitive trend (3m in South Wales, because of compressional deformation of more ductile beds) and it is proposed that this interval should have trend coincidence with a candidate structure for a minimum of 10km, before any syn-depositional conclusion may be inferred. A fairly straight line may indicate structural control, but, equally, may represent a well-established major channel belt that is not structurally controlled. Very sinuous splits are unlikely to represent any tectonic control.

5.7 Assessing syn-depositional movement on tectonic faults: some examples

Although examples illustrating the identification of syn-depositional features might be described from all major coalfields, those that are considered best documented, and helpful in discussing interpretational subtleties, are from Scotland and the Pennine Basin. This reflects the nature of the regional data sets as well as tectonic settings. Various published examples (see 5.1) from northeast England and South Wales are based mainly on opencast data, reflecting difficulties in accessing massed deep mining data. In South Wales, there are further interpretational difficulties because of the clustered deep mines data distribution. For South Wales, the reader is referred to Jones (1989) and Hartley & Gillespie (1990); see also Chapter 10 for a discussion on possible syn-depositional deformation in Kent. Regarding Oxfordshire, this large field remains un-mined, and insufficiently known to contribute to this account. However, the late Westphalian igneous province there (Chapter 8) indicates a likelihood of significant syn-depositionally-active faulting.

5.7.1 Scottish Midland Valley

In Scotland, contemporaneous intrusions and extrusions add substantially to the potential for detecting syn-depositionally active faults, compared with most English and Welsh coalfields. Francis (1991a) grouped faults inferred as syn-depositionally significant into two sets: SW-NE trending strike slip faults, and W-E trending normal faults, the former by considering both igneous and sedimentological features, the latter by their effects on sill emplacements (Francis & Walker 1987). Many references (see Francis 1991a) deal with specific movements. Examples include the SW-NE Kerse Loch/Littlemill Faults (Ayrshire), illustrating abrupt formation and coal thickness changes across fault zones, interpreted as due largely to strike slip movement; and the Ardross Fault (Fife), implicated as a vent locus, and again interpreted as an essentially strike slip feature. Contrasting with examples indicating movement on the regional tectonic faults, Kirk (1982) described Westphalian A gravity sliding near Kirkconnel (Sanquhar outlier, Fig. 5.1) that was stratigraphically restricted to one sedimentary cycle, and interpreted it as reflecting a local slope on a lake margin, with no regional significance.

Recent mining data in the Kincardine Basin support both of Francis's (1991a) generalisations, and provide further evidence for syn-depositional movement on at least some faults in the W-E set, as follows: 1. Many have low fault plane dips, commonly 45° and locally less. 2. Mining data suggest that small quasi-igneous features similar to those described by Barnett (1985), which commonly seem to reflect sill disposition (Fig. 8.5), are locally intensified adjacent to certain faults. 3. There is local evidence for subtle, and stratigraphically-specific sedimentological variations adjacent to some faults (although this is rare, and most apparent formation thickenings are essentially structural dilations). 4. There is a high vertical and horizontal displacement gradient, up to 1 in 5 or even 1 in 3 for the larger faults. None of these items would by themselves be adequate evidence, it is their combination that is important.

The Langfauld Fault (Fig. 5.9) is a prominent member of the W-E set, and is described here to illustrate several interacting features that together suggest minor syn-depositional movement during deposition of the Upper Limestone Formation. According to Rippon *et al.* (1996), the Kincardine Basin was subsiding rapidly at this time, in a generalised W-E extensional setting. Although in regional terms, the fault is part of the W-E set, it contributes to a local swing in the overall structural strike, and is aligned WNW, making it prone to minor transtensional movement, on the assumption that it was already in place. The Langfauld Fault was named by Francis & Walker (1987) as part of the Abbey Craig Fault (see Fig. 5.9) but is now known from seismic reflection data to be a separate structure. It is a complex zone in the west, and a relatively simple large fault in its central-eastern parts. The field data may be interpreted as showing movement particularly during the accumulation of peat that was later to become the Upper Hirst coal.

The main evidence is summarised as follows. 1. The (post-compaction) coal is at least twice its regional (i.e. Kincardine Basin) thickness in the immediate hangingwall area. There are also extra coals developed below, and these are not thought, from local sedimentological mapping, to be related to channel abandonments (Rippon & Spears 1989). 2. There are no other comparable thickness variations in this coal elsewhere in the basin. 3. The coal in the footwall is generally below regional thickness, and closely overlies a near-contemporary sill (Barnett 1985); there is no equivalent sill in the hangingwall (Fig. 8.5). 4. The elongation of the area of significantly thicker coal is coincident with the central and northwestern parts of the fault zone. 5. The overall fault plane dip is low, and very low in the western areas. That the thicker coal area extends across the present main western splay, and lies in the hangingwall of a lesser branch, does not reduce the argument for movement during this depositional period; cross sections of the fault zone show that the northwestern splay ("A" on Fig. 5.9) is probably the more significant element structurally, separating a simple footwall from a complex hangingwall. In summary, the data are sufficiently consistent (particularly with respect to geographical coincidences) to allow interpretation of limited movement in a transtensional setting, producing coal thickness variations across the fault zone, and magma migrations into the footwall area. (In other circumstances, thicker coal could have formed, and been preserved, in the footwall area, depending on water table balance with regional and local subsidence. Indeed there is some evidence from mining data that some coals in the underlying Limestone Coal Formation are thicker in the footwall of this fault. Usually, however, thicker coals across structural highs tend to be composites of individually thinner seams.)

5.7.2 The Pennine Basin

The Pennine Basin coalfields are extensive, have been mined at many horizons, and, especially in the eastern fields, intensively mapped sedimentologically for mining purposes. The rarity of described syn-sedimentary structures in the east is therefore thought to represent a genuine scarcity, certainly compared with Scotland. It may of course reflect thick mantling of faults active at depth, but some structures that have been identified as active lie in relatively central parts of the basin (e.g. the Brimington Anticline example, see below). Guion & Fielding (1988) summarised structures thought to have been active during the Westphalian, concluding that recognisable movement was more common in earlier Westphalian A times than later, but this may reflect the limited stratigraphical ranges that were studied. Later references include Giles (1989), Chisholm (1990), Waters *et al.* (1994) and Rippon (1996), the last inferring a general lack of structural control, even by large structures such as sub-basin bounding faults, on most channel systems.

In the western Pennine Basin coalfields, descriptions of syn-sedimentary faults are rare. Broadhurst & France (1986) investigated depositional patterns in Lancashire, but did not find any obvious structural controls; they considered that syn-tectonism should be more apparent in the coals, rather than the intervening clastics, because of the proportion of time occupied by peat accumulation. In North Staffordshire, internal NCB reports (P. Norman, in R.E. Elliott pers. comm. 1979) describe what may be small gravity slides at the Yard/Ragman horizon (Westphalian B) at Florence Colliery (E. 390500, N. 340500). These structures lie on a zone of locally increased dip, down WSW, compatible with movement on structures precursive to large post-depositional faults which trend predominantly NNW-SSE. Various unpublished NCB reports (J. O'Dell, pers. comm.

1996) describe gravity slides above the Haig Yard Coal (Westphalian A, Lancashire), and the Burnwood (Westphalian B) and Great Row (Westphalian C) Coals (South Staffordshire). These three examples are not thought to be related to tectonic faults.

The following examples from the Pennine Basin are chosen to illustrate the use of the different data types and investigative scales that apply to assessment of syn-depositional movements on tectonic faults and folds. In all these, some degree of subjectivity is inevitable, and even the best data sets will cover only a proportion of the geological record. The key point is that conclusions should be supported from both structural and sedimentological data.

The Deerplay Fault and the Union coal (Westphalian A), Lancashire. One of the few published studies from the Pennine Basin is by Broadhurst & Simpson (1983). This is instructive regarding the subtleties that can arise when investigating contemporaneous movement. Figure 5.10 shows the area investigated by these authors, together with the wider context. The evidence presented was essentially trend coincidence between the Union coal split, and the large Deerplay Fault that parallels it just northeast, together with the identification of "rigs" (small, locally arcuate clastic infills in the lower coal) as features of a contemporaneously-sloping mire surface. However very similar features to these "rigs" are known elsewhere, in places where there is no structural control. (An example is known in the First Piper coal (Westphalian A), below a small channel belt, at Pleasley (E. 451000, N. 363000) in the eastern Pennine Basin.) The Deerplay Fault, and all locally comparable faults, dips northeast, away from the splitting direction, requiring unsubstantiated throw reversals to achieve any causal relationship between the fault, and the split in its footwall. The split defines the northeastern margin of a channel belt, and the following interpretations may be considered. 1. The channel trend here is unrelated to any structure; 2, the channel belt actually lay along the hangingwall of a syn-depositionally-active Bacup Fault (Fig. 5.10), and fortuitously in the footwall of a future Deerplay Fault; this is unlikely, as there should be a comparable coal split to the southwest; 3, the overall channel trajectory is controlled by a more deep-seated and regional structural low, and the post-depositional fault trends are themselves a reflection of this. The present author favours the last option, but such structural control would not have been operating throughout the Westphalian (at least two other Westphalian A trends cross that of the Union split at a high angle, see Rippon 1996, figure 8).

The Brimington Anticline and related folds (eastern Pennine Basin) (Fig. 5.11). In Derbyshire, the Brimington Anticline (which approximates to the Edale Gulf southern boundary) presents a good case for movement during deposition of the Silkstone coals (Westphalian A). Smith *et al.* (1967) show the split in the Top Silkstone coal trending neatly around the southeastern nose of this fold, where these seams outcrop. NCB mapping substantiated this and also found a similar pattern for the Low/Top Silkstone split. This mapping is in an area of high data density and quality. Figure 5.11 also shows these stratigraphical levels in the wider coalfield, where similar folds, even those in line with the Brimington Anticline, have little or no effect on contemporary sedimentation. For example a sluggish "cannel channel" crossed the Mansfield Anticline during much of the time in which the Low Silkstone peat was accumulating, immediately prior to the inferred movement on the Brimington Anticline. The split within the Top Silkstone also crosses the Mansfield Anticline, further west; a bend in this may, or may not record syn-depositional movement. Movement sufficient to affect the depositional pattern was obviously very specific in time and space. No other effects on sedimentation are known by any other structures within the bounds of Figure 5.11, throughout the mid-A to mid-C Westphalian sequences.

A structurally-initiated gravity slide may be interpreted from mining detail in the High Main coal (Westphalian C) of Bestwood Colliery, near Nottingham. Elliott (in internal NCB reports: pers. comm.1978) detailed a probable syn-sedimentary structure, redrawn as Figure 5.12. The particular interest here is that a gravity slide above the High Main appears to be associated with the tip monocline of a small fault proved in underlying coals. The suggestion is that the growing fault produced a minor gradient change at the contemporary surface. Only lacustrine claystones are involved, the nearest channel belt lying several kilometres to the east, so the observed structure is unlikely to have been produced by channel-side slipping. Soft sediment deformational structures support interpretation of syn-depositional movement; here, the double rarity of a gravity slide coinciding with a tip monocline is taken as good evidence of a causal relationship; the criteria of 5.6.2 (above), relating to channel belt and coal splitting patterns, do not apply here.

5.7.3 Discussion

Obviously there are many ways in which syn- and post-depositional features can coexist, or be confused, while fault spacings and trends, together with palaeo-channel frequencies, branchings, and sinuosities, will give many potential trend coincidences. Further, the faults that are prominent now may not have been those that were actively affecting sedimentation during the Carboniferous. For example, the Kincardine Basin appears to have been related to growth of a structure that is now buried, rather than to the prominent Ochil Fault, which truncates this sub-basin (see Rippon *et al.* 1996); on a more local scale, Namurian movement on the Langfauld Fault may have been restricted to what now appears to be a minor splay (see 5.7.1).

Unambiguous identification of syn-depositional movement on a specific fault will be rare, and as noted, assessments will always be subjective. In this account, subjectivity is present in the choice of examples (which by themselves are insufficient to formalise the criteria of Section 5.6); and especially in the assessment of sedimentological criteria (5.6.2). Regarding this latter issue, the author can only appeal to the large volume of unpublished sedimentological mapping by the NCB, and to its general validation by mining over some 25 years (see Rippon 1996). That other examples in the Pennine Basin have not been chosen for comment here is largely because the NCB resource has not identified many other possible cases.

From the present study, therefore, it is considered that the existing literature has inevitably promoted an over-emphasis on control on sedimentation by specific faults, in most English and Welsh coalfields, although there probably were broad corridors, defined by inherited structures, that were locally important as channel focuses. However, given the possibility that movements are likely to be more evident away from tectonic depocentres, it follows that the Durham part of the Northeast Coalfield (coincident with the down-dip extension of the Alston Block, Fig. 5.2), should provide more obvious examples than the main Pennine Basin fields (Fielding 1984).

A full inventory of likely syn-depositional structures in England would, in principle, make it possible to assess them for information on Carboniferous stress regimes (Corfield *et al.* 1996). From the present analysis, this would involve only those structures which were part of the tectonic framework: most gravity slides, and the fault categories of Section 5.5 that are related solely to sedimentation, compaction, and igneous processes, would be irrelevant; it is concluded that there are too few known, and unambiguous, candidate structures to allow a valid assessment.

5.8 Conclusions

The recognition of syn-depositional movement on specific faults, initiated directly by tectonic activity, requires very careful assessment, and excellent data quality. It is all too easy to invoke movement on a structure to explain variations in depositional pattems that are within the normal range of sedimentological possibilities. It is concluded that identifiable syn-depositionally-active structures (below the scale of a sub-basin) are rare in most coalfields except in the Scottish Midland Valley, reflecting mainly post-rift, thick basin-fill settings. The main evidence is the lack of candidate features in the coals themselves: precursor peats accumulated across wide areas with exceptionally low relief, and accounted for much of the available time. However, some syn-depositional features will have gone unrecorded, or are yet to be identified. It is hoped that the present account will stimulate discussion, aid recognition of further examples, and contribute to similar analyses in other geological settings.

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5.10 Figure captions

Figure 5.1 Locations and stratigraphical ranges of Upper Carboniferous coalfields.

Figure 5.2 Tectonic settings of the main coalfields; selected lines from Soper *et al.* (1987) and Pharaoh *et al.* (1987).

Figure 5.3 Westphalian relative net depositional rates in and around the Gainsborough Trough. The 45^0 slope represents a situation in which deposition in both the sub-basin and in the footwall area would be at an equal rate. The "growth" difference is some measure of the extra deposition (and preservation, hence "net") in the trough. See text for discussion.

Figure 5.4 Faults in British coalfields; a classification by origins (modified from Boardman & Rippon (1997), with acknowledgement to the Geological Society, London).

Figure 5.5 Style differences between syn-and post-depositional tectonic normal faults.

Figure 5.6 Vertical attenuation of throw, eastern Pennine Basin and Kincardine Basin. Data from the former are for faults that may themselves have various origins and styles, although all are tectonic. See text for discussion.

Figure 5.7 Examples of fault-adjacent strains in the Kincardine Basin. These strains are structural dilations and contractions resulting from fault growth, with no measurable syn-depositional relationship. See text for discussion. Gartarry Toll is at E. 293132, N. 691256.

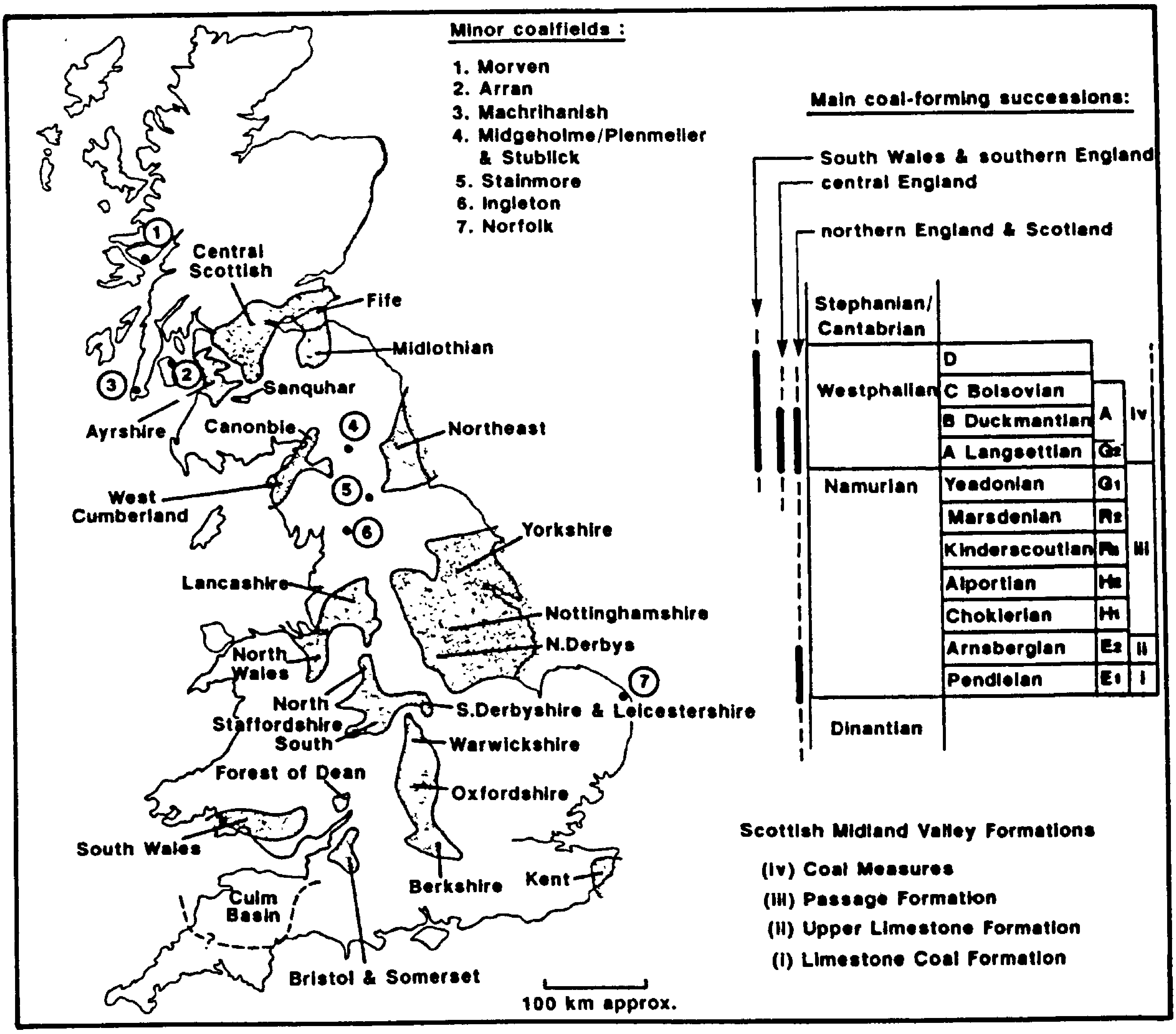
Figure 5.8 Some Westphalian depositional patterns: potential for structural control.

Figure 5.9 Detailed structural and depositional relationships, Upper Hirst coal (Arnsbergian) Kincardine Basin. (The "Clackmannan Fault" is not directly related to the Clackmannan Fault of Fig. 5.7, further west; the name perpetuates mining usage.)

Figure 5.10 Structural and depositional trends, lower Westphalian A, Lancashire. See text for a discussion on the possibilities for the Union split being structurally controlled.

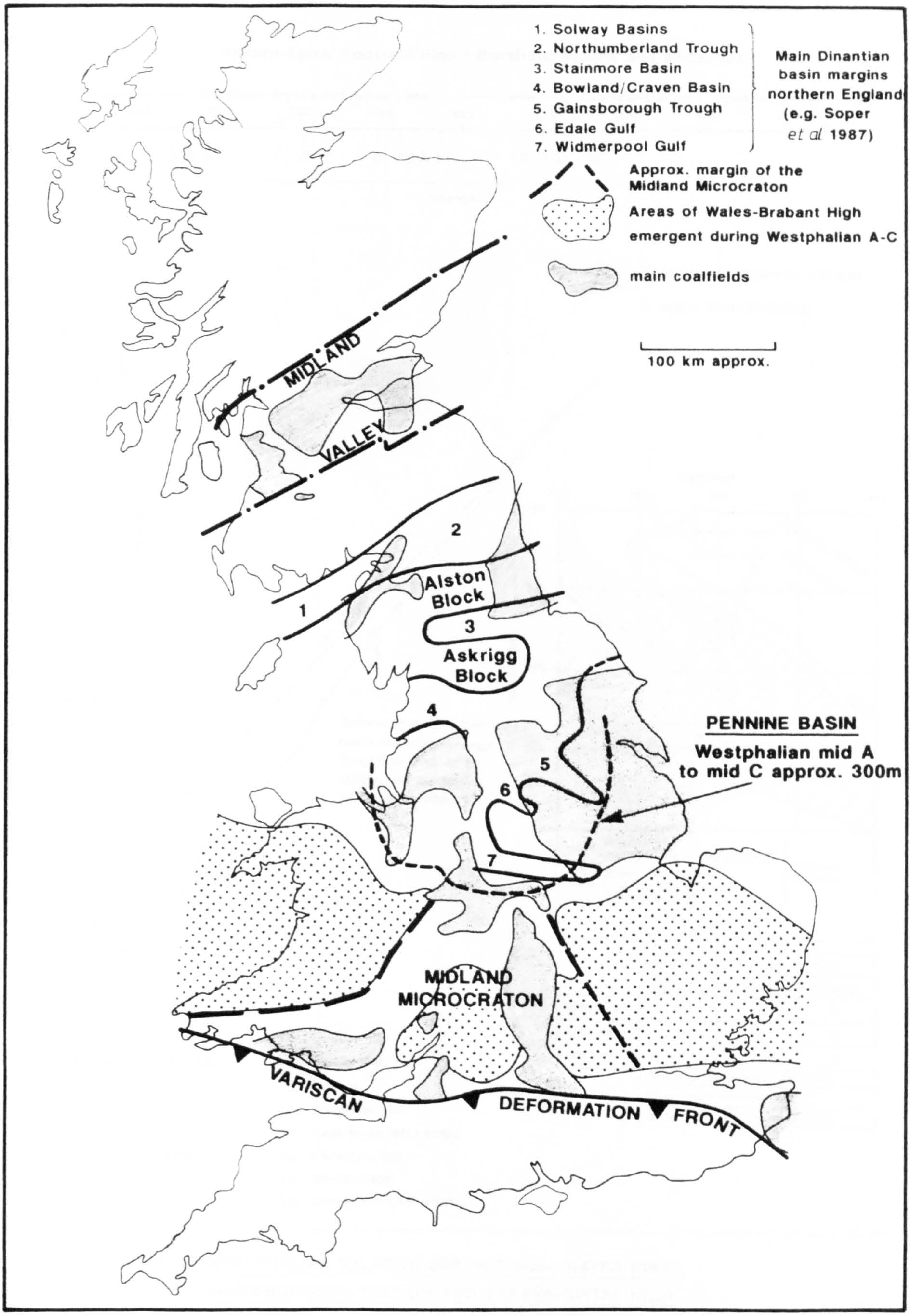
Figure 5.11 Structural and depositional trends, Silkstone coals, Westphalian A, eastern Pennine Basin. See text for discussion.

Figure 5.12 An interpreted gravity slide above the High Main coal (Westphalian C, Bestwood, north of Nottingham; redrawn from R.E. Elliott, pers. comm. 1978). The disturbance is at approximately E.453800, N. 347600. The disturbed material above the coal is thought to be lacustrine claystones, mobilised by upwards growth on a small tectonic fault.



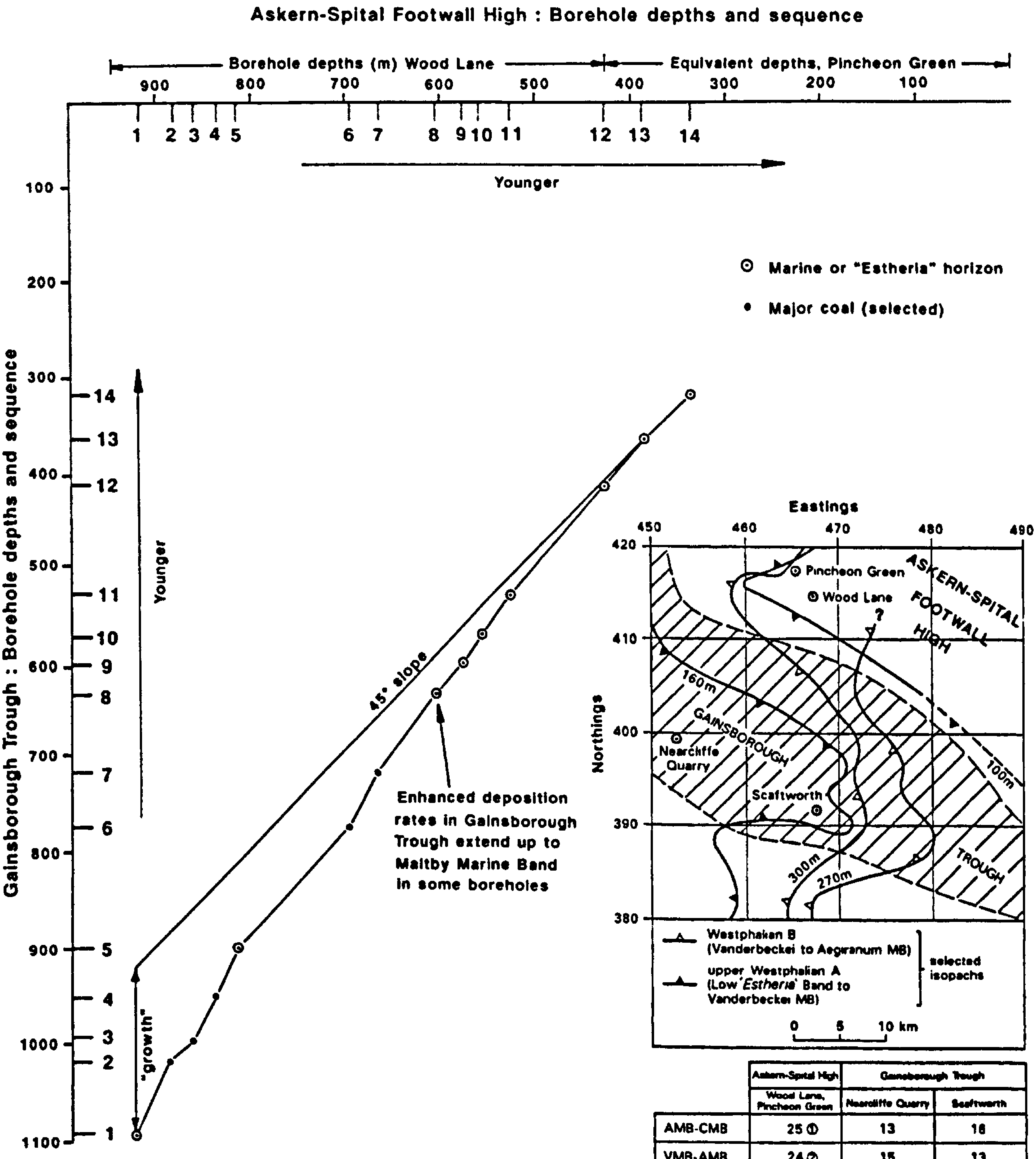
Location and stratigraphical summary of the Upper Carboniferous coalfields

Fig.5.1



Tectonic framework of the main Upper Carboniferous coalfields

Fig.5.2



	Askern-Spital High	Gainsborough Trough	
	Wood Lane, Pincheon Green	Nearcliffe Quarry	Scaftworth
AMB-CMB	25 ①	13	16
VMB-AMB	24 ②	15	13
LEB-VMB	18	27 ③	19

% sand (approx.) in Westphalian intervals

① includes Glasshoughton Rock
② includes channel sands below Barnsley coal
③ includes Silkstone and Parkgate Rocks

1. Low 'Estheria' Band (LEB)
2. Thorncliffe
3. Parkgate
4. Flocktons
5. Vanderbeckel MB (VMB)
6. Barnsley
7. Kents Thick
8. Maltby MB
9. Clowne
10. Haughton MB
11. Aegiranum MB (AMB)
12. Edmondia MB
13. Shafton MB
14. Cambriense MB (CMB)

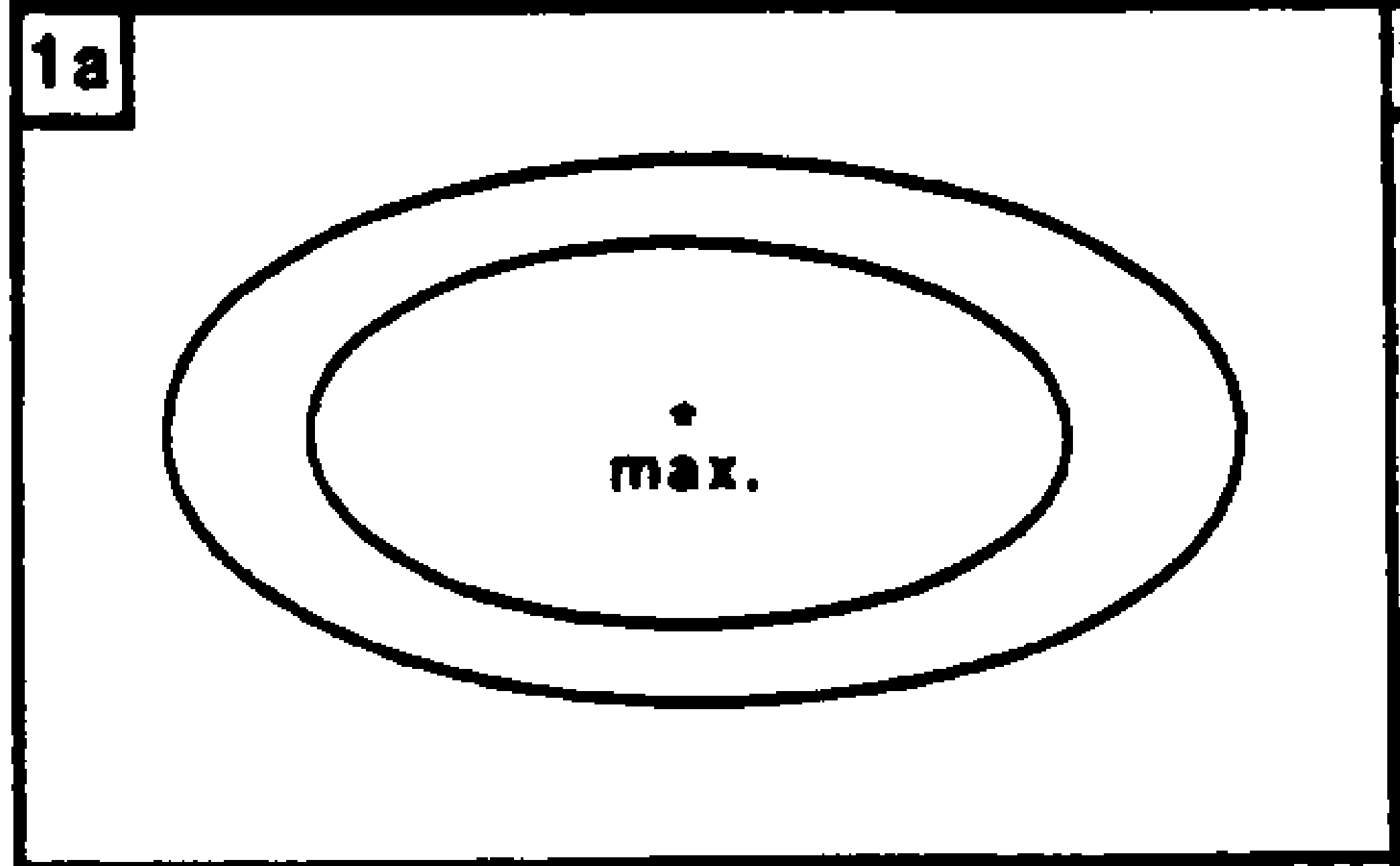
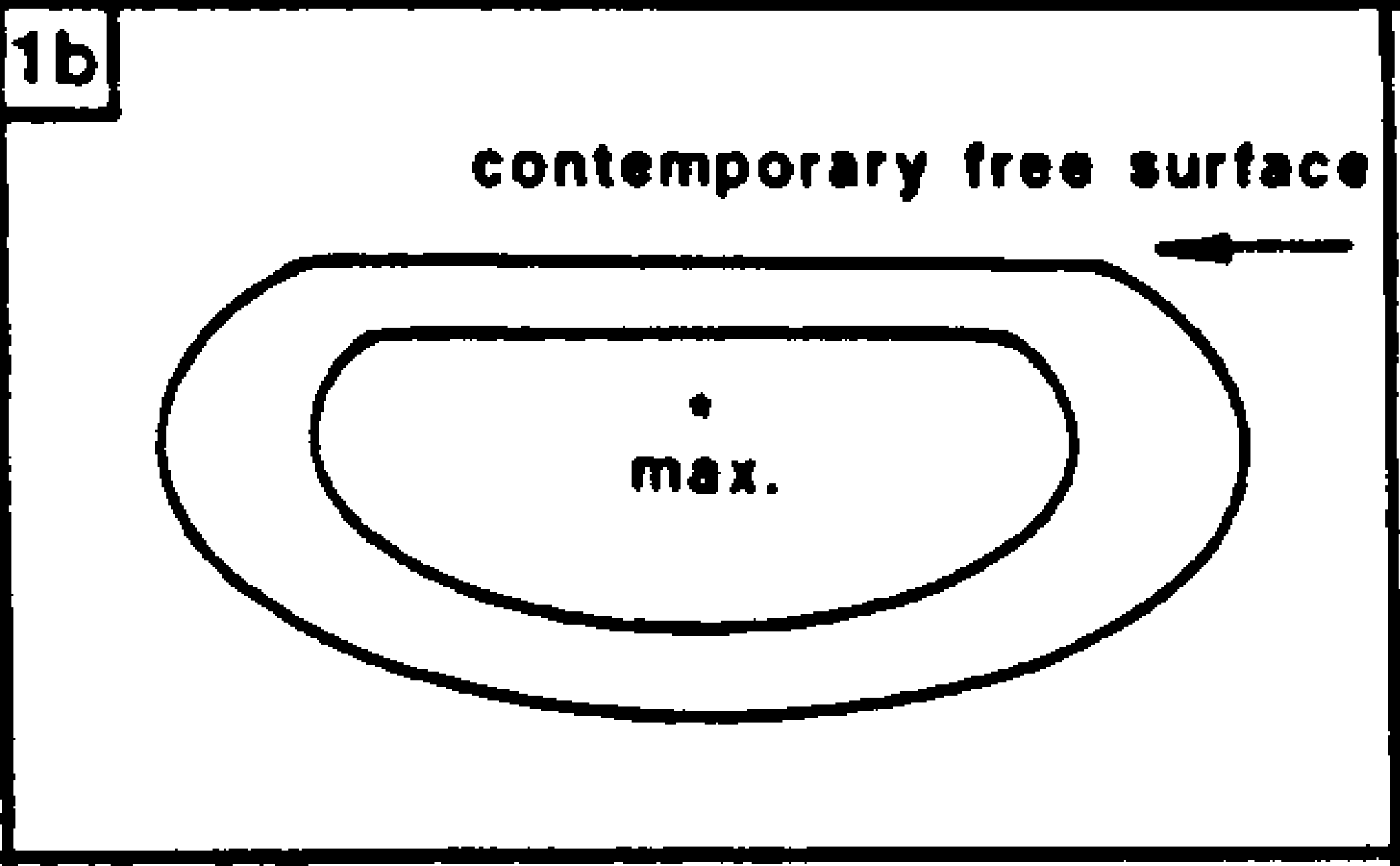
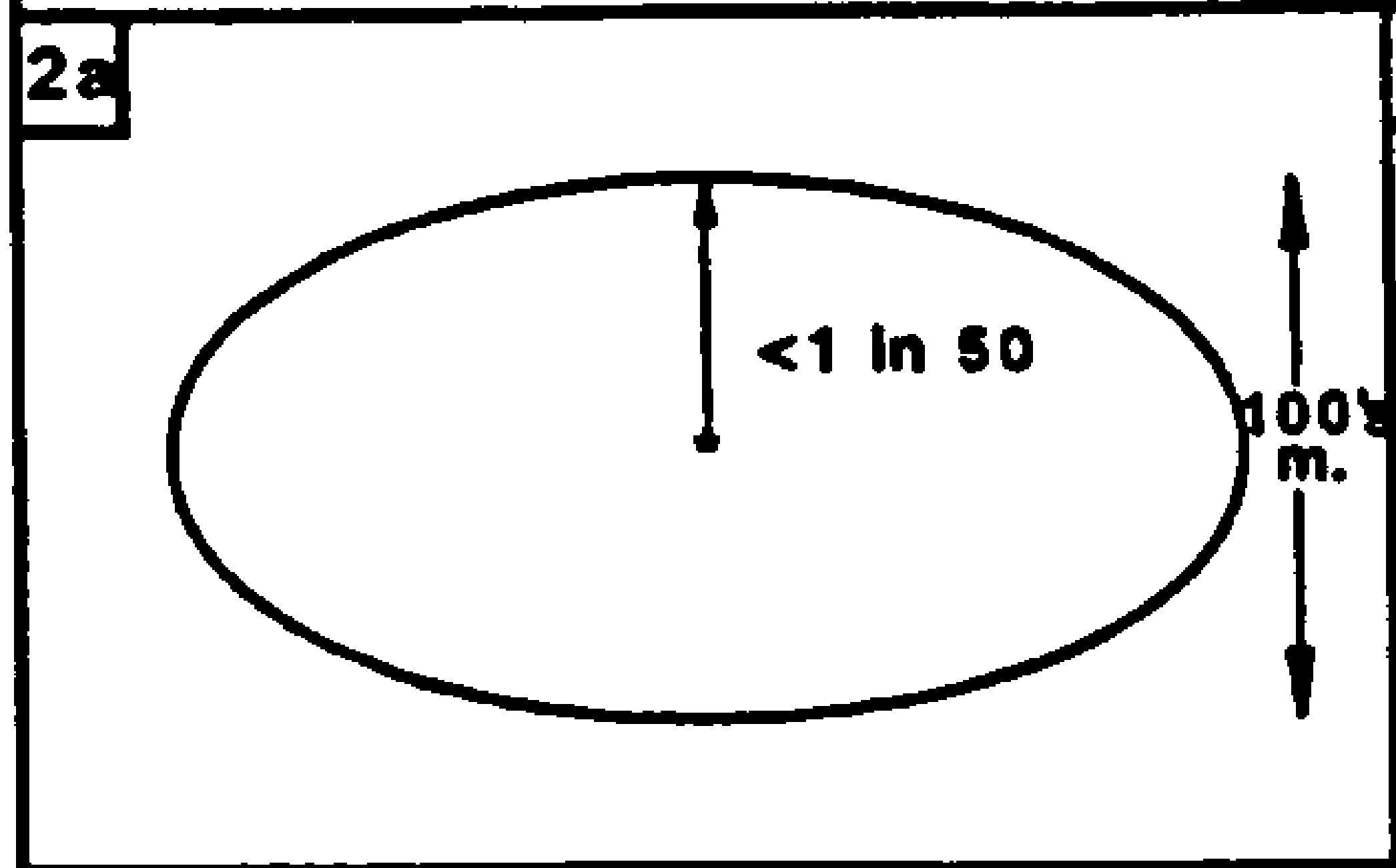
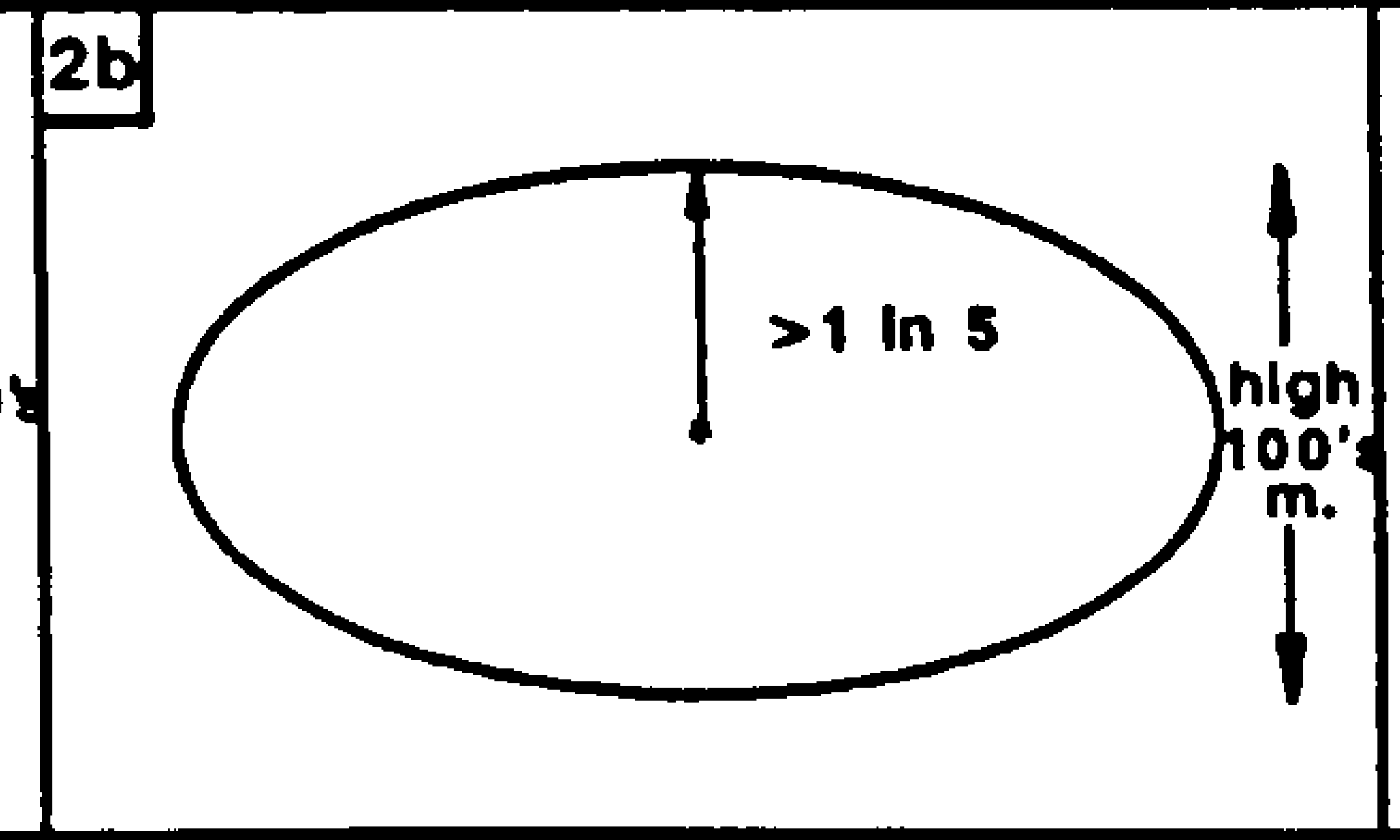
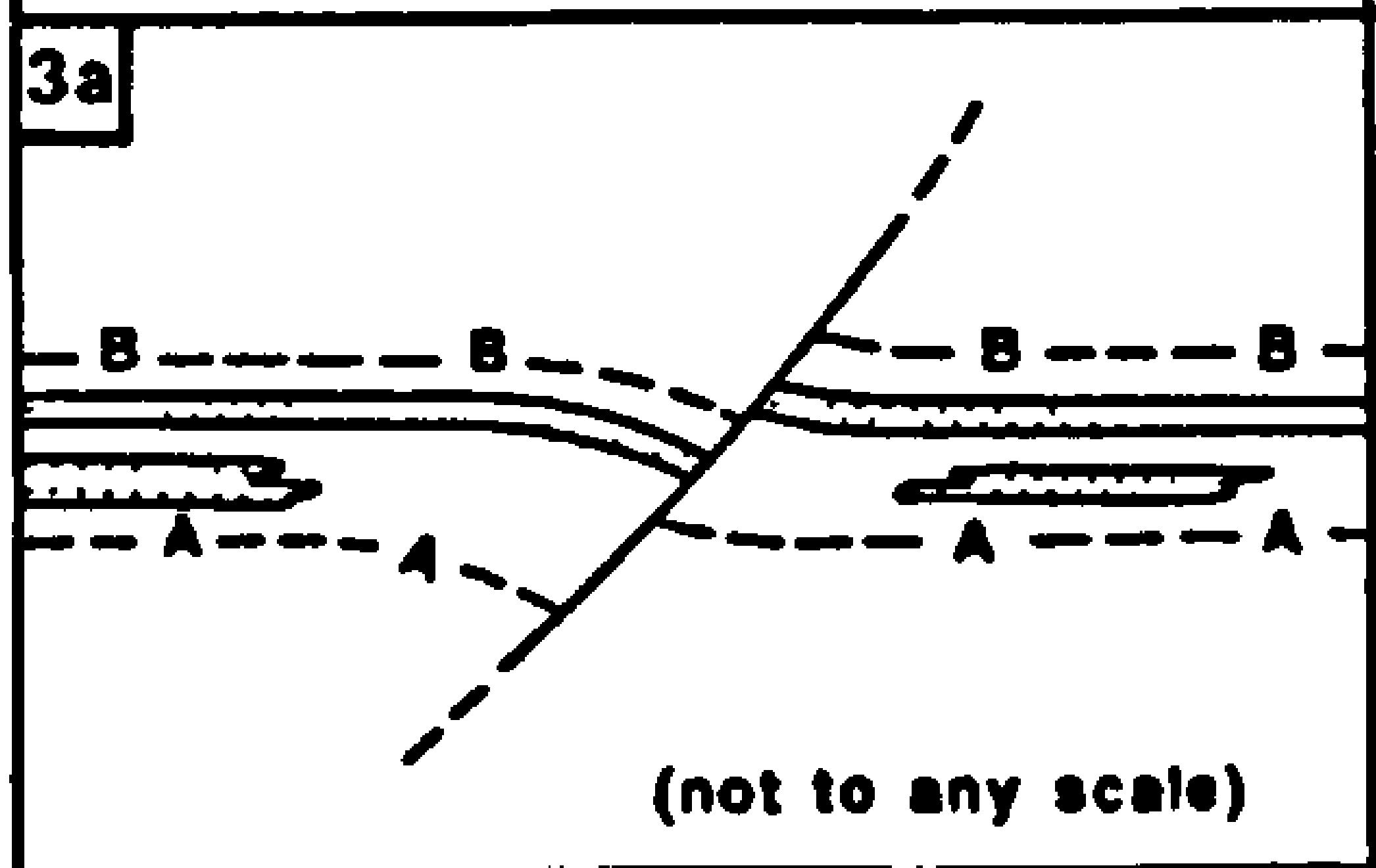
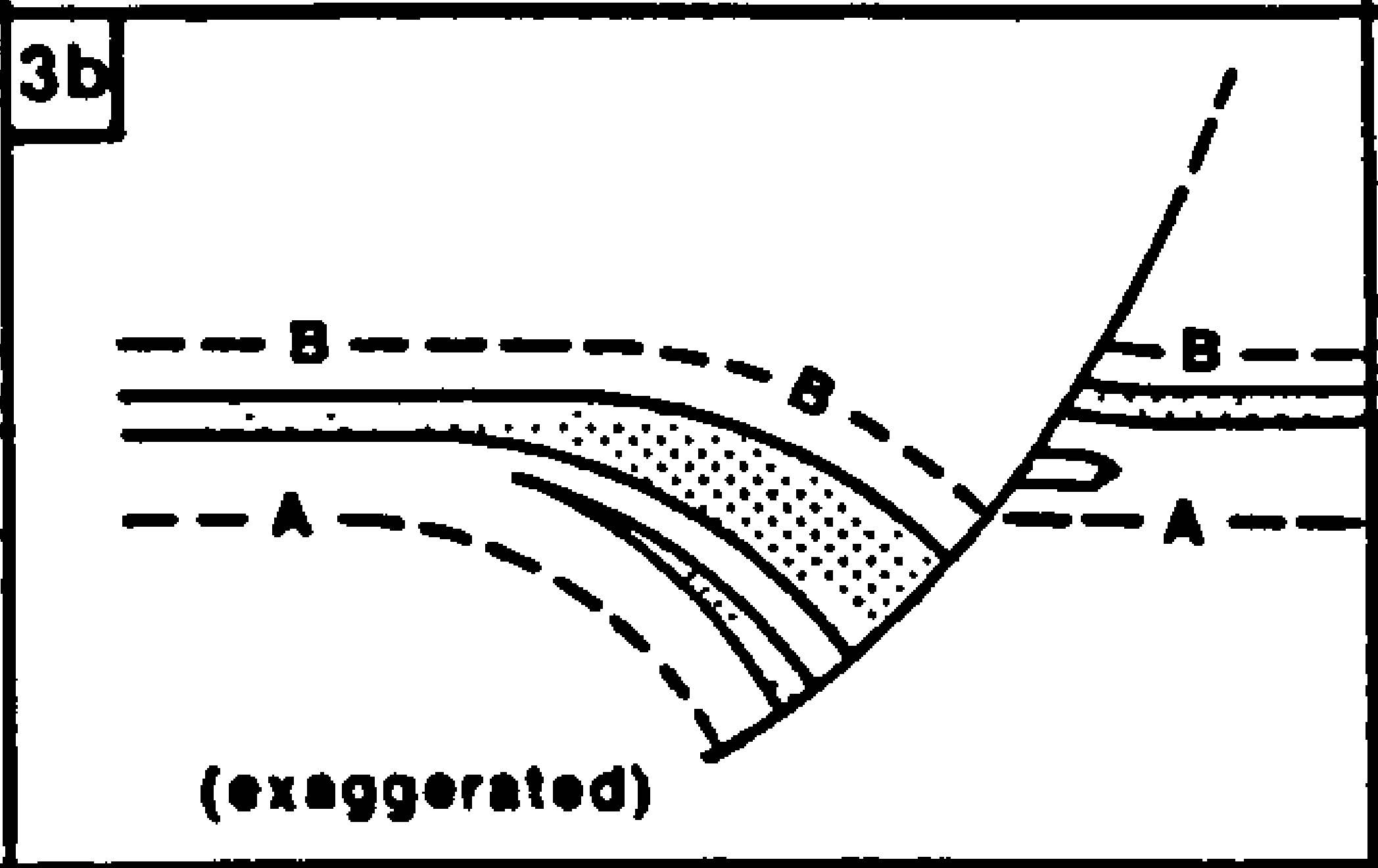
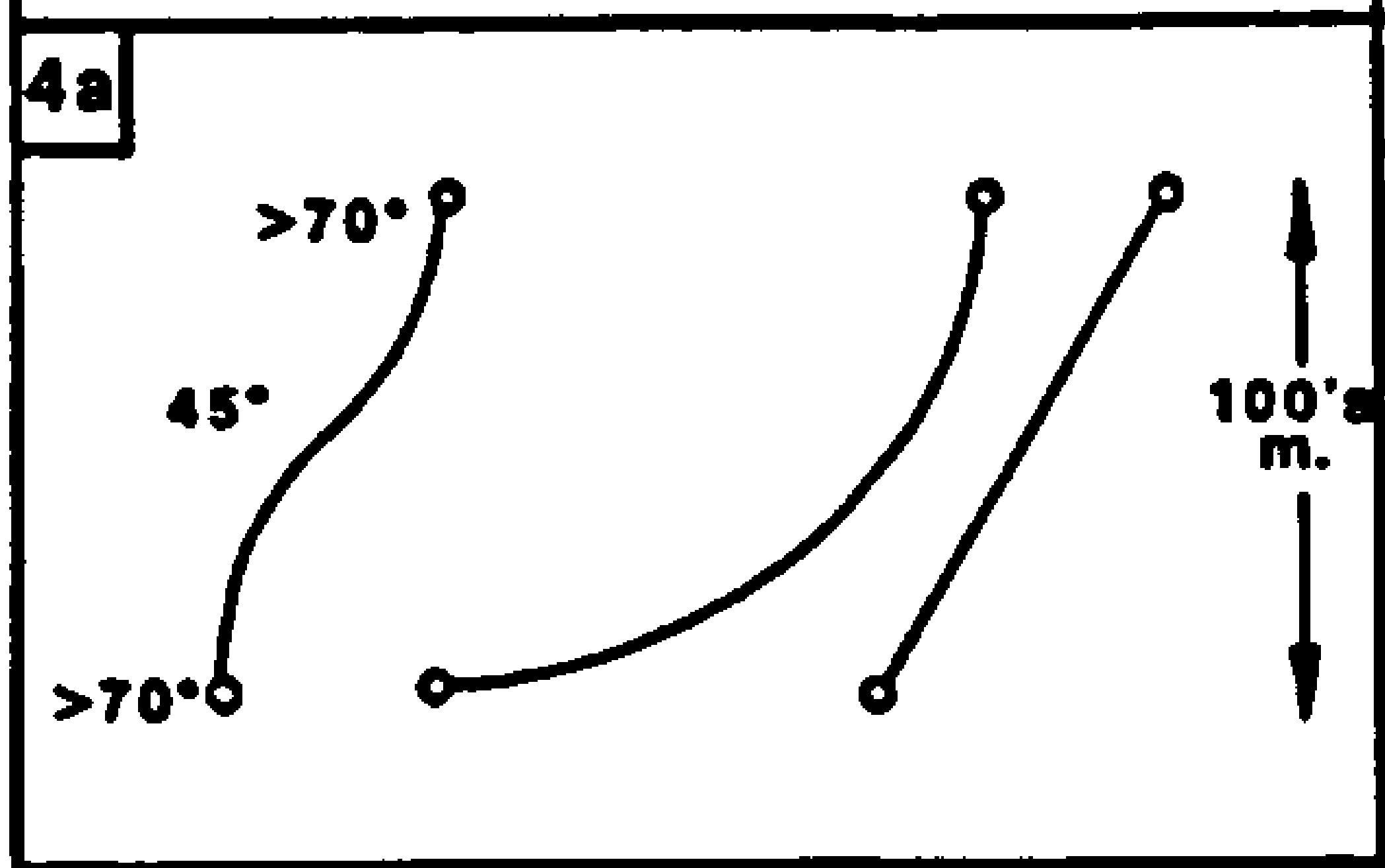
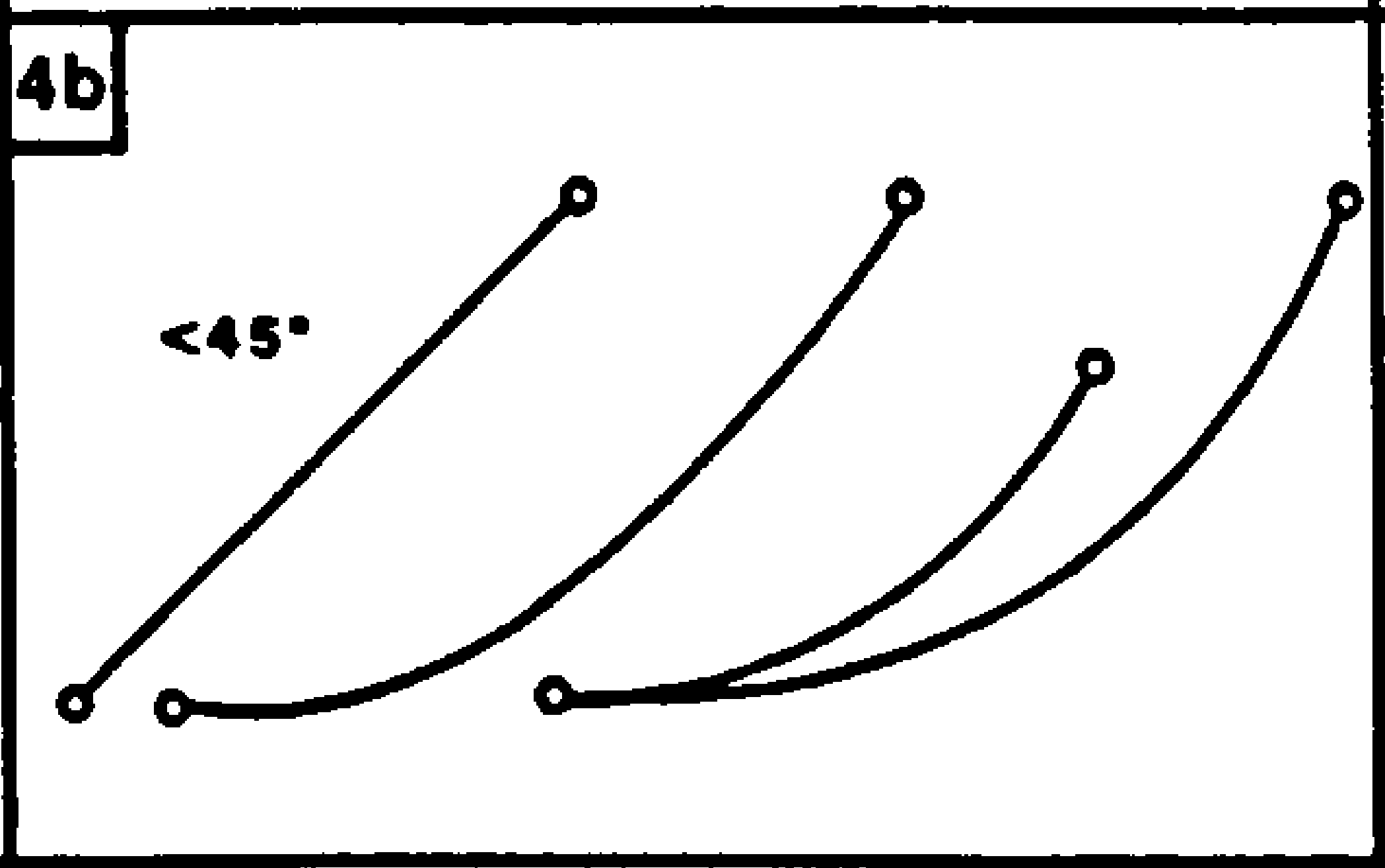
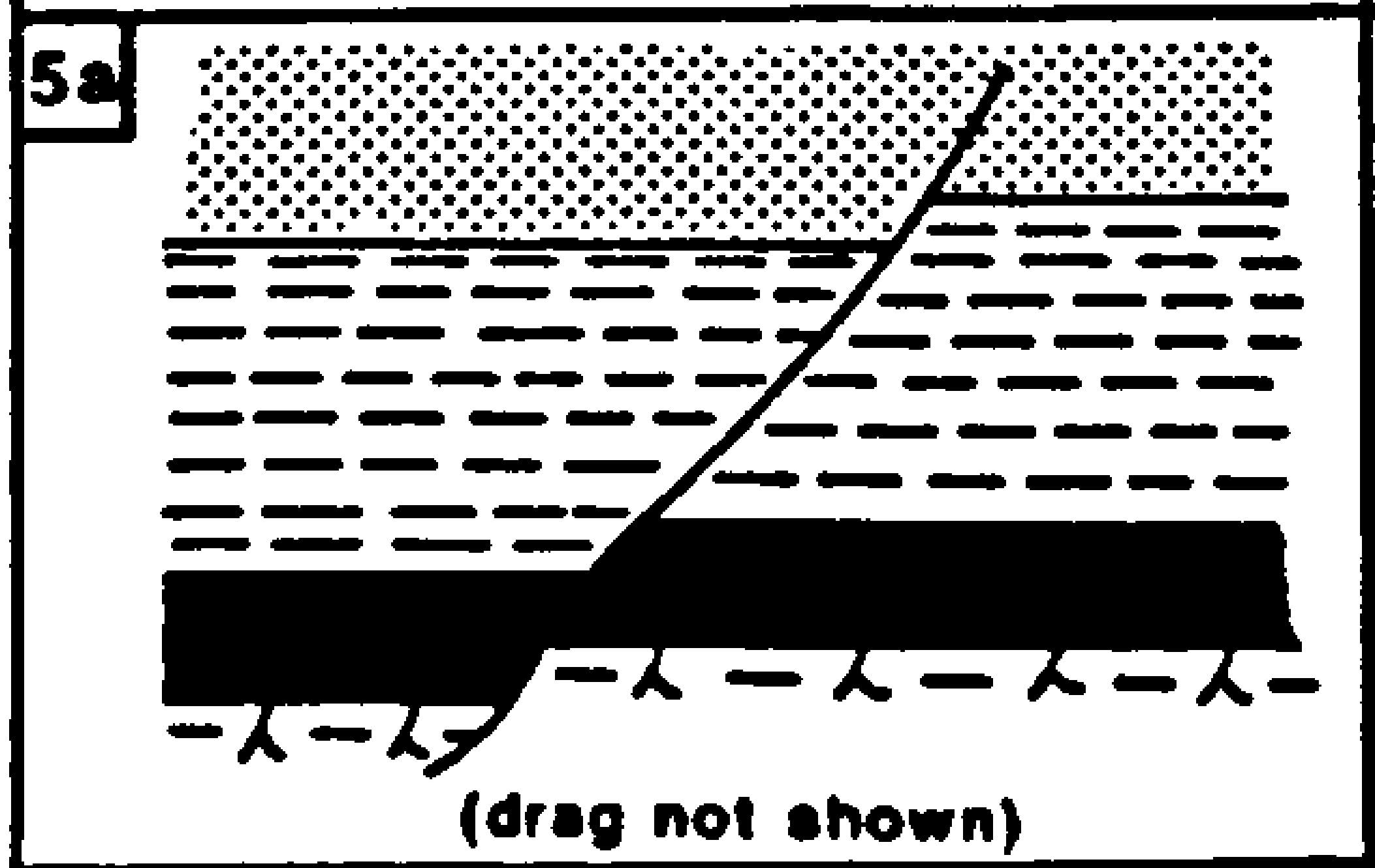
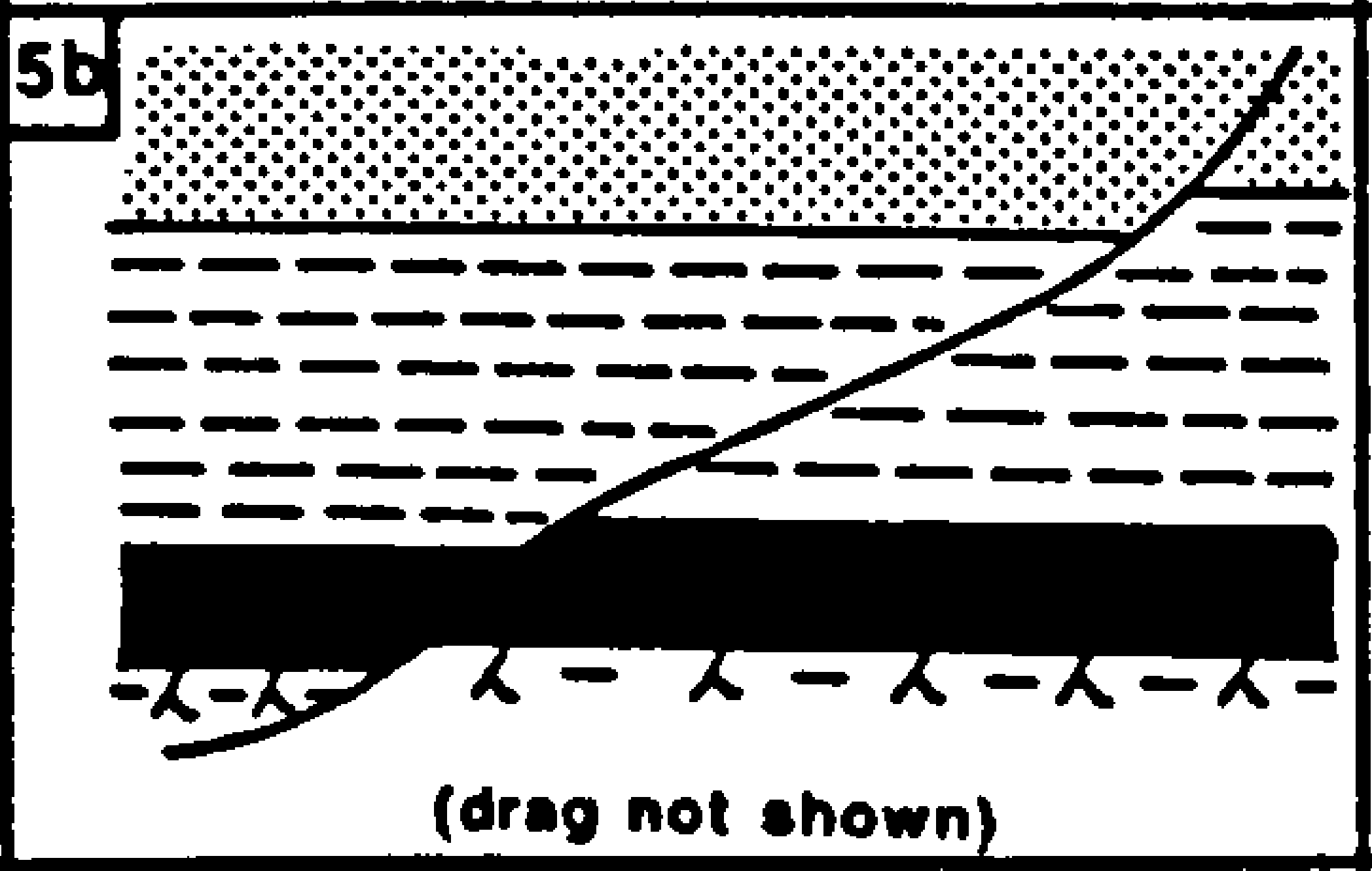
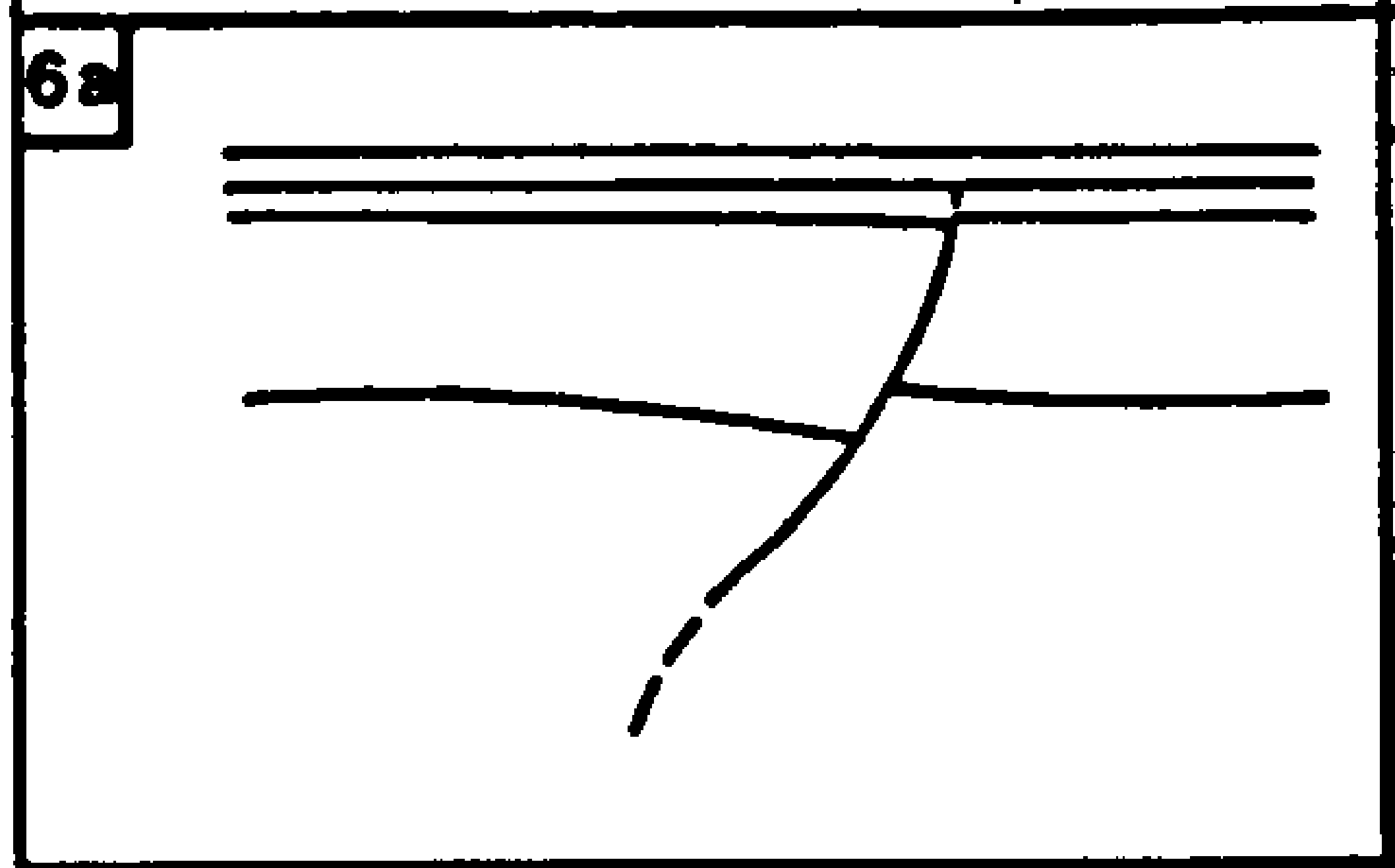
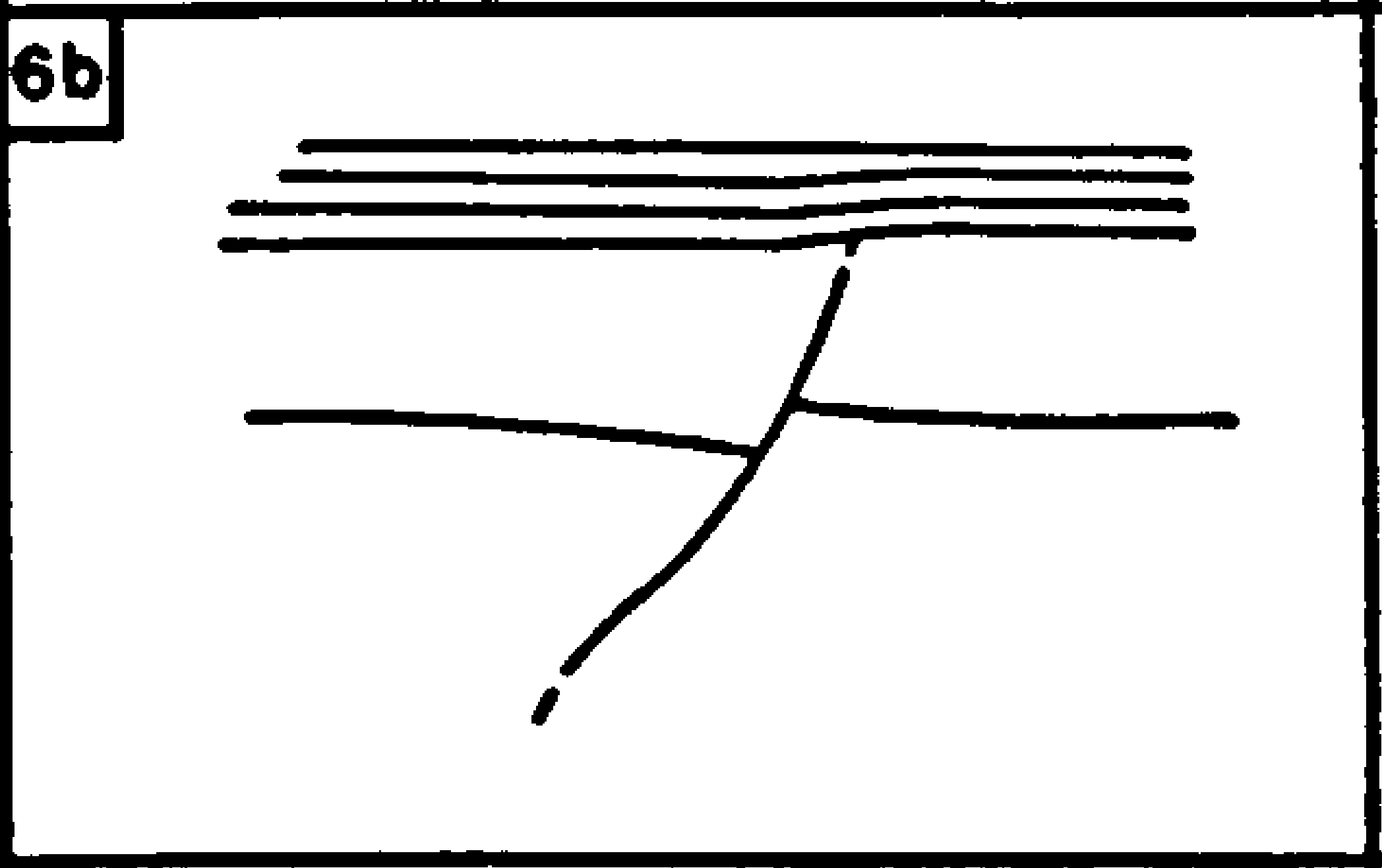
WESTPHALIAN RELATIVE DEPOSITIONAL RATES (NET), GAINSBOROUGH TROUGH AND ASKERN-SPITAL HIGH

Fig.5.3

Post-depositional tectonic faulting is by far the most common

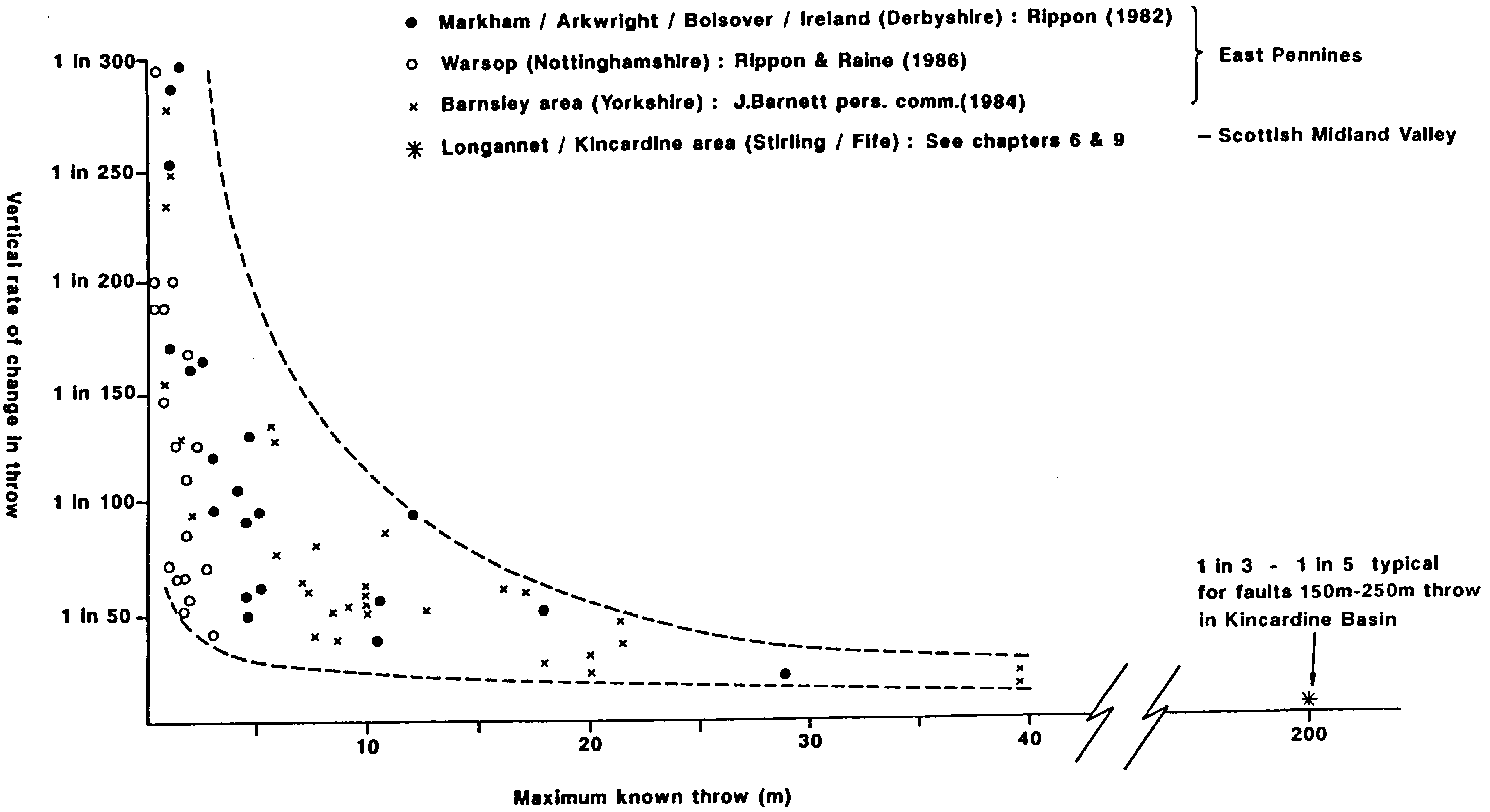
FAULTS IN THE BRITISH COAL-BEARING SILESIAN : A CLASSIFICATION BY ORIGINS

Fig.5.4

post-depositional	syn-depositional	
		1. **Fault shape** a. Idealised blind normal fault with elliptical throw contours (eg. Rippon 1985a) b. Throw contours restricted by contemporary free surface (Nicol et al. 1996)
		2. **Fault growth** a. "Standard" model (eg. Watterson 1986) b. Throw accumulates internally after early large scale fracturing.
		3. **Rollovers** a. No obvious depositional boundary; excess formation thickness accounted for by structural dilation b. Depositional boundary; formation thickness well in excess of any structural dilation.
		4. **Fault plane dips (overall)** a. Some "standard" post-depositional dips. b. Some "standard" syndepositional dips and styles.
		5. **Fault plane dips (detail)** a. Relatively muted refractions (fully compacted sequence). b. Pronounced dip changes; refractions emphasised by compaction.
		6. **Upper tip lines** a. Minimal ductile strain. b. Preserved monocline (warping of semi-consolidated sediment).
7a drag : relatively muted differences through varied lithologies. gouge : varied often with prominent cataclasis.	7b drag : may be exaggerated in coal (peat) and clays. gouge : thin smearing across coal (peat) and clays.	7. **Damage zone detail** All styles will be substantially modified by multi-phase movement.

