Geological Society Memoir 28

An Atlas of Carboniferous Basin Evolution in Northern England

A. J. Fraser and R. L. Gawthorpe

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An Atlas of Carboniferous Basin Evolution in Northern England

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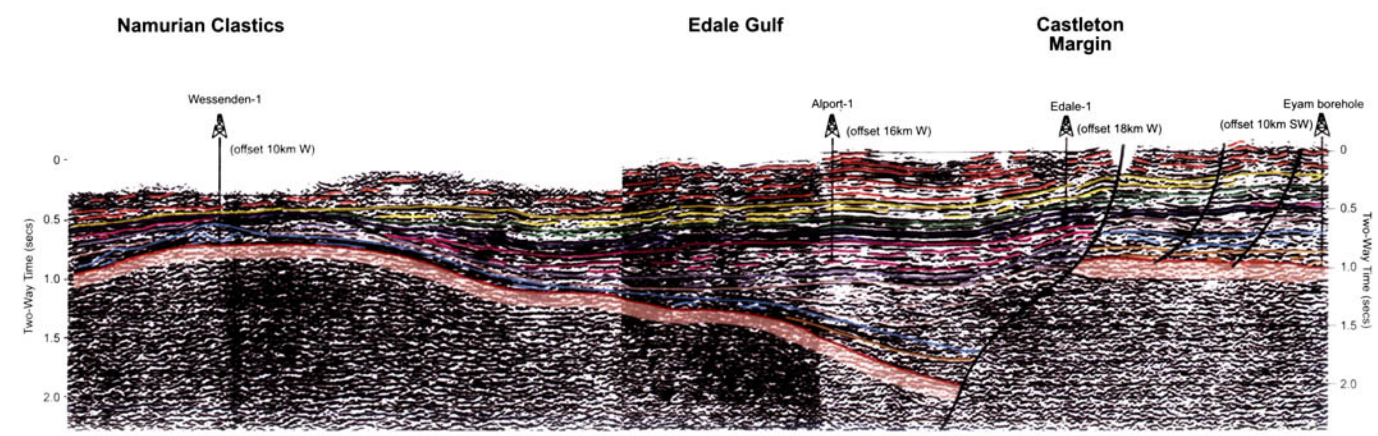

View looking east along Hope Valley from Mam Tor, Derbyshire. Early Namurian Edale shales (sequence LC1a) in the valley onlap the now exhumed late Dinantian carbonate platform margin (sequence EC4) forming the righthand valley side. The left-hand valley side is composed of pro-delta Kinderscoutian turbidites and the snow capped hills in the distance late Namurian mouthbar and delta top fluvial sandstones. Below the composite seismic line from the Edale Gulf illustrates the subsurface geology to the east of the outcrop location and highlights the half graben and fault-controlled geometry of the Dinantian basins (also see Fig. 17, p. 21).

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An Atlas of Carboniferous Basin Evolution in Northern England

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Alastair J. Fraser
Robert L. Gawthorpe
August 2002

Chapter 1

Introduction

Rationale

Why an atlas of the Carboniferous in northern England? There can hardly be a more researched system in the whole of the British Isles, given its widespread distribution at outcrop and annual appearance in numerous PhD theses (including our own). But perhaps all we really know about the Carboniferous is no more than skimming the surface. In this atlas, using modern multifold seismic and borehole data collected by the oil industry in its search for petroleum accumulations, we can start to look beyond the surface exposures and gain some new insights into the structure and stratigraphy of the subsurface (and surface) Carboniferous. The main elements of this atlas are: (i) a series of regional seismic lines crossing all the basinal areas in northern England illustrating the Carboniferous in section, and (ii) a set of palaeofacies maps describing the evolution of the system in map view.

The unique appeal of this atlas of seismic sections is that it is based on data from onshore UK. That is, we can walk the seismic lines at outcrop and in many cases compare exposure to the seismic data and palaeofacies maps. For example, stand on top of Mam Tor in Derbyshire and look eastwards over Hope valley towards Castleton (see frontispiece). Here, we can look out over a Carboniferous basin fill. On the right is an exhumed Dinantian platform margin and, ahead, Namurian Edale Shales form the valley floor. On the left, the north side of the valley is composed of basinal and slope turbidites of the Kinderscoutian, and in the distance, the prominent 'gritstone' escarpments are composed of younger Marsdenian fluvial strata. But what of the basin geometry and the structural–stratigraphic relationships? Now take the Edale Gulf seismic line in this atlas (see frontispiece). The valley marks the position of a Dinantian half graben, and the carbonate platform margin is localized over the footwall of a down-to-the-north normal fault zone. The Namurian mudstones and turbidites onlap the Dinantian carbonates and are post-rift sediments, initially infilling the sediment-starved half graben with post-rift mudstones and then prograding from the north, once the basin had shallowed sufficiently, to establish fluvial sandstones across the area.

The atlas presents a unique collection of onshore seismic data from BP's once-extensive onshore database. Although these lines were originally shot as small segments targeting individual prospects and trends, they have been spliced together to produce a series of basin-scale regional lines which should be of value to academic researchers and industry alike. Unfortunately, since this seismic was collected and compiled, much of the database has been fragmented as BP made the commercial decision to withdraw from active exploration in northern England in the early 1990s. As well as providing a paper record of these data, the atlas can be used as a tool for teaching aspects of stratigraphy, basin analysis and linking outcrop and subsurface studies in one of the classic areas of UK geology. Moreover, much of the data presented in this atlas was collated as part of a major re-assessment of the petroleum potential of northern England. We have therefore included in Chapter 5 a description of the main hydrocarbon play systems in northern England, providing a dataset for teaching the key aspects of play fairway analysis as applied by the oil industry.

Previous palaeogeographic and lithofacies reconstructions for the northern England Carboniferous have relied heavily on surface outcrop mapping supplemented by shallow borehole and gravity data (e.g. Wills 1951; George 1958; Johnson 1960; Kent 1966; Leeder 1974; Miller & Grayson 1982;

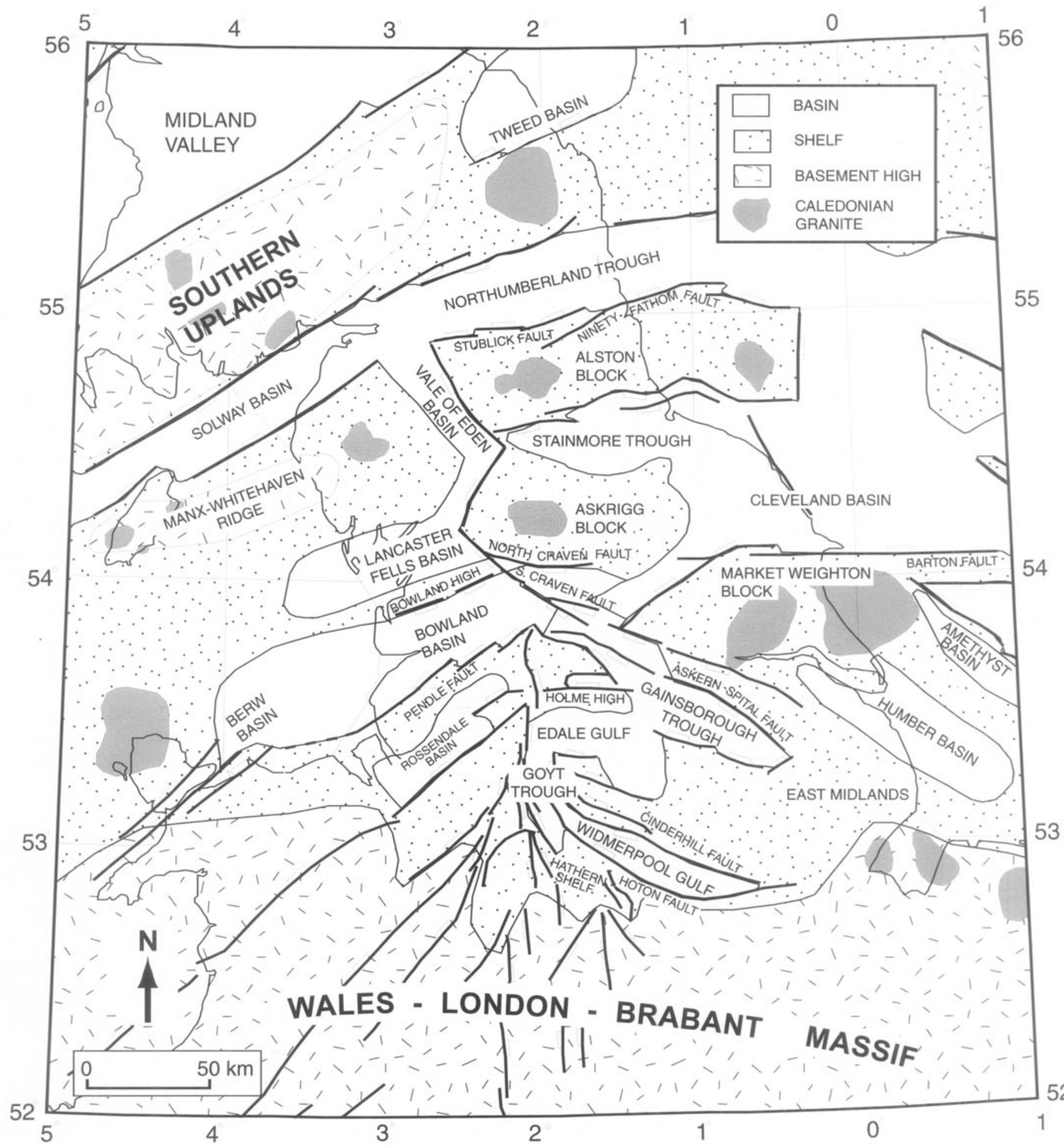


Fig. 1. Summary map of northern England Dinantian structural elements (after Fraser & Gawthorpe 1990; Corfield *et al.* 1996).

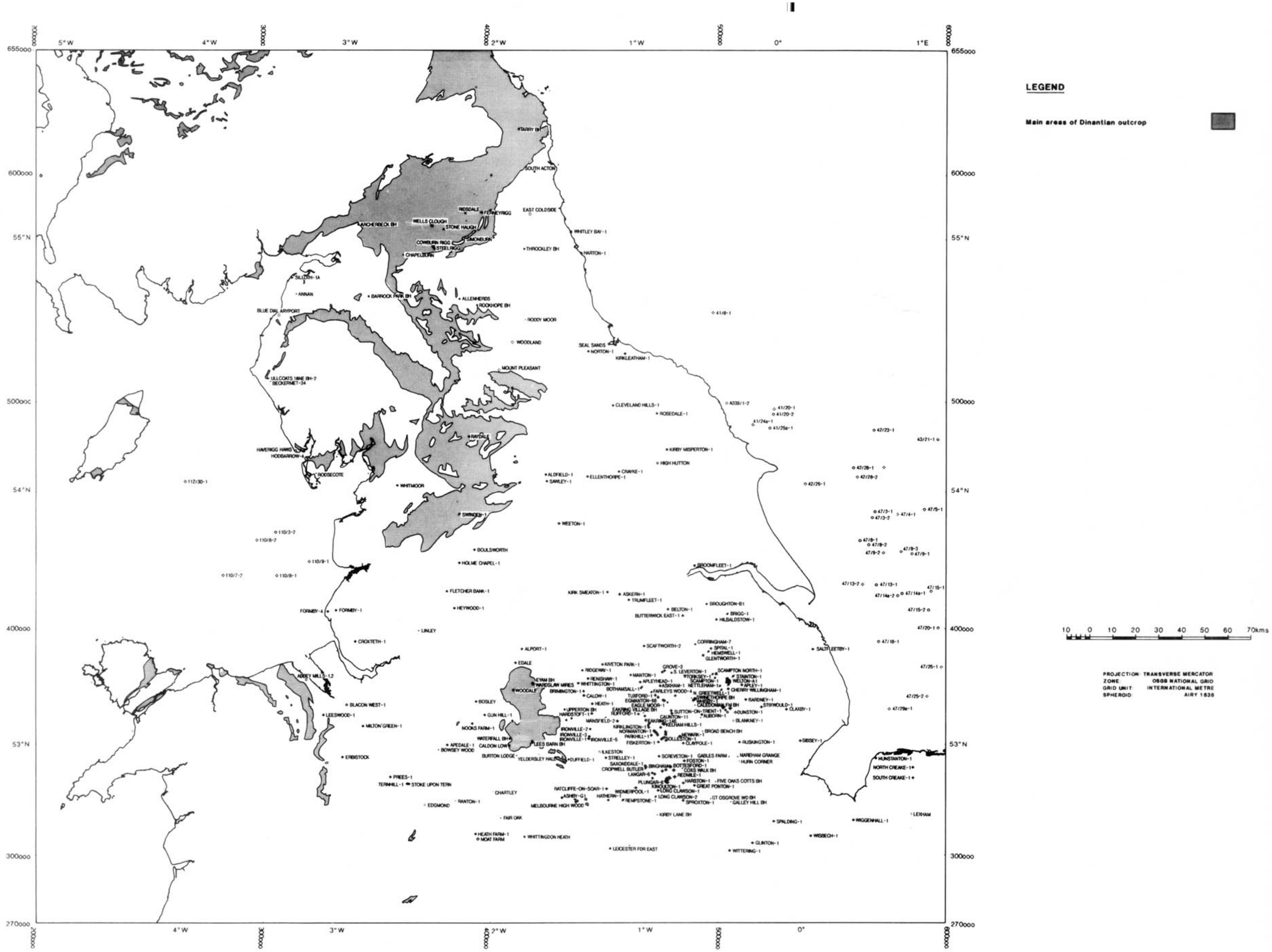


Fig. 2. Dinantian borehole and outcrop database.

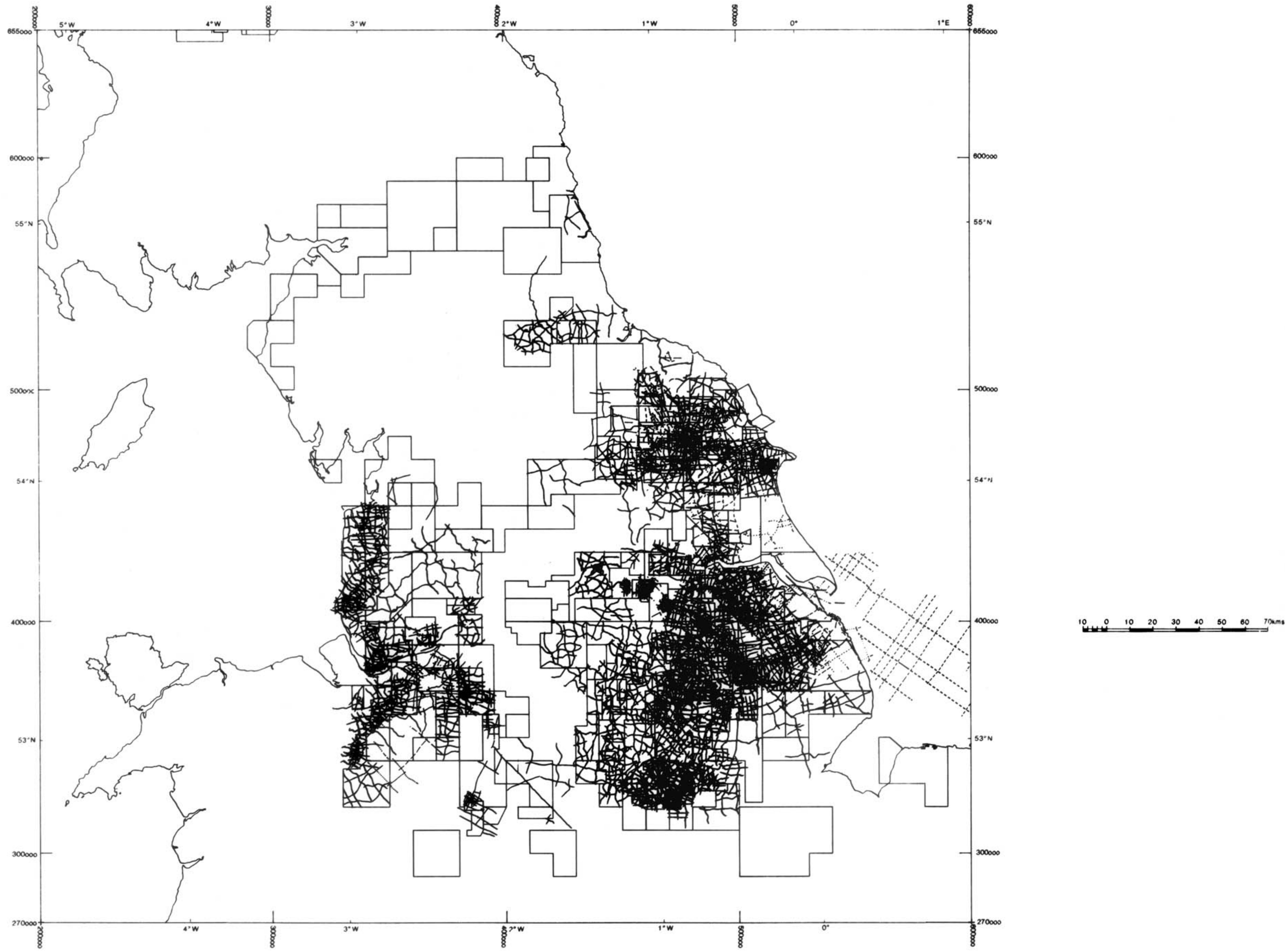


Fig. 3. 2D seismic database used in this study.

Gawthorpe 1987*a*; Gutteridge 1987; Guion & Fielding 1988; Cope *et al.* 1992). In contrast, the contents of this atlas are primarily based on subsurface (seismic and borehole) information. The borehole data have provided the main control on subsurface depositional facies; however, seismic facies analysis has been invaluable in facies interpretation in areas where there are few deep well penetrations. The seismic data have also provided a hitherto unattainable insight to the Carboniferous basin geometries. The earlier structural interpretation of 'gulfs' and 'blocks' with poorly constrained basin margins (Kent 1966), has now been integrated into a coherent structural framework.

With respect to the Carboniferous of northern England, the availability of seismic reflection data has provided a further tool for intra- and inter-basin stratigraphic correlation, in addition to the traditional use of lithostratigraphy and biostratigraphy. Vail & Mitchum (1977) suggested that a seismic reflection is generated by a time-synchronous stratal surface, that may pass through all facies belts. Seismic data, therefore, can potentially identify chronostratigraphic units through the definition of seismic sequences (Vail & Mitchum 1977). This principle provides the basis for the sequence-stratigraphic subdivision of the Carboniferous presented herein.

An ideal sequence-stratigraphic framework for correlation would divide the stratigraphy into depositional sequences and their component systems tracts, bounded by sequence boundaries, regressive surfaces, transgressive surfaces, maximum flooding surfaces and their correlative condensed intervals (e.g. Van Wagoner *et al.* 1988, 1990). Given sufficient well data and seismic resolution, this procedure is relatively straightforward and the resultant stratal packages can be considered the fundamental units for stratigraphic correlation. In the northern England Carboniferous, however, depositional sequences and their component systems tracts are below seismic resolution and thus a complete breakdown of the stratigraphy in this manner on seismic is generally impractical.

The approach described in this atlas adopts the tectono-stratigraphic methodology of Hubbard *et al.* (1985*a*, *b*) and utilizes seismic data tied to outcrop and wells in order to construct an integrated, regional tectono-stratigraphy for the Carboniferous of northern England. Although this approach does not define depositional sequences *sensu stricto*, it provides a consistent regional chronostratigraphic framework within which to interpret the structural and stratigraphic evolution of the basins and to assess the hydrocarbon habitat.

Within this tectono-stratigraphic framework and where borehole and outcrop data are sufficient, depositional sequences and systems tract mapping can provide further constraints on palaeogeography, facies relationships and the controls on stratigraphy (e.g. Church & Gawthorpe 1994). In fact, given the very high resolution framework provided by regionally extensive and biostratigraphically diagnostic marine bands, the Carboniferous of northern England has the potential to test the concepts underlying sequence stratigraphic models (e.g. Church & Gawthorpe 1997).

Atlas layout

Following this introduction, in Chapter 2, the structural setting of the northern England Carboniferous is placed in its regional plate-tectonic context in order to constrain the external controls on basin development. Having established how and when the basins were formed, Chapter 3 describes the stratigraphic fill and structural style of the depocentres with reference to a series of interpreted regional seismic profiles, tied to available well and surface geological data. The regional tectono-stratigraphic framework established in Chapter 3 provides the basis for the generation of a series of palaeogeographic maps, which are described in Chapter 4. These palaeogeographies have been compiled using a combination of borehole and outcrop information combined with published and BP in-house literature and structural, seismic, gravity and magnetic data. The datasets were correlated using a mixture of proprietary BP and published biostratigraphic data. It is important to realise that the detail and quality of the palaeogeographies varies according to the availability of biostratigraphic and lithostratigraphic data. For example, the late Devonian map is very poorly constrained, whereas the database for the late Carboniferous reconstructions is vast by comparison. Similarly, more prolific subsurface data are available for the East Midlands than for basins to the north and west. This introduces varying degrees of confidence in interpretation both within and between maps. Finally, Chapter 5 provides a summary of the main hydrocarbon play fairways in the northern England Carboniferous.

Database

The area covered by this atlas incorporates all the half graben identified in the northern England Carboniferous rift system (Fig. 1). Hence, the early Palaeozoic Southern Uplands and Wales–Brabant Massif represent the northern and southern geological limits of the study area respectively. The western and eastern boundaries of the study area extend into the Irish Sea and southern North Sea

The well and seismic database used to compile this atlas is summarized in Figures 2 & 3. A total of 270 key wells which have penetrated Lower Carboniferous strata in northern England have been incorporated. The wells have been used to control palaeogeographic maps, generate isopachs and as fence posts in seismo-stratigraphic work in the Widmerpool Gulf and Gainsborough Trough. Additional biostratigraphic studies were carried out on key wells, such as Hathern-1 in the East Midlands, which proved to be critical in the dating and correlation of sequence boundaries between half graben and with the numerous outcrop-based studies that exist in the literature for the Carboniferous. Much of this well data, including summary biostratigraphic data, is now in the public domain and can be accessed from the BGS Hydrocarbons Unit, Murchison House, West Mains Road, Edinburgh via the Department of Trade and Industry. Similarly, some of the seismic reflection data can be accessed through the UK Onshore Geophysical Library.

Chapter 2

Regional structural framework

The Caledonides of northern England

The pre-Permian geology of northern England and Wales (Wills 1973, 1978; Whittaker 1985; BGS 1985) is divided by lineaments and faults into a series of major terranes (Fig. 4). Turner (1949) and Wills (1973, 1978) realized that old Caledonian faults had exerted considerable influence on the geometry and orientation of subsequent tectonic features and recognized the presence of a triangular shaped platform with a thin, flatlying undeformed Palaeozoic cover underlying the English Midlands (Figs 4 and 5). The platform is bounded on its southern side by the Variscan thrust front, on its northwestern side by the Longmynd Fault and to the northeast by a NW–SE-trending lineament which Turner (1949) and Wills (1973) placed in different locations. The Longmynd Fault, in the NW, separates the platform from the deformed and cleaved Palaeozoic sediments of the Welsh Caledonides. The NE boundary represents a major lineament which separates the platform from a hidden East Midlands Caledonide belt, again with deformed and cleaved Lower Palaeozoic sediments. In this study, the boundary of Turner (1949) was found to be the more appropriate. This triangular platform is now referred to as the Midlands Microcraton (Pharaoh *et al.* 1987).

Turner (1949) compared the northern triangular apex of the microcraton with the Hindu Kush and suggested that the NE Caledonian trend in Wales could be traced in an arc around the apex into the East Midlands Caledonides (Figs 4 and 5). This outer arc continues northwards as far as the Iapetus suture, which separates the Welsh and East Midlands Caledonides from the Laurentian Caledonides of Scotland and the northern part of Ireland. The Iapetus suture was located using the positions suggested by Dewey (1971, 1982), Soper & Hutton (1984), Beamish & Smythe (1986) and Klemperer & Matthews (1987).

The Malvern line, which runs north–south through the apex of the microcraton is also a major lineament (Figs 4 and 5). It may continue to the north within the Caledonides following the Red Rock and Pennine–Dent fault zones. Wills (1973, 1978) also suggested that the Malvern Fault continues south of the Variscan thrust front along the 'Hawkins Line' (Fig. 5).

The Welsh Caledonides exhibit a strong NE–SW structural grain, as evidenced by the trend of the Dinorwic, Bala, Pontesford and Church Stretton Faults (Fig. 4). Many cover anticlines and synclines run parallel to these faults and curve in an arc, along with the associated cleavage, into an east–west trend where the Caledonian rocks plunge eastwards beneath younger cover sediments. Shackleton (1954) described stratigraphic variations in facies and thickness in the Cambro-Silurian in terms of a horst and graben model whereas Coward & Siddans (1979) interpreted the structure as a thin-skinned thrust belt. The latter model fails to provide a full explanation of the marked stratigraphic variations across the main faults and a modification of the Shackleton model is offered here. The horst and graben structure reflects a half-graben geometry with down-to-the-SE border faults. The surface folds and thrusts can thus be explained in terms of end-Caledonian inversion of these half graben.

The buried Caledonian of the East Midlands is interpreted to have a strong NW–SE structural grain (Fig. 4). Several authors have described the presence of pre-Carboniferous Caledonian rocks buried at depth beneath the East Midlands (Turner 1949; Bott 1967; Kent 1968; Le Bas 1972; Wills 1973, 1978; Evans 1979; Pharaoh *et al.* 1987), which have influenced the deposition of the overlying sediments. A number of exploration boreholes have encountered pre-Carboniferous basement which is typically composed of deformed Silurian phyllites or Ordovician–Silurian volcanics and granites (Falcon & Kent 1960; Le Bas 1972). Also late Precambrian sedimentary and volcanic rocks are exposed in Charnwood Forest. The gravity and aeromagnetic maps of the region (BGS 1965) show important anomalies which outline the NW–SE trend of this hidden Caledonian system. It is suggested that many of the Carboniferous and younger faults, which follow the same NW–SE strike, represent rejuvenation of Caledonian tectonic lineaments. Most of the known Carboniferous faults dip to the NE, suggesting that the Caledonian faults also dipped in this direction. Examples of rejuvenated Caledonian faults are believed to include structures such as the Hoton, Cinderhill, Eakring and Askern–Spital Faults. Figure 4 also highlights the aeromagnetic anomalies (BGS 1965) which are also thought to represent deeply buried Caledonian structures. However, not all the structures trend NW–SE. There are two important cross-trending faults through the Wash and also localized structures such as the Don Monocline that trend NE–SW. These cross-cutting structures may represent old Caledonian lateral ramps and transfer zones, geometries typical of thrust fold belt terranes.