STYLE DIFFERENCES BETWEEN SYN- & POST-DEPOSITIONAL NORMAL TECTONIC FAULTS: SOME EXAMPLES

Fig.5.5

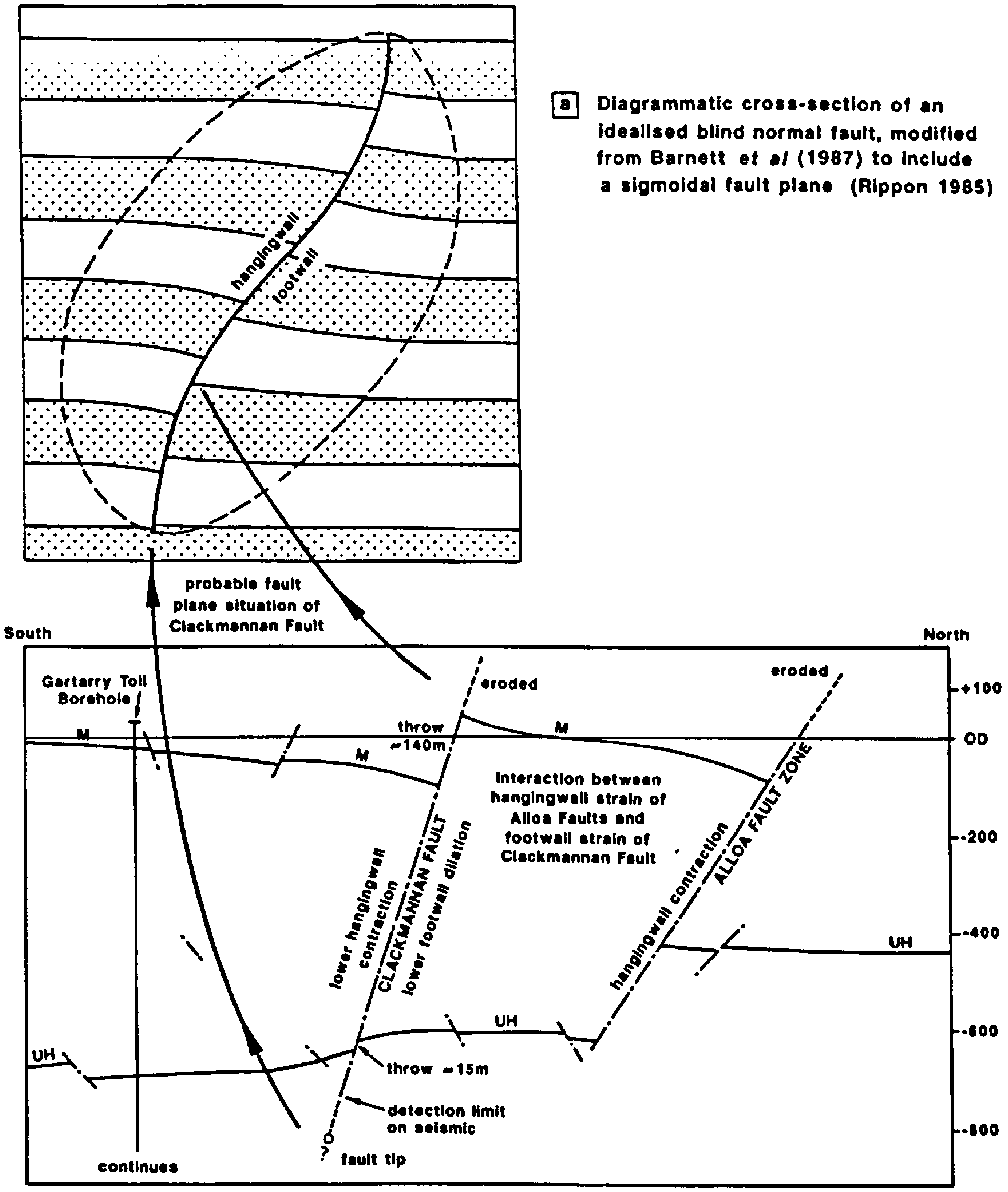


DISPLACEMENT GRADIENTS :

VERTICAL ATTENUATION OF THROW

(All faults considered essentially normal)

Fig.5.6



a Diagrammatic cross-section of an idealised blind normal fault, modified from Barnett *et al* (1987) to include a sigmoidal fault plane (Rippon 1985)

b Fault - adjacent strains in the Kincardine Basin, Scottish Midland Valley

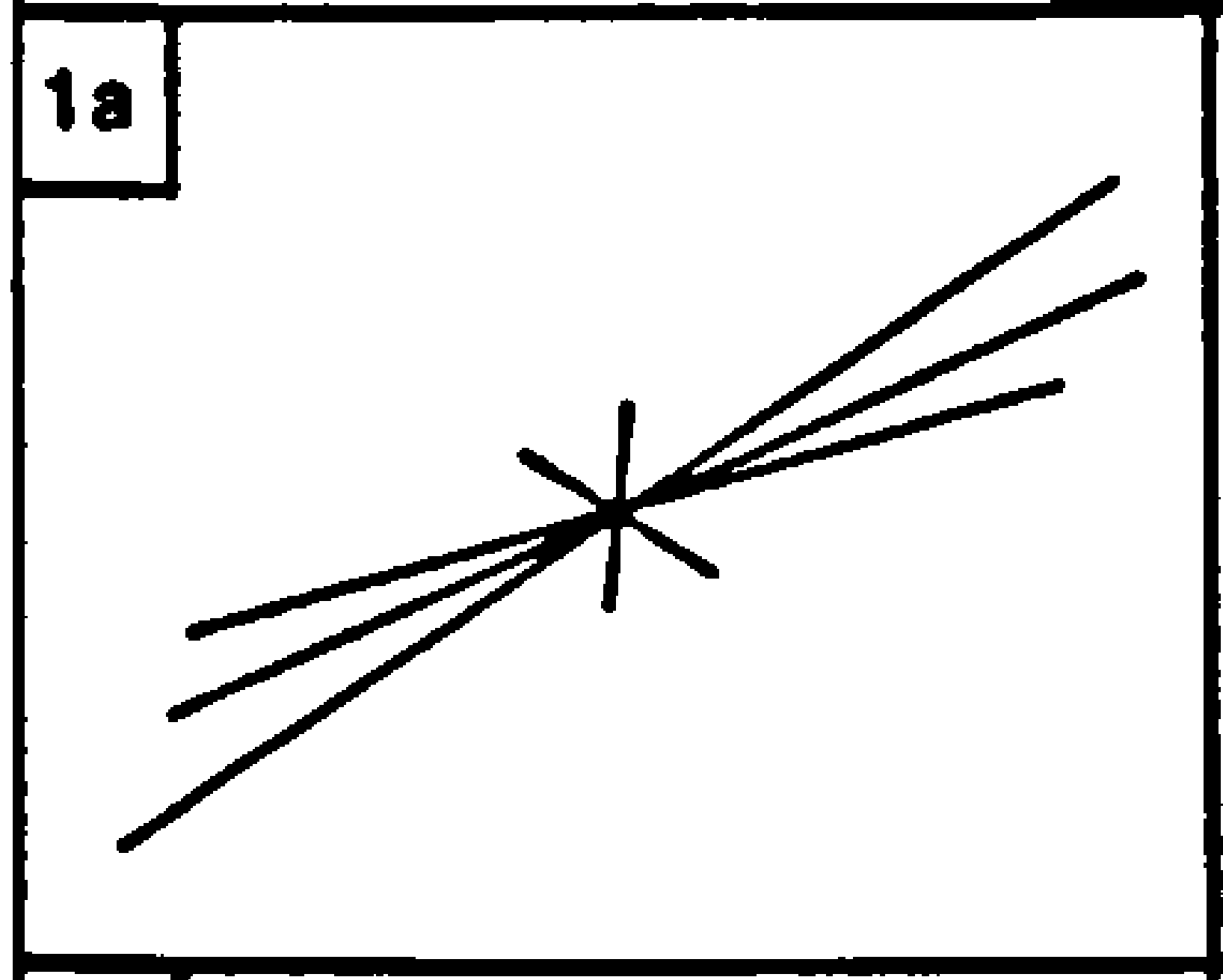
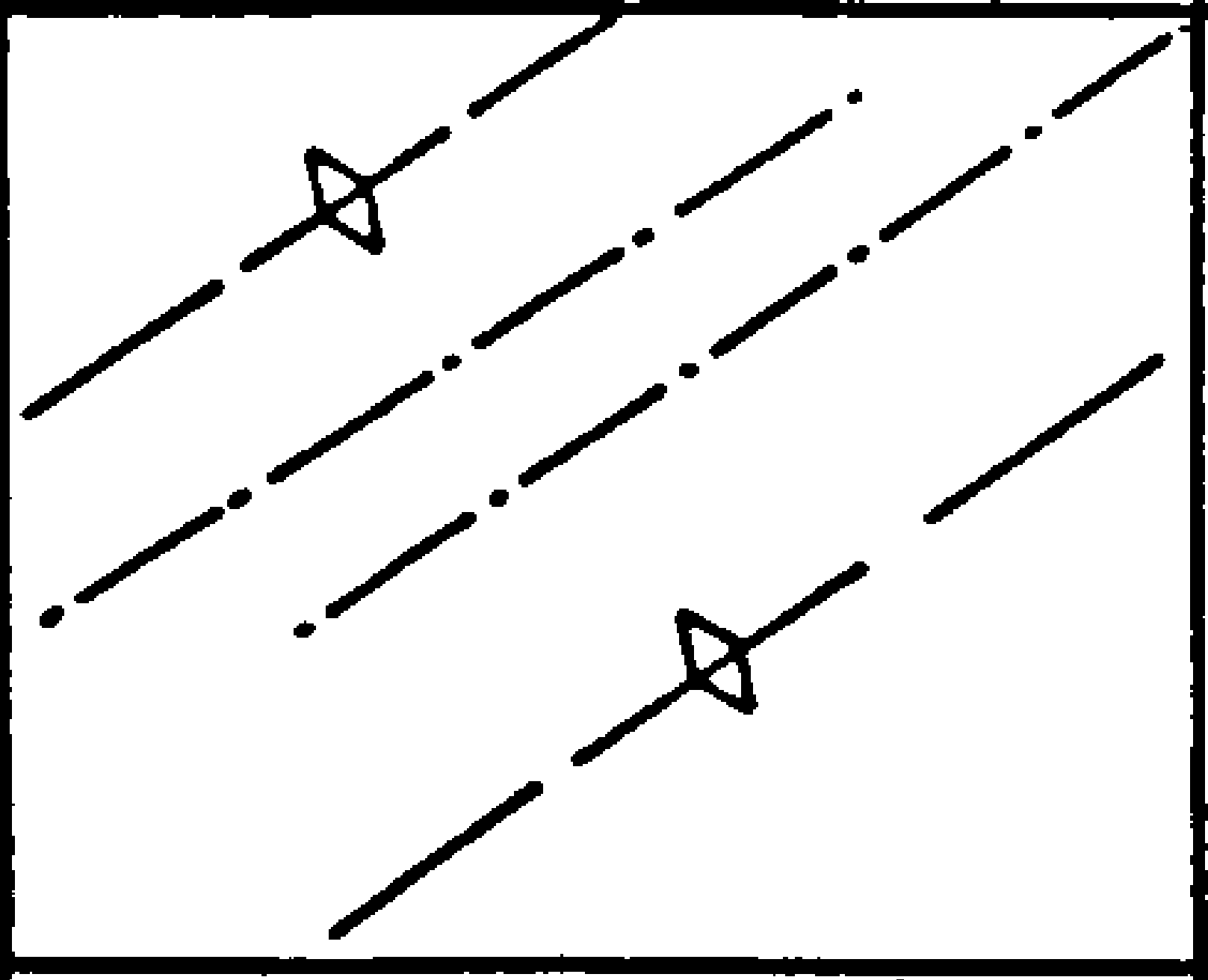
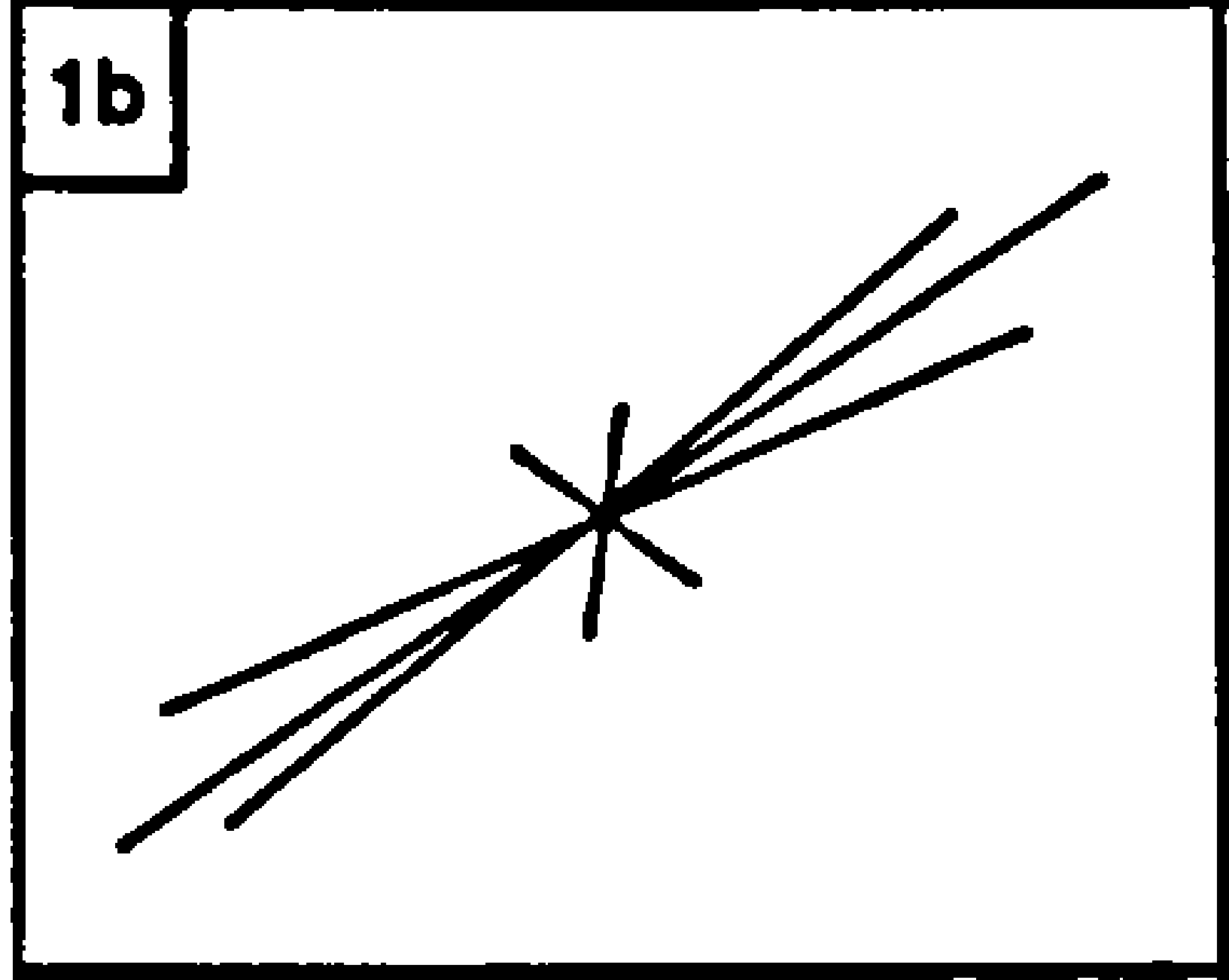
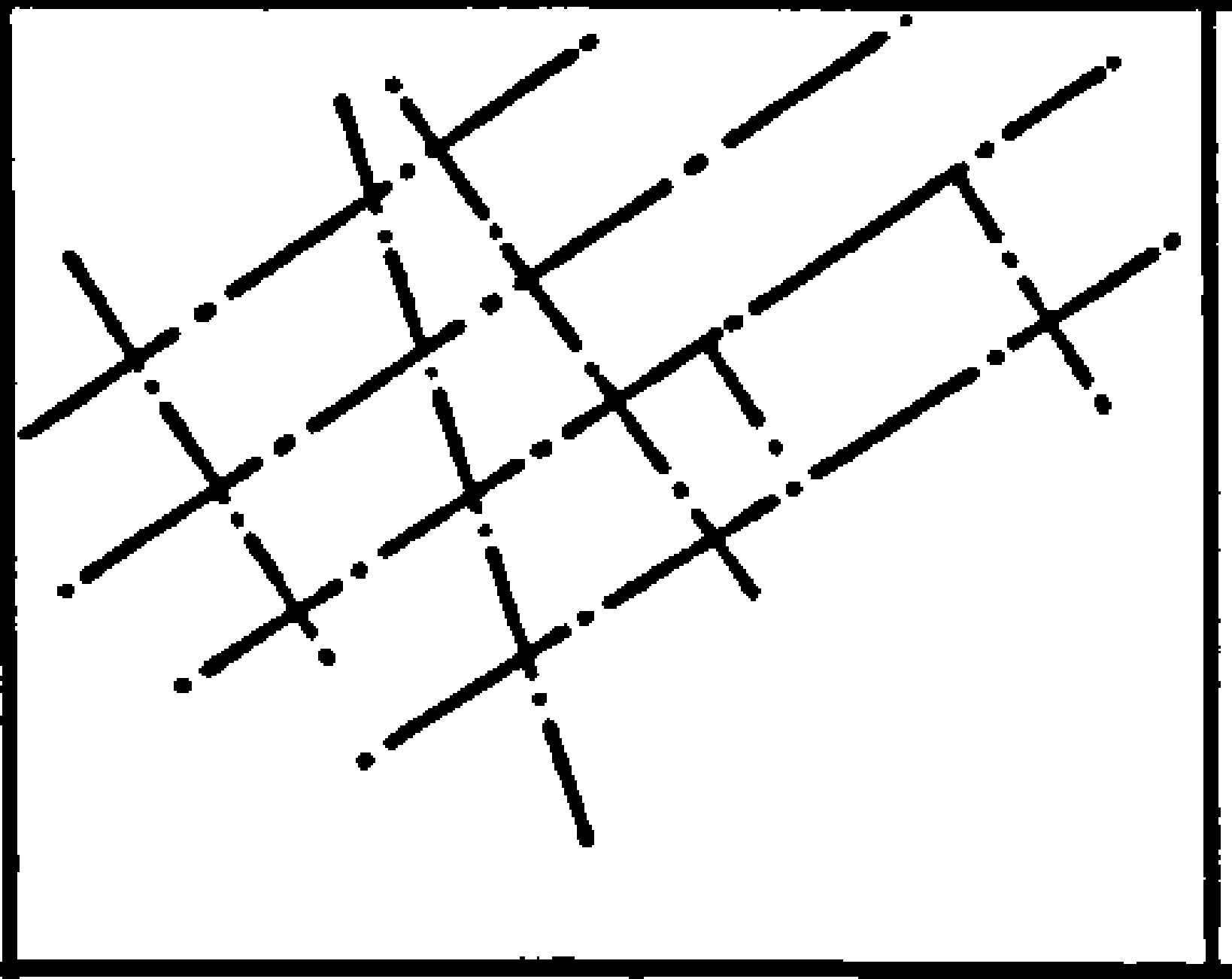
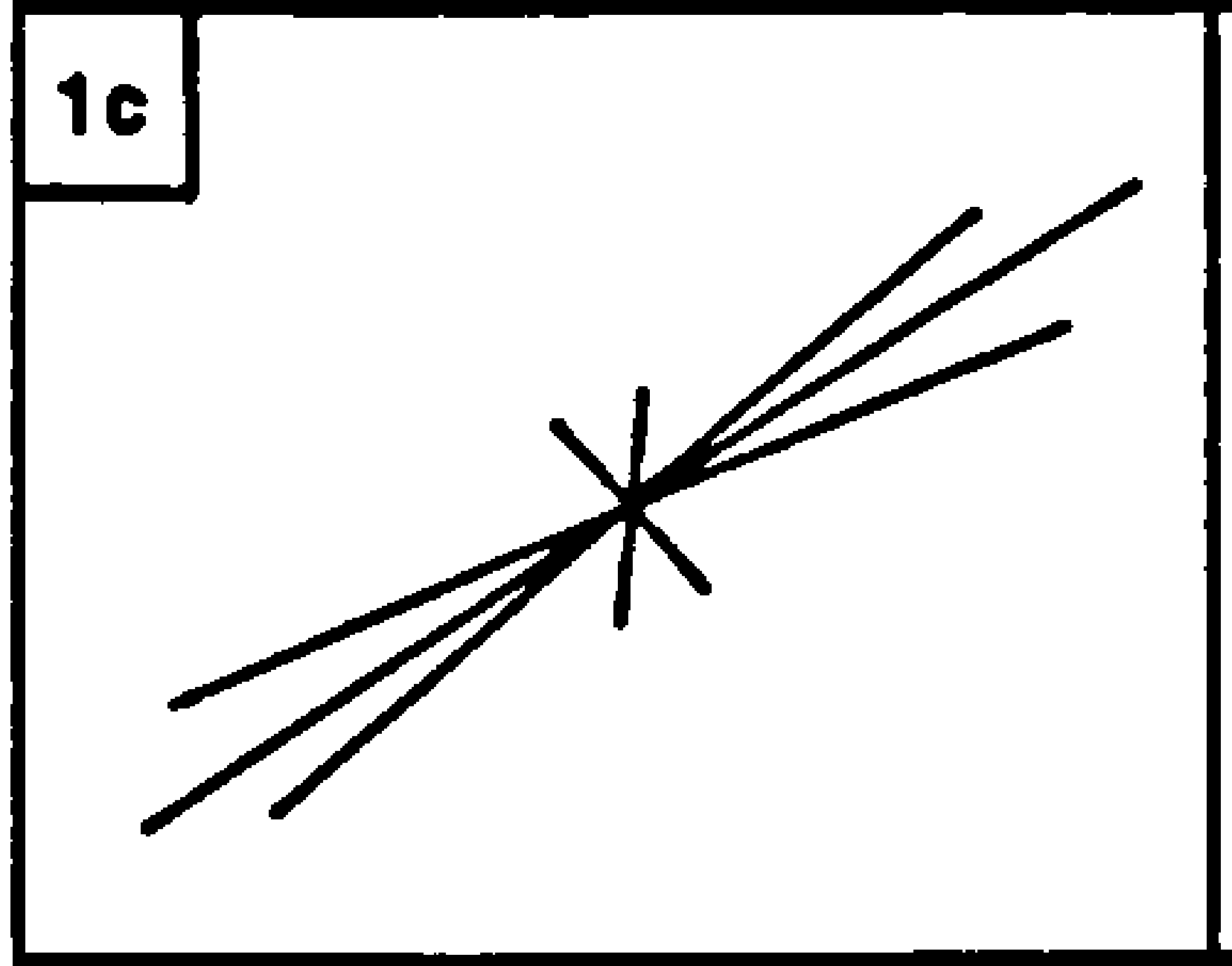
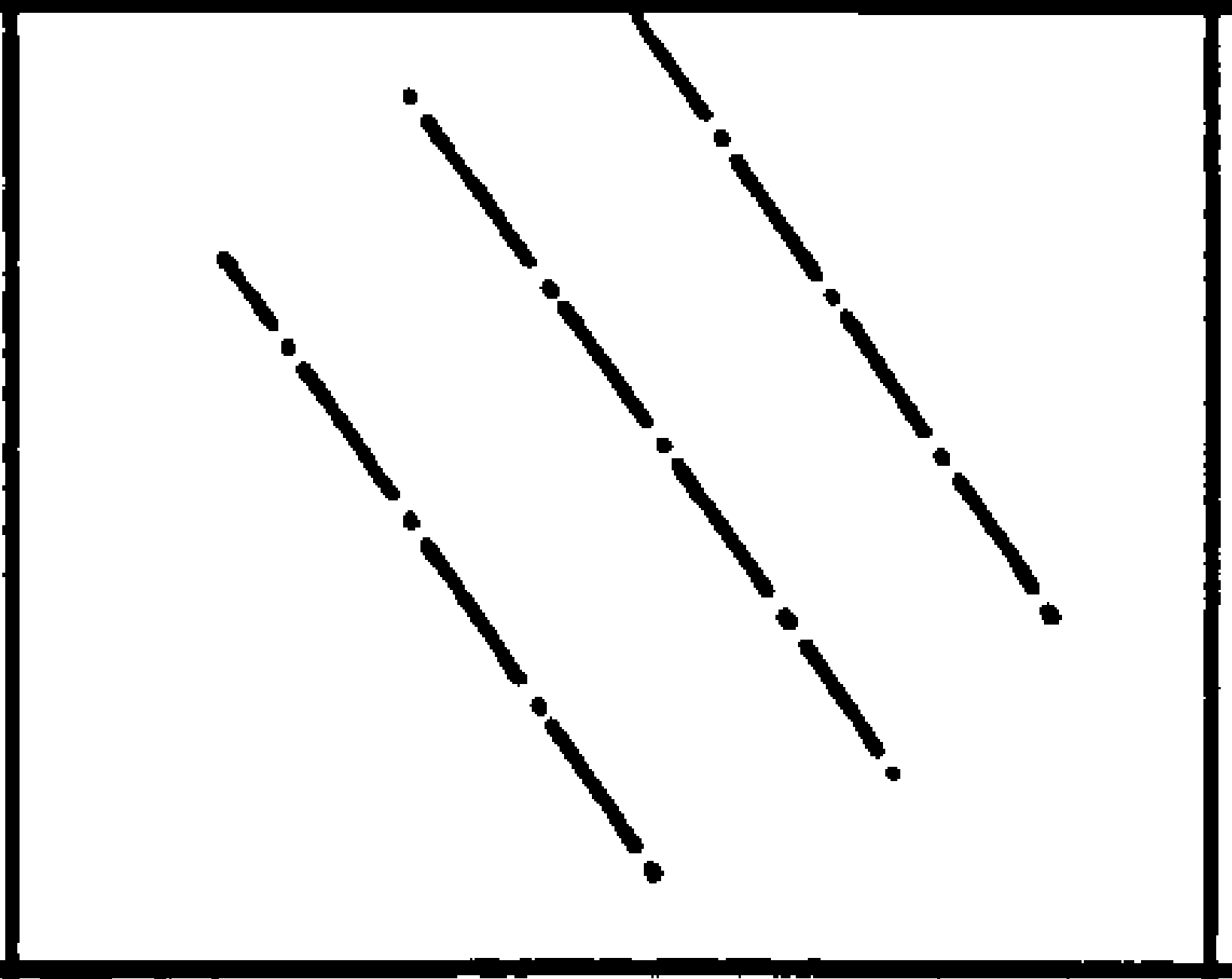
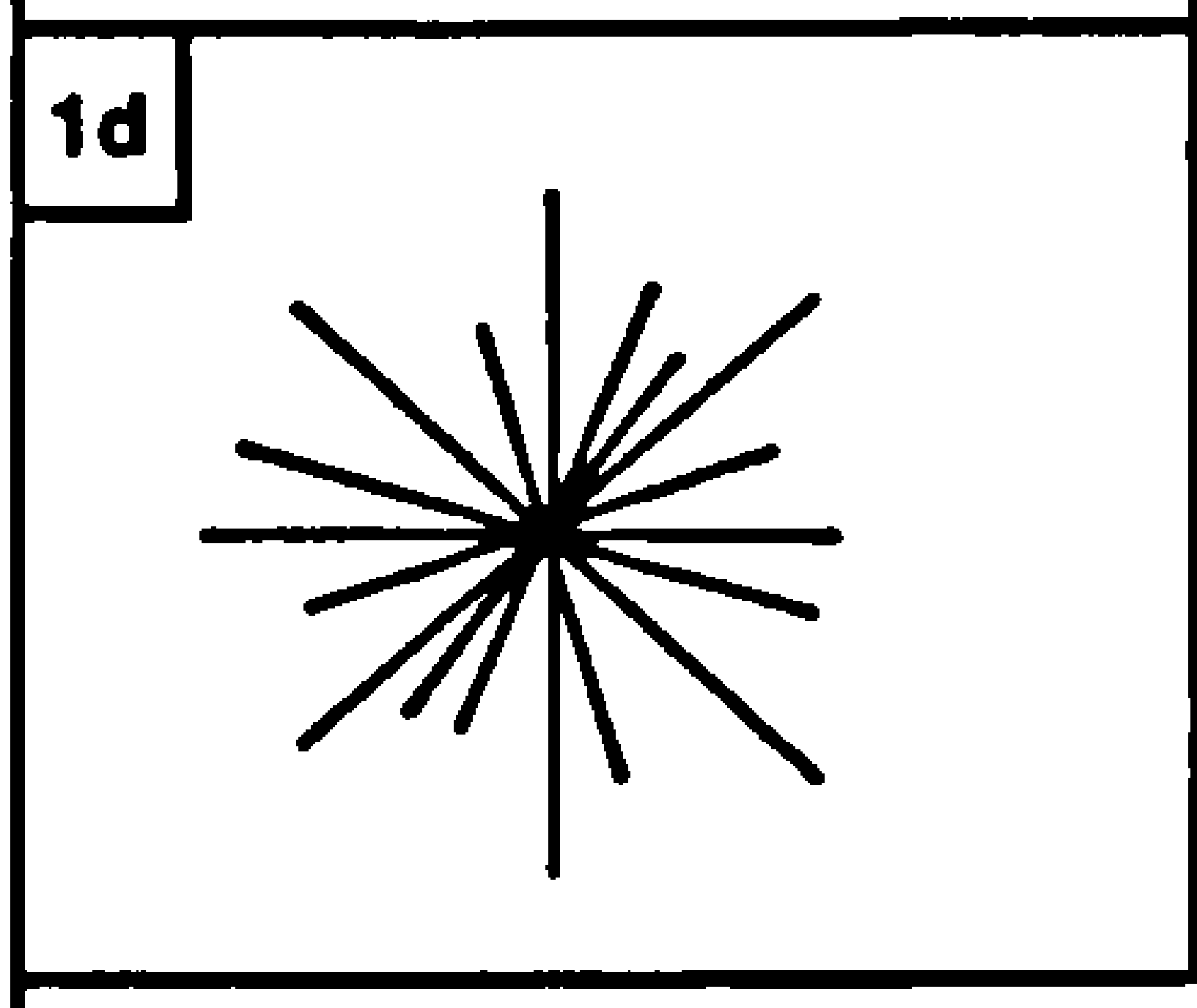
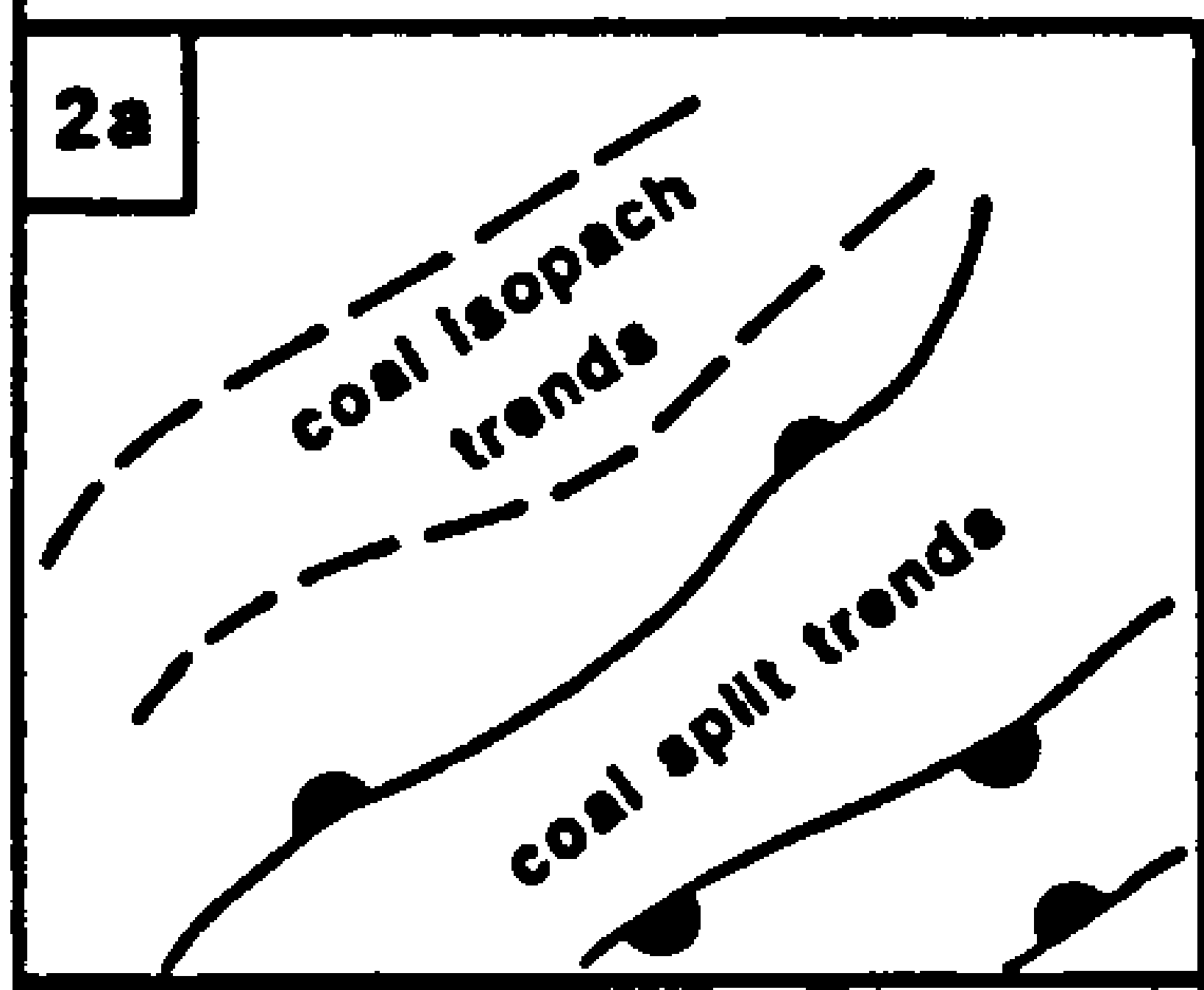
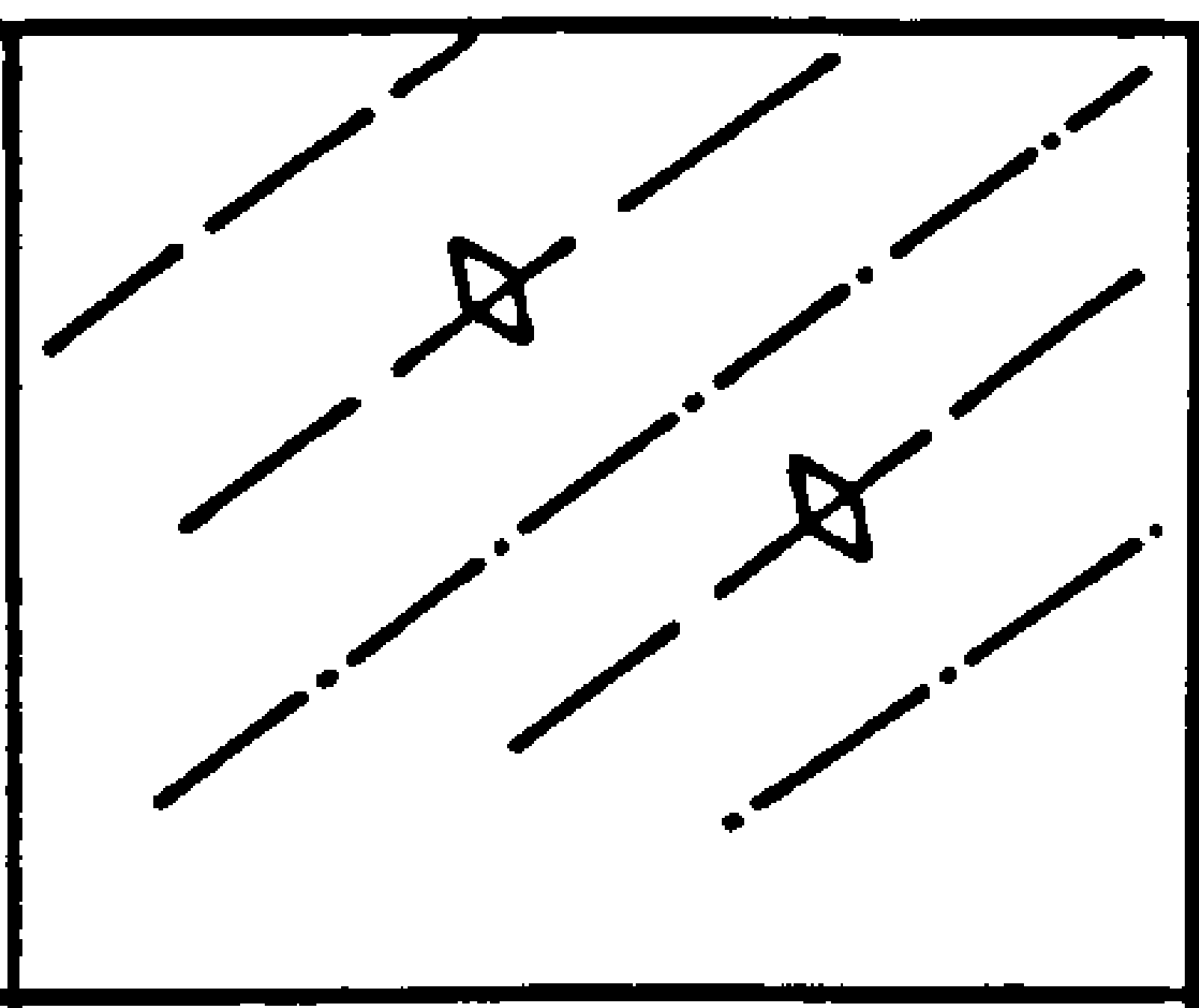
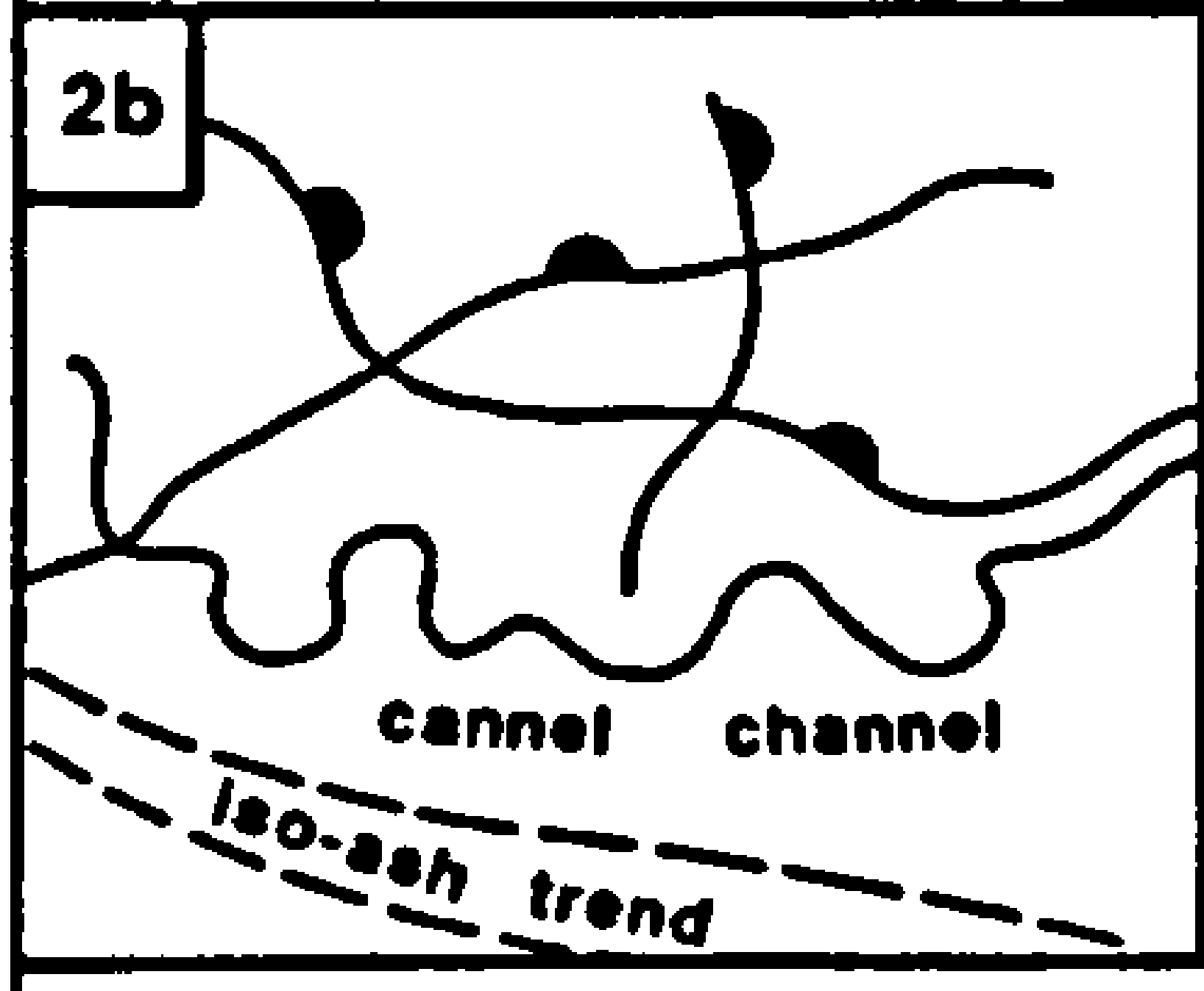
M - Mill Coal (Westphalian)

UH - Upper Hirst Coal (Namurian)

Gartarry Toll Borehole (Francis *et al.* 1970) is at E.293132 N.691256

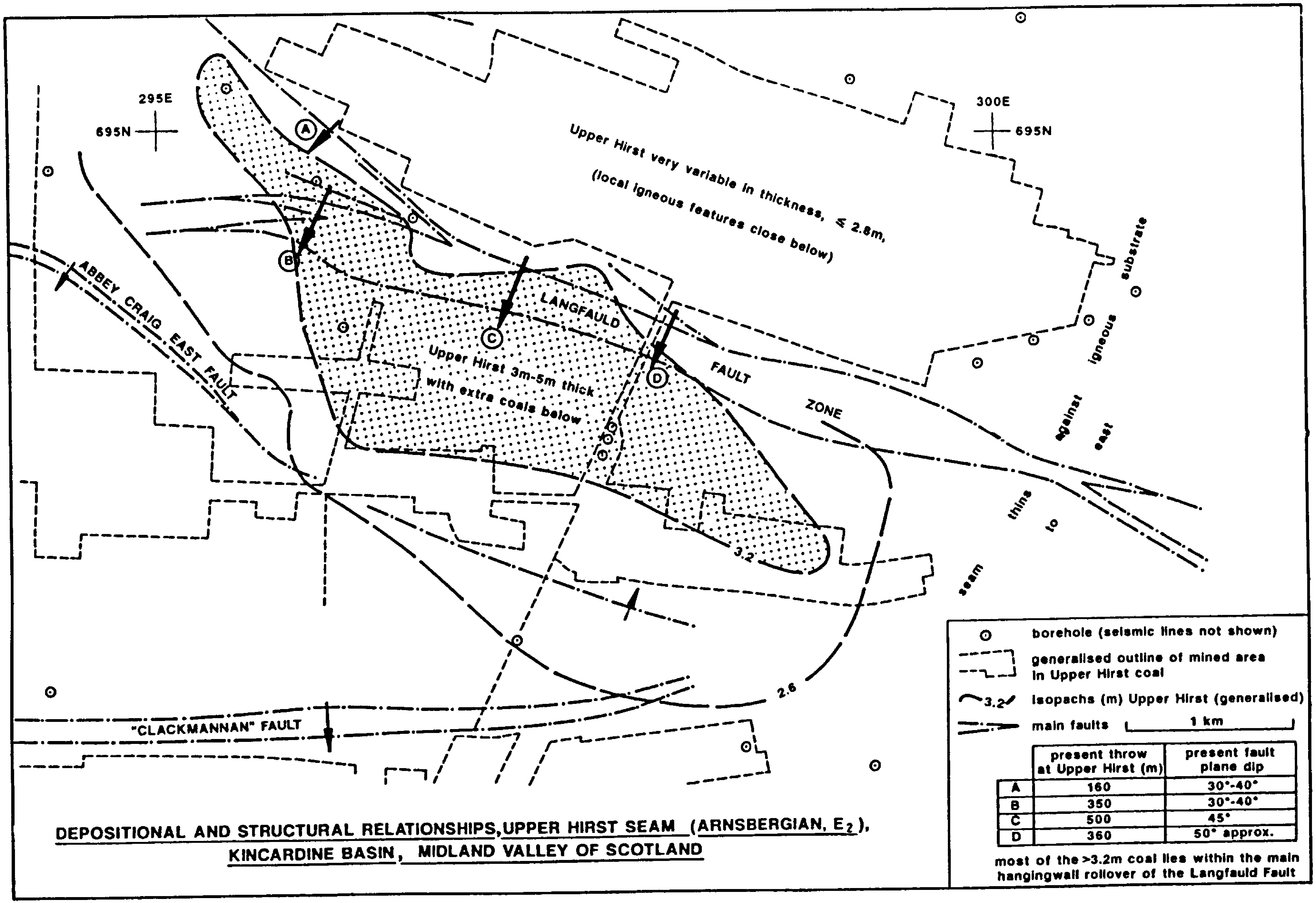
FAULT - ADJACENT STRAIN INTERPRETATIONS

Fig.5.7

channel orientation trends (Cf. Rippon 1996)	structural trends several km.	likelihood of syndepositional movement	
		good data (>1 borehole per km^2) at one horizon	good data (>1 borehole/km^2) at several horizons
1 Channel Sand Body Patterns			
1a 		possible	probable
1b 		possible	possible
1c 		very unlikely	very unlikely
1d 	any trend(s)	unlikely	very unlikely
2 Coal Depositional Patterns			
2a 		very probable	definite
2b 	any trend(s)	unlikely	very unlikely

UPPER CARBONIFEROUS DEPOSITIONAL PATTERNS : POTENTIAL FOR STRUCTURAL CONTROL

Fig.5.8

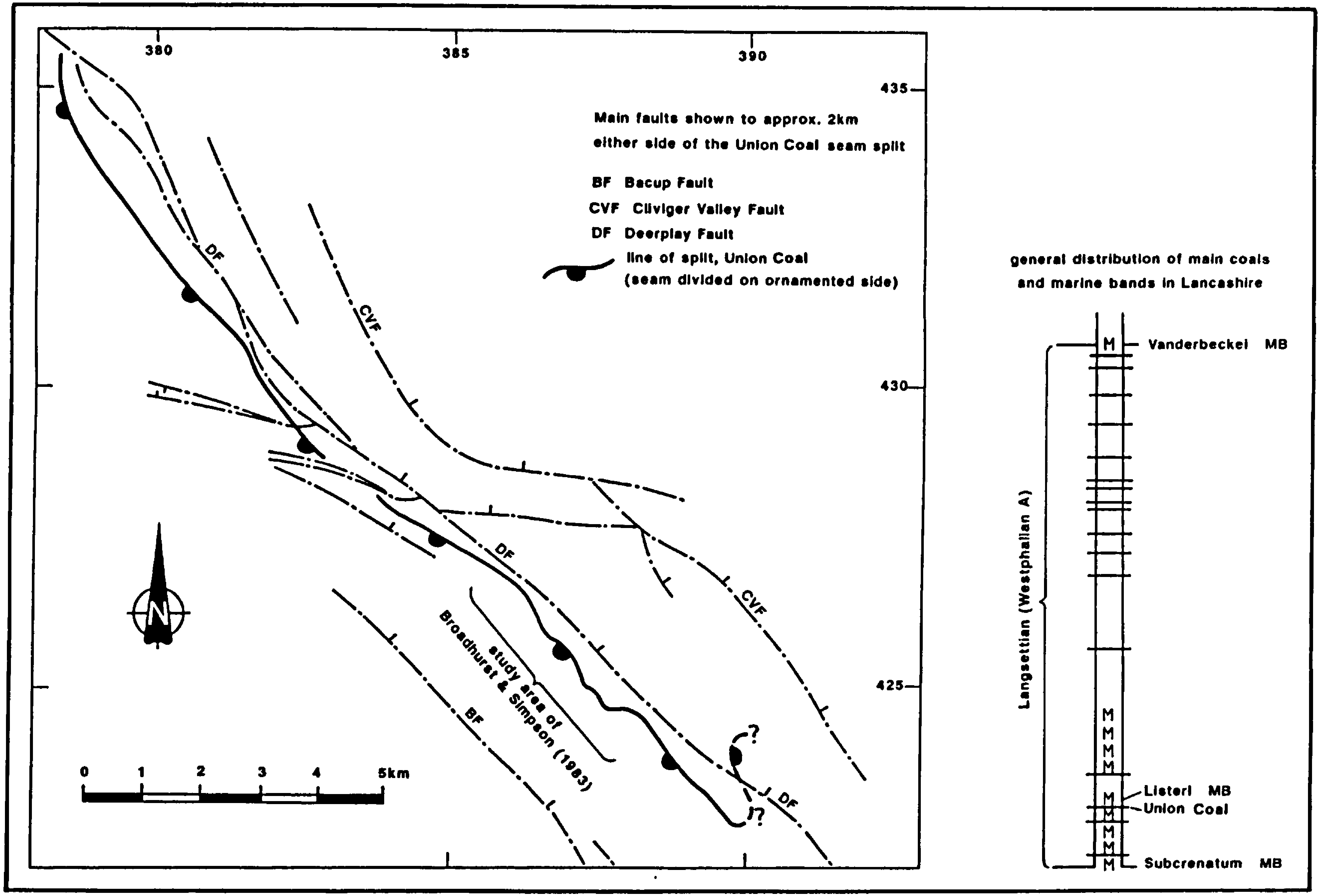


	present throw at Upper Hirst (m)	present fault plane dip
A	160	30°-40°
B	350	30°-40°
C	500	45°
D	360	50° approx.

most of the >3.2m coal lies within the main hangingwall rollover of the Langfauld Fault

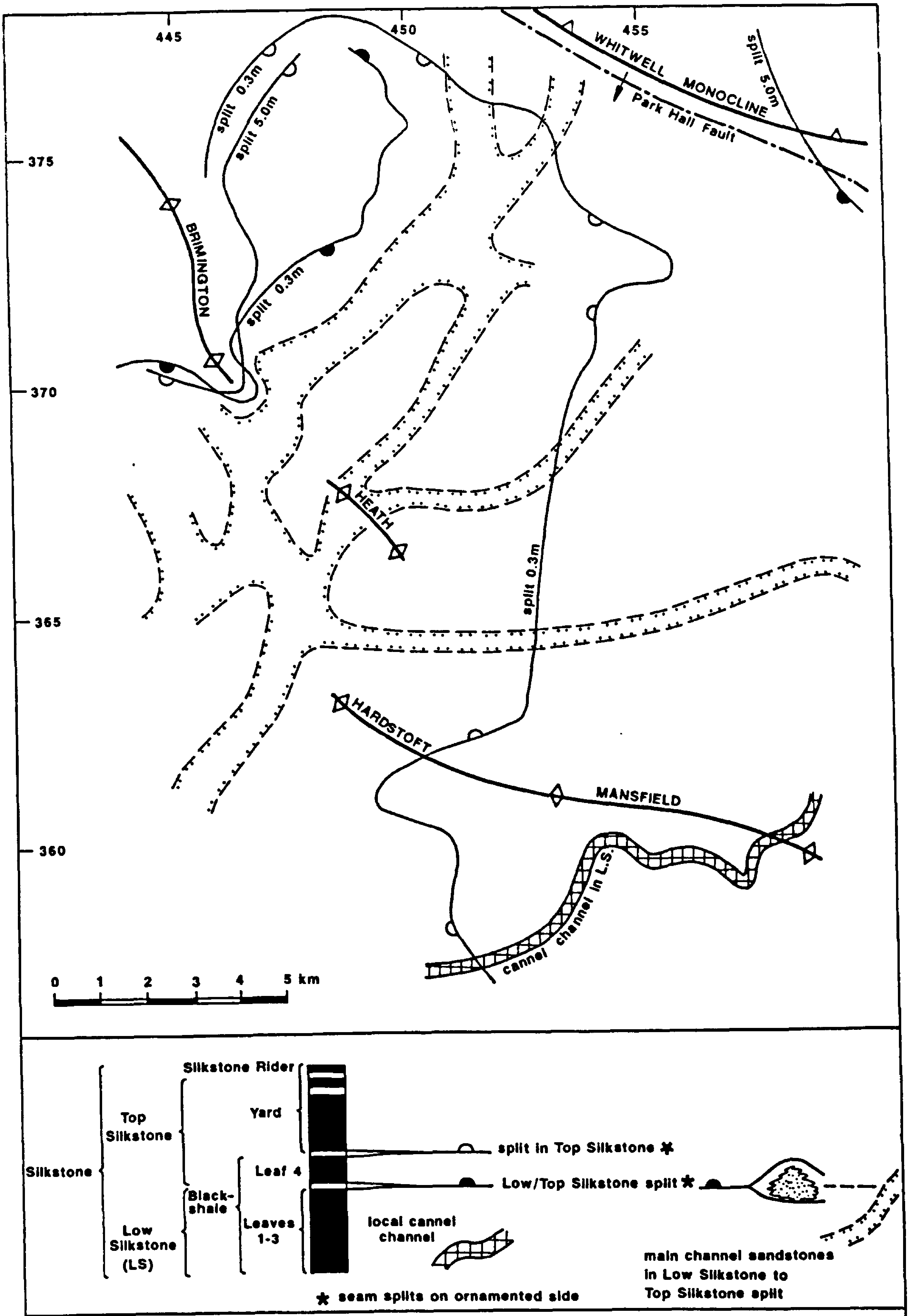
DEPOSITIONAL AND STRUCTURAL RELATIONSHIPS, UPPER HIRST SEAM (ARNSBERGIAN, E_2), KINCARDINE BASIN, MIDLAND VALLEY OF SCOTLAND

Fig.5.9



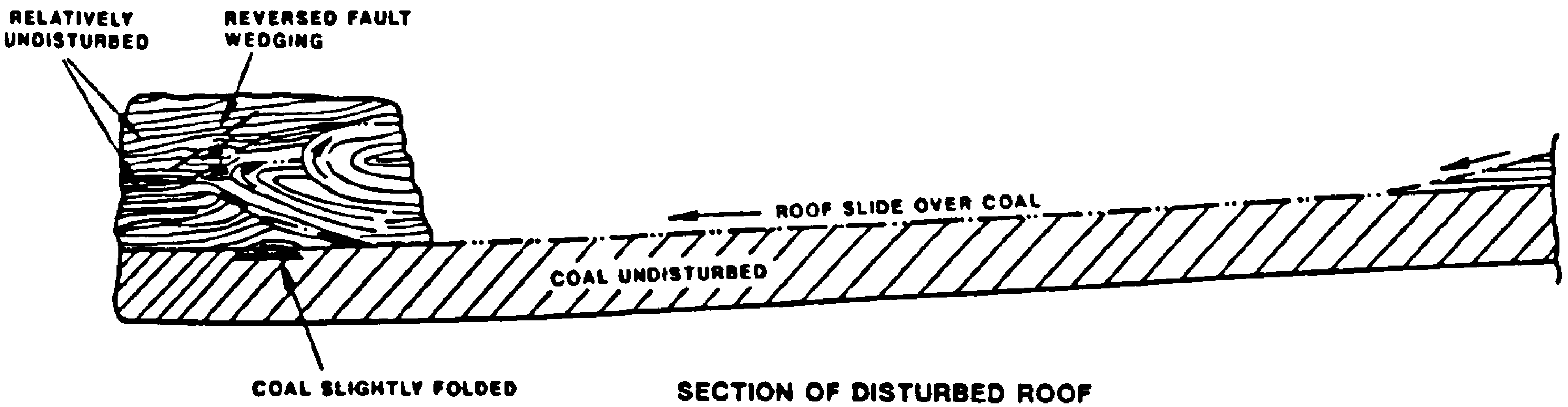
STRUCTURAL AND DEPOSITIONAL TRENDS, LOWER WESTPHALIAN A, LANCASHIRE

Fig.5.10



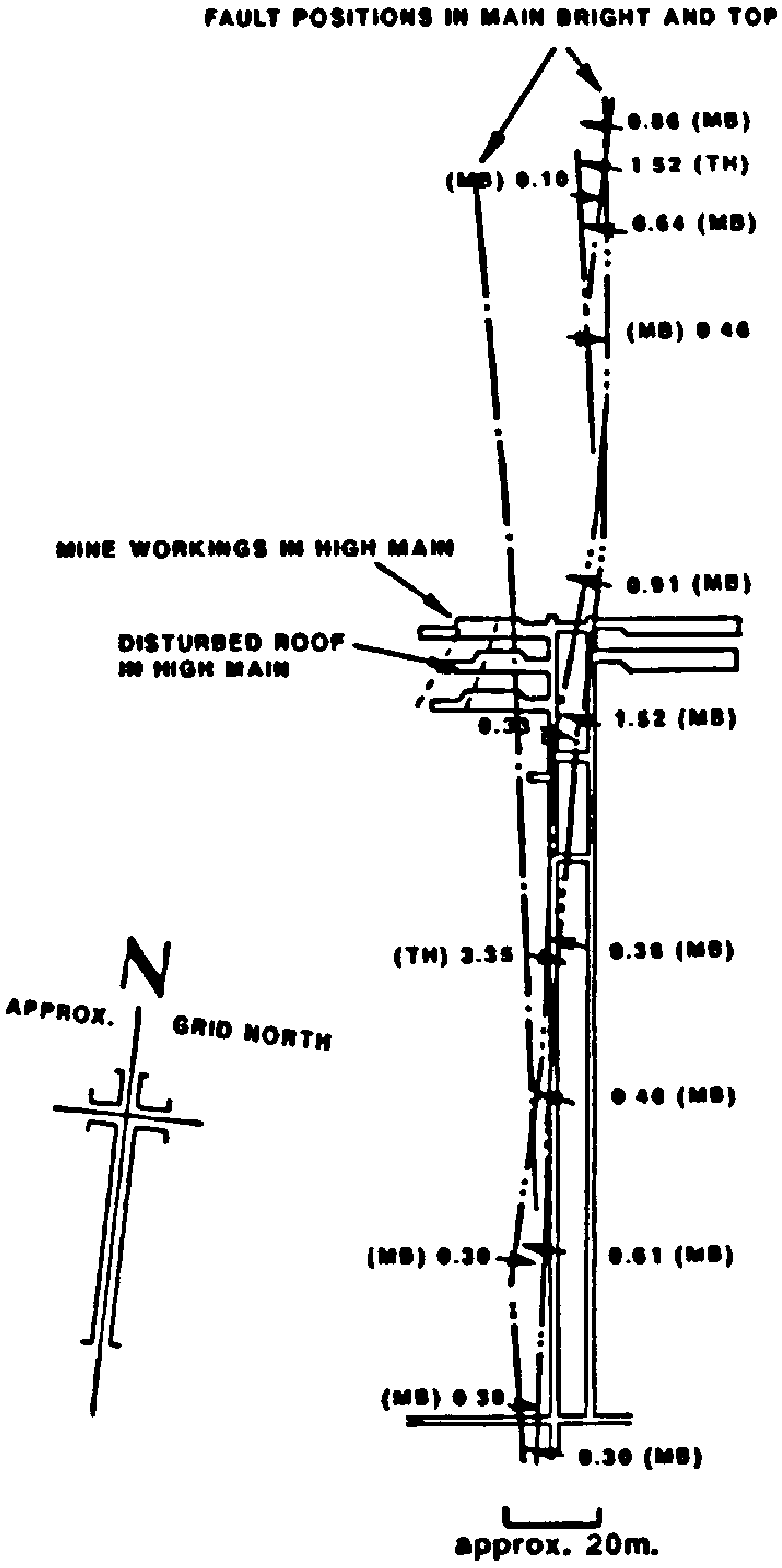
TECTONIC FEATURES, AND DEPOSITIONAL PATTERNS IN THE SILKSTONE COALS (LANGSETTIAN), DERBYSHIRE

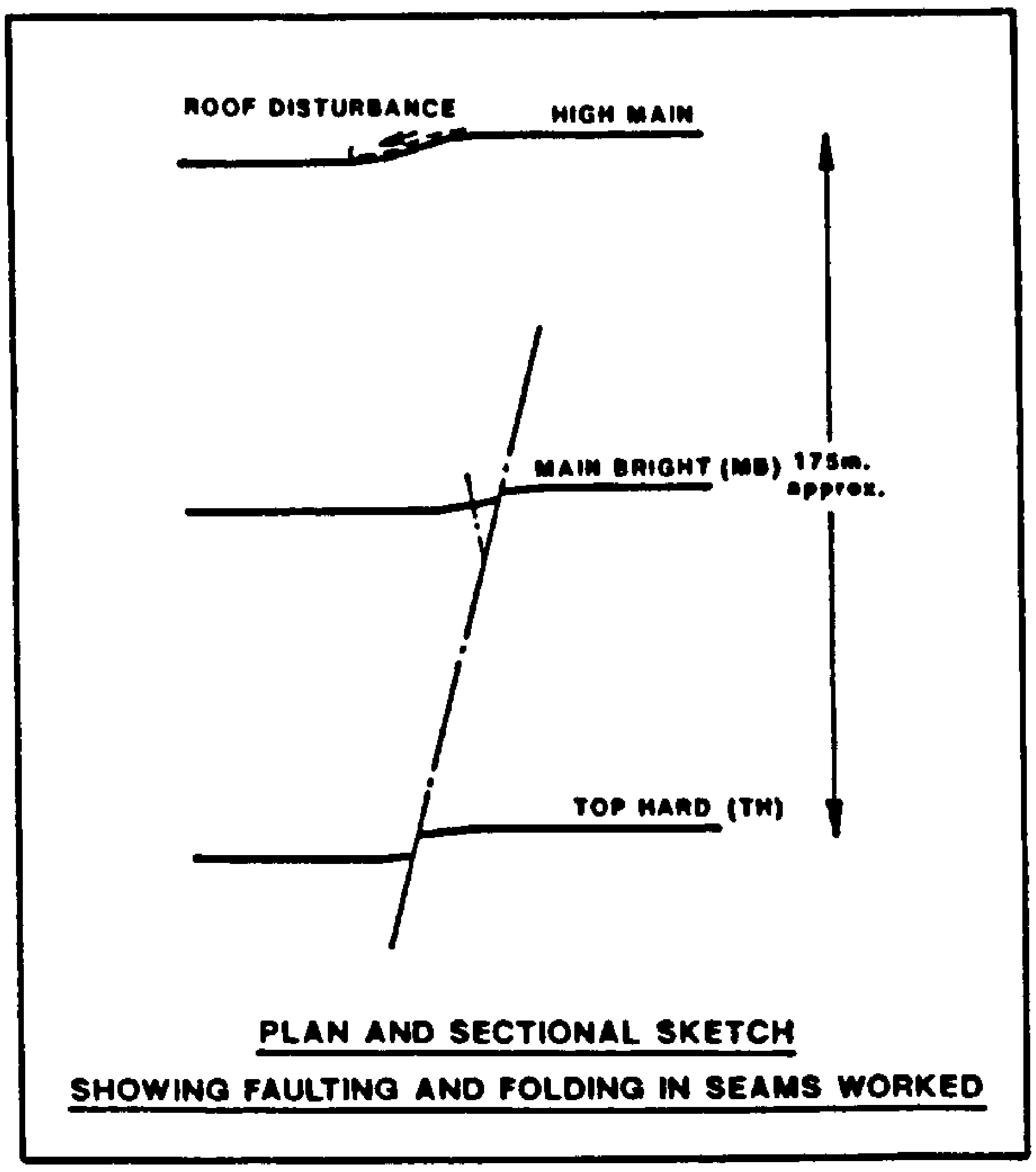
Fig.5.11



SECTION OF DISTURBED ROOF

approx. 2m.





PLAN AND SECTIONAL SKETCH
SHOWING FAULTING AND FOLDING IN SEAMS WORKED

BESTWOOD COLLIERY, NOTTINGHAMSHIRE HIGH MAIN SEAM (WESTPHALIAN C)

ROOF DISTURBANCE IN 8th. PANEL, 140's DISTRICT
Redrawn from N.C.B. October 1947
Location of disturbance E.453800, N.347600

Fig.5.12

CHAPTER 6

BRITISH CARBONIFEROUS COALFIELDS:
THEIR TECTONIC HISTORY AND STRUCTURAL STYLES

Abstract: *Varied structural styles in different coalfields result from complex histories, with inherited trends interacting with end-Carboniferous, Permian, Mesozoic and Tertiary events. This account reviews the background, and discusses structural compartmentalisation, fault patterns, densities, and growth, and other deformation characteristics in the context of regional geological history.*

6.1 Introduction

The British Carboniferous coalfields (Figs. 6.1, 6.2) occupy varied tectonic settings. Excellent data sets allow both detailed and regional geological analysis, from the syn- to post-rift Namurian to Westphalian coalfields of the Scottish Midland Valley, to the post-rift Westphalian of the Pennine Basin of central/northern England and adjacent areas, and the immediate Variscan foreland fields of South Wales and southern England. Many styles of extensional and compressional structures are present, including derivatives from multi-phase deformation; there are various inherited trends. Most fields have a heterogeneous clastic bulk lithology, including a hierarchy of fluvial-deltaic sand bodies with intervening claystone and siltstone lithofacies (Rippon 1996).

British coalfields have been prominent in the development of structural concepts over many decades. It is not the intention here to re-describe the general structure and tectonic settings of these coalfields, which are covered in many publications, particularly the memoirs of the British Geological Survey (BGS); main references cited below contain comprehensive bibliographies. Because of the breadth of structural topics covered in the literature, previous work relevant to this account is briefly reviewed within relevant sections; these are intended to widen the scope of geological interpretation through a broad review, with some new comment particularly on fault patterns and densities (6.4), fault growth and the attributes of fault-adjacent strain zones (6.5), and regional variations (6.6). The unifying consideration is tectonic history, which gives the regionally-distinctive fault styles and systematics their context. Before considering these main themes, it is necessary firstly to review the data, and the broad geological development of the coalfields.

6.2 Data

There are three main sources for structural data in British coalfields, namely mining plans, borehole logs, and seismic surveys; most coalfields include multi-horizon data.

Mine plans. Although there has been extraction in most exposed coalfields for many centuries, widespread deep mining generally dates from the mid 19th Century, when more accurate surveying was also possible. Legislation in 1911 required mining surveyors to record horizon elevations and fault details on large scale plans, and since the 1950's, these have been based on UK National Grid 1:2,500 $2km^2$ sheets; contours related to Ordnance Datum are drawn for the base of the worked seam. Fault throws 0.3m or less are commonly recorded; those up to 3m are usually shown as direct measurements, but larger faults usually prevent continuous mining through the disturbed ground, and throw may then be assessed by elevation comparisons. In each case, normal drag is not normally determinable. The mining surveyor's requirement is to record "throw", i.e. elevation differences across faults, and therefore the mine plans usually depict only dip slip, and it is important to note that (e.g.) strike slip of many 10's metres may go unrecorded, a fault being annotated only for minor vertical throw. However, most coalfields are in essentially extensional settings; reverse, and mainly strike slip, faults are comparatively rare (but see 6.6.2). In the compressionally deformed South Wales coalfield, thrusts are detailed on mine plans, although those which are virtually bedding-parallel are often unrecorded. Again, it is the surveyor's task to annotate vertical differences, and the throws recorded for thrusts are approximations of ramp height, rather than anything more systematic. Syn-depositional faults which are entirely the product of the depositional environment, compaction, etc. are not usually discriminated on these mine plans, but their characteristic geometries and relationships can usually be discerned (Chapter 5). On some pre-20th Century mine plans, "royalty" faults may sometimes be suspected: these were artefacts designed to minimise a mining company's lease obligations.

Direct proving of faults by mineworkings was most common in the pre-mechanised (mainly pre-1950's) period, in which labour-intensive methods achieved virtually complete extraction of coal across wide areas. Since then, most underground mining has been by capital-intensive longwall working, in which it is important to minimise fault intersections. The resulting reduced extraction makes these later mine plans rather less useful for, e.g., fault population studies.

Borehole data on faults include core observations, interpretation from significant loss of stratigraphical interval (extensional faults), and recording/interpretation from geophysical logs, in which advanced methods such as Formation Micro Imaging (Boardman & Rippon 1997) give very detailed data on fracture and bedding dips. Accurate recording of faults in cored lengths is not necessarily straightforward, as there are various other features which may be mistaken for tectonic faults, especially some compactional effects and joints. Fault locations and throws in boreholes are best interpreted, where there is sufficient stratigraphical control, by horizon-depth cross plotting with boreholes that are considered to be fault-free (see 1.3). This method also allows identification of subtle unconformities, and various depositional variations. Figure 6.3 illustrates the method schematically (the scale needs to be greater for practical interpretations).

Surface seismic reflection surveys became common in most coalfields from about 1980. Throw resolution to 5m at several 100's metres depth is presently possible, in good acquisition areas. Locally, resolution to <2m is achievable, and 3D surveys are particularly suitable for detecting very small throws. Coals >1m thick are excellent reflectors, and in the Scottish Namurian fields, the thicker marine limestones are also good. *Underground seismic surveys* have usually involved shooting and recording within the mined coal, to identify faults close to current workings; ranges are normally <300m. There are many subtleties in the identification of faults from seismic surveys, requiring experience not only of geophysics acquisition, processing, and interpretation, but also of the local geological setting. Interpretations lacking this combination may well be wrong.

Collated and interpreted maps derived from surveyors' 1:2,500 plans have been constructed at more regional scales. On these, faults proved in one horizon may be extrapolated using assumed fault plane dips, and not necessarily with any detailed reference to likely vertical variation in throw. Such maps therefore need treating with care during structural analysis, although they provide synopses of the regional patterns. (Similarly, many of the faults shown on published BGS maps are only extrapolations, from an underground position to the surface.)

6.3 Tectonic events affecting coalfield structural evolution

6.3.1 Background

The long history of coalfield geological description has often included interpretation of tectonic setting, e.g. in the mid 19th Century the prognosis and exploration of the Kent field were in the context of its Variscan setting (Rippon *et al.* 1997). Recent accounts of the Variscan foreland setting of South Wales are given by Jones (1989) and Gayer (1992), while late Carboniferous compressional events across the area north of the immediate Variscan foreland have been discussed by Corfield *et al.* (1996) and Peace & Besly (1997). Across the Pennine Basin and northern England, the influence of Dinantian rifting has been described by many authors, following Kent (1966). The Scottish Midland Valley has been described in numerous publications discussing tectonic context (see Rippon *et al.* 1996). The Carboniferous lies approximately midway through the Phanerozoic, and coalfield structure frequently perpetuates earlier geological trends, as well as recording the many effects of later events. Discrimination of these has practical importance in forecasting likely fault linkages. For context, it is necessary to consider the geological evolution of the coalfields. This is relatively easy for the late Carboniferous to early Permian interval, while many coalfields probably achieved their present accessible extents as a result of Triassic rifting. However, late Triassic to Tertiary history is not well understood. Interestingly, it is this interval which is increasingly well-defined in offshore areas, and dominated by development of the Atlantic, and the Central and Viking Grabens. The following brief discussion of selected issues illustrates general coalfield development.

6.3.2 Inherited features and their Upper Carboniferous history

Inherited features are fundamental to the location, and overall form, of most tectonic depocentres. This is particularly evident in the extensional provinces of central and northern Britain; in southern Britain, Variscan deformation complicates the picture. Many inherited structures, and their varied inversion histories, can be interpreted using the continental escape tectonics of Coward (1993), involving Devonian to Permian indenting and expulsion of the North Sea/Baltic block between the North American and Variscan plates. Inherited features include not only specific deep crustal fractures, but also the disposition of regional variations in depth to the Lower Palaeozoic or Precambrian basement. Price (1966) suggested that some tectonic stresses might be stored elastically for many 10's Ma.

The Wales-Brabant High (Fig. 6.2; see Rippon 1996) is is the largest and most important inherited feature, affecting disposition of major depocentres, drainage patterns, and structural style over coalfields throughout central and southern Britain. Through much of south-central England, the Precambrian and Lower Palaeozoic basement forming the high is shallow and relatively undeformed, and Lower Palaeozoic strata are only slightly metamorphosed compared with the Caledonian slate belts of Wales. An indenter model was developed by Soper *et al.* (1987) to account for variations in Caledonian cleavage trends (from SW-NE in Wales, to NW-SE in eastern England), which were considered to reflect northwards push of the Midlands Microcraton (forming part of the high in central England) through the later Devonian (see also Pharaoh *et al.* 1987). By Carboniferous times, the addition of the more deformed Caledonides had produced a regional massif which determined the limits of Westphalian deposition, and probably also the northern limit of Variscan thrust propagation (Chapter 10).

During Variscan advance, it appears that while the high acted as a buffer to pervasive compressional deformation, it did allow transmission of the northwestwards-directed principal horizontal stress at depth, which produced inversion effects in variously-oriented structures to the north (Corfield *et al.* 1996) and perhaps controlled the orientation of main cleat (coal joint) sets across central and northern England in the Variscan far field (Chapter 7). However, late Carboniferous principal stress was not always on the northwestwards Variscan trend. Chadwick & Smith (1988) and Peace & Besly (1997) inferred essentially W-E directed Stephanian compression across southern Britain, notably producing large thrusts along the Malvern line and through the western limits of the Oxfordshire coalfield, locally expressed as sinistral transpression: these features were subsequently inverted with the formation of the Triassic Worcester Basin. (Some major N-S striking transpressional structures, e.g. see Underhill *et al.* (1988), in northern England may also reflect this event.) Peace & Besly (1997) considered that these structures predated final emplacement of the Variscan nappe front. The eastern thrusts of this N-S striking system lie just west of the Oxfordshire coalfield as explored by the National Coal Board (NCB) in the 1970's and 1980's, and are not imaged on NCB seismic surveys. It is possible that sub-seismic resolution thrusts are present within this coalfield beyond the limits of the main imaged structures, but significant disturbance has not been noted in any Oxfordshire coal cores (D.Foster, pers. comm. 1996). Widespread small scale thrusting across the high was either absent, or conceivably propagated above the preserved sequence.

Dinantian sub-basins in central and northern Britain (Fig. 6.2). The identification of block and basin patterns in northern England has a long history, based on Dinantian outcrops. Kent (1966) formalised their extrapolation into the coalfields of the eastern Pennine Basin, describing the Gainsborough Trough, and the Edale and Widmerpool Gulfs. These were seen by Coward (1993) as evidence for lateral expulsion of the North Sea-Baltic block; as noted, Corfield *et al.* (1996) reviewed these and other structures for their varied responses to Variscan compression. Rippon (1996) described swings in Westphalian formation isopachs within these structures, indicating continuing extension prior to end-Carboniferous inversion. The Northumberland Trough is another known Dinantian rifting feature in northern England which experienced enhanced Westphalian depositional rates, compared with the adjacent block to the south. In this case, the Maryport-Stublick-Ninety Fathom faults which form the southern boundary (Chadwick & Holliday 1991; Chadwick *et al.* 1995) may be a later expression of the more deep seated Caledonian Iapetus Suture. Scottish Midland Valley rifting appears to have been initiated in the Lower Devonian (Rippon *et al.* 1996), continuing through the Dinantian to give the well-defined and varied inherited structural trends that influenced deposition through the post-rift Upper Carboniferous.

6.3.3 Unconformities

Chapter 5 discusses syn-depositional movements in the coal-bearing Carboniferous, noting that these should be more evident near basin margins. Of particular interest here are the intra-Silesian unconformities, that is, those with a direct tectonic control, rather than the numerous erosions and oxidation features that characterise the fluvial-deltaic deposits themselves, or the progressive Westphalian onlap (Chapter 2). Some unconformities are marked, others are much more subtle.

Within the Upper Carboniferous, the best known is the "Symon Fault" of the western Pennine Basin, in which late Westphalian Upper Coal Measures lie across folded and faulted Westphalian A and B strata, which are reddened. A similar situation is found in the eastern margins, in Lincolnshire and Nottinghamshire, where later Westphalian grits overlie progressively earlier Westphalian strata southwards. Structural compartmentalisation is marked in the various coalfields around Bristol and Somerset, only some sequences being preserved in some areas, perhaps reflecting the interaction of the proximal Variscan setting with older structural lines. A sub-Westphalian D unconformity is known in the Forest of Dean, and possibly at a similar horizon in Kent; a subtle intra-Westphalian D break is inferred below the Mynyddislwyn coal of South Wales (Rippon *et al.* 1997). A late Westphalian unconformity is also known in the Canonbie field in southern Scotland. Earlier Upper Carboniferous breaks are known elsewhere in Scotland, within the Namurian at Douglas, and in the early Westphalian A at Douglas and Canonbie.

The post-Carboniferous, pre-Permian unconformity of central and northern England is well known, with Permian rocks overlying deeply weathered Westphalian Coal Measures. As noted, main coalfield dispositions were effected by Triassic rifting, and the post-Triassic history of the coalfields is not well known. However, there will have been various phases of uplift and reburial throughout, exemplified by the intra-Mesozoic unconformities known in Kent (Creedy 1988).

6.3.4 The ages of faulting

Given the above review, faults of various ages should be expected, and although most should date from main tectonic events, some might not. Assessing the relative age of faults is a pre-requisite for practical forecasting; fault linkages will often reflect pre-existing structures. Absolute dating of faults in the coalfields has not yet proved possible. Langley (1981) attempted K-Ar dating of claystone gouges, but considered her results recorded sediment diagenesis rather than faulting. An approximation can be made where an intrusion and faulting are related; thus, dolerites along the Ochil Fault (Scottish Midland Valley) can be dated to 303 +/- 5Ma, field evidence suggesting that main extension across the fault was contemporary (Rippon *et al.* 1996).

Most faults can only be dated stratigraphically. Assessing relative ages by fault linkage characteristics will usually give ambiguous conclusions. This is because: 1, fault zones may be multi-phase; 2, fracture propagation patterns are influenced by gross lithologies; 3, linkage characteristics vary considerably, according to relative orientations; and 4, details of linkages between larger (say, >10m throw) faults are rarely recorded on mine plans. Even on regional scales, relative dating of interacting trends can be ambiguous. Unaligned normal faults either side of a strike slip zone might be interpretable as laterally displaced, or as later faults precluded from further propagation by a pre-existing dislocation. In South Wales, the relative ages of some high-dip cross faults (Woodland & Evans 1964) and Variscan thrusts remain ambiguous. Many thrusts are thought to terminate laterally against cross faults, suggesting that the latter acted as sidewall transfer faults (see Jones 1989, 1991 for discussion). However, some cross faults might simply be post-Variscan, sufficiently segmenting the thrusts so that individual elements are difficult to relate (inter-horizon thrust correlation is rarely straightforward from mine plans). Also of course, some cross faults may have existed pre-thrusting, reaching their main displacements only later.

Across the southern coalfields, Variscan thrusts are likely to have been mainly Stephanian to early Permian. To the north of the high, most coalfield faults are probably "pre-Permian" (6.6.2). Thoughout the concealed fields of eastern England, relatively few faults known in Westphalian strata cut the sub-Permian unconformity, and these have significantly reduced throws in Permian strata. After allowing for poorer data quality, most faults cutting Permian rocks (and perhaps recording Triassic rifting) seem simpler structures than their counterparts, assumed multi-phase, in the Westphalian. The age of faults that cut Triassic rocks is uncertain; in the eastern Pennine Basin, many perpetuate earlier trends, e.g. WNW-ESE arrays of faults within the Widmerpool Gulf southeast of Nottingham. Although Britain was a comparatively stable area through Mesozoic times, major extensional events in the Atlantic and North Sea areas, together with known onshore intra-Mesozoic movements, suggest that there would have been further faulting in the coalfields, although probably along existing structures.

Tertiary deformation is evident across southern England, including likely reactivation of Variscan structures (Rippon *et al.* 1997); compressional directions appear close to those of the

Variscan, with significant deformation again perhaps limited by the old basement high. This raises the possibility of some end-Carboniferous and Tertiary compressional structures co-existing within Westphalian Coal Measures. There is evidence that the high dip NW-SE faults of the Kent field are, at least partly, Tertiary strike slip structures (Chapter 10), while large NW-SE disturbances across Devon and Somerset (e.g. the Bovey Tracey and Watchet zones) are important Tertiary structures; some parallels may be expected in South Wales (6.6.1).

Muir Wood (1989) proposed four main phases of crustal deformation across northwest Europe over the last 50Ma. His final phase (8 to 2 Ma) reflected continuing deformation across the Alpine foreland, combining with push from the northeastern Atlantic to give NW-SE directed principal horizontal stress across Great Britain.

Following this review of structural history, some particular themes may now be addressed.

6.4 Fault densities and patterns

The interpretation of fault patterns has a long history, being essential to any tectonic analysis, and also for mineral and hydrocarbon evaluations. Obviously, an understanding of regional geological history is necessary for valid interpretations.

6.4.1 Introduction and definitions

Definition of terms is necessary. The term "fault population" in particular has been used to include all faults within a defined area, sometimes involving multi-phase deformational histories, and such populations are really combinations of different sets, generated under different conditions. In these cases, attempts at defining (e.g.) power law relationships for all the faults may not strictly be valid. In this account, the terms density, pattern, and population are used as follows.