Both Turner (1949) and Soper *et al.* (1987) suggested that the Lake District contains an arcuate structure that links the East Midlands–Welsh Caledonides into a single belt. The link is mainly in the form of a cleavage arc (Fig. 4). In the SW of the Lake District the late Caledonian cleavage has a NE–SW trend. It curves round continuously into an east–west trend where it is cut off against the Dent Fault (Moseley 1972). East of the fault, the Palaeozoic rocks of the Craven inlier contain WNW–ESE-trending cleavage, passing into the East Midlands aeromagnetic anomalies and presumed NW–SE Caledonide trend.

Late Caledonian granites, intruded around 390 Ma, are exposed in the Southern Uplands and the Lake District, and are also known in the subsurface in deep boreholes in Weardale and Wensleydale (Bott 1967). Granites also exist further south around Charnwood Forest (Le Bas 1972) where they have older radiometric ages of around 540 Ma. The granites had a significant impact on the style and location of subsequent tectonics because they formed isostatically buoyant areas which generally form the footwalls to subsequent extensional faults (Bott 1967; Leeder 1982).

There has always been a problem explaining these late Caledonian intrusives in terms of Iapetus subduction because they occur on both sides of the suture zone. Subduction related volcanics should only occur on the subducted side of a Benioff zone. However, recognition of the Mid European Caledonides (Ziegler 1982) suggests that these northern England Caledonian intrusives can easily have been generated by a northward-dipping subduction zone which extended from the Mid European Caledonides underneath the Midlands Microcraton.

Variscan plate cycle

Several tectonic models have been proposed to explain the origin of the late Devonian–early Carboniferous extensional basins of northern England and their subsequent inversion during the late Carboniferous. At a plate scale, northern England lies within a complex orogenic belt with a long history of continental collision from the early Palaeozoic Caledonian orogeny, through back-arc related extension reactivating the earlier Caledonian structural grain, to the accretion of micro-terranes culminating in the late Palaeozoic Variscan orogeny (Fig. 6). The main tectonic models proposed to rationalize these events include: (i) dextral megashear, (ii) north–south back-arc extension, (iii) east–west Boreal rifting and (iv) dextral escape tectonics. These main models are outlined below.

The dextral megashear model. This model, first outlined by Arthaud & Matte (1977) and later developed by Ziegler (1981), Dewey (1982), Johnson (1982), Badham (1982), Arthurton (1983) and Coward (1990), suggests that a wide zone of right lateral shear affected Europe, particularly during the Carboniferous as Gondwana docked with Laurasia. The northern England extensional basins are interpreted as being formed by rifting associated with pull-apart basins in an east–west-oriented zone of dextral shear, which linked the Alleghenides in North America to the Urals in Russia. The minor inversion events which punctuated Carboniferous rifting are interpreted as reflecting the evolution of the shear zone through a 'big bend' of the type evidenced along the San Andreas fault system in California.

Back-arc extension generated by northwards subduction of the Rheic Ocean. This model suggests that extension was driven by ductile creep of the lower crust towards a Rheic Ocean subduction zone (Leeder 1976), and as a result of back-arc extension from a northwards dipping subduction zone in southern France (Leeder 1982, 1987a). The northern England rift system is interpreted within this setting as essentially back-arc in nature, with the inversion events linked to initial pulses of the Variscan orogeny which intensified towards final collision in the late Carboniferous–early Permian.

East–west extension derived from southwards propagation of the Boreal rift. This model, with its origins based on observations in the Midland Valley of Scotland, emphasizes the progressive southwards propagation of the Boreal rift during the Carboniferous. This resulted in east–west extension, generating crustal thinning, basin formation, syn-tectonic ore deposition and volcanicity, and eventually leading to the generation of oceanic crust in the region of the present day Rockall Trough, towards the end of the Carboniferous (Haszeldine 1984, 1988, 1989; Haszeldine & Russell 1987).

Large-scale dextral escape tectonics. In the 1990s, several authors have focused on strike-slip extension models (e.g. Coward 1993; Maynard *et al.* 1997). This hypothesis asserts that late Devonian–Carboniferous tectonics in NW Europe can be explained in terms of a continuation of Caledonide events, with the northward movement of an Arcadian indentor causing eastwards (dextral) extrusion of a triangular shaped block comprising northern England, the North Sea and Baltica. During the early Carboniferous, the extruding crust was able to extend in a north–south direction as it moved eastwards. Closure of the Ural Ocean and subsequent Ural plate collision during the late Carboniferous, reversed the sense of shear along the extruded block margins as it was pushed back between the Acadian collision zones causing inversion of

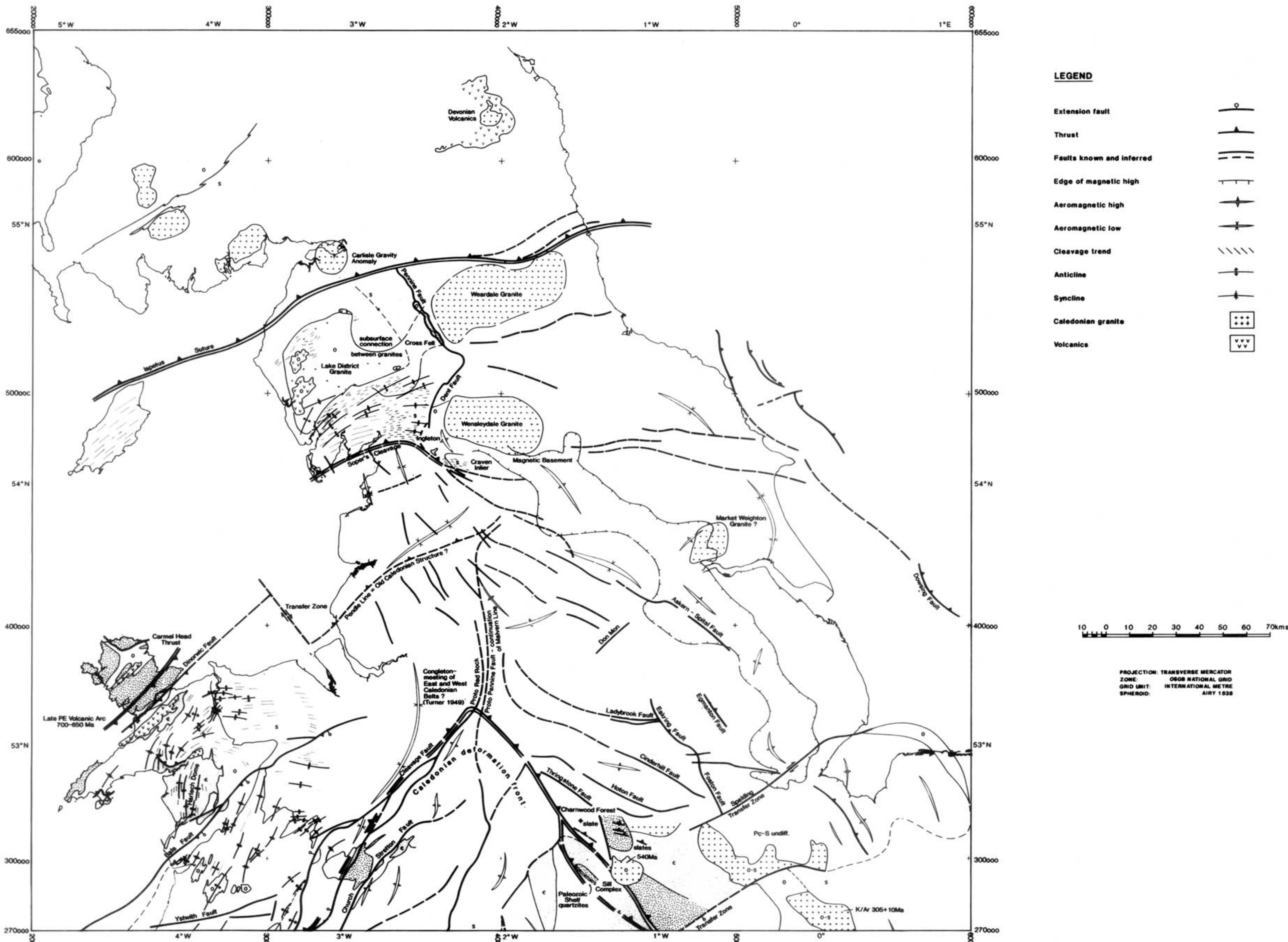


Fig. 4. Caledonian structural elements based on data from Turner 1949; Soper *et al.* 1987; Pharaoh *et al.* 1987.

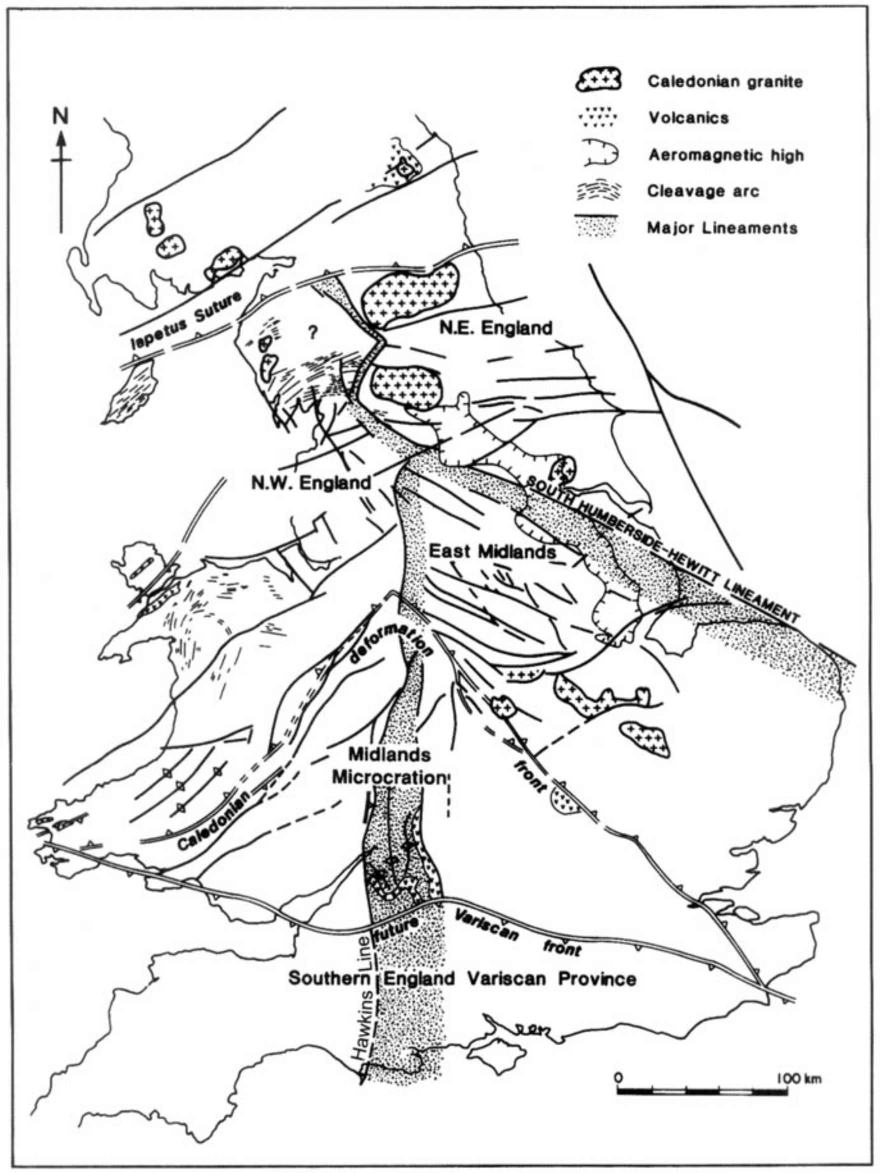


Fig. 5. Caledonian tectonic provinces of England and Wales (after Fraser *et al.* 1990 and Fraser & Gawthorpe 1990; based on data from Turner 1949; Soper *et al.* 1987; Pharaoh *et al.* 1987).

the extensional basins in northern England.

Plate reconstructions for the late Devonian–Carboniferous can provide a basis for reconciling these apparently contradictory models (Knott *et al.* 1993; Maynard *et al.* 1997). The plate reconstruction presented here (Fig. 6) was developed as a starting point in the series of maps constructed by Knott *et al.* (1993) in an analysis of the late Palaeozoic and Mesozoic evolution of the North Atlantic continental margin. Knott *et al.* (1993) had the benefit of Bathonian to Recent magnetic anomaly data as an external constraint on the relative motions of the plates. The constraints of magnetic anomaly data are not available for pre-Mid Jurassic plate reconstructions and more reliance has to be placed on palaeomagnetic and regional tectono-stratigraphic data.

The late Devonian–Carboniferous reconstruction in Figure 6 illustrates the northwards movement of Gondwana throughout the mid to late Devonian, progressively closing the Rheic and Rheno-Hercynian oceanic basins. Also shown in the reconstruction are the early attempts of the Boreal rift to propagate southwards along the line of the Caledonian collision zone between Norway and Greenland. This suggests that at least two plate margin processes were prevalent in late Devonian–Carboniferous times; an extensional system propagating southwards from the northern Boreal Ocean and a dominantly contractional system encroaching northwards on southern Britain (Knott *et al.* 1993; Maynard *et al.* 1997). Models such as early Boreal extension causing east–west rifting (Haszeldine 1988) or two-phase models involving discrete events such as back-arc rifting followed by thermal subsidence (Leeder 1988) have evolved from this basic plate tectonic framework. Maynard *et al.* (1997) suggest the above are rather too simplistic and argue for a model which rationalises the complexity of structural settings encountered in the Variscan province of NW Europe. Building on the work of Coward (1990), Maynard *et al.* (1997) propose a model of crustal escape/extrusion in which the extruding crust was able to extend north–south due to release of confining forces as it moved eastwards. Within this context, the present-day plate-tectonic setting of the eastern Mediterranean offers a modern analogue to the late Devonian to early Permian development of NW Europe in terms of size and range of local structural styles.

Variscan extension

In the late Devonian–early Carboniferous, northern England lay in an equatorial position inboard of the southern margin of Laurasia marked by the Rheno-Hercynian Ocean (Fig. 6). Along the northern margin of the Rheno-Hercynian Ocean an extensive carbonate platform, covering the area between SW England and eastern Poland, developed during the early Carboniferous. Rifting was affecting the northern margins of the Rheno-Hercynian Basin by the early-mid Devonian (Sellwood & Thomas 1986) either as a result of simple back-arc extension related to the NW-directed subduction of the Rheic Ocean beneath the Armorican microcraton (Burg & Matte 1978, Leeder 1987*a*, 1988) or the continued extrusion of crust eastwards from the developing Appalachian orogen to the west (Maynard *et al.* 1997). To the south, in the Massif Central region, calc-alkaline volcanic activity was driven by the subducting Rheic oceanic crust (Fig. 6). The presence of a subduction zone to the south of the South Armorican shear zone is supported by dismembered ophiolitic material thrust southwards in the Massif Central on the south side of the suture (Burg & Matte 1978). Further evidence for subduction includes the presence of blueschists on the Ile de Groix and further west in the Vendee (Guiraud *et al.* 1987) and the associated high-temperature/low-pressure assemblages in Brittany (Lefort 1979).

The back-arc nature of the Rheno-Hercynian Ocean is supported by the chemistry of tholeiitic basalts in Cornwall (Floyd 1982) and also by the association of 'oceanic' volcanic rocks with thick greywackes (Matte 1986). Early (Early–Mid Devonian) extension within this back-arc setting was dominantly north–south oriented (e.g. Benton and Ritec Faults in South Wales, Houchen 1988). Sellwood & Thomas (1986) have suggested that the basins on the northern margin of the rift in Devon and Cornwall developed as a series of half graben controlled by a set of down-to-the-south normal faults (Fig. 7) as evidenced by the formation of the Trevone and South Devon Basins in the region. It has been suggested that the South Devon Basin has certain oceanic affinities and the crustal-scale cross-section interprets the zone as lying very near to the continent–ocean transition after break-up (Chandler & Isaac 1982) (Fig. 7). The Upper Devonian to Lower Carboniferous facies in the half-graben trend from clastics in the early syn-rift, to reefal and pelagic carbonates with black shale/cherts towards the end of the rift phase. The reefs typically developed on the footwalls of the rotated fault blocks (Fig. 7). There are clearly similarities here with the Mesozoic Biscay margin, where Kimmeridgian reefs developed on tilted footwall blocks prior to break-up (Montadert *et al.* 1977). Slivers of MORB basalts under the Giessen–Selke nappe (Wederpohl *et al.* 1983) provide further evidence that late Devonian oceanic crust was generated in the Rheno-Hercynian Basin. The age of final break-up, when the rift became oceanic, is thought to be late Givetian (375 Ma).

A period of renewed rifting in the Frasnian was focused along the centre of the Rheno-Hercynian Basin (Houchen 1988). This phase of rifting was possibly associated with dextral shear, as a result of oblique subduction of the Rheic Ocean. In the Gramscatho Basin in southern Cornwall, stretching at a right-handed offset in the resulting dextral transform system increased extension to the point at which dyke intrusion began and finally led to the generation of the Lizard ophiolite complex. Palaeomagnetic data suggest a spreading axis oriented NNW–SSE (Hailwood *et al.* 1984; Barnes & Andrews 1986). This presents a problem as this orientation is largely incompatible with north–south extension unless the oceanic crust was generated along a leaky transform system linking actively spreading segments of the main back-arc system.

Isotopic studies of the Lizard ophiolite complex in western Rheno-Hercynia suggest oceanic crust generation at 375 Ma followed by obduction between 370 and 355 Ma (Davies 1984). However, older dates of up to 400 Ma (Halliday & Mitchell 1976; Styles & Rundle 1984) would place its generation during the earlier Early Devonian normal extension.

Variscan compression

Compression and subduction of the Rheic Ocean continued into the late Dinantian (Fraser & Gawthorpe 1990). A schematic cross-section, illustrating the degree of shortening in the British Variscides, is shown in Figure 7. The timing of the transition between overall extension and overall compression (from subduction and back-arc spreading to collision) is uncertain and is likely to have been diachronous. Burg & Matte (1978) considered the Rheic Ocean to have closed towards the end of the Devonian, whereas Leeder (1987*a*) argued for continued subduction and associated back-arc extension throughout the early Carboniferous in order to explain early Dinantian rifting in northern England. Maynard *et al.* (1997) suggest that by late Dinantian times the width of the Rheic Ocean was such that continental collision would have commenced. Further evidence is provided by the deepwater flysch-like deposits (Culm) of southern England which were derived from a southerly source suggesting the early presence of Variscan mountains and the initial development of the Variscan foreland basin. Early thrusting, marked by the obduction of the Lizard complex in the early Carboniferous (365–345 Ma Fammenian–Chadian) (Barnes & Andrews 1986; Dodson & Rex 1971), provides further evidence that the change from extensional to compressional tectonics in the south of the British Isles probably took place in the late Dinantian. The associated deformation migrated northwards with the western parts of the South Devon and Trevone Basins inverting in the late Visean (Sellwood & Thomas 1986) and minor inversion in the East Midlands basins at the end of the Brigantian (Fraser *et al.* 1990).

In Westphalian C/D times, the final collision of Gondwana with both Laurentia to the west and Iberia to the south took place. This marked the culmination of the Variscan deformation and the inversion of the late Devonian–early Carboniferous rift basins of northern England. In common with the late extensional phase, there appears to be an important component of dextral shear during compression. Sanderson (1984) considered that compression took place in a dextral transpression regime. Several major faults show evidence of Variscan dextral shear, principally the Bray Fault (Matte 1986) and the North and South Armorican shear zones (Cogne 1960; Chauris 1969; Watts & Williams 1979; Jegouzo 1981). In SW England, Coward & Smallwood (1984)

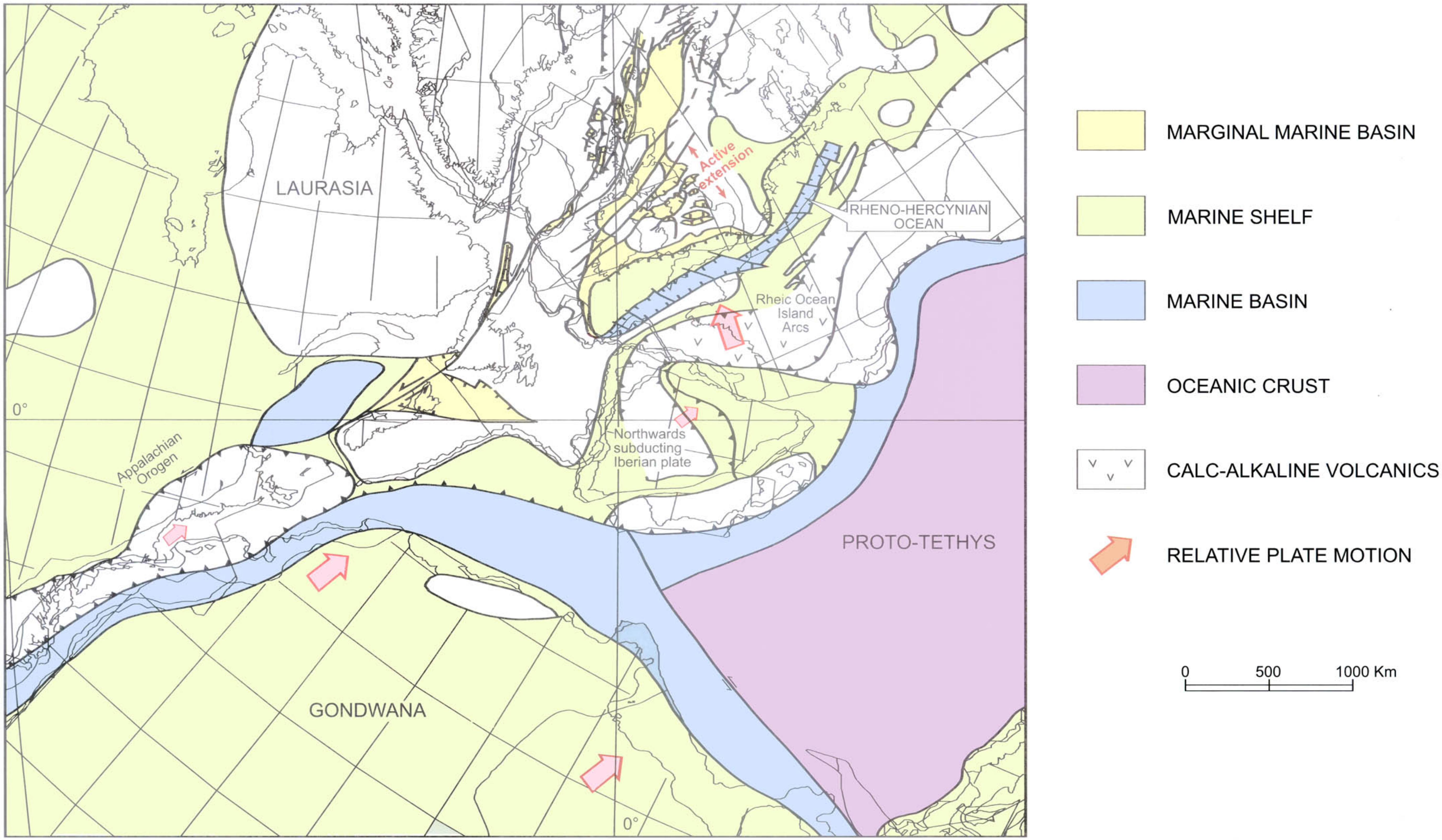


Fig. 6. Early Carboniferous plate reconstruction based on the study of Knott *et al.* (1993).