Fault density is a measure of the full number of faults in an area (or, ideally, volume). *A fault population* is a specific set of faults of probably common origin, for which there is a definable numerical relationship between faults of different displacement dimensions, commonly expressed in self-similar patterns. *A fault pattern* is a well-defined, kinematically-consistent and essentially repeatable geometrical arrangement of faults. Only in relatively young geological formations, in which faulting is referrable to a single process, will a population usually equate to overall fault density: such would be expected, for example, in the ongoing rifting across Iceland. In all contexts, more small faults might be expected than large ones, but not necessarily with a meaningful numerical relationship; this often appears the case in British coalfields (Boardman & Rippon 1997), when the term *pseudo-population* is appropriate. It is not easy to demonstrate this, and any interpretation will depend on investigative scale and data availability. Fault densities, populations, and patterns will all be influenced by gross lithology, depth of fault initiations, inherited trends, and the relationship of all local factors to formative stress vectors. Commonly, all are assessed only from plan view, and only from one horizon, but in many coalfields, multi-horizon evaluations are possible over a depth range of hundreds of metres. Most recent interest in fault statistics has been for hydrocarbon reservoir description, assuming that fracture permeability can be gauged by applying population relationships to faults imaged by seismic surveys, and extrapolating to those below resolution. Validity here assumes firstly that the faults are treatable (at least in practical terms) as a population, and secondly that fault patterns and densities in the reservoir rocks are necessarily forecastable from those at the seismic reflector horizons.

6.4.2 A brief review and discussion of previous work

Mining interest in fault densities and patterns has been recurrent since at least the 1960's. Many approaches have been attempted, reflecting differing structural styles and practical requirements. Interest in all methods of fault forecasting grew in response to capital-intensive mechanisation, mainly through the 1970's. In Great Britain, mine planning in poorly-proved areas was assessed by a gaming technique (Geosimplan) in which statistics on fault orientations, dimensions, and spacings were devised, and arranged into alternative geologies, against which the mine planning could be tested. Development through the 1980's of high definition seismic reflection surveys eventually replaced formal modelling exercises in Great Britain. However, it remains true that any area, even if well explored, will always benefit from regional modelling, to aid context. Apart from evaluation by fault statistics, such modelling can also include assessment of shortening, in the thrust-prone ground of South Wales (Jones 1989), and extension, especially in the multi-horizon data sets of parts of the Pennine Basin. Rippon & Raine (1986) suggested forecasting unknown faults on two trends by summation of known displacements in fully proved areas, with estimation by difference elsewhere, on the assumption that extension, normal to both trends, was constant across a defined block (Fig. 6.4). These authors developed the idea of "structural cells", in which defined blocks had structural parameters significantly different to their neighbours, including vertical variation in fault density; this will be discussed later. Elliott (1978) collated and edited several unpublished papers by NCB geologists, detailing fault style variations in most British coalfields, illustrating current thinking on densities and patterns. Figure 6.5 shows a 1970's NCB histogram, essentially a fault population plot, for one trend at Cotgrave, near Nottingham. The illustrated trend parallels the boundary fault of the Widmerpool Gulf, just north; probably most of the extension represented by these faults is intra/post Triassic. More recently, part of the eastern Pennine Basin has been studied by Watterson *et al.* (1996); an area of 87km^2 of intensive mining data was assessed, and a fault population was interpreted, illustrated by cumulative frequency plots. The geological context and implications of these studies will be discussed later.

Statistical methods have been used widely in central and eastern European coalfields, often in proximal Variscan settings. There is an extensive literature. An early overview of the Dutch coalfields is given by Sax (1946), who interpreted fault orientations and densities in relation to regional structural context. In western Germany, context was also essential in formulating the "tectonic index" (Ehrhardt 1978), a mine planning device that delineated areas of equal tectonic (palaeo)stress. This took detailed note of differences between (e.g.) graben and horsts, between differently-shaped structural blocks, and between areas above and below large thrusts. The possibility that some areas were protected from structural disturbances was also considered. Beyond Europe, most coalfield work has been in Australia, e.g. Shepherd & Burns (1978) and Shepherd *et al.* (1981), who emphasised the need to consider fault spacings. Although in many coalfields, study of fault densities and patterns has been superseded by improved exploration techniques, application to hydrocarbon reservoir descriptions is ongoing, with a growing literature following (e.g.) Yielding *et al.* (1992), Gillespie *et al.* (1993) and Walsh & Watterson (1993).

6.4.3 Some comment on fault populations interpretation

It is worth summarising here a few relevant comments from coalfield experience. 1. Fault densities and patterns will always reflect local tectonic setting and history; some may be treatable as populations. 2. Fault densities vary areally, but also through the rock volume; multi-horizon studies are to be preferred where possible. 3. Gross lithological control on fault density variations is probably common. 4. In fault population cumulative frequency plots, curves result from lack of sufficient data at the "small" end, usually interpreted as reflecting resolution or documentation limits (and at the "large" end, by non-inclusion of necessarily rarer features); however, "small end" curves are not necessarily artefacts, as most British coalfields do not demonstrate an ever-increasing frequency of smaller throws (Boardman & Rippon 1997).

This last comment has to be based on experience rather than proof, because of the nature of the data set. It can be argued that not all faults have been recorded, especially in thicker (>2m) coals. This sometimes is the case, but it is the everyday experience of close observation in mines that coals are not subject to an ever-increasing frequency of smaller throws. If this were the case, it would undoubtably be known as a standard feature. Obviously there will be small throws where larger faults are dying, and individual small faults are known. But the "small end" population aspect, implying a somewhat uniform spatial distribution of ever-smaller faults, would not be recognised by any coalfield geologist. For "small end" curves to be more than artefacts, it is necessary for the ever-smaller fractures to be subject to spacing limitations, i.e. progressively confined within fault zones; the definition of faults and fault zones then becomes an issue. Perhaps also there is a generalised size cut-off (say, around 1m in the eastern Pennine Basin) resulting from continuing growth of those faults which were initiated at the outset of the main deformation, with few entirely new faults developing subsequently.

6.4.4 Variations between and within the coalfields

It follows from the earlier review (6.3) that there will be significant differences in structural style, and therefore fault densities and patterns, across the coalfields. Obviously, contrasting styles would be expected in fields with very different structural histories, such as the Variscan-proximal

South Wales compared with the English Midlands, and those of the latter compared with the Scottish Midland Valley. Figure 6.6 shows the Clackmannan Syncline area, together with part of the eastern Pennine Basin in northeast Derbyshire, on the same scale. Context and detail for the former is given by Rippon *et al.* (1996), and for the latter by Rippon (1985 a,b). The Clackmannan Syncline area shows two main fault trends, the larger throws being on the "W-E" set. Compared with Derbyshire, there are several large (100's metres throw) faults, and relatively few minor faults (not shown on either map, both being simplified). In both cases, most faults are demonstrably normal, although an overall transtensional setting can be interpreted (6.6.2).

Within individual coalfields, reasons for pattern changes may be fairly easy to detect, such as the predominance of NW-SE faults within the Widmerpool Gulf southeast of Nottingham, parallel to the sub-basin boundary fault, reflecting Dinantian extensional patterns (see later, Fig. 6.23). However, other pattern variations may be much less straightforward, and the following example serves as an introduction. Figure 6.7 shows a simplification of much of the eastern Pennine Basin, together with context maps. Main pattern differences in the Yorkshire part of the field, north of Sheffield, compared with the East Midlands to the south are the prominence of the northeasterly fault set, and greater fault continuity and length; in more detail, there are also many larger fault throws in Yorkshire. The East Midlands is characterised by prominent anticlines on a generally NW-SE trend; there are folds in the Yorkshire field, but (with the exception of the Don Monocline) these are minor, and steeper dips are associated more with specific large strike slip fault zones (see 6.6). These differences within the eastern Pennine Basin, discernible on this admittedly much simplified map, have been well known to coalfield geologists, and can be substantiated by mine plan detail. However, reasons for the differences have not formally been investigated. The change has been considered anecdotally to lie along the W-E line of disturbances which includes the Thurcroft Fault. This unusually-oriented structural line lies within the Gainsborough Trough as defined by Westphalian formation isopachs, but undoubtably represents a major feature at depth (see later, and Fig. 6.21). Differences on this scale are known in other coalfields, a good example being the Neath Disturbance in South Wales (Chapter 7; Fig. 7.10). Such regional variations suggest deep compartmentalisation of the crust, with large blocks responding to successive deformation events in different ways, often revealed only subtly in Westphalian successions.

6.4.5 Structural blocks and cells

That larger coalfields may be divided into significant structural blocks as just discussed is implied in much of the existing literature. This is most obvious from studies on the Scottish Midland Valley (Fig. 6.8) which includes various structurally separate coalfields, and shows evidence for compartmentalisation into discrete sub-basins and highs during Carboniferous deposition (e.g. Rippon *et al.* 1996), each of which seems to have had its own depositional rates, and subsequent structural style. The overall effect is a mosaic of individual structural units recording geological history in often quite different ways, in terms of fault densities and patterns, incidence of minor folds, and volcanism. These internal divisions of the Midland Valley cannot always be related to immediately visible faults (see discussion on the Bo'ness Line in Rippon *et al.* 1996), but it may be assumed that important fractures are present at depth. Many of these Midland Valley structural units extend across some 300 to 500km^2.

A similar situation may be envisaged for the Pennine Basin, but with generally thicker sedimentation masking many internal divisions: compartmentalisation here will be more obvious in the earlier Carboniferous or, in the Westphalian, around the margins. In the eastern Pennine Basin coalfield, the possibility of significant structural compartmentalisation was considered for practical forecasting purposes by Rippon & Raine (1986). Their study may be developed further, by considering the mining evidence within a wider structural context. Mining evidence suggests that this field can be subdivided into units significantly smaller than those in the Midland Valley, probably representing mainly post-depositional faulting of the Carboniferous succession.

Following Rippon & Raine (1986), a *structural cell* is defined here as a 3-dimensional unit within which structural attributes differ significantly from adjacent units. It is useful to use this term, as "block" already has particular connotations (including depositional factors), whereas "cell" suggests the wider framework that is intended. It should be noted that the degree of inter-cell difference is relative to investigative requirements: for mining purposes, cells <25km^2 extents may be discriminated. The main structural variants are: fault orientations and linkage characteristics, strike slip/dip slip proportions, fault densities, preferred fault nucleation and termination horizons, the degree of complexity of fault damage zones, and joint set characteristics including mineralisation. (There is also a possibility that, at the local scale, there may be variations in the present principal horizontal stress vector, see Whitworth 1994.) Cell boundaries are usually defined by faults of a higher order than those within cells. However some boundaries may be inherited, with basement features identifiable only as structural "ghosts". In South Wales, any structural cell model would also need to consider the gross lithological differences between the mid-A to mid-C Westphalian sequence, and the later Pennant Measures.

The structural cell model in the eastern Pennine Basin was originally proposed to account for variations in fault density in the Markham area of northeast Derbyshire, where exploitable coals are present over a vertical interval of about 600m (Fig. 6.9). The unpublished NCB Markham Fault Study of Rippon (1982) investigated an intensively mined area of $40km^2$, detailing fault plane hades (90^o - dip), vertical and horizontal throw attenuation rates, attenuation rates related to maximum throws (see later, Fig. 6.15, and discussion in Chapter 5), lateral/vertical fault plane axial ratios (the aspect ratio of Nicol *et al.* 1996), and especially the variation of fault density with depth. This study also included the first strike projection of fault throw contours. The geological background was published by Rippon (1985a, b), and Rippon & Raine (1986). The practical issue in the 1980's was whether the known fault densities in previously mined coals were relevant to reserves in lower seams, given evidence that some faults in higher horizons were small or absent below. The best data were from the Top Hard coal, mined to total extraction over wide areas.

When considering fault density, it is necessary firstly to define what constitutes an individual fault: even the simplest can include multiple fractures. In the Markham area, Rippon (1982) treated all faults as zones of greater or lesser complexity; the primary discriminant was fault strike backed up by traceable continuity from seam to seam. However, with very complex zones, it is a matter of judgement whether to treat a zone as an entity, or to subdivide where possible into separate major planes; much depends on required objectives. In the Markham Fault Study, this definition problem was largely overcome by assessment method, which measured fault traces by line length: most faults were thought to be sufficiently depicted on the plans to give a similar degree of representation across the area, although it was recognised that the few larger (>10m throw) "individual" faults would have been recorded more schematically. Fault trace lengths were measured for plan areas of 0.5 x 0.5 = 0.25km^2 squares based on the National Grid, within which there was judged to be sufficient coal extraction, i.e. good data, at several horizons. This included squares in which there were no recorded faults. Within acceptable squares, seams vertically close together (<15m) with complementary worked areas were treated as one horizon; faults considered to be the products of the depositional environment were excluded, and in one square a main fault zone with numerous fractures was exluded as, because of fault dips, it was present in only one seam. Figure 6.10, from Rippon & Raine (1986) shows the composite result for 25 acceptable squares (160 in the full study area), indicating decrease in fault density with depth. This led to a reappraisal of mine planning for lower seams; mining from 1982 to closure of the workings around 1993 validated the conclusions. As line length is some measure of throw size, the results were also an indirect method of illustrating varying throw sizes with depth, as well as fault density.

While noting that fault density decrease with depth was characteristic of at least most of the Markham study area, Rippon (1982) did not specify any geological boundaries. However, a study by J.D. Raine (in Elliott 1978) indicated that faults within a particular block at Warsop, just to the east (Fig. 6.9) were increasing downwards in throw. The Markham and Warsop areas are close (shaft locations only about 10km apart) and it was concluded that different rules on fault patterns applied to these areas. Similar situations may be inferred across the eastern Pennine Basin coalfield; from this, Rippon & Raine (1986) suggested the stylised relationships of Figure 6.11.

These studies predated the fault statistics work of Watterson *et al.* (1996) who reported fault populations across a wider area, but at essentially only one horizon, compared with the more geographically-restricted, but 3-dimensional mining studies. A combination of these approaches is ideally required. Rippon (1982) and Watterson *et al.* (1996) did not interpret their results in terms of regional tectonic history: an initial account is summarised later (6.2.3).

Although much of the eastern Pennine Basin suggests a gross division into cells with distinctive fault hierarchies, apparently numerically related, it is important to note that this model is not necessarily exportable to other coalfields with different geological histories. Figure 6.12 is a development of the stylised structural cells of Figure 6.11, showing possibilities that might be encountered elsewhere. In the author's opinion, the eastern Pennine Basin is one of the few areas in which fault population studies such as those of Watterson *et al.* (1996) are likely to be valid on any regional scale (see 6.4.1), although most coalfields are readily divisible into structural cells. Areas between large "W-E" faults in the Clackmannan Syncline (Fig. 6.6 A) have very few smaller "W-E" faults, although there are minor faults on other trends, particularly northeasterly; the northeasterly faults have an inherited trend (Rippon *et al.* 1996) and there does not seem to be a valid population for the "W-E" faults alone.

6.5 Fault growth; variations in the deformed rock volume

6.5.1 Background and previous work

The recent advances in understandings of fault systematics originated within British coalfields for use in mine planning, although most present interest is for hydrocarbon reservoir evaluation. The first 1980's publications illustrating systematic variations, in fault plane dips and throw, described structures in the eastern Pennine Basin field (Rippon 1985a, b). In these, the objective was to describe small, well-documented faults. Many were interpretable from the multi-horizon mining data, and it was shown that individual normal fault planes approximated to elliptically-shaped fractures, the long axis lying horizontal, and with contours of throw arranged elliptically around a central point of maximum throw, the fault limit (tip line) being a contour of zero throw. There, fault plane dip was shown to conform ideally to a sigmoidal cross-sectional shape, with greater dips towards vertical terminations. Figure 6.13 illustrates a fault that approximates to the ideal, from Rippon (1985a). Locally, significant thicknesses of more, or less, ductile rocks affected throw and dip contouring, and also influenced fault terminations. However, because all the studied faults were small, the necessary ductile strain in adjacent ground was not described, as it was generally too small to have been recorded in the existing dataset. Barnett *et al.* (1987) developed this aspect, describing strain in an ellipsoidal volume around an idealised normal fault, noting that upper hangingwalls and lower footwalls would be dilated compared with upper footwalls and lower hangingwalls. (In the present account, dilation and contraction are terms used in the context of fault-adjacent strain, as extension and compression (see e.g. Lindsay *et al.* 1993) have more regional connotations.) Various authors using coalfield data (see e.g. Gibson *et al.* 1989, Huggins *et al.* 1995 and Nicol *et al.* 1996) have progressed the interpretational work, notably on fault displacement and dimension relationships, fault plane dip variations, lithological controls, the varied geometries of relay zones, and fault populations. Two issues that have not yet been extensively researched using coalfield data sets are the characteristics of fault-adjacent ductile strain, and the sealing characteristics of faults and fault zones, both of which are of present interest for hydrocarbon evaluations. These are now considered.

6.5.2 Fault-adjacent strain

The initial study of structural variations adjacent to faults has the same basic requirement as that used by Rippon (1985a, b) for the related throw variations: it is necessary to use simple structures to derive ideal models. However, regarding fault-adjacent strain, it is also necessary to use larger faults, as only these will have strained ground that is obvious enough for study. Maximum throws >100m are ideally required, immediately limiting candidate faults in some coalfields, as fields where larger faults are characteristic do not always have good multi-horizon data sets. However, there are areas where suitable mining data are available, especially where backed up by good seismic reflection surveys, such as the Clackmannan Syncline and adjoining areas, where the "W-E" fault set (Fig. 6.6A) includes maximum throws up to 500m. Mine plan data are available from workings in the Namurian Limestone Coal Formation on the synclinal limbs, and Westphalian Coal Measures within the syncline, but key mining and seismic data are from the Namurian Upper Hirst coal, lying approximately mid-way between the earlier and later mined horizons.

Of many well-documented faults here, the Abbey Craig East Fault (Boardman & Rippon 1997) is very suitable for assessing adjacent strain as it is somewhat isolated. Figure 6.14 illustrates this, showing current extent of Upper Hirst mineworkings, seismic reflection traverses, and deduced limits of strain in both footwall and hangingwall, in the Upper Hirst. These limits summarise observations of gradient changes in the workings, and the incidence of minor faults proved by mining (especially those strike-parallel to the main fault), together with interpretations from seismic reflection surveys. Supporting evidence includes fault-adjacent incidences of syn-depositional thermal metamorphism (Chapter 8). It is emphasised that the interpreted strain limits of Figure 6.14 are practical, rather than theoretical (Gibson *et al.* 1989) because: 1, displacement across the fault is not measurable from the seismic profiles, only throw ; 2, the strain distance is necessarily measured along a stratigraphical horizon, which must be assumed to approximate to a plane that would ideally record the ductile strain; and 3, theoretical strain will anyway extend beyond what is practicably measurable.

Similar strain zone extents, related to throw, typify other large faults in the "W-E" set, and the following features are characteristic. 1. Hangingwall and footwall limits are similar, but there is a distinct tendency for hangingwall rollover to be more pronounced than footwall uplift, and for the footwall strain zone to include minor faults; hangingwall rollover is not to be confused with excess sedimentation in the context of a syn-depositional fault (Chapter 5, and Fig. 5.7). 2. The degree of both ductile and brittle deformation increases rapidly towards the main fault plane. 3. Volumetric differences between adjacent hangingwall and footwall zones are large: many cross sections (see Fig. 5.7) show differences of +/- 15% or more, compared with regional stratigraphical thicknesses. 4. Within the zones, seismic reflectors lose integrity. 5. In-seam seismic surveys have difficulty imaging large faults, suggesting reduced channel wave containment within the strained volume.

Interaction between closely-spaced large faults will obviously affect the strained volume character, and this may partly explain why some faults do not show the footwall uplifts and hangingwall rollovers described here. However in some cases, bedding dip is regional, or even down towards the fault through the footwall, and simple interaction is not an adequate explanation. Some of the W-E faults may have been modified to include significant strike slip character, while others, especially the largest, suggest a mainly passive footwall. Many of these faults may have been initiated syn-depositionally, and their displacement attenuation rates are high (Fig. 6.15; see 5.6.1). For these reasons, it is not necessarily appropriate to use these for modelling elsewhere. Nonetheless, comparisons are found with large normal faults in other coalfields.

These effects have important consequences for mine planning and exploration near to large faults, and also implications for hydrocarbon reservoir evaluation. A +/- 15% variation in cross-sectional thickness of a stratigraphical interval implies a basic fabric difference between adjacent footwall and hangingwall. Mining observations are usually limited to coal, and adjacent clastics; excess coal jointing is sometimes reported on the approach to large faults (Chapter 7). Also it is likely that significant fabric differences are to be found in any volumetrically-greater sandstones (in which there are necessarily few direct observations) with, e.g. extra fracture permeability in upper hangingwalls. Of course, such variations would be prone to modification by later geological processes (Boardman & Rippon 1997).

One further feature that results from deformation within the strained volume is bedding-parallel (or subparallel) shear. This is not easily documented, but is an important factor when modelling mine drivage and face design, giving preferred loci for fluid migrations and bed separations above longwall mineworkings. In the heterogeneous sediments characteristic of coal sequences, bedding-parallel shear tends to locate at prominent lithological boundaries.

6.5.3 Fault damage zone characteristics and sealing properties

It is appropriate here to comment briefly on characteristics of actual fault planes and "fault rocks". As would be expected from previous sections, these might be very variable, depending on the history of fault development; geometrical models for forecasting reservoir sealing (e.g. Lindsay *et al.* 1993) are unlikely to be generally applicable to faults in Carboniferous strata. The term "damage zone" is used here to refer to the immediate faulted volume across which there is measurable displacement, and which includes gouge and normal drag, and excludes the wider adjacent zones of ductile strain (Boardman & Rippon 1997). There are numerous drawings of faults (in cross section as intersected by mine roadways) in NCB geological records; the following is a summary of typical relationships. 1. There is no straightforward relationship between gouge thickness and fault throw (Robertson 1983; Knott 1994) when all fault styles are considered, but there probably is for simple faults in individual sets; there may be a wide damage zone with apparently chaotic interlinking planes, or very simple, neat fracturing, for faults of the same overall throw (see later). 2. Anastomosing planes are typical, even of the simplest faults. 3. Simple clay smears are usually restricted to small faults, especially those of suspected syn-depositional origin; elsewhere, cataclasis is typical, usually involving polished claystones (and coal where recorded near seams); rotated, sheared sandstone fragments are found only where proximal to a sandstone source (the claystones are distributed more widely, reflecting generally greater abundance in Westphalian strata, and the effects of injection and flow). 4. Normal drag is widely observed. 5. In some faults where strike slip is dominant, drag width may be much greater than compatible with recorded dip slip (6.2). 6. For faults in a transtensional setting, the gouge may be accompanied by an adjacent thickness of deformed sediment in a pull-apart (Fig. 6.16, see later). 7. Sandstone wall rocks may show petrographic changes resulting from abrasion, recrystallisation or re-cementing from fluid flows along the fault planes. 8. Larger faults often include mineralisation.

Fault sealing properties will obviously depend on many variations beyond simple geometrical juxtaposing of differing lithologies. In mining contexts, fault sealing character affects migration of water and gas during extraction. Some sealing during geological history may be evidenced by geochemical variations, especially chlorine in the coal (see 1.4.2). Intersections of oil by mineworkings have not been investigated with respect to individual fault seals. Generally, mining experience indicates that large, complex faults have greater sealing potential than simple small faults, in all fluid flow contexts.

6.6 Structural style variations related to regional tectonics

The range of structural styles found in the coalfields results from complex interactions between inherited trends and varied intra/post Carboniferous stress vectors. This section considers some of these interactions. The intention is not a review or compilation of existing work but an outline of particular aspects, deducible from mining data, that are not fully incorporated into existing literature, but which do impact on tectonic interpretation. Some structural attributes of the Scottish Midland Valley and Kent are detailed in Chapters 9 and 10 respectively. The following account deals mainly with the eastern Pennine Basin, together with some further comment on South Wales and Scotland. Varied topics are covered here, within the unifying consideration of tectonic history.

6.6.1 The Variscan-proximal coalfields, especially South Wales

Variscan effects progressively dominated over any inherited trends in the late Carboniferous, giving the thrust-prone province so different structurally to coalfields north of the Wales-Brabant High. Jones (1989, 1991) and Frodsham & Gayer (1997) describe varied thrust styles and their relationships to other coalfield features, and Gayer (1992) summarises present understanding of coalfield evolution during Variscan advance. The recent accounts of the South Wales field (see also the bibliographies in cited references) make much further comment unnecessary here, but the following points are usefully discussed. (Figure 10.8 is a summary map of South Wales.)

A foreland basin model has been adopted for the South Wales coalfield by various authors following Kelling (1988), summarised by Gayer (1992), but it may be argued that full foreland basin characteristics, particularly transverse sediment supply from the orogenic highlands to the south, were not established until around mid-Westphalian C times. Depositional patterns between the mid-A and mid-C Westphalian indicate dominant inflows from the west/southwest (Rippon 1996), with major channel trends aligning north-northeasterly across the coalfield, paralleling the axis of the depositional basin and its successor syncline. Many depositional relationships (coal-prone and marine horizons, cyclicity, channel hierarchies and disposition of lithofacies) are comparable to those of the Pennine Basin in this sequence, although many sandstones are petrographically different (probably reflecting different sourcelands as well as burial history), and the axial trend produced less varied coal splitting patterns. Initial Variscan influences are discernible in the growth of intra-basin folds, and especially development of the Usk Anticline just beyond the coalfield to the east (Jones 1989). Given the somewhat variable data control on construction of basin-form ispoachs, the depocentre itself may not have moved significantly further north throughout Westphalian A and B times. The axial trend of major channels may indicate earlier Westphalian development of a foreland flexure, but equally it might be argued that channel parallelism was merely responding to inherited Caledonide trends, perhaps the Neath and Usk structures (and further northeast, the Hereford Straits/Church Stretton Fault). It is concluded that Westphalian A and B depositional patterns record an incipient Variscan imprint across an area that probably included inherited structural trends, and that in many respects was little different to most other British coalfields. Full evolution of the foreland basin through the later Carboniferous is documented by Gayer (1992).

Variscan deformation structures do not seem evenly distributed through the coalfield. Frodsham & Gayer (1997) give an overview, particularly for the intensively-deformed western areas and zones along the south crop, and the effects of gross lithological control. There is a lack of good data in key subsurface areas (especially west of the Neath Disturbance, where there are large areas of the main Westphalian coal-bearing sequence that have not been mined or explored). However, even after accounting for these, it is obvious from mining data that there is much less thrust deformation in the eastern third of the field. There, coals in the Westphalian A to mid-C succession have been mined in a structural environment little different in many ways from parts of the Pennine Basin. The following factors may be relevant: 1, individual structural blocks, based on inherited trend boundaries, presented varied opportunities for thrust propagation; 2, the main detachments may have been at a higher horizon in the east, perhaps even above preserved Westphalian strata; 3, the eastern area may have been protected by the buttressing effect of the Usk Anticline; 4, the western area lay nearer the Variscan Deformation Front (Chapter 10) by some 20km, perhaps also closer to the stable foreland to the north, and had lesser cover to crystalline basement, all three promoting a more thrust-prone environment.

Tertiary deformation must also be considered (see 6.3.4 and Chapter 10). In both South Wales and Kent, there is the possibility of significant strike slip faulting, comparable in trend to (e.g.) the Watchet fault zone of southwest England. A pre-existing cross fault (Woodland & Evans 1964) acting as a sidewall during Variscan advance has been suggested to account for an apparent dextral offset of the Variscan Deformation Front to the west and east of Swansea Bay (Gayer 1992). Such a fault may have been a precursor for any Tertiary structure. There is no direct evidence for either a major Variscan sidewall or Tertiary strike slip feature within South Wales itself, but such a structure could lie offshore.

The geology of outburst-prone coal is rarely discussed in geological publications, although there are many mining accounts, and an extensive international literature. Some horizons in the western part of the South Wales field have been prone to localised outbursts of overpressured gas (mainly methane) and powdered coal into mineworkings, with one inferred initiation at depth by drilling from the surface. Dumpleton (1990) describes the geological background in South Wales. None of the recent geological literature dealing with regional tectonics has discussed these phenomena in any detail, and a full investigation (beyond the scope of the present account) is required that integrates modem tectonic interpretations with the mining data. In brief, outbursts occur when discrete volumes of coal are intersected; powdered coal and gas, confined under pressure, overwhelm mineworkings and ventilation unless preventative systems are in place. Outburst locations are often associated with rapidly varying coal joint densities, and can be located adjacent to thrusts. The Big Vein (Westphalian B) at Cynheidre (E.250000, N.210000) has been particularly prone to outbursts, and further confinement by thick sandstone above the coal may be an added factor. Dumpleton (1990) plotted horizons/depths of outbursts, and absence of outbursts, deducing a trend that indicated they were more prone to occur at shallower depths to the west. Outbursts have not occurred in underground mines where the cover to surface is <200m.

This last point suggests that relaxation in the near-surface is an important control, with formerly overpressured areas destressed. Overpressured coal could result from the intense Variscan compressional deformations which characterise this part of the coalfield, but this would imply that these features remained overpressured throughout post-Variscan history (some 300 Ma), including an interval of significant Mesozoic extension. Perhaps variations in density of the coal jointing fabric allowed survival of impermeable coal volumes, but the origin of these in the first place is conceptually difficult in the absence of igneous metamorphism (Chapters 7, 8). Also, Tertiary compressive stress could have caused local overpressuring, sufficiently young to be retained; but again the origin of the discrete volumes would remain to be explained. Perhaps the coal was locally indurated during Variscan advance, by hot fluids using selected fractures as pathways (Gayer & Pesek 1992), to a degree where regional joint development was subsequently unable to induce typical coal fracture permeablity (Chapter 7).

6.6.2 The Pennine Basin

The Pennine basin is by British standards a large feature, and a full description is beyond the present scope. Its northern margin in Westphalian times is unknown, but may have been the southern side of the Askrigg Block (Fig. 6.2). The western side is prominently dissected by many large (100's m throws), generally north-northwesterly striking faults, which probably record mainly Triassic rifting. The eastern side is characterised by varied fault trends and inherited sub-basins and there does not appear to be a representative structural trend sympathetic to overall basin form isopachs. The southern margin is irregular: the 300m isopach for the mid-A to mid-C Westphalian represents the thickness at which an overall basin form is seen. South of this, formation isopachs (Fulton & Williams 1988) are strongly influenced by northwesterly or northeasterly striking fault blocks along the northern margin of the Wales-Brabant High. Details of structural control affecting Westphalian basin subsidence north of these fault blocks in unknown. It could be that there is a significant north-dipping major fault in the basement, providing a pathway for sill magmas to have risen in parts of the southern Pennine Basin. Alternatively, magmas may have risen up some of the "northerly"-trending faults (such as the Permian Whitwick Dolerite, Chapter 8). The general west-east alignment of the southern margin of the Pennine Basin, together with that of the Widmerpool Gulf and the high itself (Fig. 6.2) could suggest a significant deep structure on that trend. Indeed, the northern apex of the Midlands Microcraton of the indenter model of Soper *et al.* (1987) and Pharaoh *et al.* (1987) is brought into question, in the Westphalian, by these features. Overall, the shape of the Westphalian basin probably reflects thermal subsidence with extension on a combination of internal and marginal structures. The present structural asymmetry (gentle dips, few large faults in the east; greater and more complex disturbance in the west) could well represent asymmetry in earlier basin evolution. For the later Westphalian, some Variscan flexural subsidence might also be expected, sedimentation from the southern orogenic uplands eventually forming the bulk of late Carboniferous basin fill.

The following discussion deals with the eastern side of the basin, with its wide extent of mining and exploration data. This is a field remote from immediate Variscan compressional deformation, Triassic rifting is less pronounced than elsewhere, and it is, therefore, an area where the interaction of varied trends is readily studied. In some ways the eastern Pennine Basin coalfield appears more structurally complex (as opposed to structurally disturbed) than South Wales.

Strike slip faults have rarely been considered. In all the existing literature, most faults throughout the eastern Pennine Basin field have been regarded as normal, with reverse structures attracting particular attention (these are found mainly associated with folds attributable to Variscan inversion, Corfield *et al.* 1996). A few specific strike slip faults have been described, particularly the northwesterly-trending fault of Smith *et al.* (1967, p. 219) and the Holgate Hospital Fault of Goossens & Smith (1973), and there is considerable evidence from fault trace patterns that several of the large northwesterly faults in Yorkshire have a prominent strike slip element (6.2.4); according to S.Graham (pers. comm. 1991), W-E oriented strike slip fault zones characterise parts of the Yorkshire coalfield in the Selby area, south of York.

Faults and zones which are essentially strike slip can demonstrate numerous patterns in plan and cross section, varying with depth, and with formative vectors interacting through often multiphase fault histories. Straight-trace, near-vertical faults are rare in most coalfields (but see the high dip fault shown on Fig.10.4, in Kent), but structures such as illustrated by Figure 6.16 (in Scotland) are not. A transtensional character for this zone is interpreted from the overall vertical disposition of the zone, the offset array of individual faults within it, steep fault plane dips, the presence of pull-aparts, and (regionally) vent location (Chapters 8, 9). In the eastern Pennine Basin, there are many examples of offset arrays of minor fractures between parallel bounding faults, especially where the bounding faults are northwesterly. On mine plans, most of the individual faults would be recorded as normal by surveyors, and in most cases this would be the correct identification: it is the overall zone which usually reveals strike slip attributes.

It is rarely possible to determine any detailed displacement patterns for strike slip faults in coalfields because of mine plan limitations, and because unambiguous horizontal offsets of sedimentological variations or other features are rare. Fracture linkage patterns are also difficult to determine, partly because of rapid displacement variations within the zones. However, Figure 6.17 illustrates a well-constrained example from Derbyshire. Here, the plan trace of the fault zone approximates to vertical over an interval of 400m, with varied dispositions of high-dip fractures, and (compare with Fig. 6.13) the dip slip throw distribution on a strike projection is not easily contoured. The plan shows further arrays of northerly-striking faults between the illustrated zone and the Inkersall Fault; individual faults in the northerly-trending array are not continuous between mined horizons <100m apart. The overall structure indicates dextral transtension.

Fault zone complexity is common in the eastern Pennine Basin coalfields. Figures 6.18 and 6.19 show sections through some well-proved Derbyshire fault zones from the Markham Fault Study (Rippon 1982), to illustrate this (all individual throws are too small to be evident on the section scale; the key issue is inter-horizon linkage characteristics). Not all zones in the Markham area are as complex as those illustrated, and most have a definite preferred downthrow direction. However, wide fracture zones with little overall vertical displacement are common, on both northwesterly and northeasterly trends. In general, the simpler structures tend to be northeasterly. The complex zones invite a multiphase and/or transtensional interpretation, but particularly the latter, as multiphase faulting appears to re-use existing fractures. The overall impression from the illustrated zones is chaotic fracturing within near-vertical zones, again suggesting a strike slip component. Two figures are shown to make the point that these characteristics typify two separate trends.

Structural trends in the eastern Pennine Basin are illustrated by Figures 6.20 to 6.23. The maps are derived from mining plans of various scales, usually collated to 1:10,000 or 1:25,000, and draw from data at different horizons. Some faults interpreted from surface mapping or seismic surveys are shown where well-controlled. There is no discrimination between areas of differing data density, and the apparent fault distribution therefore largely reflects mined areas, rather than geological variations. As the data are derived from previously collated plans, there is scope for inaccuracy, but at the scale illustrated, this is not considered significant. Faults of all throw sizes are shown; within mined areas, probably most faults with >5m throw are included. Some of the area north of Northings 430 has been accurately determined, and discussed for fault attributes (especially populations) by Watterson *et al.* (1996). The intention here is simply to illustrate regional fracture trends and relationships, in the context of geological history, summarised in Table 6.1. Main elements can be categorised as follows (bearings relate to UK Grid North), with ages of faulting derived from structural style combined with known stratigraphical relationships.

(i) Major fault zones at N.110-120° E., include the Morley-Campsall/Askern-Spital and Cinderhill Fault Zones (forming the northern boundaries of the Gainsborough Trough and Widmerpool Gulf, respectively, see Figs. 6.20, 6.23) together with many other laterally extensive zones throughout the coalfield. At least some are reactivated inherited structures (6.3.2); others may be presumed to have been latent during Westphalian times. Multiphase history of the Morley-Campsall zone includes presumed simple Dinantian extension; continued extension through the Westphalian (Rippon 1996); Variscan inversion (Corfield *et al.* 1996); further pre-Permian transtension (see below); and post-Permian extension, probably late or post-Triassic. (It is important to note that "pre-Permian" necessarily means prior to deposition of the lowest Permian sediments: Smith (1994) suggests that some 40Ma elapsed between the analogous Westphalian C and Permian strata of the Northeast field.) The other zones presumably share at least some of these phases.

(ii) Anticlines with a variety of northwesterly trends are prominent mainly south of Northings 390. It is assumed that these represent basement structures reactivated by Variscan compression, their orientation being particularly appropriate to an "indenter" model involving the Midland Microcraton, although the W-E compression of Peace & Besly (1997) might also apply. Their post-Variscan history appears similar to that described for the fault zones (i) described above.

(iii) Prominent fault zones at N.130-150° E. lie between the major fault zones of (i) above in patterns strongly suggestive of overall dextral transtension: e.g. between Barnsley and Rotherham (Fig. 6.20), and south of the Whitwell Monocline (Fig. 6.22). Following (i) above, these are likely to be post-Variscan; some are known to intersect Permian strata.

(iv) Northeasterly fault zones, particularly N.40-50° E. are very prominent north of Northings 360, and, with the northwesterly set (i) produce the strongly rhomboidal fault pattern of Yorkshire (Fig. 6.20). It is assumed that these too are likely to be (mainly) post-Variscan: they include complex pre-Permian transtensional zones (6.6.2), but some intersect Permian strata. The Don Monocline and related faults are described separately below.

(v) North-northwesterly trending faults, some large, are common in the area north of Derby (Fig. 6.23). Little is known about their relationships, but they may be originally extensional faults which responded to northwards push by the Midlands Microcraton, and may now include transpressional elements, such as the Ironville Anticline. They have some trend similarities to (vi), below.

(vi) A minor fault trend (N.160° E.) is found northeast of Rotherham (Fig. 6.20). Relationships are uncertain, there is no Permian cover. These faults do not have large throws but are laterally persistent; their trend is continued by minor folds. They seem to record an event different to those responsible for the rhomboidal-pattern faults; given the folding, the setting may have been transpressional, recalling the late-Carboniferous/early Permian movements described for the Dent system by Underhill *et al.* (1988) and other more northerly-trending compressional structures in northern England (6.3.2); their particular location here might then presuppose inherited features at depth. Overall, the composite fault pattern of Figure 6.20 suggests that at least four significant trends can co-exist, with formative stress vectors sufficiently different to require generation of new-trend fractures, rather than re-use of existing ones.

Apart from these main elements, two major structures require special comment. The SW-NE Don Monocline (Figs. 6.20, 6.21) has probably the largest displacement of any structure in eastern Pennine Basin Westphalian strata, and no folding of any significance is known elsewhere in the coalfield on this trend. The overall southeastwards normal downthrow suggests that this is not a straightforward Variscan inversion. Also, the structure is not on an "easterly Caledonide" trend (Soper *et al.* 1987), and is unlikely to be pre-Westphalian. Perhaps the post-Carboniferous to pre-Permian extension inferred here found an opportunity to concentrate displacement on this particular structure, and its location with respect to the Thurcroft-Gainsborough structure may be significant. This is a segmented line of roughly W-E structures (Fig. 6.21), possibly representing a significant feature at depth (6.4.4). Such a structure might be expected to be inherited, but it did not form the southern boundary of the Gainsborough Trough in the Westphalian (Rippon 1996) despite being suitably located. But given that the Thurcroft-Gainsborough structure does seem to incorporate Variscan compression, it must be assumed to have existed in Westphalian times. It is concluded that this structural line was inherited, but remained dormant while other faults (especially the Morley-Campsall zone) were more appropriately oriented for re-use. Together, the

Don and Thurcroft-Gainsborough structures appear to have formed the boundaries of a structural low, assumed to be end-Carboniferous/early-Permian.

Given the variety of structural trends and movement phases to which most fault zones were prone, it is not surprising that the resultant interactions are quite intricate, with strong local character. Thus, the interaction between the north-northwesterly "Ironville" trend with that referable to the Widmerpool Gulf extensional system northwest of Nottingham (Fig. 6.23) is not found elsewhere in the coalfield, while the Mansfield, Thurcroft-Gainsborough and Morley-Campsall structures are distinctive compartmentalising zones. Such variations within the overall coalfield provide the regional divides for structural cell discrimination (6.4.4). Across this involved fracture network, the simplicity of the regional coal jointing (cleat) pattern is striking, strongly suggesting northwesterly directed principal stress in the late Carboniferous (Chapter 7; and see Corfield *et al.* 1996). But while the cleat pattern is compatible with Variscan reactivation of some inherited trends, it does not readily relate to the generality of faults on all the main trends, some of which were older, and others younger; and it is concluded that it offers a late Carboniferous stress snapshot, albeit one with a potential duration of >15Ma. The eastern Pennine Basin is therefore seen as recording a complex interaction of tectonic events (see Table 6.1); various post-Permian solutions are possible and a simple stress vector synopsis is inapplicable.

6.6.3 The Scottish Midland Valley

Chapter 9 deals in detail with aspects of the geological history of the Midland Valley, and the present section considers, in outline only, one particular aspect which has wider relevance, namely the identification of structural controls on sub-basin locations. Rippon *et al.* (1996) showed the Carboniferous evolution of the Kincardine Basin to be complex, and not readily relatable to the basin-bounding West Ochil Fault; rather, basin development appears linked to extension across a north-northeasterly structural line (the Bo'ness Line). Figure 6.8 illustrates part of the eastern Midland Valley, which includes four prominent sub-basins. These are located by the greatest mappable isopach for successive Carboniferous formations. The Leven and Midlothian sub-basins are likely to share similar overall histories to the Kincardine Basin; the small Westfield Basin is individual in its gross coal development in the later Namurian (Francis 1991).

As with the Kincardine Basin, the Midlothian Basin is offset from the present syncline, and is bounded by a large structure (in this case the Pentland Fault, displacing Upper Carboniferous sediments against Devonian igneous rocks), again inviting a generic relationship, Here, it is possible that basin development was more directly related to the major fault, simply because basin form isopachs are elongated (sub)parallel to it. However the Pentland Fault as now preserved is at least locally a reverse structure, with variable dip directions, and probably has a significant strike slip component. A major inversion from an earlier form would therefore be necessary for a causal relationship with the Midlothian Basin, and it must again be possible that the fault, as now known, merely truncates a depositional area that in this case formerly extended further west. Lower Carboniferous strata preserved west and east of the Pentland Fault suggest some depositional continuity. It is initially concluded that the present Pentland Fault, essentially a late to post-Carboniferous feature, represents an earlier Caledonian-trend structure at depth

The Leven and Midlothian Basins are depositionally and structurally separate (Fig. 6.8): the Firth of Forth Fault develops between them, and the Midlothian/Leven Syncline (assumed late Carboniferous to early Permian) realigns across this, suggesting compartmentalisation along the fault during folding. Also, the Pentland Fault dies out in the neighbourhood. These relationships are known from offshore NCB seismic surveys. Again, structural controls on the development of a basin are not immediately interpretable. The Leven Basin depocentre occupied essentially the same location from Dinantian to at least Westphalian B times, and is coincident with the syncline. With the possible exception of the Lower Limestone Formation, a discrete depocentre is evidenced by formation isopachs, while the very low incidence of faults within the basin (known from mining on the western limb, and supported by offshore seismic data) suggests a simple internal organisation. However, structural lines that must have controlled basin development are obscure. To the west and south, the deeper precursor structures of the Burntisland Anticline and Firth of Forth Fault are candidates. A continuation of the line of the Pentland Fault at depth, segmented by the Firth of Forth Fault, is a possible control on the eastern side, and this may have been the dominant extensional structure. Post-rift sedimentation must have mantled the controlling faults in a manner similar to that envisaged for the Bo'ness Line.

In the wider Midland Valley context, these eastern basins and swells form part of the overall structural mosaic (6.4.4). The basic compartmentalisation of the Midland Valley must have occurred during Devonian and earlier Dinantian times, locally using inherited Caledonian structures such as suggested for the Pentland Fault, with some of the "cells" remaining tectonically active to various times through, and after the Carboniferous.

6.7 Conclusions

Obviously many conclusions could be drawn from this account. The following are considered to be important for all the coalfields.

Firstly, no single stress regime can be invoked for any coalfield, and explaining structural lines using simple palaeo-stress templates will not adequately address varied multiphase deformation histories. Secondly, it follows that orthodoxies developed in one field will not readily transfer elsewhere; this is apparent for both fault population and fault growth studies. Thirdly, the recognition of strike slip, transtensional and transpressional systems requires careful assessment in these differing settings; what appears straightforward in Scotland is rather more subtle in the eastern Pennine Basin. Fourthly, the eastern Pennine Basin field in particular shows the degree of trend complexities that can result from multiphase deformation, and suggests that at least four distinct fault trends can develop before further movements are largely accomodated on existing fractures. Overall, the importance of inherited features is emphasised, in particular those major structures at depth which, compartmentalising large areas, moved syn-depositionally, and controlled local responses to many later events.

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6.9 Table and Figure captions

Table 6.1 Eastern Pennine Basin: main tectonic events affecting Westphalian Coal Measures.

Figure 6.1 Coalfield locations and generalised stratigraphical ranges.

Figure 6.2 Generalised tectonic framework of the Upper Carboniferous coalfields.

Figure 6.3 Horizon-depth cross-plots between boreholes; an example from the Kincardine Basin, showing identification of faulted horizons.

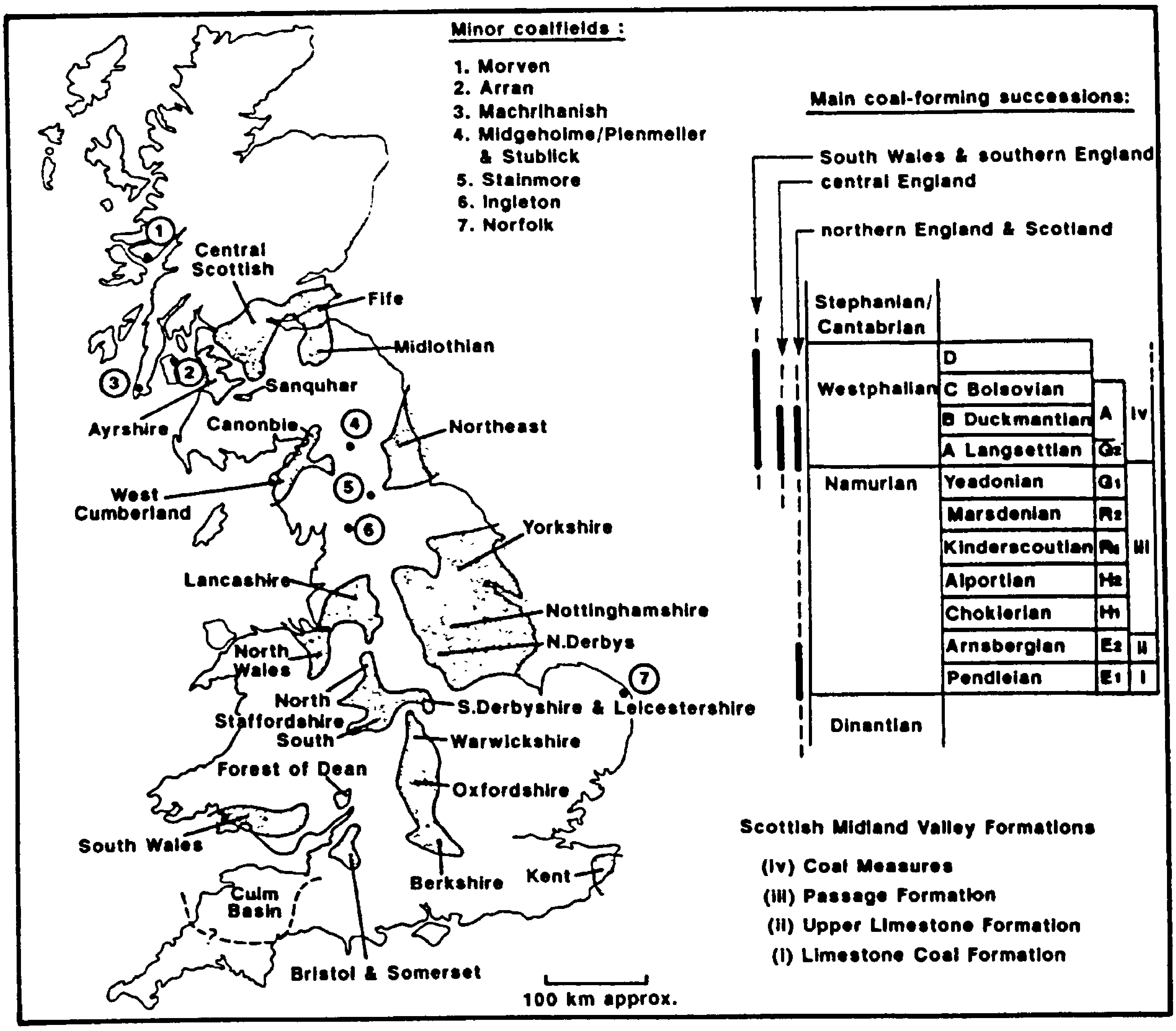
Figure 6.4 Forecasting extension across unmined areas (from Rippon & Raine 1986).

EASTERN PENNINE BASIN: MAIN TECTONIC EVENTS AFFECTING WESTPHALIAN COAL MEASURES

Structural Components	Trend	Movements	Timings
A. Major west-northwesterly fault zones with many fractures and splays (including Morley-Campsall zone)	N.110°-120°E	A.1: origin - extensional faults (Dinantian)	Westphalian A-D growth on selected fault zones
		A.2: inversion of some inherited structures; dextral transpression	Variscan; late Carboniferous
		A.3: extension with possible dextral transtension	post-Carboniferous/pre-Permian*
		A.4: extension	post-Permian (various phases)
B. Main northwesterly folds and related faults	northwesterly (varied)	B.1: origin - inversion of main inherited structures; dextral transpression	Variscan; late Carboniferous
		B.2: extension with possible dextral transtension	post-Carboniferous/pre-Permian*
		B.3: extension	post-Permian (various phases)
C. Northwesterly fault zones lying between major zones (A, above)	N.130°-150°E.	C.1: origin - dextral transtension between major faults	post-Carboniferous/pre-Permian*
		C.2: extension	post-Permian (various phases)
D. Northeasterly fault zones and Don Monocline	N.40°-50°E.	D.1: origin - extensional faults	post-Carboniferous/pre-Permian*
		D.2: extension; some new faults	post-Permian (various phases)
E. North-northwesterly faults (north of Derby) ("Ironville" trend)	N.N.W.(varied)	probably includes inherited structures and Variscan transpression, with reactivation as transtensional zones across the Widmerpool Gulf, cf. C.3, C.4 above	
F. North-north-westerly faults (north of Rotherham)	N.160°E.	possible strike slip faults, probably post-Permian	
G. Thurcroft-Gainsborough structure	W.-E.	assumed inherited structure at depth with imposed Variscan transpression and later extensional phases.	

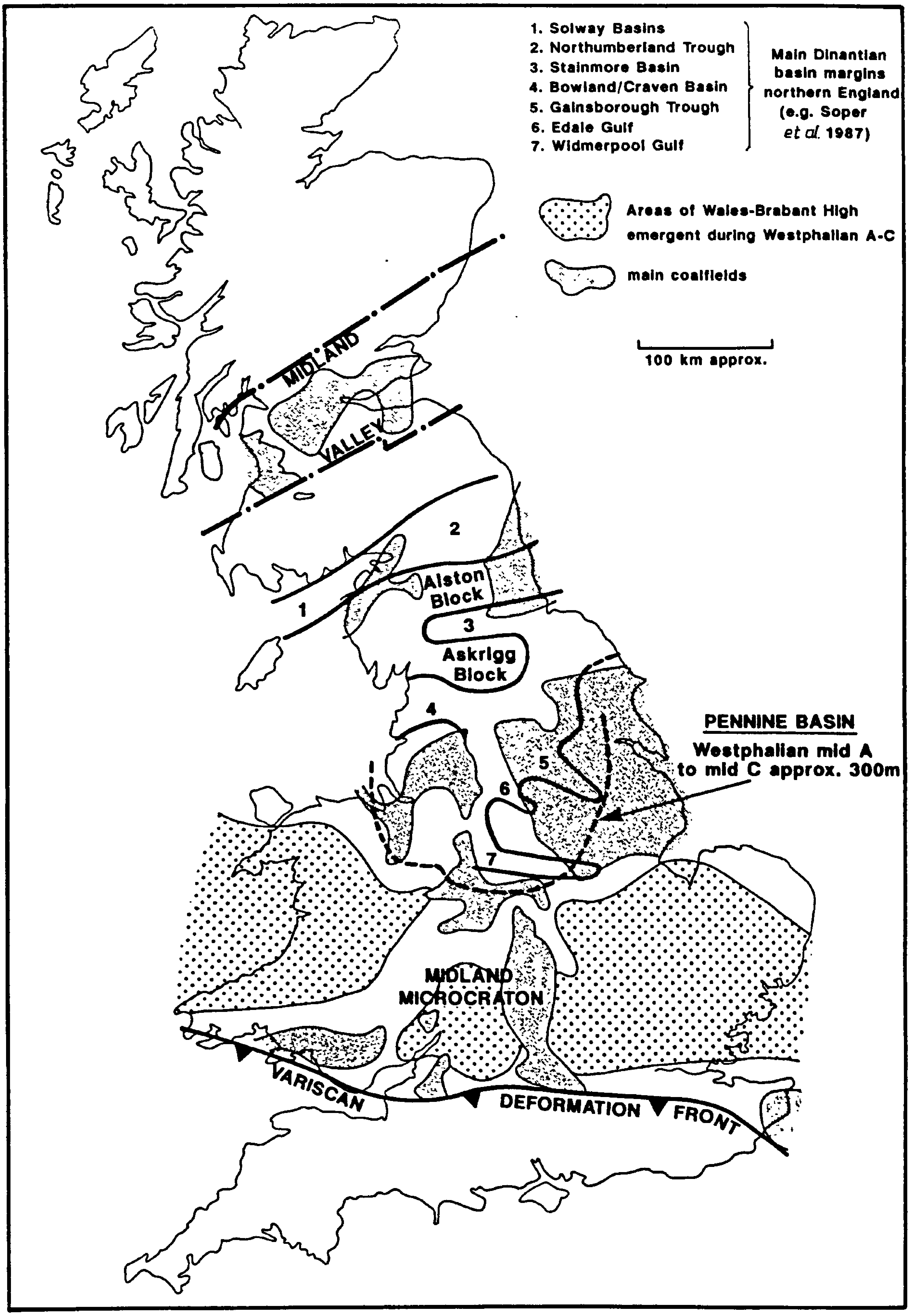
* "pre-Permian": ie before deposition of earliest local Permian sediments (Smith 1994)

Table 6.1



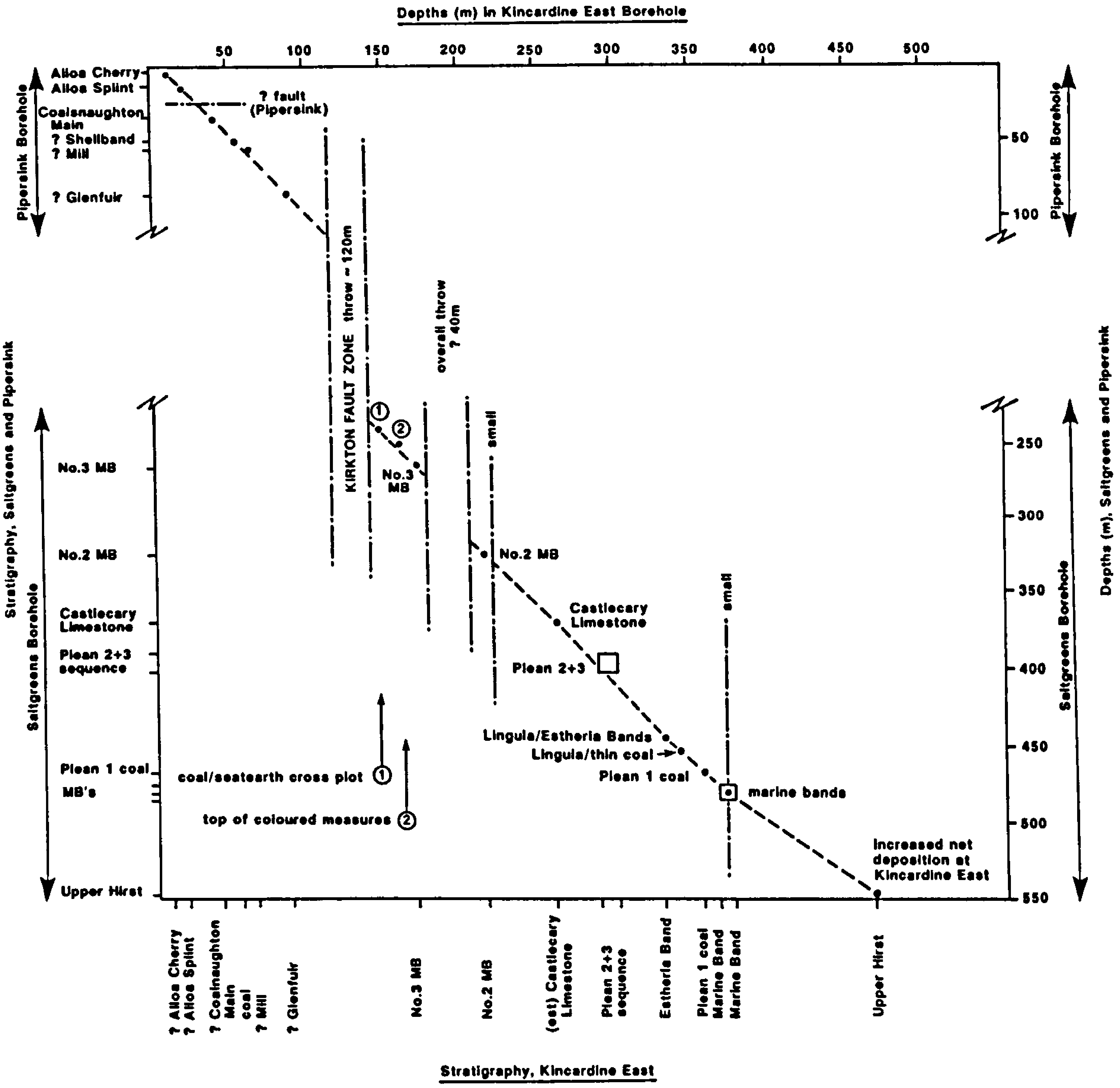
Location and stratigraphical summary of the Upper Carboniferous coalfields

Fig.6.1



Tectonic framework of the main Upper Carboniferous coalfields

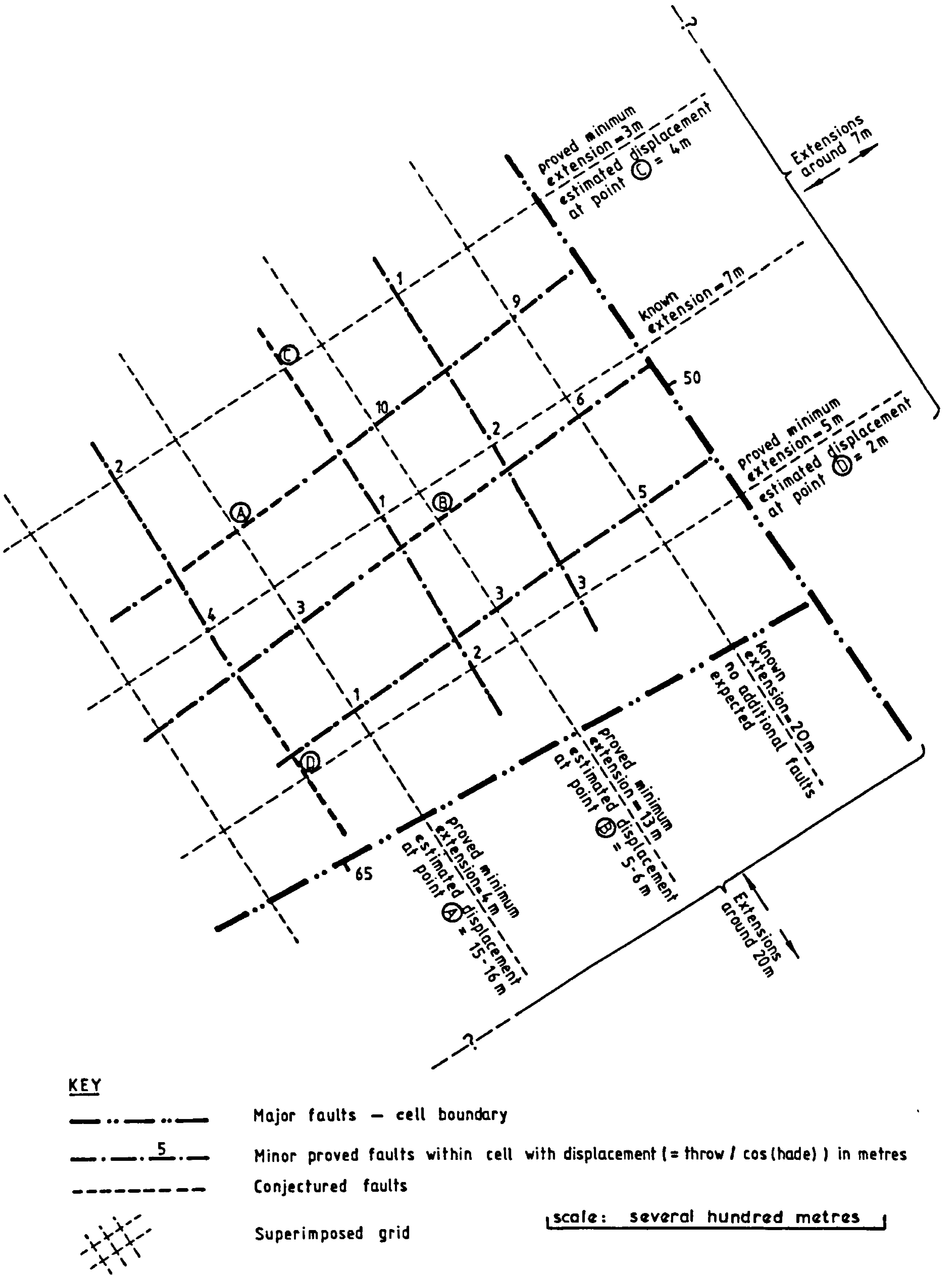
Fig.6.2



KINCARDINE EAST BOREHOLE (NS 98 NW/230)

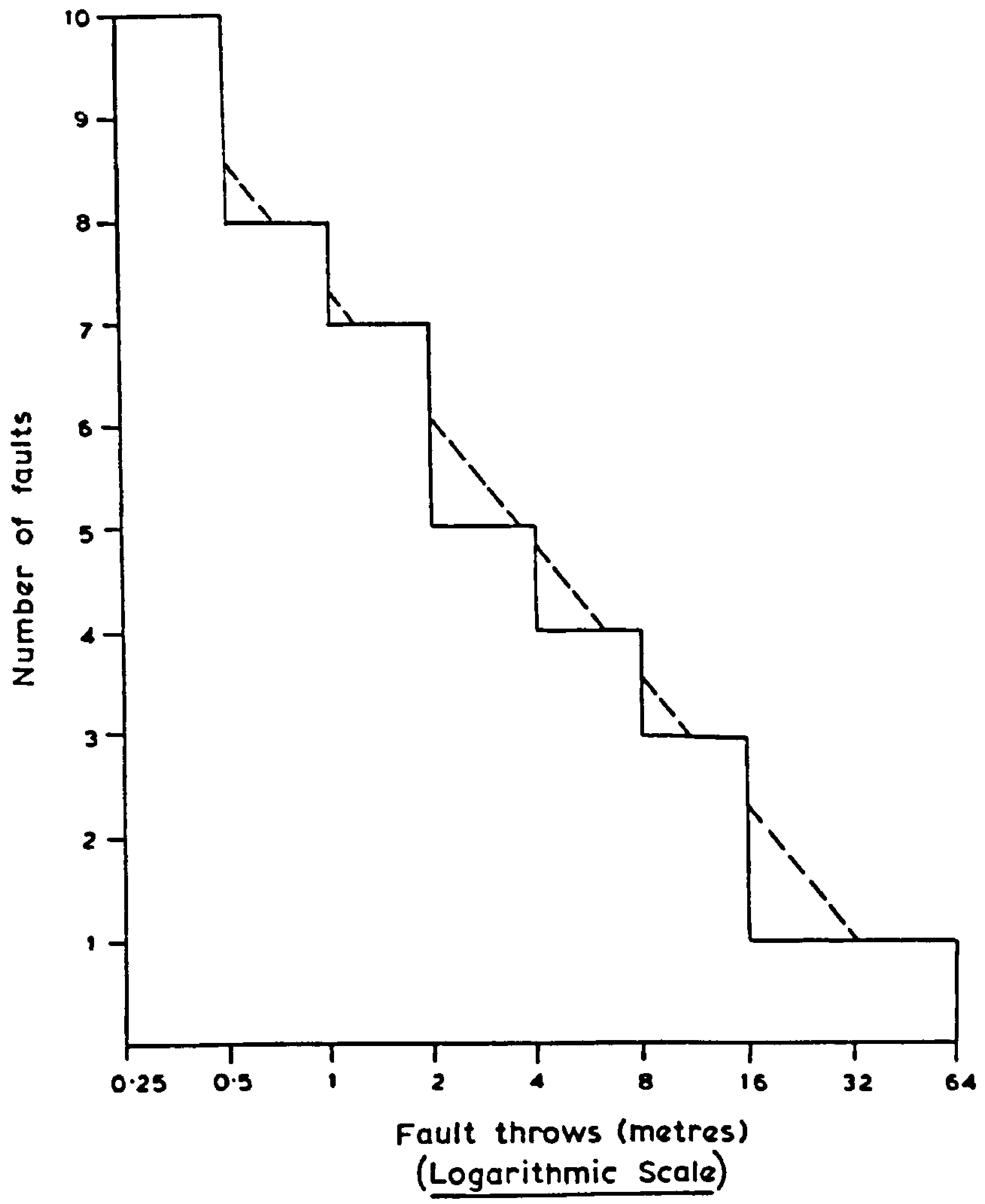
Depth cross plots with Saltgreens (NS 98 NW/197)
and Pipersink (NS 98 NW/195) Boreholes
Correlation and structural analysis

Fig.6.3



FORECASTING EXTENSION ACROSS UNMINED AREAS

Fig.6.4



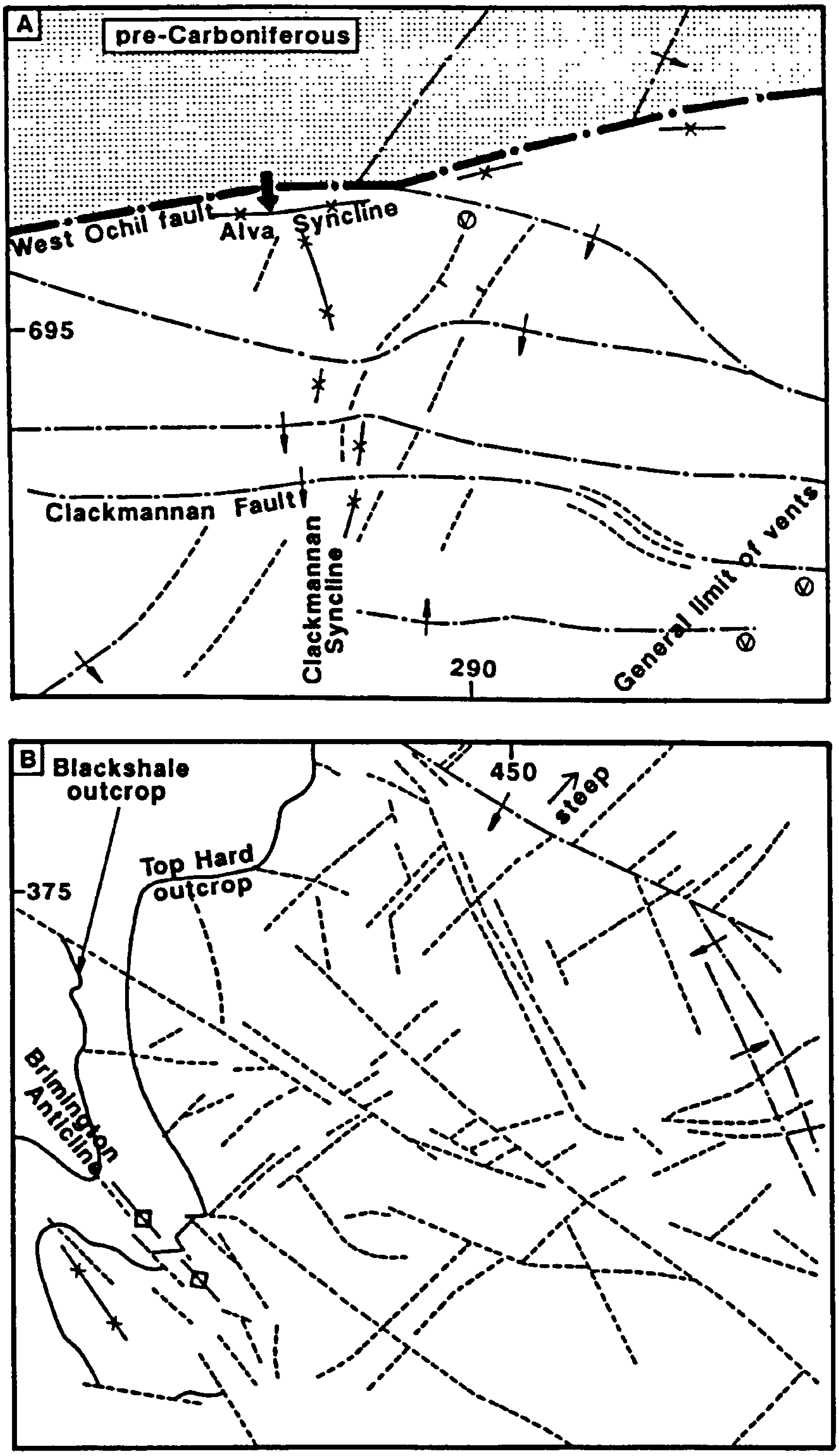
COTGRAVE COLLIERY

Fault size distribution

(National Coal Board 1970's)

(NNE-SSW Access drivages and workings : 5km long)

Fig.6.5



A Schematic map of part of the Scottish Midland Valley; only selected significant faults shown (near surface)

B Schematic map of part of the East Pennine coalfield; most significant faults shown at Top Hard horizon

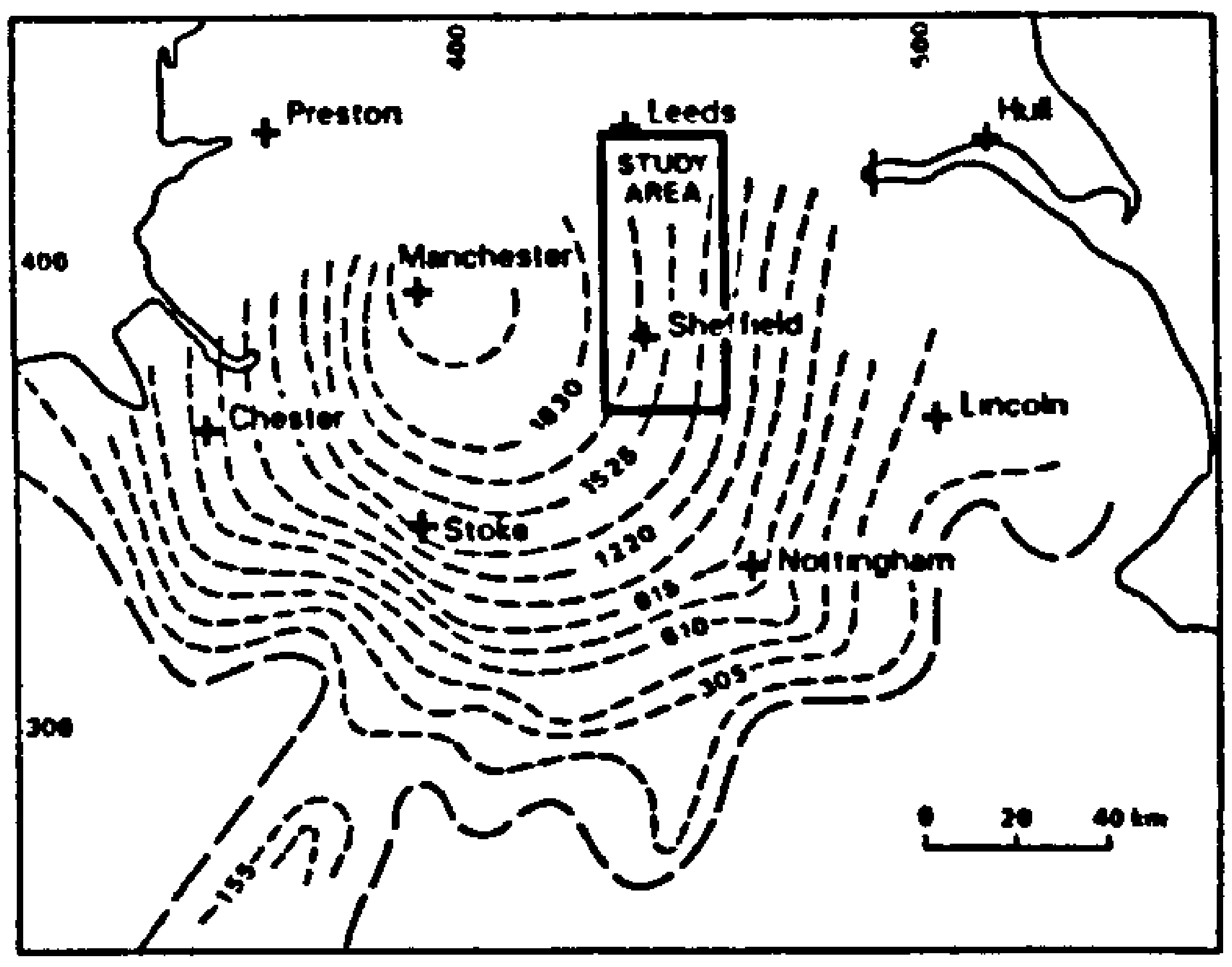
1st | order faults
2nd |
3rd |

⊘ vents

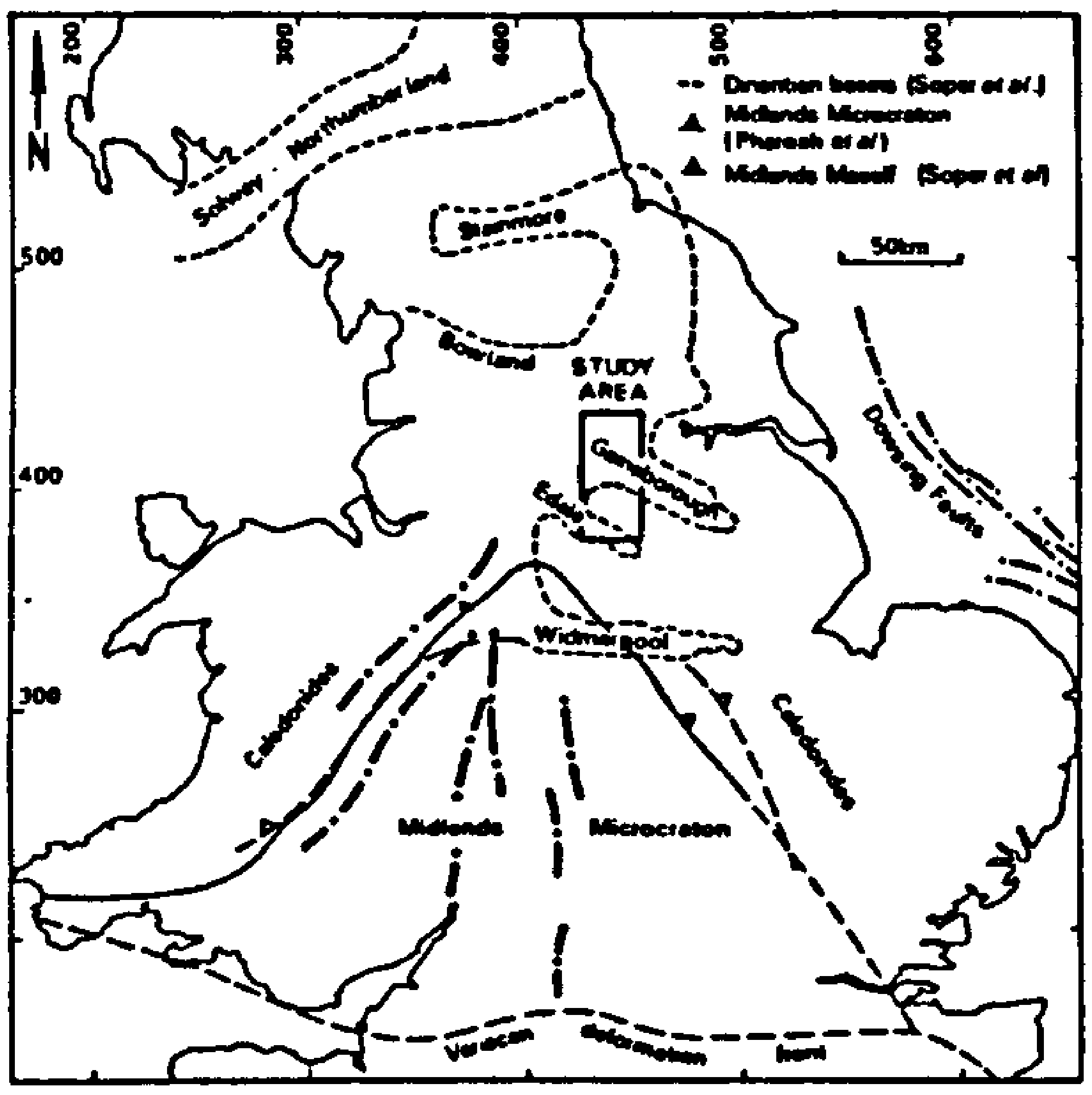
1km

STRUCTURAL CELL COMPARISONS

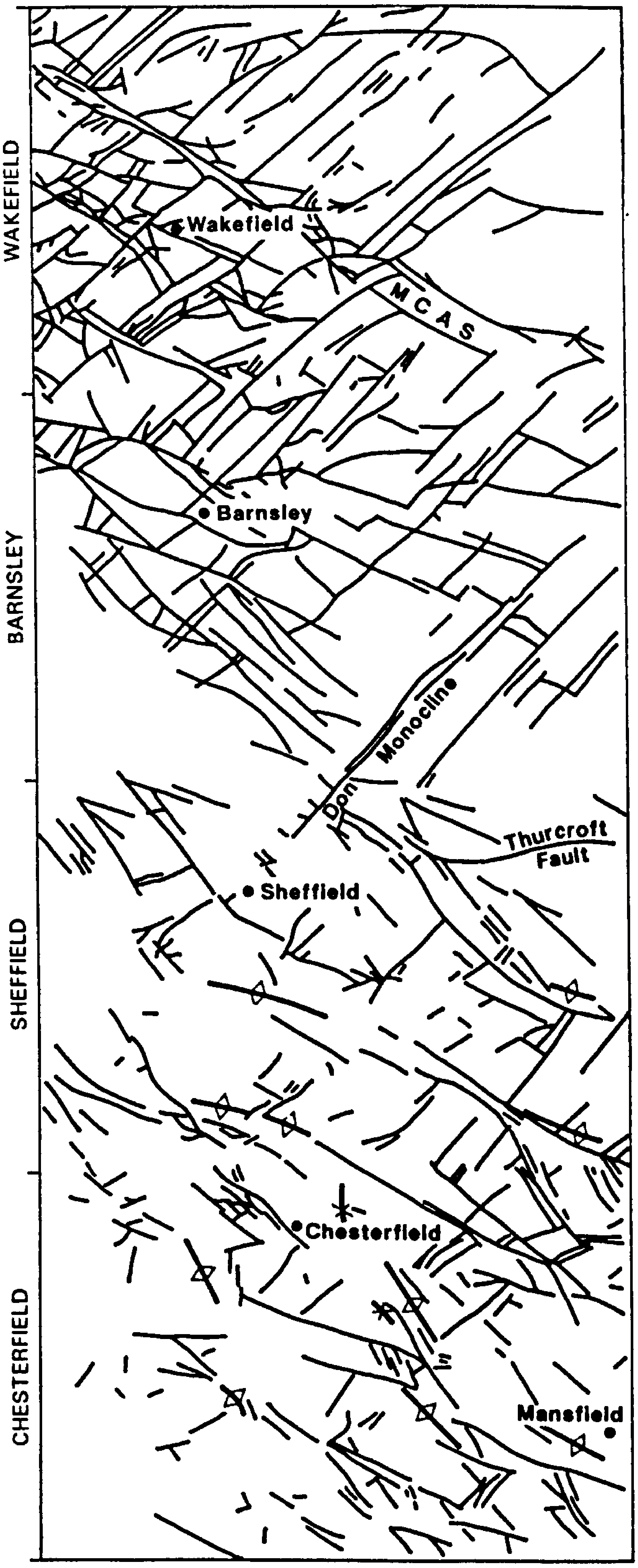
Fig.6.6



Isopachs of Subcrenatum MB to Cambriense MB (after Wills,1956)



Regional setting of E. Pennine Coalfield
Selected lines from Soper *et al* (1987) and Pharoah *et al* (1987)



Main Map

MCAS : Morley-Campsall/Askern-Spital Zone

approx 10km

STRUCTURAL STYLE VARIATIONS, EAST PENNINE COALFIELD, ENGLAND

Based on structural summary maps, Geological Survey Memoirs, for Wakefield, Barnsley, Sheffield, and Chesterfield.

Fig.6.7

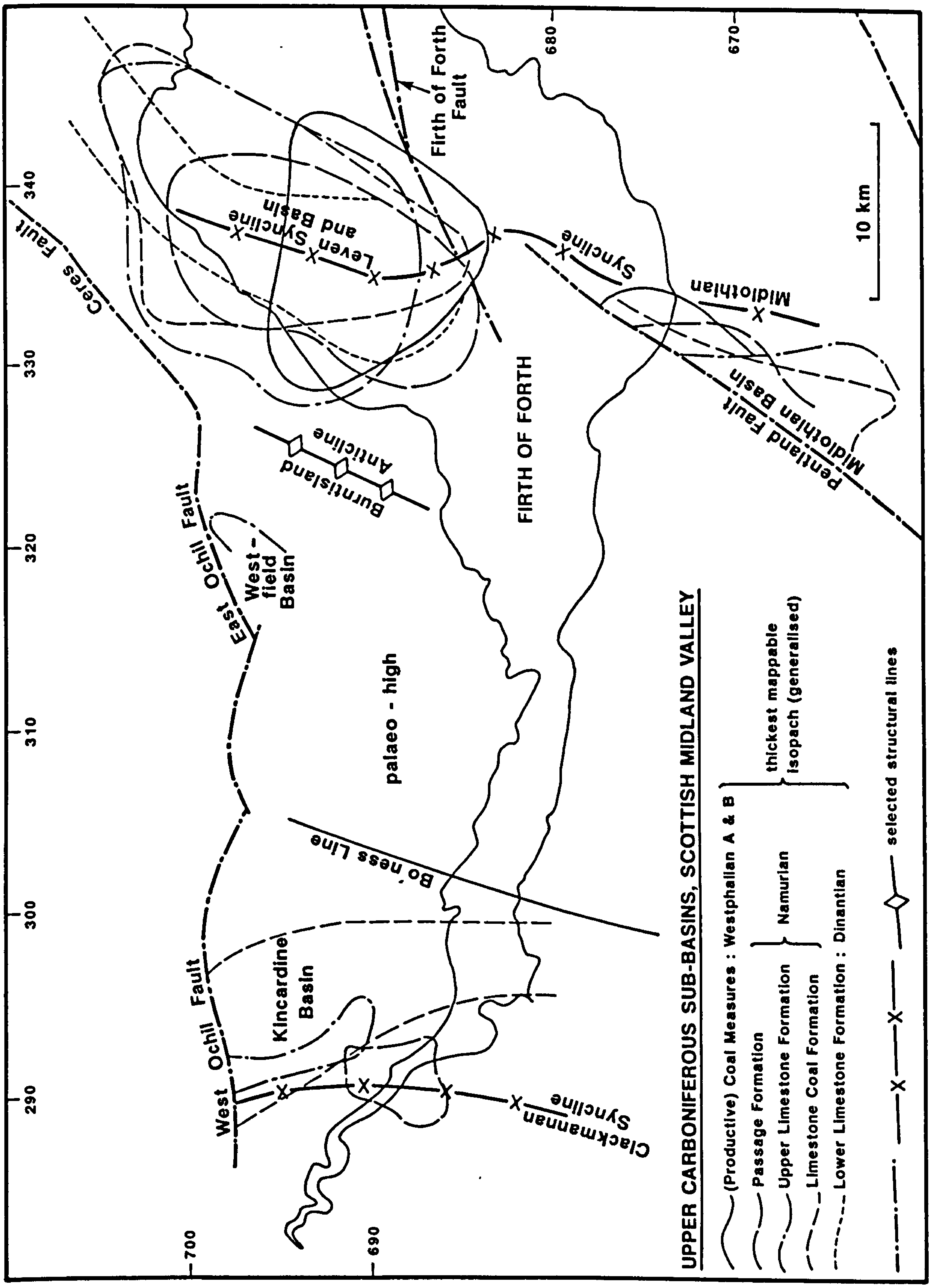
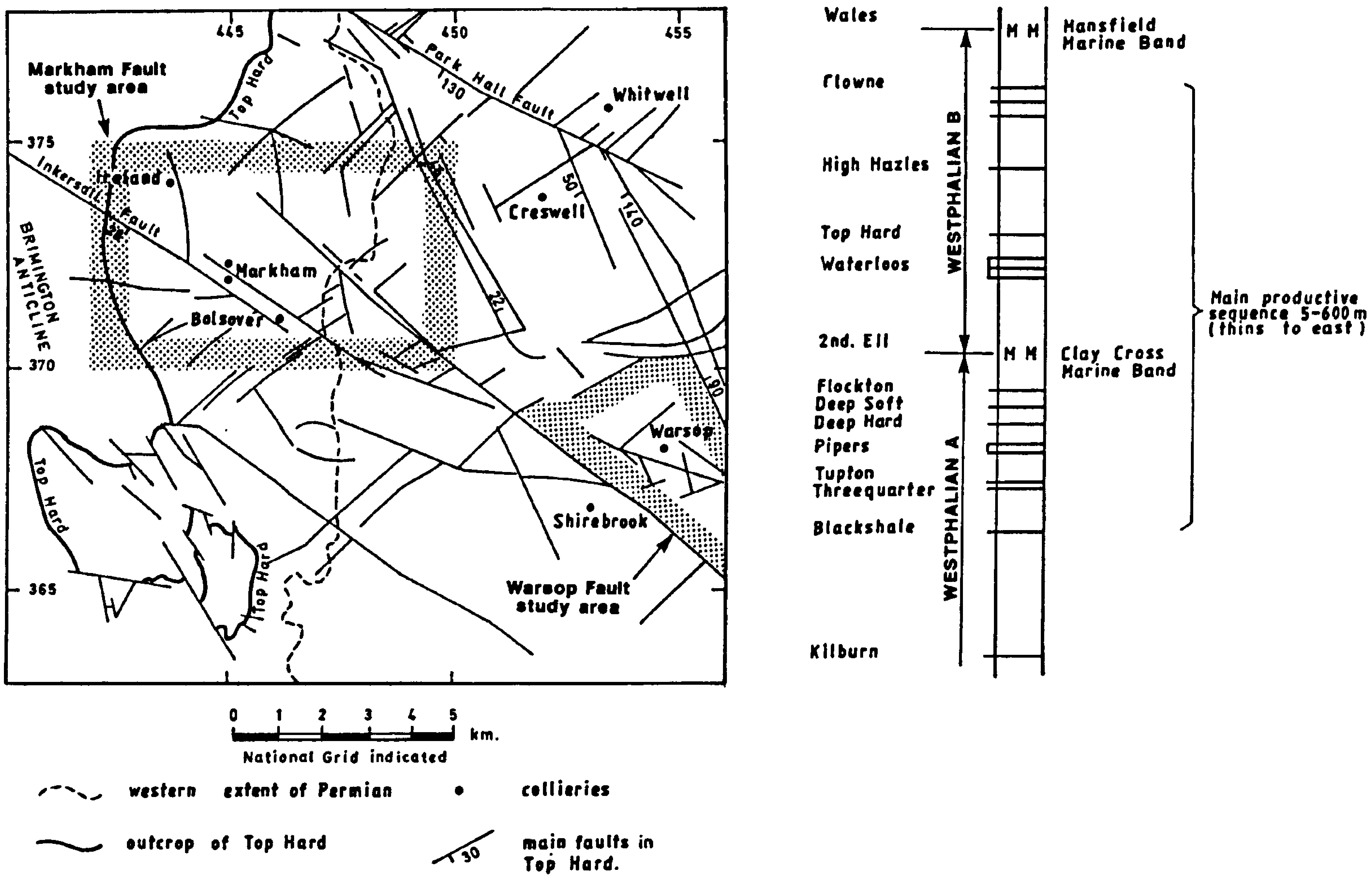
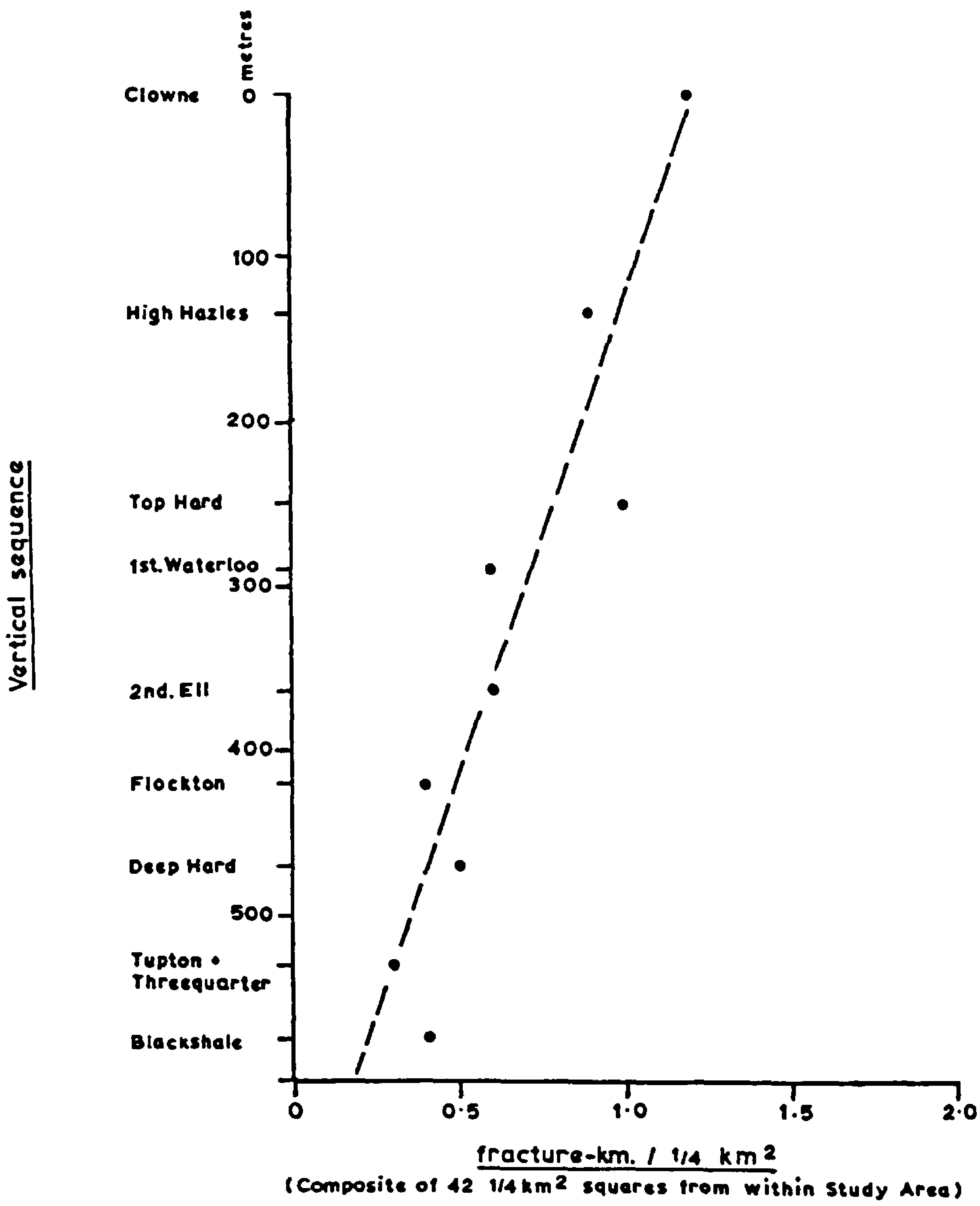

UPPER CARBONIFEROUS SUB-BASINS, SCOTTISH MIDLAND VALLEY
(Productive) Coal Measures : Westphalian A & B
Passage Formation
Upper Limestone Formation
Limestone Coal Formation
Lower Limestone Formation : Dinantian
Namurian
thickest mappable isopach (generalised)
selected structural lines
10 km
290
300
310
320
330
340
700
690
680
670
West Ochil Fault
East Ochil Fault
Ceres Fault
Firth of Forth Fault
Pentland Fault
Kincardine Basin
West-field Basin
Leven Syncline and Basin
Clackmannan Syncline
Burntisland Anticline
Bo'ness Line
palaeo - high
FIRTH OF FORTH
Midlothian Syncline
Midlothian Basin

Fig.6.8



GENERALISED FAULT PATTERN AND SEAM SEQUENCE IN NORTHEAST DERBYSHIRE

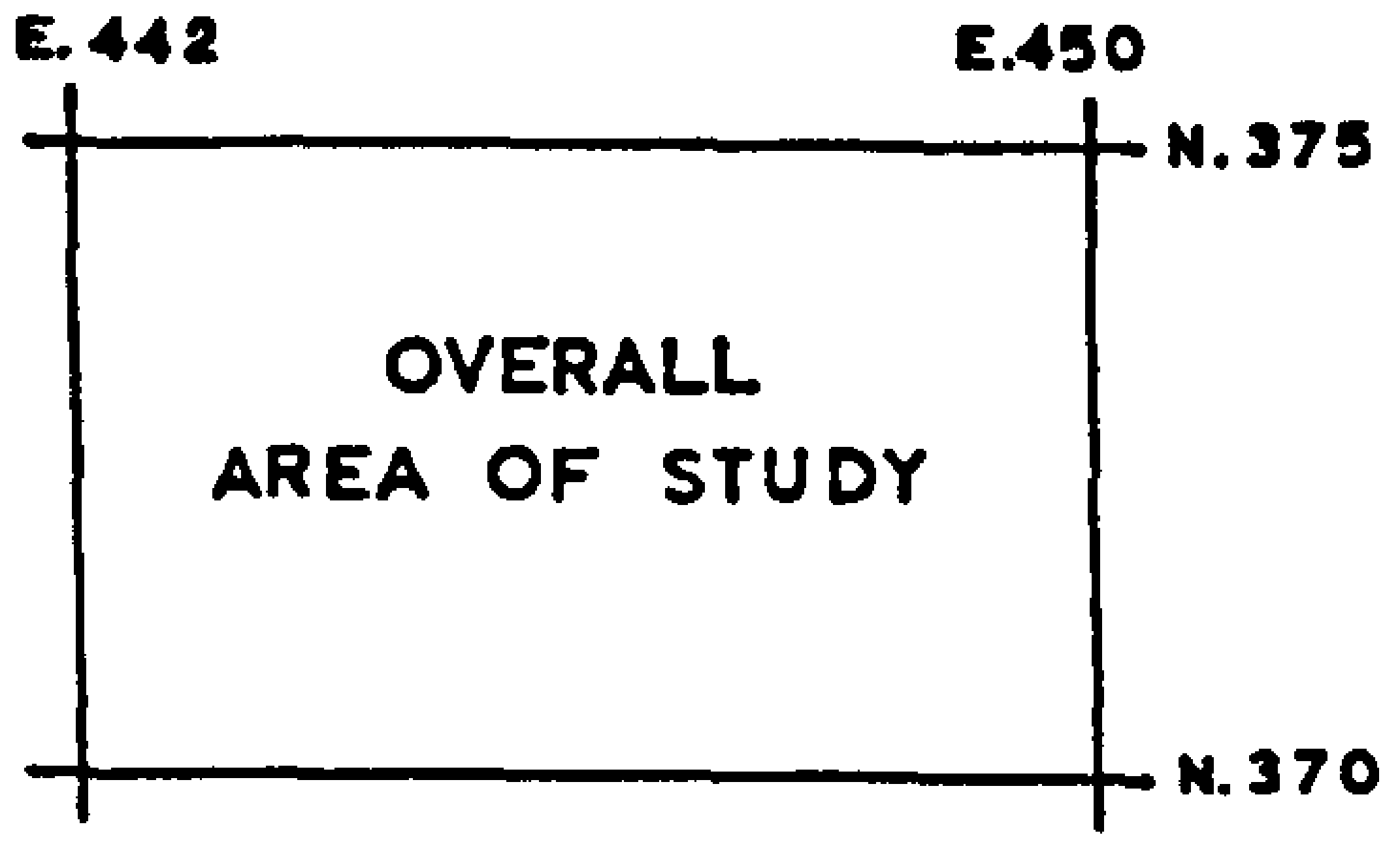
Fig.6.9



No. of 1/4 km² squares assessed
(based on N.G. 1/2 km. intersections)

Clowne	3	Flockton	26
High Hazles	6	Deep Hard	24
Top Hard	36	Tupton / Threequarter	7
1st. Waterloo	10	Blackshale	15
2nd Ell	23		

Includes squares with no known faulting

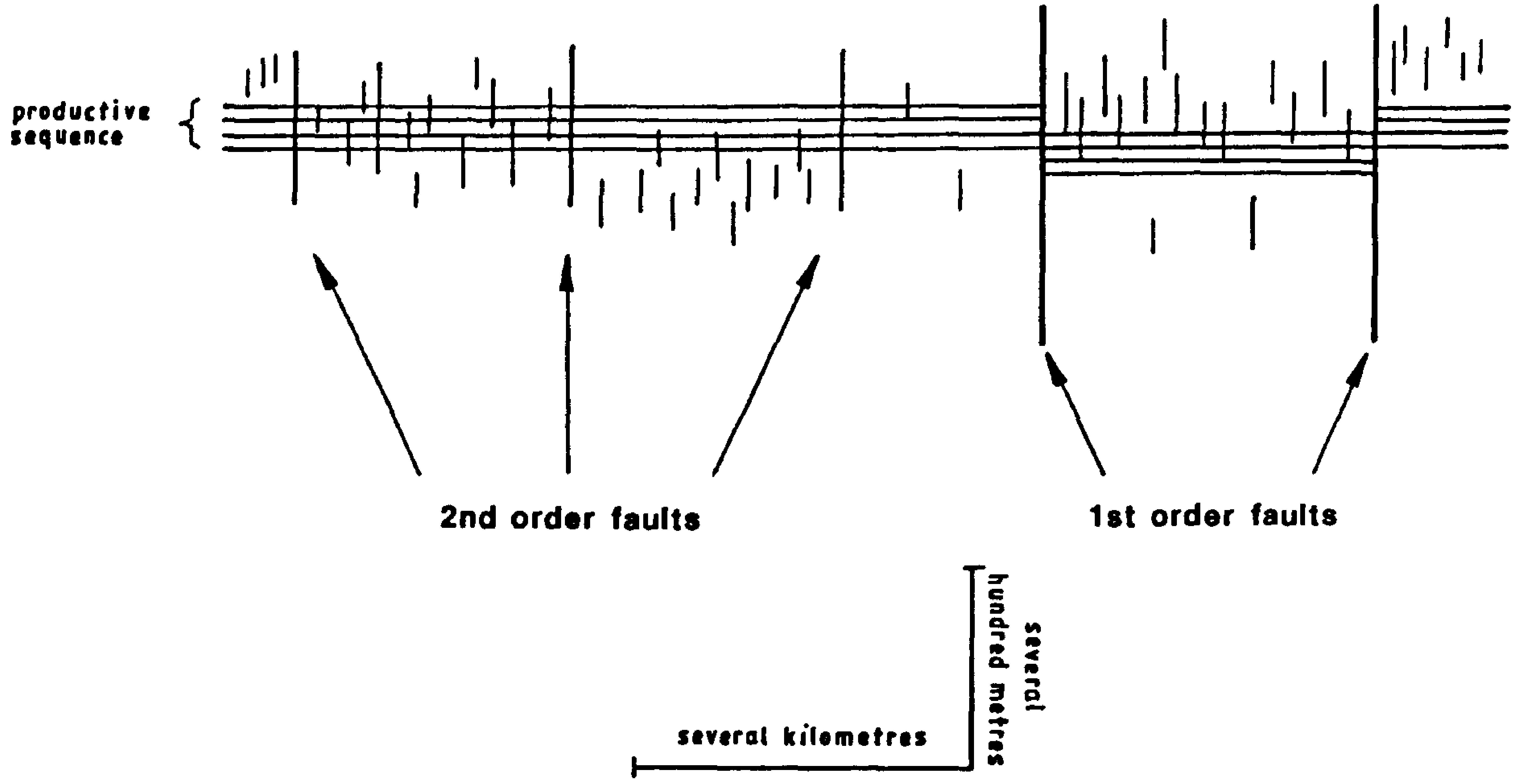


FAULT DENSITY : VARIATION WITH DEPTH
(expressed as lengths of fractures in different seams)

MARKHAM FAULT STUDY
(from Rippon & Raine, 1986)

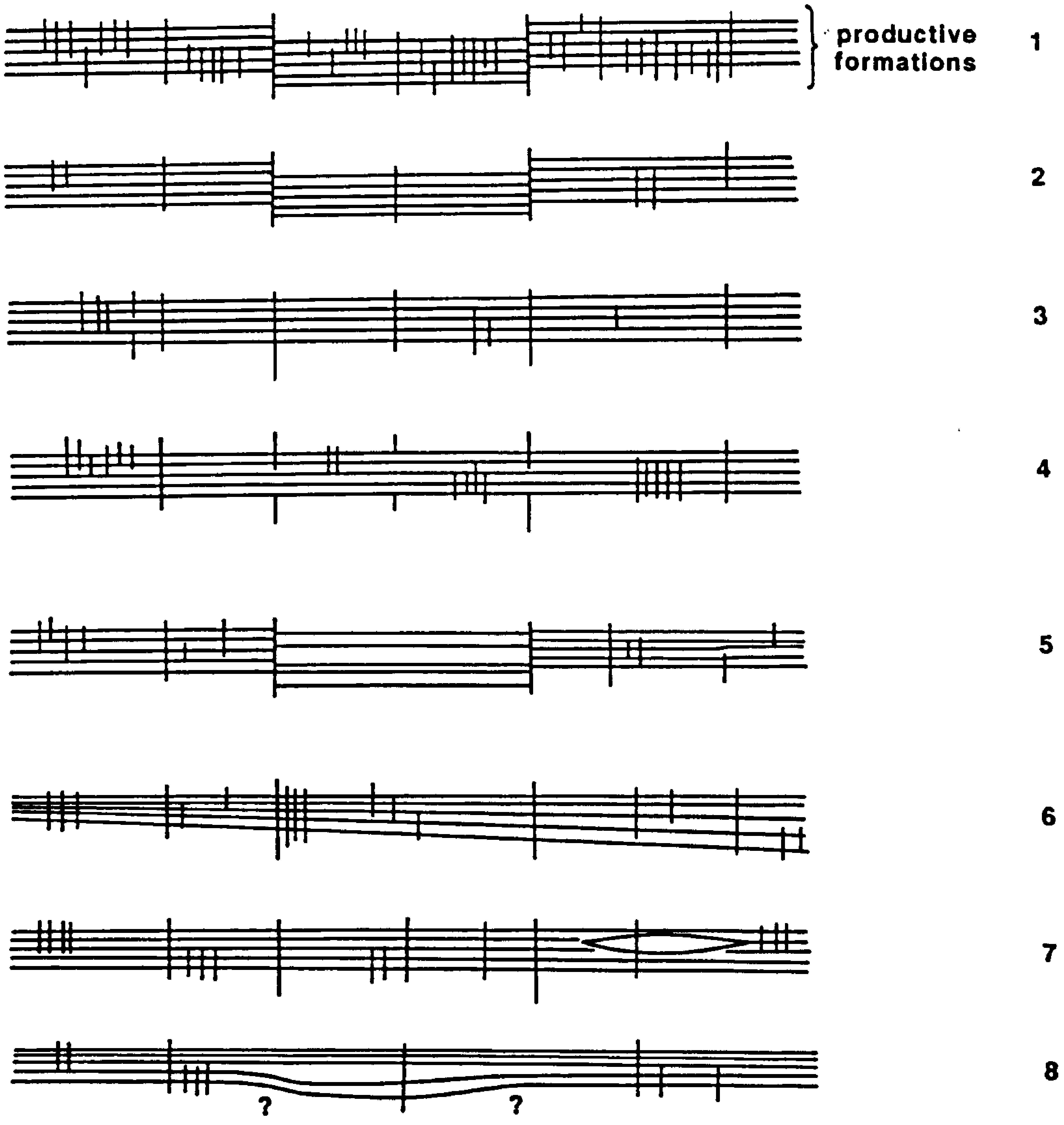
Fig.6.10

STRUCTURAL CELLS Fault concentrations at different levels relative to the productive sequence (schematic)



VARIATION IN FAULT DENSITY WITH DEPTH (EAST PENNINE COALFIELD)

Fig.6.11

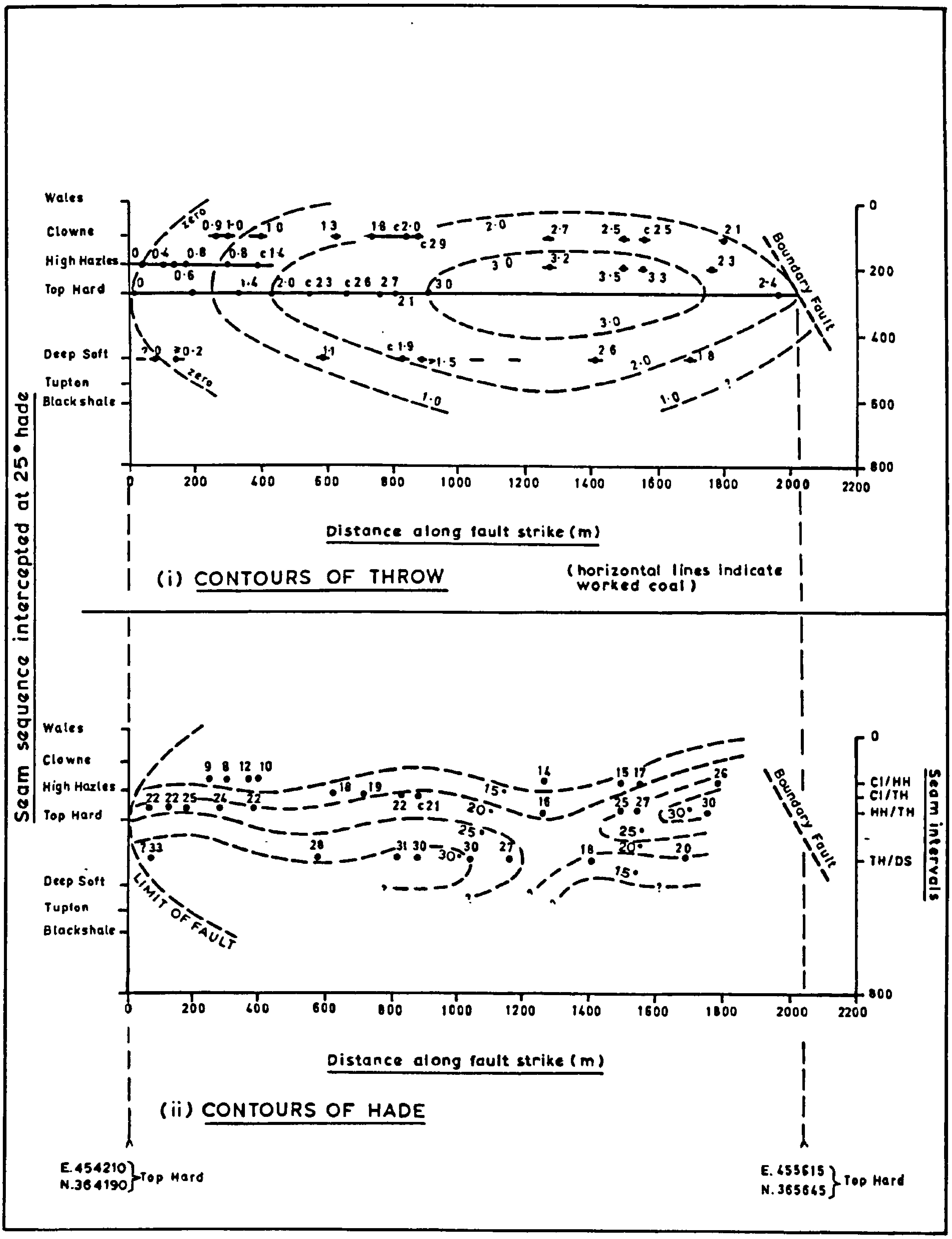


1 Structure post-depositional: distinctive fault hierarchies, numerically related
2 Structure post-depositional: distinctive fault hierarchies, not numerically related
3 Structure post-depositional: subdued fault hierarchies
4 Structure post-depositional: reactivation of subdued major faults
5 Significant syndepositional movement on major faults
6 General basin development with mainly post-depositional faults
7 Disposition of major sand bodies primarily reflects delta switching
8 Sub-basin development; migration of formation depocentres; margins not structurally well defined

No scale; no pre-sequence characteristics or fault characteristics assumed etc.

STRUCTURAL CELLS - SOME POSSIBLE VARIATIONS

Fig.6.12



(i) CONTOURS OF THROW

(horizontal lines indicate worked coal)

(ii) CONTOURS OF HADE

CONTOURS OF THROW AND HADE FOR A SIMPLE NORMAL FAULT (Shirebrook, Derbyshire)

Fig.6.13

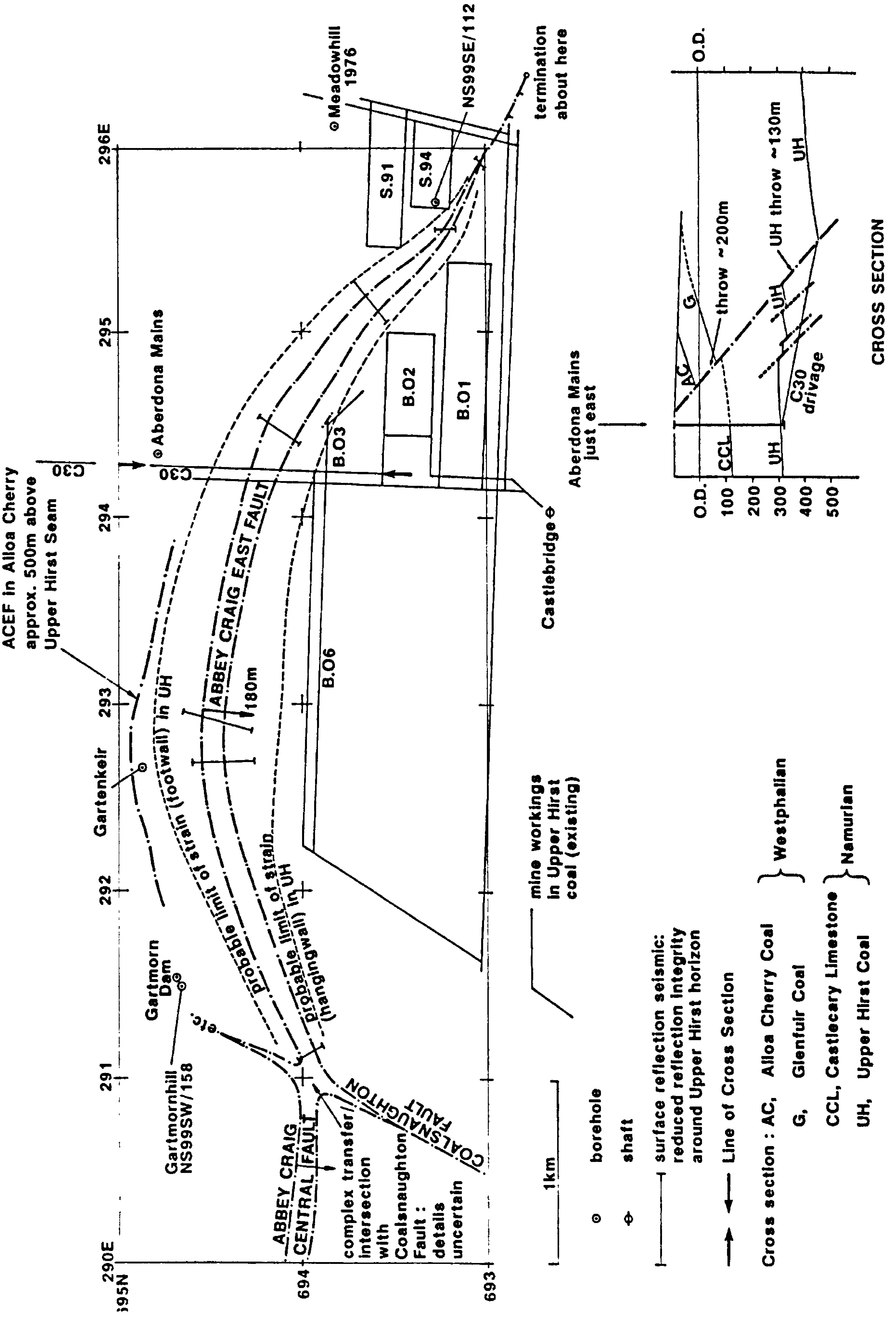
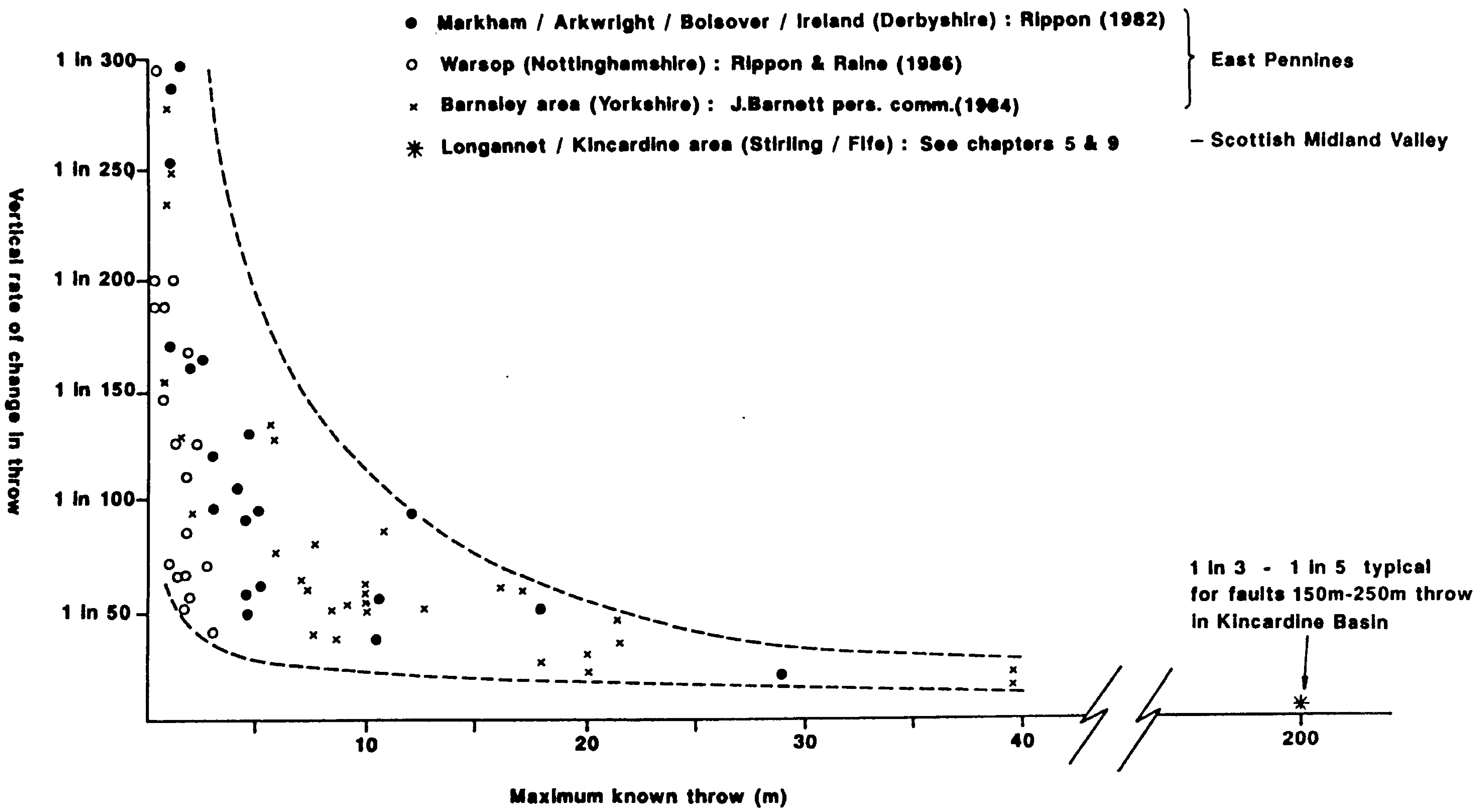

ACEF in Alloa Cherry approx. 500m above Upper Hirst Seam
Aberdona Mains
Meadowhill 1976
NS99SE/112
termination about here
290E
291
292
293
294
295
296E
295N
694
693
Gartenkeir
Gartmorn Dam
Gartmornhill NS99SW/158
etc.
ABBEY CRAIG CENTRAL FAULT
complex transfer/intersection with Coalsnaughton Fault : details uncertain
COALSNAUGHTON FAULT
probable limit of strain (footwall) in UH
probable limit of strain (hangingwall) in UH
ABBEY CRAIG EAST FAULT
180m
C30
B.O6
B.O3
B.O2
B.O1
S.91
S.94
Castlebridge
Aberdona Mains just east
1km
borehole
shaft
surface reflection seismic: reduced reflection integrity around Upper Hirst horizon
Line of Cross Section
mine workings in Upper Hirst coal (existing)
Cross section : AC, Alloa Cherry Coal
G, Glenfuir Coal
CCL, Castlecary Limestone
UH, Upper Hirst Coal
Westphalian
Namurian
O.D.
100
200
300
400
500
AC
G
CCL
UH
throw ~200m
UH throw ~130m
~UH
C30 drivage
CROSS SECTION

Fig. 6.14

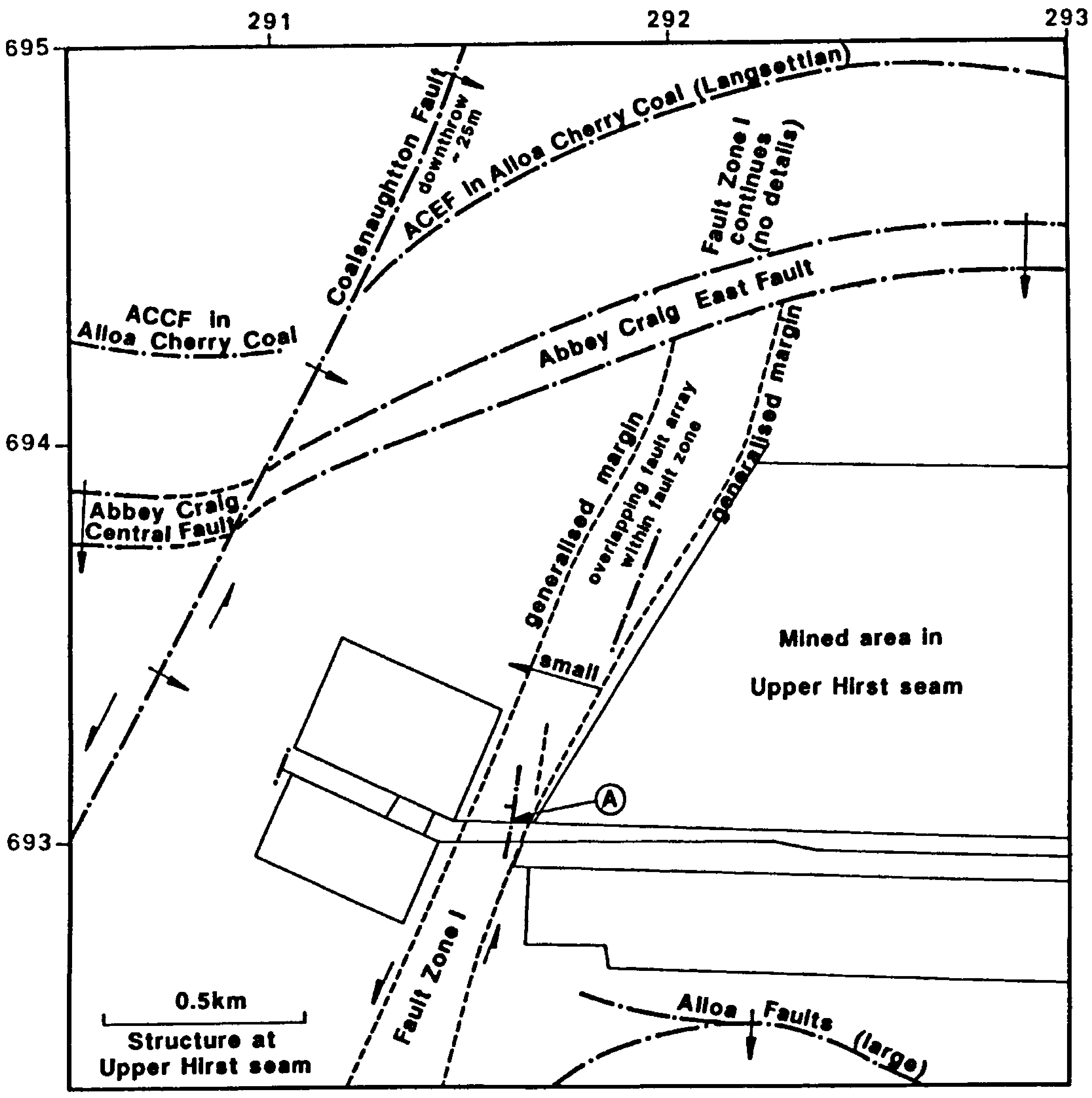


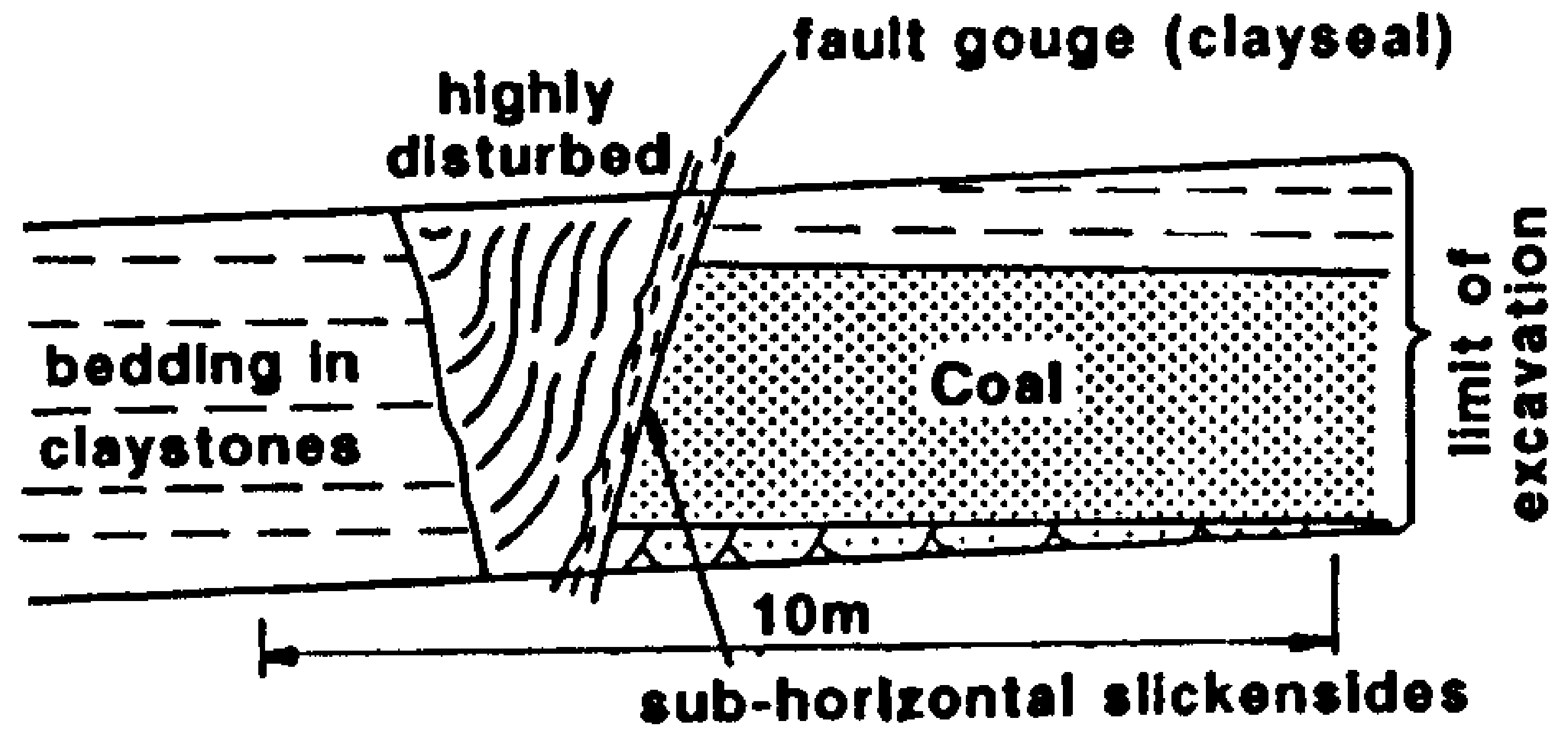
DISPLACEMENT GRADIENTS :

VERTICAL ATTENUATION OF THROW

(All faults considered essentially normal)

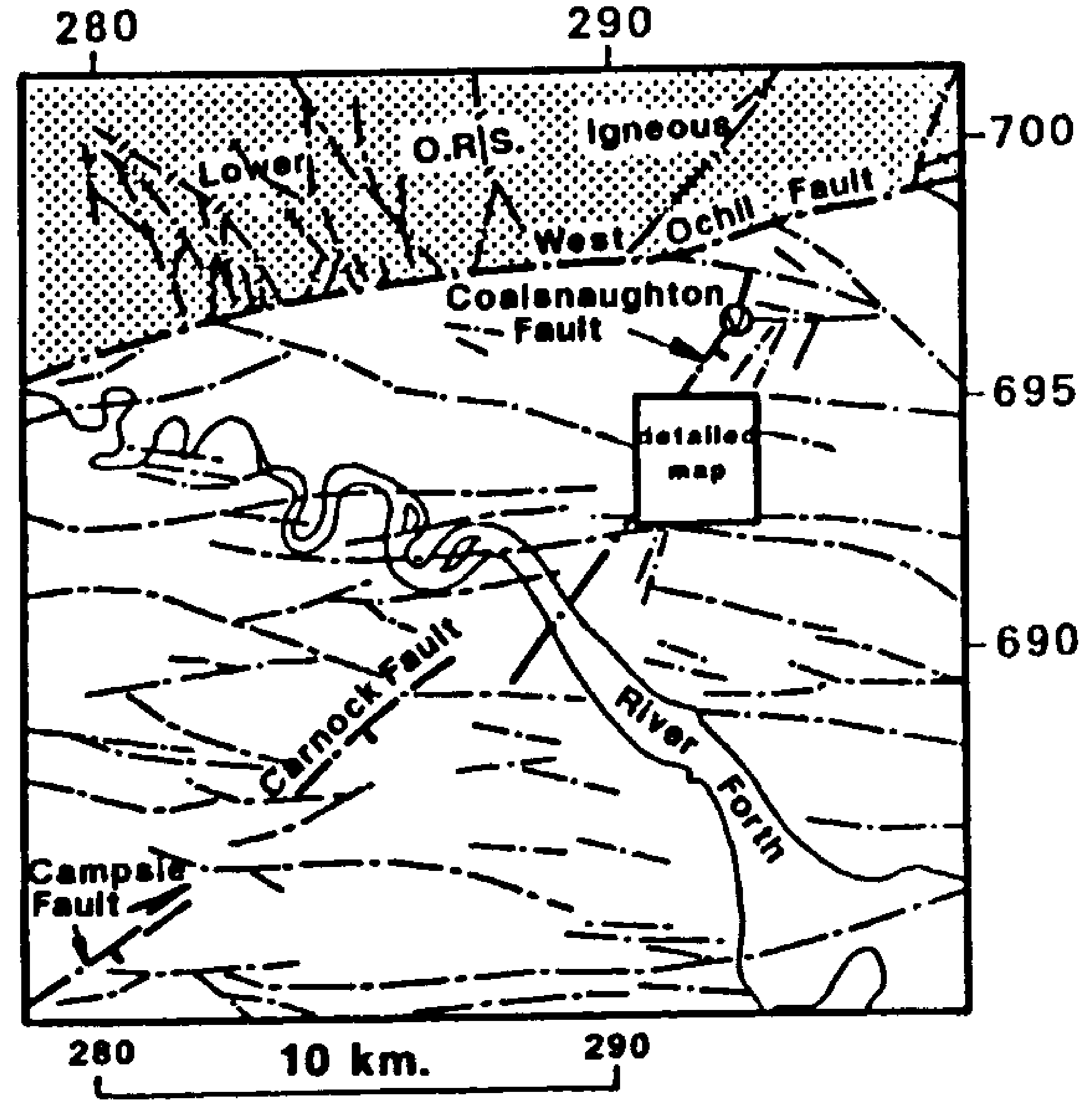
Fig.6.15





Sketch* at point Ⓐ (shale-fill pull-apart)

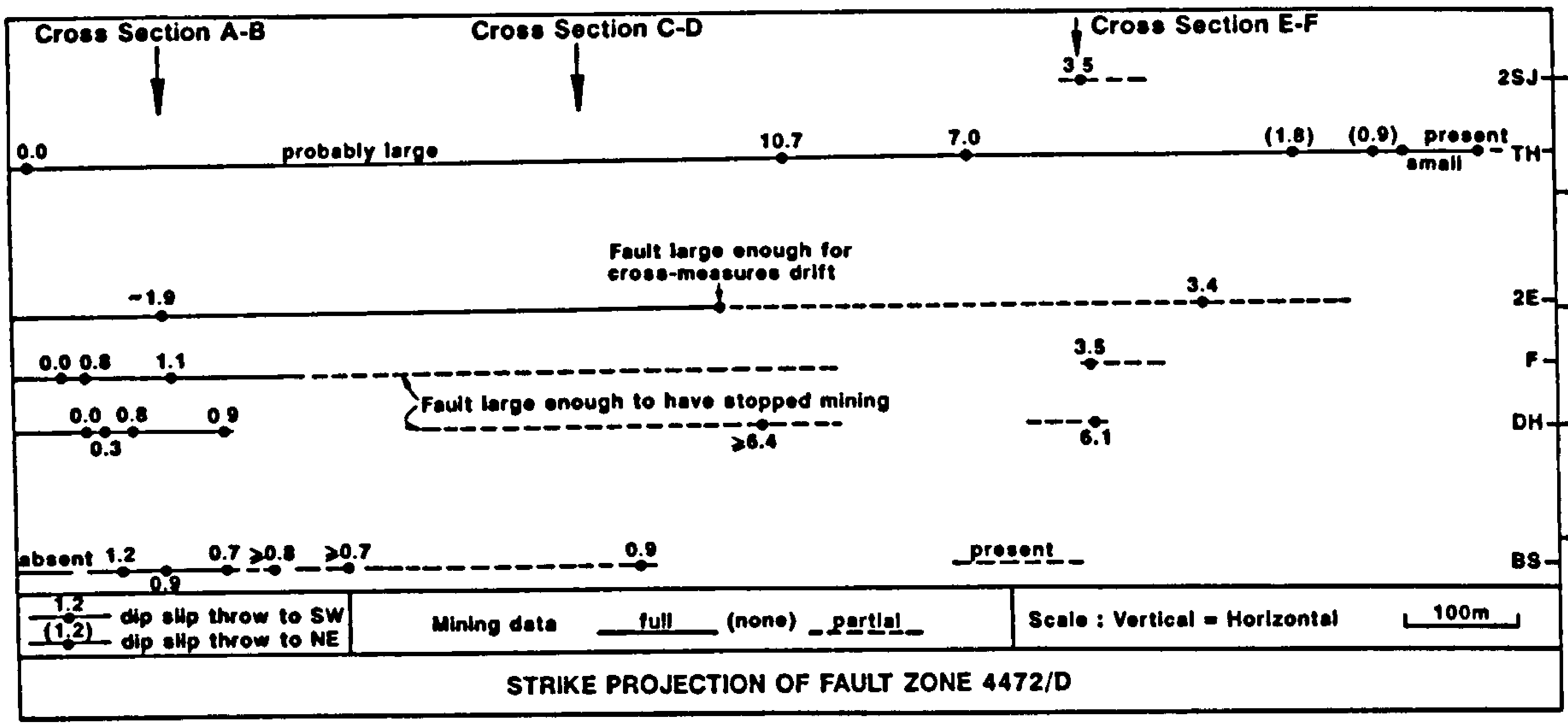
* by C.Flaws

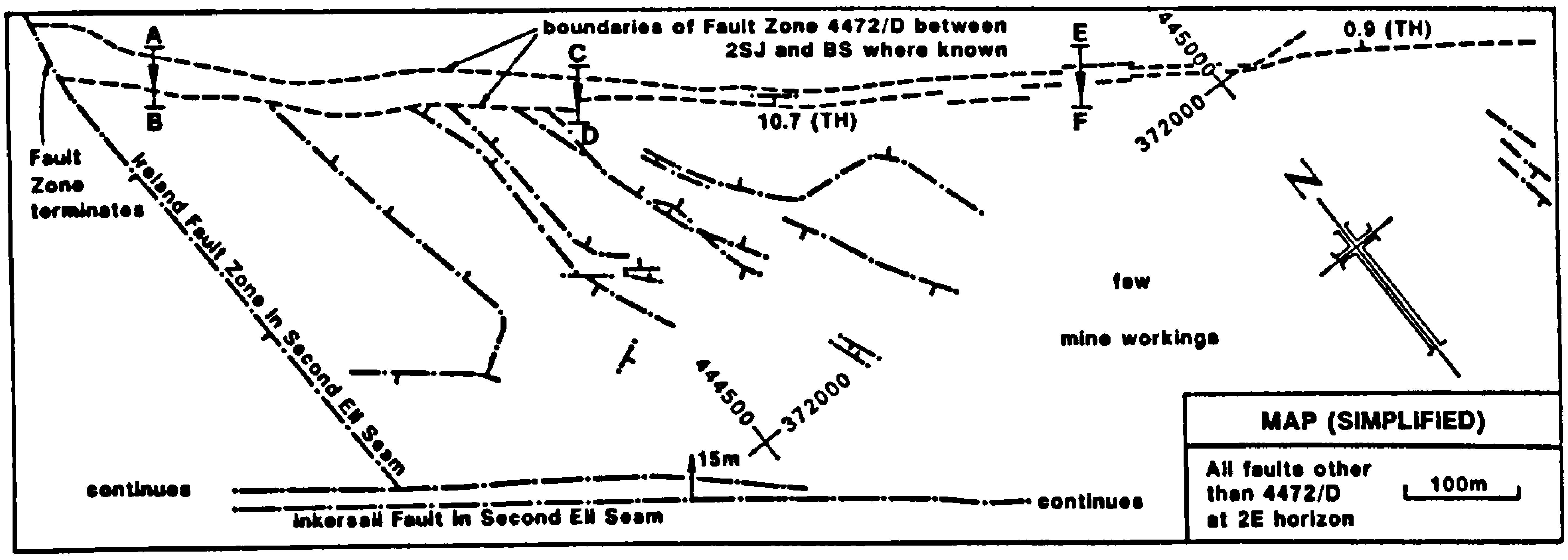


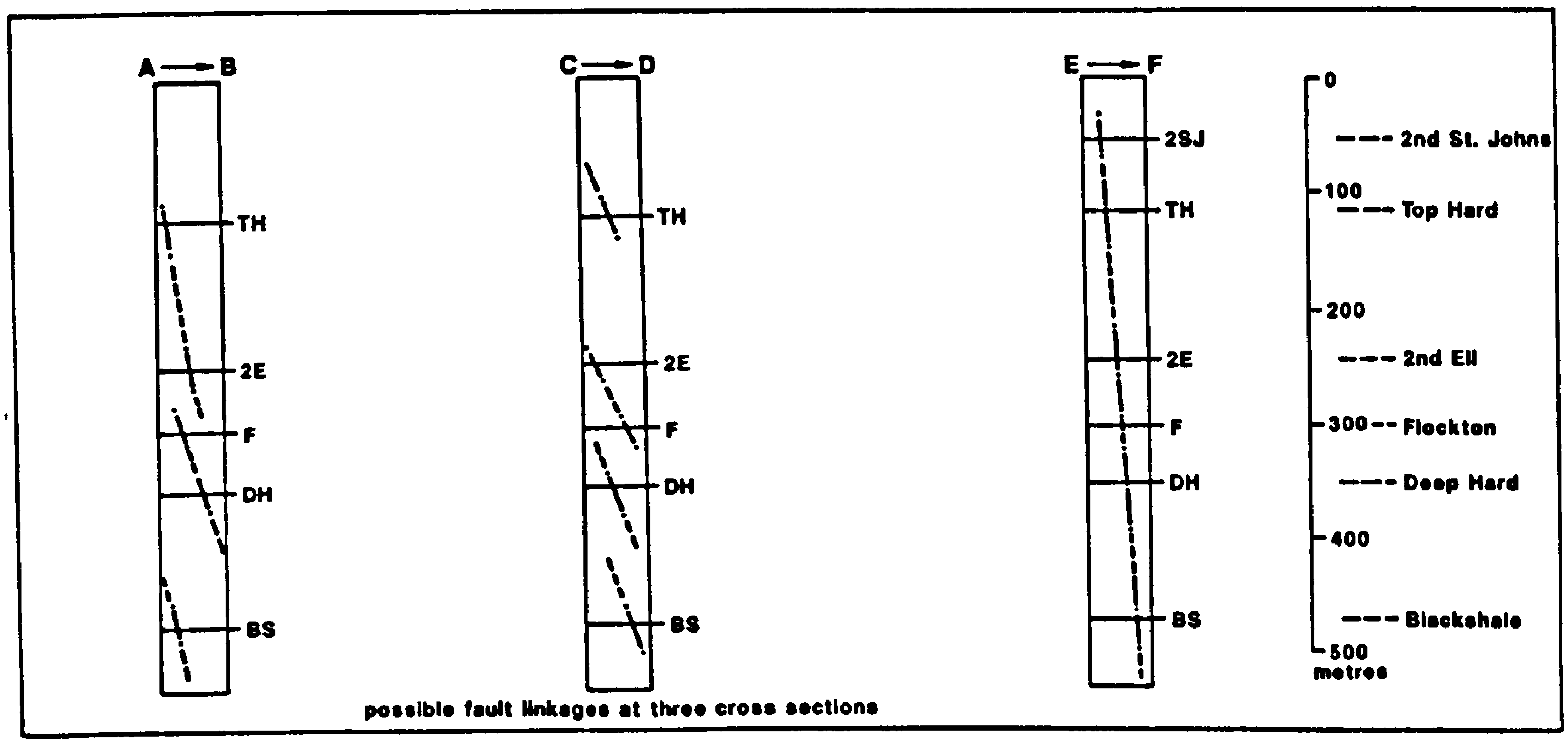
⊘ Namurian vent (Tillicoultry borehole)

COALSNAUGHTON & ANTITHETIC ("ZONE I") FAULTS

Fig.6.16







FAULT ZONE 4472/D* AND INKERSALL FAULT ZONE, MARKHAM COLLIERY, DERBYSHIRE
(RIGHT - LATERAL STRIKE SLIP)

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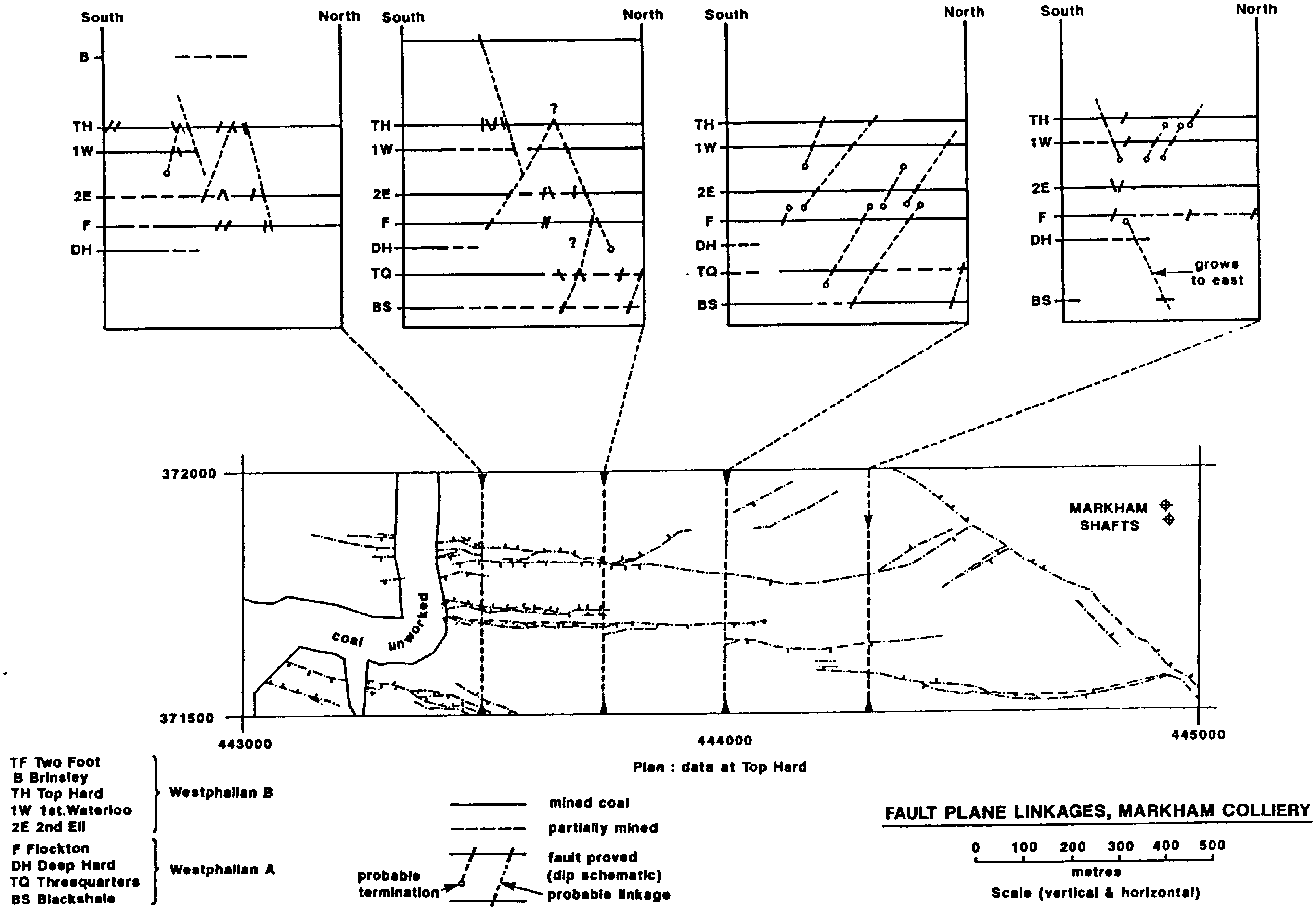
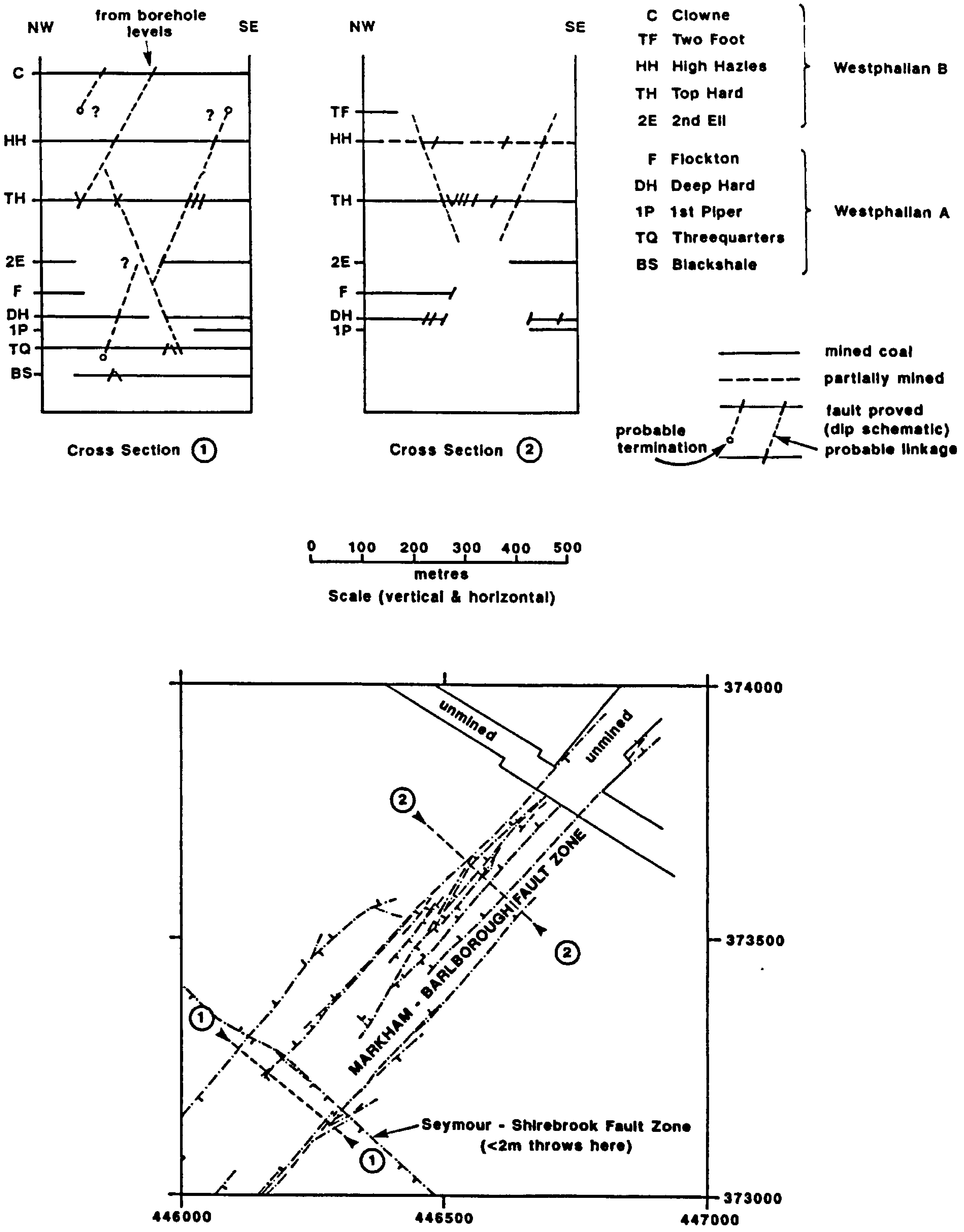
* Smith et al. 1967 p. 219

Fig.6.17



FAULT PLANE LINKAGES, MARKHAM COLLIERY

Fig.6.18



Plan : data at Top Hard

FAULT PLANE LINKAGE, MARKHAM COLLIERY

MARKHAM - BARLBOROUGH FAULT ZONE

Fig.6.19

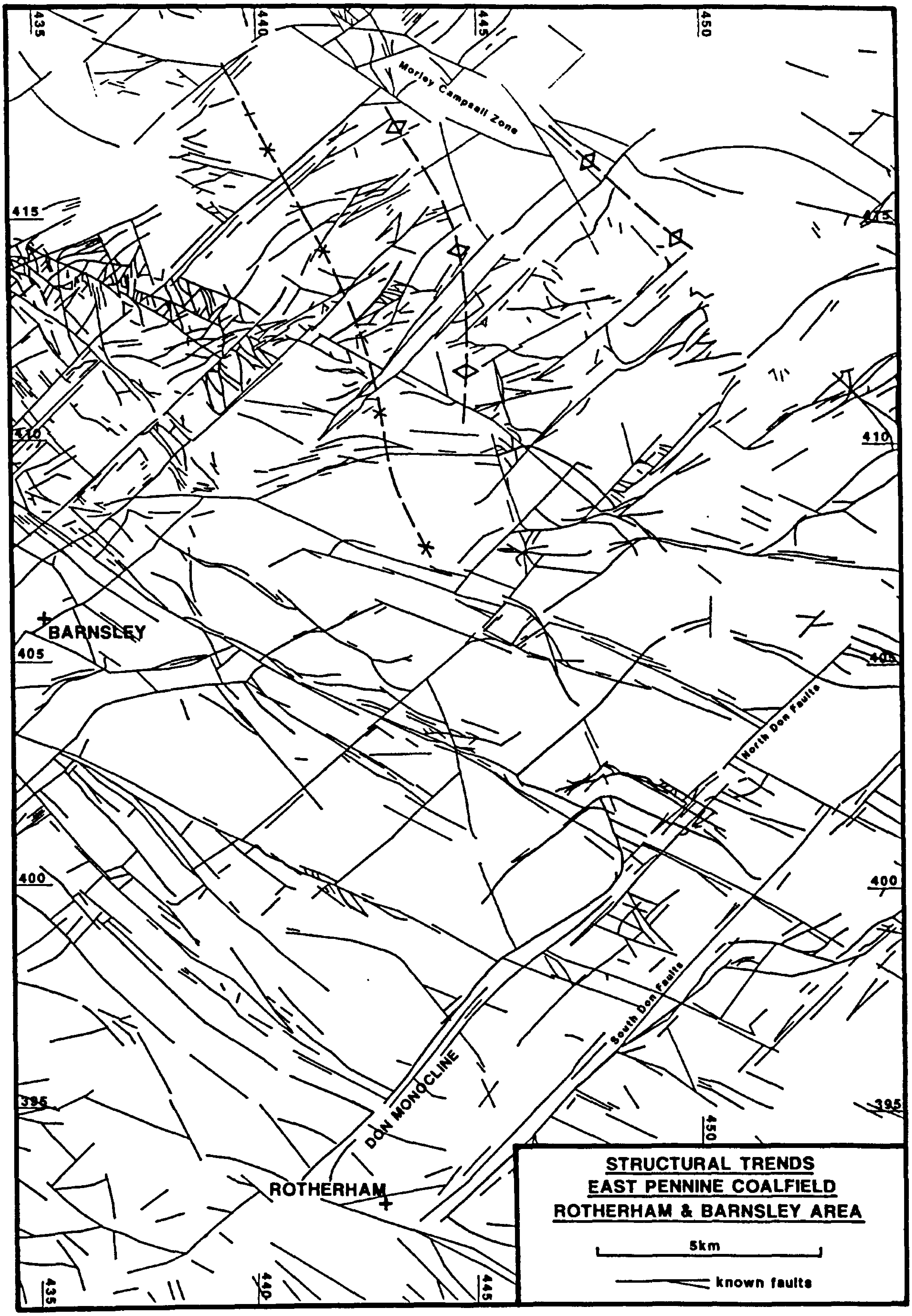

435
440
445
450
415
410
405
400
395
Morley Campsall Zone
BARNSLEY
North Don Faults
South Don Faults
DON MONOCLINE
ROTHERHAM
STRUCTURAL TRENDS
EAST PENNINE COALFIELD
ROTHERHAM & BARNSLEY AREA
5km
known faults

Fig.6.20

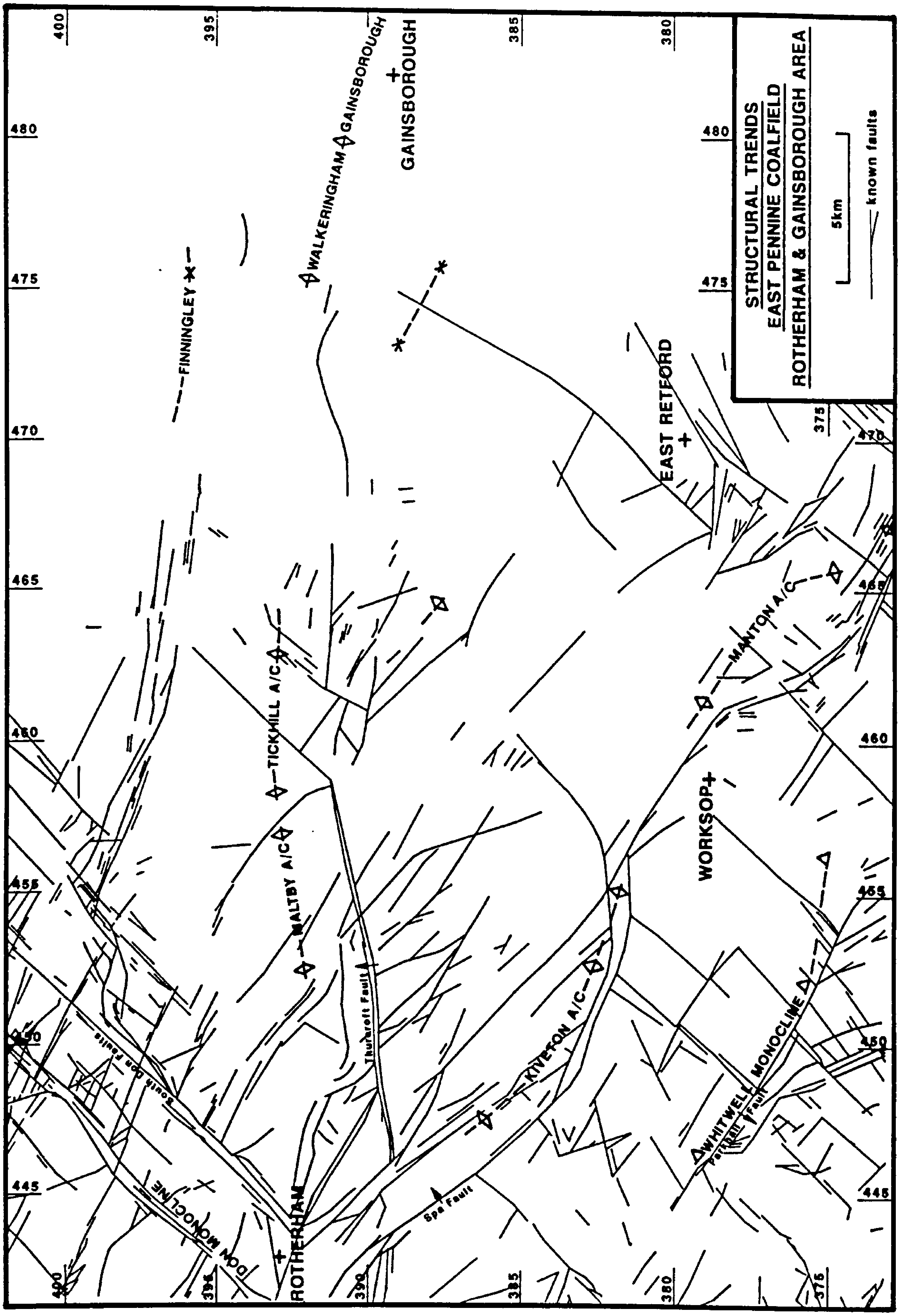

STRUCTURAL TRENDS
EAST PENNINE COALFIELD
ROTHERHAM & GAINSBOROUGH AREA
5km
known faults
GAINSBOROUGH
WALKERINGHAM GAINSBOROUGH
FINNINGLEY
EAST RETFORD
TICKHILL A/C
MALTBY A/C
MANTON A/C
WORKSOP
KIVETON A/C
WHITWELL MONOCLINE
Pebley Fault
Thurcroft Fault
Spa Fault
South Don Faults
DON MONOCLINE
ROTHERHAM
400
395
390
385
380
375
480
475
470
465
460
455
450
445

Fig.6.21

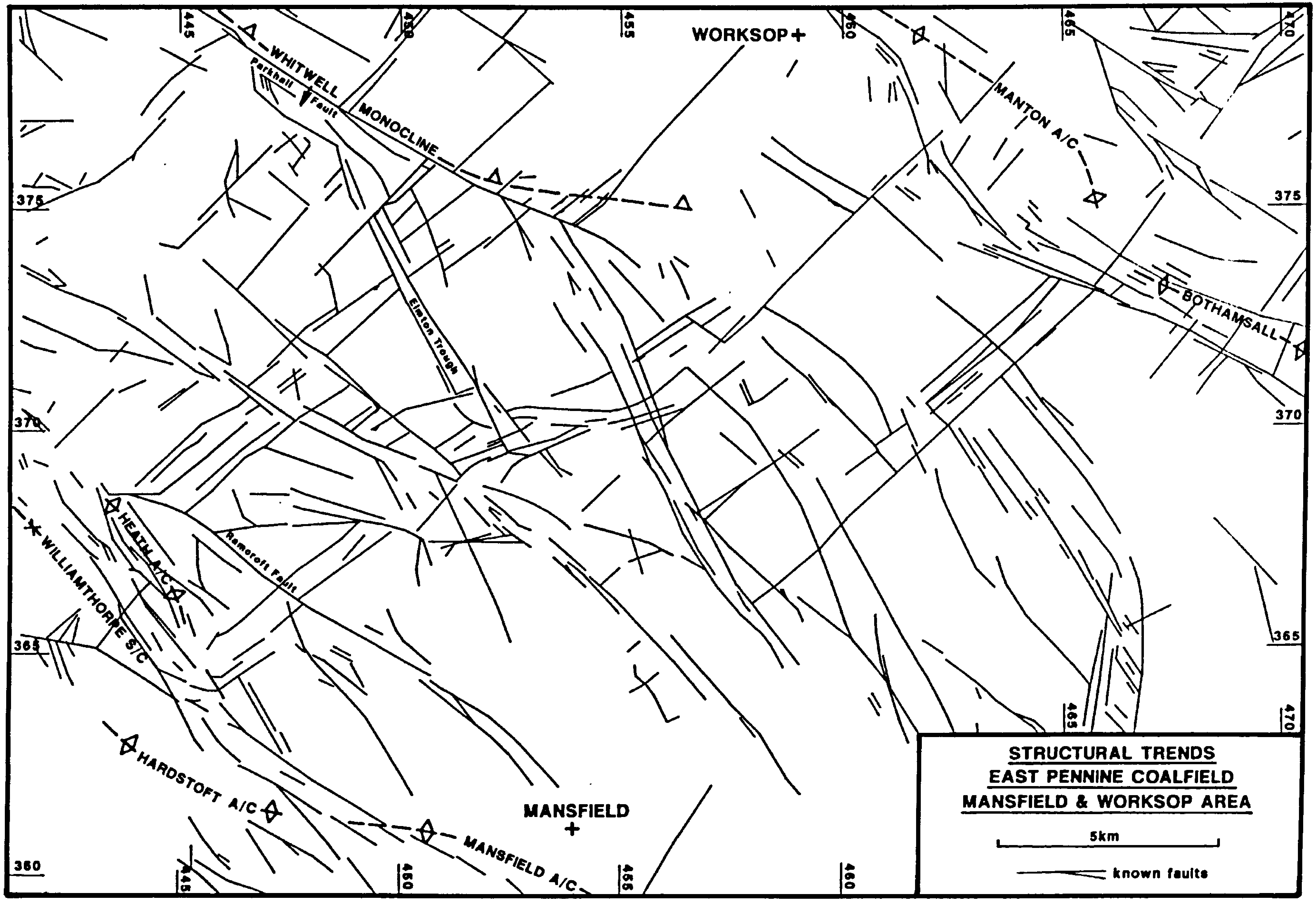

STRUCTURAL TRENDS
EAST PENNINE COALFIELD
MANSFIELD & WORKSOP AREA
5km
known faults
WORKSOP
MANSFIELD
WHITWELL MONOCLINE
Parkhall Fault
MANTON A/C
BOTHAMSALL
Elmton Trough
Ramcroft Fault
HEATH A/C
WILLIAMTHORPE S/C
HARDSTOFT A/C
MANSFIELD A/C
445
450
455
460
465
470
360
365
370
375

Fig.6.22

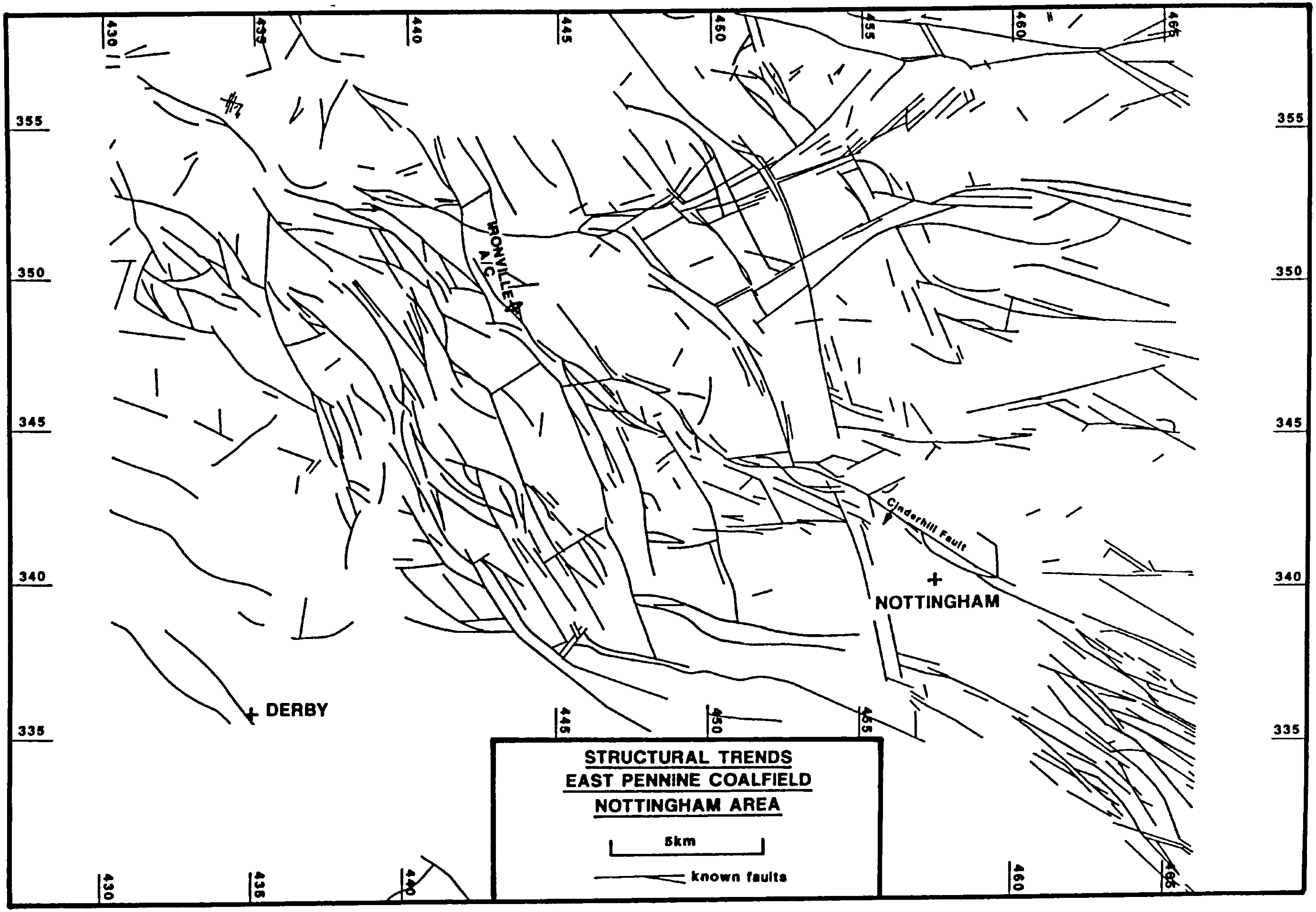

STRUCTURAL TRENDS
EAST PENNINE COALFIELD
NOTTINGHAM AREA
5km
known faults
NOTTINGHAM
DERBY
Cinderhill Fault
IRONVILLE A/C
430
435
440
445
450
455
460
465
335
340
345
350
355

Fig.6.23

CHAPTER 7

JOINTS, ESPECIALLY CLEATS, IN THE UPPER CARBONIFEROUS COALS OF GREAT BRITAIN

Abstract: *Variations in cleat orientations are reviewed, and interpreted as largely reflecting Variscan compressive stress. In the immediate Variscan foreland, varied cleat strikes may record stress deflection and block rotation, whereas north of the Wales-Brabant High, a far-field situation promoted a more consistent main cleat orientation, essentially parallel to the principal horizontal stress. In the Scottish Midland Valley, the far-field was commonly over-ridden by local structural developments. Cleat orientation is thought to record a specific orogenic event, but its relationship to regional faulting history remains uncertain; it is assumed that most faults post-dated most cleats. Cleat variations related to other geological features are also reviewed.*

7.1 Introduction

Coal has many characteristics not found in other lithologies, and one of these is distinctive jointing. Together with the practical importance of joint sets in mining, this has led to specific terminologies. In the English-speaking world, these have largely been rationalised to "cleat" and "slip", defined below. Both are readily distinguished from faults, and from shears immediately related to faulting. Their individuality is also noticeable with respect to jointing in associated clastics, in terms of spacings, and often orientations. The reasons why coal has such distinctive jointing will depend partly upon the progressive mechanical attributes of the peat-lignite-coal series, and partly upon the regionally varying circumstances of burial history, particularly the timing and vectors of fracture-initiating stress regimes at key coalification stages. The origins of joints in many contexts remain uncertain; those in coal are no exception. This account is primarily concerned with their main orientations, and their field relationships with other features in British Carboniferous coalfields (Figs. 7.1, 7.2). From these, it is hoped to add to the understanding of controls on their formation, and perhaps to joints in other settings. Chapter 6 summarises key regional differences in structure through the coalfields.