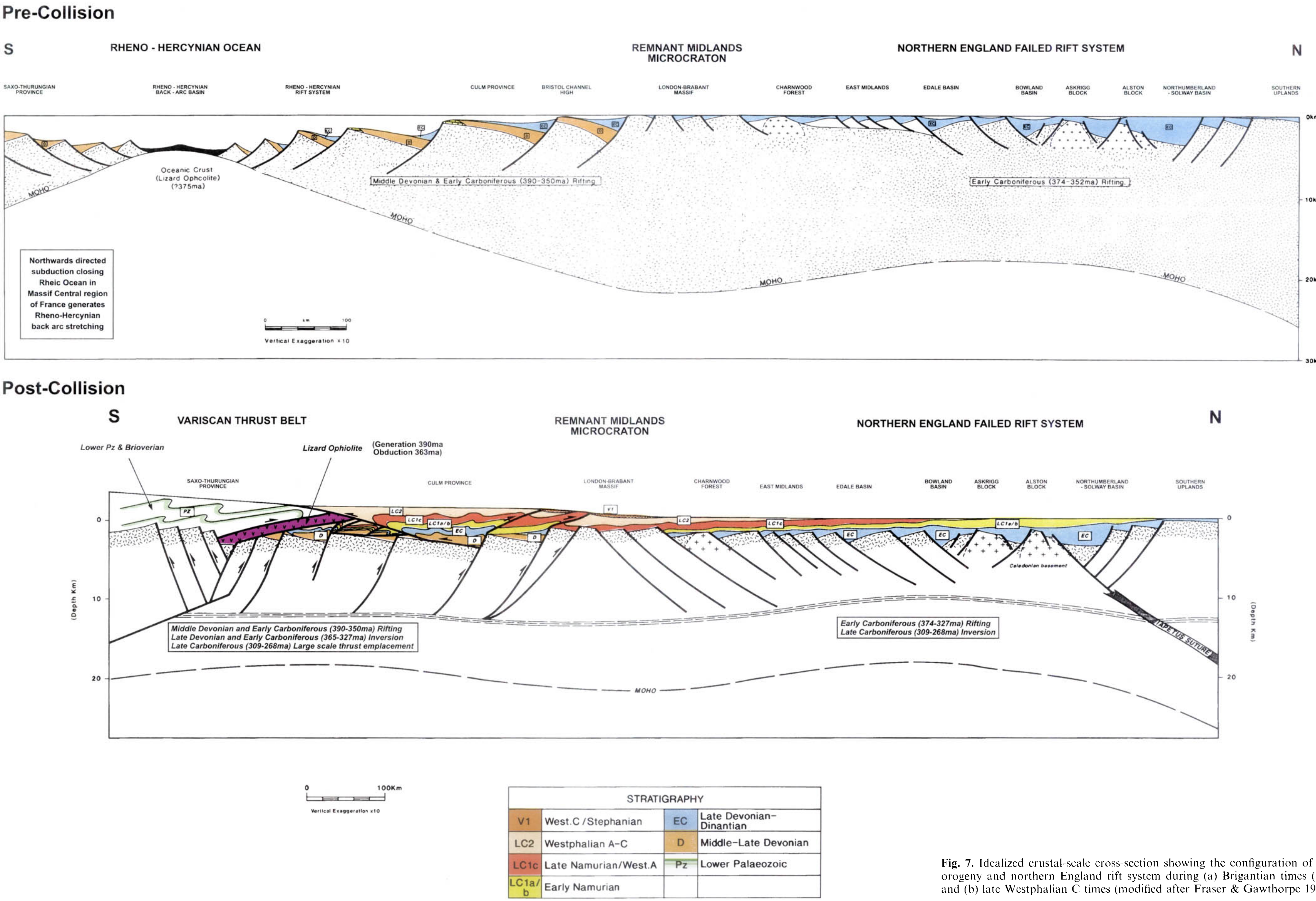


Fig. 7. Idealized crustal-scale cross-section showing the configuration of the Variscan orogeny and northern England rift system during (a) Brigantian times (pre-collision) and (b) late Westphalian C times (modified after Fraser & Gawthorpe 1990).

also cite the obliquity of thrust transport directions to the Variscan Front to suggest a component of dextral displacement.

Variscan structures of northern England

The main Carboniferous structural elements of northern England are illustrated in Figure 1. Surface structural trends, taken from BGS 1 : 500 000 and 1 : 625 000 geological maps, have been combined with trends mapped from, gravity and aeromagnetic data (BGS 1965) and interpretation of seismic reflection data. The structures illustrated on Figure 1 are those which significantly affect Carboniferous strata, although many of the lineaments shown are believed to have an early Palaeozoic origin and a structural history which extends well into the Tertiary.

In the north, the Northumberland–Solway Basin follows the ENE–WSW trend of the Iapetus suture that underlies it. The main boundary fault lies on the north side of the basin with down-to-the-south extension. On the southern margin there are two important east-west-trending antithetic faults which downthrow northwards away from the Alston Block. These are the Stublick and Ninety-Fathom Faults. They die out westwards towards the NNW–SSE-trending Eden–Pennine Faults.

East–west fault trends are also evident in the Stainmore Trough, which separates the Askrigg and Alston Blocks and is bounded to the north by the en echelon Lunedale, Wigglesworth and Butterknowle Faults. The Alston Block is bounded to the west by the Dent Fault and on the south side by the Craven fault system. Both the Alston and Askrigg Blocks form the footwalls to significant half graben and both blocks are intruded by Lower Devonian granite plutons (Bott 1961, 1964, 1967, 1974; Bott & Masson-Smith 1957*a*, *b*, 1960). The east–west structural trends extend as far as the southern North Sea, where NW–SE trends become apparent.

West of the Pennine–Dent–South Craven Faults, the early Carboniferous extensional faults trend NE–SW, following the strike of the underlying Welsh Caledonides. The Pendle Fault defines the southern margin of the Bowland Basin and is postulated to follow the surface monocline on the south side of the basin (Fig. 1). Both the monocline and the fault die out north of the Mersey estuary. Further east and SE in the central Pennines several faults inferred from gravity studies (Lee 1988) and confirmed by seismic (e.g. Fraser & Gawthorpe 1990; Evans & Kirby 1999) have a east-west strike and influenced Dinantian and early Namurian deposition, for example the Holme Fault (Fig. 1). In North Wales, several Caledonian fault trends were probably reactivated in the Carboniferous (e.g. Church Stretton, Clwyd, Pontesford and Prees Faults). Dinantian movement is inferred on the Bala and Llanelidian Faults to explain stratigraphic thickness changes across the fault zones (George 1958; Gawthorpe *et al.* 1989) and the presence of the Rossendale Basin (Fig. 1).

In the East Midlands, the dominant trend of structures (usually faults associated with folds) is NW–SE. Faults such as the Morley–Campsall, Askern–Spital, Egmanton, Bakewell–Ladybrook, Bonsall and Cinderhill Faults form major lineaments extending across the East Midlands Platform. This structural domain is bounded to the north by the Craven–Lincoln fault system and its eastward extension, the Brigg Fault, and to the south by the Hoton Fault. To the south of the Hoton Fault, the major boundary faults between the East Midlands basins and the London–Brabant Massif trend NW–SE to east–west (the Thringstone and Sileby Faults). Basins such as the Gainsborough Trough and Widmerpool Gulf are essentially half graben bounded by the NW–SE-trending faults. The NW–SE trend extends westwards into Derbyshire, where it again forms the bounding faults for the half graben (Smith *et al.* 1985; Gutteridge 1987). On depth-converted reflection seismic data the NW–SE-trending faults appear planar in cross section and probably have similar geometries to major border faults in areas of active extension such as the Aegean and Basin and Range (e.g. Jackson 1987; Stein & Barientos 1985) (see following sections).

Superimposed on the NW–SE trend are two further structural trends, NNW–SSE and NE–SW (Fig. 1). The faults and folds that trend NNW-SSE are generally limited in length and branch off the major NW–SE-trending structures. Structures such as the Ironville, Calow, Hardstoft, Eakring–Foston and Nocton Faults lie in this category. The faults of this trend predominantly throw down-to-the-NE and are associated with small, tightly folded hanging-wall anticlines. The NE–SW trend of faults that dominates most of the northern and western areas of northern England is of limited areal extent and influence in the East Midlands. This trend has been extrapolated from surface geology and gravity modelling in an area of Mesozoic cover in the NW of the East Midlands province and appears to affect the subsurface structure, particularly at the NW and SE limits of the Gainsborough Trough. The Don Monocline lies on this trend (Fig. 4).

Towards the western end of the Derbyshire Dome area, the dominant NW–SE trend also swings into a NNW–SSE trend merging with the north–south-trending Pennine axis. Here surface folds and folds have north–south trends and borehole information indicates a deep basin, the Goyt Trough, immediately to the east of the Pennine axis. A north–south extensional fault has been postulated to explain the location of the trough. This has been placed on the western side of the Goyt Trough, with down-to-the-east displacement, following the Pennine axis. Southwards, the postulated fault can be traced into the Malvern Line and also splaying into the Boothorpe–Thringstone trend. There are present-day surface folds in south Derbyshire which define the arc into the Thringstone trend. To the north, the Goyt Trough boundary fault probably swings round to join the South Craven Fault, following the trend of the large surface anticline here.

Overview of Carboniferous tectono-stratigraphy

The aim of this section is to provide an overview of the regional tectono-stratigraphy derived from the integrated study of regional seismic reflection data tied to biostratigraphically constrained well and outcrop data. The Variscan plate cycle can be divided into syn-rift, post-rift and inversion megasequences (Figs 8 and 9), which describe a late Devonian–Dinantian rift-controlled subsidence (syn-rift megasequence), a Namurian–Westphalian thermally driven subsidence (post-rift megasequence) and a late Westphalian – early Permian inversion or foreland-basin phase (inversion megasequence) (Ebdon *et al.* 1990; Fraser *et al.* 1990; Fraser & Gawthorpe 1990). As such, each megasequence represents a particular phase in the basin evolution and is characterized by a dominant basin-forming process. The three megasequences can in turn be broken down into a series of tectono-stratigraphic sequences that describe the late Devonian–Carboniferous fill of the basins. The detailed characteristics of the megasequences and component tectono-stratigraphic sequences are presented in the following chapters.

For comparison with existing outcrop-based studies, the megasequence and sequence scheme summarised in Figures 8 and 9 is compared to the British stages of the Carboniferous (George *et al.* 1976; Ramsbottom *et al.* 1978). However, recognition of the stage boundaries in the subsurface has proved difficult due to extreme facies variations within the Dinantian, faunal provincialism, and the difficulty of identifying certain fossil groups in borehole samples. Furthermore, re-evaluation of macropalaeontological, micropalaeontological and microfloral data has modified the ranges of certain key fossil species and brought into question the criteria for recognising some of the Dinantian stage boundaries (e.g. Ebdon *et al.* 1990).

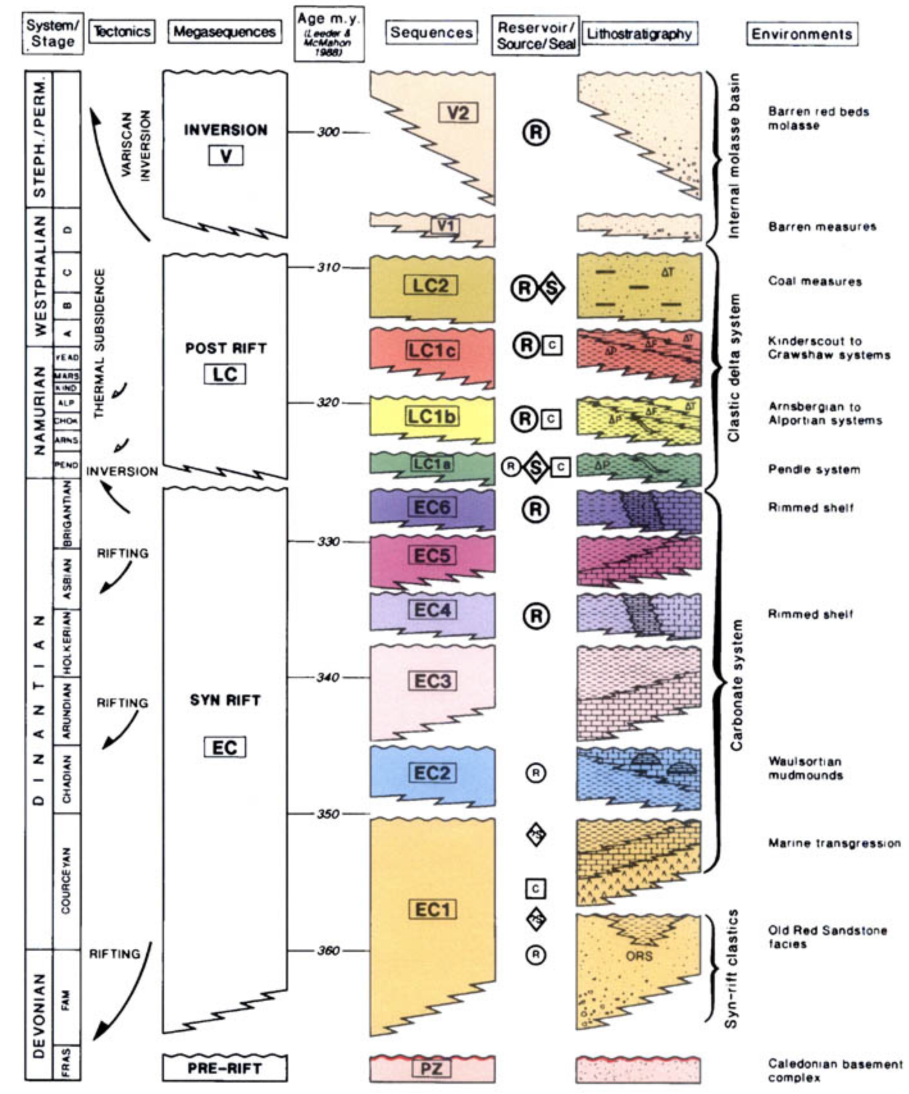
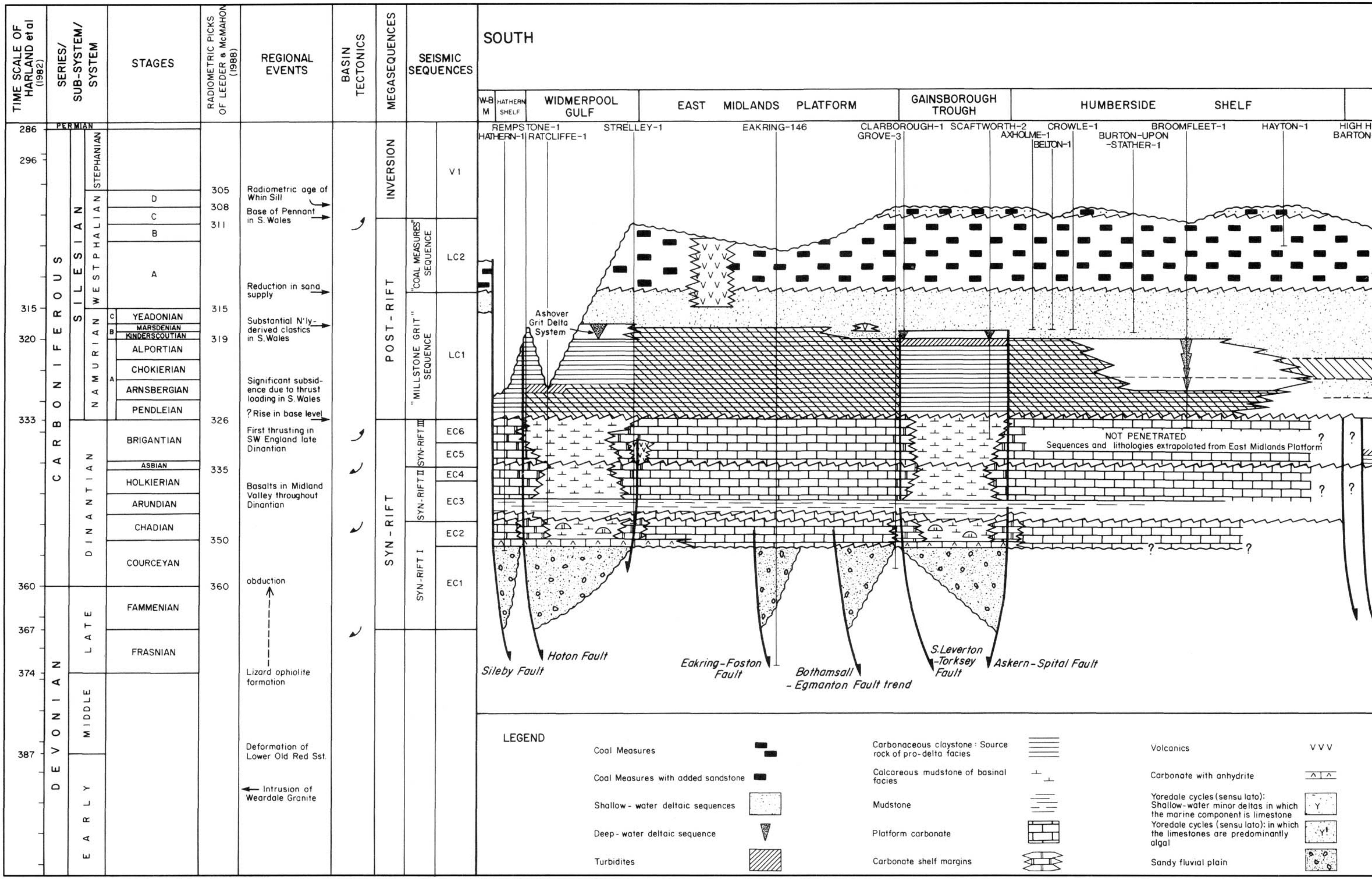


Fig. 8. Summarized stratigraphy of the Variscan plate cycle in the East Midlands showing megasequence and sequence development (after Fraser & Gawthorpe 1990). ΔT, delta top; ΔF, delta front; ΔP, pro delta.

The boundaries of the tectono-stratigraphic sequences presented in this atlas may vary markedly around the basin due to spatial variations in accommodation development and/or sediment supply (see Gawthorpe *et al.* 1994; Church & Gawthorpe 1997), thus they are not necessarily depositional sequence boundaries *sensu* Van Wagoner *et al.* (1990). This spatial variability is most pronounced in the syn-rift megasequence. Locally the boundary of a tectono-stratigraphic sequence may be a depositional sequence boundary, characterized by subaerial exposure, incision and a basinward shift in facies, for example in the footwall of an active normal fault. Elsewhere the correlative surface may be a downlap or marine onlap surface, for example in the half graben depocentre. To address this variability, a pragmatic application of seismic and sequence stratigraphic concepts has been used to develop a robust regional chronostratigraphic subdivision of the stratigraphy developed during active phases of basin evolution.

The syn-rift megasequence ranges from the late Devonian to the early Brigantian and is characterized by marked facies and thickness variations


TIME SCALE OF HARLAND et al (1982)
SERIES/ SUB-SYSTEM/ SYSTEM
STAGES
RADIOMETRIC PICKS OF LEEDER & McMAHON (1988)
REGIONAL EVENTS
BASIN TECTONICS
MEGASEQUENCES
SEISMIC SEQUENCES
SOUTH
W-B M
HATHERN SHELF
WIDMERPOOL GULF
EAST MIDLANDS PLATFORM
GAINSBOROUGH TROUGH
HUMBERSIDE SHELF
REMPSTONE-1
HATHERN-1
RATCLIFFE-1
STRELLEY-1
EAKRING-146
CLARBOROUGH-1
GROVE-3
SCAFTWORTH-2
AXHOLME-1
BELTON-1
CROWLE-1
BURTON-UPON -STATHER-1
BROOMFLEET-1
HAYTON-1
HIGH H
BARTON
286
296
315
320
333
360
367
374
387
PERMIAN
CARBONIFEROUS
SILESIAN
STEPHANIAN
WESTPHALIAN
NAMURIAN
DINANTIAN
DEVONIAN
LATE
MIDDLE
EARLY
D
C
B
A
YEADONIAN
MARSDENIAN
KINDERSCOUTIAN
ALPORTIAN
CHOKIERIAN
ARNSBERGIAN
PENDLEIAN
BRIGANTIAN
ASBIAN
HOLKIERIAN
ARUNDIAN
CHADIAN
COURCEYAN
FAMMENIAN
FRASNIAN
305
308
311
315
319
326
335
350
360
Radiometric age of Whin Sill
Base of Pennant in S. Wales
Reduction in sand supply
Substantial N'ly-derived clastics in S.Wales
Significant subsidence due to thrust loading in S.Wales
? Rise in base level
First thrusting in SW England late Dinantian
Basalts in Midland Valley throughout Dinantian
obduction
Lizard ophiolite formation
Deformation of Lower Old Red Sst.
Intrusion of Weardale Granite
INVERSION
POST-RIFT
SYN-RIFT
"COAL MEASURES" SEQUENCE
"MILLSTONE GRIT" SEQUENCE
SYN-RIFT III
SYN-RIFT II
SYN-RIFT I
V1
LC2
LC1
EC6
EC5
EC4
EC3
EC2
EC1
Ashover Grit Delta System
NOT PENETRATED
Sequences and lithologies extrapolated from East Midlands Platform
Sileby Fault
Hoton Fault
Eakring-Foston Fault
Bothamsall - Egmanton Fault trend
S.Leverton -Torksey Fault
Askern-Spital Fault
LEGEND
Coal Measures
Coal Measures with added sandstone
Shallow-water deltaic sequences
Deep-water deltaic sequence
Turbidites
Carbonaceous claystone: Source rock of pro-delta facies
Calcareous mudstone of basinal facies
Mudstone
Platform carbonate
Carbonate shelf margins
Volcanics
Carbonate with anhydrite
Yoredale cycles (sensu lato): Shallow-water minor deltas in which the marine component is limestone
Yoredale cycles (sensu lato): in which the limestones are predominantly algal
Sandy fluvial plain

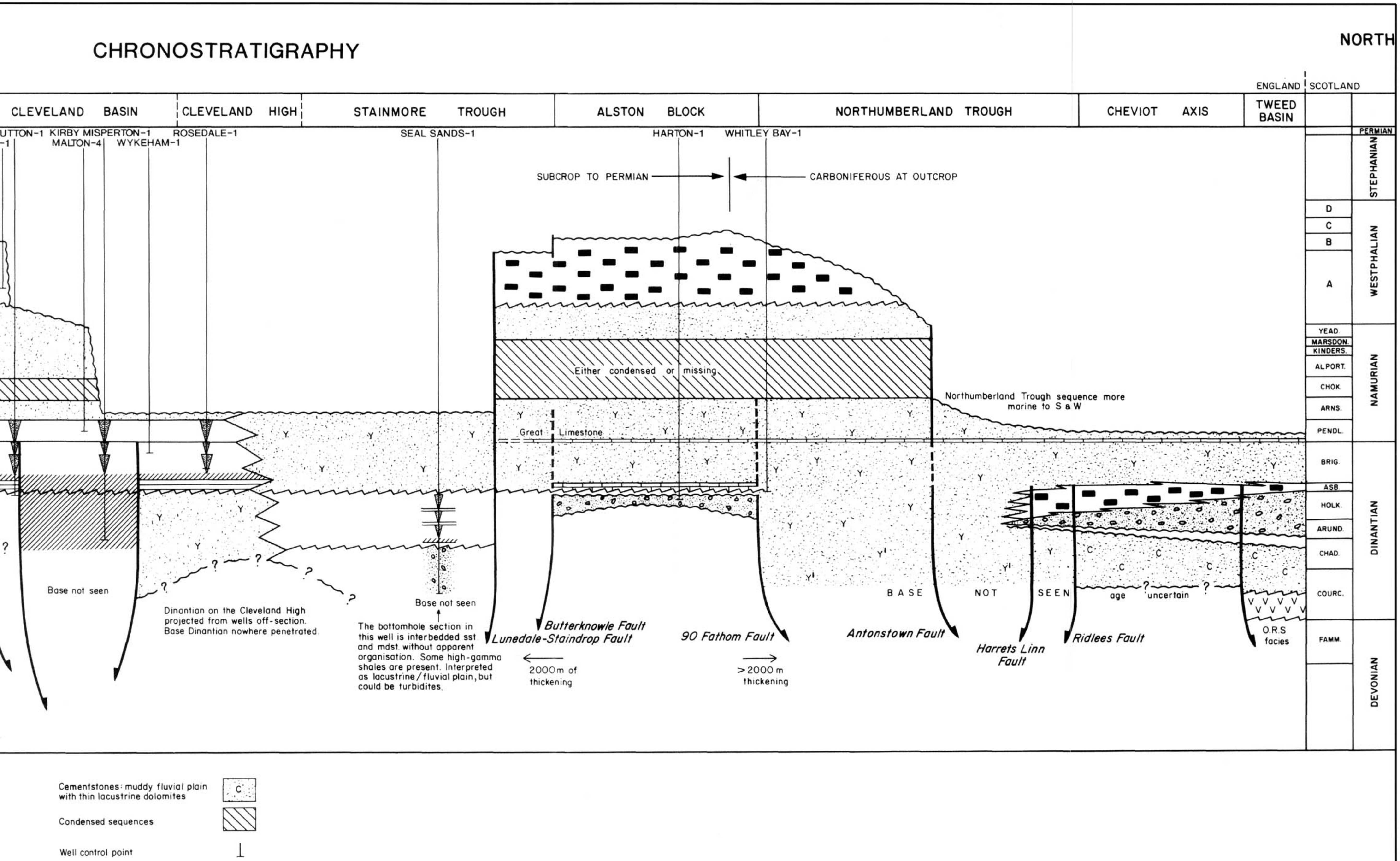


Fig. 9. Chronostratigraphy of the Carboniferous in northern England (after Fraser *et al.* 1990).

around major normal fault zones that bound half graben depocentres. It is composed of six tectono-stratigraphic sequences (EC1–EC6) (Fig. 8). Two main syn-rift depositional systems can be identified: (i) clastic fluvio-deltaic and (ii) carbonate platforms (Fig. 9). The clastic depositional systems dominate the north of the study area (e.g. Northumberland Basin) due to the proximity to the eroding remnants of the Caledonian mountain belt situated to the north. In contrast, the southern part of the study area (e.g. Widmerpool Gulf, Gainsborough Trough and Bowland Basin) was largely starved of clastic sediment during syn-rift times. In addition, the equatorial location of northern England at that time allowed shallow-water areas to become the sites of prolific carbonate production and carbonate platform development, whereas the half-graben depocentres became sediment starved and were infilled by predominantly fine-grained hemipelagic deposits (Gawthorpe 1987*a*). High-frequency cyclicity is apparent in platform carbonates, especially towards the end of the Dinantian in the Asbian and Brigantian stages (Walkden 1987; Horbury 1989).

The post-rift megasequence ranges in age from late Brigantian to late Westphalian C and was deposited regionally across northern England. The stratigraphy is dominated by fluvio-deltaic sandstones, siltstones, mudstones and coals, although initial deposition in the sediment-starved half graben in the south of the area is characterized by basinal mudstones and deepwater turbidites. High-frequency cyclicity in the Namurian and Westphalian has been long recognized (Bott & Johnson 1967; Ramsbottom 1973, 1977), and more recently these cycles have been recognized to form high-frequency depositional sequences and component systems tracts (e.g. Church & Gawthorpe 1994; Wignall & Maynard 1996; Hampson 1997; Hampson *et al.* 1997; Jones & Chisholm 1997). In recent years major changes in provenance and source area compositions in the late Namurian and Westphalian of the Pennine Basin have been identified, suggesting extra-basinal controls on sediment source areas and sediment transport pathways (e.g. Glover *et al.* 1996; Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000)

The inversion megasequence ranges in age from late Westphalian C to early Permian. This megasequence records the development of a series of inversion anticlines and widespread uplift and erosion of the original syn-rift depocentres (e.g. Corfield *et al.* 1996). Associated with this uplift was a change in the depositional style, with progressive development of red beds and coarse pebbly sandstones and conglomerates from the inversion axes and from the south. The inversion megasequence can locally be subdivided into two tectono-stratigraphic sequences; however, the lack of preserved stratigraphy due to progressive uplift and erosion precludes the development of a regional framework.