Cleat is a term that has been used in varying ways in the geological literature, sometimes inclusive of all fractures in a coal, and sometimes very specifically. It is used for both an individual fracture (a cleat) and also for a fracture set (the cleat). It is used here in its British mining sense, that is, a joint set confined within a coal, and arranged (sub)normal to bed boundaries. There may or may not be mineralisation within the fractures. Usually, there are two mappable sets, essentially orthogonal at about 85^0. These two trends have been variously described as face, back, or butt cleats, terms originally used to define orientation with respect to mineworkings. It is necessary to simplify these for geological analysis to main and subsidiary cleat, with strike defined by azimuth. (The terms primary and secondary cleat are avoided, as they may suggest relative initiation timings.) Obviously, main cleat is the set that is dominant, but this may be subjective, particularly where carbonate mineralisation visually emphasises one set; however, it is usually sufficiently obvious to give a clear local and regional trend, and the subsidiary cleat of some localities is really part of this trend, although less prominent. Measurable vertical displacement on a cleat is very uncommon, indeed essentially absent although slickensides are seen, particularly on any mineralisation, and then probably relating to later movement (mineralisation itself implies some separation at some stage). Cleat is found in all coals, however thin: individual plant stems and leaves, preserved as films of bright coal, are intensely cleated, and there is a general inverse relationship between cleat frequency and bed thickness. Individual cleats are commonly restricted by intra-seam lithotypes, only sometimes extending through more than a few 10's millimetres. Cleat frequencies are typically >30/m in bright coals (see later), but are much closer spaced, often >150/m, in the coals of the immediate Variscan foreland, from South Wales to Kent. (Frequencies used in this account are those that are reasonably recordable in sometimes difficult field conditions; the existing data set, see below, reflects this.)

Cleat is pervasive in all the coalfields, and main cleat is commonly oriented consistently across many 1000's km^2, but with local variations, especially near some faults. Apart from local fault-related variations, main cleat strike is usually the same at all horizons, at any one location (even in coal clasts in fluvial sandstones), in most coalfields. Some exceptions are noted later.

Slip is different to cleat. Slip fractures generally dip 35° to 70°, commonly 40° to 50°, and typically cross a full coalbed thickness, sometimes >2m. Slip is usually confined within coalbed boundaries. Earlier terminology was again related to the orientation of mineworkings; main and subsidiary slip are more appropriate. One strike orientation for main slip can usually be mapped, commonly involving conjugate fracturing in which the dominant dip direction may change very locally. Subsidiary slips may strike at a variety of angles to the main slip. Main slip frequency typically varies from 1/m to 6/m. Measurable displacement is rare, but slip surfaces are commonly polished, with slickensides and finely divided coal ("slip dust").

Slip is pervasive in the coalfields of the immediate Variscan foreland in South Wales and southern England, where main slip strike is oriented consistently across 100's km^2, and is essentially the same in all coal seams at any one location. There is rarely any mineralisation of slip surfaces (some is reported from Kent), but this may simply reflect coalfield location: there is also less obvious cleat mineralisation in the southern coalfields compared with those of the Pennine Basin and further north (see later). In those essentially extensional areas, slip is found only occasionally, where it is associated with large structures. It has been recorded specifically in North Wales and Staffordshire, very locally in Yorkshire, and in the hangingwall of the Stublick Fault, on the south side of the Northumberland Basin. Slips adjacent to intrusions, recorded in Scotland and the Northeast, may have different origins (see later).

In the immediate Variscan foreland fields, strikes of main slip and main cleat rarely coincide. Earlier literature (see Fox 1965) on slip regarded some fractures as induced by mining. It is now known that slips as described here are natural. Mining-induced fractures are not considered further in this account. In South Wales and Kent, coals commonly exhibit millimetric-scale striated conical structures, similar to cone-in-cone, the vertical axis approximately bed-normal. These are not well-reported (but see Bustin 1982); their significance in British coalfields requires further study.

7.2 Previous work

There are numerous studies on cleat, mainly in earlier mining literature. It is beyond the scope of this account to review all these. The main publications quoted below provide useful bibliographies.

Most work on the cleat and slip of British coalfields was undertaken in the first half of the 20th Century, when mining became widespread. Many observations were made by mining engineers and surveyors, as the orientation and frequency of the fracture systems affected both drivage design and coal extraction. As coal mining was of major national importance, leading geologists were also directly involved in the interpretation of the depositional and structural variations of coals. Prominent amongst these regarding cleat was P.F. Kendall, who knew not only the British coalfields, but also many around the world. However, the first published account of cleat was in 1834 by Edward Mammatt (quoted with other early references in Raistrick & Marshall (1939).

The regional parallelism of the main cleat was of major interest. Kendall & Briggs (1933) considered that there was a pre-disposition to a NW-SE trend across the northern (and perhaps also the southern) hemisphere. These authors considered many options for its origins. They discounted shrinkage cracks, and were uncertain about the relationship, suggested by some (see their bibliography) with the magnetic meridian; simple tensional stress was unsatisfactory, and they considered that the field evidence suggested shear in a rotational system; certainly, cleat was a brittle fracture feature. While recognising that cleat characteristics could modify adjacent to specific structures, they concluded that regional trends required an origin beyond local structural processes. Cleat strike regularity was best exhibited in the largest and least structurally-disturbed fields.Their favoured origin was alternating torsional stress provided by semi-diurnal tidal force over time, and argued that this should be compatible with their suggestion that cleat was better developed in higher latitudes.

With the increasing mechanisation of mining, cleat became less important, but there was a surge of interest in the 1950's and 1960's, partly because coal ploughing, common elsewhere in Europe, was being considered for the British industry. Ploughing involves dragging a fixed array of picks along a coal face, and its success depends very much on the bulk strength of the coal, and the orientation of the main cleat. During this period, numerous observations of cleat orientation and frequency were made by the National Coal Board's (NCB) Coal Survey Laboratory, and the results give the best existing data across most coalfields.

These and other cleat and slip data were reviewed by Fox (1965) in a wide-ranging but unpublished report for the NCB. He found no general relationship between cleat and coal rank although intense cleating, together with pervasive slip, was characteristic of the higher rank coals of South Wales and Kent. He noted anomalies in cleat trend adjacent to some structures, also the distinct tendency for the main slip in South Wales to lie (sub)parallel to the coalfield's cross faults (Woodland & Evans 1964). Cleat frequency was greater in bright coals than in durains or cannels; whole-seam assessments rarely reflected finer petrographic variations, especially where there were many thin durains, or significant fusain (in which cleats were not reported). Fox (1965) collated the data in a series of "dial diagrams" which showed main and subsidiary cleat in most coalfields, together with slip in South Wales. Main cleat strike was northwesterly in Midlothian, and in all the coalfields of central and northern England and North Wales, with a tendency to a more northerly trend southwards through the Pennine Basin. In South Wales, main cleat was generally northeasterly, east of the Neath Disturbance, and variable (often around W-E) to the west. In Kent, main cleat strike was northerly, with most readings just east of north. Figure 7.3 summarises Fox's cleat results, with some later additions by the present author. In his monograph on the coals of South Wales, Adams (1967) commented further on the NCB data, confirming the trends noted by Fox (1965), and describing some field characteristics.

The strength of most British coals meant that ploughing was never a preferred option except for certain thinner seams, and most coal faces were mechanised using rotary machines sufficiently powerful to make any directional advantage less important. Therefore, through the 1970's and 1980's, cleat observations were made only where there was a specific need, or where a geologist maintained a personal interest, resulting in a thirty-year period during which cleat orientation, one of the easiest of features to record underground, was not widely documented.

The best exposures of cleat are usually in opencast mines, where freshly-exposed material gives easy viewing in three dimensions. Often, operational practice has involved stripping the upper surface of the coal, allowing very detailed mapping. In an unpublished study of cleats, and joints in associated clastic rocks, by the British Geological Survey in opencast exposures in the eastern Pennine Basin, it was noted (R.Ellison, pers. comm. 1997) that: 1, cleat sets were usually orthogonal, with a change to 60° conjugate sets adjacent to major structures, particularly the Morley-Campsall/Askern-Spital fault zone and the Cinderhill Fault (Fig. 7.6, this chapter; see also Chapter 6); 2, there was a consistent 5° to 10° clockwise rotation of joints in superjacent clastics compared with coal cleats (also a consistent 5° clockwise rotation in a cannel coal attached to bright coal in a single seam); 3, subsidiary cleat was better developed adjacent to certain faults; and 4, cleat orientation was deflected around heterogeneities such as upright sigillarian stumps. Meanwhile, Corfield (1990, 1991) described cleat relationships in North Staffordshire (western Pennine Basin); he noted typically orthogonal cleat sets, and also compressional conjugate shears, interpreted as effects of layer-parallel shortening prior to development of a major fold.

Through the 1990's, interest in cleat has revived, from two different quarters. Firstly, support systems in mine roadways have moved from passive supports to rock bolting, in which rock strength and fracture systems, together with the prevailing stress, require careful assessment. Secondly, extraction of coalbed methane by surface boreholes benefits from assessment of fracture permeability, and likely orientation of hydrofractures. Much work in these fields remains unpublished. However, there have recently been regional cleat studies in two British coalfields. S. Graham (pers. comm. 1991) studied overall faulting and cleat patterns in the Selby area of Yorkshire (SE 63, 64), concluding that the Morley-Campsall Fault was an important structural boundary. Main cleat was typically northwesterly, south of this structure, but westerly to the north. He interpreted this in terms of depth to basement, and the development of W-E faults bounding the Market Weighton High, a prominent Mesozoic uplift east of the mined coalfield. Some W-E fractures were interpreted as conjugate shears, and had a pronounced bed-parallel decoration reminiscent of cone-in-cone or even shattercone structures ("cleat shear"). In South Wales, Gayer & Pesek (1992) and Gayer *et al.* (1996) discussed the timing of cleat formation using the palynology of cleated coal clasts in later Westphalian sandstones, concluding that some cleating predated clast deposition, based on their assessment of clast cleat orientation. Regional cleat was interpreted as a burial/compaction fabric formed in dewatering coals, with extension fractures developing in advance of the Variscan Deformation Front. They envisaged the cleat, together with thrusts, providing pathways for fluids, forced into the basin and up-ranking the coals.

The world-wide distinctiveness of cleat is reflected in a considerable international literature, which has also grown again recently because of the interest in coalbed methane, particularly in the USA and Australia. Various studies and bibliographies are given in Gayer & Harris (1996). Many of these are in specific tectonic settings. Obviously it is important that coal cleat is not studied in isolation from joint systems in the associated clastics. Some of these are commented upon later. In the existing literature, the reference most relevant to this study is Moseley & Ahmed (1967). These authors reviewed joint trends, and their relationship to faults, across much of northern England, from Lower Palaeozoic to Triassic rocks, and from a variety of lithologies; a few coal cleat records were included. They concluded that many joint trends in Carboniferous rocks were inherited from the Caledonides in the context of a general W-E stress field; NW and ENE trends developed as sinistral and dextral structures respectively. Joints in Permian limestones and Triassic sandstones were considered to be related to Alpine tectonics, although trends were inherited from the Carboniferous.

7.3 Data

As noted, most cleat data in British coalfields were recorded by the NCB in the 1950's and early 1960's. Probably few of these surveys would have been by geologists. Most are thought to have been made by staff during routine sampling of the coals for laboratory analyses; it is likely that mining surveyors were involved in the recording. According to Fox (1965), measurements were by clinometer and mine surveying, compasses being useless underground because of steel supports and machinery, although they were used in some surveys of opencast sites. In a few cases, oriented blocks of coal were removed for detailed measurements in the laboratory. Underground data were recorded clockwise from the coal face in question, so that the mining effect could be ascertained. Location was normally surveyed to UK National Grid, with an accuracy of +/-10mm, both Eastings and Northings. Accuracy tests on sample orientation methods were made in opencast sites, and it was concluded that errors of >10° were possible underground. Cleat frequencies were also recorded, sometimes including the variations found in different coal lithotypes. In the case of slip, the true dip of the slip plane was recorded, but was not reported upon by Fox (1965) as he was concerned only with the strike of cleat and slip. In practice, some of the individual data points were not related to grid north in the final reporting. This historical data set is invaluable, as it covers a sufficient geographical scale and stratigraphical range to allow comment on regional geological relationships, in most coalfields. Because the data set is the product of a single organisational system, but built up by many different field workers, it has a considerable degree of objectivity. Fox (1965) only assessed regional variations in cleat strike by coalfield averages (Fig. 7.3). In some fields, NCB geologists further analysed the results to produce regional cleat maps, notably in Yorkshire, Nottinghamshire and Derbyshire, and (with slip) South Wales. Additions were made from subsequent underground observations, but as these maps were usually on a small scale, their present accuracy cannot be guaranteed.

It is apparent that cleat can usefully be studied on scales from the microscopic to the continental, and a true understanding requires all of these. Many arguments in the geological literature on the origins of cleat, and indeed joints, may result simply from workers addressing data on differing geological scales. The British data, to which this account is only an introduction, allows integration of many scales, but because most data locations are now inaccessible through mine closures, detailed geological context cannot always be investigated.

7.4 Cleat and slip trends; a review and discussion

Cleat data are available over most fields, although relatively scarce in western Scotland. This account draws mainly upon data in eastern Scotland, the eastern Pennine Basin (Yorkshire, Nottinghamshire, and Derbyshire) and South Wales. These three fields represent very different tectonic settings, varying from the post-rift Midland Valley of Scotland with its very prominent depositional sub-basins and common large extensional and strike slip fault systems (Rippon *et al.* 1996) to the post-rift Pennine Basin, and to the immediate Variscan foreland setting of South Wales (Chapter 6). In Scotland, cleat orientations in early Namurian to Westphalian B coals may be studied. A range of hard coal ranks and lithotypes is available, including variations adjacent to igneous intrusions. Further work is required particularly in the western Pennine Basin, where cleat variability, and the presence of slip, suggest significant differences in fracture development compared with fields to the east.

7.4.1 Scottish Midland Valley

Much of the Midland Valley Carboniferous is coal-bearing, especially in the Limestone Coal Formation (Namurian); Westphalian Coal Measures are preserved across much of the western and central area, and in synclines in the east. The Midlothian coalfield was the only one reported on in any detail by Fox (1965), who stated that one reason for this choice was geological simplicity. The reasoning behind this statement is uncertain. This field does not have the complications of contemporaneous igneous features, and overall fault density is lower than in some other Scottish areas, but structural relationships in and around the Midlothian field are far from clear. It occupies the overall SSW-NNE-striking Midlothian Syncline, the westerly limb of which is locally sub-vertical adjacent to the Pentland Fault (see 6.6.3). Rippon *et al.* (1996) summarise the regional context. The syncline is offset eastwards from its precursor depocentre. Within the syncline, the structure is dominated by a few large arcuate normal faults, some with possible syn-depositional origins, in between which are local fault patterns suggestive of largely W-E oriented strike slip. A system of late Carboniferous quartz dolerite dykes trends W-E across the northern area of the syncline, which is itself probably a late Carboniferous or early Permian structure (Chapter 6). In Midlothian, Fox (1965) recorded a considerable number of cleat orientations, and his summary "dial diagram" is the most complex of all those in his study; this is not thought to reflect any greater diligence on the part of the data collectors. Based mainly on the Great coal (Namurian), main cleat occupied most of the NW quadrant, with records for individual mines showing particular polarities within this. Three subsidiary cleat orientations were found in places. Nevertheless, the overall result showed most readings of main cleat lying within a NW quadrant range similar to that for many English fields (Fig. 7.3) and the general impression is of a dominant regional orientation, locally modified close to faults of varying style and orientation.

Comparisons may be made between Midlothian and the eastern Fife coalfield in the Leven Syncline (Fig. 7.4). This is effectively an offset continuation of the Midlothian Syncline (see 6.6.3), but is structurally simpler: it is coincident with its precursor depocentre, and there are far fewer faults within the area mined in Westphalian coals (much of the western limb). Cleat in these was recorded by NCB geologists in the 1970's and 1980's at Seafield and Frances mines, and the results are summarised in Figure 7.4, together with Fox's and other regional data. The dominant NW cleat trend in the Leven Syncline is comparable to the main polarity in the Midlothian Syncline, and a common origin for this regional set should be expected.

By contrast, Figure 7.4 also shows a W-E striking main cleat in the Clackmannan Syncline area further west. Some cleat orientation details here, together with present principal horizontal stress, are illustrated by Boardman & Rippon (1997) and by Figure 7.5 here. In this area, the main cleat is carbonate-mineralised, and the overall W-E trend parallels the prominent normal fault set (Chapter 6); arcuate variations in the fault set are followed by the cleat. The greatest fault displacements were probably late Carboniferous, contemporary with a major growth of the basin-bounding West Ochil Fault to the north, and emplacement at depth of the Midland Valley Sill (Rippon *et al.* 1996). Perhaps the W-E cleat set here developed in harmony with the parallel faults, the mineralisation dating from the main extensional event. The generally fault-parallel cleat is locally modified immediately adjacent to some faults (of whatever displacement), the cleat apparently noding in to meet fault planes at high angles (see 7.5.5).

Elsewhere in Scotland, cleat records are widely scattered and not readily interpretable. The following data on main cleat orientation averages are known (all referred to UK National Grid). Main cleat at Cardowan (NS 66, Namurian coals) is 92°, and at Polkemmet (NS 96, Westphalian) is 30° to 60° in two different coals, at about 20m vertical interval. Local strike differences between coals were also recorded by Fox (1965) in the Wilsontown area (NS 95), and at various mines in Ayrshire and Lanarkshire. In Killoch and Barony mines in Ayrshire (NS 42), main cleat varied 80° to 120° in NCB records, with a 20° difference in polarity between different seams at Barony.

7.4.2 Northern and central England, and North Wales

As in eastern Scotland, the main cleat strike, in all the larger fields from the Northeast south to Warwickshire, lies within the NW quadrant (Fig. 7.3) with only local intra-coalfield variations. This consistency is one of the key issues that must be addressed when discussing cleat origins. Fox (1965) however noted that there was an overall tendency to a more northerly trend southwards through central England, and indeed in North Wales. This may reflect local structural control, or merely less recording. However as will be seen, there is also a swing to a more northerly trend through Nottinghamshire, with good data density. This prompts the question as to whether cleat strike varies with depth to basement, towards the Pennine Basin's southern margin, but there is no correlation between Westphalian formation thicknesses and cleat strikes.

West Cumberland and the Northeast. Apart from the overall dominance of northwesterly cleat trends, Fox (1965) also noted that higher rank coals tended to be better cleated, in terms of density of both main and subsidiary sets. (Main rank variation patterns in the Northeast largely result from late/end Carboniferous dykes and sills.) He also noted that slip was found within heat-altered coals immediately adjacent to dykes (some of which are Tertiary). No field descriptions are available, and these slips could be similar to the features of Skipsey (1958) or the polygonal jointing described for the Upper Hirst coal (see later), and may be different to slip as typically described from South Wales.

The Pennine Basin coalfields (central England and North Wales). Across much of the eastern Pennine Basin, cleat orientation records have been collated into regional maps by coalfield geologists, notably R.F. Goossens and W.H. Wilcockson in Yorkshire, and R.E.Elliott in northeast Derbyshire and Nottinghamshire. Together with some later observations, these are used in Figure 7.6 (regional pattern) and Figures 7.7 to 7.9 (local detail).

The descriptions of Fox (1965) and Corfield (1990, 1991) indicate that coal cleats are more complex in the western Pennine Basin than the eastern, and the simplest explanation for this is the generally greater structural disturbance in the west. Nonetheless, there is still a pronounced tendency for the main cleat to strike northwesterly. (This suggests that, for the eastern Pennine Basin fields, any interpretation involving correlation between the main cleat strike in Carboniferous coals, and the eastern Caledonide cleavage trend of Soper *et al.* (1987) is not straightforward. This could correspondingly require a NE-trend cleat in the western fields, sympathetic with the western

Caledonides (and also, of course, a valid inheritance mechanism.) The structurally less-deformed eastern fields are more likely to reveal clues to regional cleating history.

The distribution of observations on Figure 7.6 is determined largely by active mining areas around 1960, and there is plenty of scope for additions to the data set, although these would now have to be largely surface observations because of widespread mine closures. From this regional map, the importance of the Morley-Campsall/Askern-Spital structure can be seen in changes in main cleat strike. This major feature formed the northern boundary of the Gainsborough Trough (Kent 1966) from Dinantian to at least mid-Westphalian times, and is part of a larger lineament extending from the central Pennine Basin towards the east coast. By contrast, the Cinderhill Fault, which has some important similarities (as a sub-basin boundary fault inherited from Dinantian rifting) appears to have little effect on cleat strike. In terms of present greatest displacement in the Westphalian succession, the largest structure on this map is probably the SW-NE Don Monocline and its associated faults (Chapter 6); this also has no relationship to regional cleat strike. Many of the main faults that contribute to the general rhomboidal pattern over much of the field have a significant post-Permian component, and it is assumed that the main development of the visible Don faults post-dated most cleating.

Figures 7.7 to 7.9 illustrate particular areas of interest across the eastern Pennine Basin. The faults shown on these maps were compiled from mining plans mainly at scales of 1:10,000 and 1: 25,000, themselves derived from more detailed plans. As a generality, all faults with throws >5m are shown. The cleat data were collated originally at 1:63,360. There is some scope for inaccuracy in the re-plotting, but it is considered that accuracy is easily good enough for geological analysis. Both cleat and fault data are from a range of Westphalian A to mid-C coals; the faults are shown only from their main proving horizon. Some surface and seismically interpreted faults are shown, where well defined, where there is no mining detail. Although no horizon elevations are shown, the main fold axes are identified.

Figure 7.7 shows cleat and fault relationships in the Doncaster area. The Morley-Campsall zone includes several large arcuate faults in an overall strike slip pattern, although this is more obvious in the area northwest from that illustrated, which is chosen to show the detail of the transition from

NW-SE cleat to W-E across this zone. Figure 7.8 shows the area around Worksop and Mansfield, further south. Here, the NW trend is well-established, and seemingly unrelated overall to the fault pattern. However, given the variety of fault trends, it is inevitable that there will be some trend coincidences. Within the area of Figure 7.8, most individual faults are essentially normal (Rippon 1985), but it is probable that the overall setting is transtensional: for example, there are various areas where arrays of more NW faults lie between WNW-trending larger features, e.g. south from the Whitwell Monocline (see 6.6.2). Most of the main WNW faults and northwesterly folds are thought to be largely end-Carboniferous with a Caledonide inheritance aspect, the folds reflecting either NW-directed Variscan pressure by the Midlands Microcraton (Pharoah *et al.* 1987; Corfield *et al.* 1996) or W-E directed Stephanian compression across southern Britain (Peace & Besly 1997), or both (Chapter 6). Again, the NE faults often have a significant post-Permian contribution. The particular interests in Figure 7.9 are firstly, the apparent irrelevance of the Cinderhill Fault to cleat strike, and secondly the pronounced swing to a more northerly trend through Nottingham. This compares with a similar change in fault strike. The structural background to this NNW fault set is not yet understood, but there is evidence for local syn-depositional movement on this trend during early Westphalian C, from a gravity slide coincident with a fault tip monocline at E.453800, N.347600 (Chapter 5, and Fig. 5.12). The faults parallel to the Cinderhill Fault, southeast of Nottingham, include many intra- or post-Triassic elements.

Figures 7.7, 7.8 and 7.9, together with other regional data, show that: 1, the Morley-Campsall zone was an important boundary; 2, the northwesterly orientation of the main cleat is probably unrelatable directly to any particular fault trend, with the possible exception of the NNW set through Nottingham; and 3, there is evidence for syn-depositional movement on both that set, and the Morley-Campsall zone (but also on certain other structures, including the Cinderhill Fault).

7.4.3 South Wales and Kent

As in the eastern Pennine Basin, coal jointing maps were produced on a scale of 1: 63,360 by NCB geologists, particularly C. Parry in South Wales. Data are mainly from the Westphalian mid-A to mid-B coals with some from later horizons, including Westphalian D coals. Most data points included recordings of main and subsidiary cleat, and main and subsidiary slip. Figures 7.10 and 7.11 show regional syntheses of main cleat and main slip data in relation to some major structures, which are selected because they appear to define significant changes in jointing strikes. There are many other large structures that could be shown.

The cleat map (Fig. 7.10) is presented using rose diagrams for squares based on the National Grid, because there is much more local strike variation than found on the slip map of Figure 7.11, and much of this variation is likely to reflect very local structural control. The scatter may also reflect multiple cleat development, that is, more than one "main cleat" at a locality (R.A.Gayer, pers. comm. 1997). Variations in cleat strikes noted by Adams (1967) are well seen, particularly the dominance of the northeasterly trend east of the Neath Disturbance, and the variability of more westerly observations, with a tendency to W-E. The few observations on the south crop of the field suggest a further regional swing south of the Moel Gilau Fault; these data are close to large W-E striking Variscan backthrusts. The overall structural context is described by Jones (1989).

The geological histories of the compartmentalising structures shown on Figure 7.10 are not straightforward, but are briefly summarised. The Neath Disturbance and the Usk Anticline may represent structures inherited from Caledonian deformation (Chapter 6), with uplift on the latter strongly influencing Westphalian depositional patterns. The Neath Disturbance has been variously interpreted. According to Woodland & Evans (1964) it included a prominent sinistral strike slip element; its post-Westphalian character was thought by them to be younger than the cross faults. The Carreg Cennen and Trimsaran Disturbances are large Variscan thrust belts. The Moel Gilau Fault is now seen as a large south-downthrowing normal fault, with most displacement thought to be Mesozoic; however, it may well have originated as a major Variscan thrust. Figure 7.10 also shows the cleat locations reported on by Gayer & Pesek (1992).

Figure 7.11 illustrates the strike of main slip, substantiating the observations of Adams (1967). Main slip orientation is much more regular, compared with main cleat. East of the Neath Disturbance, a northwesterly strike parallels the main cross faults (Woodland & Evans 1964), and also parallels these to the west, where both cross faults and main slip strike are essentially N-S. Again, the Neath Disturbance is a principal compartmentalising structure. The tentative observation by Adams (1967) that the dip of slip planes tends to be greater in the east of the coalfield is not ruled out by the data, but remains uncertain.

7.5 Relationships of cleat and slip to other geological features

7.5.1 Coal lithotypes and rank

The variations of cleat frequency with coal lithologies are very well known, and common to many world coalfields. The main field distinction is between well cleated bright coals, and poorly cleated dull and cannel coals. In the NCB survey reported on by Fox (1965), cleat frequencies were scaled between <20/m (very low frequency, and typical of most thicker durains) and >160/m (very high); greatest densities were recorded in the bright coals of Kent, locally >400/m. It is assumed that Fox's scale related only to one (assumed the main) cleat set. It is outside the scope of this account to comment on the detailed petrographic relationships of cleat development; a general review is given by Spears & Caswell (1986): the present purpose is to consider particularly the field relationships, and the following points are of regional interest.

Regarding rank, the higher ranks of the Scottish Midland Valley and the Northeast fields are largely the result of local igneous intrusions, and need to be distinguished from the regional uprankings of South Wales and Kent. These latter fields have much higher cleat frequencies than coals further north, but there is not a straightforward rank relationship, as (e.g.) coking rank coals in areas devoid of intrusions, such as parts of the Pennine Basin, have frequencies comparable to those in local non-coking coals, rather than with similar ranks in South Wales. Earlier authors considered that anthracites in South Wales were not cleated. This is a view still held informally within the mining industry, but is now to be discounted geologically. Most anthracites are intensely cleated, but often highly disturbed as well. Very locally, fracture density varies rapidly in areas prone to outbursts of coal and gas (6.6.1): this is a particular issue that cannot be dealt with here.

A striking *field* attribute of South Wales and Kent coals is their overall (whole-seam) brightness compared to their equivalents in central and northern Britain. This, together with the intense cleating, and common compressional deformation, is distinctive. This brightness difference has long been recognised, albeit (it is stressed) subjectively, within the mining industry. It has usually been ascribed to upranking, but even the higher volatile coals of eastern South Wales can appear very bright. This requires formal investigation through palaeo-environmental and maceral analysis of the coals, which cannot be covered here. However, it may be noted that routine assays in the main Westphalian A/B coals rarely record prominent durains, compared with Pennine Basin fields. Although this may partly reflect recording practices, it is thought that this is a genuine geological difference in South Wales, where cannels are also relatively rare. Subtleties in depositional environment, especially a slightly higher water table, may be one reason for overall brightness. Perhaps the brightness results from a combination of lithotype characteristics and ranking processes. However the greater cleat frequency itself may promote the impression of brightness, simply by offering a greater number of reflecting fracture surfaces to an observer, while any lesser mineralisation (see below) will also have a brightening effect.

7.5.2 Cleat mineralisation

In many coalfields, cleats have prominent mineral infills. Broadly, mineralisation appears best developed in the Pennine Basin fields, and least in South Wales, a generalisation based largely on the prominence or otherwise of carbonate deposits. Spears & Caswell (1986) described the mineralisation in South Staffordshire, also noting that cleat frequency varied with lithotype and was inversely proportional to bed thickness. A general mineralising progression was identified, from early sulphides, to silicates, to later carbonates. Minerals were related to diagenetic sequences in other rocks, the result of pore fluid evolution and migration during burial history, with the coals contributing sulphur. Mineralisation was thought to have developed around a maximum of 110^{0} C, depending on heating duration. The later carbonate phase might have been coincident with stress-relieving uplift. In South Wales, there appears to be a common sequence of carbonates, oxides, and clay minerals followed by gold and base metal sulphides (R.A.Gayer, pers. comm. 1997).

In the Pennine Basin in general, carbonates are volumetrically dominant. Sulphides are important in parts of the eastern coalfields, and a relationship to the orefield hosted in the Dinantian, beyond the western outcrop of the Westphalian, has sometimes been suggested. Discussing the origins of that orefield, Plant & Jones (1989) suggested mineralisation from fluids expelled from (especially) Namurian shales during loading by Westphalian strata. The apparently poorer cleat mineralisation in South Wales is interesting with respect to the proposal by Gayer & Pesek (1992) that cleating may have aided migration of fluids expelled during advance of the Variscan nappe front. Such expulsions must have occurred, and of course fluid migration may leave little evidence via mineralisation. This issue is discussed later. Obviously, a clear distinction needs to be made between cleat initiations, fluid migrations, mineralisation, and any emphasising of joint patterns by later uplift and destressing.

7.5.3 Coalification and burial depths

There is an extensive international literature on coalification and burial depths (see, e.g. Stach 1982). A key observation for the present account is that jointing is widely reported in lignites, although some workers consider lignite jointing to be different to hard coal cleats (see, e.g., Levine 1993). However, hard coals were once lignites, and whatever the terminology, it must be assumed that early joints would now be seen as cleats, even if they did not become the main cleat. In British Carboniferous fields, this needs to be discussed in the context of cleat strike regularity and frequency through significant formation thicknesses, which contain coals over a considerable age range. For example, in the eastern Scottish Midland Valley, cleat strikes are broadly similar through a minimum stratigraphical range from Pendleian to Westphalian B (Fig. 7.1), which is locally a *compacted* thickness of >1000m. In the eastern Pennine Basin, main cleat strike and general frequency are essentially the same at any one location through a minimum duration from the mid-A to mid-C Westphalian, in a *compacted* thickness of at least 1000m in places. As the main strike from eastern Scotland to the English Midlands is consistently northwesterly, these observations combine to suggest that cleating processes were similar over 100,000's km^2, and if continuous, through a duration of at least 15 Ma (Chapter 1; Fig. 1.2).

To achieve these regularities, either the cleat sets must have been largely imprinted after burial of the entire succession, or the formative stress vectors were constant through the progressive burial depths of each horizon. The coalification jump from lignite to bituminous coal is thought to be dependent more on heating and its duration than on simple burial depth. Stach (1982) notes that this jump can be at depths between 1500m and 2600m in the Tertiary of the Rhine Graben, depending on local geothermal gradient. However, it may well be that in British fields (particularly, perhaps, in the Scottish Midland Valley, where coals of significantly different ages are present) earlier seams would already be undergoing coalification while later seams, now with the same cleating characteristics, were still capable of further compaction (Elliott 1985). It is useful to note here that, whatever the mechanism that imposed the consistent *strike* of the main cleat, both main and subsidiary cleat formation (invariably near-perpendicular to the bedding) should be seen as ultimately reflecting vertical loading.

7.5.4 Igneous relationships

While it is well known that coals are modified by igneous intrusions, there are few accounts that relate these changes to variations in the fracture patterns. In the Clackmannan Syncline, recent observations of the Upper Hirst coal (Namurian) illustrate some of these. This horizon is largely unaffected by the more regional-scale upranking that resulted from intrusion of the Midland Valley Sill (Chapter 8), but there are various smaller intra-Namurian intrusions, and also the "crypto-volcanic" hot gas phase described by Barnett (1985). On the approach to heated areas, the Upper Hirst loses its generally bright nature, and becomes very hard and dull. The regional cleat is not present, and instead a high-frequency bedding-normal fracture system is developed, often as polygonal full-seam joints. Perhaps the regional cleat developed later than the contemporary igneous activity, inhibited in its propagation through the heated and dulled coal. It could be that the mechanical properties of this dulled coal were similar to those of durains in unaffected coals; as noted, durains in all coalfields have lower cleat densities. Skipsey (1958) described slip-like fractures in higher-rank, heat-altered coals along the western margins of the Clackmannan Syncline, and it is possible that these were comparable to the polygonal jointing described here.

7.5.5 Joints in associated rocks

The regularity of cleat strike through significant stratigraphical ranges contrasts with the frequent observation that joints in associated rock, especially sandstone, are commonly oriented a few degrees different (see Ellison, R. pers comm. in Section 7.2). At a local scale, orientation changes within, say, a depositional cycle, might be ascribed to a constantly changing stress field, with the coal cleat merely one snapshot. However, it is inconceivable that stress vectors would be re-set for each successive coal. It must be concluded that orientation changes between coal cleats, and joints in the associated clastics, result either from one formative stress system producing different trends in geo-mechanically different strata, or from varying stress vectors imprinting different trends on different lithologies after formation burial. This latter case might arise if lignite/coal were more sensitive to early joint formation, thereby recording the effects of an earlier and slightly different stress regime.

Apart from these lithological variations, and the influence of specific local structure, Moseley & Ahmed (1967) showed that regional joint trends, in mainly non-coal lithologies, across northern England are essentially compatible with cleat orientations in the coals. (It is worth noting here that presently-open joints are known at depths of at least 500m in some coalfields. That these are natural and not mining-induced is evident from mineralisation of joint faces; some joints are open to several 10's millimetres. Their incidence is unknown (observational difficulties in mine-workings are common) and they have not, to the author's knowledge, ever been investigated specifically. Also within coal-bearing sequences, a variety of fractures, entirely different to the regional joint sets, are common, and result mainly from the compaction of heterogeneous sediments. These are not considered here, but investigators need to be aware of their existence.)

7.5.6 Local structure

Whatever the overall origins of cleat and slip orientations, it is apparent that they can reflect both regional, and also local, structural history. An increase in cleat frequency has long been used in mining as an indicator of fault proximity, especially where emphasised by carbonate mineralisation. Also, very local changes in cleat strike are noted adjacent to some faults of all throw sizes, with cleat strike swinging to intersect the fault plane at high angles. But neither of these relationships always hold. Commonly, there is no increase in cleat frequency; and cleat strikes may remain regional, or lie parallel to a fault.

These only occasional, but nonetheless noticeable relationships may be explained by considering fault and joint growth. Briefly, the volume changes, from regional stratigraphical thickness, that are necessary to accommodate the growth of an idealised normal fault will be dilational in the upper hangingwall and lower footwall, and contractional in the upper footwall and lower hangingwall (see 6.5.1). These volumetric changes must, at least in part, be accompanied by variations in joint characteristics, and the otherwise ambiguous mining observations on cleat densities may simply be the result of location with respect to this varying fault-adjacent strain. Regarding cleat strike changes only locally being found adjacent to faults, an immediate comparison may be drawn with the noding patterns reported by (e.g.) Rawnsley *et al.* (1992) in which joint sets converge to particular points along a fault, thought to reflect roughness during fault growth. Coalfield data are insufficient to substantiate this for local cleat swings, but such noding would fit some observations. Of course, both cleat frequency and cleat orientation changes found adjacent to only some faults could also simply mean that those faults developed mainly at a time pertinent to coal joint formation; as noted in 7.4.3, there is evidence for intra-Carboniferous movement on some faults that may have influenced more regional cleat orientation.

7.6 Regional tectonics and the origins of cleat and slip

7.6.1 Near-field, far-field and distant-field settings

At the regional scale, the compartmentalising influence of a restricted number of major structures, such as the Morley-Campsall/Askern-Spital zone and the Neath Disturbance, has already been noted. However, at the largest scale, the divide in cleat characteristics north and south of the Midlands Microcraton (Fig. 7.2) is fundamental to the understanding of cleat origins in British coalfields. At this scale, the possibility that main cleat orientation is a far-field effect, parallel to the principal compressive stress in advance of an orogenic front, must be considered. This has been proposed for various regional patterns of extensional joints, e.g. Lorenz *et al.* (1991), Bevan & Hancock (1986), and also contributes to the ranking model for South Wales by Gayer & Pesek (1992). Across southern Britain, the principal horizontal stresses for both the Variscan and the Alpine orogenic fronts were similar (Rippon *et al.* 1997); Gayer & Nemcok (1994) and Corfield *et* *al.* (1996) indicate an overall northwesterly-directed maximum compressive stress for the Variscan. However, the northeasterly cleat strikes recorded in Kent and South Wales do not fit with this, and given the proximity of these fields to the Variscan deformation front, it may be that far-field fabrics are not relevant here.

A more regular, definitive far-field signature may be looked for north of the microcraton; this must have allowed transmission of the principal horizontal stress at depth, especially if the indenter model of Soper *et al.* (1978) is correct for overall Carboniferous structural development across northern England. Cleat regularity north of the microcraton might follow from a consistently-oriented northwesterly principal horizontal stress, which is compatible with the general direction of maximum shortening proposed by Corfield *et al.* (1996). Figure 7.12 shows the late Westphalian position of the Variscan Deformation Front, the direction of maximum Variscan horizontal stress as presently understood (see Rippon *et al.* 1997), and, north of the microcraton, the average coalfield cleat orientations of Fox (1965).

Local variations such as the W-E main cleats in the Clackmannan Syncline would then represent specific structural control, sufficient to over-ride any regional stress field, at a time crucial for cleat formation. A distinction might be drawn between "far-field," and "distant-field", in which local processes may frequently dominate. Should an orogenic far-field model be the most approriate for overall main cleat orientation across Britain, then it remains to discuss further the variations in the immediate Variscan foreland, and also why only a restricted number of settings in the far-field of central and northern Britain were able to impose local cleat trends.

7.6.2 The origins of cleat and slip: a discussion

From this review of British Carboniferous data, various relationships between cleat strike and other geological factors have been identified. The main issues relating to origins are: 1, the timing of cleat initiations, and growth with respect to individual coals, and to a full coal-bearing succession; 2, cleat regularities across large areas and through significant stratigraphical ranges, especially north of the Midlands Microcraton; 3, the specific patterns to the south of the microcraton; and 4, structural compartmentalisation, both to north and south.

Two major mechanisms have been suggested that could be involved in the initiation and development of regional cleat sets. These are the tidal force mechanism of Kendall & Briggs (1933); and growth during progressive burial, with the main set orientation recording an orogenic far-field. Both of these would give a background default pattern that could be over-ridden by local structural developments of suitable magnitude and orientation (for example the major N-S extension across the West Ochil Fault, resulting in a generalised W-E cleat pattern in the Clackmannan Syncline to the south). A tidal mechanism, if valid, might of course be expected to give consistent fracture patterns well beyond the geographical and stratigraphical scope of this study. Indeed, northwesterly joints in Mesozoic rocks across southern England, would, on this interpretation, be candidates. But these were interpreted by Bevan & Hancock (1986) as an Alpine far-field effect. From observations of the present field, it is known that an essentially regular principal horizontal stress (Figure 7.5b illustrates some local modifications) can extend for 1000's km; across Britain the present regime is thought to combine residual Alpine compressional stress with continuing evolution of the NE Atlantic plates (Muir Wood 1989). Principal horizontal stress is consistent from at least the Scottish Midland Valley to the Jura (see Bevan & Hancock 1986). The simplest explanation of main cleat strikes in Carboniferous coals is that they illustrate a Variscan fabric, modified by local structural settings.

This conclusion helps the interpretation of cleat regularity north of the microcraton, but, as noted, cleats in the proximal Variscan foreland area in South Wales and Kent do not immediately fit this model. The contemporary horizontal compression vectors in the proximal Jura area are normal to the thrust front. If the main cleats in South Wales were imposed as Variscan extensional joints, they must record local kinematic variations rather than the overall northwesterly stress. Caledonide trends would already be established across South Wales, probably with deep compartmentalisation into blocks by major structures. As suggested by Gayer & Nemcok (1994), dextral transpression in South Wales may have led to stress deflection and block rotation; on a block-by-block basis, this could well explain the cleat variations described here. The most obvious candidate is the block between the Neath and Usk structures (Fig. 7.10). This would be compatible with sinistral strike slip on the Neath Disturbance. Assuming that the Moel Gilau Fault originated as a major Variscan thrust, it is interesting that main cleat strikes (east of the Neath Disturbance) tend to lie normal to it.

The South Wales discussion needs to be taken further, as the cleat there (as in Kent) is generally regarded as pre-thrusting. The proposed near-field block-rotation model would require imposition of an early cleat fabric, as the compartmentalised blocks began to respond to Variscan advance, with subsequent deformation by later, pervasive northwards-directed thrusting: a Moel Gilau thrust might well have been an earlier feature. The situation is envisaged in which an evolving compressional deformation history was reflected in progressive cleat changes, some cleat sets predating some thrusting. Careful field study of cleat and thrust geometries would be required to resolve these issues. Especially when considering coals further north in Britain, including the Namurian coals of Scotland, it may well be that cleat initiation timings differed regionally, although default orientations were similar, given a common far-field origin. Perhaps the broad but noticeable change in strike of the main cleat, from near N-S to northwesterly, north across the Pennine Basin (Fig. 7.12) is simply a reflection of a progressively anticlockwise swing in principal Variscan stress direction, the northwesterly trend being the latest.

The development of cleat in coals representing at least 15 Ma would (in the far-field model) be through progressive loading by the sedimentary column (giving sub-vertical cleat sets) across which a NW-directed principal stress was consistently operating (giving the default strike). The further north, the greater the scope for local structural over-rides there would have been, particularly in the Scottish Midland Valley with its well-attested syn-depositional movements. (Of course, situations might arise in which a local structure is itself reactivated by the orogenic far-field stress, which would not strictly be an "over-ride".)

Apart from the distant Scottish fields, there is also the regionally significant variation in main cleat strike north of the microcraton along and north of the Morley-Campsall/Askern Spital zone. Although data are sparse here, there appears to be a large area which includes significant W-E structures (including the major Coxwold-Gilling fault system to the north of Figure 7.6). As noted earlier, W-E strike slip fault zones are inferred in this part of Yorkshire. The background to this different structural setting remains uncertain. The W-E directed Stephanian compressional event of Peace & Besly (1997) gives one possibility for developing a W-E fabric: perhaps the block between the Morley-Campsall and Coxwold-Gilling zones was already responding to this, sufficiently to over-ride a Variscan far-field effect at a time pertinent to cleat initiation.

It remains necessary to discuss regional slip orientation in South Wales and Kent. As noted, main slip strike is quite regular, and closely follows the strike of the cross faults, whether northwesterly, east of the Neath Disturbance, or northerly, to the west. The geological history of these faults is debated. Woodland & Evans (1964) considered them to have been developing during folding in the coalfield syncline (although later than some thrusts) and probably pre-Triassic. Jones (1989, 1991) suggested they originated as strike slip structures lateral to ENE-WSW thrust frontal ramps, later reactivated as extensional faults; some may have been syn-depositional. Whatever their origins, many now appear to be relatively simple, large normal faults, and main fault growth must represent a post-Variscan extensional phase (presumed contemporary with either the early Permian extension inferred for the Pennine Basin, or with the widespread Triassic rifting, see Chapter 6). Perhaps the slip fabric developed beneath a significant loading of Variscan thrust sheets. If this were the case, and the slips are related to cross fault development, then it is likely that main cross faulting was early Permian, rather than Triassic, i.e. before significant erosion of the overburden.

7.7 Conclusions

Of the various scales at which coal joints can be investigated, the regional is essential for any understanding of the origins of these fabrics. Perhaps because of the particular mechanical attributes of the peat/lignite/coal series (Stach 1982), joints in coal can be very well developed, and sensitive to the interplay of local, and distantly-generated stress vectors. They may also develop slightly earlier than joints in associated clastic rocks. Most cleats are likely to have formed at depths at which coalification was becoming advanced (say, >1000m). The generally sub-vertical, orthogonal cleat sets, and the specific strikes of these, will result from interaction of vertical stress (representing depth of burial of dewatering, compacting coals) with horizontal stress vectors (representing regional and local tectonic developments). The most straightforward explanation for main cleat orientations is therefore that these record the Variscan near-field, far-field, and distant-field stress, sometimes moderated or over-ridden by more local structural controls. The variations, both regional and adjacent to specific structures, suggest deep crustal compartmentalisation across Britain through the later Carboniferous.

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7.9 Figure captions

Figure 7.1 Generalised locations and stratigraphical ranges of British Carboniferous coalfields.

Figure 7.2 Tectonic framework of the coalfields: main structural elements.

Figure 7.3 Typical cleat orientation averages based on Fox (1965) with some later additions.

Figure 7.4 Cleat trends and structural features in the Scottish Midland Valley.

Figure 7.5 Cleat trends and present principal horizontal stress direction in the Upper Hirst coal, Clackmannan Syncline (from Boardman & Rippon 1997).

Figure 7.6 Generalised cleat trends and selected major structures, eastern Pennine Basin.

Figure 7.7 Cleat trends and fault patterns, Doncaster district.

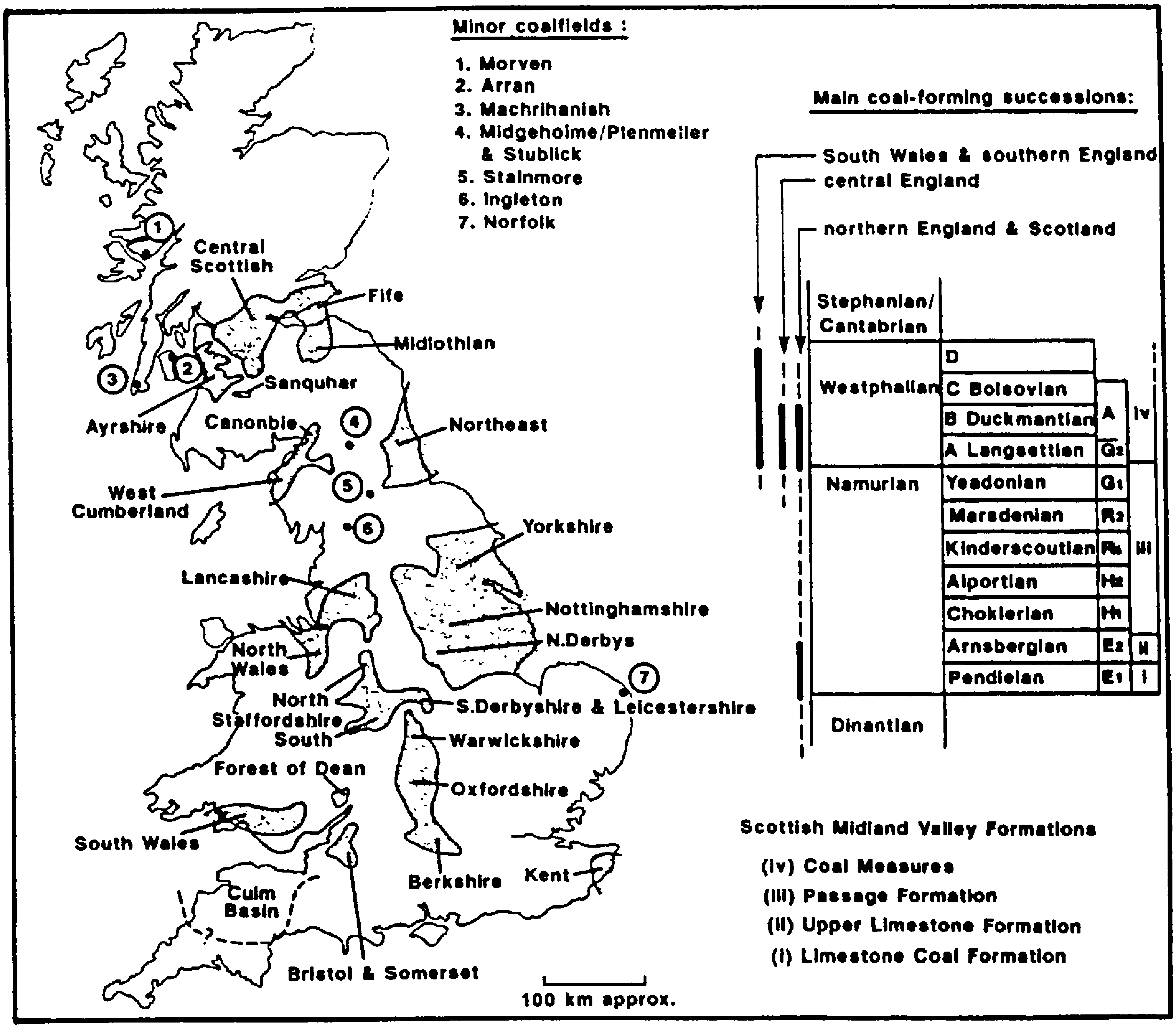
Figure 7.8 Cleat trends and fault patterns, Worksop district.

Figure 7.9 Cleat trends and fault patterns, Nottingham district.

Figure 7.10 Cleat trends and selected major structures, South Wales.

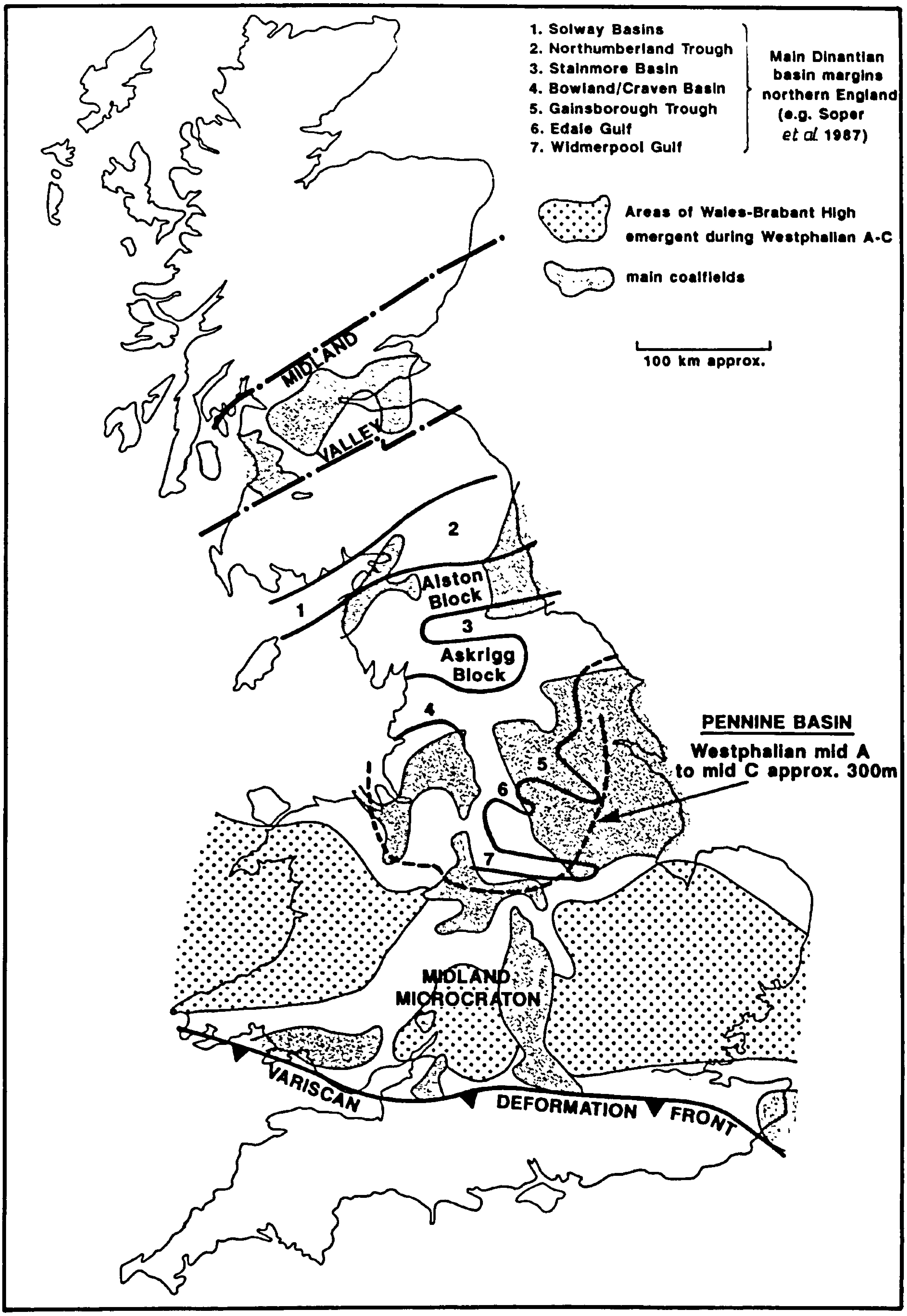
Figure 7.11 Slip trends and selected major structures, South Wales.

Figure 7.12 The end-Carboniferous location of the Variscan Deformation Front, likely principal horizontal stress direction, and orientation of main cleat north of the Midlands Microcraton (based on Rippon *et al.* 1997).



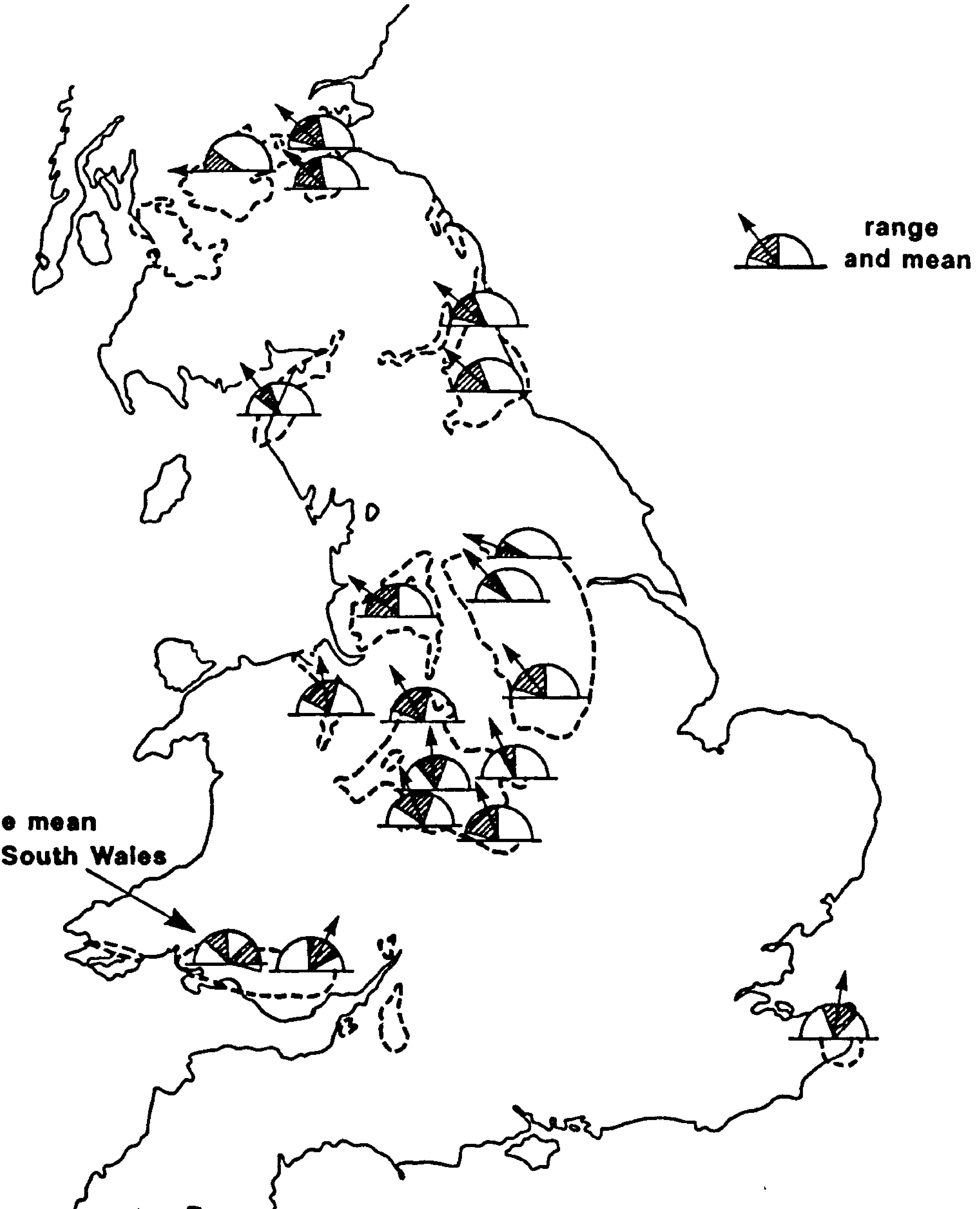
Location and stratigraphical summary of the Upper Carboniferous coalfields

Fig.7.1



Tectonic framework of the main Upper Carboniferous coalfields

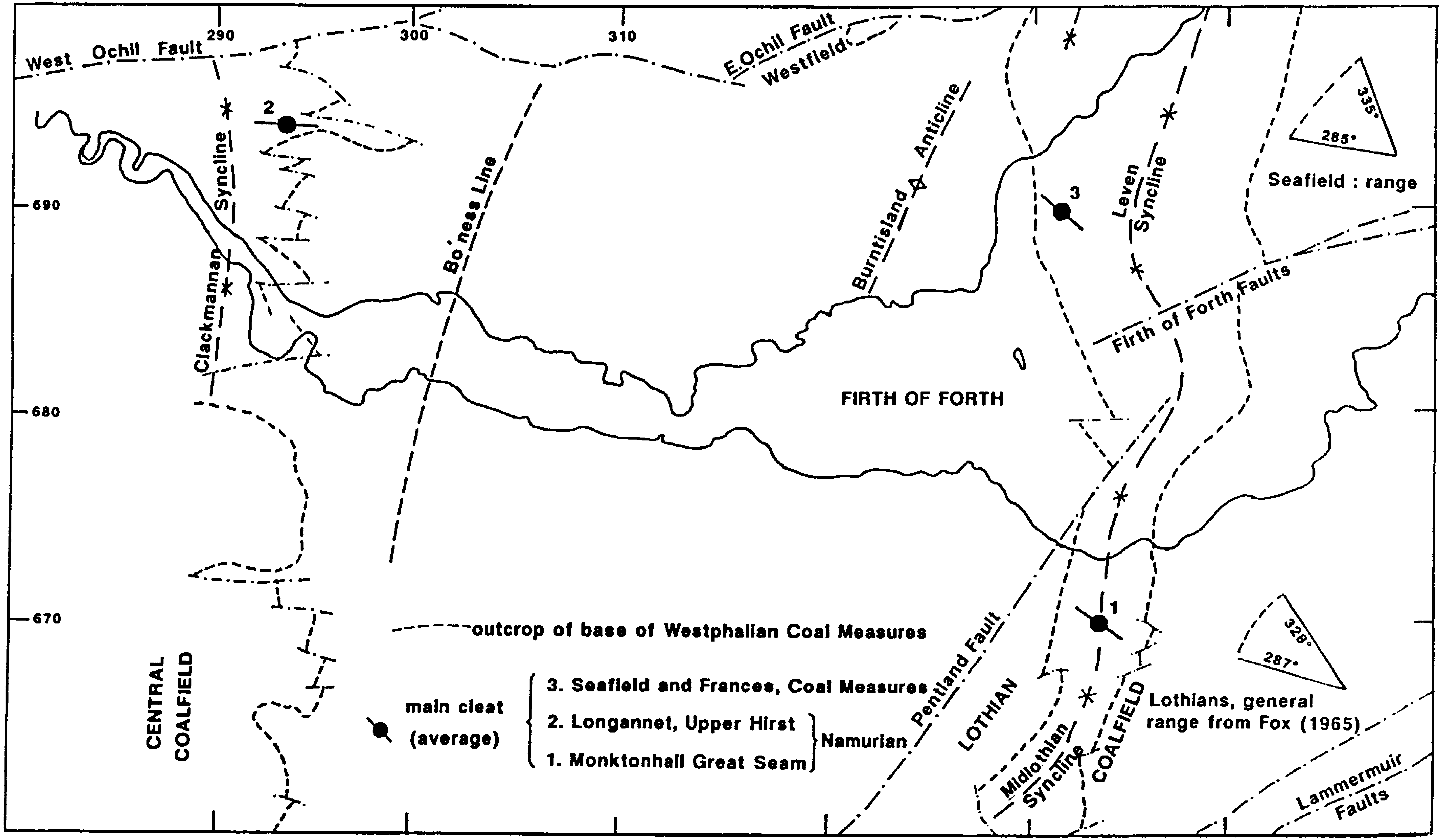
Fig.7.2



Normal range of main cleat strike in British coalfields

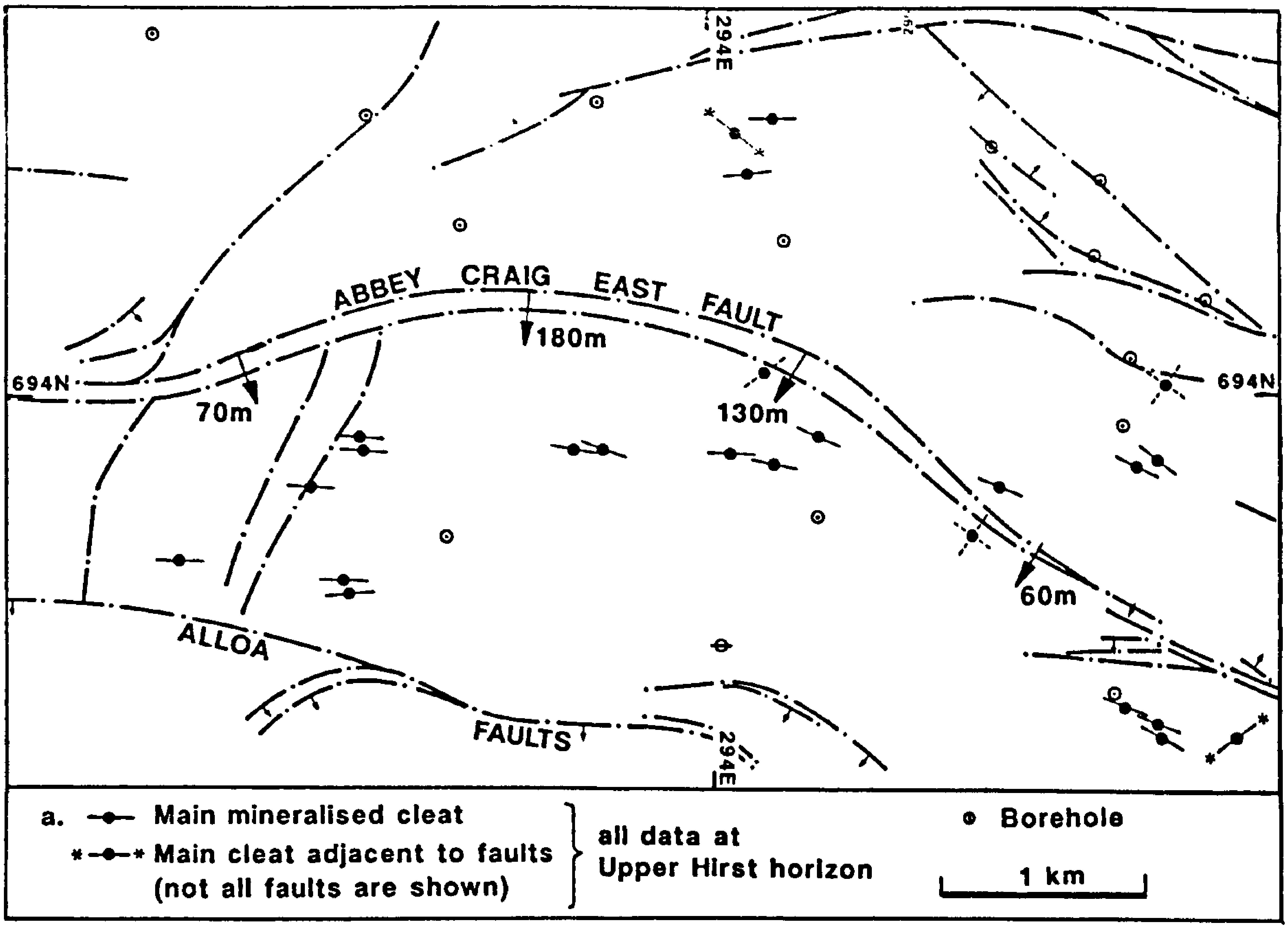
After Fox (1965) with some later additions

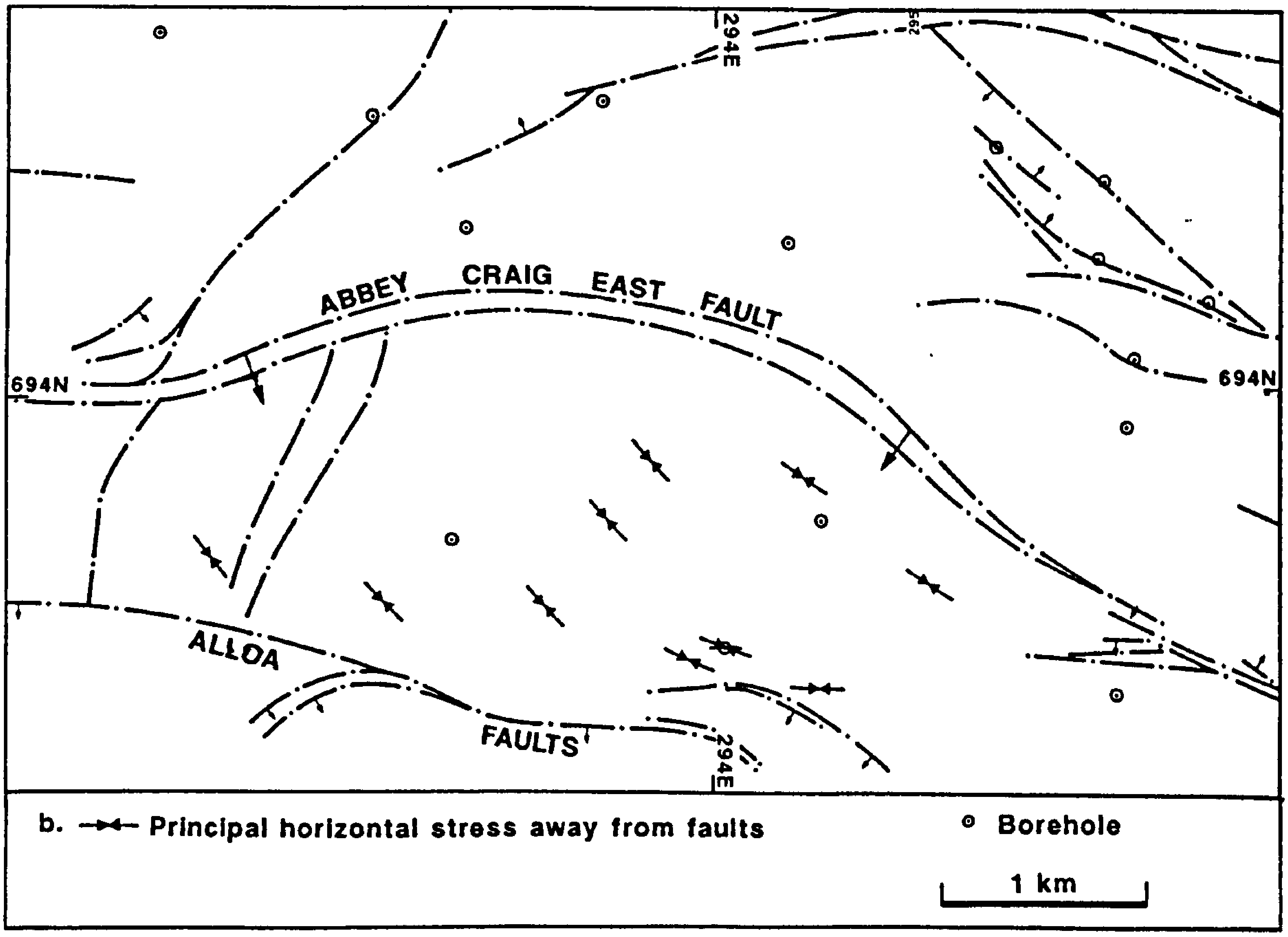
Fig.7.3



CLEAT TRENDS, SCOTTISH MIDLAND VALLEY

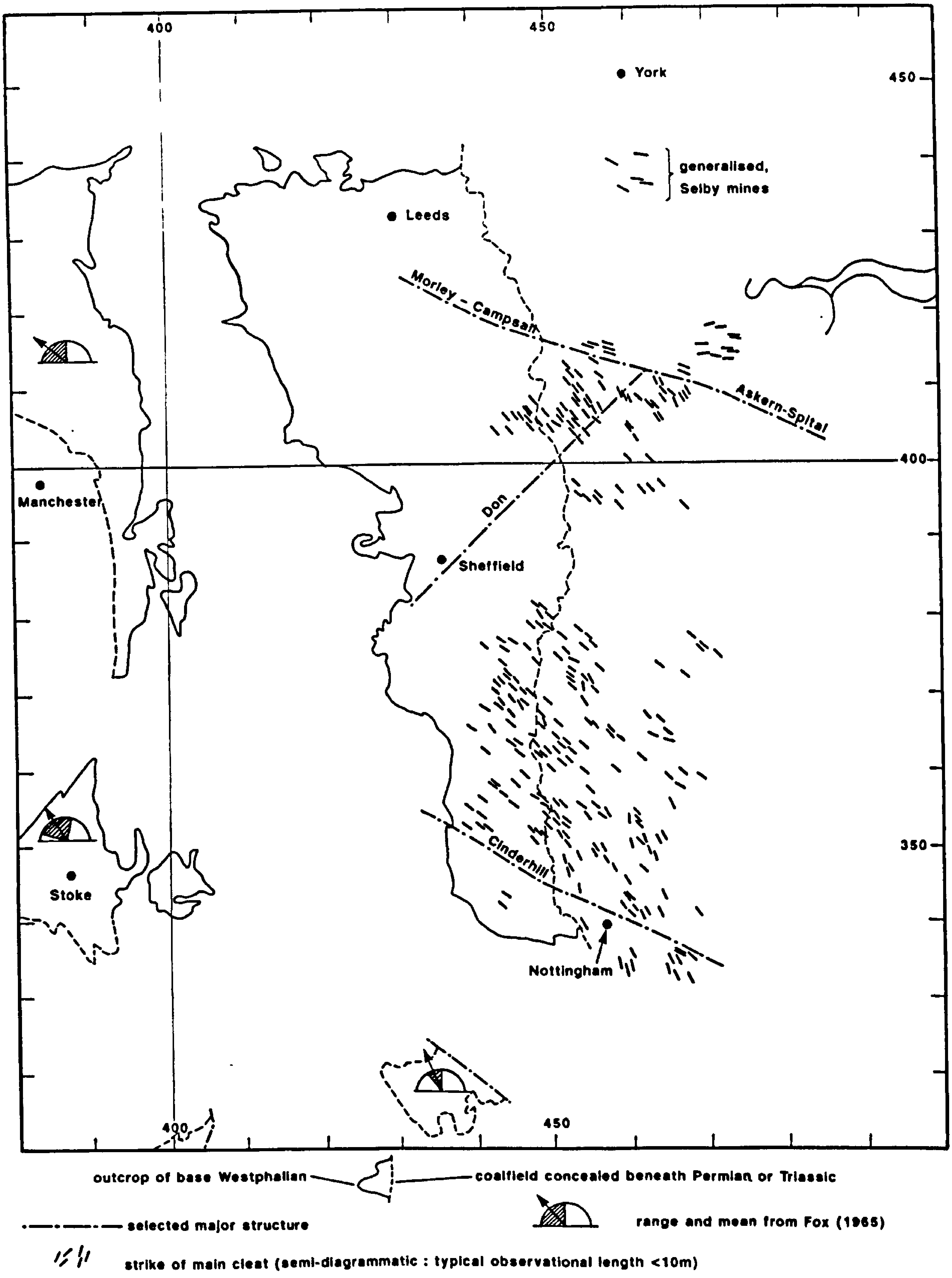
Fig.7.4





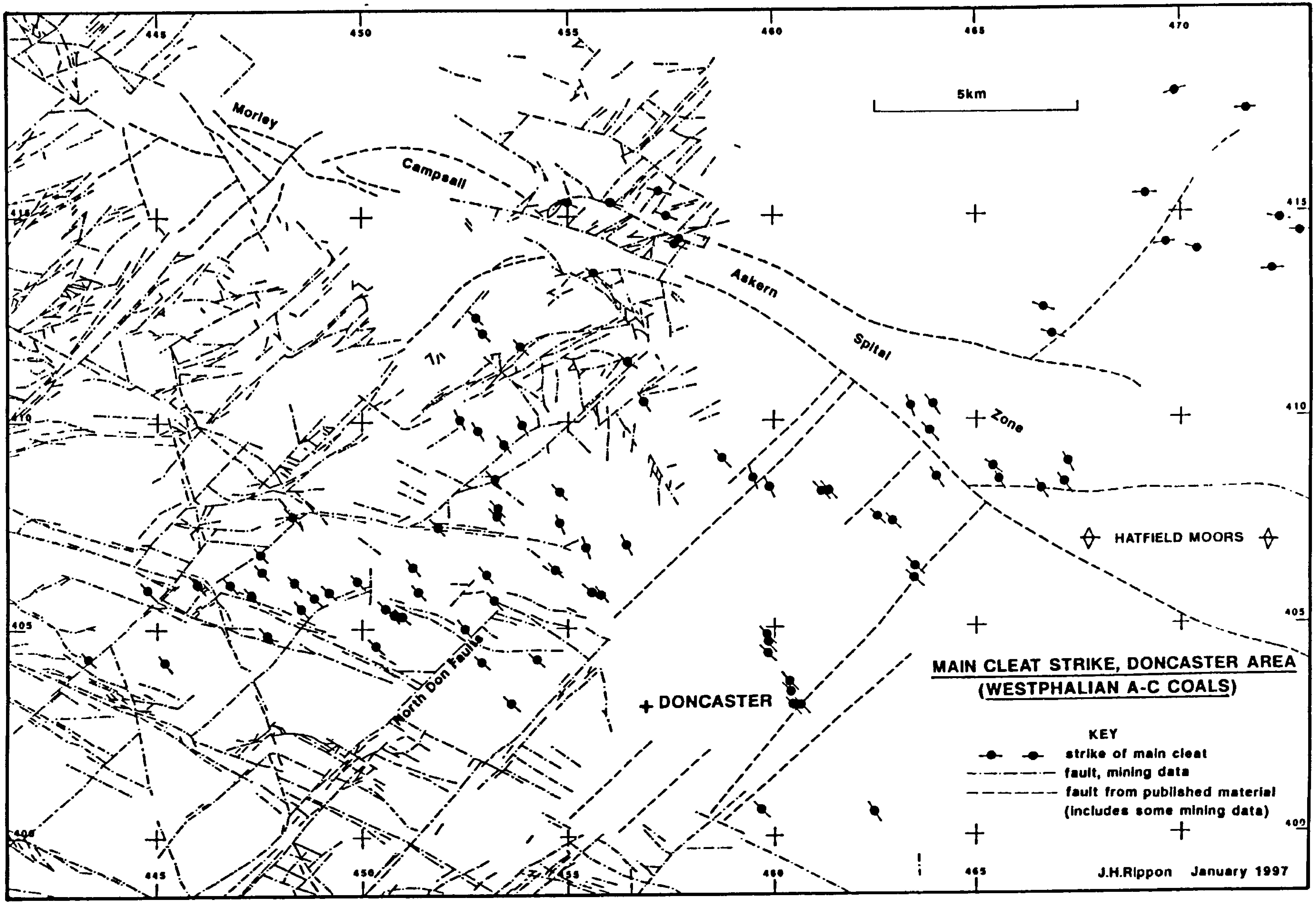
CLEAT (a) AND PRESENT STRESS (b) IN PART OF THE CLACKMANNAN SYNCLINE