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Chapter 3

Carboniferous basin development

The Carboniferous basin development of northern England is illustrated in a series of regional seismic lines presented in this chapter. Each of the major syn-rift basins will be described in turn, using representative seismic lines (Fig. 10) that have been tied to well and outcrop control. In addition to the seismic data, depth converted geological interpretations for each of the seismic lines are presented to illustrate the development of these tectono-stratigraphic sequences across the province. Particular attention is paid to the Widmerpool Gulf because the combination of seismic quality, well penetrations and the presence of exposure of the syn-rift along-strike in Derbyshire allows us to discuss the tectono-stratigraphic sequences in detail.

The depth converted geological interpretations are based on corrected sonic logs taken from nearby boreholes, where available. Elsewhere, and for the deeper Dinantian section on most lines, seismic stacking velocities have been applied. The errors inherent in this latter method could result in errors in the depth section of as much as ±10%. Typical velocities used in the depth conversion of the Eakring and Welton sections in the East Midlands and the Northumberland Trough (Kimbell *et al.* 1989) are shown in Table 1.

Table 1. *Example velocities used in depth conversion of the regional seismic profiles derived from borehole velocity analysis and seismic stacking velocities over the Eakring and Welton oilfields and the Northumberland Trough (Figs 10, 11 & 22)*

Sequence	Velocity (m s^{-1})
Welton	
Jurassic	2450
Triassic (Sherwood Sandstone)	3290
Permian (Magnesian Limestone)	3470
Late Westphalian (Variscan)	3700
Westphalian (Coal Measures)	3450
Namurian (Millstone Grit)	3700
Dinantian (EC6)	5350
Dinantian (EC5)	5600
Dinantian (EC4)	5650
Dinantian (EC3)	5700
Dinantian (EC2)	5750
Dinantian (EC1)	5500
Palaeozoic basement	7000
Eakring	
Triassic (Sherwood Sandstone)	2700
Permian (Magnesian Limestone)	3730
Westphalian (Coal Measures)	3100
Namurian (Millstone Grit)	3300
Dinantian (EC6)	5000
Dinantian (EC5)	5350
Dinantian (EC4)	5400
Dinantian (EC3)	5500
Dinantian (EC2)	5700
Dinantian (EC1)	5500
Palaeozoic basement	7000
Northumberland Trough (Kimbell et al. 1989)	
Stainmore Group (LC1)	3600
Liddlesdale Group (EC4-EC6)	3980
Upper Border Group (EC3)	4130
Cambeck Beds (EC2)	4780
Lower Border Group (EC1)	5500

Widmerpool Gulf

The Widmerpool Gulf is typical of the many fault-bounded Carboniferous basins of northern England forming the southern of two main depocentres that comprise the East Midlands province (Figs 1 and 11). It is bounded to the south by the Hoton Fault, the major basin-bounding fault, and to the north by the Cinderhill Fault, a major antithetic fault (Figs 1 and 11). The Hathern Shelf and the East Midlands Platform form the respective footwalls of these faults. The geometry of the Widmerpool Gulf is that of a strongly asymmetric graben that was inverted along its southern bounding fault in the late Carboniferous (Fig. 12).

The seismo-stratigraphic scheme proposed for the Widmerpool Gulf, and applied throughout this chapter, was introduced by Fraser *et al.* (1990) and further developed by Fraser & Gawthorpe (1990) and Ebdon *et al.* (1990) (Figs 8, 9 and 13). The scheme is based on the integration of approximately 200 km of high-quality, multifold seismic reflection data, well data (from which lithological and biostratigraphical data have been obtained) and outcrop data from the nearby Derbyshire carbonate platform. Observations from other northern England Carboniferous basins (notably those of Gawthorpe 1987*a*, Gawthorpe *et al.* 1989 from the Bowland Basin) are also included. Each tectono-stratigraphic sequence is described below from oldest to youngest.

Pre-rift

Seismic character. The top of the pre-rift is marked by a high-amplitude reflector that is laterally continuous at the basin margins, becoming discontinuous and of lower amplitude into the basin. Internally the pre-rift is characterless (Fig. 12).

Facies. Where penetrated, the pre-rift megasequence is composed of metasediments or igneous intrusives.

Interpretation. The pre-rift megasequence represents Caledonian basement.

Age. The metasediments of the hanging-wall are of undefined Palaeozoic age. Granodiorite from the footwall has been dated as Caledonian, possibly Silurian in age (Pharaoh *et al.* 1987).

Correlation. South of the Widmerpool Gulf, on the London–Brabant Massif, Charnian (Precambrian) metasediments and igneous rocks crop out. To the NW, on the Derbyshire Dome, the Eyam and Woo Dale boreholes penetrated pre-Dinantian volcanic rocks and Lower Palaeozoic rocks respectively (Cope 1973; Dunham 1973; Strank 1985, 1986). To the NE, in the East Midlands, a number of boreholes have penetrated pre-Dinantian basement composed of metasedimentary and intrusive rocks (Pharaoh *et al.* 1987).

EC1 sequence

Seismic character. Reflectors within the sequence diverge into, and overall the sequence thickens into the Hoton Fault and ultimately the Thringstone–Sileby Fault, which was the major basin-bounding fault at this time and lies to the SW of Figure 12 (see Figs 1 and 45). The base shows a suggestion of progressive northwards onlap onto the pre-rift megasequence in the hanging-wall. The top of the sequence is marked by a high-amplitude, laterally continuous reflector. Internally the sequence is characterized by low-amplitude, high-frequency, laterally discontinuous events (Fig. 12).

Facies and biostratigraphy. Sequence EC1 has not been penetrated by boreholes in the Widmerpool Gulf.

Interpretation. The marked thickening of the EC1 sequence into the major basin-bounding faults (the Hoton and Thringstone–Sileby Faults) indicates that deposition occurred during a phase of extension and normal faulting. This early phase of faulting represents the initial development of the half graben. Downlapping alluvial fans, similar to those penetrated in the hanging-wall of the Eakring/Foston Faults (e.g. Eakring-146, Fig. 12), are envisaged adjacent to both the Hoton and Sileby Faults. The alluvial fans are interpreted to pass basinward into fluvial plain deposits of Old Red Sandstone facies towards the basin centre and hanging-wall dipslope. A marine transgression is marked by the progressive onlap of the basement by carbonate deposits.

Age. Late Devonian–Courceyan. The age is based on borehole data from the Hathern Shelf and regional correlation (see below).

Correlation. Sediments of the EC1 sequence have been penetrated to the south of the Widmerpool Gulf by the Hathern-1 borehole. At the base of Hathern-1, anhydrites were encountered, indicating that there was restricted marine influence by this time in the half graben (Falcon & Kent 1960; Llewellyn & Stabbins 1968, 1970). Palynological analysis (Llewellyn *et al.* 1969) indicates a Courceyan age equivalent to the CM Zone of Clayton *et al.* (1977). Elsewhere in the East Midlands, EC1 is confined to incipient half graben, and has only been encountered in the subsurface in a small inverted half graben (penetrated in Eakring-146) and on the footwall of the Widmerpool Gulf (Caldon Low borehole; Institute of Geological Sciences 1978; Welsh & Owens 1983). In both locations EC1 consists of red, fluvial conglomeratic sandstones, which are inferred to be of late Devonian–Courceyan age and rest on basement. Direct comparison with outcrop from the Derbyshire carbonate platform is not possible as the complete Dinantian section is not exposed. The Eyam borehole (Dunham 1973; Strank 1985), however, revealed Courceyan evaporites overlying Ordovician metasediments.

EC2 sequence

Seismic character. Sequence EC2 comprises high-amplitude, laterally continuous reflectors in the basin centre, that diverge and thicken along the hanging-wall dipslope, where hummocky downlapping clinoforms are tentatively identified. The base of the sequence is marked by a high amplitude, laterally continuous reflector (top EC1). The top of the sequence is marked by onlap of the overlying sequence (Fig. 12).

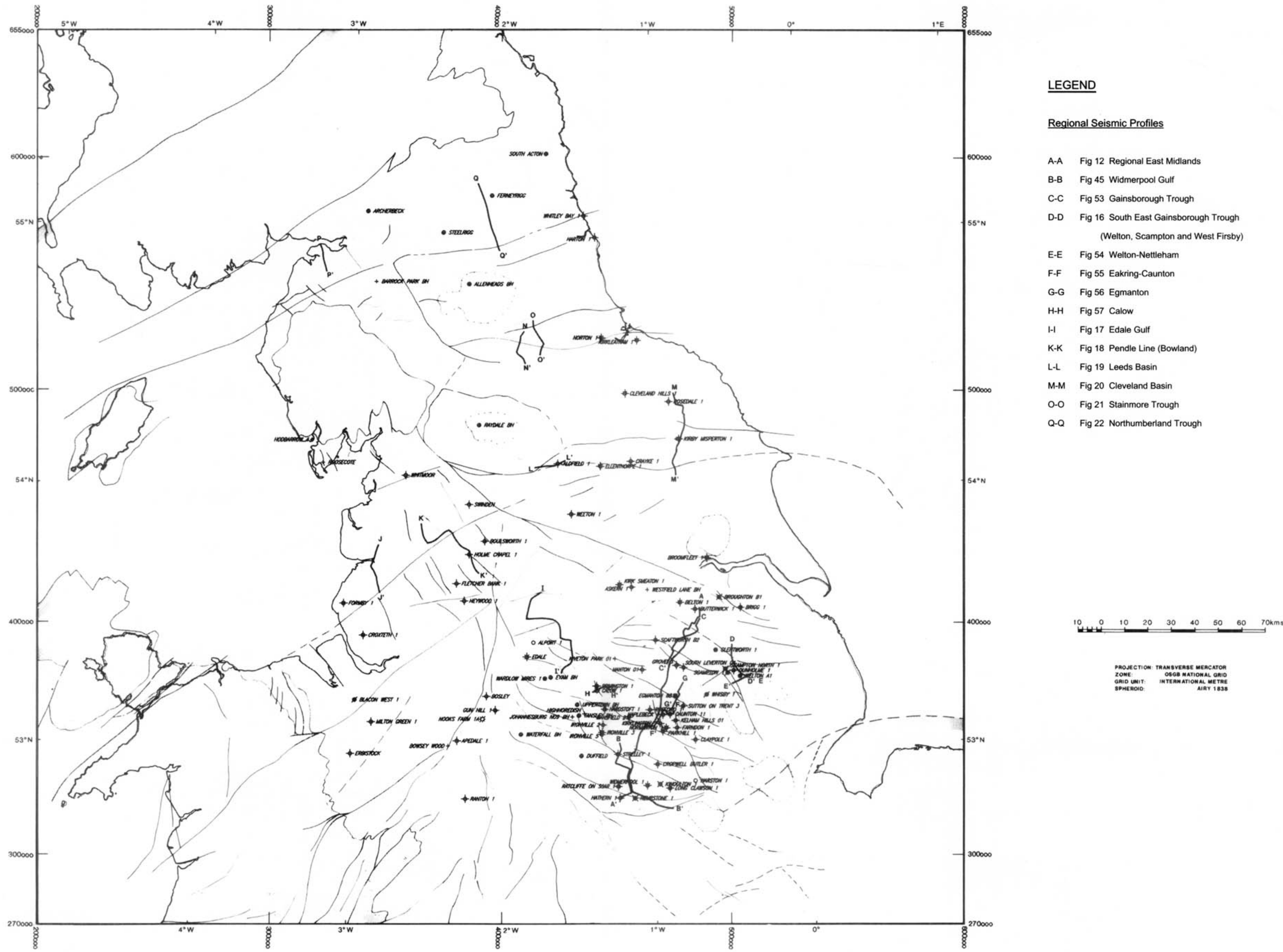


Fig. 10. Map illustrating the location of regional seismic lines and cross sections illustrated in this study, together with simplified structural elements.

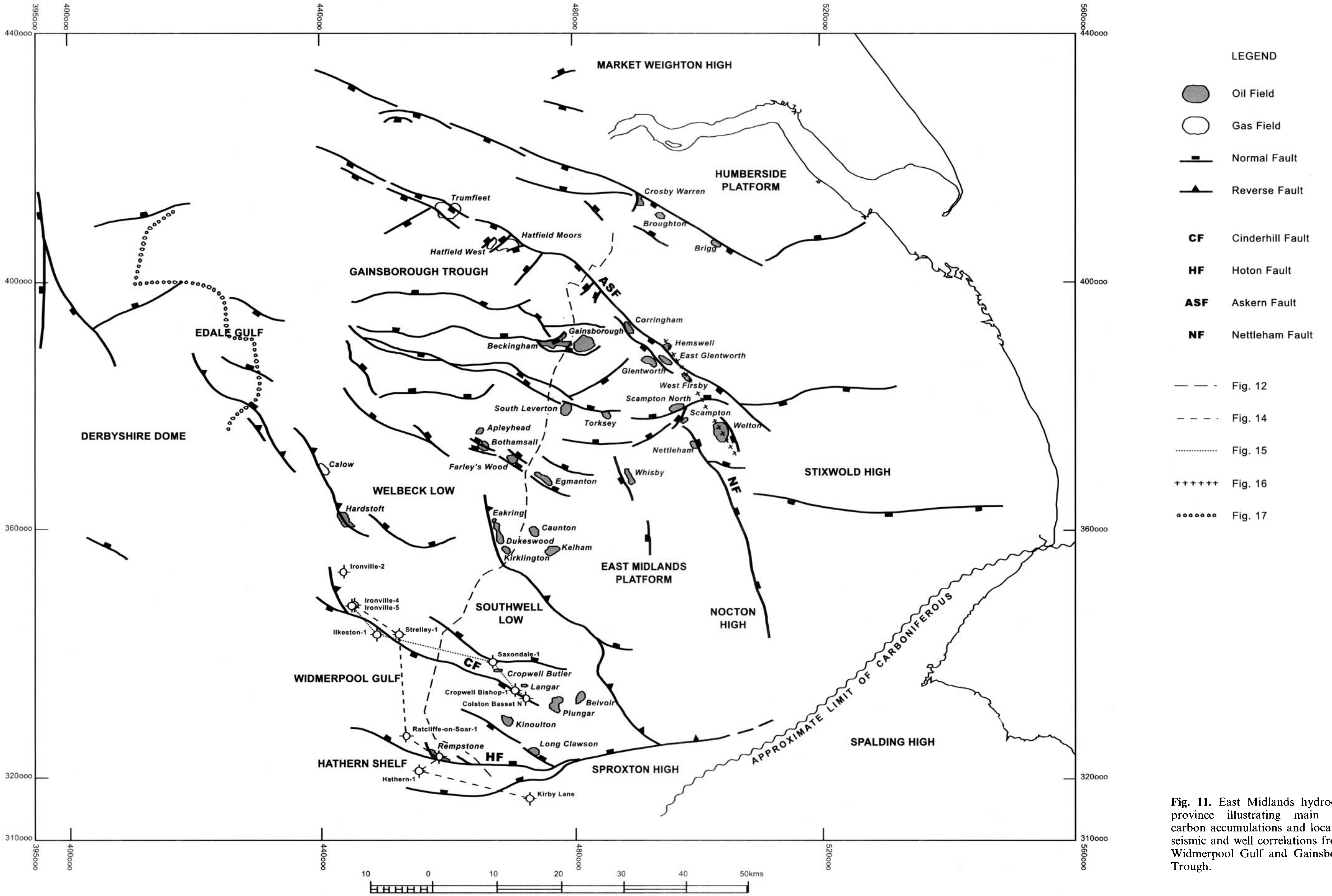


Fig. 11. East Midlands hydrocarbon province illustrating main hydrocarbon accumulations and location of seismic and well correlations from the Widmerpool Gulf and Gainsborough Trough.

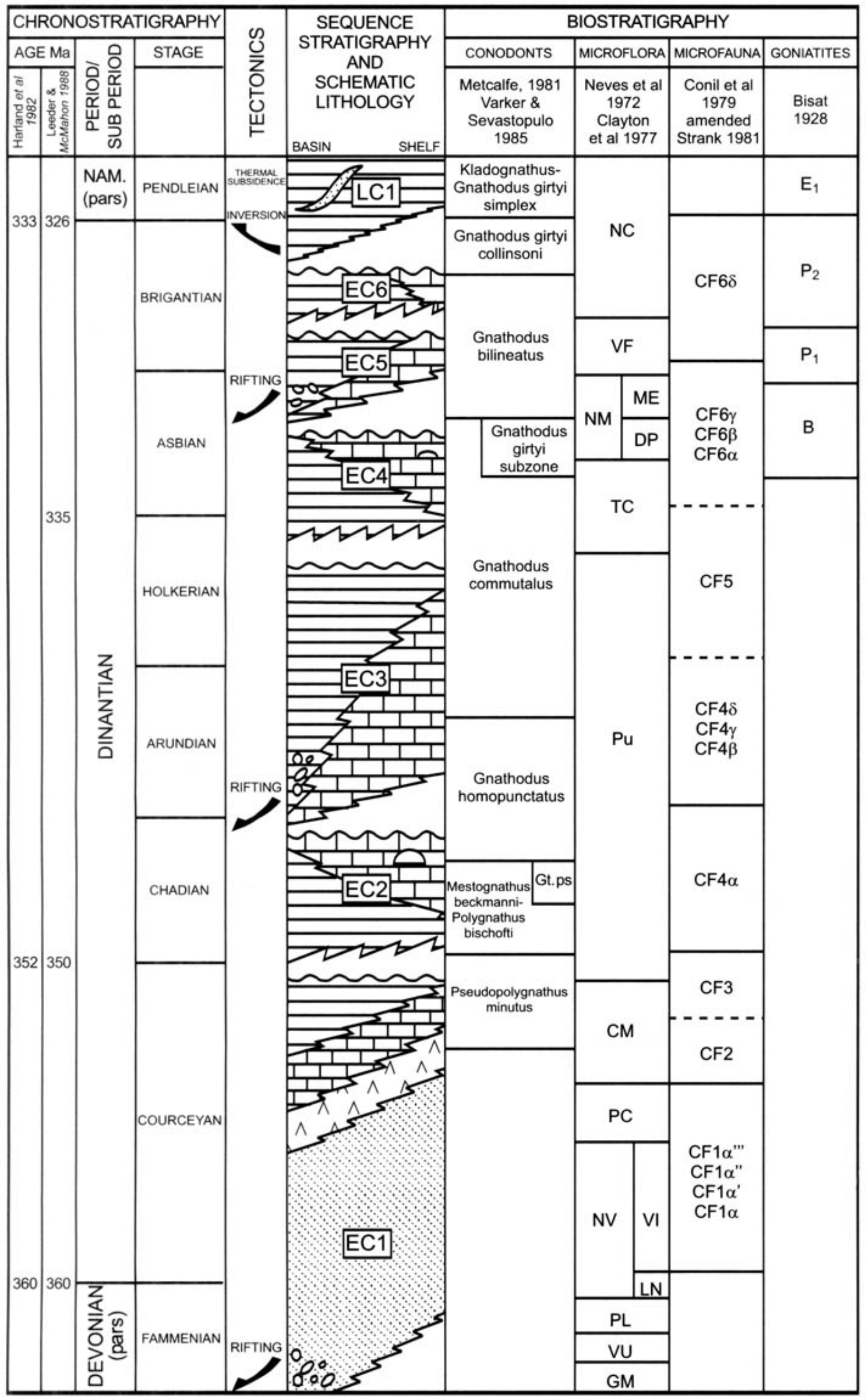


Fig. 13. Dinantian–early Namurian seismo-stratigraphy of the Widmerpool Gulf after Ebdon *et al.* 1990). Gt ps is the *Gnathodus pseudosemiglabar* Subzone. Lithology symbols as in Figure 9.

Facies and biostratigraphy. The EC2 sequence has not been penetrated by boreholes in the Widmerpool Gulf. The upper part of the sequence was penetrated on the southern margin of the gulf in the Strelley-1 borehole (Fig. 14). Here the interval is represented by a series of shelf margin, carbonate grainstones.

Interpretation. The high-amplitude, laterally continuous reflectors in the basin are believed to represent carbonates. During EC2, aggradational to progradational carbonate ramps and rimmed shelves developed. This interpretation is based on the thickening of EC2 across the hanging-wall dipslope and the tentative identification of hummocky downlapping clinoforms. The lack of thickening and reflector divergence into the Hoton and Thringstone–Sileby Faults suggests that EC2 was a phase of tectonic quiescence.

Age. Chadian, possibly as old as late Courceyan, based on correlation with outcrop and well data.

Correlation. EC2 has been penetrated by Hathern-1 on the footwall of the Hoton Fault. Here the sequence is developed as shelf limestones (Llewellyn & Stabbins 1968, 1970), which are dated as no older than the CF4 Zone of Conil *et al.* (1979). On the adjacent East Midlands Platform, EC2 comprises shelf limestones and is the oldest of the Dinantian sequences preserved. Comparison with Strank (1987) suggests that EC2 is no older than late Courceyan in the shelf setting. At Dovedale, on the Derbyshire carbonate platform along strike from the Widmerpool Gulf, elongate Waulsortian buildups are reported by Bridges & Chapman (1988). These buildups developed on a ramp to the SW of an evolving carbonate platform during Chadian times.

EC3 sequence

Seismic character. The EC3 sequence thickens significantly into the Hoton Fault and thins progressively northwards onto the hanging-wall dipslope. In footwall locations, major truncation of older sequences is observed (Fig. 12). At the base of the sequence there is progressive onlap onto the underlying EC2 sequence. The upper boundary of the sequence is marked by apparent truncation of reflectors (Fig. 12). Internally the sequence consists of low-amplitude, high-frequency, laterally discontinuous events which progressively onlap onto the hanging-wall dipslope (Fig. 12).

Facies. Where penetrated in the basin, the sequence comprises a monotonous series of variably calcareous, carbonaceous, pyritic, dark grey mudstones thinly interbedded with grey, dolomitic limestones (e.g. Ratcliffe-on-Soar-1, Fig. 14). The seismic character of EC3 exhibits no lateral variation, reflecting the monotonous character of the facies across the Widmerpool Gulf. On the adjacent East Midlands Platform the sequence is represented by shelf limestones.

Biostratigraphy. Only the top part of the sequence has been penetrated in the basin. Miospore assemblages recovered from the sequence include abundant *Lycospora pusilla* in association with *Schulzospora campyloptera, Stenozonotriletes coronatus, V. baccatus, C. aculeata, P. tesselatus* and *Waltzispora planiangulata* (Ebdon *et al.* 1990). The miospore assemblages recovered from the upper part of the interval are broadly equivalent to the TC Zone of Neves *et al.* (1972). Although conodont analysis has been undertaken, no biostratigraphically significant assemblages have been recovered.

Interpretation. The geometry of the sequence, particularly the significant thickening into the Hoton Fault, indicates that deposition of EC3 was initiated by rejuvenation of the major basin-bounding fault. This phase of extension was associated with rotation of the fault blocks and significant footwall erosion. Carbonate shelf margins which developed during EC2 on the footwall blocks were eroded, those located on hanging-wall dipslopes were drowned.

Age. Late Chadian–late Holkerian. The age of the lowermost part of EC3 is based on analogy with sections in the Bowland Basin (e.g. Gawthorpe 1987*a*). The age of the upper part of the sequence is defined by the identification of the TC Zone of Neves *et al.* (1972). The base of the TC Zone is in the late Holkerian (Ebdon *et al.* 1990).

Correlation. In the Bowland Basin there was a period of enhanced tectonic activity during the late Chadian–early Arundian (Gawthorpe 1987*a*). At outcrop this is marked by horizons of debris flow, carbonate breccias and sedimentary slides which unconformably overlie calciturbidites of the preceding EC2 sequence. This is believed to correlate approximately with the onset of the EC3 rifting in the Widmerpool Gulf. On the East Midlands Platform a widespread Arundian shale horizon marks the cessation of carbonate growth within the platform and is believed to represent the maximum extent of the EC3 transgression.

EC4 sequence

Seismic character. The sequence is thickest at the margins of the basin, along the Hoton and Cinderhill fault systems, and thins into the basin centre (Fig. 12). The base of the sequence shows downlap onto the underlying EC3 sequence along the hanging-wall dipslope, becoming subparallel with EC3 towards the basin centre. The top of the sequence is marked by progressive onlap of the overlying sequence (Fig. 12). Internally, in the basin, the sequence comprises high-amplitude, low-frequency, laterally continuous reflectors. Along the Hoton Fault EC4 comprises high-amplitude, low-frequency, subtle high-angle reflectors that represent vertically and laterally accreting clinoforms that prograde northwards into the basin (Fig. 12). Along the hanging-wall dipslope the sequence is largely characterless, but in places high-amplitude, low-frequency, hummocky clinoforms are identified, prograding southwards into the basin and downlapping onto EC3.

Facies. In the basin the high-amplitude reflectors are interpreted to represent an increase in high-velocity carbonates within an otherwise monotonous sequence of mudstones. The clinoforms identified along the basin margins are believed to represent the progradation and aggradation of carbonate platforms. Boreholes penetrating the area of topset reflectors up-dip of the clinoforms (e.g. Ironville-5, Figs. 12 and 14) prove the presence of shallow-water marine limestones interpreted as shelfal carbonates.

Biostratigraphy. The age of the sequence is constrained biostratigraphically through borehole data tied to seismic sections. Diverse conodont faunas include *Paragnathodus commutatus, Gnathodus homopunctatus, Gnathodus girtyi girtyi, Cavusgnathus unicornis* and *Apatognathus* sp. in association with bivalve spat, ostracodes and brachiopod spines (Ebdon *et al.* 1990). The sequence equates to the *G. girtyi* Subzone of the *P. commutatus* Zone (Metcalfe 1981). The upper boundary of the sequence coincides with the boundary between the *G. bilineatus* and *P. commutatus* zones (Metcalfe 1981). Palynofloras are broadly equivalent to the NM Zone and the upper part of the TC Zone (Neves *et al.* 1972).

Interpretation. Sequence EC4 is interpreted as having developed during a phase of limited tectonic activity during which carbonate deposition was re-established along the basin margins and low rates of subsidence prevailed. This enabled the carbonate platforms to become established and prograde both southward and northward from the hanging-wall and footwall margins respectively.

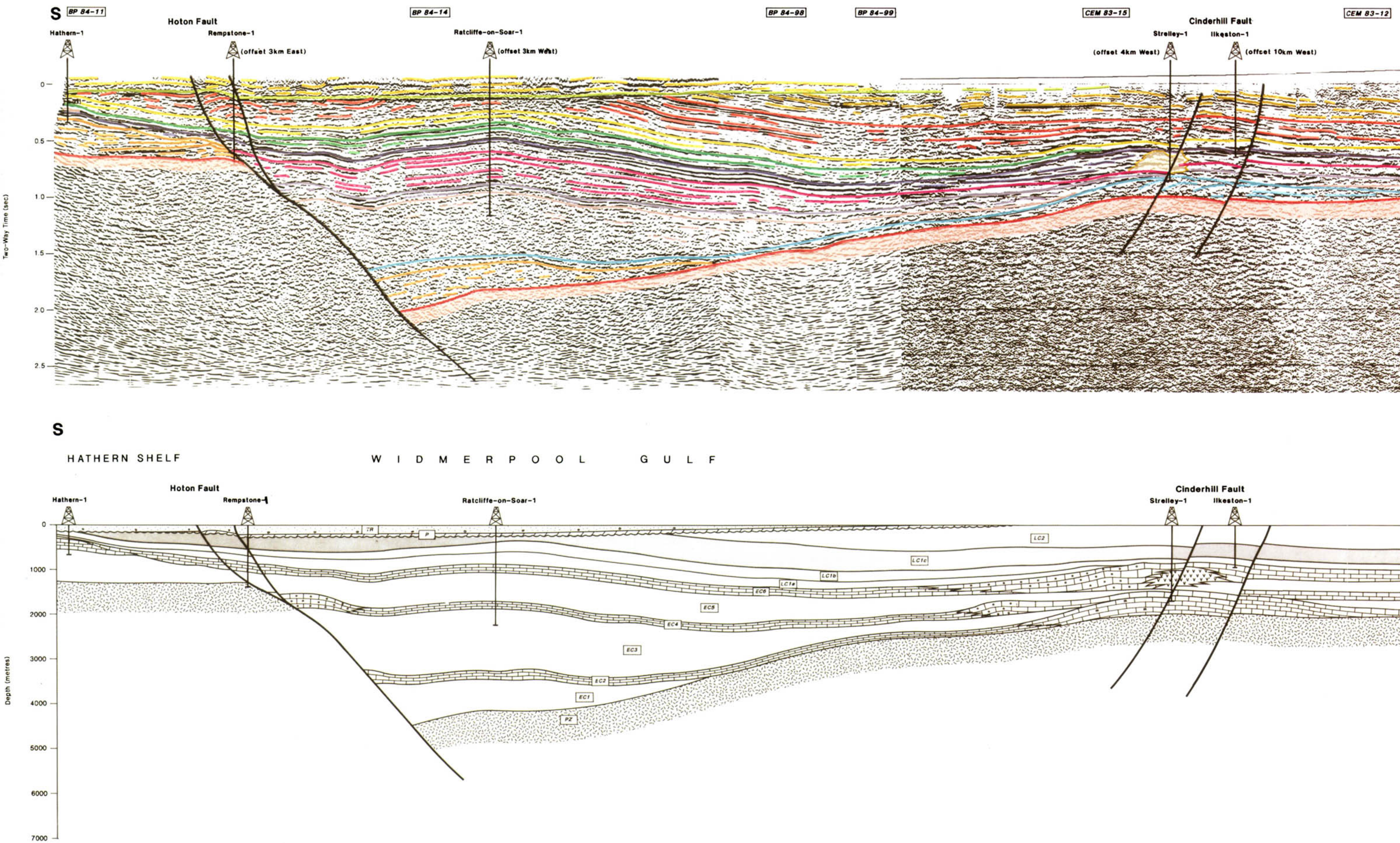
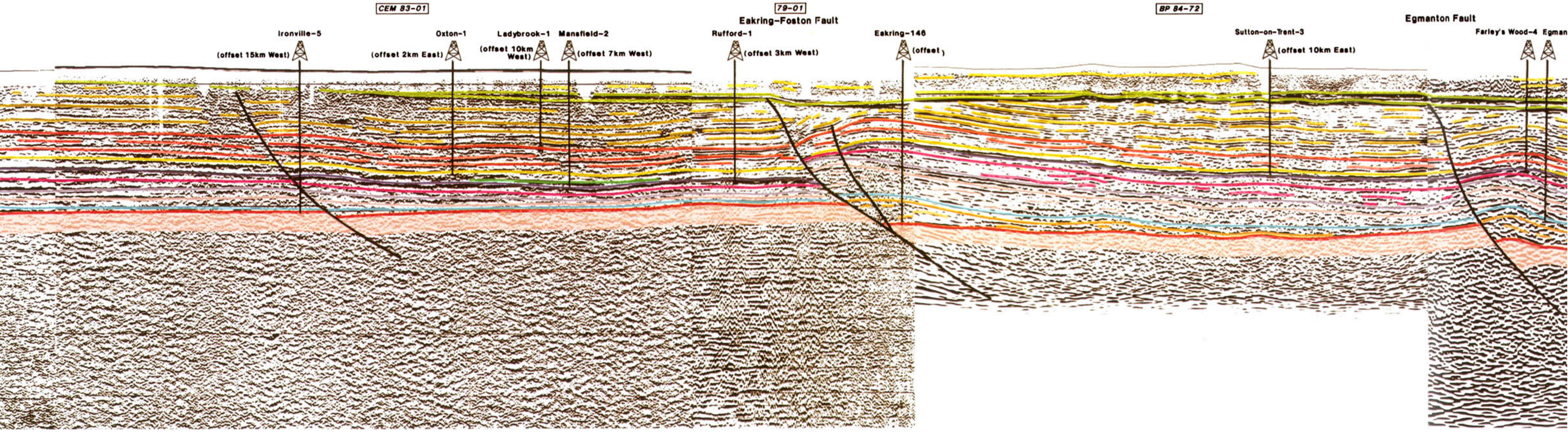
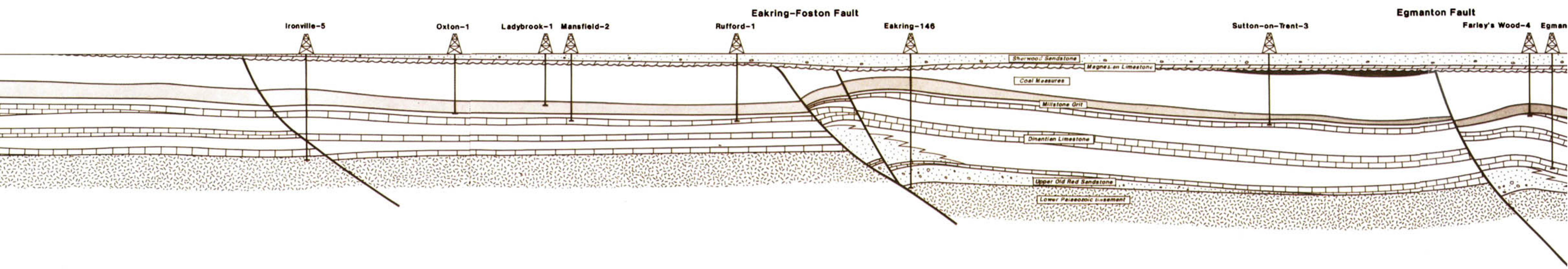
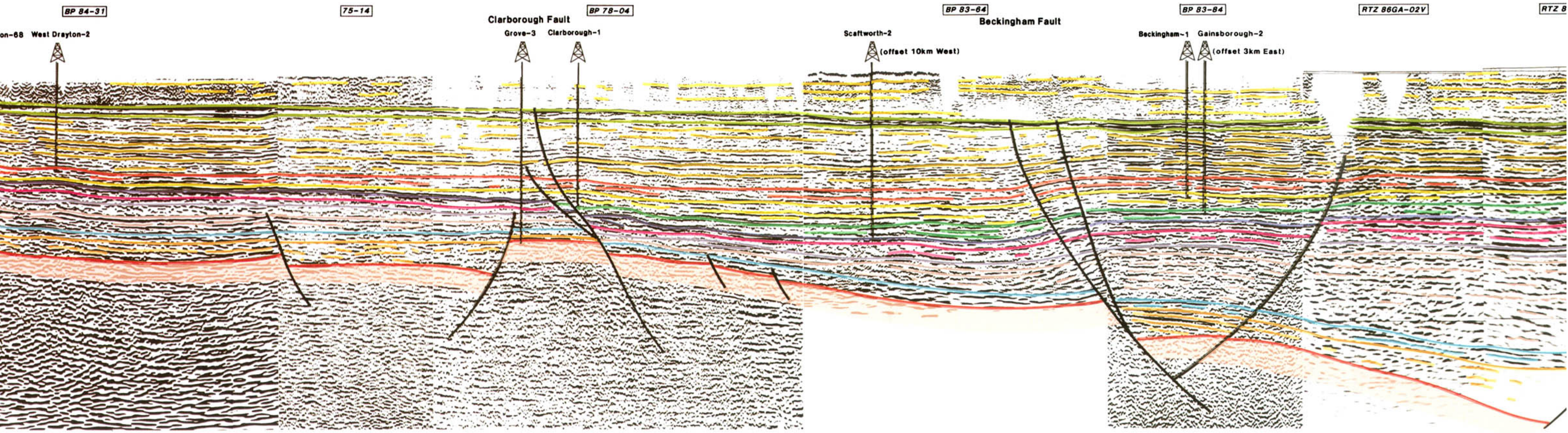


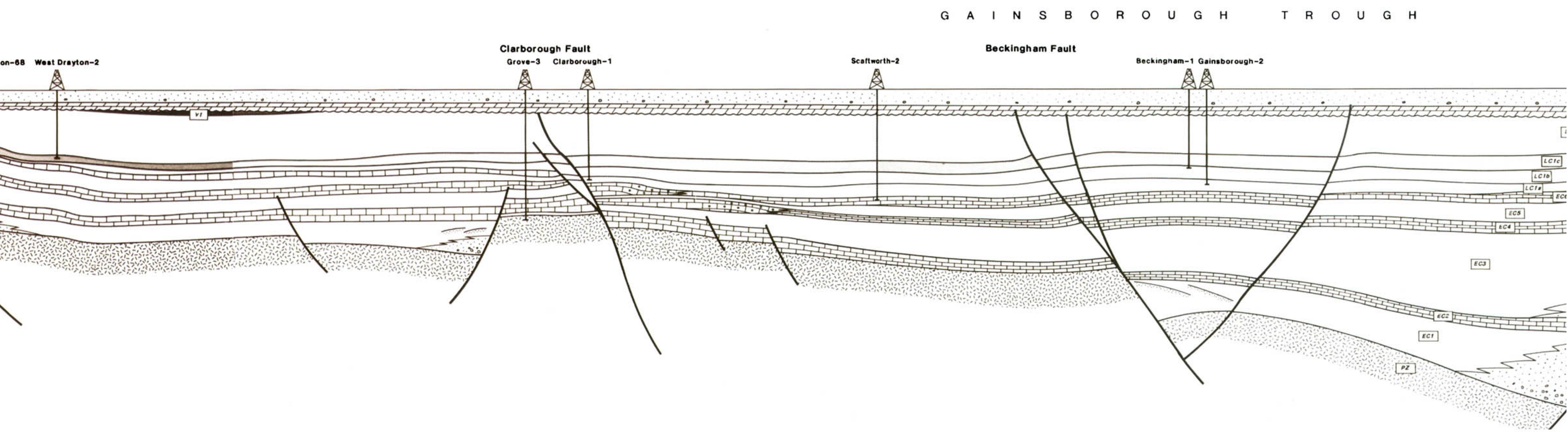
Fig. 12. Composite north–south 2D seismic line and interpreted geological cross section across the East Midlands hydrocarbon province from the Widmerpool Gulf to the Gainsborough Trough (modified after Fraser *et al.* 1990; Fraser & Gawthorpe 1990; see Figs 10 and 11 for location of the seismic).

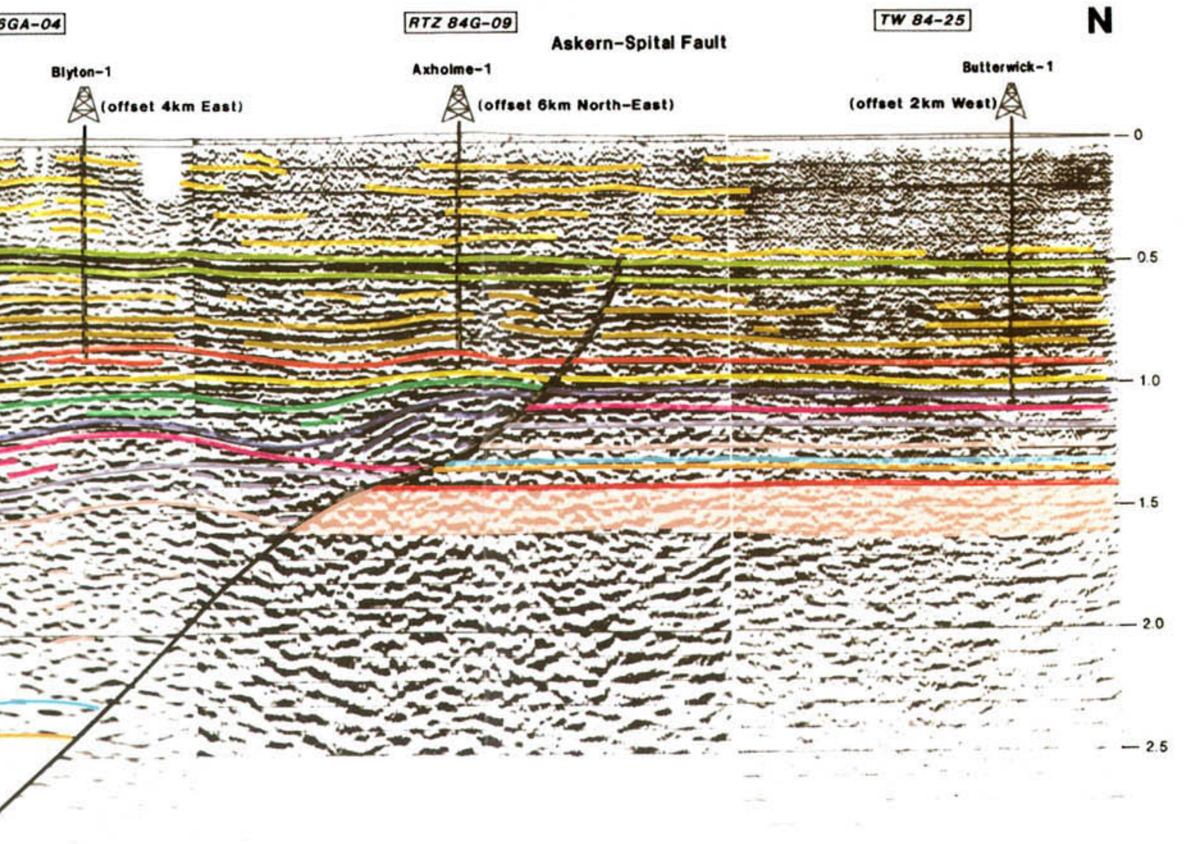


E A S T   M I D L A N D S   S H E L F

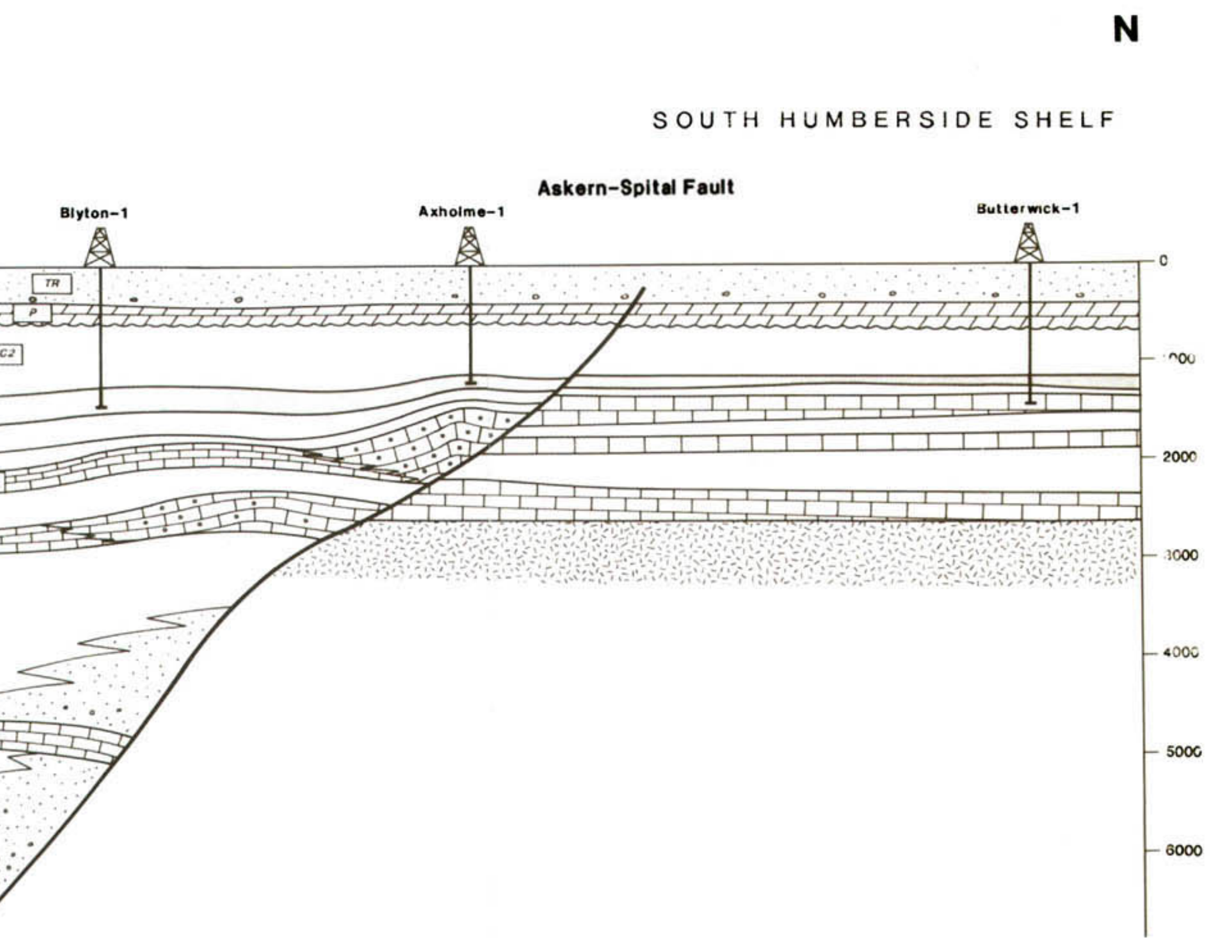



BP 84-31
75-14
BP 78-04
BP 83-64
BP 83-84
RTZ 86GA-02V
Clarborough Fault
Beckingham Fault
West Drayton-2
Grove-3
Clarborough-1
Scaftworth-2
(offset 10km West)
Beckingham-1
Gainsborough-2
(offset 3km East)


G A I N S B O R O U G H T R O U G H
Clarborough Fault
Beckingham Fault
West Drayton-2
Grove-3
Clarborough-1
Scaftworth-2
Beckingham-1
Gainsborough-2
LC1c
LC1b
EC5
EC3
EC2
EC1
PZ



GA-04
RTZ 84G-09
TW 84-25
N
Askern-Spital Fault
Blyton-1
(offset 4km East)
Axholme-1
(offset 6km North-East)
Butterwick-1
(offset 2km West)
0
0.5
1.0
1.5
2.0
2.5



N
SOUTH HUMBERSIDE SHELF
Askern-Spital Fault
Blyton-1
Axholme-1
Butterwick-1
TR
P
0
2000
3000
4000
5000
6000

Age. Late Holkerian to mid-Asbian. The oldest age for the sequence is defined by the presence of the TC Zone (Neves *et al.* 1972) at the base of EC4. The youngest age for the sequence is defined by the top of the *G. girtyi* Subzone, *P. commutatus* Zone of Metcalfe (1981).

Correlation. Similar high-angle shelf margins to those developed along the Hoton Fault are exposed nearby at Castleton in Derbyshire. In this case the Asbian grainstone shelf margin forms the northern margin of the Derbyshire Dome and supplied carbonate sediment northward into the Edale Gulf. Gutteridge (1987) concluded that in the region of the present-day Derbyshire Dome a major carbonate shelf developed across earlier basement topography. The strong parallel reflectors seen across the Widmerpool Gulf in sequence EC4 are believed to represent interbedded hemipelagic carbonates and calciturbidites deposited basinward of the evolving carbonate shelf margins, comparable to the time-equivalent succession described from the Bowland Basin (Gawthorpe 1987*a*).

EC5 sequence

Seismic character. The EC5 sequence, like the ECl and EC3 sequences, diverges and thickens into the Hoton Fault and thins northwards onto the hanging-wall dipslope (Fig. 12). The base of the sequence shows progressive onlap onto EC4. Internally the sequence consists of low amplitude, high-frequency, laterally continuous parallel events that progressively onlap the hanging-wall dipslope (Fig. 12).

Facies. In the basinal setting borehole evidence indicates that EC5 consists of calcareous mudstones and thin dolomitic limestones. In contrast, shallow-marine shelf limestones accumulated on the East Midlands Platform and Hathern Shelf (Strank 1987). Volcanic centres along the Cinderhill Fault were active during EC5 times (e.g. Strelley-1 borehole, Fig. 14).

Biostratigraphy. Conodont faunas are impoverished towards the base of the sequence where assemblages are indeterminate and become progressively richer and more diverse at the top of the sequence. In boreholes, the top of EC5 occurs within the *G. bilineatus* Zone (Metcalfe 1981). Assemblages are characterized by *G. bilineatus, G. homopunctatus, P. commutatus* and *G. girtyi* (Ebdon *et al.* 1990). Mestognathids, including *Mestognathus beckmanni,* characteristically occur at the top of the sequence and indicate a shallowing of the system with time. Towards the base of the sequence the indeterminate faunas include fragmented conodonts, foraminiferal casts, isolated brachiopod spines and goniatite spat.

Palynofloral assemblages from the sequence can be assigned to the VF zone of Neves *et al.* (1972). Assemblages typically contain species of *Lycospora* and *Densosporites* which are common, in association with *Schulzospora* species, *Spelaeotriletes arenaceous, Raistrickia nigra* and *Remysporites magnificus* (Ebdon *et al.* 1990).

Interpretation. The pronounced thickening of the sequence into the major basin-bounding fault (the Hoton Fault) indicates that EC5 was deposited during a phase of active rifting. This was accompanied by footwall rotation, which generated both uplift and erosion. Contemporaneous volcanic rocks were extruded from centres of igneous activity aligned along the Cinderhill Fault. Microfaunal evidence indicates that the sediment during the early stages of EC5 was derived from a mixed source, suggesting a contribution from the emergent EC4 carbonate shelf. By the end of EC5 times shallow-water conditions were developed across the Widmerpool Gulf as sedimentation exceeded subsidence.

Age. Late Asbian–early Brigantian. The oldest age of EC5 is well constrained by the youngest age of the underlying EC4 sequence. The record of palynofloras belonging to the NM Zone (Neves *et al.* 1972), ME Subzone (Clayton *et al.* 1977) is consistent with the late Asbian age assigned to the base of the sequence. The upper age limit is less well constrained, being approximately equivalent to the VF-NC miospore zone boundary of Neves *et al.* (1972). Clayton *et al.* (1977) equates the base of the NC Zone to a position within the P2 goniatite Zone.

Correlation. Sequence EC5 ties in well with a late Asbian–early Brigantian phase of tectonic activity in the Bowland Basin (Gawthorpe 1986, 1987*a*). Basaltic lavas on the Derbyshire Dome (the Lower and Upper Miller's Dale Lavas) lie along strike from, and are stratigraphically equivalent to, the volcanic centres developed along the hanging-wall margin of the Widmerpool Gulf (Macdonald *et al.* 1984). This volcanism is interpreted to be associated with reactivation of extensional faults. Gutteridge (1987) records two periods of emergence and karstic erosion on the Derbyshire carbonate platform in the late Asbian and early Brigantian. These are believed to correspond to two pulses of extension in the area during EC5 times, leading to footwall uplift and erosion. Horizons of debris flows, carbonate breccias and sedimentary slides occur in the Bowland Basin associated with this phase of extension, as with earlier phases, e.g. EC3 (Gawthorpe 1987*a*). During EC5 times fine terrigenous clastics related to the advance of major delta systems from the north reached the Bowland Basin.

EC6 sequence

Seismic character. EC6 is thickest along the Cinderhill Fault with a carbonate shelf margin developed basinward of the EC5 volcanic centres (Figs 12 and 14). The base of the sequence exhibits downlap onto EC5 along the hanging-wall dipslope, becoming sub-parallel to EC5 in the basin centre. The top of the sequence is marked by progressive onlap of the overlying sequence LC1 (Fig. 12). Along the hanging-wall dipslope, EC6 comprises a series of complex sigmoidal and oblique, high-amplitude, low-frequency clinoforms (Fig. 12). These change character along the hanging-wall dipslope to hummocky clinoforms on parallel seismic lines, and pass southwards into high-amplitude, high-frequency parallel events in the basin (Fig. 12). In addition, mounded features up to 0.5 km across have been identified on the Hathern Shelf.

Facies. In the basin EC6 comprises a monotonous series of thinly bedded, dark grey, calcareous mudstones and brown, dolomitic, muddy limestones. Volcanic centres along the Cinderhill Fault continued to be active during EC6 times as evidenced by the basalts and tuffs penetrated in the Strelley-1 borehole (Figs 12 and 14).