Fig.7.5



<u>Orientation of Main Cleat, Pennine Basin Westphalian</u>

Fig.7.6



MAIN CLEAT STRIKE, DONCASTER AREA
(WESTPHALIAN A-C COALS)
KEY
strike of main cleat
fault, mining data
fault from published material
(includes some mining data)
J.H.Rippon January 1997
5km
HATFIELD MOORS
DONCASTER
Morley
Campsall
Askern
Spital
Zone
North Don Faults
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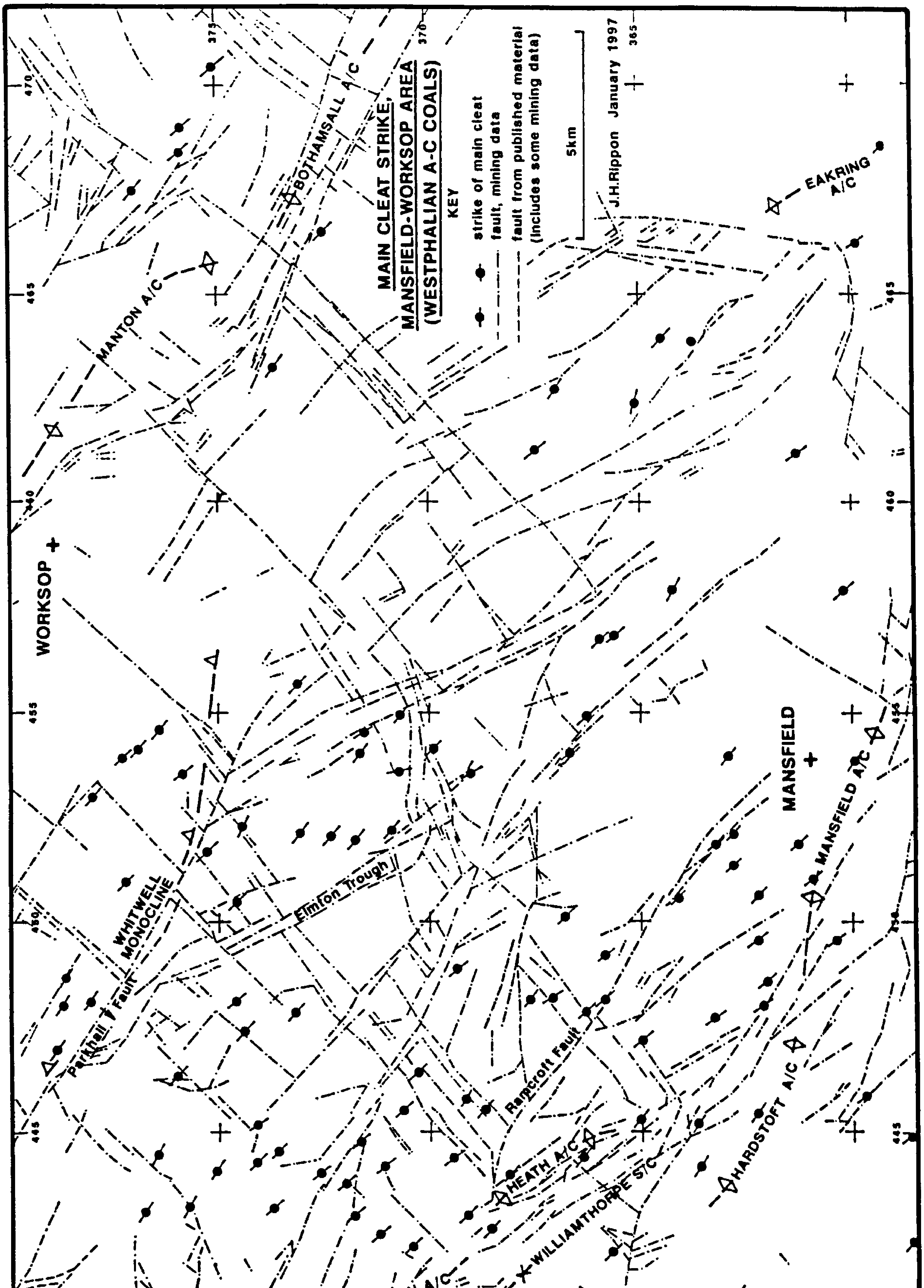
Fig.7.7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MANSFIELD-WORKSOP AREA
(WESTPHALIAN A-C COALS)
KEY
strike of main cleat
fault, mining data
fault from published material
(includes some mining data)
5km
J.H.Rippon January 1997
WORKSOP
MANSFIELD
MANTON A/C
BOTHAMSALL A/C
EAKRING A/C
WHITWELL MONOCLINE
Elmton Trough
Parkhall Fault
Ramcroft Fault
HEATH A/C
WILLIAMTHORPE S/C
BRIMMINGTON A/C
HARDSTOFT A/C
MANSFIELD A/C
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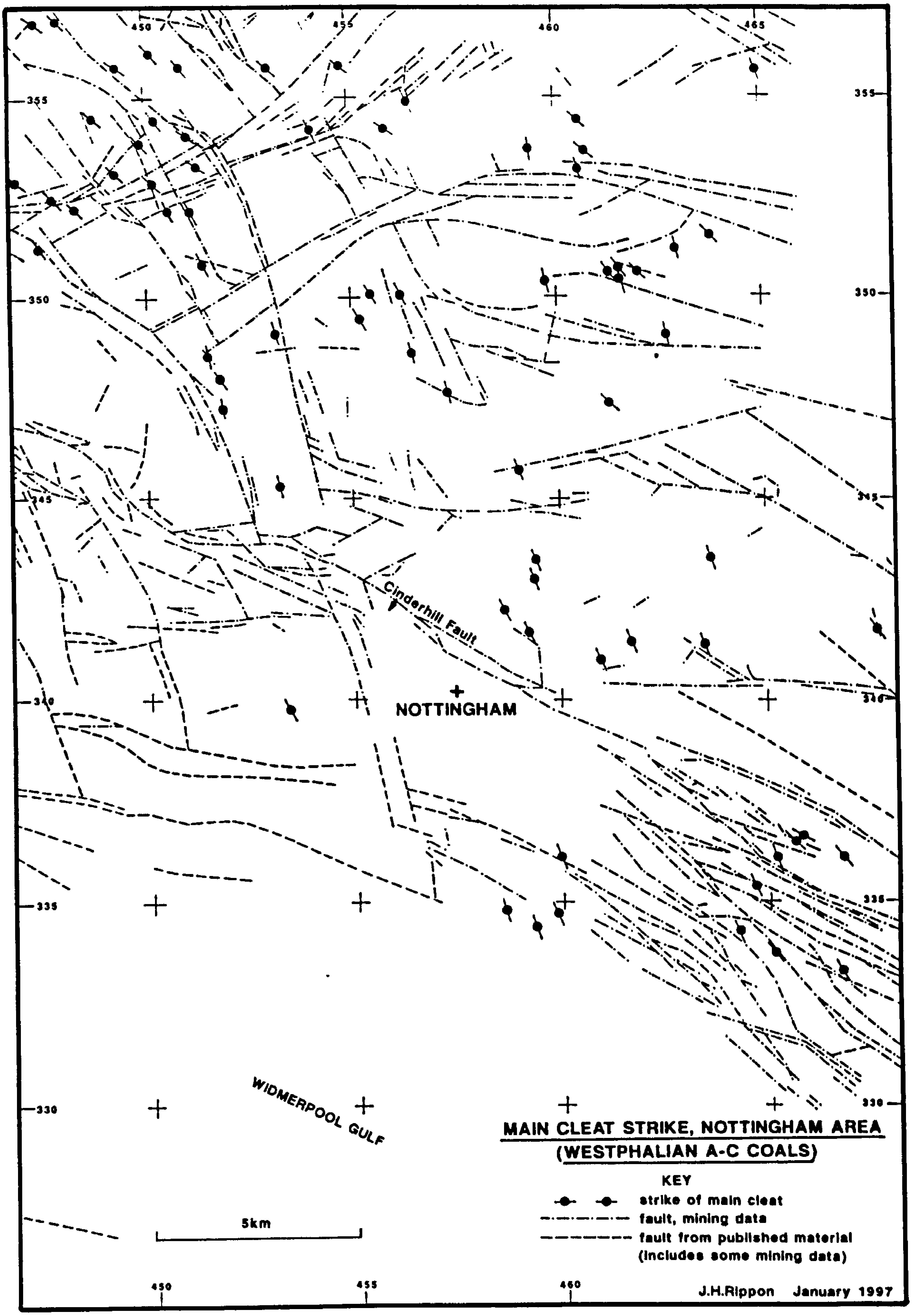
Fig.7.8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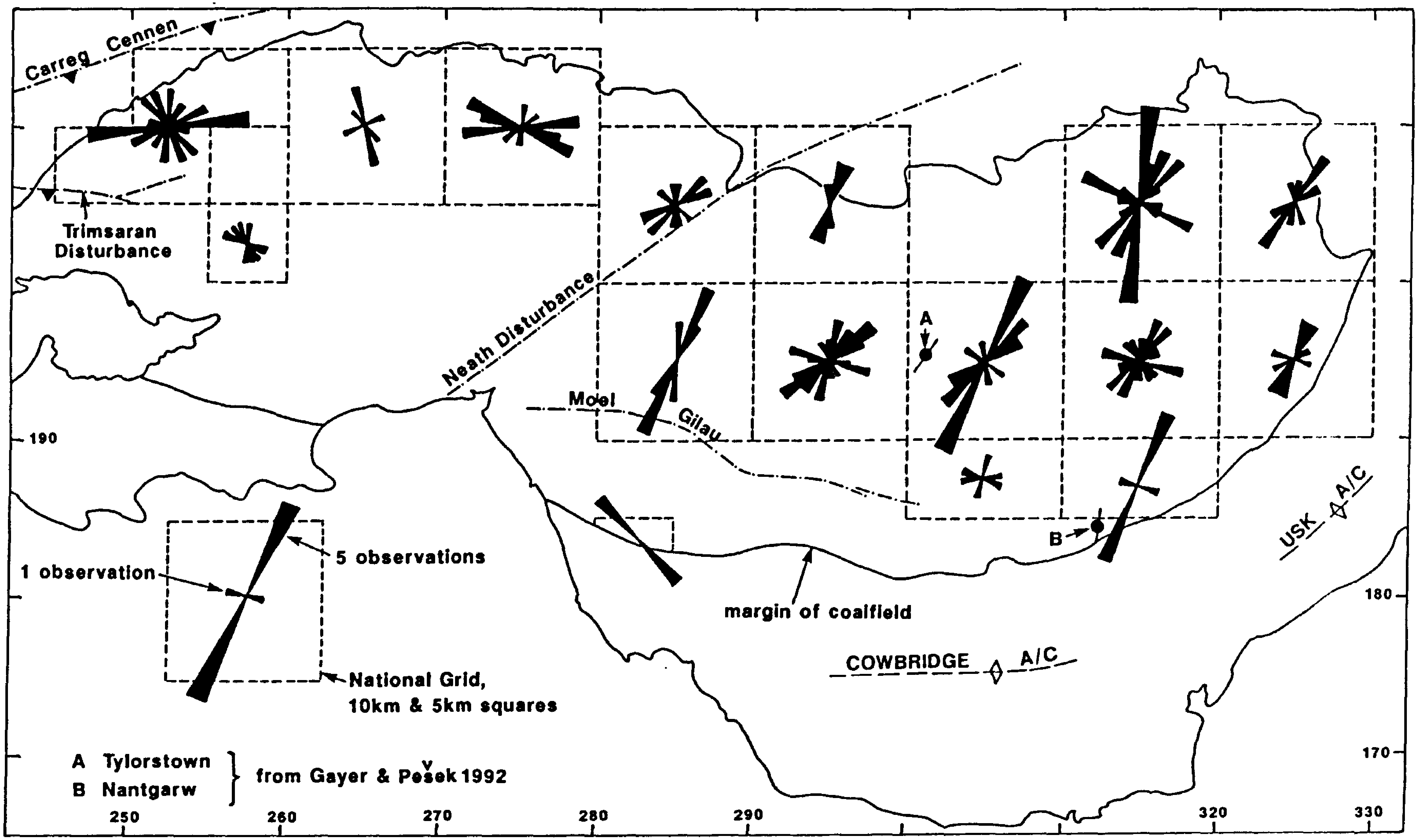
Cinderhill Fault
NOTTINGHAM
WIDMERPOOL GULF
MAIN CLEAT STRIKE, NOTTINGHAM AREA
(WESTPHALIAN A-C COALS)
KEY
strike of main cleat
fault, mining data
fault from published material (includes some mining data)
5km
J.H.Rippon January 1997

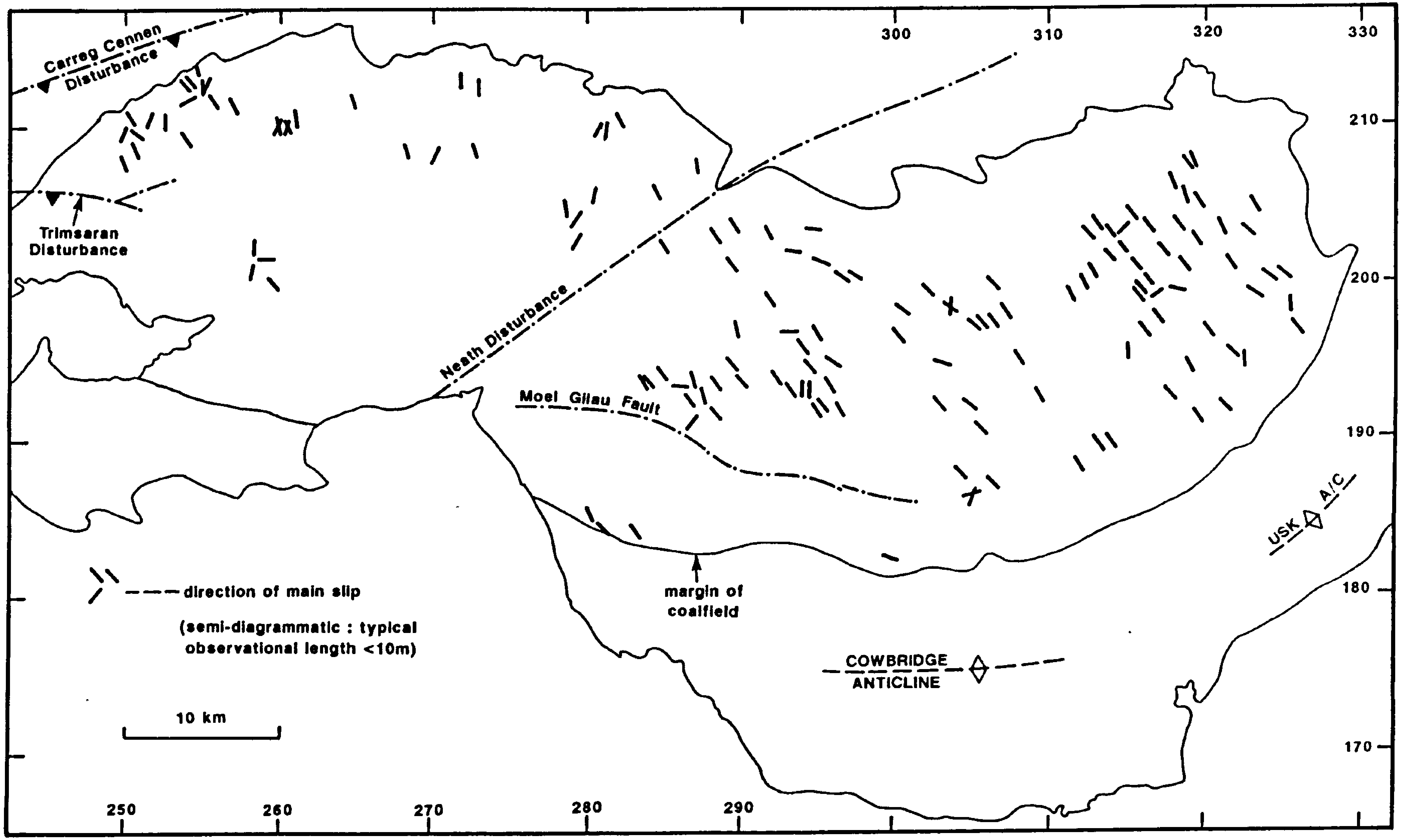
Fig.7.9



ORIENTATION OF MAIN CLEAT, SOUTH WALES

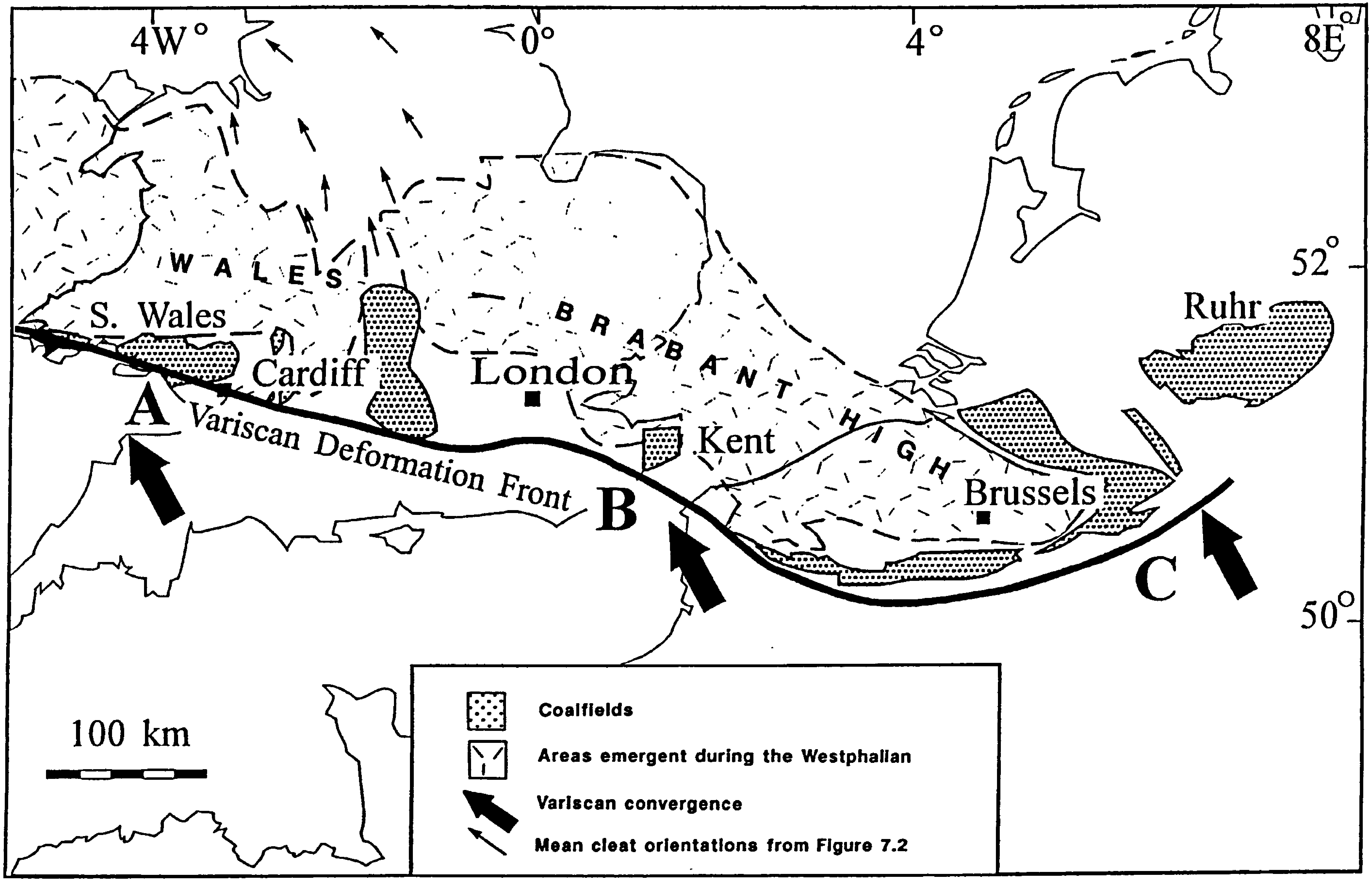
(WESTPHALIAN A-C COALS)

Fig.7.10



ORIENTATION OF MAIN SLIP, SOUTH WALES
(WESTPHALIAN A-C COALS)

Fig.7.11



CLEAT ORIENTATION, PENNINE BASIN, AND DIRECTION OF VARISCAN CONVERGENCE

Fig.7.12

CHAPTER 8

SOME IGNEOUS RELATIONSHIPS IN BRITISH CARBONIFEROUS COALFIELDS

Abstract: *Some field relationships of igneous rocks are briefly reviewed using recent mining and exploration data. Syn-depositional volcanism is discussed with respect to vent location and ash fall mapping. Sills are considered for their varying effects at different intrusion levels, and an initial model for some sill migrations during fault growth is proposed. Relationships between dykes and faults are discussed. In central and southern England, Westphalian igneous activity remains poorly understood, particularly in the Oxfordshire province, for which a mechanism is suggested.*

8.1 Introduction

British Carboniferous coalfields (Figs. 8.1, 8.2) include a wide range of igneous features, especially in the Scottish Midland Valley, where the study of igneous geology had many of its roots. In the Midland Valley, there are numerous syn-depositional intrusions and volcanic suites, and large-scale end-Carboniferous quartz dolerites, together with Permian and Tertiary activity in the west. End-Carboniferous and Tertiary intrusions are also found in the Northeast field of England (with some Tertiary dykes as far south as Staffordshire). Westphalian igneous features, other than ash-fall tonsteins, are largely absent in coalfields to the south with the following exceptions. 1. Syn-depositional volcanism and small sills are known along the southern parts of the Pennine Basin; the Calton Hill vents (Kirton 1984) of Staffordshire indicate late Westphalian volcanism within 30km of the (Westphalian A to mid-C) Pennine Basin depocentre. 2. Sills, basalts and agglomerates are found in the later Westphalian successions of Oxfordshire (see later). 3. In the area around the South Wales coalfield, there are various small dykes and a neck, thought to be Carboniferous, although field relationships are uncertain (e.g. Francis 1970).

As mining is now concentrated in areas and successions that are less prone to igneous complications, there has been only local study of igneous relationships by mining geologists in recent years, even in Scotland. However, there is a large literature; Francis (1991) provides an introduction and extensive bibliography. It is not the intention here to review this literature, but to develop selected strands of interest from recent work that can complement existing publications.

8.2 Syn-depositional volcanism

In British coalfields, syn-depositional volcanism is largely confined to the Scottish Midland Valley, the southern margin of the Pennine Basin, and across the Wales-Brabant High in Oxfordshire, the high being largely emergent during main Westphalian deposition (Fig. 8.2), and incorporating the Midland Microcraton (Corfield *et al.* 1996). Chapters 5, 6, and 7 discuss the regional structural context. In the Midland Valley, volcanism persisted through much of the Carboniferous, although main Westphalian activity was confined to eastern Fife. In the southern Pennine Basin, Westphalian volcanism perpetuated some earlier Carboniferous locations, continuing mainly into Westphalian B, although locally through to Westphalian D times (Kirton 1984). The widespread Oxfordshire province (later Westphalian C to D) comprises volcanic rocks with some intrusions. The southern Pennine Basin igneous province is much less reported in the literature, compared with that of the Midland Valley, and the little that is published on Oxfordshire igneous features (e.g. Poole 1977) largely predates extensive exploration undertaken in the later 1970's and 1980's by the National Coal Board (NCB). A detailed re-interpretation of the Westphalian igneous rocks of central England is now needed, but this is beyond the scope of the present account.

Recent mining data in Scotland have not added significantly to existing knowledge, apart from the identification of a likely Namurian vent at Tillicoultry borehole (Fig. 8.3). This is interesting as it lies close to the contemporary Kincardine Basin depocentre, analogous to the Westphalian vents in the Leven Syncline in eastern Fife. Francis (1991) rightly noted that Scottish volcanic centres were concentrated on palaeo-highs rather than in sub-basins, but this is not exclusive. Tillicoultry borehole indicates vent proximity because of thick agglomerates, steep dips, and highly fractured ground; the hole terminated in a basalt (or possibly a sill intruded into the near-surface) which is not known in other nearby provings. The Upper Hirst coal (Fig. 8.3) is anomalously high in sulphur here (Chapter 4), perhaps through post-eruptive fluid flow; main venting is thought to have been late in the Upper Hirst/Plean 1 sequence. This interpreted vent is located on the.Coalsnaughton Fault, considered to represent a deep fracture (Rippon *et al.* 1996). Tuffs at the sub-Plean 1 horizon are relatively thick in other boreholes close to this fault, and there may be further minor vents. In principal, there is no good reason why vents should not locate in depocentres, so long as there is an attendant deep fracture in tension.

Relative timings, and correlations of vent agglomerates and ash falls can be achieved where there is good borehole control. Ash falls are much easier to map than vents, which would require a very high data density for full mapping. Figure 8.4 shows five tuffaceous beds across the Kincardine Basin, revealed by the many boreholes to the Upper Hirst coal. A sixth is known locally in the Castlecary Limestone, but this is commonly eroded by palaeo-channels, and the ash is ummappable. There is no good evidence for later syn-depositional volcanism in this basin. The mappable limits of these five ash beds will be less than their actual extents, but they are probably less extensive than that mapped by Francis *et al.* (1968) in the Westphalian A succession east of Nottingham, which was referred to at least three vents. It is inappropriate to draw firm conclusions on wind directions from any of these ash falls, but all are compatible with easterlies.

In the eastern Pennine Basin, it is sometimes possible to relate certain tonsteins in coals to mappable tuffs at the same horizon, and over relatively short distances (<25km). These are the basic tonsteins of Spears & Kanaris-Sotiriou (1979), discriminated on geochemical and mineralogical grounds from those related to acid volcanic ash. The latter tonsteins are those which give high peaks on gamma logs, and are thought to represent distant volcanism, giving continental scale ash falls (Rippon & Spears 1989). The sub-Clowne tonstein (Westphalian B), described by these authors was variously preserved across a range of depositional environments, and illustrates the difficulties of using such features for correlation.

8.3 Sill emplacement: some details and a discussion

8.3.1 Some effects of shallow sill emplacements

The effects of sill emplacement on associated strata will depend upon their lithologies, the size and composition of the intrusion, the interval between a sill and any specified horizon (usually a coal), the thickness of contemporary overburden, and local structure. Many syn-depositional sills, both in the Scottish Namurian and the southern Pennine Basin Westphalian are thought to have been intruded beneath shallow cover into poorly-compacted, and only partly dewatered sediments, and some sills are difficult to distinguish from lava flows.

The overburden thickness may be a key factor in the distribution of certain quasi-igneous disturbances in the Upper Hirst coal of the Kincardine Basin. In the east of the basin, the coal is frequently disrupted by small fractures and country-rock infills. Barnett (1985) showed that many of these could be interpreted as ring and radial fracture patterns associated with crypto-volcanic centres; his suggested centres have not been proved by subsequent mining or exploration, but, as they would lie some distance below the mined horizon, this is only to be expected. After more than 10 years of further mining, his overall model remains valid. However, there are many other small (commonly a few m^3) "intrusions" within the coal, described in mining reports (following Francis 1957) as non-igneous tuff (NIT) which are distributed more widely and apparently without reference to Barnett's (1985) centres.

These are invariably irregular masses of sandstone, often dark grey and very well-cemented, locally with bedding laminations near the margins, which tend to be very irregular and micro-faulted. Adjacent coal is dulled, and may include the whole-seam polygonal jointing that can be found in locally-heated seams (see 7.5.4). The distribution of these more widespread NIT masses correlates with an underlying sill rather than with any known or suspected vents or crypto-volcanic centres. Across the area characterised by these, a dolerite lies some 60m to 80m below the coal. This was identified by Francis & Walker (1987) as the western part of their wider Oaklands-Kinnedar-Parklands (OKP) sill which lay between the Abbey Craig and Clackmannan Faults. (Note: The Abbey Craig Fault of these authors is now known in mining documentation as the Langfauld Fault (Chapter 5, and Fig. 5.9), separate from the Abbey Craig structure of the Stirling district; it is also doubtful if their Clackmannan Fault is kinematically related to the structure of the same name further west; but these comments do not affect the validity of their conclusions.)

In the area relevant to Upper Hirst mining (Fig. 8.5), the OKP sill is proved by the occasional boreholes, notably Parklands, but may also be traced on some surface reflection seismic profiles. To the north, in the Solsgirth and Dollar area, Barnett (1985) suggested that numerous small disturbances of the coal reflected emplacement of a sill that was often <5m below. This is thought to be part of the Caimfold-Dollar-Tillicoultry (CDT) sill of Francis & Walker (1987), who considered it not linked to the OKP sill because of zero sill isopachs and petrographic differences, and thought that it was emplaced with very little overburden. No significant NIT masses are recorded in the Upper Hirst coal above the CDT sill.

The difference between widespread NIT above the OKP sill, and essential absence above the CDT, may be explained by differences in intrusion volatiles, and overburden during emplacement (Fig. 8.5). It is suggested that, with <10m overburden, a sill could readily de-gas, whereas at depths of >50m, de-gassing would be constrained, leading to explosive venting of hot fluids, the coal hosting mobilised and originally uncemented sediment, later strongly cemented by localised diagenesis. There would be a depth below which a sill would have no disruptive effect on an overlying coal, the greater interval (?>100m) combining with progressive lithification of the sediments, to give a situation in which de-gassing occurred mainly where the sill encountered contemporaneously available faults (e.g. the Langfauld and Abbey Craig faults, Chapter 5).

Francis & Walker (1987) considered that, under certain circumstances, sill magma migrated gravitationally to contemporary lows, with an implication that little lithological trace between destination and source might be left, where there was only a limited supply of magma. This leads to some ambiguity when considering mapped coincidences between the OKP sill and the NIT, as it would follow that some NIT masses would lie above areas where the sill cannot now be easily identified. Nevertheless, it is considered that mapped coincidence is sufficiently well-defined. Francis & Walker (1987) also considered that their boundary faults were syn-depositional; this is supported by recent observations of increased NIT distribution adjacent to some large faults, particularly the Abbey Craig Fault (Fig. 8.5; and see 6.5.1).

8.3.2 Sill migrations and fault zones

Assuming that Francis & Walker's (1987) assessment of these faults affecting Namurian sill distribution is correct, it needs to be recognised that they would not have had the displacement dimensions now seen: most displacement is late/post Westphalian (Rippon *et al.* 1996) and contemporary throws would have been much smaller, especially at shallow depths. At that stage of structural evolution, the existence of a simple discontinuity may be an important factor in sill distribution (of course, the existing fault might be large at depth, and itself a pathway for magma), but a different situation might apply where a sill approaches a fault that is already large (10's to 100's m throw) and which lies through more compacted sediments.

It is well known that sills use faults for risers, but it is interesting why some faults are used, and not others. A Scottish example is illustrated by Skipsey (1958), where a 90m thick dolerite sill uses the Abbey Craig Fault (of Stirling) and a nearby minor structure, but not the parallel but large Crook and Blackgrange Faults. Figure 8.6 suggests a mechanism for some cases. For an idealised normal fault, the dilated upper hangingwall and lower footwall zones (6.5.1) might offer preferred migration options compared with corresponding contractional zones adjacent to the fault. In detail, much would depend upon magma forcing pressures, and the degree to which the full fault plane extent itself remained available as a magma pathway. And obviously, the faulted volume might have undergone burial history which significantly modified the nature of formerly dilated zones. In the case illustrated by Skipsey (1958), it is likely that the faults in question were achieving maximum displacements around the time of sill emplacement (end-Carboniferous; Rippon *et al.* 1996), and their interacting stress effects may well have influenced sill pathways.

In the related case of the regionally-important West Ochil and Arndean faults to the north of the Kincardine Basin (Fig. 8.7), these fault planes are also now occupied in places (perhaps extensively originally) by end-Carboniferous quartz dolerites (Francis *et al.* 1970). These were interpreted by Rippon *et al.* (1996) as contemporary with the main extensional developments of these structures. Related minor quartz dolerite sills are known very locally, adjacent to the Arndean Fault, where they are intruded some 100's metres into the hangingwall around the Castlecary Limestone horizon at Castlebeg and Arndean boreholes. These two major faults seem to have been used as risers from the major Midland Valley Sill at depth; the sills at the two boreholes are however only very local. Developing the migration model outlined above, they may simply reflect the distance to the limit of effective hangingwall dilation during main phase fault growth. Similar small sills are not proved in the hangingwall of the West Ochil Fault, but Westphalian coals are significantly devolatilised at Dollar (Fig. 8.7) and Skipsey (1958) descibed proximal heat alteration of the Coalsnaughton Main coal (Westphalian A) there; it is thought that the areal extent of the upranked coals is too great for the fault plane dolerite itself to have effected the metamorphism. It is interesting to note that the mapped extent and field relations of the Whitwick Dolerite (Permian; Worssam & Old 1988) in the hangingwall of the major Thringstone Fault in Leicestershire show comparisons with the Ochil and Arndean fault plane and hangingwall dolerites, as described here.

8.4 Dyke disposition: a discussion

Dykes present a wide range of problems to mining; apart from physical disruption of coal, they may also be a safety concern, e.g. with water retained in voids, or with gas held at pressure, and prone to destructive outburst. The latter situation may occur where heated coals in the dyke walls are hardened, and not fractured by subsequent development of the regional cleat (see 7.5.4), trapping discrete overpressured reservoirs.

Dykes within the coalfields are extensively reported, usually as very detailed field descriptions, or at the regional tectonics scale (Francis 1991). But few studies attempt to relate dyke disposition to structure at the intermediate, kilometric scale, although some close dyke/fault relationships are reported (e.g. Fowler 1936, p.123, on the Causey Park Dyke, Northumberland). It is interesting that some dykes tend to occupy separate fracture systems compared with close and parallel faults, where there is a reasonable likelihood that the faults were pre-existing. Presumably faulting that developed parallel to existing dykes generated new fractures, at least partly because of induration and cementing of the dyke walls. Different mechanisms would anyway be needed for regional, vertical dyke fracturing, compared with those required for generating fault planes, commonly segmented, and sometimes flattening with depth. The following situations may be envisaged.

Dykes that were syn-depositional are not documented. It is assumed that the syn-depositional sills of the Scottish Namurian and English Westphalian provinces were fed via faults or vents.

Dykes that are comparable in date to major faulting may be investigated in Scotland, where end-Carboniferous quartz dolerite dykes are assumed to be co-magmatic with the Midland Valley Sill, dated to around 303 +/- 5Ma (see Rippon *et al.* 1996). As noted earlier, the West Ochil and

Arndean fault zones contain dolerites of this age, and these structures appear to have been sufficiently large to have been used as major risers on the north side of the Kincardine Basin, where there is no dyke development. However, the Denny-Grangemouth dykes (Fig. 8.7) lie along the southern margins of the Kincardine Basin, where there is some alignment with the large North Carriden (Grangemouth) Fault over several kilometres. Main extension on this fault may well have been contemporary with that on the West Ochil Fault; it may have been large enough (500m throw in Namurian sequences) to have connected with the Midland Valley Sill at depth.

The main extension phase on the North Carriden Fault, and the dyke emplacements, could be close in time, and their (sub)parallel strikes are effectively compatible with the same principal horizontal stress during formation. In this case, there is no common fracture usage at observable horizons. The North Carriden Fault is probably the main element of a zone which may include a significant strike slip component, and there are very steep bedding dips in a complex hangingwall. It is only really trend-coincidental with the dykes in the area east of Grangemouth, where at least two dykes occur, and where the faulting is also more complex. Given a potentially close association of formation time and vectors, it is possible that here, dyke disposition details are reflecting preferred use of dilational zones related to specific major fault segments. However, the simplest explanation is that the North Carriden Fault was not large enough to offer a magma pathway, and (in contrast to the situation in the north of the basin), dykes developed. Also of course, the relative timings may not have been as close as suggested here.

For dykes significantly post-dating a major fault, there is unlikely to be any detailed control by the fault, as this would effectively be a fossil feature, with little unrelieved stress of its own, and with rocks of similar bulk lithology and fracture permeability on either side.

8.5 Westphalian igneous activity in southern Britain

A review by Francis (1970) of all southern Britain included the various small features of the Welsh Borders, such as the Bartestree Dyke, northeast along the line of the Neath Disturbance. Early Westphalian activity seems to have been widespread through much of Nottinghamshire and intermittently along the southern Pennine Basin margin from Leicestershire to west of Birmingham

(Fig. 8.2; see Burgess 1982, Kirton 1984). Volcanism and sills are now known through much of the Westphalian A succession, especially in the earlier part. In the Widmerpool Gulf (Kent, 1985) sills are known to at least mid-Westphalian B times. Further south, Westphalian C/D activity is known across much of the Oxfordshire coalfield, and south towards Berkshire. Perhaps igneous activity was very widespread in the late Carboniferous across the Wales-Brabant palaeo-high (Chapter 6). However, the relationships of these events to the regional tectonic picture remain uncertain.

The earlier Westphalian activity within the Pennine Basin readily fits with a post-rift, but on-going extensional phase. Figure 8.8 shows sills in the Asfordby area, in the south of the Widmerpool Gulf (North & Jeffrey 1991). The limits and horizons of these are known from many boreholes and high resolution reflection seismic. No feeders are known, and it is thought that the sills most likely migrated down into the sub-basin from the Southern Boundary Fault (J.D.Raine, pers. comm. 1997; compare with Francis & Walker 1987). Some control on sill extent is shown by minor faults. Sills are also known in Westphalian A strata on the north side of the sub-basin in Cotgrave Colliery; by analogy, these might be migrations down from the Cinderhill Fault. At Cotgrave, there is evidence that minor step faulting accompanied sill emplacement. However, sills are more widely known beyond the sub-basin, with intrusions, especially in the lowest Westphalian A, well to the north, and generally below the level reached by most NCB boreholes. The most likely structural relationship of these (and perhaps also the vents of Francis *et al.* 1968) is with the set of significant faults trending generally northwest, of which the Cinderhill Fault is one.

Regarding the widespread later Westphalian igneous activity in Oxfordshire (Poole 1977), this might be discussed in relation to advance of the Variscan Deformation Front. A full review of the regional tectonic context is required here, beyond the scope of this account. However, the effects of the Variscan thrust front advance on the foreland have been discussed recently by Corfield *et al.* (1996) and by Peace & Besly (1997). Various inversion effects were interpreted across the palaeo-high and further north. Peace & Besly (1997) inferred a major Stephanian W-E directed compressional event across and beyond the high, pre-dating final (N/NW-directed) Variscan deformation. Extension compared with the Pennine Basin is not an option for the igneous activity across the high in Oxfordshire. Here, Westphalian A, B and earlier C strata proved in boreholes are preserved only as very local condensed or incomplete sequences; agglomerates, basalts, and dolerites lie near the base of the Westphalian D succession (usually below the Aston coal), commonly directly on Devonian or Lower Palaeozoic rocks. Deposition of the coal-bearing Westphalian D across the high, and the syn-depositional igneous activity, would have pre-dated the W-E directed compressional event of Peace & Besly (1997), and also the final Variscan deformation to the south. Perhaps large extensional fractures developed across the high through persistent northerly- or northwesterly-directed compressive stress during later Westphalian C/D times, with deep cracking promoting the igneous activity. This might be linked with development of some Variscan far-field coal joint fabrics to the north (Chapter 7), which would have required transmission of regional compressive stress through the microcraton. However, this is entirely speculative and it is not possible, with existing data density, even to relate the igneous activity to structural trends, while the igneous geochemistry is also poorly known.

Any future work on these southern igneous provinces might consider why only certain areas along the southern margin of the Pennine Basin were igneous-prone in Westphalian times. For example, no activity is known in the mined Warwickshire coalfield. This field is essentially a horst, with a condensed Westphalian A/B sequence often directly overlying Lower Palaeozoic and Precambrian basement rocks, and its major Western Boundary Fault downthrows the Westphalian strata (presently only imaged by seismic reflection) west into the Triassic Knowle Basin (Fig. 2.9). Further west again, in the exposed West Midlands coalfield, igneous activity is well documented. Following the migration model of Francis & Walker (1987), Westphalian successions within the Knowle Basin might include syn-depositional sills, the Western Boundary Fault acting as a riser, with magma migrating basin-wards, rather than into the Warwickshire field. This would, of course, also require the fault's availability; there is some evidence for this (see 4.7). By comparison with Leicestershire, there might also be an equivalent of the Permian Whitwick Dolerite.

8.6 Conclusions

High quality multi-horizon data, especially in Scotland, provide many examples of relationships between igneous features and the contemporary structural and depositional setting. However, each province will have its own particular igneous character. The least understood areas are in south-central England, in which two provinces invite further research. These are the mainly earlier Westphalian province in the continuing extensional setting of the southern Pennine Basin, and the later Westphalian province across the high to the south, especially in Oxfordshire.

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8.8 Figure captions

Figure 8.1 Location and stratigraphical range of the British Carboniferous coalfields.

Figure 8.2 Tectonic framework of the British Carboniferous coalfields.

Figure 8.3 Vent agglomerates and tuffs, Tillicoultry borehole.

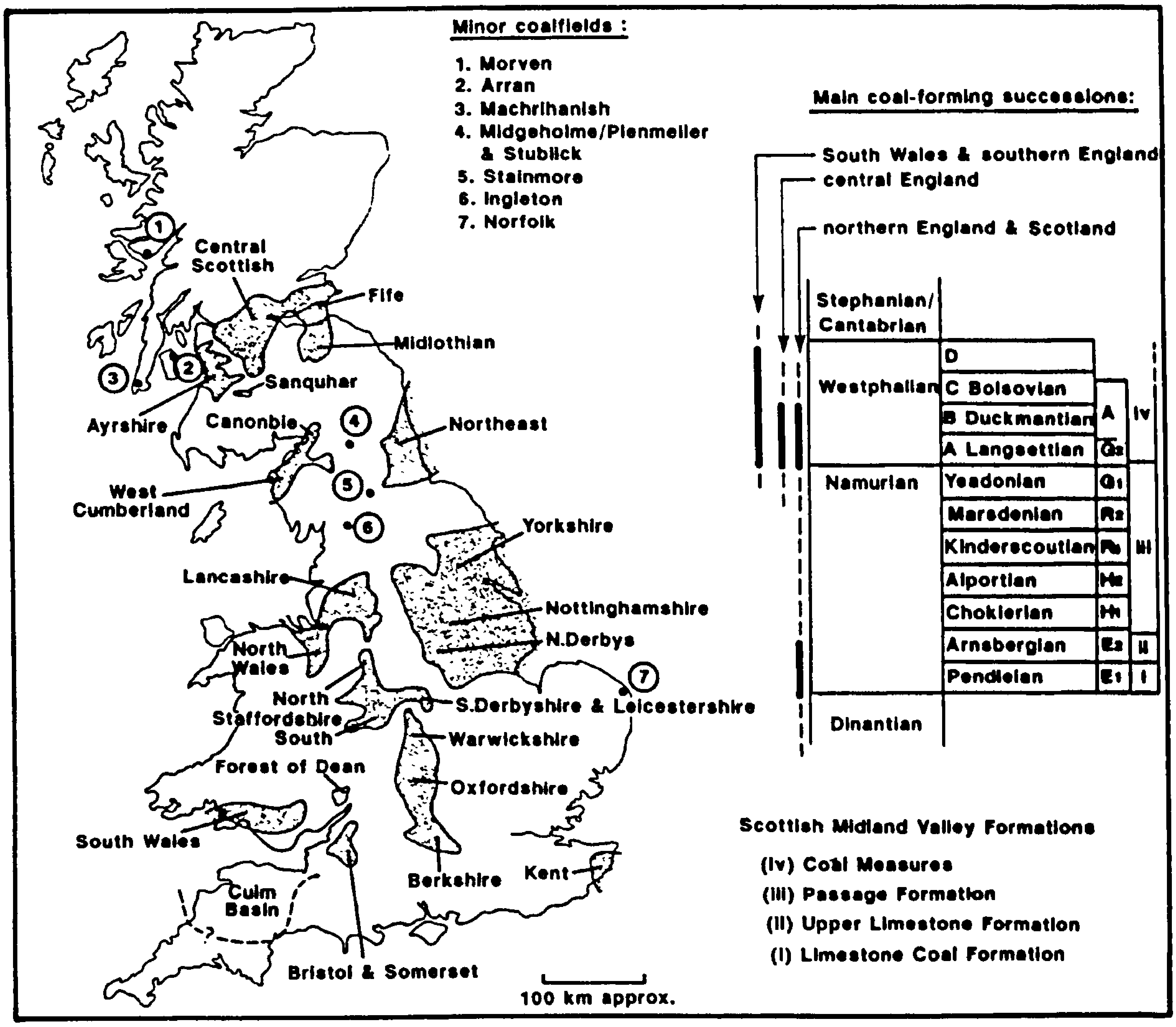
Figure 8.4 Ash falls in the Upper Limestone Formation, Kincardine Basin.

Figure 8.5 Sill intrusion levels below the Upper Hirst coal, Kincardine Basin; an interpretation.

Figure 8.6 Sill migration across faults: a possible model.

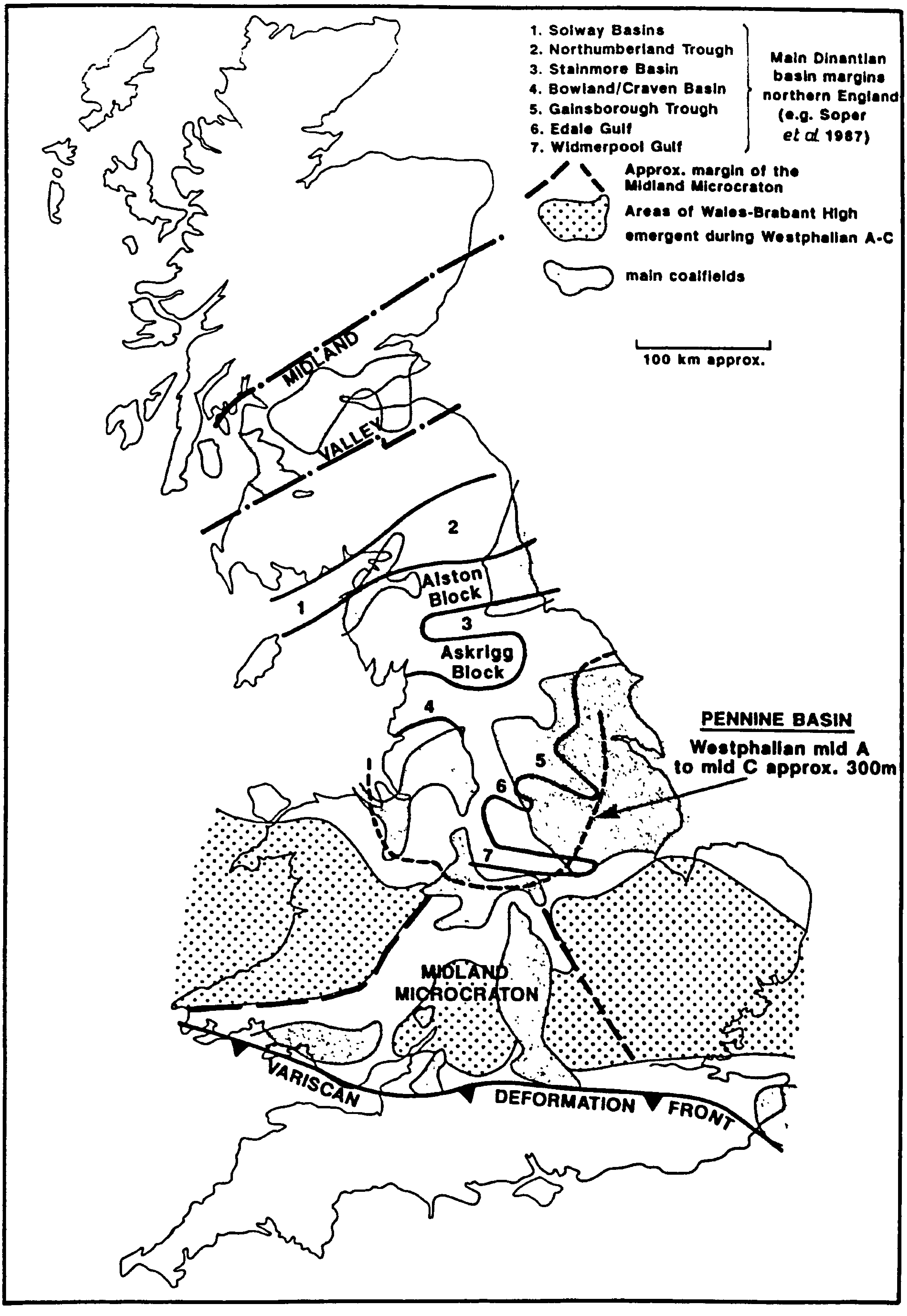
Figure 8.7 End-Carboniferous igneous intrusions in the Kincardine Basin area.

Figure 8.8 Westphalian sills, southeastern Pennine Basin.



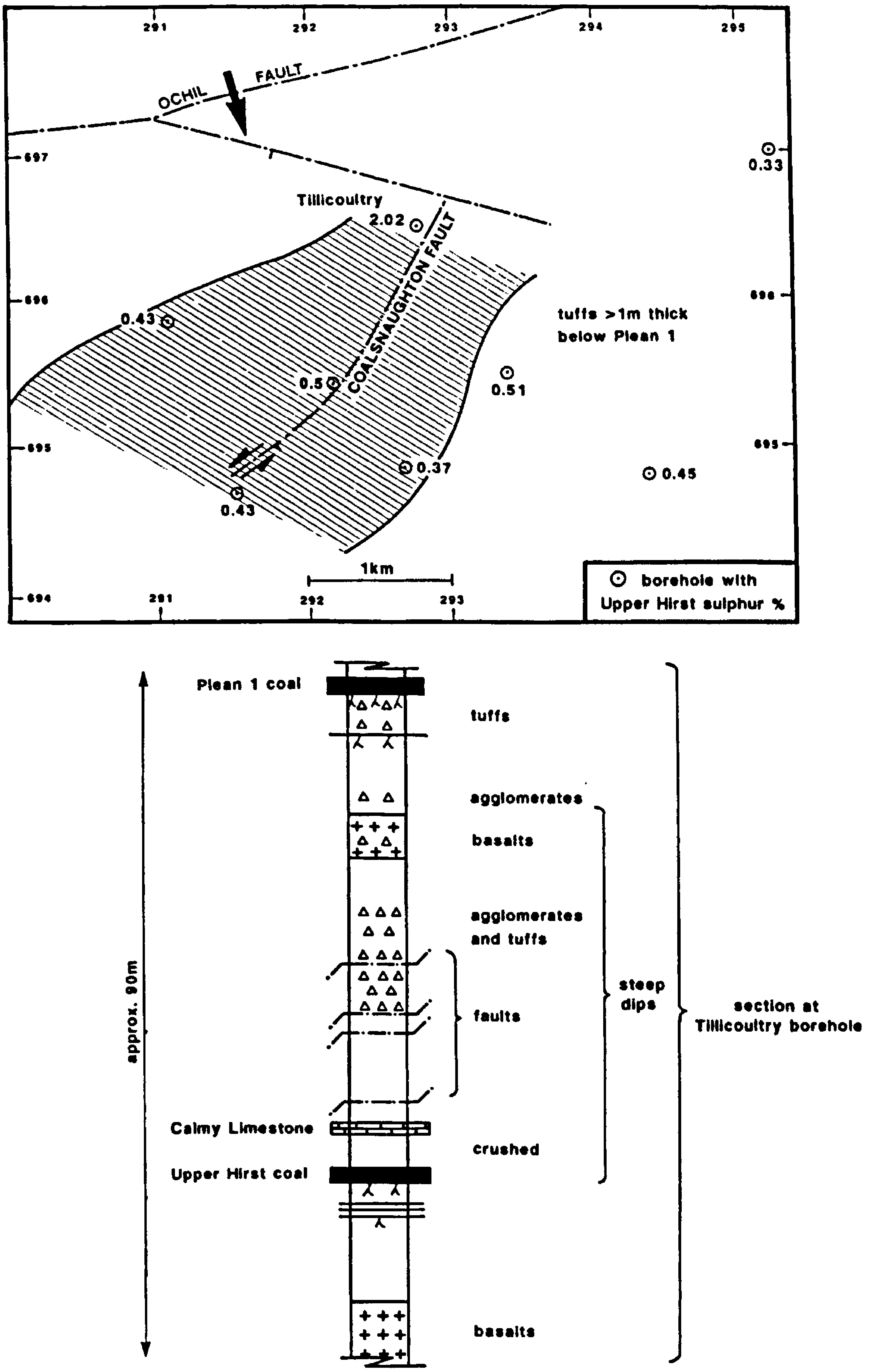
Location and stratigraphical summary of the Upper Carboniferous coalfields

Fig.8.1



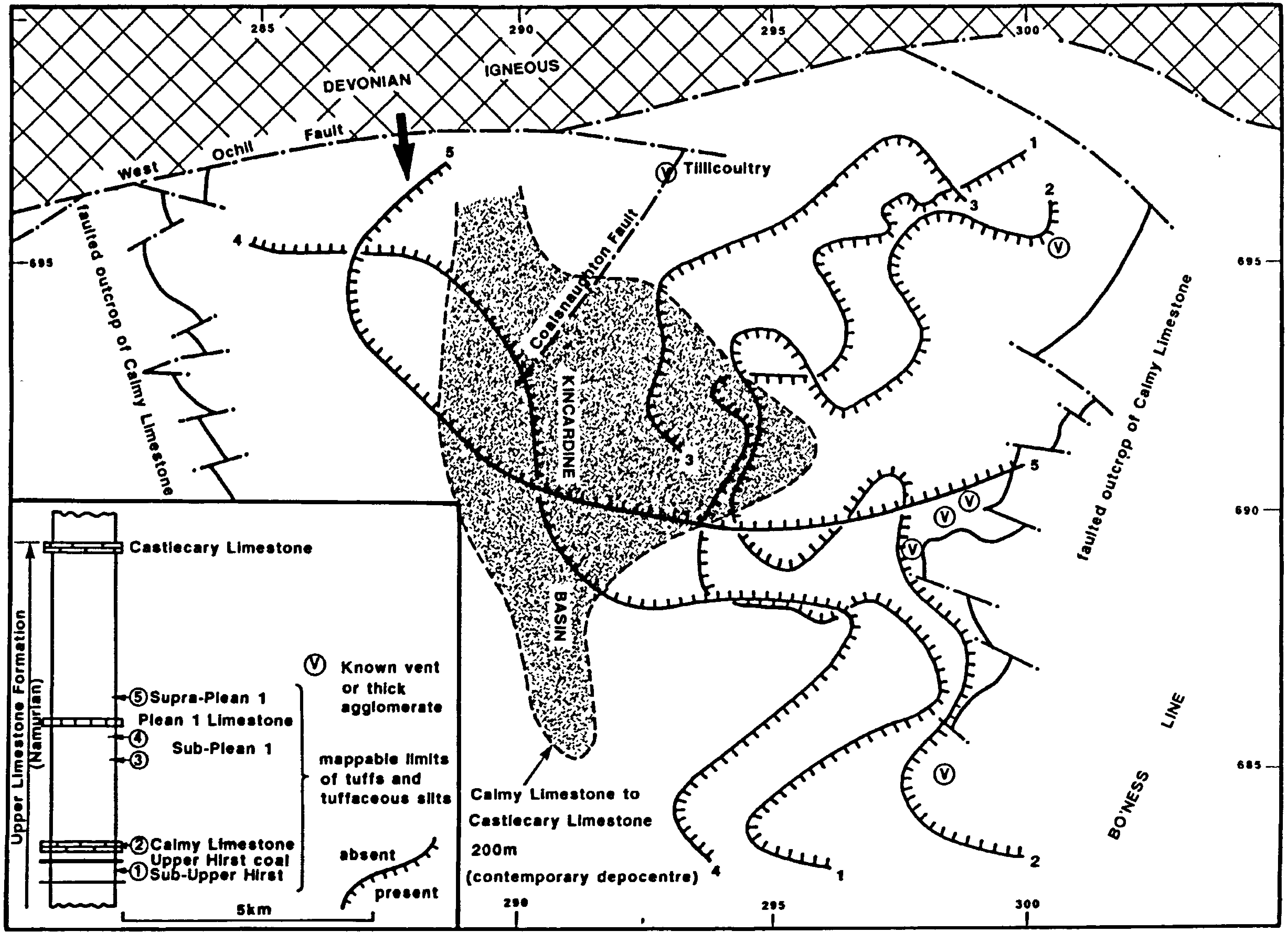
Tectonic framework of the main Upper Carboniferous coalfields

Fig.8.2



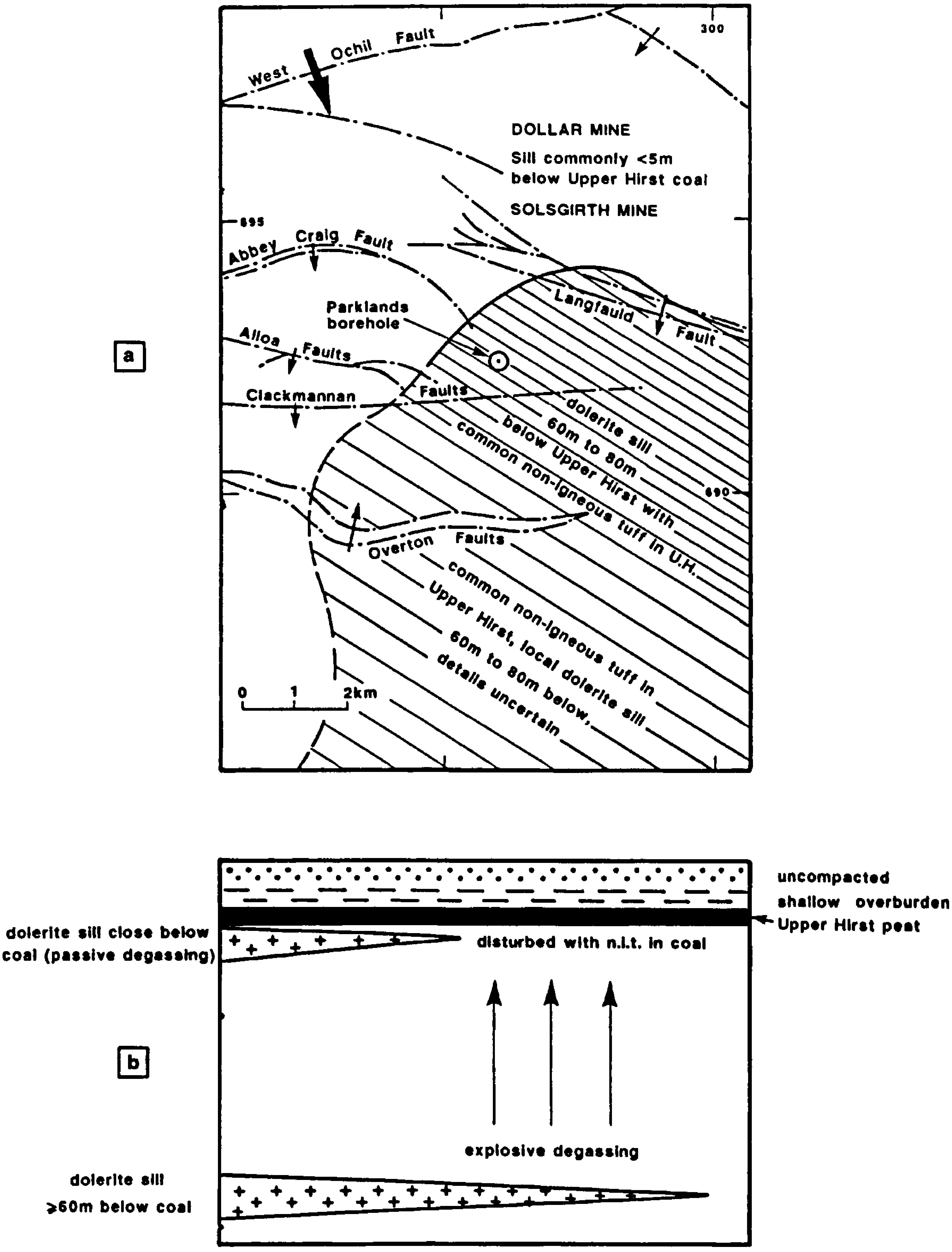
VENT AGGLOMERATES & TUFFS, TILLICOULTRY BOREHOLE

Fig.8.3



ASH FALLS IN THE UPPER LIMESTONE FORMATION (ARNSBERGIAN, E_2), KINCARDINE BASIN

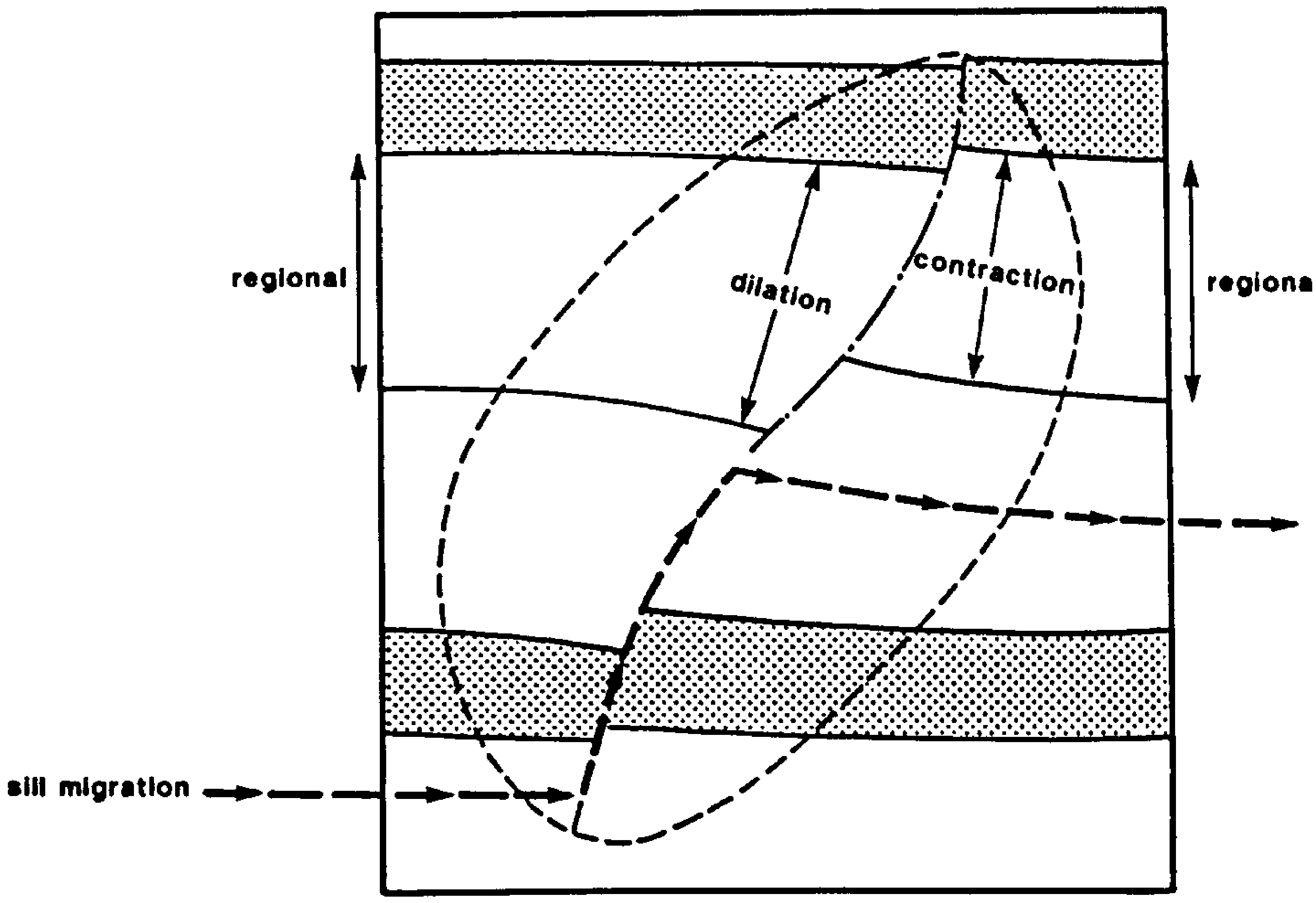
Fig.8.4



a : sketch plan; b : possible relationship between lower sill and non-igneous tuff in the coal

SILL INTRUSION LEVELS BELOW THE UPPER HIRST COAL (ARNSBERGIAN), KINCARDINE BASIN

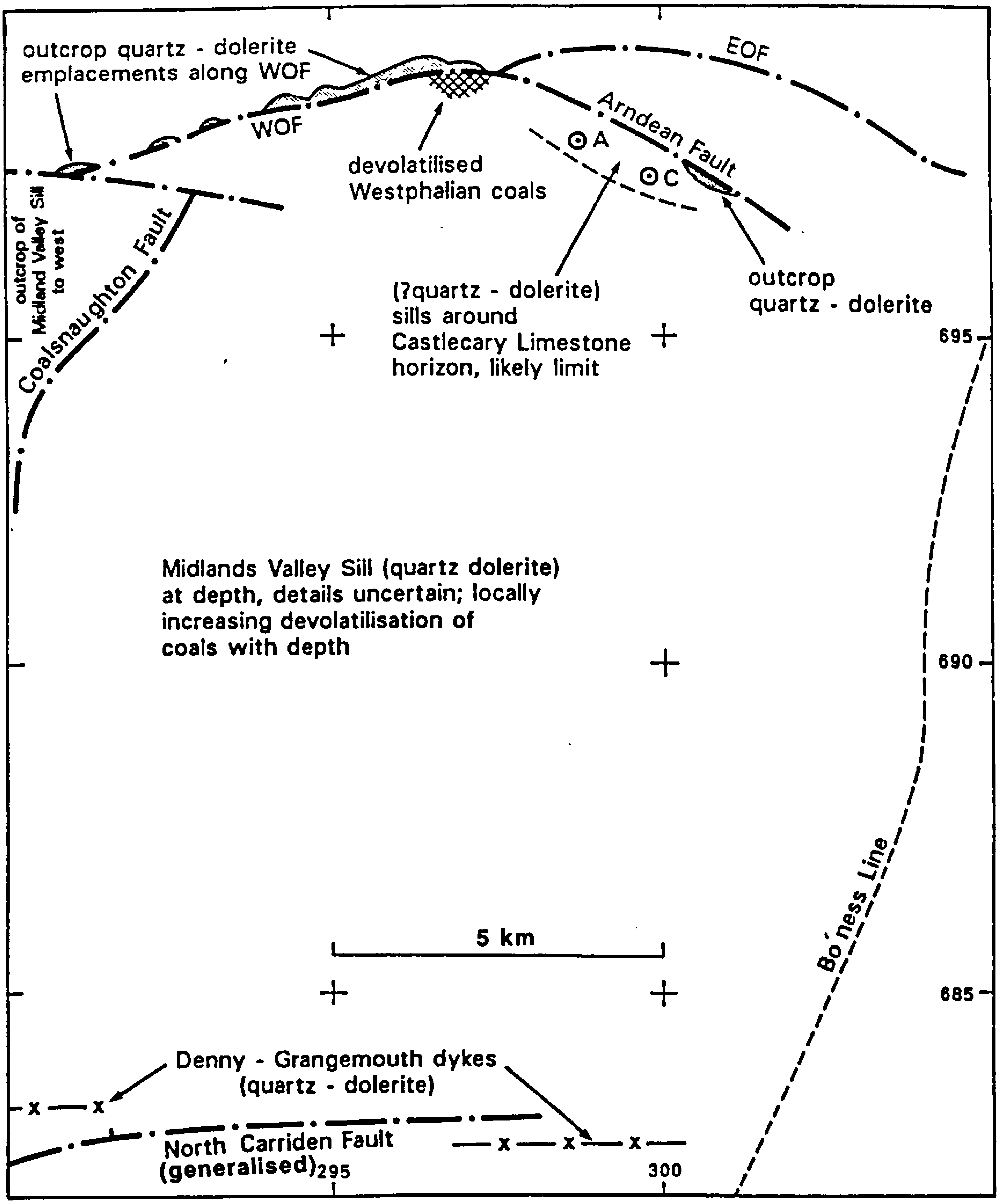
Fig.8.5



One possible model for migration : sill rises up fault plane
to new pathway in dilated lower footwall
see text for discussion

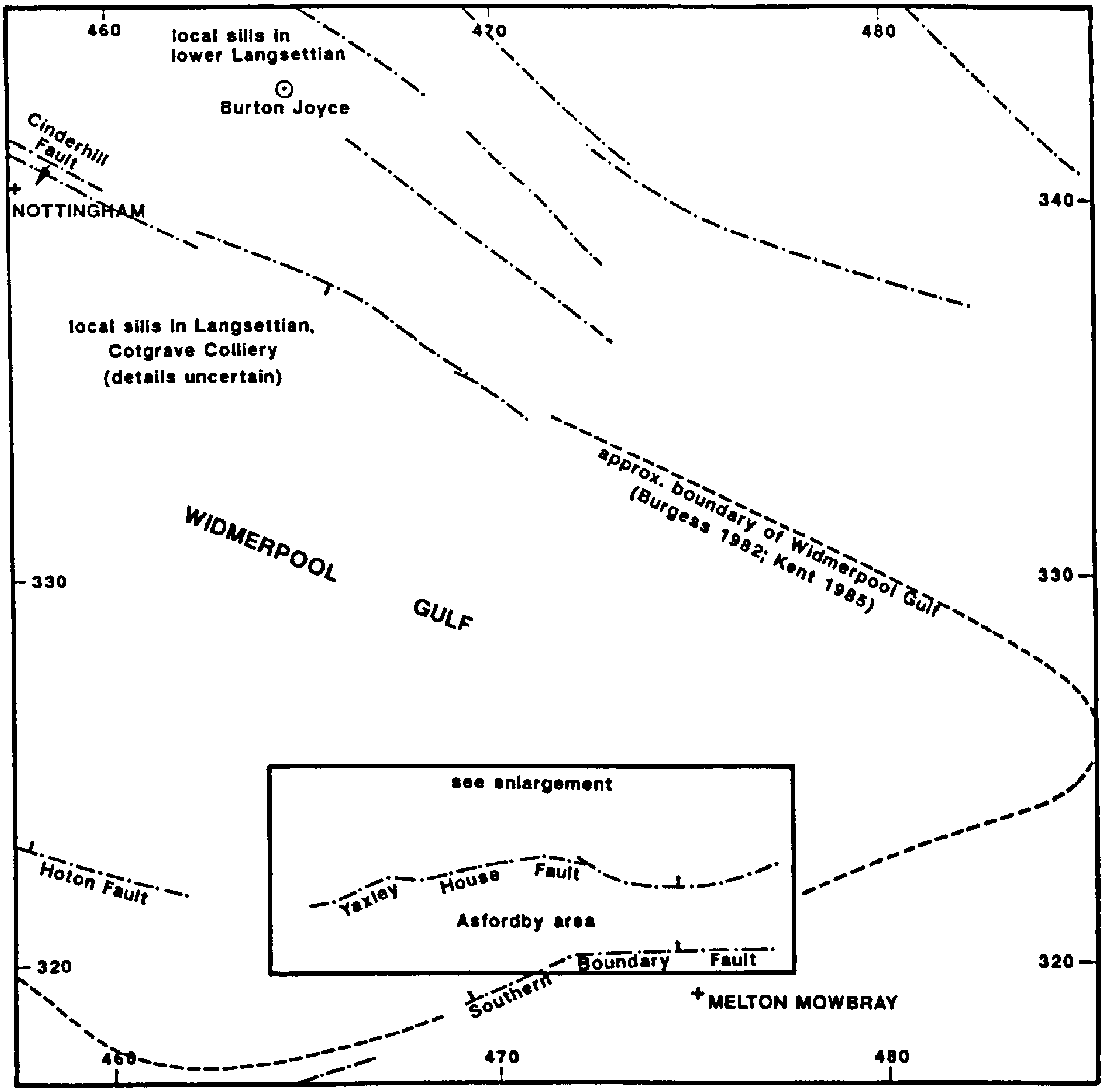
SILL MIGRATION ACROSS FAULTS : SCOTTISH MIDLAND VALLEY

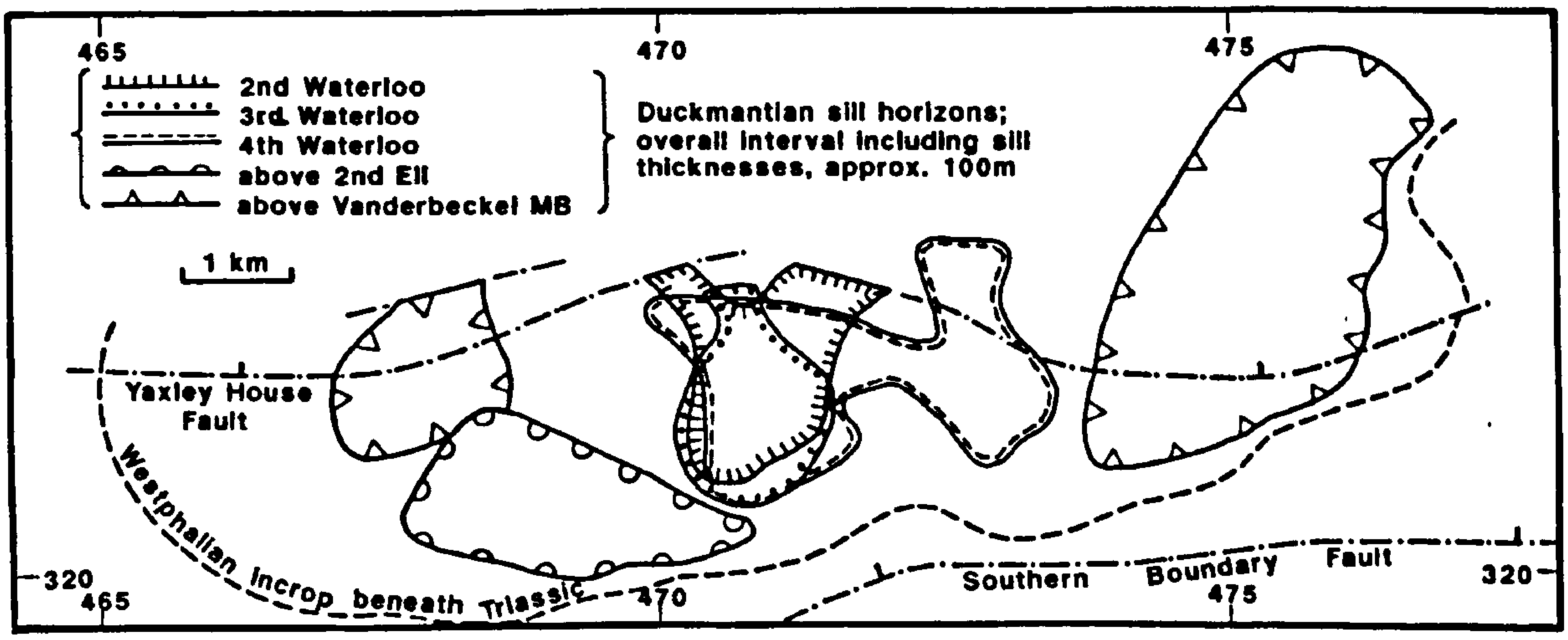
Fig.8.6



Late/Post Carboniferous igneous intrusions in the Ochil Fault/Kincardine Basin area.
A : Arndean Borehole C : Castlebeg Borehole

Fig.8.7





WESTPHALIAN SILLS, SOUTHEASTERN PENNINE BASIN

Fig.8.8

CHAPTER 9

THE OCHIL FAULT AND THE KINCARDINE BASIN: KEY STRUCTURES IN THE TECTONIC EVOLUTION OF THE MIDLAND VALLEY OF SCOTLAND

Abstract: *The Ochil Fault juxtaposes Lower Devonian against late Westphalian rocks, implying up to 4km vertical displacement. The Kincardine Basin, in its hangingwall, was subsiding during the Silesian, and trended generally N-S, perpendicular to the fault; its sedimentation shows little sign of tectonic control by that fault. It is proposed that the Ochil Fault was initiated in the Devonian, but was a sidewall feature during Naumurian basin evolution, attributed to extension on a fault along the Bo'ness Line to the east. Both faults were probably buried in Namurian times. Reactivation of the Ochil Fault during late Carboniferous extension produced at least 2km displacement, including the presently visible footwall uplift. The hangingwall may have contained a Permian basin.*

9.1 Introduction

The Ochil Fault is one of the most striking tectonic features in the Midland Valley of Scotland. Its relationship with the Clackmannan Syncline (and the precursor Kincardine Basin) on its southerly downthrown side is an intriguing tectonic problem (see Rippon *et al.* 1996, on which this account is largely based). East of Stirling, the line of the fault is marked by a W-E trending escarpment, some 640m high. This divides the low ground of the Forth Valley, underlain by Carboniferous sediments in the Clackmannan Syncline in the hangingwall, from the uplands of the Ochil Hills, formed by a north-dipping block of resistant Lower Old Red Sandstone (broadly equivalent to Lower Devonian) volcanic and intrusive rocks in the footwall (Figs. 9.1, 9.2).