Biostratigraphy. The top of the sequence is well constrained by the top of the *G. bilineatus* conodont Zone of Metcalfe (1981). Conodont assemblages are rich and diverse throughout and resemble those present in the underlying sequence. *G. bilineatus, G. homopunctatus, G. girtyi* and *P. commutatus* continue to typify the microfauna, in association with *Neoprioniodus scitulus, Neoprioniodus singularis, Hibbardella milleri* and *Ozarkodina delicatula* (Ebdon *et al.* 1990). The EC5/EC6 seismic sequence boundary is approximately coincident with the VF/NC miospore Zone boundary of Neves *et al.* 1972). The base of the NC Zone (Neves *et al.* 1972) is marked by the appearance of a number of taxa including *Bellespores nitidius, Reticulatisporites carnosus, Convolutisporites varicosus* and *Schopfipollenites ellipsoides.* Assemblages continue to be characterized by elements consistently recorded in the underlying sequence, namely *L. pusilla, R. nigra, R. magnificus, R. fracta, R. knoxii, S. nux, Triquitrites marginatus, T. trivalvis* and species of *Schukospora* (Ebdon *et al.* 1990). The EC6 sequence belongs exclusively to the NC Zone (Neves *et al.* 1972), the top of the sequence falling within the biozone.

Interpretation. High on the hanging-wall dipslope, EC6 is considered to comprise carbonate grainstones. Carbonate production was re-established following EC5 and a carbonate ramp prograded southward into the basin from the hanging-wall dipslope. The laterally and vertically accreting clinoforms observed along the hanging-wall shelf margin suggest an evolution from a carbonate ramp to a grainstone rimmed shelf. Clinoform height suggests that water depths basinward of the shelf margin were in the order of 300 m. This interpretation is further supported by conodont faunas recorded from the basinal sediments. The margins have not been penetrated by wells. Volcanic rocks, of EC5 and EC6 age, extend out into the basin as lava flows. They are believed to have generated shallow water depths around the basin margins and enhanced the development of the grainstone margin (Fig. 12). The volcanics are represented seismically by very high-amplitude, low-frequency, laterally continuous reflectors.

Age. Early to mid-Brigantian. The top and base of the sequence are well constrained biostratigraphically. The oldest age for the base of EC6 is constrained by the base of the NC Zone (Neves *et al.* 1972) which Clayton *et al.* (1977) correlated to the middle of the P2 goniatite Zone (Bisat 1928). The age of the top of EC6 is constrained by the top of the *G. bilineatus* conodont Zone, placed by Metcalfe (1981) within the P2b goniatite Subzone.

Correlation. The carbonate grainstone shelf margin interpreted along the hanging-wall dipslope in the subsurface of the Widmerpool Gulf lies along strike from the Wirksworth carbonate grainstone margin in Derbyshire (Walkden 1982). The Wirksworth grainstone shelf margin lies above a volcanic horizon, the Lower Matlock Lava, which is believed to be of early Brigantian age (Walkden 1982). The grainstone margin–volcanic rock association on the northern margin of the Widmerpool Gulf adds further credibility to the interpretation made from the seismic data. Mounded features mapped on the Hathern Shelf are interpreted to be analogous to the carbonate buildups of the Coalhills complex in Derbyshire (Walkden 1982). In contrast, the Bowland Basin at this time was dominated by deep water pro-delta mudstones and basinal turbidites (Bowland Shale and Pendleside Sandstone) (e.g. Collinson 1988).

LC1 sequence

Seismic character. The LC1 sequence is thickest within the basin just north of the Hoton Fault and thins northward and southward onto the hanging-wall and footwall margins respectively (Fig. 12). The lower part of the LC1 sequence internally comprises high-amplitude, high frequency, continuous parallel reflectors which display subtle downlap onto EC6 within the basin, and onlap onto the EC6 carbonate platform margins.

Facies. The lower part of the sequence comprises interbedded dark grey, pyritic, carbonaceous mudstones and thin turbiditic sandstones. Thin

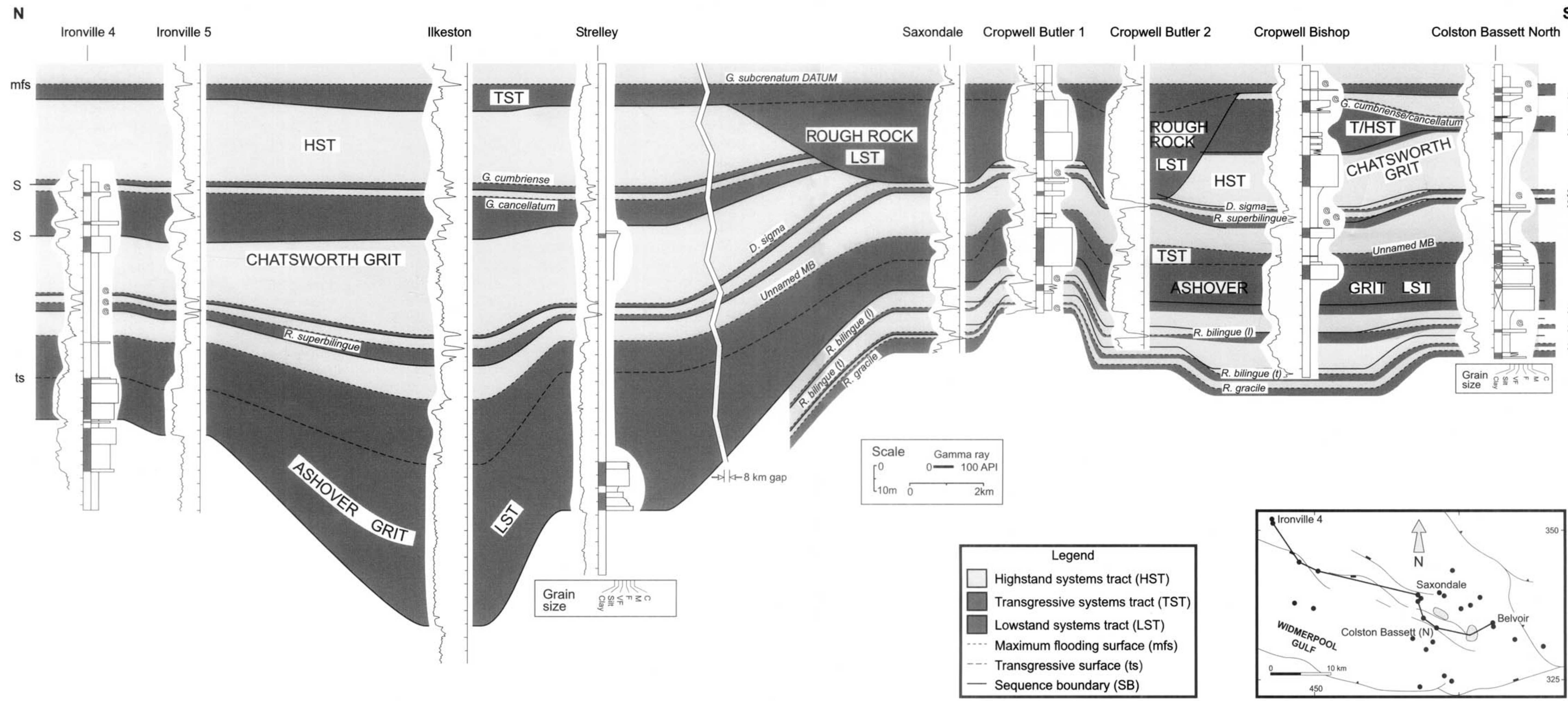


Fig. 15. High-resolution depositional sequences and component systems tracts from the northern margin of the Widmerpool Gulf for the upper part of seismic sequence LC1 (LC1c), between R. gracile and G. subcrenatum marine bands (see Fig. 11 for location of wells). After Church & Gawthorpe (1994).

tuffaceous units occur sporadically towards the base of the unit. The upper part of the sequence is represented by a series of shallowing upwards deltaic cycles consisting of interbedded sandstones and grey mudstones, each of which becomes progressively sandstone-dominated towards the top (Fig. 14). Sequence stratigraphic analysis of these deltaic cycles suggests they represent high frequency depositional sequences reflecting relative sea-level changes (e.g. Church & Gawthorpe 1994; Fig. 15).

Biostratigraphy. The boundary between the LC1 sequence and the underlying EC6 sequence equates to the boundary between the *G. girtyi collinsoni* Zone (Varker & Sevastopulo 1985) and the *G. bilineatus* Zone (Metcalfe 1981). Conodont faunas from the lower part of the LC1 sequence are diverse, and as well as *G. girtyi collinsoni* include *G. girtyi intermedius, G. bilineatus bilineatus, Neoprionoidus spathatus* subsp. A, *N. scitulus, Cavusgnathus naviculus* and *P. commutatus* (Ebdon *et al.* 1990). At the base of the sequence, brachiopod spines and the internal casts of foraminifers are important accessories to the microfauna. The palynoflora remains unchanged from the underlying sequence, being assignable at the base of LC1 to the NC Zone (Neves *et al.* 1972).

Interpretation. Following EC6 there was a minor inversion event, with the strongest inversion concentrated along NNW–SSE-trending faults. Both the Hathern Shelf and, to a lesser extent, the Widmerpool Gulf were inverted. Evidence of inversion within the Widmerpool Gulf is provided by the northward offset from the Hoton Fault of the thickest part of the LC1 sequence (Fig. 12). LC1 is divisible into a number of higher frequency seismic sequences (Figs 12 and 14), and high-resolution depositional sequences and constituent systems tracts based on borehole and outcrop data (e.g. Church & Gawthorpe 1994; Fig. 15). The sediments of LC1 are not generally fault controlled and represent an overall progradational sediment package deposited during the initial stages of thermal subsidence that followed Dinantian rifting. The earliest sediments of LC1 are distal prodelta mudstones and basinal turbidites of the advancing Silesian delta system which had already filled basins

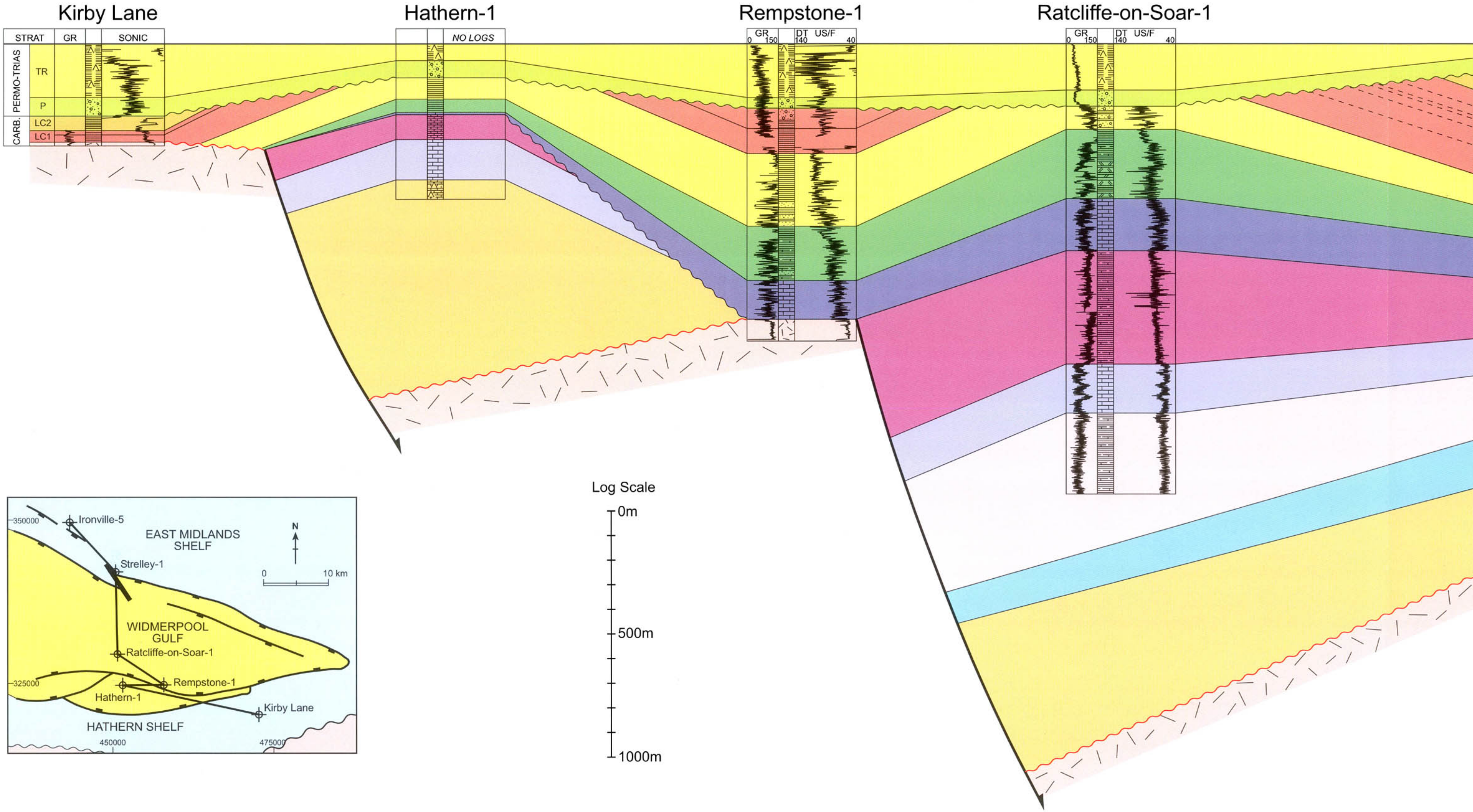
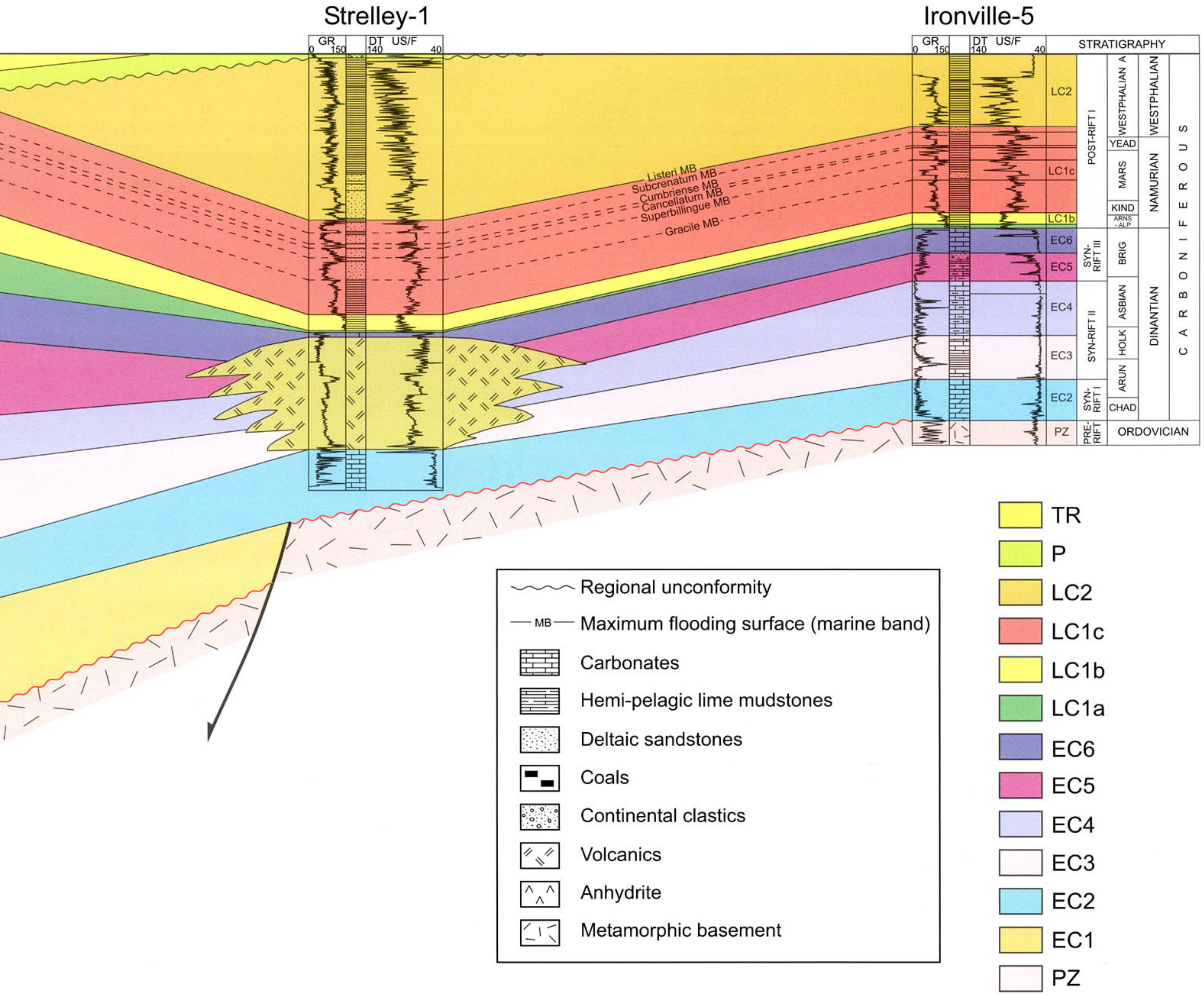


Fig. 14. Regional well correlation across the Widmerpool Gulf showing well-log expression of seismo-stratigraphic sequences (see Fig.



11 for location of wells).

to the north by this time (e.g. Collinson 1988; Fraser *et al.* 1990). Facies and thickness of this advancing delta system were strongly influenced by the existing fault-produced bathymetry. Backstripping of regional seismic data suggests a water depth of about 300 m in the Widmerpool Gulf during the initial stages of LC1, an interpretation supported by the predominance of deep water conodont faunas. However, for most of the Namurian and early Westphalian, northern England was dominated by laterally extensive 'sheet-like' deltas with little differentiation into shelf and deep water basinal environments. The entire seismic dataset for the East Midlands resolves only one example of clinoforms associated with the delta system prograding into a deep water environment — from the Ashover delta (LC1c) advancing along the axis of the gulf. Clinoform height suggests basinal water depths of 150–200 m and is supported by borehole and outcrop studies by Jones (1980).

Age. Late Brigantian to early Westphalian A. The base of the LCl sequence is no older than the *G. girtyi collinsoni* Zone, suggesting a late Brigantian age. Regional evidence indicates that the sequence ranges into the early Westphalian A.

Correlation. The inversion at the end of EC6 is recorded at outcrop on the nearby Derbyshire carbonate platform. This inversion led to the creation of late Brigantian intrashelf basins (Gutteridge 1987), such as the Welbeck Low (Fig. 11). The Welbeck Low formed between the Anston–Manton, Ladybrook and Eakring inversion anticlines present along its north, south and eastern margins respectively. An easterly-dipping carbonate ramp developed during the early part of LC1. Similar intrashelf basins are described from outcrop in Derbyshire (Gutteridge 1987). Elsewhere, over the majority of the East Midlands Platform, shelf carbonates continued to accumulate during late Brigantian times. The overlying clastic sequences represent the progressive infill of the basin by the deposits of increasingly shallow water delta systems.

LC2 sequence

Seismic character. The LC2 sequence is thickest on the northern and southern margins of the Widmerpool Gulf. It is absent over much of the central part of the basin due to inversion, uplift and erosion in late Carboniferous times (Fig. 12). The sequence is characterized by laterally persistent, high-amplitude reflectors that overlie LC1 with subtle onlap.

Facies. The sequence comprises interbedded grey carbonaceous mudstones, siltstones, sandstones and coal seams deposited in an upper delta plain depositional setting (Fig. 14) (e.g. Guion & Fielding 1988).

Biostratigraphy. The boundary between the LC2 sequence and the underlying LC1 sequence is marked by a pronounced 'bulge' on the sonic log, equating to the Amaliae Marine Band in the Strelley, Ilkeston and Ironville-5 boreholes (Fig. 14).

Interpretation. By the end of LC1 times, shallow-water deltaic conditions were widespread over the Widmerpool Gulf. The LC1/LC2 boundary reflects a marked change in depositional facies from lower delta plain to upper delta plain. The continuous high-amplitude reflectors that are characteristic of LC2 seismic facies are generated by the many coal seams developed throughout the seismic sequence.

Age. Early Westphalian A to late Westphalian C. The base of the LC2 sequence lies within the early Westphalian A. Regional evidence indicates that the sequence ranges into the Westphalian C where it was terminated by the onset of Variscan inversion in the area. The initial phase of inversion is interpreted to have occurred between the *Anthraconauta phillipsi* and *A. tenuis* zones of the Upper Carboniferous (Wills 1956).

Correlation. A major shift from lower delta plain to upper delta plain conditions throughout the northern England Pennine Basin, approximating to the Amaliae Marine Band, has been described by Guion & Fielding (1988). This event is thought to have regional significance throughout northern England. The periodic tectonic activity evidenced on several of the major basin-bounding faults during the early part of the post-rift had almost ceased by early Westphalian A times. This also coincided approximately with the cessation of igneous activity in the East Midlands (Kirton 1984). During LC2, upper delta plain, coal swamp conditions were established over most of northern England, forming an internally drained basin north of the Wales-Brabant Massif (Guion & Fielding 1988).

Gainsborough Trough

The Gainsborough Trough forms the northern of the two main depocentres that comprise the East Midlands province (Fig. 11). It comprises a major half graben controlled by the Askern–Spital Fault in the north which downthrows the Dinantian section to the south (Figs 11 and 12). A four-fold increase in thickness of the Dinantian section (EC1-EC6) is evidenced across the fault (Fig. 12). The Gainsborough Trough contains a more complete Namurian and Westphalian section than the Widmerpool Gulf to the south. Within the depocentre there are no borehole penetrations below the top Dinantian (EC6). The major control on the stratigraphy is provided by the Grove-3 borehole, which penetrated a complete, but condensed, Dinantian section sitting above ?Charnian metamorphic basement on the southern flank of the half graben (Fig. 12).

Major rifting occurred in the Gainsborough Trough during EC1 (late Devonian-Courceyan) and EC3 (Arundian–early Holkerian) times. Both the EC1 and EC3 sequences exhibit classic wedge-shaped geometries, typical of syn-rift sedimentation. The present deep burial of the early syn-rift sediments of late Devonian–Courceyan age in northern England generally precludes any valid seismic facies analysis interpretation. However, the regional seismic line compiled for the East Midlands and Gainsborough Trough provides some indication of the nature of the earliest syn-rift sediment package (Fig. 12). The hanging-wall of the Beckingham Fault contains a series of broadly progradational downlapping reflectors interpreted as alluvial fans or fan deltas that prograded into a lake or marginal marine gulf. These probably form part of a series of similar coalescing footwall-sourced fans extending some 4–5 km into the basin.

The seismic data illustrate major backstepping of the southern bounding fault of the basin between EC1 and EC3 rifting. At the onset of EC3 rifting, fault control shifted southwards some 7 km from the Beckingham Fault to the Clarborough Fault. This is a common occurrence in evolving rift basins and has been particularly well demonstrated from the East African rift valley by Rosendahl *et al.* (1986). In contrast to the Widmerpool Gulf, there is very little evidence for a well-developed EC5 (late Asbian–early Brigantian) rift phase.

The syn-rift facies shown on the geological interpretation (Fig. 12) are largely inferred from seismic character. In the Gainsborough Trough both footwall and hanging-wall shelf margins are well preserved along the Askern–Spital and corresponding antithetic faults respectively. The seismic data suggest the development of shelf margin complexes during the Chadian (EC2), late Holkerian–mid Asbian (EC4) and Brigantian (EC6). Onlapping relationships are represented by the Arundian–Holkerian (EC3) and a very thin late Brigantian–early Pendleian (LC1a).

The overlying Silesian post-rift (LC1–LC2) has been described in detail by Steele (1988). The thickening of the Namurian sequence into the Gainsborough Trough is ascribed to three processes: (i) the infill of existing pre-Namurian bathymetry, (ii) differential compaction, and (iii) localized Namurian tectonic activity. The earliest Namurian sediments deposited in the half graben were organic-rich mudstones deposited in relatively deep water. Steele estimates some 300 m of bathymetry existed at the end Dinantian in the centre of the basin. The subsequent fill of the basin has been one of progressive advance of the Kinderscout, Ashover and Chatsworth–Crawshaw shallower water delta systems which infilled the trough from the north (Steele 1988). The culmination of this process was the deposition of extensive coal deposits in the Westphalian which, on seismic data, are represented by strong, laterally continuous high-amplitude reflectors (Figs 12 and 16).

In the late Namurian (LC1c), mild reactivation of extensional faults occurred particularly in the eastern Gainsborough Trough. Here some 200 m of relief developed on the NE–SW-trending Scampton Fault (Fig. 16) establishing a strong footwall unconformity and thick (150 m) sandstone deposition (Rough Rock equivalent) in the hanging-wall. Localized inversion features are recorded along the Askern–Spital and Nettleham Faults (Figs 11 and 16) forming the West Firsby, Glentworth, Nettleham and Welton oilfields (Fig. 11). In the West Firsby area, where a thick LC2 (Westphalian A/B) sequence is preserved, an intra-LC2 tectonic event is evidenced by folding of the pre-LC2b sequence and onlap of the subsequent deposits (LC2b) in the hanging-wall of the Askern–Spital Fault (Fig. 16). This may represent either an early compressional pulse of the Variscan orogeny or a late extensional faulting phase evidenced in the Beckingham area (Fraser & Gawthorpe 1990, their fig. 8). Aitken *et al.* (1999) have recognized similar intra-LC2 tectonic event and major erosion at the level of the Wooley Edge Rock (mid-late Westphalian B).

Edale Gulf

The Edale Gulf forms the third of the major half graben within the East Midlands province (Figs 11 and 17). It lies to the north of the Derbyshire carbonate platform and is buried beneath the Upper Carboniferous of the Central Pennine Basin. The basin was originally thought to be part of a large Dinantian trough that extended northwards to the Askrigg Block and was connected to the Bowland Basin (George 1958; Ramsbottom 1969). Lee (1988) using 3D, 2D and residual gravity modelling, and Smith *et al.* (1985) have suggested that the Edale Gulf comprises a half graben controlled by a major east–west-trending fault that underlies the northern margin of the Derbyshire carbonate platform. Lee (1988) also identified a residual gravity high underlying the Holme area some 15 km to the north of this fault. The regional seismic profile (Fig. 17) confirms the Edale Gulf to comprise a half graben with the main bounding fault underlying the northern margin of the Derbyshire carbonate platform. The hanging-wall dipslope rises northwards to a basement high underlying the Holme area. Evans & Kirby (1999) show that the Holme High is fault bounded along its northern margin by the east–west-trending Holme Fault.

The Alport and Edale boreholes provide data on Dinantian sedimentation in the Edale Gulf. These were drilled on the Alport and Edale anticlines lying some 12 km and 3 km north of the Derbyshire carbonate platform. The Dinantian stratigraphy of these boreholes has been described by Hudson & Cotton (1945*a*, *b*). More recently, the Wessenden borehole, drilled on the crest of the Holme High, penetrated Chadian and Arundian shallow-water

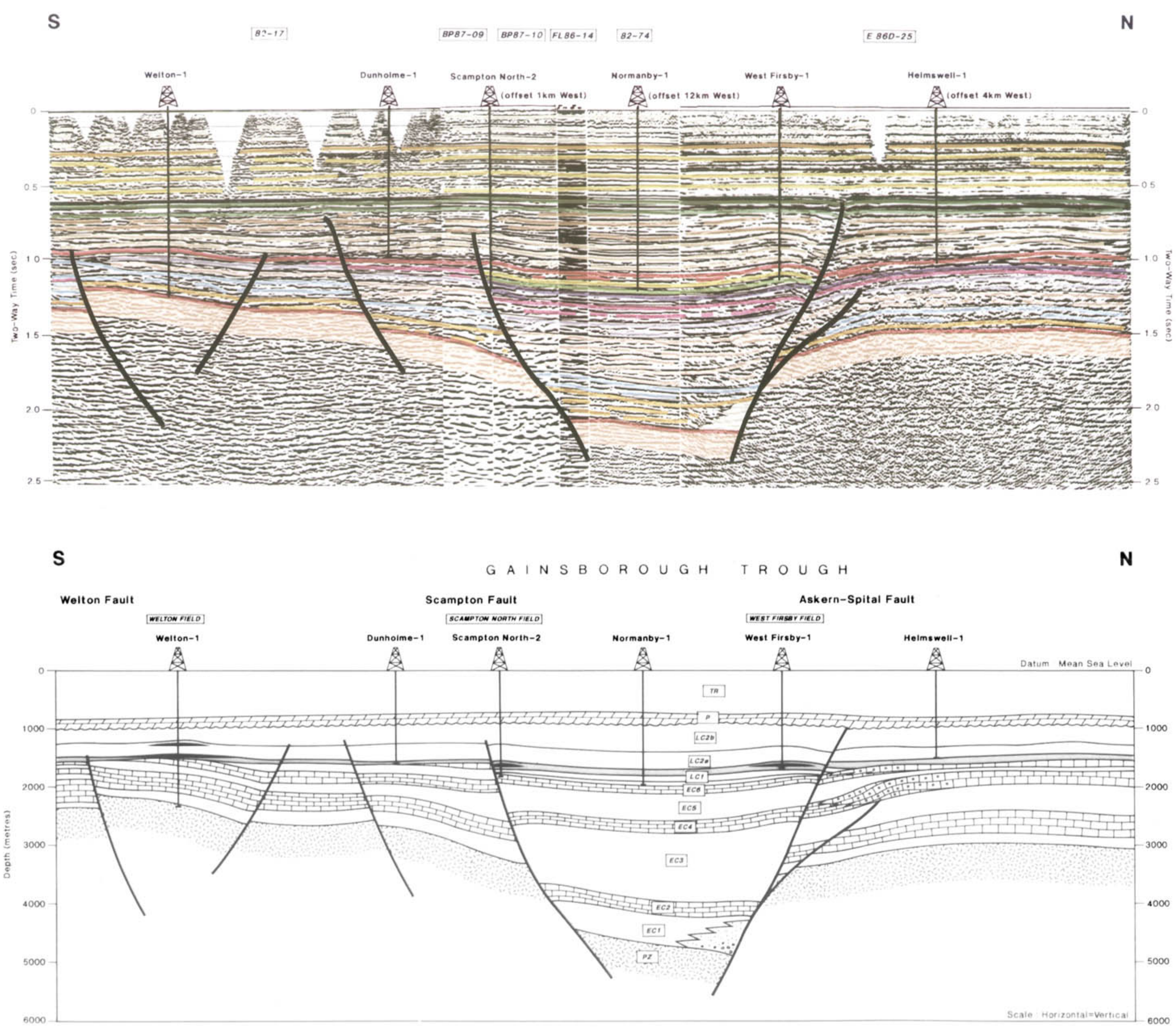


Fig. 16. Composite 2D seismic line and interpreted geological cross section across the SE margin of the Gainsborough Trough (see Figs 10 and 11 for location of the seismic).

carbonates, with no late Asbian or Brigantian strata present (Evans & Kirby 1999). Non-deposition or erosion is interpreted on the crest of the high in late Dinantian to early Namurian times, prior to overstepping by Edale Shales in the Kinderscoutian (Evans & Kirby 1999). The Eyam borehole (Strank, 1985) provides important control on the Dinantian stratigraphy on the southern footwall of the basin. The nearest Dinantian outcrop to the Edale Gulf is the Derbyshire carbonate platform, whose northern margin is exposed a few kilometres to the west of the regional seismic profile at Castleton. The evolution of the basin margin facies during the late Dinantian provides the context in which to evaluate the tectono-stratigraphic development of the Edale Gulf.

Sediments older than EC2 are interpreted to lie at the base of the Edale Gulf by analogy with similar basins in northern England and the presence of EC1 continental facies in the Eyam borehole on the footwall of the gulf (Fig. 17). Carbonate buildups developed on the northern margin in the Chadian early Holkerian (EC2). During the Arundian to early Asbian (EC3/EC4), deposition within the Edale Gulf was on a carbonate ramp/rimmed shelf, prograding southwards from the Holme High towards the Derbyshire carbonate platform (Evans & Kirby 1999). Deposition in the basin was mainly of resedimented shallow water carbonates shed from the southern footwall and northern dipslope, together with basinal shales and volcaniclastic sediments.

During the Asbian (EC4), the Derbyshire carbonate platform was fringed to the north by a high angle margin with depositional dips of up to 30 towards the basin (Stevenson & Gaunt 1971, Broadhurst & Simpson 1967, 1973). In the late Asbian and early Brigantian (EC5) a complex of coarse bioclastic grainstone shoals developed in association with the platform margin (Eden *et al.* 1964, Stevenson & Gaunt 1971). These shoals comprise stacked large-scale bedforms that prograded basinward in response to a rise in sea-level of some 20–25 m at the onset of EC5 rifting (Gawthorpe & Gutteridge 1990). The presence of an angular unconformity in the late Asbian–early Brigantian of the Alport borehole suggests that the southern bounding fault of the Edale Gulf was active during EC5 rifting. In contrast, the northern margin of the basin and the immediate footwall of the Holme High became a site of non-deposition in late Dinantian times (Evans & Kirby 1999).

At the base of Winnat's Pass near Castleton, the Beach Beds form a distinctive unit of coarse turbiditic bioclastic grainstone onlapping the Asbian foreslope (Eden *et al* 1964; Stevenson & Gaunt 1971, Sadler 1964). Evidence from the Castleton borehole shows that the Beach Beds interfinger with and are overlain by basinal sediments. The stratigraphic position of the Beach Beds suggests that they may be basinal equivalents of the late Asbian–early Brigantian (EC5) shelf margin grainstone shoals. The Derbyshire carbonate platform was finally onlapped in the late Brigantian–early Namurian (LC1a) by basinal sediments consisting of pro-delta Edale Shales, and the basin was subsequently infilled by deposits of the Kinderscout and subsequent deltas (LC1b & c).

Bowland/Craven Basin

The Bowland/Craven Basin (hereafter referred to as the Bowland Basin) comprises a major NE–SW–trending Dinantian half graben (Figs 10 and 18). The basin underwent intense folding and uplift during the late Carboniferous Variscan inversion such that sediments of Courceyan age (EC1) are exposed at surface along the axis of the basin (Fig. 18). More than 4 km of Dinantian sediments are indicated from the seismo-stratigraphic interpretation (Fig. 18) and gravity modelling (Lee 1988, Corfield *et al.* 1996). This contrasts with 500 m of shallow water carbonates proven by the Holme Chapel borehole on the footwall block to the south (Ramsbottom 1974; Miller & Grayson 1982;

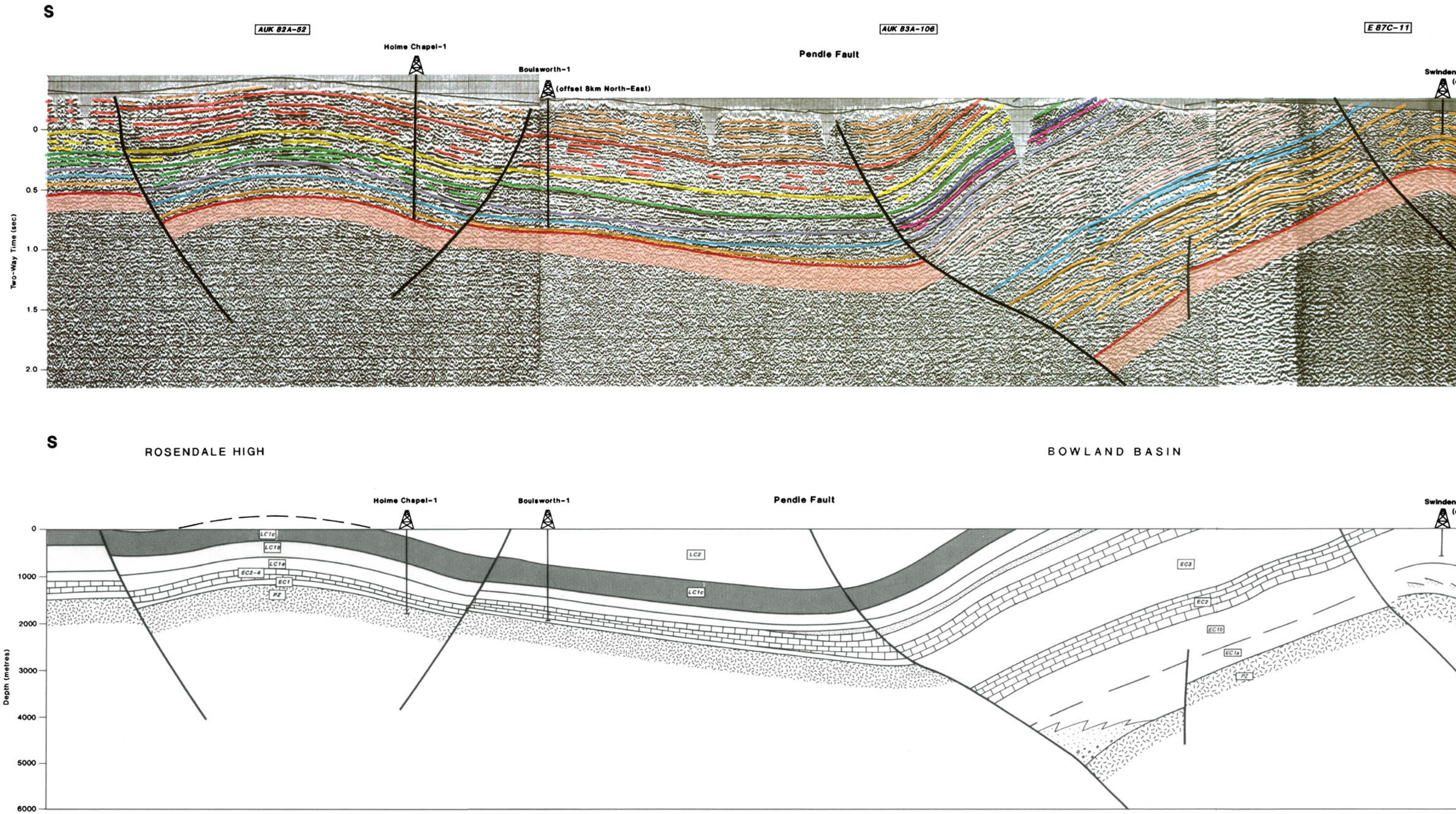
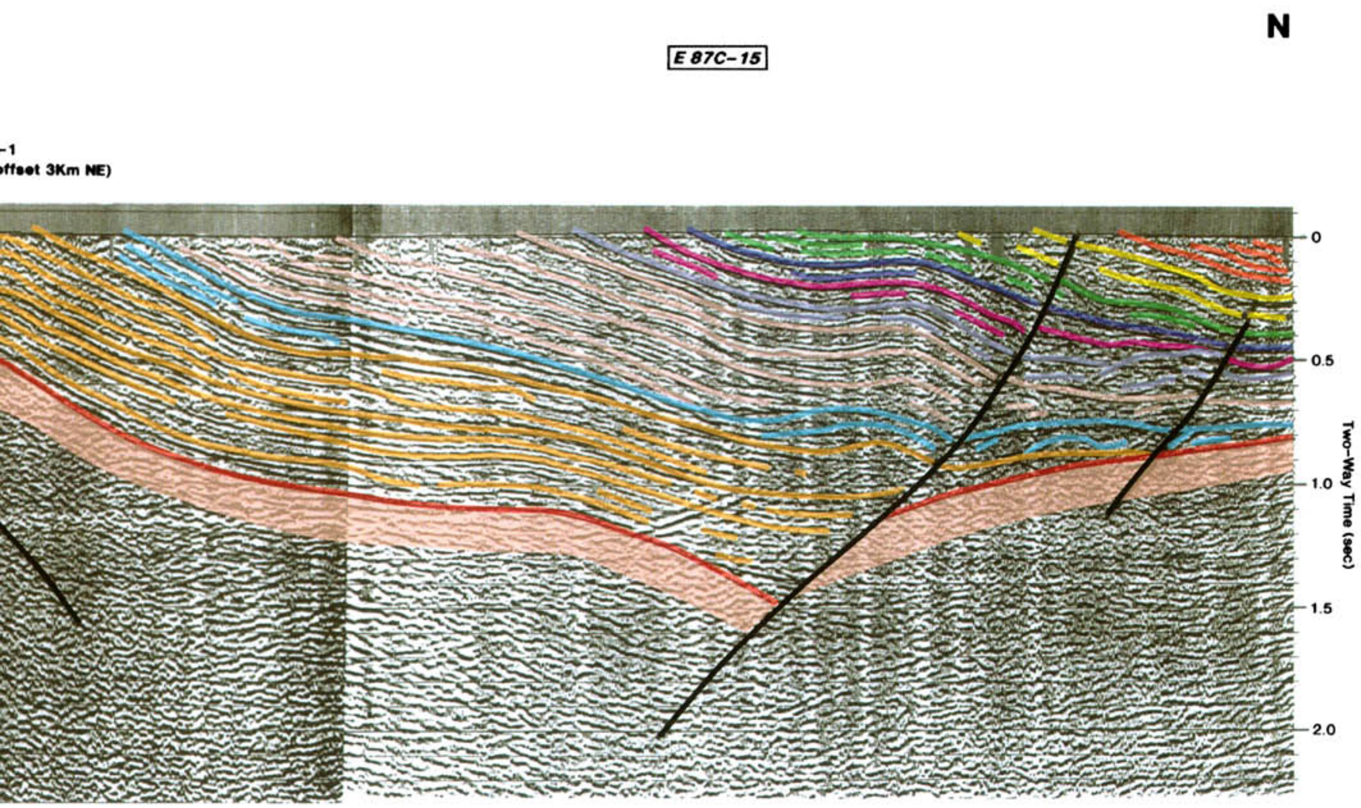
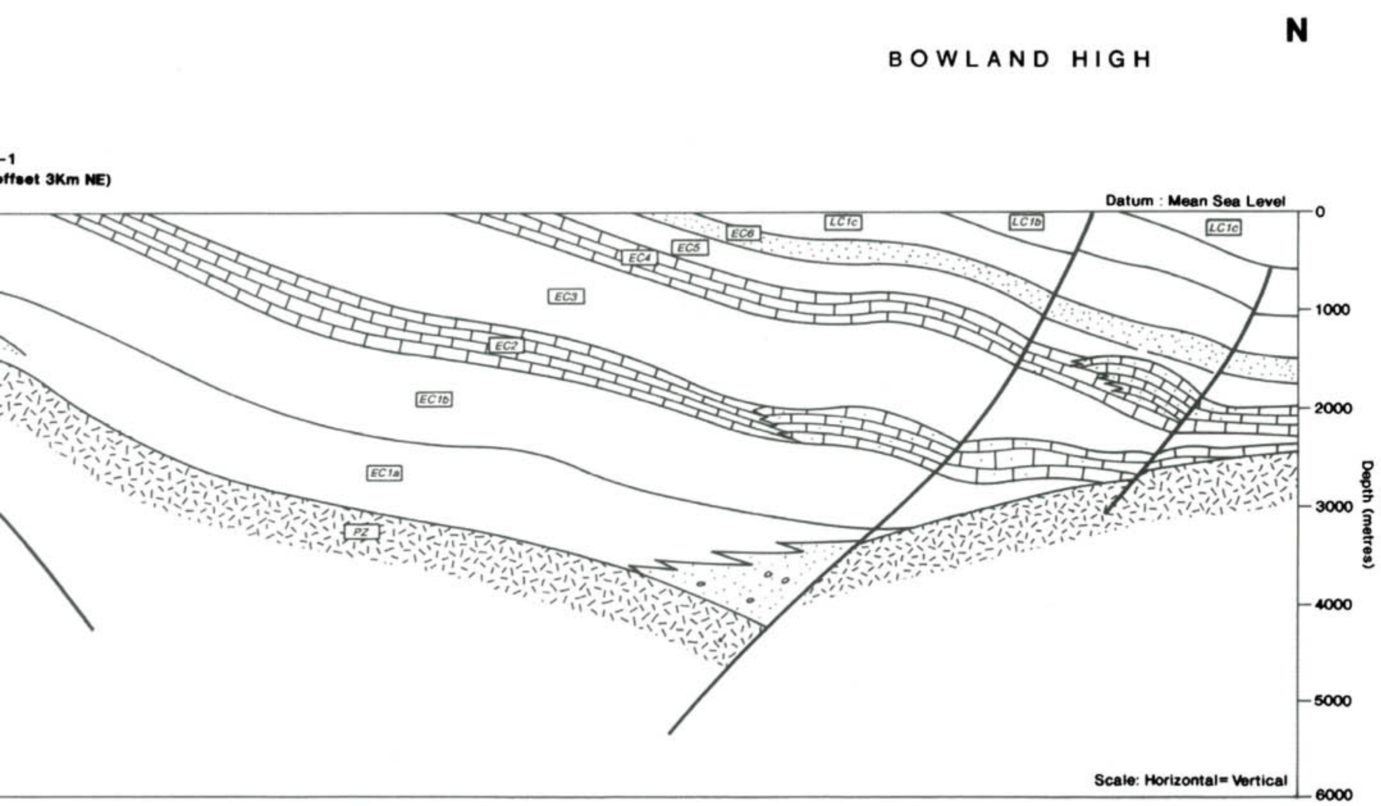


Fig. 18. Composite 2D seismic line and interpreted geological cross section across the Lancashire Coal Field, Pendle Monocline and Bowland Basin (see Fig. 10 for





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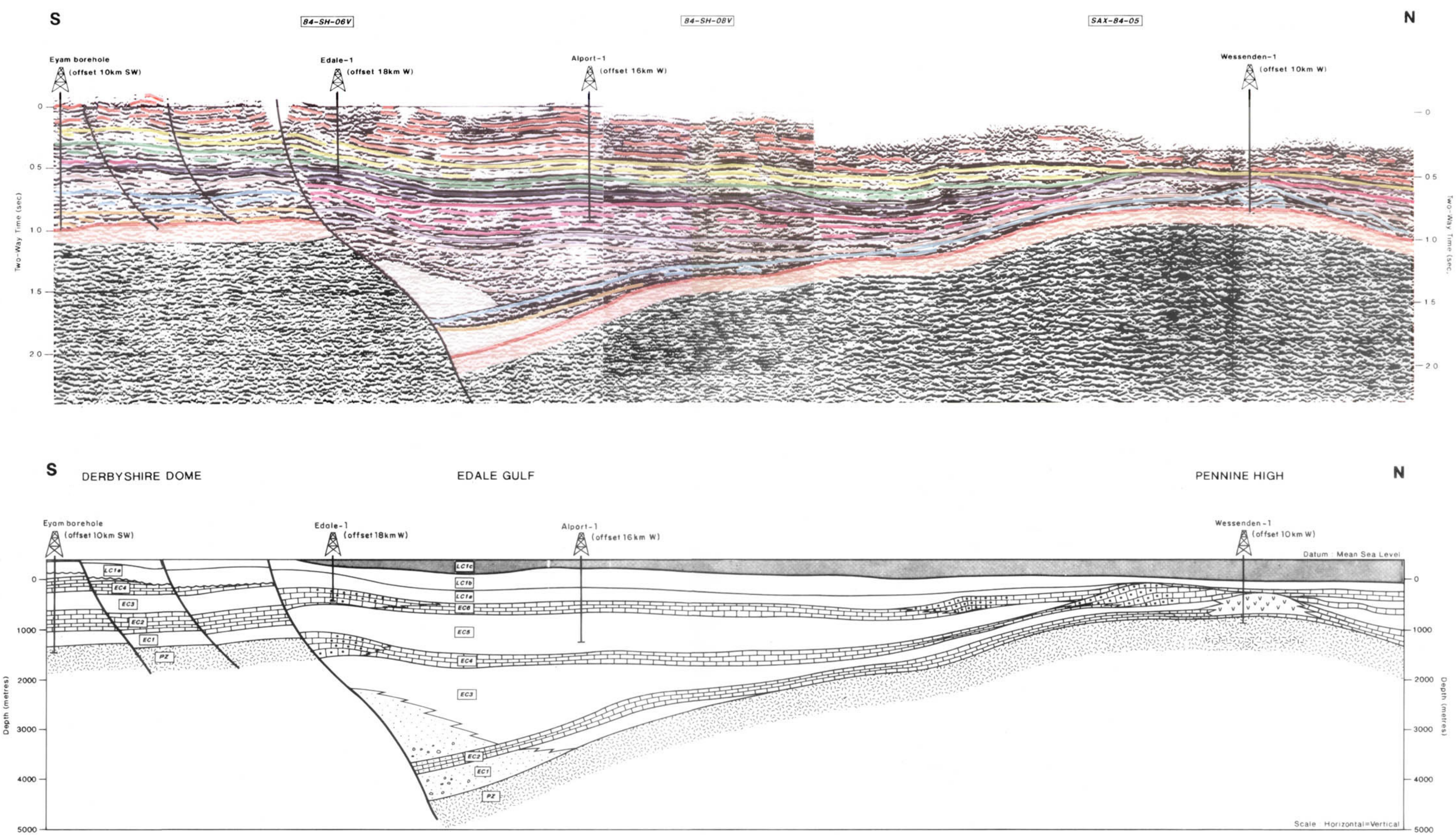


Fig. 17. Composite 2D seismic line and interpreted geological cross section across the Edale Gulf (see Figs 10 and 11 for location of the seismic).

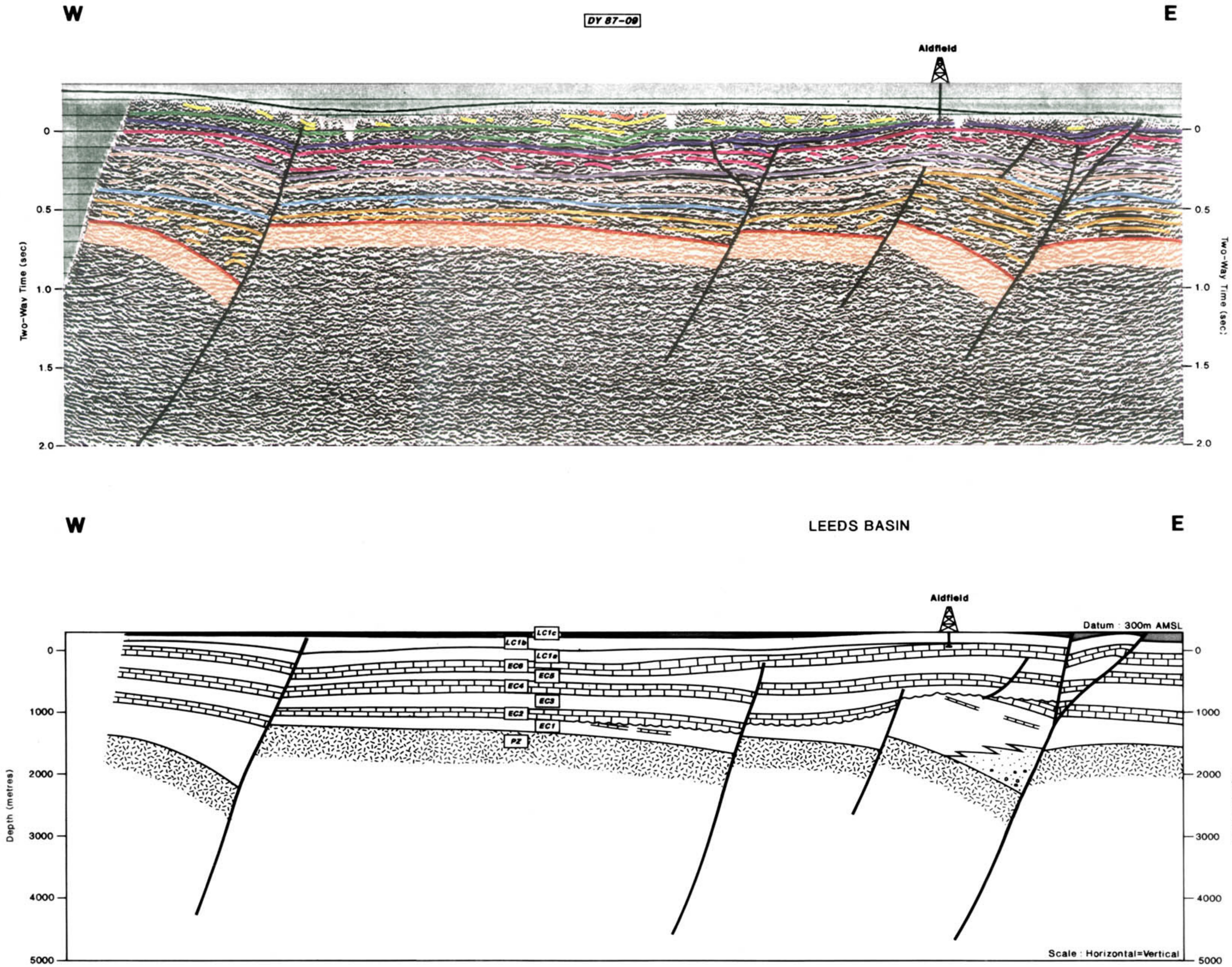


Fig. 19. Composite 2D seismic line and interpreted geological cross section across the Leeds Basin (see Fig. 10 for location of the seismic).