On the British Geological Survey's 1:50,000 Alloa map (Sheet 39E), the Clackmannan Syncline is seen to plunge gently northwards towards the Ochil Fault, against which the strata on both flanks of the syncline abut almost at right angles. A similar geometry seems to have characterised the Kincardine Basin, as formation isopachs on both flanks generally approach the Ochil Fault at a high angle (Read 1988). On the Bouguer anomaly map of the Midland Valley, the Ochil Fault stands out clearly as a W-E line which separates a gravity high over the Ochil Hills from a low over the syncline to the south. The line of the fault is also distinguishable, but is less obvious, on the aeromagnetic anomaly map (Browne *et al.* 1987, figs. 32-33). All the above features emphasise an abrupt break in structural and stratigraphical continuity across the Ochil Fault.

A striking feature of the fault is the marked variation in southerly downthrow, which decreases rapidly, in terms of stratigraphical displacement, both westwards and, less markedly, to the east from the point of maximum displacement, where strata of late Westphalian age are placed against Lower Old Red Sandstone volcanic rocks. This account concentrates on the West Ochil Fault, with the Clackmannan Syncline and Kincardine Basin immediately to the south. The East Ochil Fault is considered to have had a different geological history and is not considered in any detail.

The Kincardine Basin subsided rapidly during most of the Upper Carboniferous (Silesian), and lay between the West Ochil Fault and an area of reduced deposition, south of a line between the eastern end of the Campsie Fault and the Forth estuary (Fig. 9.1). To the west, the basin was bounded by the pile of Dinantian basalts forming the eastern part of the Clyde Plateau massif, and to the east by a SSW-NNE zone of low subsidence and persistent Carboniferous volcanicity known as the Bo'ness Line (Read 1988). A gap between the bounding highs on the west and south sides of the basin, known as the Denny Gap, connected into the Kilsyth Trough, to the southwest. The juxtaposition of the Ochil Fault with the basin in its hangingwall suggests a genetic relationship between the two structures, and the main purpose of this account is to examine evidence for this by reviewing the tectonic evolution of both structures.

9.2 Previous views

B. N. Peach of the Geological Survey, who mapped the Stirling area and the district to the west in 1865-1872, recognised the Ochil Fault as one of the most important fractures in the Midland Valley. Early seismological studies (Davison 1924) suggested that it might be a reverse fault, but Haldane (1927) used outcrop evidence to demonstrate that the fault plane dipped south in three places. Francis *et al.* (1970) described evidence from detailed surface mapping, shallow boreholes and geophysical techniques demonstrating that the Ochil Fault can be traced westwards from the western end of the escarpment at Causewayhead (E.279400, N.695400) through poorly exposed ground, dying out at E.266500 N.695200, 13km west of Stirling. They suggested that the fault may have been initiated before the Upper Old Red Sandstone was deposited, and that it probably controlled subsidence and deposition during much of the Carboniferous.

The Kincardine Basin has been studied by Read and co-workers (see Read & Dean 1982, and references therein) who analysed quantitative relationships between net subsidence of the basin and a series of bulk lithological variables, together with numbers of cycles, numbers of coals, etc., for various Silesian stratigraphical divisions.

Several contrasting tectonic models have been proposed. Gibbs (1987, fig.15) postulated that the Ochil Fault is a reverse fault, dipping north, with an implied combination of dip-slip and strike-slip displacement. He considered the Kincardine Basin in the context of a complex system of listric duplexes, in which the intermediate and upper fault leaves had developed as a "carapace" to simpler strike-slip shears in the basement, the upper leaf carrying the Silesian strata. Coward & Gibbs (1988) postulated dextral strike-slip faults in the central part of the Midland Valley, linked by east-facing "headwall" faults, one of which was placed near Stirling. Dentith (1988) used geophysical data to construct a model of the Kincardine Basin and Ochil Fault in which the fault dips steeply southwards, and a sub-horizontal detachment lies at depth below the basin. This detachment was drawn at a refractor taken to be the base of the Lower Palaeozoic succession.

Haszeldine (1984) and Stedman (1988) proposed a W-E extensional stress system for the Midland Valley during the Namurian, whereas Dewey (1982), followed by Read (1988) suggested instead that Dinantian WNW-ESE lithospheric extension and rifting accompanied by widespread alkali-basaltic volcanicity was followed by Silesian thermal subsidence, upon which a component of dextral strike-slip motion was superimposed.

Read (1989) discussed the evidence for a Carboniferous dextral strike-slip component along the East Ochil Fault, suggesting that a major fracture underlay and linked the Paisley Ruck, the East Campsie Fault and the East Ochil Fault (Fig. 9.1), active possibly as early as Brigantian times, but concluded that most strike-slip movement occurred at the end of the Silesian. A gently-dipping detachment at depth beneath the Kincardine Basin was suggested, following Dentith (1988), but placed at a shallower level, possibly in evaporites within the early Dinantian Ballagan Formation.

Both Dentith (1988) and Read (1989) suggested that the Ochil Fault may have been initiated as a late Caledonian sinistral strike-slip fault, later re-activated as a Carboniferous dip-slip fault.

In evaluating kinematic models of the Devonian-Carboniferous period (eg. see, most recently, Coward 1993), the role of such an important structure as the Ochil Fault in the tectonic evolution of the Midland Valley is critical. This account will therefore assess evidence for the various stages of movement of the fault, and for movement direction during each of these, and attempt to decide, for example, whether dextral strike-slip motion played a significant part in Carboniferous movements. Existing published data are evaluated, together with a large amount of unpublished high-quality coalfield data in the hangingwall area of the Ochil Fault.

9.3 The Kincardine Basin

The spatial relationship between the fault and the basin raises the problem of when the latter was initiated, and secondly of whether the basin is genetically related to the fault (in an early phase of its development), or whether depositional systems extended across the fault. Much of the relevant information relating to hangingwall stratigraphy (Fig. 9.3) can be summarised as isopach and channel loci maps (Fig. 9.4). These are based on a set of largely cored and geophysically-logged boreholes, drilled by the National Coal Board (NCB, latterly British Coal Corporation, BCC); those since 1975 have been mainly in connection with exploration for the Upper Hirst coal. Throughout the period from late Devonian to late Silesian, most basin sediments appear to have been derived from the north, principally from metamorphic rocks of the southern Grampian Highlands (i.e. north of the Highland Boundary Fault - see Figs. 9.1, 9.2), as is apparent from identifiable Dalradian clasts (Francis *et al.* 1970), backed by palaeocurrent vector evidence (Read & Johnson 1967).

9.3.1 Pre-Late Devonian

The section across the Kincardine Basin modelled from the north-south MAVIS II seismic refraction traverse (Dentith 1988) shows the "combined Lower Old Red Sandstone and Lower Palaeozoic" succession thinning over a few kilometres from more than 6km to less than 2km as it is traced southwards across the West Ochil Fault. This abrupt change is likely to indicate that the thick pile of Lower Old Red Sandstone volcanics of the footwall area is absent (or much reduced) in the hangingwall, which in turn suggests that the present fault may coincide with a much older (pre-Upper Old Red Sandstone) structure, possibly with strike-slip displacement as proposed by Dentith (1988). Support for this hypothesis comes from the suggestion of Conway *et al.* (1987) that the Strathmore Syncline, northwest of the Ochil Fault, is offset by some 20km in the MAVIS I (N) refraction profile, implying a mid-Devonian (Acadian) sinistral strike-slip displacement.

9.3.2 Late Devonian to Dinantian

The sediments of the Stratheden and Strathclyde Groups (formerly the Upper Old Red Sandstone and Calciferous Sandstone, respectively) and the overlying Dinantian basalts of the Clyde Plateau Volcanic Group thin eastwards towards Stirling, at the west end of the hangingwall of the West Ochil Fault (Francis *et al.* 1970) (Fig. 9.2). Thus the western flank of the Kincardine Basin may be underlain by an eastward-tapering wedge of Dinantian basalts, which would have some bearing on subsequent basin geometry. The marked eastward thickening of the Lower Limestone Formation east of Stirling (Francis *et al.* 1970, fig. 17) indicates that the basin was already in existence by the late Brigantian, but there is little information on its central and eastern parts at this stage.

9.3.3 Limestone Coal Formation (Pendleian, E_1)

Several boreholes are core-proved over much of this sequence in the Clackmannan Syncline, and NCB/BCC seismic sections supplement these. Overall data density is sufficient for defining broad thickness variations. Blackfaulds borehole (Fig. 9.4b) is particularly useful regarding Ochil Fault relationships, lying within 1.5km of the surface trace of the fault.

The isopach map of the Black Metals Marine Band to Index Limestone interval (Fig. 9.3) shows an asymmetrical basin with gentle western and steeper eastern flanks (Fig. 9.4b). The basin is elongated north-south, its axis through Parklands borehole (E.296075; N. 692430), and the contours are cut off abruptly at the West Ochil Fault. It is significant that this interval (*c.* 285m) and gross lithology at Blackfaulds is little different to that at, say, Kincardine Bridge borehole (E.291655; N.687150) some 8.3km further south. Trend-surface analysis (Read & Dean 1967, fig.

4) suggested that the total thickness of coal increases steadily eastwards across the Kincardine Basin, but decreases abruptly close to the Bo'ness Line. A similar abrupt decrease is seen in the overall proportion of coal in the succession. According to Read & Dean (1967), channels entering the basin from the northeast tend to follow a depression, the Tulliallan Trough, whereas channels entering from the northwest swing round the basin's western flank to join the first set in the southwest near the Denny Gap (Fig. 9.4f). During deposition of the Limestone Coal Formation, active alkali-basaltic volcanicity occurred along the Bo'ness Line, which is aligned with, and corresponds approximately to, the steeper eastern flank of the basin (Read 1988).

9.3.4 Upper Limestone Formation (Pendleian-Arnsbergian, E_1 -E_2)

Over thirty modern and largely cored boreholes with supporting geophysical logs and surface reflection seismic (60km) acquired over the last twenty years in the wider hangingwall area, together with many earlier cored holes, provide an excellent data set down to the Upper Hirst coal (Fig. 9.3). As with the Limestone Coal Formation, contours of intervals within the Upper Limestone Formation are aligned north-south, meeting the Ochil Fault at a high angle (Fig. 9.4c). The map suggests a westward shift of the axis, to around Gartarry Toll borehole (E.293132, N.691256), east of Clackmannan. The basin now appears more symmetrical but continues to plunge northwards.

A wealth of data on major horizon intervals has been examined within the Clackmannan Syncline. None of the mapped intervals shows any apparent relationship to the West Ochil Fault in terms of either isopach pattern (e.g. Fig. 9.4d) or coal quality and splitting. Indeed lithofacies mapping using cored borehole data in the near-field hangingwall indicates that one sand body, close above the Upper Hirst coal, trends at about 045^o near the fault. In view of its size and assumed derivation from the northeast, this channel must have extended across the footwall for several kilometres. The thick multi-storey sandstones that are typical of the formation are thought to be concentrated in the Denny Gap (Fig. 9.1), with sandstones stacked vertically, sand having been transported westwards through this gap into the adjacent Kilsyth Trough (Read 1988).

Volcanic activity seems to have persisted along the Bo'ness Line, albeit at a reduced level during Upper Limestone Formation deposition. Basin-centre volcanism is also present, assumed to be related to the SSW-NNE-trending Coalsnaughton Fault (see later), suggesting that it, too, may have been an active extensional (or transtensional) fault at this time. Significantly, this fault runs sub-parallel to the Bo'ness Line.

9.3.5 Passage Formation (later Namurian, E_2 -G_1, plus earliest Westphalian)

Because of post-Carboniferous erosion, complete borehole sections through this formation are confined to the central part of the Clackmannan Syncline, and less is known about the flanks. However there is no evidence of continued volcanicity along the Bo'ness Line (Read 1988). The formation isopach map (Fig. 9.4e) shows some similarities with that of the Upper Limestone Formation in that the main depocentre is still located near the Gartarry Toll borehole; however the contours now reveal a basin shape no longer truncated by the West Ochil Fault, and with no hint of asymmetry. The contour closures between the depocentre and the West Ochil Fault lie up to 6km from the fault (Fig. 9.4e). The beginning of this period was marked by uplift and erosion in the Grampian Highlands, resulting in a surge of coarse-grained siliciclastic sediments from the north and the appearance of a new and distinctive suite of heavy minerals (Muir 1963). Muir identified different heavy mineral contributions to the basal Passage Formation sandstones in the Midland Valley from the northwest (C-zircon) and the northeast (K-zircon), and also identified the same (Highland) sources of supply near the top of the formation. This evidence was supported by the palaeochannel mapping of Read & Dean (1982, fig. 9). Uplift also occurred in the western part of the Midland Valley (see Read 1989), but there is little indication of any local structural control in the Kincardine Basin during this period (other than the residual development of the basin itself).

9.3.6 Coal Measures (Westphalian)

The preserved Coal Measures of the Kincardine Basin are thought to belong almost entirely to the Scottish Lower and Middle Coal Measures, and thus to be of largely Westphalian A and B age (Francis *et al.* 1970, Read 1988). Post-Carboniferous erosion has largely confined their present outcrop to the axial areas of the Clackmannan Syncline. Because the area of preserved Coal Measures is small, it is only possible to draw isopachs of restricted intervals. However both the interval between the Glenfuir and Mill Coals, and that between the Mill and Coalsnaughton Main Coal (Westphalian A) show an overall tendency to thin northwards towards the West Ochil Fault (Francis 1956, figs. 9a,b), continuing the pattern established in the late Namurian. Coal Measures sedimentology in the Kincardine Basin is not well known and most information is from old shallow boreholes and mine plans. However one significant palaeochannel is shown on the published 1:10560 sheet NS89NE, eroding the Alloa Splint coal (Westphalian A) over a width of around 0.3km, and aligned NNW-SSE at a high angle to the West Ochil Fault's surface trace, <2km to the north (see 2.5.1). Later Westphalian (C/?D) sediments are poorly known and are mainly red beds, particularly the Devon Red Sandstone (Francis *et al.* 1970).

9.3.7 Summary of the evolution of the Kincardine Basin

The Kincardine Basin is defined and characterised by several distinctive features. 1. Formation thicknesses increase significantly towards the basin centre, sometimes by over 100% compared with the margins. 2. The main depositional basin occupied broadly the same area, at least from Dinantian to Westphalian B Coal Measures times. 3. Rates of thickness changes are greatest along well-defined "hinges" just within the definable depositional basin; this effect is particularly prominent in the Limestone Coal Formation. 4. The isopachs generally, and the hinge zone in particular, bear no obvious relationship to the Ochil Fault, but the hinge appears to be aligned N-S or NNE-SSW near to, and roughly parallel to, the Bo'ness Line. 5. One important lithological change, at least in the Limestone Coal Formation and Upper Limestone Formation, is the often rapid increase in coal thickness from the margin, across the hinge, and into the basin centre. This is more prominent than variations in sandstone thicknesses. 6. The roughly circular shape of the basin during Passage Formation deposition, along with the lack of evidence for structural control, suggests that basin development was controlled by a different mechanism at this stage.

9.4 The Ochil Fault and associated structures

Structures associated with the Ochil Fault are here considered to include all major elements lying generally within 10km of the Ochil Fault, even though some may represent older or younger tectonic phases. The immediate hangingwall area has been investigated by NCB/BCC (and some oil exploration) seismic reflection surveys. Some seismic lines extend up to, or just across, the surface trace of the fault. These are supplemented by a number of modern boreholes, which provide hangingwall information on bedding dips and the incidence of minor faults.

The modern exploration for the Upper Hirst coal is complemented by extensive structural proving by older mine workings in Westphalian coals, particularly in the Alva Syncline (Fig. 9.5), which provide crucial data on fault-adjacent strains, and the style and spacing of minor faults (throws up to 30m). Further, some of the workings lie within 100m of the projected subsurface position of the Ochil Fault (from surface and seismic observations described below) and therefore contribute to assessment of its fault plane dip in the upper sequences. These mineworkings extend laterally up to 2km away from the Ochil Fault, over a vertical range of around 400m.

9.4.1 The Ochil Fault

Surface trace. The Ochil Fault has been traced eastwards by boreholes and geophysics from near Boquan Home Farm (E.267000, N.695200) east of Kippen, where its throw seems to be negligible, to a point immediately north of Stirling, from where it can easily be traced at the surface along the Ochil escarpment (Fig. 9.5). Here, the fault divides into two branches which re-unite after 3-4km (Francis *et al.* 1970). The fault then runs east-northeastwards along the foot of the escarpment past Alva, Tillicoultry and Dollar to a point (E.299300, N.699400) about 3km ENE of Dollar (Haldane 1927, Francis *et al.* 1970) where the Arndean Fault branches southeastwards, appearing to take up a large part of the throw. The Arndean Fault itself may be the main structure here. East of this junction, the Ochil escarpment becomes lower and less steep, but continues east-northeastwards, whereas the named Ochil Fault swings southeast in two southward concave arcs to a point (E.314900, N.696400) 18km east of Dollar, from where it continues east-northeastwards with a much reduced but variable throw. Seen from around 20km to the south, the topographical form of the West Ochil Fault footwall hills shows a smooth arc, the highest point of which is roughly coincident with the area of likely maximum throw at Alva.

The fault at depth. Four cross sections, originally drawn on a scale of 1:5000, illustrate the area of maximum throw, and integrate information in the immediate hangingwall (Fig. 9.6). Although masked by superficial deposits on each line of cross section, the outcrop of the fault is essentially well controlled. Outcrop and mining data indicate a fault plane dip varying from 60° to 70° to the S in the upper 1km, and the migrated positions of the available seismic reflectors at depth indicate a continuing steep fault plane dip (around 65° S) to at least 2.5km depth, supporting the original interpretation of a southerly dip (Haldane 1927). These observations, together with the descriptions of the footwall and hangingwall geology which follow, indicate a large south-dipping fault on which the main displacement was essentially normal.

Seismic activity. The area of the Ochil Fault has experienced recent seismicity, and this has led to speculation about its structure at depth. The seismicity has typically been in swarms of minor felt events, interspersed with quiet periods of several decades (Francis *et al.* 1970). Most felt events have been located north of the Ochil Fault rather than along it, despite the distribution of settlements/observers being mainly in the valley to the south, along the hangingwall, and Haldane (1927) noted other faults in the area which could have been active, in particular, some prominent NW-SE and SW-NE faults in the Ochil Fault footwall. In the light of the evidence that the Ochil Fault dips southwards, to at least 2.5km depth, it is concluded that the NW or NE faults in the footwall are more likely to be responsible for the seismic activity.

9.4.2 Structure of the hangingwall

Folds. The published 1:10560 maps NS89NE, NS99NW, NS99NE (Geological Survey 1959 editions), summarised on the 1:50,000 Sheet 39E (Alloa) illustrate three small W-E synclines preserving Westphalian Coal Measures in the immediate hangingwall of the Ochil Fault, the largest of which is the Alva Syncline (Fig. 9.5). The cross sections of Figure 9.6, through the Alva Syncline, illustrate a steepening (up to 20° over a distance of about 2km) of the northerly bedding dips which characterise the coalfield for some 10km south from the probable area of maximum throw of the Ochil Fault. The mine workings and seismic data show that the incidence of minor faults is no greater than that typical of many British coalfields, and there is no increase in their numbers on the approach to the Ochil Fault. The steep south-dipping northern limb of the Alva Syncline is interpreted as normal drag against the Ochil Fault and the northerly dip of the southern limb as reverse drag (Gibson *et al.* 1989).

W-E faults. A series of south-dipping major normal faults with displacements of up to 100's of metres characterises the coalfield south of the Ochil Fault (Figs. 9.5, 9.6). These faults are usually essentially planar in overall cross section where proved, although in plan some fault traces show concavity usually towards the hangingwall. They typically have fault plane dips of around 45° S. Most of them have prominent reverse drag, particularly in the hangingwall (see 6.5.1). Some of the W-E faults appear to have been active occasionally during Namurian deposition (see 5.7.1), and there is evidence that Namurian alkali-dolerites were emplaced between existing faults and used them as risers (Chapter 8; Francis & Walker 1987). Given the context of large scale extension during the main phase of Ochil Fault movement (see later), it is likely that these faults were rotated by 10° to 15° (ie. from ~60° dip to ~45°) as the main fault developed.

NW-SE faults. Two large NW-SE faults meet the Ochil Fault east of Tillicoultry (E.292000, N.697000) (Fig. 9.5), namely the Sheardale and Arndean Faults (Francis *et al.* 1970, p.254). It is considered that these are splays of the Ochil Fault, contributing to the eastern breakup from its maximum displacement. The Sheardale Fault has a maximum throw of around 200m, the Arndean probably over 1000m (Francis *et al.* 1970).

SW-NE to SSW-NNE faults. Faults on this trend seem generally better developed in Westphalian, rather than Namurian strata, but this may represent recording differences. Most are small, <5m maximum throw. Two fault zones are particularly prominent; the main zone constitutes the Coalsnaughton Fault (Francis *et al.* 1970, p. 253) and the other, just east, dips towards the Coalsnaughton Fault in a probable antithetic relationship. The former has a maximum throw of <50m in the West Ochil Fault hangingwall area but it is laterally extensive, and traceable for many kilometres as a zone, although compartmentalised into segments by the W-E faults. Although the Coalsnaughton Fault itself has no surface exposures, and proving mine workings are long-abandoned, recent workings in the Upper Hirst coal intersected the antithetic fault zone, one element of which strikes at 020° with a steep (75° W) fault plane, and exhibits subhorizontal slickensides. The overall pattern of fractures proved in the Upper Hirst shows a zone with overlapping fault segments, the arrangement of which indicates sinistral strike slip (Fig. 6.16).

Other faults on this trend are represented by the north-eastern end of the Campsie Fault and the Carnock Fault, both of which lie along-strike of the Coalsnaughton Fault to the southwest (Fig. 9.5). Faults on this trend are also present in the Lower Devonian igneous complex in the Ochil Fault footwall, one lying roughly along-strike of the Coalsnaughton Fault (see below). Differential subsidence to the southeast seems to have taken place across the line of the Campsie Fault during earlier Carboniferous deposition. It is therefore possible that a large fault on this trend is present at depth below the coalfield, the lesser faults inheriting the trend (6.4.5; Fig. 6.6).

The possibility that the Coalsnaughton Fault continues to depth is suggested partly by the lateral persistence of the zone, but also by the likelihood that it was a locus for volcanic activity in Upper Limestone Formation times. A series of agglomerates, together with basalts, is known at Tillicoultry borehole (E.292764; N.696528), mainly between the Calmy and Plean 1 Limestones (Fig. 9.3) indicating a vent probably within 0.5km of the borehole, which intersects this fault around the basal Westphalian horizon (see Chapters 4 and 8, and Fig. 8.3). Other nearby boreholes along the line of the Coalsnaughton Fault show tuffs within the Upper Limestone Formation, probably thickening towards the fault and suggesting a line of small vents. Volcanism of this age on the eastern margin of the Clackmannan Syncline towards the Bo'ness Line has already been noted. The Coalsnaughton Fault may therefore represent a long established system, perhaps extending (in the Lower Devonian basement) through both the hangingwall and footwall of the Ochil Fault, and which may have a significant strike-slip element, at least in part of its development.

Fault patterns in the Alva Syncline. Mineworkings in the Westphalian seams of the Alva Syncline provide records of the fault patterns. The following generalisations may be made.

1. All the faults are recorded (by surveyors) as normal. The possibility of an unrecorded strike-slip element may be addressed indirectly by studying the fault trace pattern, and by consideration of the throw distribution after the method of Rippon (1985). Using both criteria, it is concluded that most faults are essentially normal, although there remains the possibility of some strike-slip component, especially on NE-trending faults.

2. Few faults in the Alva Syncline have vertical displacements >10m, and most are <5m.

3. There is a variety of fault orientations. The most prominent are W-E, subparallel to the West Ochil Fault, with fault plane dips generally southwards, in some cases <45°. Other orientations recall the prominent SW-NE and NW-SE faults in the Ochil Fault footwall to the north.

4. Fault intensity, in terms of maximum throws, fault trace lengths and spacing, is low, except within particular fault zones; this observation is qualitative, and based on visual assessment, as the area is too small for any rigorous statistical study. However it is assumed that fault recording by mining surveyors was comprehensive at their level of detection, which would have been to the high standard required by UK mining legislation; where coal was worked, it is unlikely that any throw >0.5m would have been unrecorded in these relatively thin seams. There appears to be no straightforward relationship between the numbers of larger and smaller faults as found in fault population studies in the eastern Pennine Basin coalfield (Watterson *et al.* 1996). It is concluded that the principal faults (ie the West Ochil Fault and the faults in its wider hangingwall with throws >100m) have generally been re-used, rather than further extension promoting new fractures.

Quartz-dolerite intrusions. Both the Ochil and Arndean faults are invaded by quartz dolerite intrusions (Fig. 9.7), known to be of late or post-Carboniferous age, since adjacent Westphalian coals at Dollar show enhanced ranking. Other, small, quartz dolerite sills are known in the Arndean hangingwall (1:10560 Geological Survey Sheet NS99NE) and in the Castlebeg and Arndean boreholes, indicating invasion of the hangingwall to at least 500m away from the fault plane, at horizons around the Castlecary Limestone (Fig. 9.3), which gives some indication of the extent of the contemporary hangingwall strain (see discussions in 6.5.1 and 8.3.2).

9.4.3 Structure of the footwall

The footwall geology derived from the published 1:10,560 maps consists of a thick pile of Lower Old Red Sandstone volcanic rocks with minor intercalated sediments, which have an essentially SW-NE regional strike, and dip at 10-20° NW. This regional structure is clearly pre-Upper Old Red Sandstone in age, since it is truncated by the unconformable, gently south-dipping, Upper Old Red Sandstone at the western termination of the West Ochil Fault. Only immediately north of the fault itself does the dip appear to relate to movement on the fault, in a zone up to 500m wide, where the strike is parallel to the fault trace, and the dip appears to become shallower to near-horizontal, suggesting a poorly developed footwall anticline. This structure corresponds to the zone of maximum throw and the highest part of the escarpment.

The faults in the West Ochil Fault footwall consist of two sets: a prominent set trending NW-SE, locally bending into a N-S orientation, and a numerically minor SW-NE set (Fig. 9.5). In addition, north of Dollar a WSW-ENE fault parallels the main fault, and further east, three W-E faults occur, also parallel to the main fault. The NW to N-trending set, effectively cross-faults, are concentrated at the western end of the West Ochil Fault. These faults contribute to the rapid westwards decrease in throw referred to earlier, and may perhaps reflect footwall deformation during uplift, accommodating increased footwall uplift towards the east. Two large SW-NE faults extend northeastwards from Tillicoultry and Dollar respectively. One of these (probably the eastern one, since it has the larger throw) may represent the northward continuation of the Coalsnaughton Fault zone described in the hangingwall (see above) and interpreted as a possible basement lineament.

Joint directions in the Lower Devonian volcanic rocks cluster around 045^{0} and 135^{0}, with a third set parallel to the West Ochil Fault only near the fault trace. This contrasts with a pervasive W-E coal cleat trend in the hangingwall (Chapter 7; Fig. 7.5). The contrast in joint and fault directions north and south of the West Ochil Fault strongly suggests that the footwall structure predominantly reflects much older deformation (pre-Upper Old Red Sandstone), and that the effects of end-Carboniferous movement are much more obvious in the hangingwall than in the footwall.

9.4.4 Net throw and displacement on the West Ochil Fault

The total net throw on the present West Ochil Fault is difficult to quantify precisely, because the relevant stratigraphy in the footwall is missing. However, assuming that at least an attenuated (halved?) Namurian to Westphalian sequence extended northwards onto the footwall (see later), and adding the present topographic relief of 640m, a minimum throw of about 2100m is indicated at the point of maximum uplift. Also, an unknown thickness of Upper Devonian and Dinantian strata (possibly up to a further 2,000m) may also have been removed from the footwall, although, as indicated later, the footwall may have been emergent for at least part of this period.

The reverse drag or rollover structure in the hangingwall is indicated by the northward plunging region of the Clackmannan Syncline, which extends for about 9.5km southwards towards the River Forth (Fig. 9.8) and steepens at its northern end into the Alva Syncline. The lack of an obvious northwards tilt in the footwall may be partly due to the difficulty of distinguishing such a structure from the pre-existing northwestwards dips of the Lower Old Red Sandstone.

The possibility has been considered that one or both of the refractor horizons identified on the MAVIS II S profile (Fig. 9.8) acted as detachment horizons for the extension, following Dentith (1988). Refractor 1 is identified by Dentith (1988) as the base of the Upper Old Red Sandstone, while Refractor 2 is identified with the base of the Palaeozoic (or top of the crystalline basement). However the fact that the fault plane has a uniform dip of about 65^0 to at least 2.5km depth, coupled with the relatively shallow depth of the reflectors (the lower reflector lies at a depth of only about 4km) suggests that a listric model is probably inappropriate. A more appropriate model for the West Ochil Fault is considered to be the flexural cantilever model (Kusznir & Egan 1989) from which footwall uplift and basin geometries for various combinations of flexural rigidity and amount of extension can be calculated (see below).

9.5 Discussion

9.5.1 The initiation of the Ochil Fault

The abrupt change in thickness of Layer 2 (Lower Old Red Sandstone/Lower Palaeozoic) on the MAVIS I (N) seismic refraction profile (Conway *et al.* 1987) from 6km to 2km across the Ochil Fault strongly suggests an early phase of Devonian activity. The western continuation of the present fault is overstepped by the Upper Old Red Sandstone, and it is probable therefore, that the precursor of the Ochil Fault was initiated in lower to mid-Devonian times, possibly as part of a sinistral strike-slip regime then operating in the Midland Valley (eg. Bluck 1984, Soper & Hutton 1984 & Hutton 1987) (Fig. 9.9a). The southward continuation of the Lower Devonian volcanic pile exposed in the footwall may thus now lie buried beneath the eastern flank of the Kincardine Basin.

However field evidence from the footwall volcanic sequence (pyroclastic beds become thicker, coarser and more numerous towards the West Ochil Fault) suggests venting along the fault line; the abrupt change in thickness across the fault may be (wholly or partly) original.

9.5.2 Relationships between the Kincardine Basin and the Ochil Fault

It is tempting to visualise the Kincardine Basin as a simple case of a hangingwall basin produced by Silesian movements on the West Ochil Fault. There are several problems with this.

1. Basin-form contour patterns reflect thickness variations in the coals, shales and limestones, which are the lithofacies most sensitive to subsidence and other bathymetric factors, and these illustrate a gradually evolving basin form through the Namurian. However the main movement on the West Ochil Fault as revealed by the hangingwall structure is late Carboniferous/early Permian in age (see below), and therefore there can be no simple relationship between the hangingwall strain relating to this event, and the formation and evolution of the (earlier) Kincardine Basin.

2. The Silesian isopach patterns of Figure 9.4 show a rather narrow basin elongated on a N-S trend, approximately perpendicular to that of the West Ochil Fault, rather than parallel to it as would be expected were the two structures simply related.

3. The isopach patterns are not centred adjacent to the sector of present maximum throw on the fault, which lies between 3km and 10km further west. Moreover the basin migrates westwards with time, rather than southwards (as would be expected); the centre in the later Namurian, as shown by the closed isopach patterns, lies a significant distance from the fault.

4. The lack of marginal facies and the presence of some channel axes aligned at very high angles to the West Ochil Fault suggest that the footwall was not emergent or active for much of the Silesian. The channel patterns in Figure 9.4f could be interpreted as resulting from footwall uplift over the eastern sector of the fault; that is, the channels may have been diverted around the ends of an uplifted (though not necessarily emergent) fault segment in a similar manner to the major fans of the Sperchios Basin described by Eliet & Gawthorpe (1995). If the uplifted segment were submerged, it would explain the lack of footwall derived marginal facies.

The critical factor is basin geometry, which indicates a relationship with the SSW-NNE Bo'ness Line rather than with the West Ochil Fault. It is suggested that the basin was initiated by extension on a pre-Brigantian normal fault along the Bo'ness Line, with its known concentration of alkali-basaltic volcanicity (Fig. 9,9b). There is no trace of the continuation of the Bo'ness lineament into the Ochil Fault footwall (where it should be clearly visible because of the lack of Carboniferous cover) and it is therefore concluded that the basin was bounded along its northern margin, roughly along the present outcrop of the West Ochil Fault, during the period of active extension (Dinantian to early Namurian times) on the Bo'ness Line. It is also suggested that the precursor Ochil Fault during this period acted as a sidewall fault, confining active extension and depression to its south side. But the disposition of large Namurian channels indicates that the area of deposition, if not the basin as such, extended northwards well beyond the West Ochil Fault.

9.5.3 Dinantian extension in the Midland Valley

The prevalence of extensional sub-basins within the Midland Valley generally during the Dinantian, together with the adjacent alkaline volcanicity of the Clyde Plateau lavas to the west, suggest that the Kincardine Basin was initiated by an active extensional fault at this time. The initiation and early development of these basins was attributed by Stedman (1988) to W-E extension and by Leeder (1988) to N-S extension. Several authors point to the importance of dextral strike-slip movements, see Read (1989), Dentith & Hall (1990), Burn (1990) and Dailly (1990). The WSW-ESE trend of a series of linear vent systems and multiple dykes which fed the Campsie volcanics (Craig 1980) might suggest a component of NNW-SSE extension during the early Dinantian.

However from this evaluation of the Kincardine Basin, there is no evidence of contemporary N-S extension across the Ochil Fault (e.g. all the contemporary igneous activity is related to the NNE-SSW Bo'ness and Coalsnaughton lineaments) and that a more likely tectonic scenario is a component of intra-Carboniferous W-E extension activating the Bo'ness Line (see Fig. 9.9b). W-E extension is compatible with the recent Coward (1993) model of the evolution of the Midland Valley, in which sinistral strike-slip is visualised as continuing through the Carboniferous, to be replaced by dextral strike-slip only during the end-Carboniferous movements, which resulted in inversion of many previously formed structures. The possibility of dextral strike-slip movements in the Midland Valley during Dinantian/Namurian times is not precluded, but the evidence cited above offers no positive support for it. According to Coward (1993) the early Carboniferous tectonics of Europe continued to be dominated by the pattern established during the Devonian, with a sinistral strike-slip regime in northern Britain along the major SW-NE Caledonian lineaments. A sinistral strike-slip regime, as implied by Coward (1993, fig. 8) would create W-E extension across the SSW-NNE Bo'ness Line, as required by the above model.

9.5.4 Namurian/Westphalian evolution of the basin

The stratigraphical/sedimentological evidence from the Namurian Limestone Coal and Upper Limestone Formations suggests that the basin was rapidly subsiding at this time. As explained above, it is believed that this subsidence was due to a continuation of active extension along the Bo'ness line on its eastern flank, which was a continuing locus of volcanic activity. The geometry of the channels suggests that the drainage pattern may reflect a topographic high in the region of present maximum uplift of the footwall of the West Ochil Fault, for at least part of this period. Since there is no surface fault along the Bo'ness Line cutting the Namurian formations, the active faulting postulated for the Dinantian may have been replaced by a monoclinal structure.

Although detailed information is lacking from the Coal Measures, the general pattern of thickness variation in the Passage Formation and Coal Measures suggests a continuation of the basin to at least Westphalian B times. The indications from the depocentre and channel locations provide no evidence of continuing activity either on the Ochil Fault or on the Bo'ness Line. Nor is the basin shape, in the Passage Formation (Fig. 9.4e) and the Westphalian, characteristic of the type of basin controlled by active faulting. Thermal subsidence generated from a Dinantian and Namurian extensional phase would generate a much larger-scale basin, more comparable with the Midland Valley as a whole, and although this mechanism must contribute to the continuation of regional subsidence during the later Silesian, the continuation of the local Kincardine Basin shape during this period should probably be attributed to the effects of sediment loading, accentuated by differential compaction of the greater thickness of coal and shale lithologies in the basin.

9.5.5 Late Carboniferous inversion

The "N-S" fold structures in this part of the Midland Valley (Fig. 9.2), including the Clackmannan Syncline together with the neighbouring Burntisland Anticline and Leven Syncline, were formed by W-E compression during late Carboniferous inversion (Coward 1993) during which many of the normal faults produced during Dinantian extension may have been re-activated in reverse mode (Fig. 9.9c). It is significant that the many small SSW-NNE folds in the hangingwall of the Ochil Fault are concentrated on the eastern flank of the Kincardine Basin, east of, and parallel to, the Bo'ness Line (Fig. 9.5), where Carboniferous cover was probably much reduced in thickness.

9.5.6 End-Carboniferous movement on the Ochil Fault

The present Ochil Fault, together with the suite of W-E faults in its hangingwall and the related strain effects (e.g. coal cleat) is the result of an important phase of N-S extension (Fig. 9.9d). This seems certain to have occurred during late Carboniferous to early Permian times, coinciding with the emplacement of the widespread quartz-dolerite intrusive suite, which is locally represented by sheet-like bodies along the line of the fault itself and of some of its splays, and which yield a late Carboniferous age of 303 +/-5 Ma (Foster & Warrington 1985). It is assumed that emplacement of the intrusions coincides with the extension; the magma may have facilitated movement on the West Ochil and Arndean Fault planes, thus partly explaining the lack of additional fracturing in the hangingwall proximal to the West Ochil Fault. The cleats parallel to the W-E faults in the hangingwall are carbonate-mineralised, probably reflecting fluid migration during this extension.

The hangingwall structure includes the Alva Syncline and the larger-scale 9.5km regional tilt formed by the northward plunge of the Clackmannan Syncline. The extent and size of this combined structure is consistent with a vertical displacement of the hangingwall of about 1460m. Assuming that at least an attenuated Namurian to Westphalian sequence extended northwards onto the footwall, and adding the footwall uplift, estimated from the present topographic relief on the fault scarp to be about 640m, a minimum throw of about 2100m is estimated at the point of maximum present uplift. The restored section across the hangingwall (Fig. 9.8) indicates an extension of 1.75km (12%).

Footwall uplift and basin geometry can be calculated for various combinations of amount of extension and flexural rigidity using the flexural cantilever model of Kusznir & Egan (1989). This fault model takes into account lower lithosphere extension and its resulting thermal effects, and also the effects of sedimentary loading of the hangingwall. An effective lithosphere elastic thickness of between 3 and 10km is believed by Egan (1992) to be a realistic value in the case of natural basins studied by Kusznir & Egan (1989) and Marsden *et al.* (1990). Applying the model to the Ochil Fault, using an effective elastic thickness of 5km and extensions of 2 and 3km, footwall uplift of about 30% of the total throw is predicted (Egan, pers. comm. in Rippon *et al.* 1996). Doubling the effective elastic thickness to 10km produces only a slight change in this ratio. This figure is identical to the estimate (30%) obtained by assuming that present topographic relief on the fault scarp (~ 640m) represents the exhumed "basement" expression of the footwall uplift. It may be concluded therefore that 640m of footwall uplift is of the right order of magnitude for the estimated amount of extension.

The marked difference in structural pattern between the Lower Devonian footwall and the Silesian hangingwall may be explained by the development of the former during the Devonian or Dinantian tectonic phases and the latter during the end-Carboniferous phase. Thus the prominent NW-SE to NNW-SSE fault/joint system may reflect a transverse Devonian "Caledonoid" extensional joint pattern, whereas the dominant W-E faults and coal cleat in the hangingwall reflect end-Carboniferous N-S extension. N-S extension direction (approximately pure dip-slip) during the end-Carboniferous phase is consistent with the dextral strike-slip model for the Midland Valley as a whole, as indicated , eg. by Coward (1993) (see Fig. 9.9d).

9.5.7 Was the Clackmannan Syncline a Permian (or Permo-Triassic) basin?

A question arising out of the above analysis, which dates the main visible fault displacement to around the Carboniferous-Permian boundary, is whether the hangingwall basin was filled by Permian (or even Permo-Triassic) sediments, now eroded. A local analogy would be with the Mauchline Basin in Ayrshire (Fig. 9.1), where about 610m of Permian volcanic rocks and red beds overlie Westphalian strata (Eyles *et al.* 1949). This structure is bounded by major lineaments, the

SW-NE to WSW-ENE Inchgotrick Fault to the north and the SW-NE Kerse Loch Fault to the south, which may have acted as extensional faults controlling basin formation. It should be noted that Mykura (1967) believed that the Mauchline Basin was controlled by a NW-SE lineament (see also Hall 1974, McLean 1978, Francis 1978, and Russell & Smythe 1978). However dykes with petrological affinities to the Permian Mauchline lavas have a W-E trend, as have the distinctive late-Carboniferous tholeiitic basalts (Eyles *et al.* 1949, Monro, in press), suggesting that N-S extension may well have been responsible for the Mauchline Basin also.

It is unlikely that the Ochil Fault was re-activated during later movements (e.g. Tertiary), as there is no evidence of later faulting of the Permo-Carboniferous fault plane intrusions.

Overall, the post-Carboniferous burial history of the Ochil Fault/Kincardine Basin area is unlikely to have involved burial depths greater than those typical of most UK coalfields, as assessed from coal ranks where unmodified by igneous effects; these are comparable, for example, with those of the southern margin of the Pennine Basin of central England.

9.5.8 Regional context

It is not possible to give a complete explanation of the structures considered in this account without reference to the broader tectonic context of the Midland Valley as a whole, a full treatment of which is outside the scope. However it should be noted that, in comparison with some of the well documented fault/basin structures in the literature, the Kincardine Basin is quite small, and may be regarded as only a sub-basin within a wider basin occupying much of the area of the Midland Valley. In the latter context, the Kincardine and Leven basins correspond to sub-basins separated by an intrabasinal high over the Burntisland Anticline, and the Kilsyth Trough to the SW, although defined as a separate structure by the isopachs, may be regarded as linking with the Kincardine Basin (Fig. 9.1). The Ochil Fault hangingwall basin resulting from end-Carboniferous movement must have been considerably wider than the present Clackmannan Syncline.

9.6 Conclusions

The following main conclusions are drawn.

1. A precursor to the present West Ochil Fault is thought to have been active either during Lower Old Red Sandstone times, or in the mid-Devonian, prior to deposition of the Upper Old Red Sandstone, possibly with a sinistral strike-slip displacement (Fig. 9.9a).

2. The initiation and evolution of the Kincardine Basin during Dinantian to early Namurian times is attributed to W-E extension on a hypothetical normal fault along the Bo'ness Line; the precursor West Ochil Fault is considered to have acted as a sidewall fault bounding the basin to the north (Fig. 9.9b). The Bo'ness fault may have been replaced by a monocline by the early Namurian.

3. The late Namurian/Westphalian evolution of the Kincardine Basin is referred to the post-extensional stage; the continuation of the basin shape is attributed to the effects of sediment loading, particularly on basin-fill clay rocks and coals.

4. The Clackmannan Syncline, together with neighbouring N-S folds, is attributed to W-E compression during late Carboniferous inversion (Fig. 9.9c), which may have re-activated the hypothetical Bo'ness fault and similar structures south of the Ochil Fault in reverse mode.

5. The main movement on the West Ochil Fault, responsible for the visible footwall uplift, the Alva Syncline, the suite of W-E faults in the hangingwall, and other related structures, is attributed to an end-Carboniferous phase of N-S extension (Fig. 9.9d), dated by accompanying quartz-dolerite intrusions at ~303 Ma. A restored section indicates an extension of 1.75km (12%) with a minimum estimated throw on the main fault of ~ 2100m, including ~ 640m of footwall uplift. It is suggested that the hangingwall basin relating to this phase of movement may have been filled by Permian (or Permo-Triassic) sediments analogous to those of the Mauchline Basin.

6. The significant regional kinematic change within the Midland Valley from Dinantian W-E extension to late/end Carboniferous W-E compression and N-S extension can be attributed to a change from sinistral strike-slip to dextral strike-slip along the boundary faults (Fig. 9.9).

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9.8 Figure captions

Figure 9.1 Key tectonic features of the Midland Valley. The mainly Upper Palaeozoic rocks of the Midland Valley are shown by open stipple, with sub-basins as close stipple. The Grampian Highlands and Southern Uplands (ruled) comprise late Precambrian and Lower Palaeozoic rocks.

Figure 9.2 Simplified map of the central/eastern Midland Valley.

Figure 9.3 Simplified succession in the hangingwall of the West Ochil Fault.

Figure 9.4 Isopachs and channel axes illustrating Namurian development of the Kincardine Basin. BL, Bo'ness Line; B, Blackfaulds; EOF/WOF, East/West Ochil Faults. Isopachs in metres.

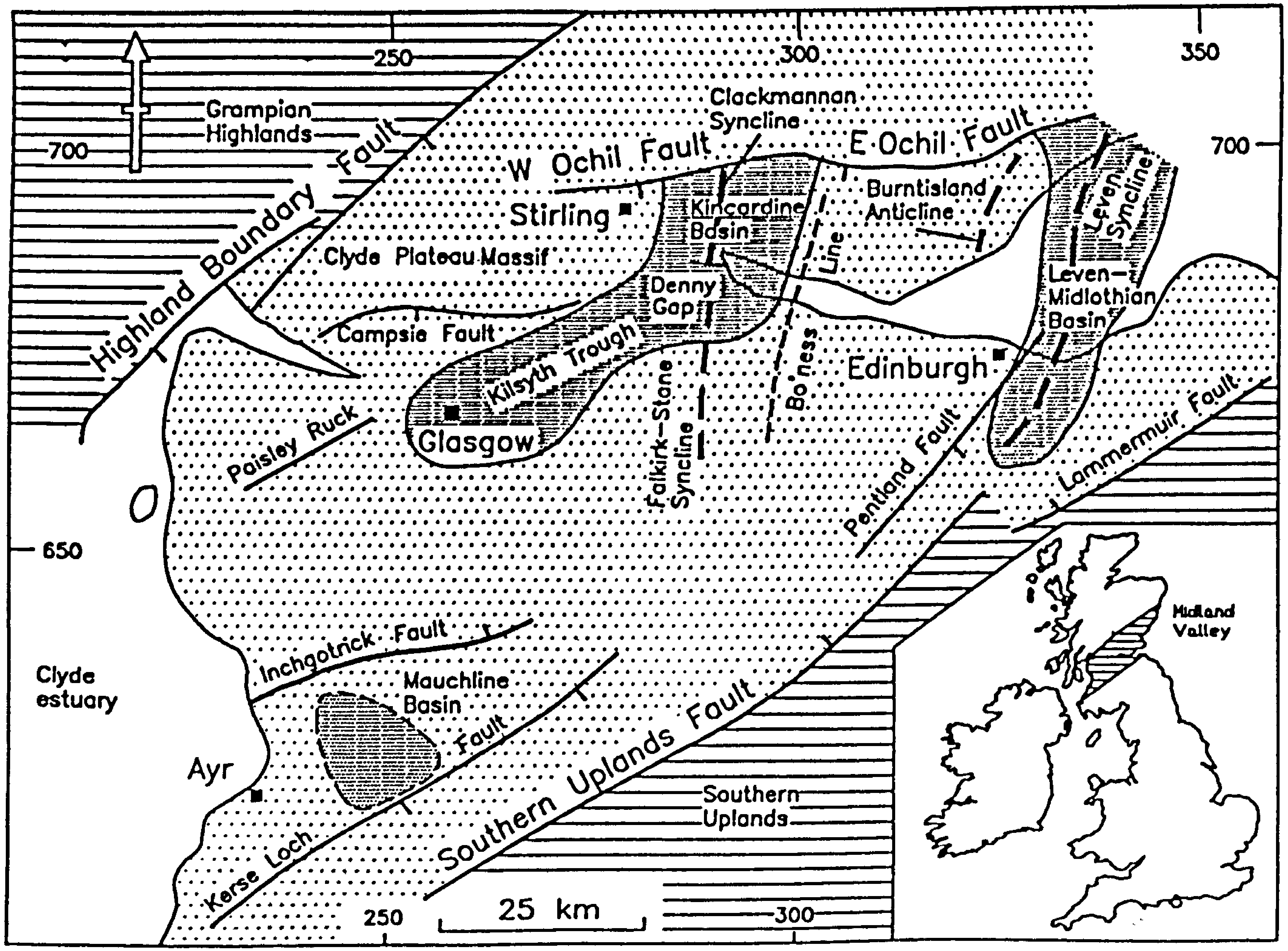
Figure 9.5 Main structural elements of the area adjacent to the Ochil Fault. ACCF, Abbey Craig Central Fault; LF, Langfauld Fault; SF, Sheardale Fault. Faults shown are compiled from both surface and underground mapping. Box indicates area of Figure 9.6.

Figure 9.6 Simplified cross-sections of the immediate hangingwall of the West Ochil Fault. Coal seams: UH, Upper Hirst; CNM, Coalsnaughton Main; AS, Alloa Splint; AC, Alloa Cherry; L9, Lower Nine Foot; U5, Upper Five Foot; TF, Two Foot.

Figure 9.7 Late Carboniferous/Permian igneous intrusions. Boreholes: A, Arndean, C, Castlebeg.

Figure 9.8 **(a)** Simplified cross-section from the Ochil Fault to the River Forth based on the MAVIS II seismic refraction profile (Dentith 1988) with additional interpretation from Rippon *et al.* (1996), indicating inferred geometry of the hangingwall. LORS, Lower Old Red Sandstone; LCF, Limestone Coal Formation; ULF, Upper Limestone Formation; PF, Passage Formation; the Alva Syncline contains Westphalian Coal Measures. **(b)** Restored section to base Passage Formation.

Figure 9.9 Kinematic interpretation of the tectonic setting from Devonian to late Carboniferous and early Permian times. Dark half-arrows, strike slip movement; light arrows, extension and compression directions. **(a)** Lower Devonian; **(b)** Dinantian/earlier Namurian; **(c)** late Carboniferous; **(d)** end-Carboniferous/early Permian. See Figure 9.1 for ornaments. GL, Glasgow; ST, Stirling; ED, Edinburgh; HBF, Highland Boundary Fault; EOF/WOF, East/West Ochil Faults; PR, Paisley Ruck; CF, Campsie Fault; IGF, Inchgotrick Fault; KLF, Kerse Loch Fault; SUF, Southern Uplands Fault; BL, Bo'ness Line; CS, Clackmannan Syncline; FSS, Falkirk-Stane Syncline; BA, Burntisland Anticline; LS, Leven Syncline; MB, Mauchline Basin.



KEY TECTONIC FEATURES OF THE MIDLAND VALLEY OF SCOTLAND

Fig.9.1

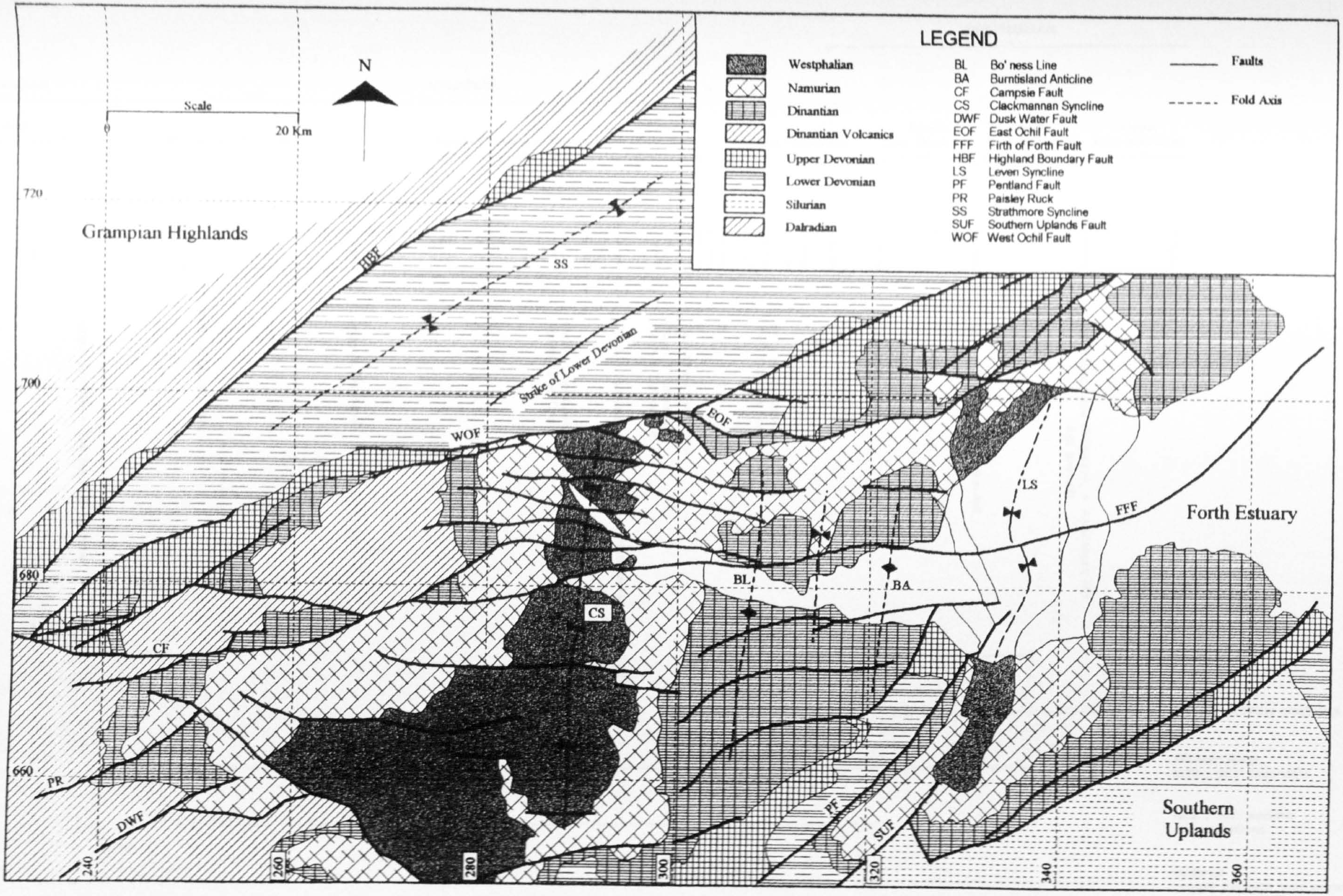
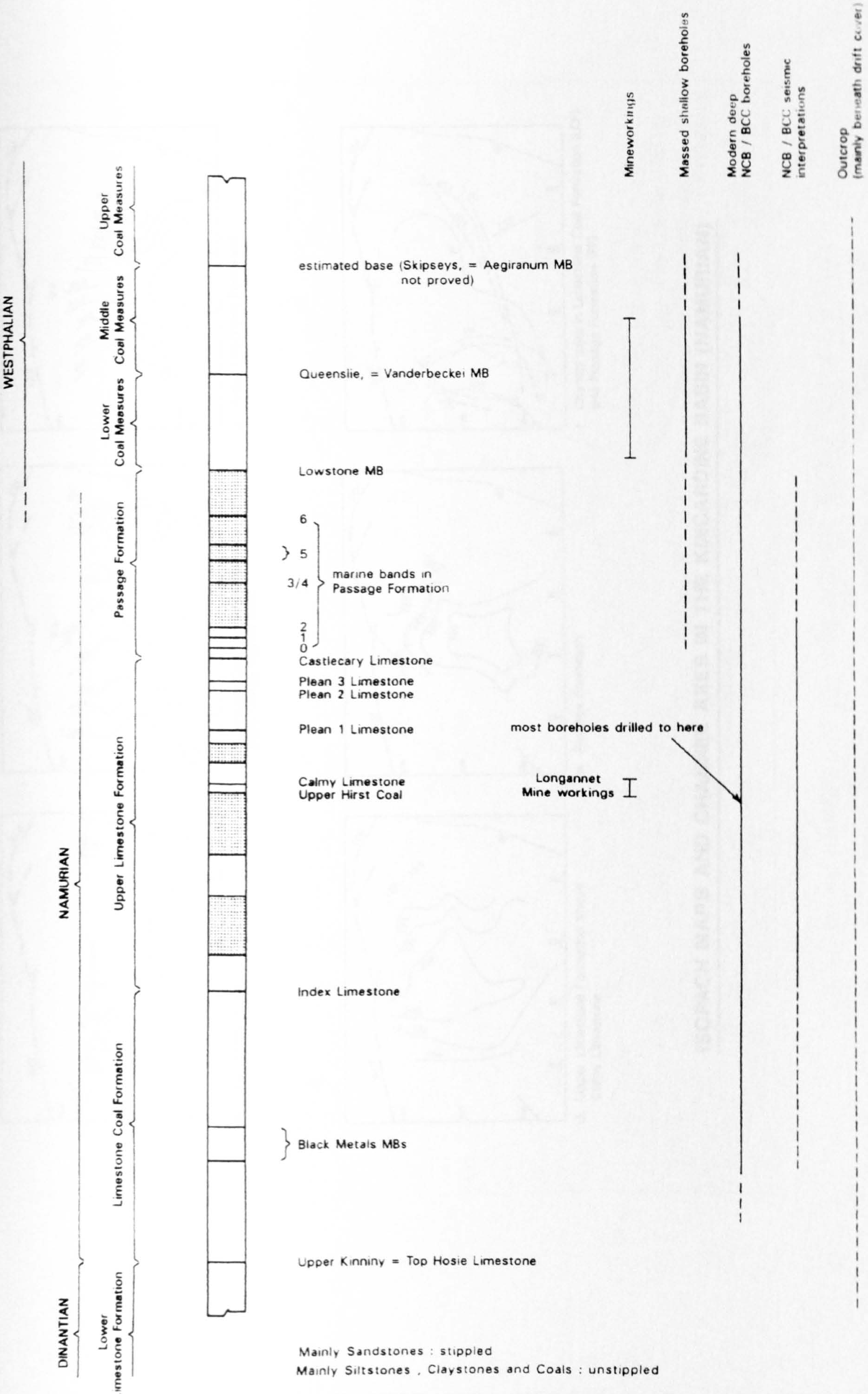
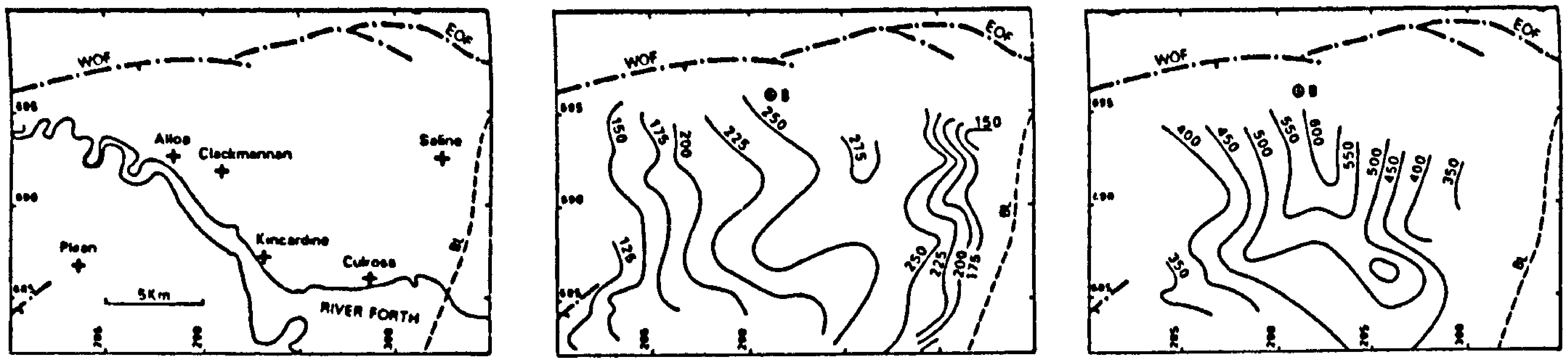

LEGEND
Westphalian
Namurian
Dinantian
Dinantian Volcanics
Upper Devonian
Lower Devonian
Silurian
Dalradian
BL Bo' ness Line
BA Burntisland Anticline
CF Campsie Fault
CS Clackmannan Syncline
DWF Dusk Water Fault
EOF East Ochil Fault
FFF Firth of Forth Fault
HBF Highland Boundary Fault
LS Leven Syncline
PF Pentland Fault
PR Paisley Ruck
SS Strathmore Syncline
SUF Southern Uplands Fault
WOF West Ochil Fault
Faults
Fold Axis
N
Scale
0
20 Km
Grampian Highlands
HBF
SS
Strike of Lower Devonian
WOF
EOF
LS
FFF
Forth Estuary
BL
BA
CS
CF
PR
DWF
PF
SUF
Southern Uplands
720
700
680
660
240
260
280
300
320
340
360

Fig. 9.2



SIMPLIFIED STRATIGRAPHICAL SUCCESSION IN THE HANGINGWALL OF THE WEST OCHIL FAULT

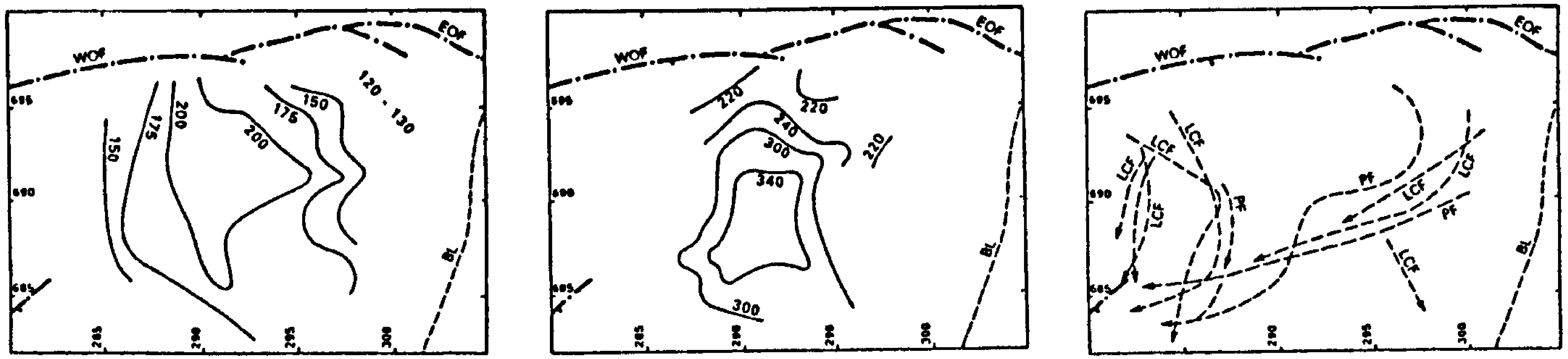
Fig.9.3



a. Location and scale

b. Limestone Coal Formation above Black Metals Marine Band

c. Upper Limestone Formation



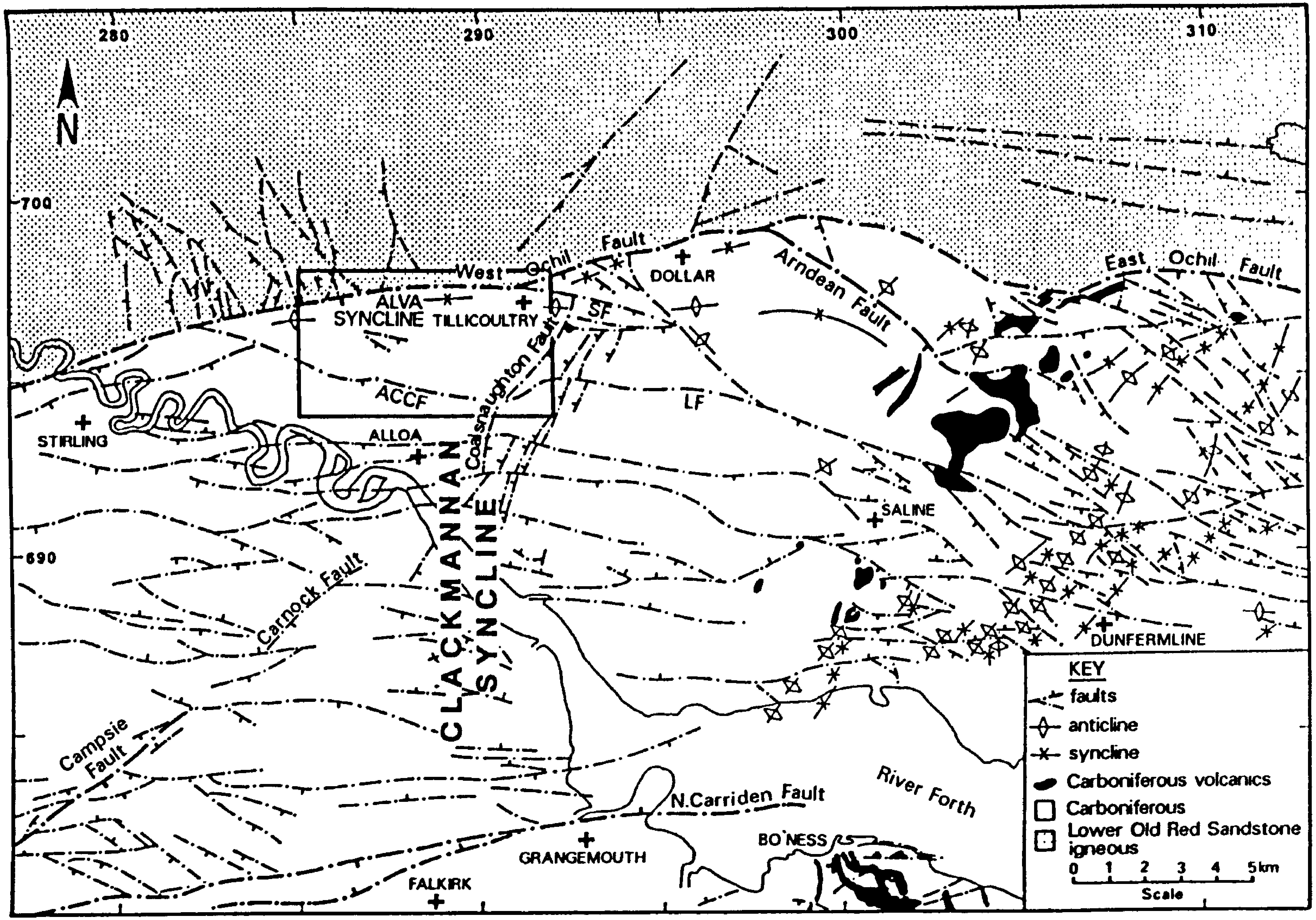
d. Upper Limestone Formation above Calmy Limestone

e. Passage Formation

f. Channel axes in Limestone Coal Formation (LCF) and Passage Formation (PF)

ISOPACH MAPS AND CHANNEL AXES IN THE KINCARDINE BASIN (NAMURIAN)

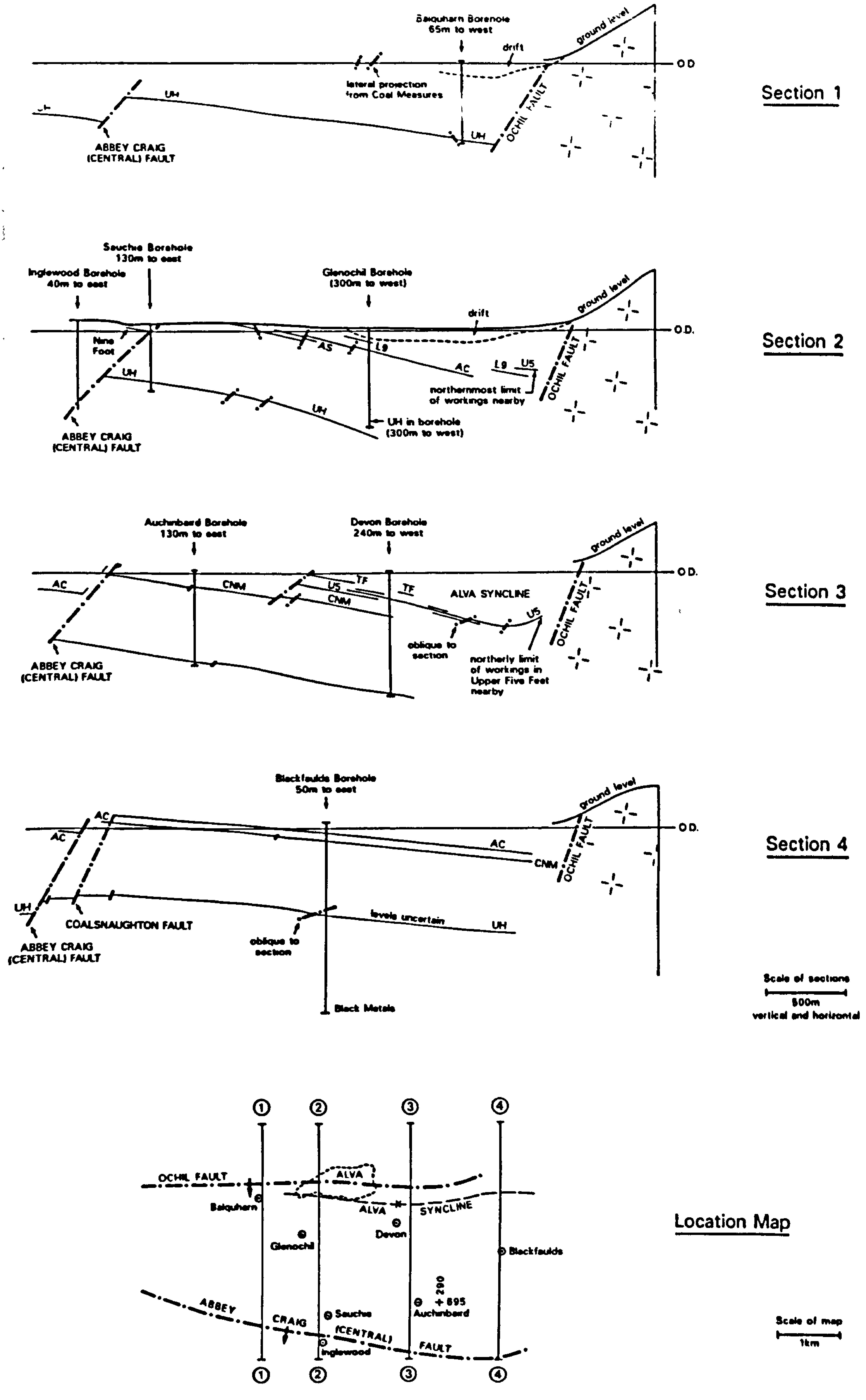
Fig.9.4



Main structural elements of the area adjacent to the West Ochil Fault

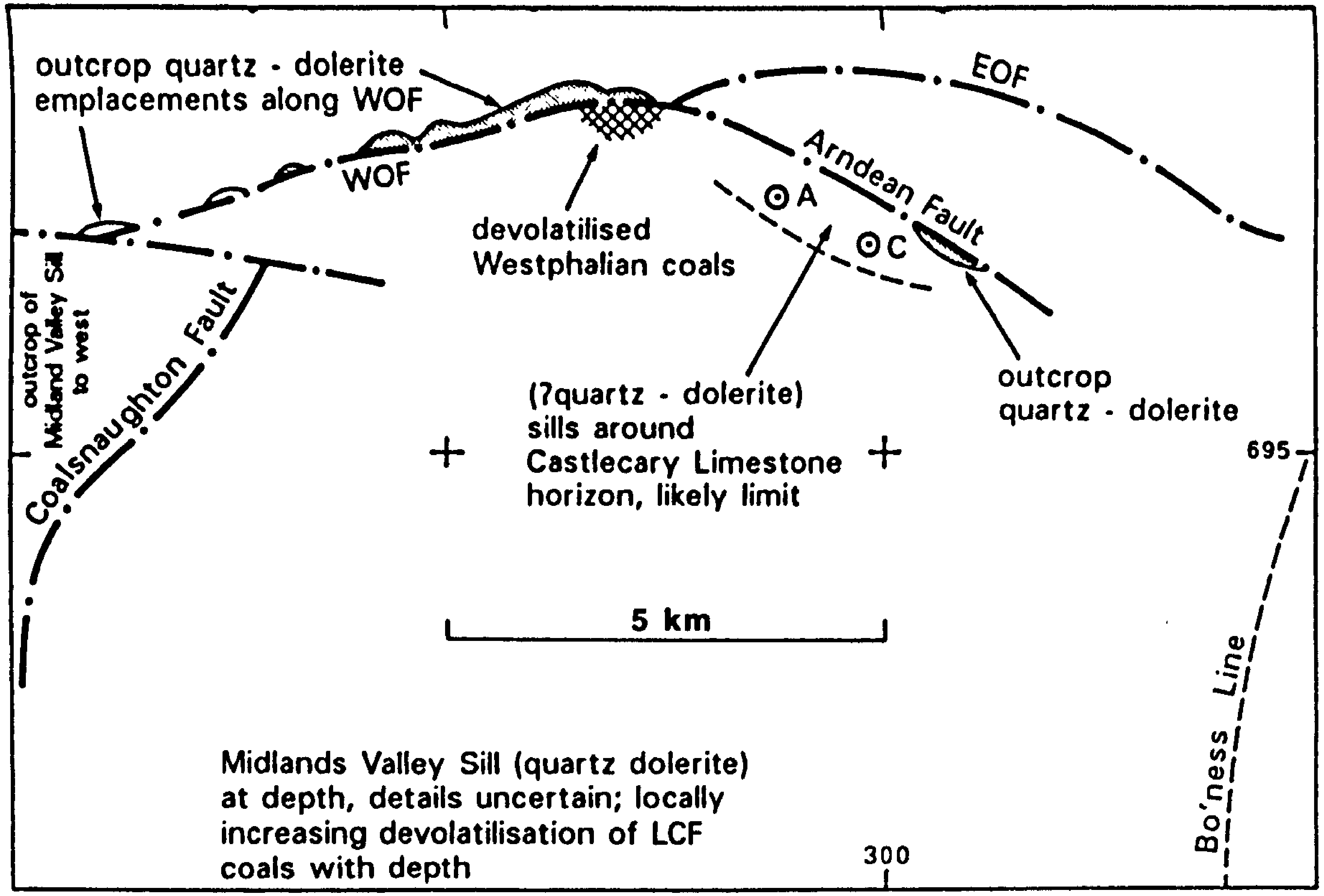
Faults : ACCF, Abbey Craig Central ; LF, Langfauld Fault ; SF, Sheardale Fault

Fig.9.5



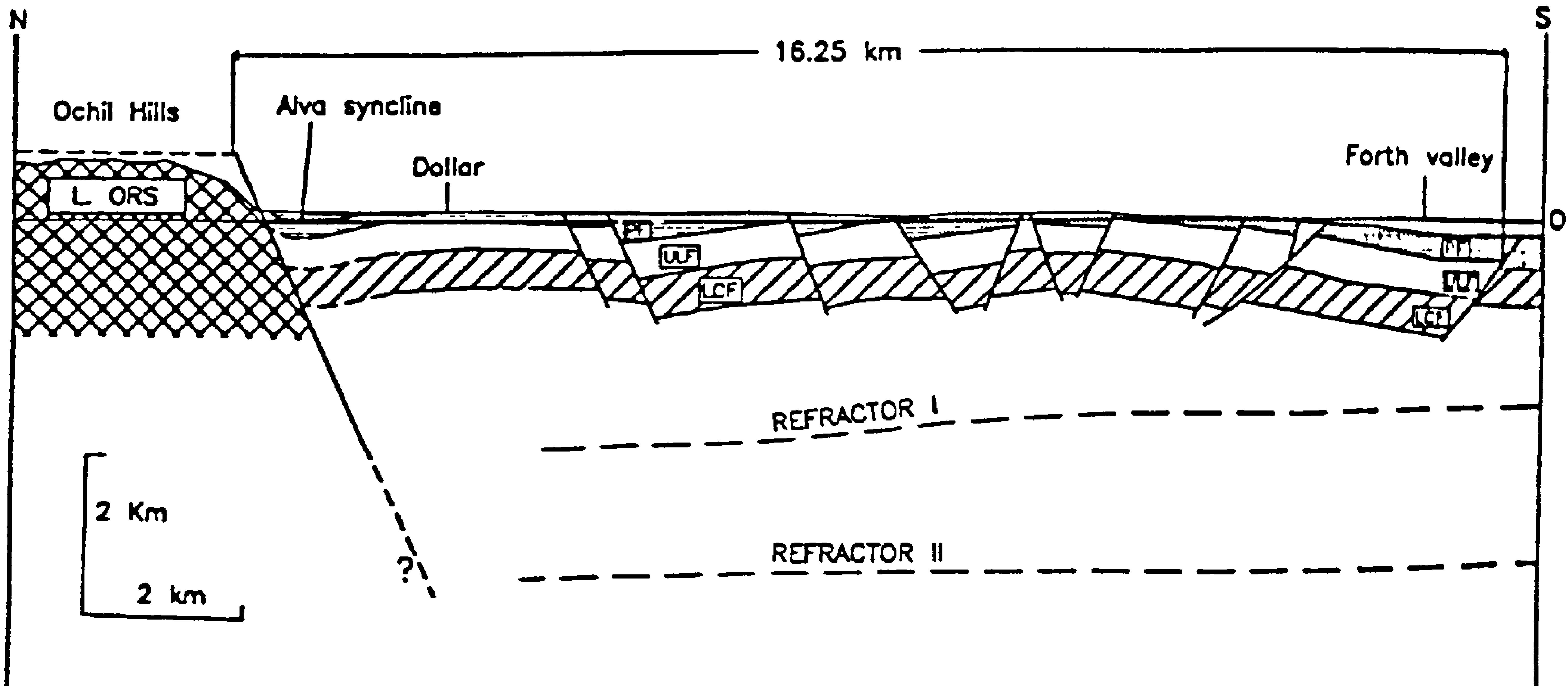
Ochil Fault and Alva Syncline, Simplified Cross Sections

Fig.9.6

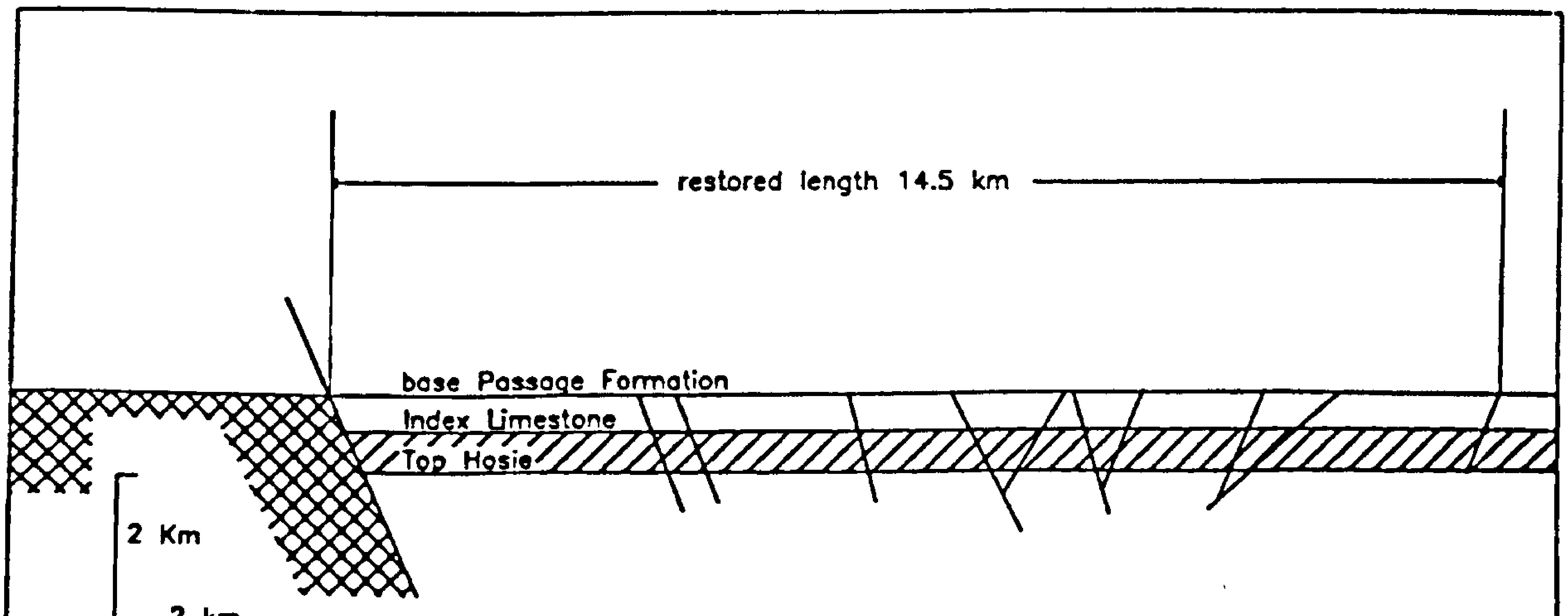


LATE CARBONIFEROUS/PERMIAN IGNEOUS INTRUSIONS
IN THE OCHIL FAULT/KINCARDINE BASIN AREA

Fig.9.7



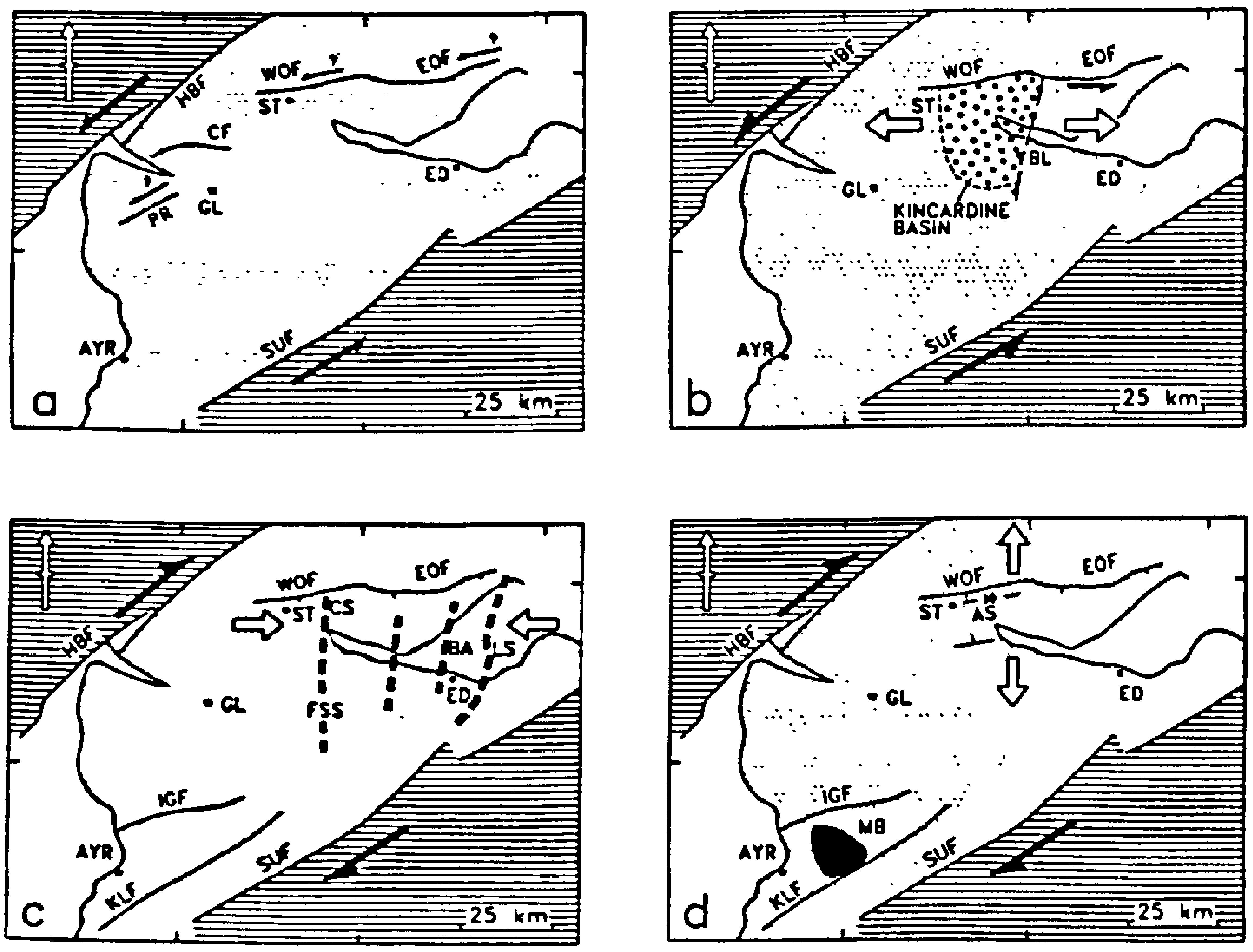
8a SIMPLIFIED CROSS SECTION FROM THE WEST OCHIL FAULT TO THE RIVER FORTH



8b RESTORED SECTION TO BASE PASSAGE FORMATION

SIMPLIFIED CROSS SECTION AND RESTORED SECTION FROM THE WEST OCHIL FAULT TO THE RIVER FORTH

Fig.9.8



KINEMATIC INTERPRETATION OF THE TECTONIC SETTING OF THE OCHIL FAULT AND BO'NESS LINE FROM DEVONIAN TO LATE CARBONIFEROUS/EARLY PERMIAN TIMES

Fig.9.9

CHAPTER 10

VARISCAN STRUCTURES IN THE KENT COALFIELD, AND THEIR REGIONAL SIGNIFICANCE

Abstract: *The Kent coalfield's southern areas lie some 20km north of the commonly accepted position of the Variscan Deformation Front, but despite intense intra-coal deformation, the literature is ambivalent about Variscan compression. The main deformation is interpreted here as Variscan thrusting, structural style being imposed by the sandstone-dominated lithology. As in South Wales, a zone of thrusting many 10's km wide lies in advance of the main front. Trends are consistent with an overall swing in the front from W-E across much of central-southern England, to more NW-SE across northeastern France, suggesting a transpressional transfer zone, with stress deflection and block rotation producing thrust vergence oblique to the overall direction of maximum compression.*

10.1 Introduction

The Kent coalfield (Fig.10.1) occupies a NW-SE syncline southeast of Canterbury, and passes to the southeast under the English Channel. There are no offshore provings, but the Boulonnais field of France has long been seen as its continuation (e.g. Bertrand 1893). Westphalian Coal Measures, probably of the Lenisulcata Zone, lie unconformably on Dinantian strata. The Coal Measures sequence extends upwards into at least Westphalian D, and is everywhere concealed unconformably by various Mesozoic formations (Shephard-Thorn 1988). Figure 10.2 illustrates generalised Westphalian stratigraphy, together with South Wales for comparison. This account is based largely on Rippon *et al.* (1997).

Around thirty individual coal seams have been identified, with down-stratigraphy numbering, by the mining industry, adopted for the most prominent. Kent 1 to 5 seams lie in the Westphalian D sandstone-rich (Pennant) sequence. Kent 6 is the seam best known from mining and borehole data, and is considered to lie near the Westphalian C/D boundary. The apparent absence of the Phillipsii Zone (Shephard-Thorn 1988) suggests a subtle intra-Westphalian unconformity. The well-defined sub-Westphalian D unconformity of the Forest of Dean (Green 1992) occurs at a similar stratigraphical level to the Kent 6. Kent 7 to 14 seams are of Westphalian A and B age.

The existence of a concealed field in Kent was first promoted by Godwin-Austen (1856) and confirmed in 1890 by drilling at Shakespeare Cliff, Dover (Dawkins 1897). Numerous boreholes were subsequently drilled to the Coal Measures, and there were various shaft sinkings. Five mines produced coal, commencing with Shakespeare Cliff in the late 1890's. The others (Betteshanger, Chislet, Snowdown, and Tilmanstone: Fig. 10.1) continued to the 1950's (Chislet) and the 1980's. Mining ceased in 1989, with the closure of Betteshanger.

This account does not attempt a full description of the coalfield's geology, but describes those aspects which are considered to relate to Variscan deformation. As will be seen, there has been considerable debate over the presence of compressional structures in the Kent Westphalian. By consideration of a specific structural style, and by comparisons with South Wales, it is hoped to resolve this debate, and thereby integrate the coalfield into a late Carboniferous tectonic setting consistent with other parts of northwest Europe.

10.2 Available data

Various seams have been mined in very limited areas adjacent to shafts, but there has been more extensive extraction in the Kent 1 at Snowdown and Tilmanstone, Kent 6 at Betteshanger, Snowdown and Tilmanstone, and Kent 7 at Betteshanger and Chislet. The most widespread mining, and therefore geological knowledge, is at the Kent 6 horizon. Given its Westphalian C/D age, the geological characteristics of this seam may be different to those in Westphalian A/B. Much of the coalfield remains unmined in any seam, so a wider understanding of both depositional and structural geology is not straightforward. The coalfield is proved by around sixty surface boreholes, many of which were drilled into Dinantian strata, although a significant number of more recent holes were drilled only to prove the main reserves seams (Kent 7 and 6). Some boreholes on the margins of the coalfield proved only residual or absent Westphalian rocks. Within the mined areas, there were also many underground boreholes, providing detailed local information. National Coal Board/British Coal Corporation (NCB/BCC) surface reflection seismic surveys were undertaken around the previously-active mines, and locally beyond. However, the key data are the records of the mine workings themselves.

10.3 Previous interpretations

The existing literature is divided on the issue of whether there are significant Variscan compressional structures in Kent. It is invariably acknowledged that the coals are deformed, but this has been assigned to both depositional and structural processes, or a combination of these. The debate has involved not only the conflicting geological arguments, but also significant observations by mining engineers, and it is pertinent to summarise the main contributions here.

Godwin-Austen's (1856) forecast of a concealed field in Kent implied a Variscan setting, and the possibility of compressional structures was considered reasonable by many geologists and mining engineers as exploration and mining progressed through the early 20th Century. Authors from both backgrounds noted regional trends in the Variscan-disturbed coalfields of Somerset to the west, and northern France to the south and east, but generally considered that evidence for Variscan compression in Kent was indirect and inconclusive.

Arber (1914), summarising the early exploration and mining phase, found "no indication of an overthrust", although Professor Henry Louis (1914), in a discussion in Arber's paper, maintained that extreme variations in the coal thicknesses and disposition in the ground ("excessively false bedded") suggested that the coalfield may have been "traversed by very flat overthrust faults, which would easily escape notice in a boring, and ....have the effect of producing or accentuating the appearance of false bedding"; he expected thrust faults to be found during future exploitation of the coalfield. Louis' (1914) observations on coal variabilities were borne out by many later observers, but not all supported a structural origin. Thus White (1928), noting the rapid lateral thickness changes in the coals, and quoting Bolton (1915), regarded these variations as the results of "contemporary denudation", implying incision and deposition from major floods. Those trying to interpret the stratigraphy (e.g. Bolton 1915) obviously found it less easy than in other English coalfields farther north, and structural disturbance was sometimes invoked.

Dines (1933) considered that there was evidence of folding during deposition of the Coal Measures, especially for the later Westphalian C/D successions. This was based on inter-seam isopach patterns reflecting a basin form, but he considered that most folding was post-depositional. Regarding compressional structures, he noted that Stonehall borehole (E.627069, N.145466) "contained an unusual amount of thick coals, several of the thicknesses being repeated exactly. The bore may have passed through an area of reversed faulting or overthrusting, causing repetition of the seams...". He also noted compressional structures in the overlying "roof" of the Beresford (Kent 1) seam at Tilmanstone, but gave no details. Dines (1933) further reported on the generality of geological disturbances, especially in the Kent 6 of Snowdown and Chislet, and the H and I seams (approximately Kent 7/8, Fig.10.2) of Betteshanger. These features, which excluded obvious high-dip fault planes, included many "floor rolls", i.e. linear emplacements of underlying clastic rocks into the coal, usually within the overall thickness of the seam rather than completely replacing it. Dines regarded these as having formed during or immediately after coal deposition, with their mainly NW-SE trend reflecting syndepositional folding. He also noted sudden thickening of coals along zones adjacent to belts of thin coal, which was ascribed to redeposition by flooding. Elsewhere in the coalfield, Dines (1933) maintained that the majority of the "non-fault" disturbances were essentially depositional.

Baker (1935) undertook a regional assessment of the extent of coalfields in southeastern England, suggesting an undiscovered field beneath the north Kent/Thames Estuary area. This was envisaged as structurally separate from the known Kent coalfield, and included the interpretation of an inverted sequence in a NE-verging thrust system north of Chislet. Smart *et al.* (1966) briefly reviewed the structure in the Canterbury and Folkestone district, largely away from mining areas, and did not report any specific compressional structures.

Shephard-Thom *et al.* (1972 p.100) discussed regional structures and considered that thrusts were absent in the Kent field. The Appendix to this paper by P. Rumsby dealt specifically with structure revealed by mining, but recorded only high-dip faults which were mainly regarded as normal, with some reversals. No thrusts were reported, although "channels and ridges" of thick and thin coals trending roughly parallel to the "main fault system" (i.e. NW-SE) of the coalfield were noted. Shephard-Thom (1988) considered that the Dover and Ramsgate area of the coalfield lay sufficiently far to the north of the Variscan Deformation Front (which was suggested to cross the English coast near Dymchurch) to have been unaffected by thrusts.

Unpublished NCB/BCC reports dealing with the Kent coalfield include many drawings of various styles of seam disturbances, together with interpretative comment. These mainly follow arguments for a depositional origin. However, some observers considered the disturbances to be largely tectonic, with individual structures sometimes being initiated on depositional heterogeneities such as erosional scours. Reports on coal quality and thickness by the Coal Survey and particularly by H.R.Bloodworth (see Figure 10.3), illustrate and describe both thrusts and characterisic seam variabilities, usually without speculation on their geological origins.

Many logs of the earlier deep boreholes have been published, mainly by the Geological Survey and in mining literature, but the majority of these lack detail. The earliest boreholes were not recorded to a standard that would allow straightforward detection of low-dip fault planes. No recent detailed core descriptions have been published, but some of the modern boreholes are known to include prominent low-dip and highly brecciated disturbances, e.g. at Swanton Court (E. 623865, N. 144309). Unpublished NCB/BCC surface reflection seismic profiles are available, especially across the main mined areas; no specific compressional structures were reported from these, within the limits of resolution and interpretable depth.

10.4 Structural styles in the Kent coalfield

It is apparent that there is no consensus in the published accounts relating to Variscan deformation effects. On the one hand, the regional setting immediately north of the Variscan Deformation Front (Fig. 10.1) suggests that compressional structures should be evident; on the other hand, authors are divided over whether these are present. The existing literature indicates that, if compressional structures are present, they are much less obvious than in South Wales (Frodsham & Gayer 1997) despite a similar distance from the main front as mapped. Some of the structural features of the Kent coalfield are now described and discussed.

10.4.1 Compressional structures

Regional scale folding. The overall Kent coalfield syncline includes a poorly-defined anticline, striking NW/SE just southwest from the main synclinal axis (Shephard-Thorn 1988). Also, the present western margin of the field is an abrupt rise (Shephard-Thorn *et al.* 1972) and may involve steeper dips, or possibly large-scale faulting (Shephard-Thorn 1988). Otherwise, evidence of folding at the regional scale (several km^2) has not been published, and is essentially unknown.

Local folding. Apart from the steeper dips associated with some fault zones, more gentle flexures, on a crest-to-crest scale of a few hundreds of metres, and with amplitudes of a few tens, are discernible on depth-contoured mine plans. Such flexures, with no readily-mappable trends, occur at Betteshanger, where those in the Kent 7 appear disharmonic with similar-scale features in the Kent 6, some 100m above. The lack of vertical continuity may reflect the inferred unconformity below the Tenuis Zone, but may also result from open folding with detachments, for which there is evidence from depth-contoured mine plans at various locations in South Wales. It is thought that these contour differences do not reflect depositional thickness variations; similar intervals in coalfields with no pervasive compressional deformation, such as the English Pennine Basin fields, do not show comparable features.

Small scale folding. On a scale of centimetres to tens of metres wave length, there is pervasive folding in the Kent 6 Seam (notably at Betteshanger) together with some deformation of adjacent clastics, and it is probable that this characterises other coals that are less known. This folding is commonly strongly asymmetrical, with some recumbent limbs and with crests which have a prominent NW-SE strike, and is associated with the interpreted thrust faults described below.

Reverse and thrust faults. Faults recorded as reverse on mining plans and in NCB/BCC reports are relatively rare, and display a variety of strikes. Some may be elements of overall strike-slip systems, and these tend to lie in groups along with other small faults, which are recorded as normal. Others are more isolated with generalised W-E or NW-SE trends. Most of these various reverse faults are thought to have relatively steep fault plane dips, probably greater than 50^o, based on occasional drawings in the mining records; however, they have not been described as thrusts, and are to be distinguished from the features described below. As noted, thrust faults in the Kent coalfield have not been reported in the existing literature (Shephard-Thorn *et al.* 1972, p.100; Shephard-Thorn 1988, p.31) despite proximity to the Variscan Deformation Front, commonly drawn close by through Dungeness or Dymchurch (Fig. 10.1); moreover, they are only occasionally specified in unpublished mining records.

One such record (Bloodworth 1963), redrawn here as Figure 10.3, shows thrusting in the Kent 7 coal at Chislet in the north of the coalfield. In other coalfields, structures such as this can be found as a product of the depositional environment, where mass failure of the banks of a palaeo-channel has involved a detachment within or close to an underlying coal (peat), resulting in small-scale thrusts along the toe (e.g. Jones *et al.* 1995). The depositional environment in the neighbourhood of this feature at Chislet is not known, and would now be difficult to establish from the mining data. It is emphasised, however, that thrusts of this origin are very rarely reported in British coalfields.

So far as can be ascertained, the coals at Chislet did not exhibit the extremes of thickening and thinning found farther south, for example at Betteshanger. The mining records for Betteshanger include "isopachyte" plans for the Kent 6, showing thickness variations (and perhaps implying in the title description that they were considered to be of depositional origin). Figure 10.4 is a redrawing of part of the main "isopachyte" plan, and Figure 10.5 shows some detail. The typical lengths and widths of the thick and thin coal zones can clearly be seen, as can a characteristic spacing; it will be noted that the thick zones are typically just NE of the thin zones. It is difficult to envisage any depositional effects that could reproduce the consistent orientations, spacings, and thick/thin dispositions shown here, and the simplest explanation of these structures is that they are tectonically-driven thrusts confined by gross lithology to within, or immediately adjacent to, the coal. Figure 10.6 shows detailed cross-sections in the Kent 6 at Betteshanger: the intense small-scale deformation of the coal shown here includes thrusts and folds verging to the NE, which is compatible with a thrust interpretation for the thickness variations. Figure 10.7 shows these variations schematically, noting the restricted observational height available, and the resulting difficulty of recording bed repetitions.

10.4.2 Other structures

A detailed account of the non-thrust structures in the coalfield is beyond the scope of this account; some detail is given by Shephard-Thorn *et al.* (1972) and Shephard-Thorn (1988). These papers regarded most of the high dip faults as normal, although some reversals of throw direction were recorded. It is likely that many of the characteristic NW-SE high-dip faults have a prominent strike slip component, based on the following observations.

1. Fault traces on mine plans are often very straight, and dip slip throw distributions are not always systematic: these can be quite variable, and maxima are often less than would be expected from the recorded extents of the fault traces. Further, disturbances on this strike are known which show significant disruption of the ground without any recorded dip slip.

2. Fault plane dips are often >70° (Rumsby, in Shephard-Thorn *et al.* 1972), steeper than typical for most British coalfields, although this may simply reflect the gross strength of the sequence; elsewhere, planes are known to refract to steeper dips through sandstones (e.g. Rippon 1985).

3. Individual faults show throw reversals along their map traces; elsewhere, clusters of reverse faults co-exist closely with apparently normal faults.

There is no readily available information on whether these have offset other structures or depositional features; the high-dip fault shown across Figures 10.4 and 10.5 does not appear to offset the interpreted thrusts, but it is likely to have only a small strike slip displacement anyway. The relationship of these faults to Variscan deformation is therefore uncertain, but there is evidence of faulting on this trend and style cutting the Mesozoic cover (Shephard-Thorn 1988, p.31) and therefore at least some of these features may reflect Tertiary movements.

10.5 Regional setting: comparisons with South Wales

The Westphalian coalfields of South Wales and southern England (Fig. 10.1)are separated from those of the English Midlands by the Wales-Brabant High (Rippon 1996; see Chapter 2). Communication between South Wales and the Midlands in the mid-A to mid-C Westphalian sequence was inferred by Trueman (1947) and Wills (1956) on the basis of faunas and intervening remnant outcrops; further similarities in the coal sequences suggest some common external control on overall base level in all depositional areas. There may also have been communication through Oxfordshire into the southern province in Berkshire (Foster *et al.* 1989). The high was overstepped through the later Westphalian. Peace & Besly (1997) describe the evolution of the Variscan foreland and the high in the late Carboniferous.

In South Wales (Fig. 10.8), deposition south of the high has been interpreted (Kelling 1988) to have been in a foreland basin setting related to the developing Variscan orogeny. The more intensively deformed Bristol and Somerset fields, east of South Wales, are less well known and like Kent, most spatial mining data are in the later Westphalian. Some details are given in recent publications of the British Geological Survey, e.g. Green (1992) and Kellaway & Welch (1993). The general depositional setting of the Kent coalfield is not well known. There are, however, many geological similarities with South Wales, summarised as follows.

1. The overall lithostratigraphy and seam sequence (Fig. 10.2) is comparable, although the Kent succession is thinner than most parts of South Wales. While mining detail in Kent is largely restricted to the later Westphalian C/D, borehole data show that the earlier Westphalian is also similar to South Wales in terms of typical lithofacies proportions and cyclicity.

2. Coal ranks include semi-anthracites in parts of Kent (National Coal Board 1959) in a pattern which recalls that in South Wales (White 1991).

3. The coals in both South Wales and Kent are very bright and brittle, with very high frequency (but generally only slightly mineralised) cleats (see 7.5.2). The Kent seams also contain the *c.*45^{o} dipping conjugate slip planes that characterise South Wales coals, and which are only found elsewhere in British coalfields (north of the high) close to specific large structures (see 7.1).

4. The coals and adjacent ductile clastics in both coalfields are commonly disturbed by low-dip shears and small (metre-scale) duplex structures; these verge at least locally to the NE in Kent.

In southern Ireland and South Wales the concept of the "Variscan Front" has been developed to represent the northern limit of late Palaeozoic compressional deformation (Shackleton 1984). The location of the front is, however, ambiguous, depending on the criteria used to define this limit. It is useful to discriminate here between the general N/NW-verging system, i.e. "Variscan", and certain N-S striking, end-Carboniferous, thrusts and folds found in (and well beyond) the immediate Variscan foreland (Corfield *et al.*1996, Peace & Besly 1997). The most widely used criterion is the external limit of a linked thin-skinned thrust system or decollement. Thus Shackleton (1984) placed the front in South Wales along the Ritec Fault in southwest Dyfed, and eastwards into the south crop of the South Wales coalfield, which is in general agreement with the interpretation of thrusts in the BIRPS SWAT seismic reflection profile (Le Gall 1990). However, the present day outcrop of the linked thrust system is an erosional "snapshot" of a formerly more extensive structure and the front's present geography is dependent on the depth of erosion. It is often impossible to locate the front precisely, and it is considered more appropriate to draw a zone, in which several major thrusts and associated folds are present. In South Wales, this main deformation front zone coincides with the Llannon/Trimsaran Disturbances in the west of the coalfield (Frodsham & Gayer 1997) but may be stepped to the south, across a NW-SE striking fault in the Swansea Bay area (see 6.6.1). However, there are numerous and pervasive lesser thrusts to the north beyond the main deformation front, forming a much wider zone. It is this wider zone of compression which is now discussed.

The South Wales and Kent coalfields both lie a similar distance just north of the main deformation front as commonly drawn, from western Wales, through south-central England and across the coast between Hastings and Folkestone (e.g. Robert 1989). In South Wales, thrusting is well known throughout the coalfield to its northern outcrop, which locally lies some 40km beyond the main front. By analogy, therefore, compressional tectonics might be expected throughout the Kent field, unless the main detachments were located beneath or above the coal-bearing Westphalian. However, South Wales thrusts are commonly concentrated in the more argillaceous parts of the succession (Frodsham & Gayer 1997), i.e. below the main mined horizons in Kent. The regional setting of the Kent coalfield, and similarities with South Wales, suggest that the Variscan mountain front model of Jones (1991) may be applicable to Kent.

10.6 Compressional structural styles in South Wales

It is useful at this point to review the styles of Variscan deformation in South Wales, particularly in the two very different lithostratigraphic sequences there, namely the coal-rich and largely argillaceous mid-A to mid-C Westphalian, and the coal-poor and largely arenaceous later C/early D Westphalian, that is, the South Wales Pennant Measures (Fig. 10.2). It has long been known that, in general terms, the older sequence is more intensively disturbed, the competence of the overlying Pennant sandstones having limited thrust propagation. This is a good generalisation, although thrusts are known in the Pennant Measures (e.g. Woodland & Evans 1964, p.247 and p.271). Conversely, there are parts of the coalfield where thrusts are relatively rare in the earlier argillaceous sequence. Thrusting does not seem to have been uniformly distributed (see 6.6.1), even through similar gross lithologies. Some parts of the South Wales coalfield that have relatively few thrusts are as large as the mined areas in Kent.

Thrust styles in the lower, argillaceous sequence in South Wales have been described by Frodsham & Gayer (1997). In Kent, most of this sequence is unmined, and unknown in any detail beyond borehole data. As noted, some earlier authors considered the variability of these earlier Kent coals (in terms of coal thicknesses, inter-coal intervals and, compared with other English coalfields, a tendency to extreme "splitting", i.e. uniting and dividing) as reflecting thrusting; one key concern was that the lower sequences were very difficult to correlate. All these characteristics are recognised in South Wales, particularly in the higher rank areas west of the Neath Valley.

Thrust styles in the later, arenaceous Pennant are more relevant to the main mined horizons in Kent. In South Wales, coals in this sequence are similar to the later Westphalian C/D Kent coals in as much as they are frequently no thicker than 1m, and are closely underlain and overlain by persistent, thick sandstones. In these circumstances, thrust planes are commonly confined to the coals and any immediately-adjacent clay-rich and more ductile lithologies (such as clay-rock palaeosols). In the absence of definable thrust planes, intra-coal shears are common, as are small duplex structures including arrays of sigmoidal shears indicating propagation directions compatible with known regional thrusting. Over scales of metres to tens of metres, coals exhibit thickening and thinning, and are sometimes sheared out. Structures recorded on South Wales mine plans in such seams are commonly limited to high-dip, mainly normal faults.

10.7 Re-interpretation of deformation in the Kent coalfield

10.7.1 The recognition of thrusts

It is suggested here that the previous lack of recognition of thrust faults in Kent is a consequence of a number of factors, especially the following. 1.There are no known very large thrusts in Kent compared with South Wales and Somerset. 2. There is little similarity with the thrust styles that characterise the earlier argillaceous sequence coals in South Wales (which have often been thought typical of thrusting in British coalfields). 3. There is frequent interaction between sedimentary features and the structures interpreted here as thrusts. In places, it is possible that sedimentary forms such as channel-base scours controlled the initiation and extent of individual thrusts. 4. The deformation is largely restricted to the coal horizon, and its immediately-adjacent more ductile rocks, strong sandstones close below and above being relatively undeformed. Thrusts of this style will only rarely have been recorded on mine plans, and significant ramps will be scarce. Also, such features would not be detected on seismic reflection surveys.

The envisaged thrust style would therefore involve redistribution of coal within shear zones, with few or no whole-seam repetitions within the limited mined exposures. The deformation of the coals is considered to be thrusting of tectonic origin, rather than the effects of mass movement during deposition, for the following reasons. 1. Brittle fracture effects are recorded. 2. At least some of the coal cleats are rotated/sheared. 3. There is a consistent strike of the thrust fractures, which is also consistent with the orientation of the minor recumbent fold crests. 4.The deformed coal shows duplexes and sigmoidal shears characteristic of thrust sheets in coal seams. 5. The overall complex of minor thrusts and associated folding shows essentially regular spacings between crests and between juxtaposed thick/thin coal.

Given that the pervasive thickenings and thinnings of the coals can be interpeted as products of thrust deformation restricted largely to the coal horizon by the gross lithology, it is appropriate to speculate on the degree of deformation compared with South Wales, and compare distances from the Variscan Deformation Front as mapped, e.g. through Dymchurch. It was noted above that thrust intensity in South Wales is not necessarily a straightforward measure of distance from the main deformation front. However, using the data from Kent, and bearing in mind that the main evidence is from the later, arenaceous sequence (which in South Wales is less obviously deformed), it is concluded that the Kent 6 disturbances at Betteshanger represent compression compatible with ground less than 30km from the main deformation front.

10.7.2 Implications within southeastern England

Figure 10.9 shows the Kent coalfield related to regional structural trends. While there is general parallelism between most of the lineaments mapped in southeast England and the known Variscan thrusts of northern France, the trend inferred at Betteshanger is more northwesterly. However, the northern margin of thrusting, to the north of the main deformation front, may well be expected to show different trends reflecting more local thrust propagation directions. Regional analyses in southern England (e.g. Baker 1990) show that the more northerly-lying structures in the London area are oriented roughly W-E, and a relatively tight turn to NW-SE would in any case be required across northern Kent for this margin to stay within the generalised parallelism of the overall deformation. It is interesting to note that broad W-E folds affect Mesozoic rocks (the Thanet Anticline and the Richborough Syncline, see Shephard-Thorn 1988) just north of the coalfield; it is possible that these reflect a perpetuation of a W-E trend. However, the overall likelihood is for the northern margin to swing southeastwards, compatible with the Betteshanger trend.

Specifically regarding compressional structures, it should be noted that southern England was subjected to post-Mesozoic deformation. The degree to which late Cretaceous to Tertiary stress directions coincided with Variscan vectors in southern England is an interesting question. Brooks *et al.* (1988) considered that large Mesozoic extensions in the Bristol Channel re-used Variscan thrusts, while various authors (e.g. Baker 1990) have assessed prominent structures in the Mesozoic outcrops of south-central England as the shallower expression of re-activated thrusting on Variscan features. The course of the main Tertiary deformation front through this area is largely inferred, in the literature, by specific north-verging folds and thrusts in these later rocks. On a regional scale, it seems that the Variscan and the post-Mesozoic compressional stress directions were roughly coincident. It is possible that the successor to the Wales-Brabant High north of the Variscan foreland basins once again limited, and shaped, the outer limits of the deformation front as now preserved. There could, therefore, be Tertiary compressional features within the Westphalian of Kent, and in South Wales. The broader post-Variscan history in Kent includes various periods of uplift and erosion, some details of which can be found in Smart *et al.* (1966) and Shephard-Thom (1988). Some effects on the Westphalian strata, particularly coal de-gassing during periods of uplift and erosion, are discussed by Creedy (1988).

10.7.3 The regional Variscan context

The regional trend of the northern Variscan Deformation Front in Europe shows a curvilinear trace (Fig. 10.10). In northern Germany (Ruhr) and westwards into eastern Belgium the trend is consistently SW-NE and all the fold axial traces and thrusts in the Ruhr coalfield strike parallel to this trend (e.g. Brix *et al.* 1988). Farther west in Belgium and in the Pas-de-Calais and Nord districts of northern France, the trend swings abruptly to WNW-ESE, parallel to the Grande Faille du Midi thrust. Associated smaller-scale thrusts in the coalfield to the northeast of this have a similar strike (Raoult & Meilliez 1987). This trend is followed by the principal structures in the Mesozoic outcrops of southeast England (Fig. 10.9); in central and southwest England and South Wales the trend is more nearly W-E.

As suggested above, except in northern Germany, the trends mirror the southern margin of the basement Wales-Brabant High (Fig. 10.10). In the Ruhr, no basement high has been recorded (Franke *et al.* 1990) and it is surmised that the regular geometry of Variscan structures in this region indicates an orthogonal NW vergence of Variscan deformation. Thus the areas to the west, where the trends are clockwise rotated by up to 70°, are likely to represent regions of oblique dextral convergence. Individual structures in these regions, however, do not show evidence of oblique dextral slip, as might be expected in a transpressional zone, but rather are developed as dip slip structures (e.g. Gayer & Nemcok 1994). This has been interpreted as a combination of block rotation and stress deflection where the zone of deformation forms a tapering wedge towards the foreland over the basment relief (Gayer & Nemcok 1994). Thus the inferred NW-SE striking thrusts at Betteshanger are likely to be dip slip structures developed in this regionally rotated transpressional system (Fig. 10.10).

10.8 Conclusions

The effects of Variscan deformation in the Kent coalfield are readily interpreted from pervasive shearing and compressional structures in the coals, from regular spacing and strike of the disturbances, and locally from a consistent northeastwards vergence. The compressional structural style revealed by mine workings in the sandstone-dominated later Westphalian C/D is largely a function of gross lithology; different styles might be expected in the claystone-dominated earlier Westphalian sequences, essentially unmined and therefore not described. The degree of deformation may be compared with relevant areas and similar horizons in South Wales, and is compatible with the Kent coalfield lying a few tens of kilometres north of the main Variscan Deformation Front. This is analogous to South Wales, where there is a broad thrusted zone in advance of the front as conventionally described. The strikes of compressional features within the coalfield are consistent with a broad regional swing in the Variscan deformation trend from W-E, west of London, to a more NW-SE trend, as recorded across northern France. It is suggested that this swing might represent a transpressional transfer zone across which block rotation and stress deflection produced varied thrust vergences, often oblique to the overall direction of maximum Variscan compression (see 7.6.2). These variations include northeastward vergence in Kent.

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10.10 Figure captions

Figure 10.1 Location of the Kent coalfield. Main mines mentioned in the text are: B, Betteshanger; C, Chislet; S, Snowdown; and T, Tilmanstone. Other coalfields mentioned are: 1, South Wales; 2, Forest of Dean; 3, Bristol and Somerset; 4, Berkshire; and 5, Oxfordshire (mainly Westphalian C/D overstep across the Wales-Brabant High).

Figure 10.2 Generalised Westphalian stratigraphy, eastern South Wales and Kent. The Westphalian C/D boundary in South Wales is usually placed around the Cefn Glas horizon; there may be a sub-Westphalian D unconformity in Kent (see text). Shephard-Thorn (1988) gives stratigraphical details for Kent. The eastern South Wales succession is typically 1000m, thickening westwards. U, L, T: Upper and Lower Tilmanstone Marine Bands.

Figure 10.3 Thrusting in the Kent 7 coal, "A's" face Chislet (Bloodworth 1963). **(a)** Thrusts at approximately E. 624000, N. 161800. **(b)** Typical seam section. **(c)** Regional location.

Figure 10.4 Betteshanger Kent 6 coal: "isopachyte" plan, redrawn from mining plans. The incidence of linear thick and thin coal areas is shown superimposed on mined areas. These zones are interpreted as northeast-verging thrusts. The figure also shows straight-trace high-dip faults with variable downthrows, interpreted as essentially strike-slip features of possible Tertiary age.

Figure 10.5 Betteshanger Kent 6: detail of the "isopachyte" plan (Fig. 10.4 and caption).

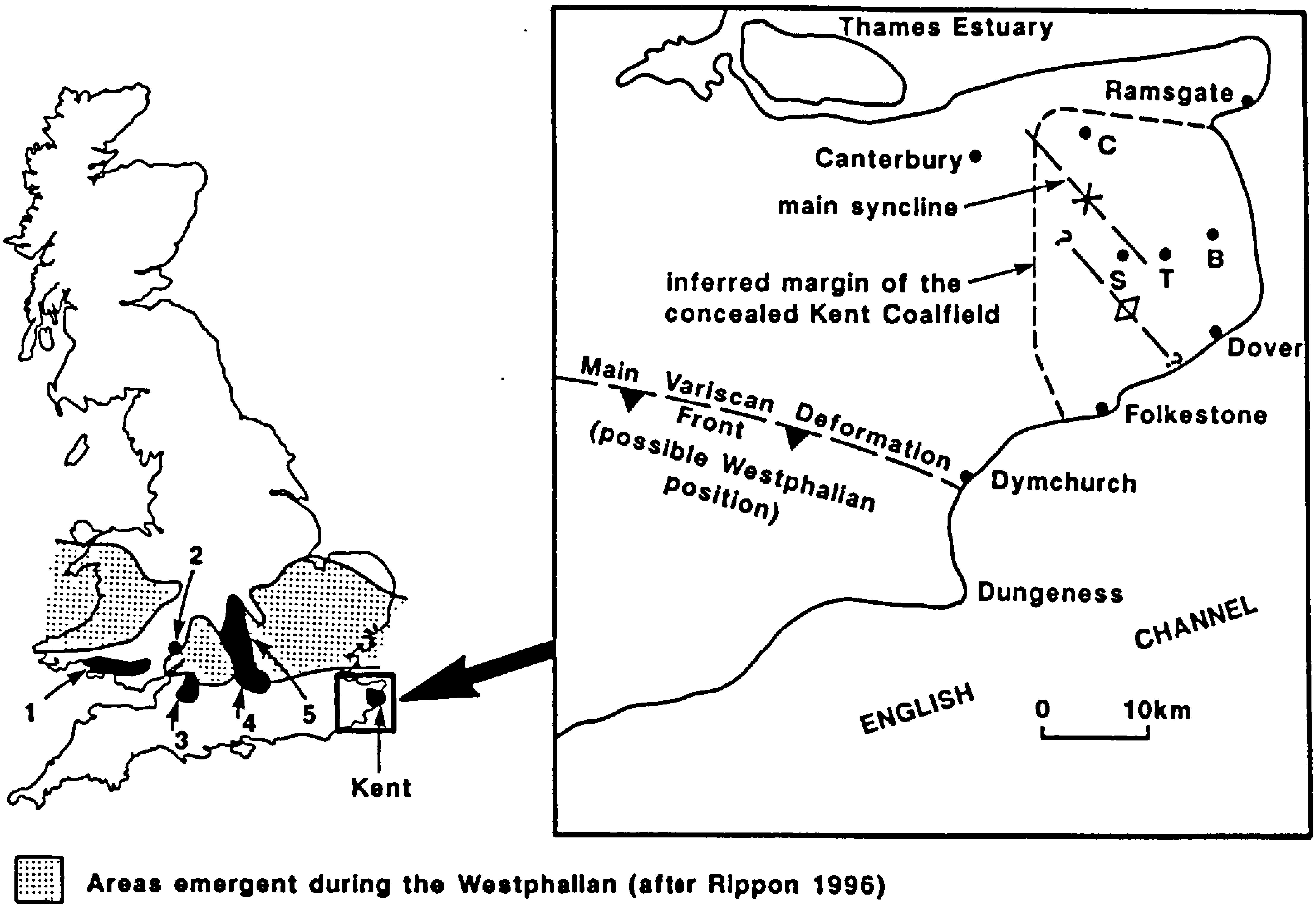
Figure 10.6 Small scale thrusts and duplexes in the Kent 6, Betteshanger, locations on "52's" face, approximately E. 634700, N. 155700. Coal and other bedding semi-diagrammatic.

Figure 10.7 Schematic thrusting style. Thick and thin zonation of the coals is produced by thrusts tending to flats within the coals, with further upward propagation inhibited by strong sandstone. Relationships with underlying palaeosols are usually masked by mining debris, with observations limited as indicated on the right of the diagram.

Figure 10.8 Map of the South Wales coalfield showing main faults and folds. CCD, Carreg Cennen Disturbance; CF, Carnafon Fault; LD, Llannon Disturbance; MGF, Moel Gilau Fault; MTB, Margam Thrust Belt; ND, Neath Disturbance; SVD, Swansea Valley Disturbance; TD, Trimsaran Disturbance; 8b shows the Ritec Fault in SW Dyfed.

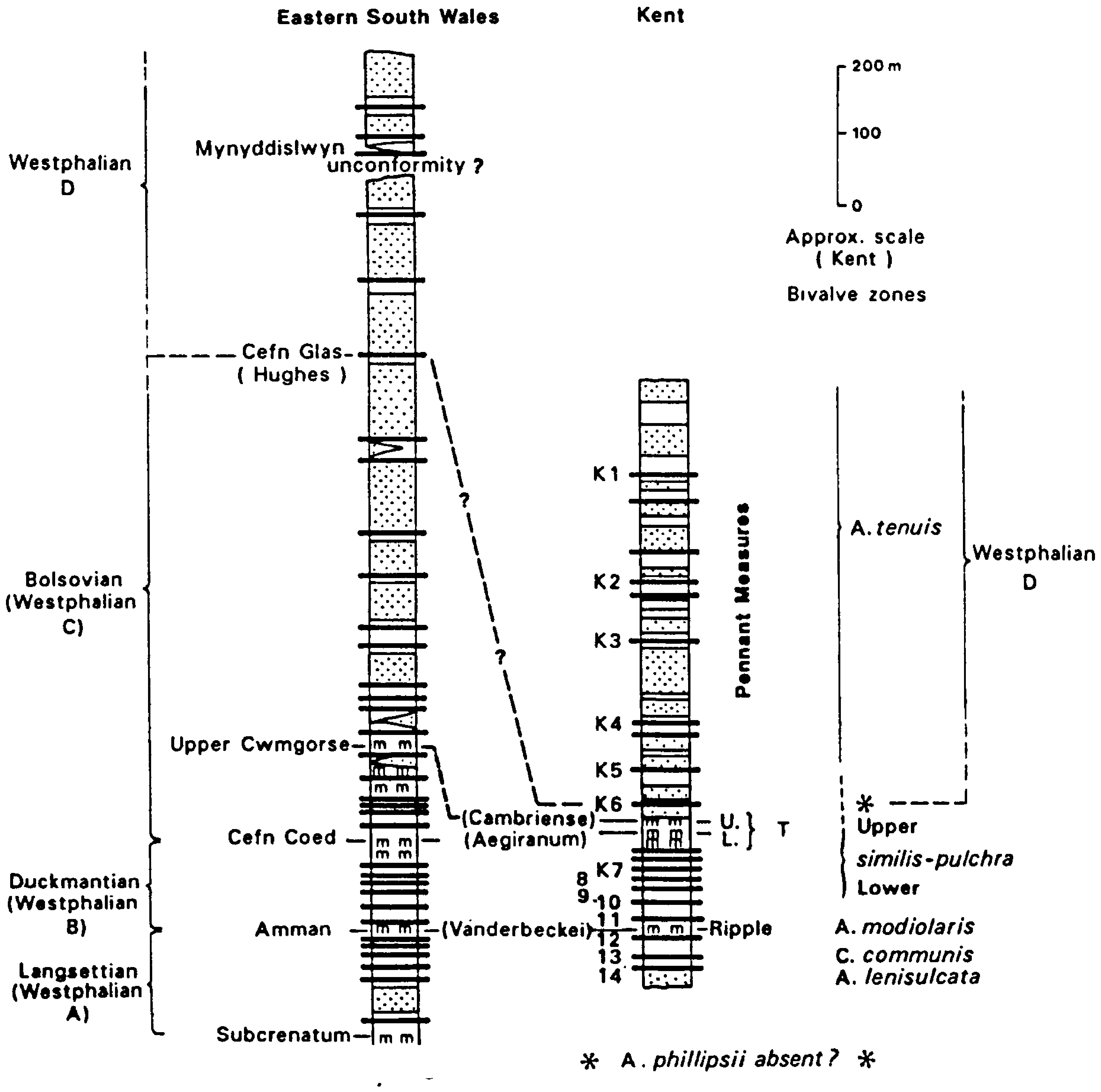
Figure 10.9 Trend variations along the Variscan Deformation Front. The front is conventionally drawn on a line that links the Dorking-Biddenden or Benenden structures across the Channel to the Grande Faille du Midi, usually interpreted as the dominant Variscan compressional structure in northeastern France. There is, however, no detailed evidence for a direct link. All of the Kent coalfield is within a thrust-prone zone in advance of this main front, and there is some evidence that thrust intensity decreases north from Betteshanger. B, Betteshanger; C, Chislet; S, Snowdown; T, Tilmanstone. Lineaments in southern England from Baker (1990); structures in northern France from Shephard-Thorn *et al.* (1972).

Figure 10.10 Major coalfields developed along the Variscan Deformation Front. Emergent areas during the Westphalian coincide with the Wales-Brabant High. The northwestwards Variscan convergence, currently assumed for this sector of the Variscides (e.g. Gayer & Nemcok 1994) produced NW vergence where compression was orthogonal at C, but N to NE vergence at A & B where block rotation and stress deflection occurred in a dextral transpressional transfer zone.



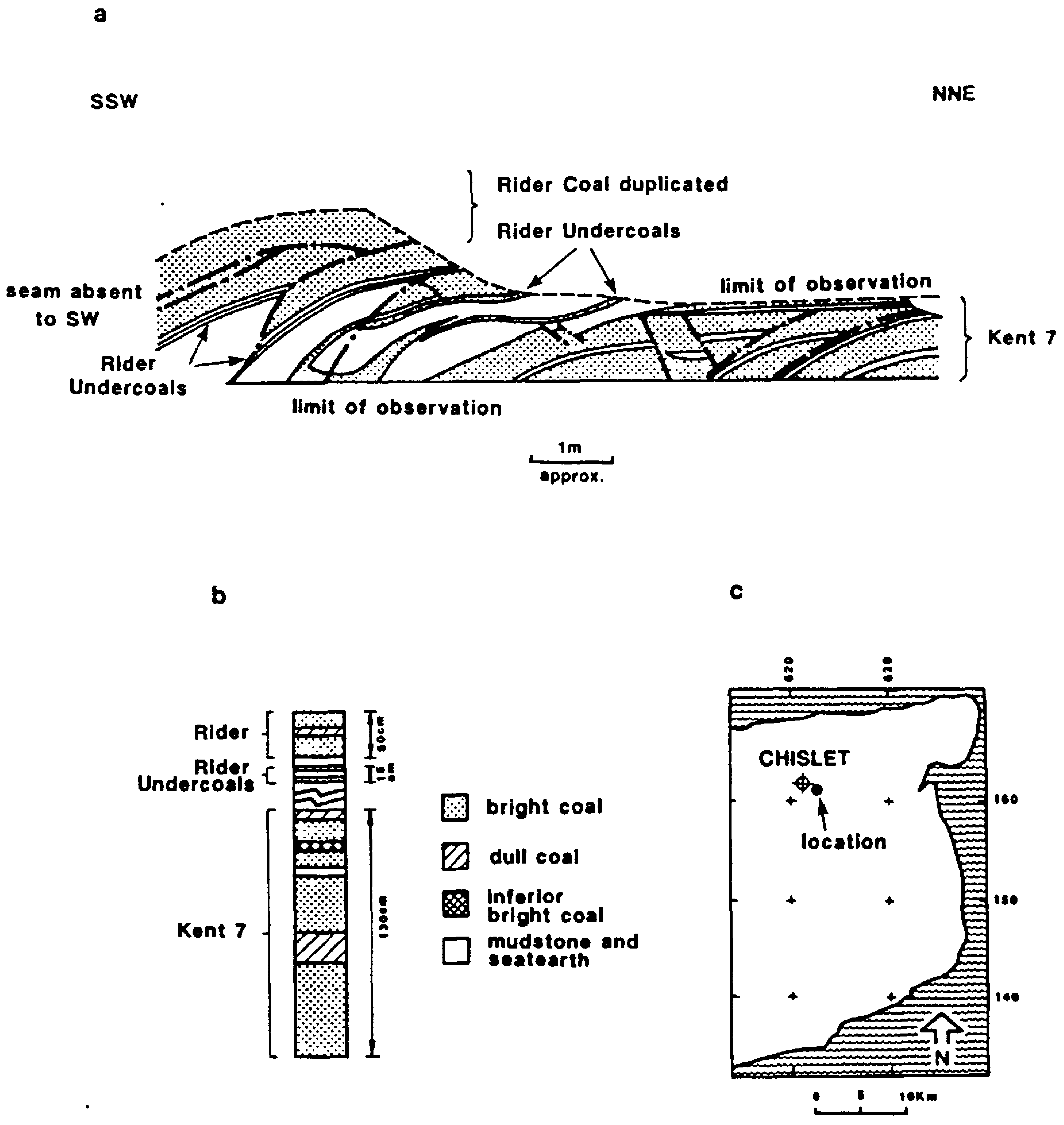
LOCATION OF THE KENT COALFIELD

Fig.10.1



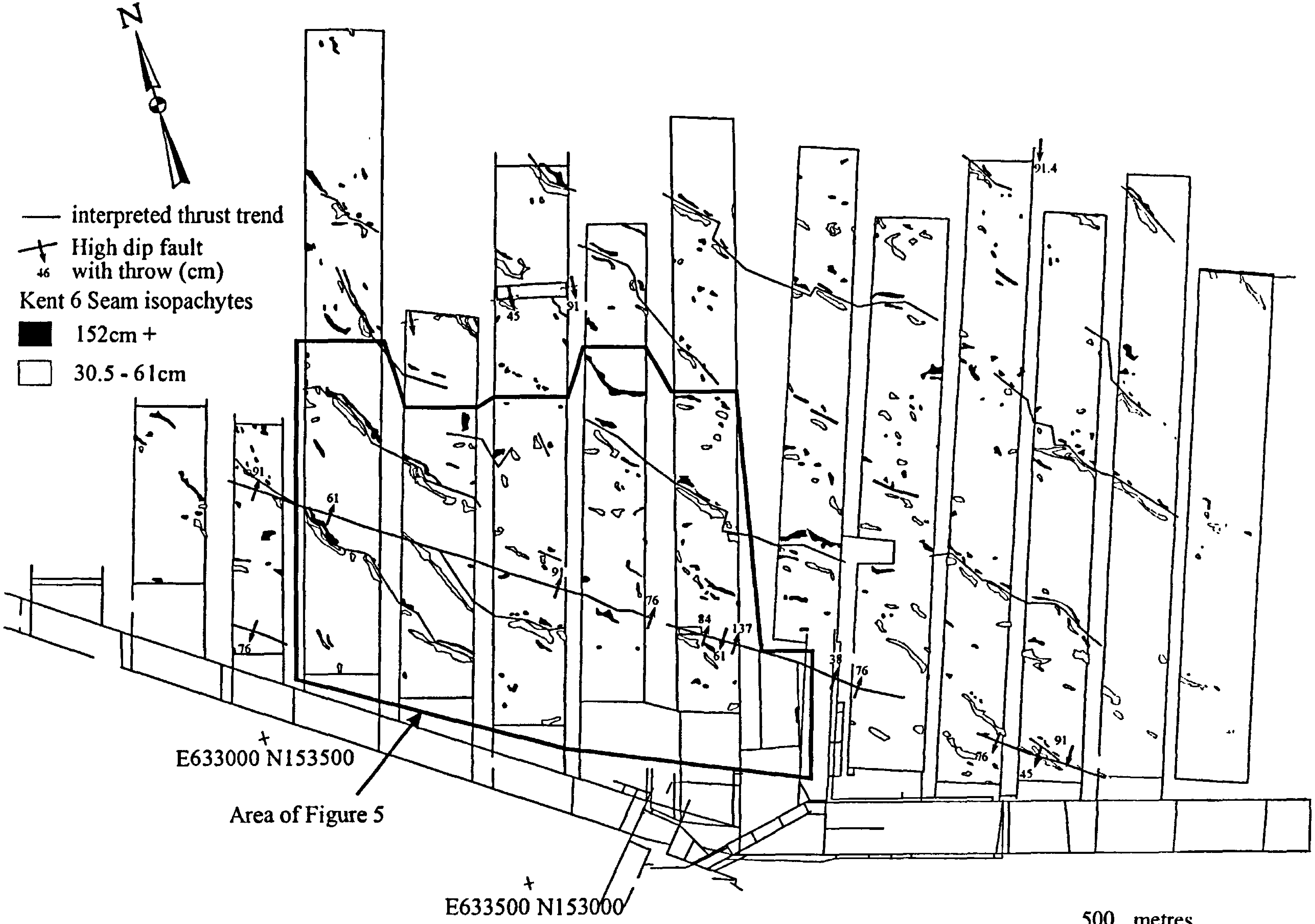
GENERALISED WESTPHALIAN STRATIGRAPHY EASTERN SOUTH WALES AND KENT

Fig.10.2



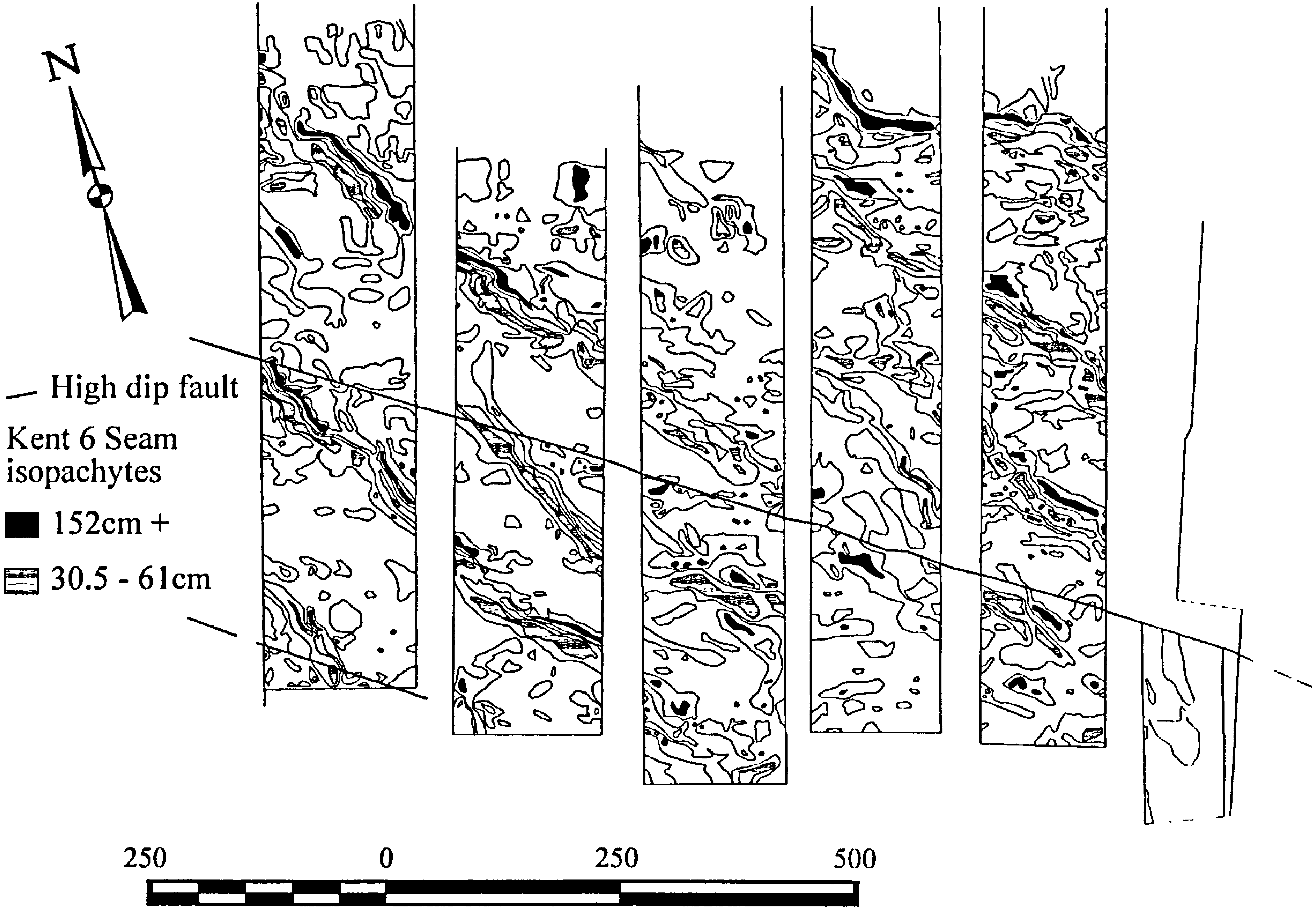
THRUSTING IN THE KENT 7 SEAM, CHISLET COLLIERY

Fig.10.3



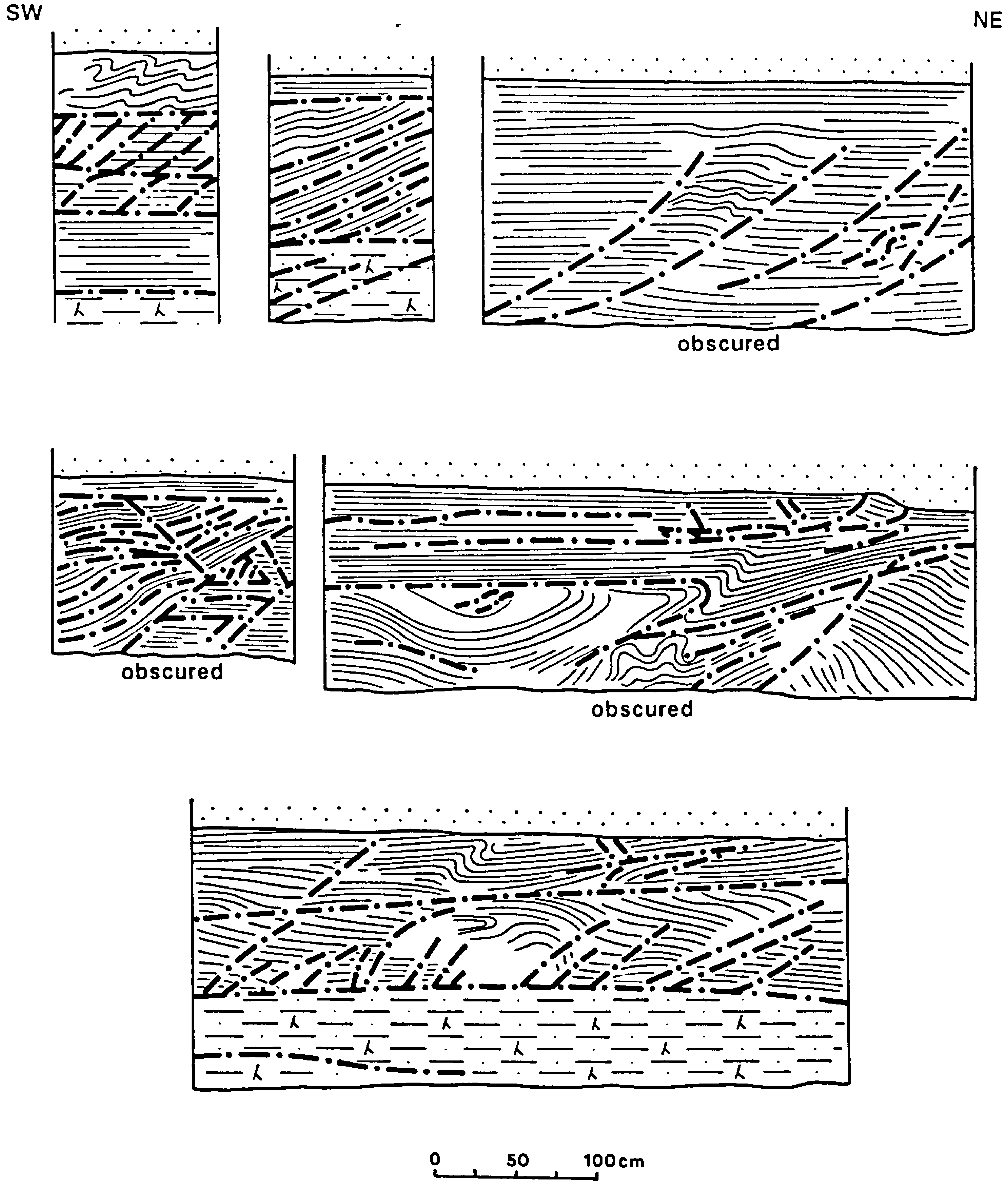
BETTESHANGER COLLIERY "ISOPACHYTE" PLAN, KENT 6 SEAM

Fig.10.4



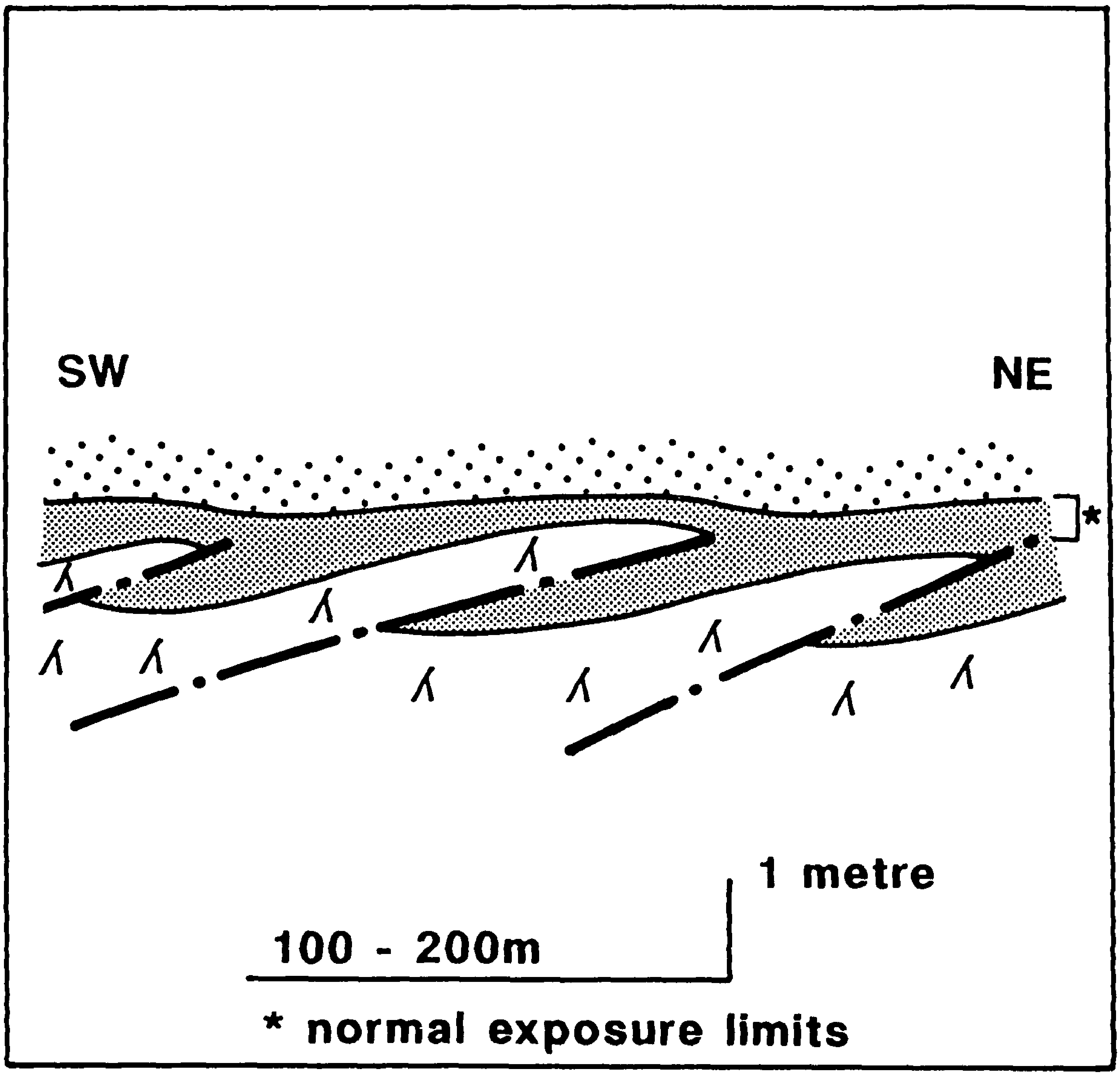
BETTESHANGER COLLIERY "ISOPACHYTE" PLAN (KENTS 6 SEAM) : SOME DETAIL

Fig.10.5



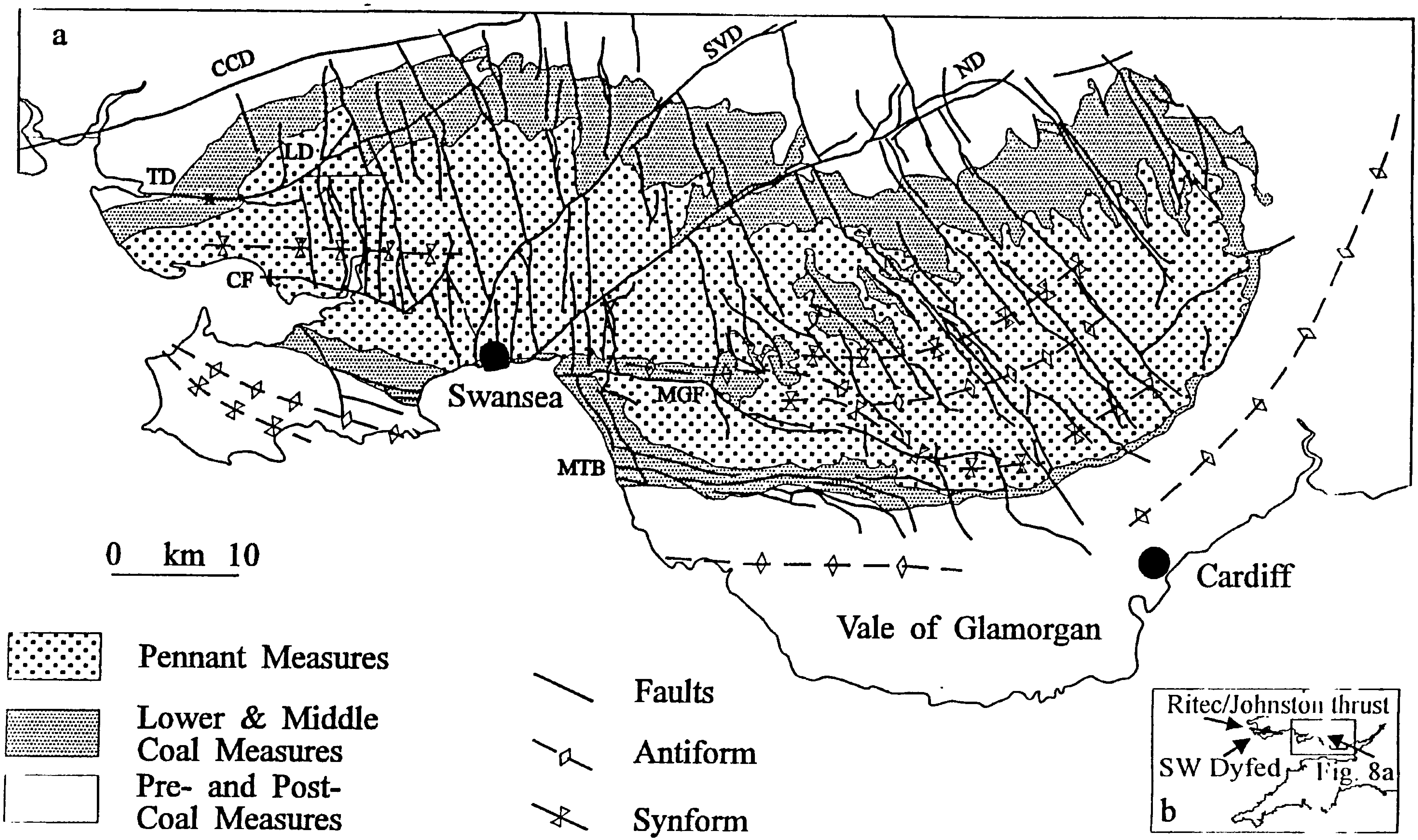
SMALL SCALE THRUSTS AND DUPLEXES IN THE KENT 6 SEAM, BETTESHANGER

Fig.10.6



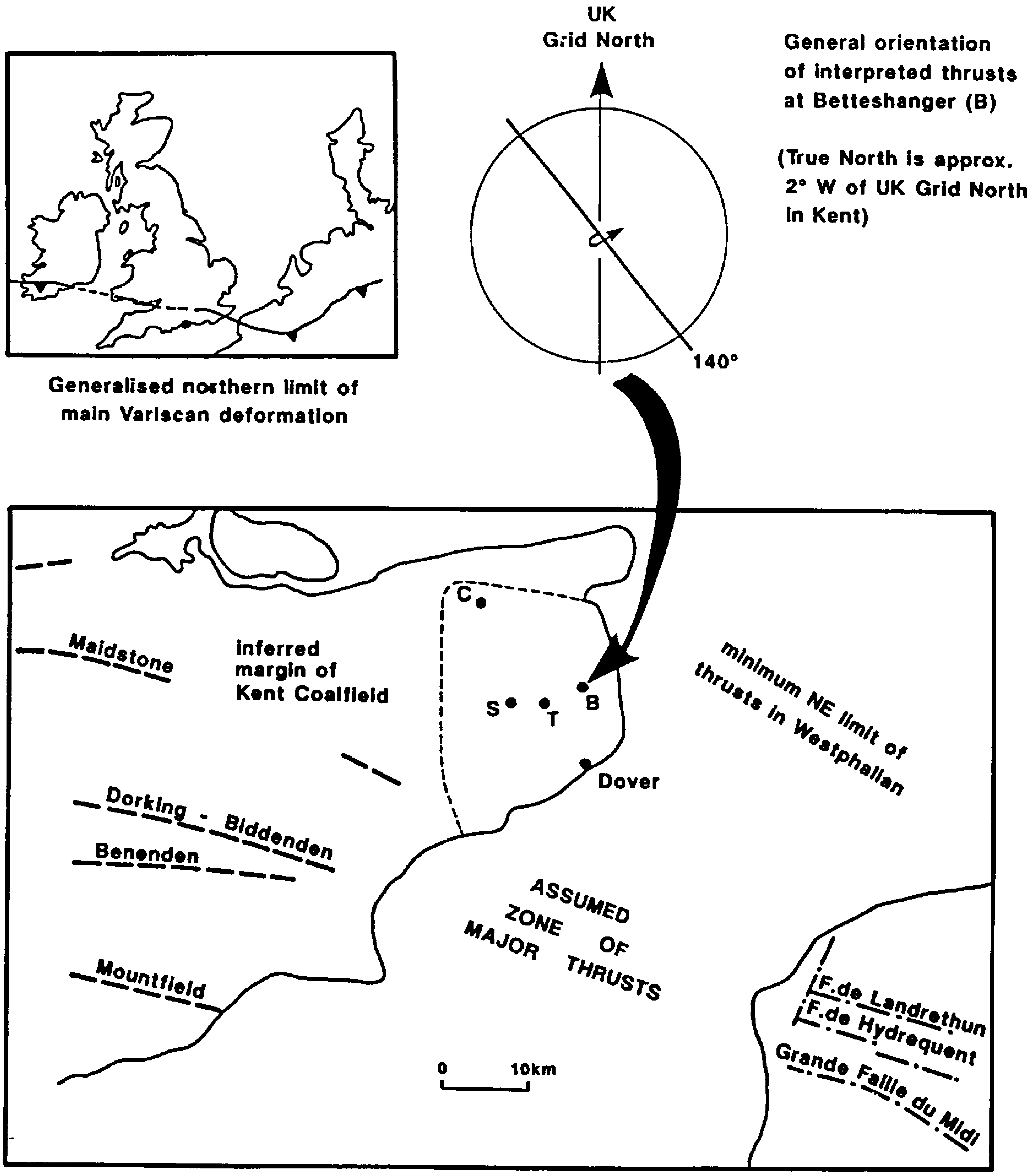
SCHEMATIC THRUSTING STYLE, KENT 6 SEAM

Fig.10.7



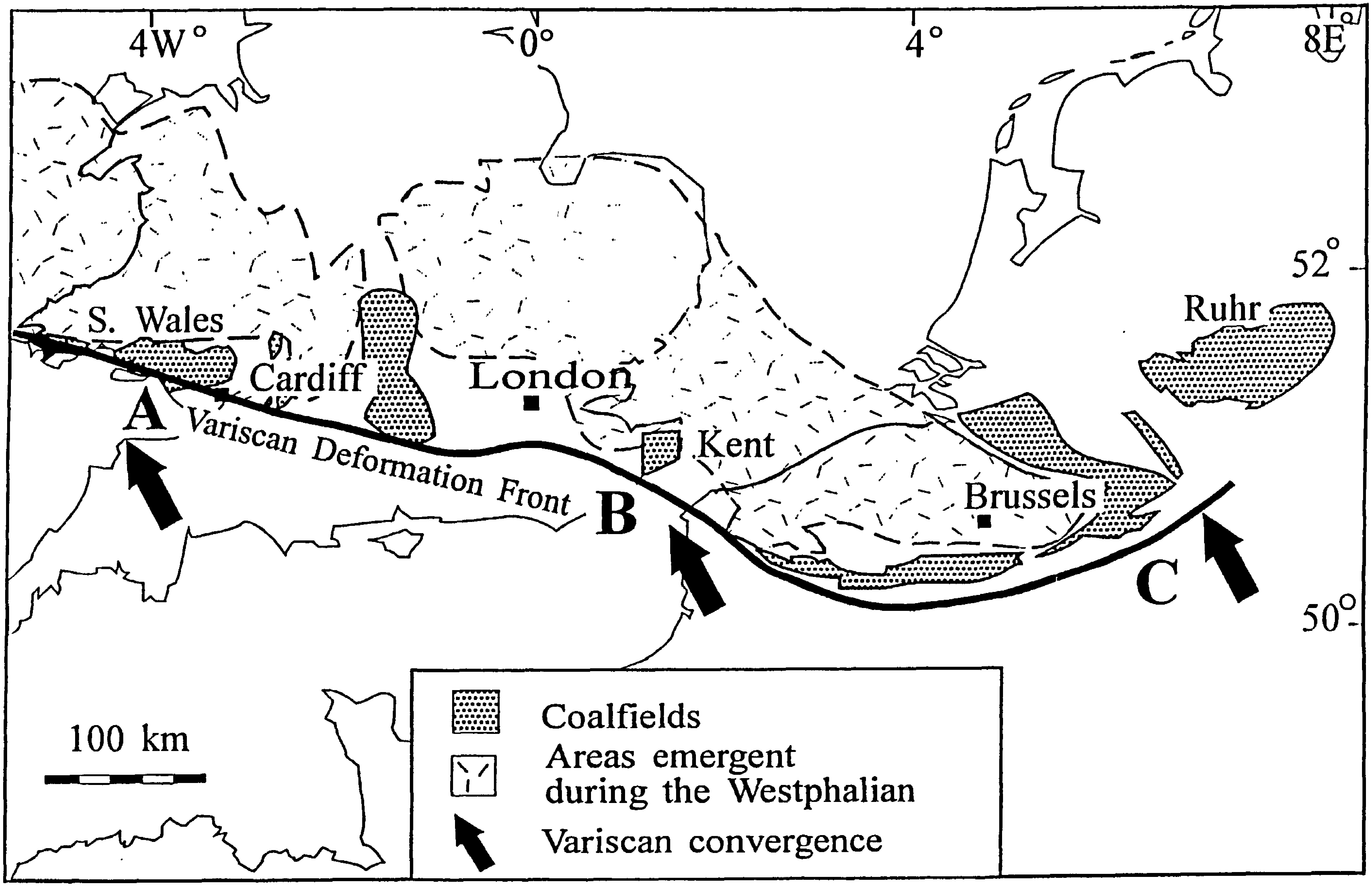
GENERALISED GEOLOGICAL MAP, SOUTH WALES COALFIELD

Fig.10.8



TREND VARIATIONS ALONG THE VARISCAN DEFORMATION FRONT

Fig.10.9



MAJOR COALFIELD DEVELOPED ALONG THE VARISCAN DEFORMATION FRONT

Fig.10.10

CONCLUSIONS

Conclusions specific to the British coalfields are now summarised, in chapter order.

Chapter 1. The geological individualism of many coalfield areas reflects the interplay of intricate depositional, structural, and burial history factors across many different settings.

Chapter 2. The depositional areas of the coal-bearing Westphalian were much more extensive than the present coalfields. Overall channel inflows were from three main source areas. Flows from the north and northeast dominated in eastern Scotland and northeast England. The westerly-derived channels of the Pennine Basin were from distant sources, possibly North America; their pathways were largely incidental to the disposition of tectonic depocentres, but basin subsidence variations imposed many effects on coal and sand body connectivity patterns; most systems prograded into fresh water lakes, and a simple sequence stratigraphical interpretation for these systems is inappropriate. Westerly systems also characterised South Wales, with southwards branching into the Culm Basin of southwest England.

Chapter 3. Many controls interacted to produce Westphalian depositional patterns, particularly source area sediment flux, basin subsidence, and some external base level control. A complex model is required, following from two key conceptual steps: firstly the recognition that main controls on channel belt incidence differed from those on coal sequence cyclicity; and secondly, that most channel systems prograded into fresh water, the rare marine invasions being irrelevant to most of the succession. A depositional model is proposed, that integrates the varied controls.

Chapter 4. Various controls on coal sulphur distribution may be considered, but the important factors were inflow water chemistry, reflecting source area attributes, and, occasionally, marine invasions. The influence of the latter is much less important than described in current literature. This is because marine incursions were very rare, with sulphur incorporation being further moderated by local factors, especially the thickness, lithology, and depositional duration of the interval between a marine horizon and underlying (or overlying) coal.

Chapter 5. Except in the Scottish Midland Valley, there is little evidence for syn-depositional movement on structures below the sub-basin scale. This may partly reflect thick post-rift mantling of faults active at depth. Movement will rarely be evidenced by channel belts, the coal-forming mires being much more susceptible to minor gradient changes. The lack of evidence from coal depositional patterns indicates rarity of these movements throughout the Westphalian coalfields. Structural control on sedimentation patterns should be assessed by combining appropriate fault growth and depositional models, and minimum-distance criteria for trend coincidences.

Chapter 6. Regarding structural variations, no simple stress regime can be invoked for any coalfield, because of multiphase deformation histories. Fault population and growth models developed in one area can rarely be transferred to others, without modification for local context. Variations in fault-adjacent strain can be modelled, with practical consequences for mining, seismic interpretation, and fracture permeability. The eastern Pennine Basin coalfield reveals a complicated structural history; a variety of patterns suggests that four separate fault trends might develop before further movements would be accommodated largely on existing fractures; mainly normal faults, developed in largely transtensional settings, are common. In all fields, inherited trends are very important, and compartmentalisation by major basement structures has been a significant control on development of the more local structural variations.

Chapter 7. Coal cleat orientations are interpreted as reflecting Variscan compressive stress. A near-field situation is found in South Wales and Kent, with varied trends reflecting differing block responses in the immediate Variscan foreland. A far-field province operated across most of the area north of the Wales-Brabant High, with a consistent northwesterly main cleat corresponding to the assumed principal stress direction. A distant-field setting is assumed for Scotland, in which more local events were able to over-ride the Variscan field.

Chapter 8. High quality data allow mapping of various igneous relationships in Scotland, and the development of models for intrusions. The Westphalian A to C/D province of the southern Pennine Basin, and the C/D province across the cratonic Wales-Brabant High in Oxfordshire, require further study in the context of Variscan tectonics; the latter may record deep crustal cracking during Variscan advance.

Chapter 9. A complex history for Upper Palaeozoic development of the Scottish Midland Valley is proposed, from study of the West Ochil Fault and the Kincardine Basin, the juxtaposition of which suggests a causal relationship which is not borne out by closer examination. The basin, with

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