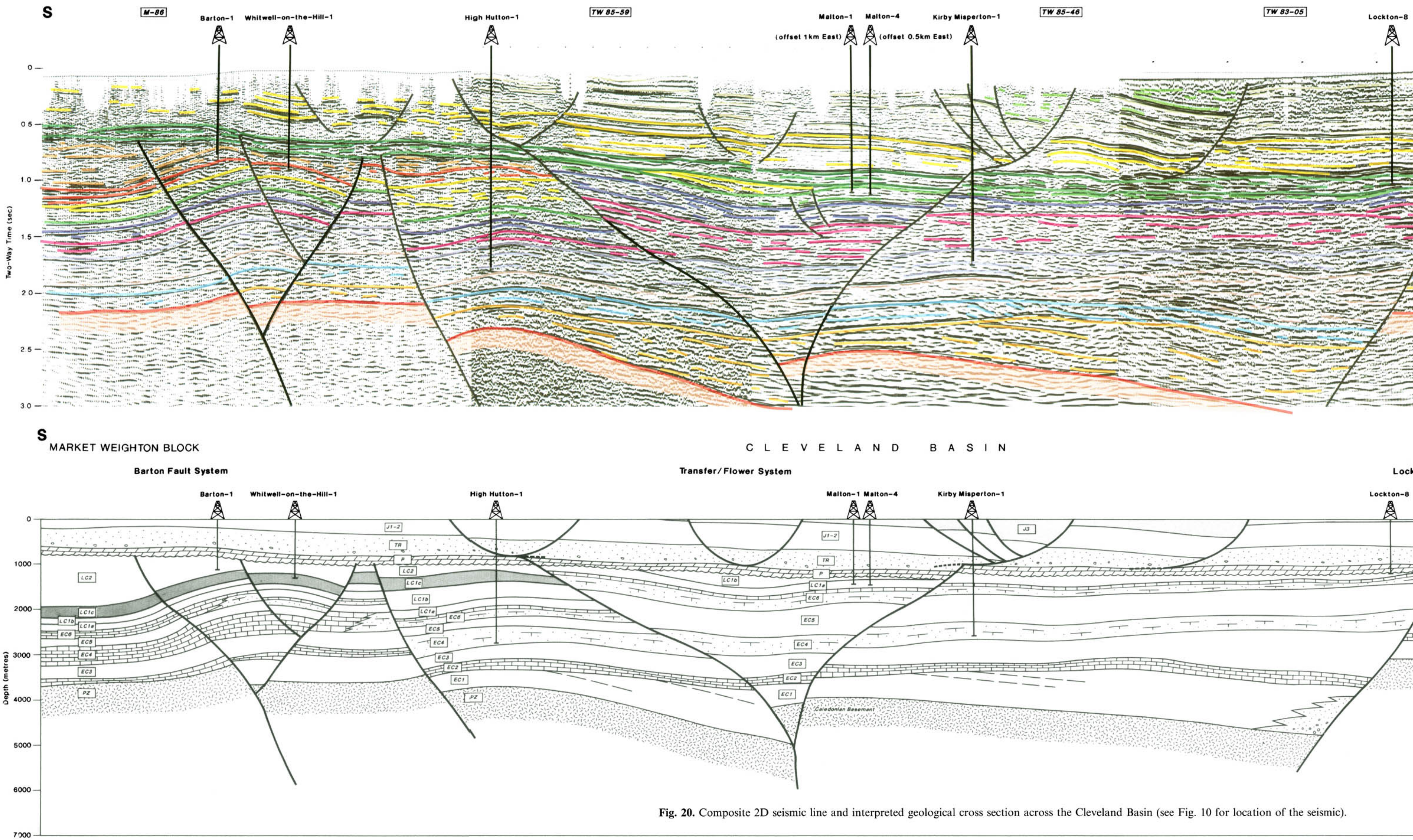
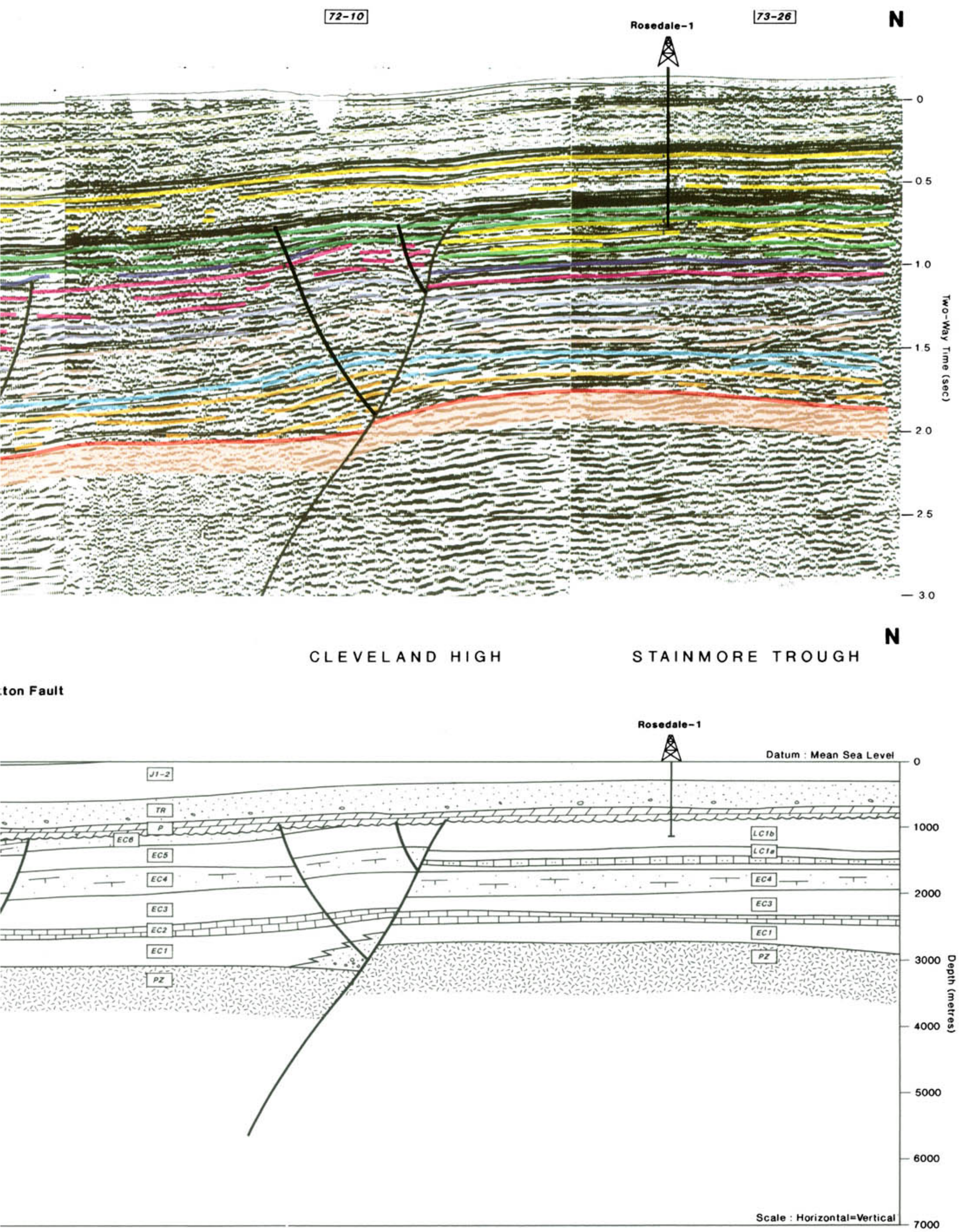
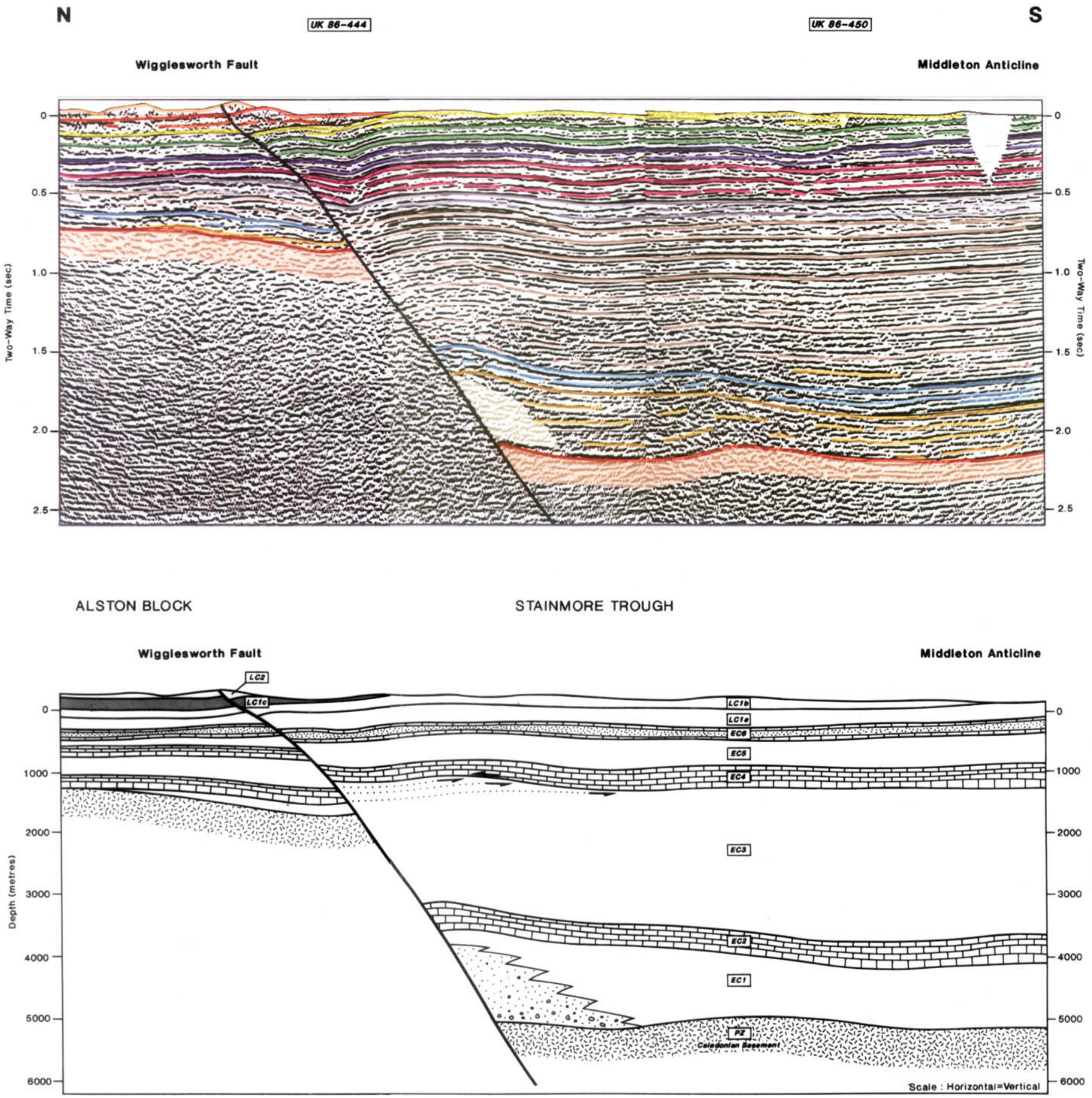


Fig. 20. Composite 2D seismic line and interpreted geological cross section across the Cleveland Basin (see Fig. 10 for location of the seismic).


72-10
73-26
Rosedale-1
N
0
0.5
1.0
1.5
2.0
2.5
3.0
Two-Way Time (sec)
CLEVELAND HIGH
STAINMORE TROUGH
N
Rosedale-1
Datum : Mean Sea Level
J1-2
TR
P
EC6
EC5
EC4
EC3
EC2
EC1
PZ
LC1b
LC1a
0
1000
2000
3000
4000
5000
6000
7000
Depth (metres)
Scale : Horizontal=Vertical



Evans & Kirby 1999). These facies and thickness variations indicate a southern fault-bounded basin margin situated at depth below the inversion-related Pendle Monocline (Fig. 18), with carbonate platform margins developed in the Chadian, Arundian and Asbian/Brigantian (Evans & Kirby 1999). The northern margin of the basin is marked by facies and thickness changes on to the Bowland High (Gawthorpe 1987*a*; Lawrence *et al.* 1987; Arthurton *et al.* 1988) and the Askrigg Block (Tiddeman 1889; Hudson 1930).

Within the basin, basement has not been penetrated by any borehole to date, the oldest proven sediments being of Courceyan age (EC1b). These were penetrated by the Swinden borehole and comprise sub-wavebase, argillaceous packstones deposited on the distal portion of a carbonate ramp (Gawthorpe *et al.* 1989). This general style of sedimentation continued into the Chadian (EC2; Chatburn and Thornton Limestones). Thickness and facies variations indicate some degree of structural control which was inherited from earlier late Devonian–Courceyan (EC1) rifting. Waulsortian carbonate buildups are often associated with the flanks of intra-basinal fault blocks (Miller & Grayson 1982; Lees & Miller 1985) that formed the sites of major Variscan inversion structures (e.g. Clitheroe, Hetton-Eshton and Slaidburn anticlines; Arthurton 1984; Gawthorpe 1987*a*; Arthurton *et al.* 1988).

The late Chadian–Holkerian (EC3) was marked by the rapid development of sea-floor topography, indicated by thickness and facies differentiation across the basin (Gawthorpe 1987*a*). This topography was associated with reactivation of extensional faults and the development of local footwall unconformities within the basin. The succession in the basin became dominated by mudstones (Worston Shales) with local developments of siliciclastic turbidites and sedimentary slides (Gawthorpe & Clemmey 1985). In addition Pb–Zn mineralization is associated with these events (Gawthorpe *et al.* 1989). The succeeding Holkerian to early Asbian (EC4) shows a progressive increase in carbonate sedimentation, culminating in the development of carbonate-rimmed shelves along the northern margin of the basin.

A further phase of tectonism occurred during the late Asbian to early Brigantian (EC5) (Gawthorpe 1986). This phase, which comprised several events, is characterized by major units of resedimented carbonate conglomerate, the common occurrence of soft sediment deformation features and major facies and thickness variations within the basin and across the northern basin margin. Background sedimentation became dominated by deep marine mudstone (Bowland Shales) with influxes of coarse grained siliciclastic turbidites (mid-Brigantian Pendleside Sandstone). Facies distributions and thickness variations indicate southerly downthrow on the Middle Craven Fault. However, slip reversal along this fault in the Brigantian may be indicated by uplift and erosion of carbonate buildups in the hanging-wall (Mundy 1980).

Namurian and Westphalian strata are some 2 km thick in the syncline that separates the Pendle Monocline from the Rossendale High (Lancashire Coalfield), and about 1500 m in the Holme Chapel and Boulsworth boreholes (Fig. 18). There is no direct evidence for original thicknesses over the central part of the basin, but they are likely to have been in excess of the preserved 2 km. Pendleian facies are typical Millstone Grits and Coal Measures, pervasive over this part of the central Pennine Basin. However, the initial clastic infill of delta-front turbidites (the Pendleian aged Pendle Grit; LC1a) is much older than in the East Midlands (e.g. Widmerpool Gulf).

Fig. 21. Composite 2D seismic line and interpreted geological cross-section across the Stainmore Trough (see Fig. 10 for location of the seismic).

Leeds Basin

The Leeds Basin forms a relatively minor, NE–SW-trending half graben which links the Edale Gulf and Cleveland Basin (Figs 10 and 19). Regional seismic data (Fig. 19) suggests up to 3 km of ?Upper Devonian and Dinantian sediments preserved in the basin. There is also evidence for a major intra-Dinantian unconformity in the area of the Aldfield borehole which may be related to either inversion or footwall erosion in late Chadian–Holkerian (EC3) times. There is little borehole control on facies as the Aldfield borehole only penetrated the uppermost part of the late Dinantian (EC6) carbonates. Facies and stratigraphy have been interpreted by regional analogy and from seismic facies analysis, therefore a degree of uncertainty exists with the geological interpretation presented in Figure 19.

Cleveland Basin

Further north within the northern England rift system, seismo-stratigraphic interpretation becomes more problematic as, unlike the East Midlands, the Dinantian basins were not sediment starved and consequently had a dominantly clastic fill. In the Cleveland Basin, biostratigraphically calibrated borehole data have been crucial to interpretation of the stratigraphy and facies (Figs 1, 10 and 20).

The Cleveland Basin trends east–west (Fig. 1) and is overlain for the most part by a thick Permian and Mesozoic cover which represents the onshore extension of the Sole Pit Trough (Kent 1975, Glennie & Boegner 1981; Van Hoorn 1987). The basin takes the form of two half graben offset by a major intra-basinal transfer system (Fig. 20). These transfer faults were reactivated to form the loci for later Mesozoic listric extensional faults that sole out within Permian Zechstein evaporites and laterally equivalent shales.

Up to 4 km of Dinantian strata are preserved in the basin but the early syn-rift fill (EC1) has not been penetrated by boreholes. Wedge-shaped geometries are observed on seismic and deposition is interpreted as alluvial fan and fan-delta by analogy with contemporaneous rift systems elsewhere in northern England. In the deeper parts of the basin a major angular unconformity is observed, overlying the wedge-shaped EC1 sequence, which may represent either the EC1/EC2 or EC2/EC3 sequence boundary (Fig. 20). The oldest Dinantian strata penetrated in two deep boreholes in the basin, High Hutton and Kirby Misperton-1, are of Holkerian age (EC3) and represent the deposits of deep water clastic delta systems which progressively infilled the basin from the north throughout the later part of the Dinantian (Fig. 9).

Intense inversion and erosion in the late Carboniferous removed most of the Namurian and Westphalian sediments from the central part of the basin north of the Barton Fault, forming a marked base Permian unconformity (Fig. 20). Where preserved on the footwall of the Barton Fault, these deposits are up to 2500 m thick and are typical Yoredale, Millstone Grit and Coal Measures facies characteristic of the shallow-water clastic delta systems encountered throughout the Pennine Basin. The 2500 m of Silesian strata on the footwall represents a lower limit for the original thickness of the post-rift which must have been deposited over the Cleveland Basin.

Stainmore Trough

The Stainmore Trough is a major east–west-trending half graben lying to the north of the Cleveland Basin (Fig. 1). In the west it is separated from the Cleveland Basin by the eastwards extension of the Askrigg Block, but probably merges with the Cleveland Basin towards the east to form a single basin in the offshore domain. The major basin-bounding faults in the north are the en echelon Lunedale, Wigglesworth and Butterknowle Faults (Figs 1, 10 and 21). The southern margin of the basin, which is not represented on the regional seismic data, is fault bounded, probably along the line of the Stockdale disturbance (Collier 1991).

Previously published interpretations of the Stainmore Trough (George *et al.* 1976; Burgess & Holliday 1979) have been based largely on outcrop and shallow borehole data, with the thickness of Dinantian strata estimated by Johnson (1982) at 1.5 km and by Bott *et al.* (1984) at 2.5 km. Seismic reflection data tied to surface outcrop and the deep Seal Sands-1 borehole (Fig. 2) have greatly improved our ability to interpret the scale and style of Dinantian sedimentation within the Stainmore Trough.

In the immediate hanging-wall of the Lunedale–Wigglesworth–Butterknowle fault zone, along the northern basin margin, up to about 6 km of Dinantian are imaged on regional seismic sections (Fig. 21). There are no well penetrations beneath the Chadian/Arundian (EC3) and the timing of rift initiation can therefore be estimated only from regional considerations. By analogy with neighbouring rift basins such as the Northumberland Trough (Leeder 1974) and the Bowland Basin (Gawthorpe 1986), the age of the earliest basin-fill sediments is interpreted to be late Devonian–Courceyan. The nearest outcrops of early Dinantian strata occur around Ravenstonedale to the west, with rapid local thickness changes and facies variations related to local valley-fill processes and to movements on growth faults such as the Swindale Beck Fault (Burgess & Harrison 1967, Burgess & Holliday 1979, Kimber & Johnston 1986). At Ravenstonedale the Pinskey Gill Formation (Courceyan), which was deposited in a nearshore environment, rests directly upon Lower Palaeozoic basement and is overlain by coarse siliciclastics of alluvial fan origin (Gawthorpe *et al.* 1989).

Early Courceyan–Arundian (EC1–EC3) rift sequences are picked from 0.75 to 2.5 s TWTT, which converts to a sedimentary thickness of about 4 km. The EC1 seismic sequence includes downlapping clinoforms located against the northern basin-bounding faults and interpreted as footwall-derived alluvial fans or fan deltas up to 4 km in diameter. Active rifting is inferred to have taken place during late Devonian–Courceyan (EC1) times in order to generate the fault scarp and basin topography necessary to accommodate the fan geometries. Within the basinal sediments of this suspected early rift sequence a number of continuous high-amplitude reflectors are observed (Fig. 21). Data from outcrop at Ravenstonedale, where shallow-water carbonates such as the Scandal Beck Limestones are encountered, suggest that the reflectors most likely represent the basinal equivalent of these carbonates. An alternative interpretation, based on analogy with the Northumberland Basin, is that the reflectors represent a limited input of early, syn-rift volcanics to the basin.

Shallow-water carbonates dominate the Arundian to early Asbian (EC3 and EC4 sequences) on the Ravenstonedale and Askrigg highs to the west and south. These carbonates are interbedded with fluvio-deltaic and shallow-marine sandstones. Within the Stainmore Trough, the seismic character of the basinal equivalents of the Ashfell Sandstone and the upper parts of the Ravenstonedale Limestone show reflectors of varying continuity and amplitude (EC3 seismic sequence). Up to 2.5 km of mudstones and sandstones with occasional thin carbonates are ascribed to this stratigraphic interval in the basin, similar to the succession penetrated between 2000 m and TD (4170 m) in the Seal Sands-1 borehole. There appears to have been only minor onlap of the Ashfell Sandstones onto the Askrigg Block and the Ravenstonedale Shelf suggesting that fault-controlled differential subsidence between the basin and surrounding footwall blocks was active throughout the late Chadian–Holkerian (EC3).

Locally low angle shingled to sigmoidal clinoforms can be resolved within the EC3 seismic sequence that prograde southwards from the northern basin margin, and these reflectors have been interpreted to represent a prograding carbonate platform (Collier 1991). However, elsewhere in the rift system carbonate margins are associated with high-angle clinoforms (e.g. Widmerpool Gulf, Fig. 12). Thus the low-angle clinoforms observed in the hanging-wall of the Wigglesworth Fault are more likely to represent a clastic depositional system, an Ashfell Sandstone equivalent, that infilled topographic lows within the Stainmore Trough.

The EC3–EC4 sequence boundary is marked in the Stainmore Trough by an angular unconformity in the hanging-wall of the main basin-bounding fault and early Asbian (early EC4) strata are absent on the Alston Block (Burgess & Holliday 1979) (Fig. 21). However, the early Asbian succession in the Stainmore Trough reaches 300 m in thickness and pinches out by onlap onto the EC3/EC4 boundary along the northern margin of the basin (Fig. 21). This unconformity may be indicative of a previously unrecognised late Holkerian basin inversion event, coinciding with the cessation of EC3 rifting.

The late Holkerian–mid Asbian (EC4) sequence is marked by the continuous and widespread Melmerby Scar/Great Scar Limestone and its southerly equivalents (Burgess & Mitchell 1976; Wilson & Cornwell 1982) (Fig. 9). This limestone marks a regional transgression over both the basin and surrounding footwall blocks. There is a variation in seismic facies of the Melmerby/Great Scar reflector across the Alston Block margin into the basin (Fig. 21). The limestone is 35–50 m thick over the Alston Block, (Woolacott 1923; Dunham *et al.* 1965) and thins across the Butterknowle and Wigglesworth Faults into the basin, where it is represented by a single high-amplitude event.

The late Asbian–Brigantian Alston Group (sequence EC5), which overlies the Great Scar Limestone, increases in thickness into the basin from 450 m to 700 m across the Wigglesworth Fault, suggesting renewed tectonic subsidence. These deposits are widely exposed in the western parts of Stainmore and form high frequency Yoredale shallow marine to fluvio-deltaic cycles (Burgess & Mitchell 1976; Leeder & Strudwick 1987). The Yoredale cycles (Fig. 9) include a variety of fluvio-deltaic and shallow marine sandstones and shallow marine carbonates, but are too thin to be resolved as separate reflections or packets of reflections on the regional seismic data.

Northumberland Trough–Solway Basin

The Northumberland Trough–Solway Basin forms a major NE–SW-trending half graben bounded to the north by the Southern Uplands and to the south by the Alston Block and Lake District Massif (Fig. 1). Geological relationships (Johnson 1984) and gravity data suggest a basement high, across which there is a change in dip polarity, partly separating the western end of the Northumberland Trough from the Solway Basin.

Although the simple view of the Northumberland Trough as a half graben (Leeder 1974, 1982) has been confirmed by seismic reflection data (Kimbell *et al.* 1989; Figs 10 and 22), it should be noted that the southern bounding extensional faults mapped at surface are Permian or younger in origin (Leeder *et al.* 1989). They are believed to overlie, or nucleate upon buried syn-depositional structures present at depth below the post-rift thermal subsidence fill, similar to structures noted in the Cleveland Basin to the south.

The Northumberland Trough is controlled by a major boundary fault in the south defined by the Stublick–Ninety Fathom Fault (Fig. 1). The Solway Basin is controlled in the north by the major fault separating it from the Southern Uplands (Tarras Fault and equivalents, Johnson 1984). Comparison of the successions in the Northumberland and Solway basins suggests that subsidence and sedimentation were largely synchronous, at least during the Dinantian (Johnson 1984). The exposed sequences are very similar in the two basins.

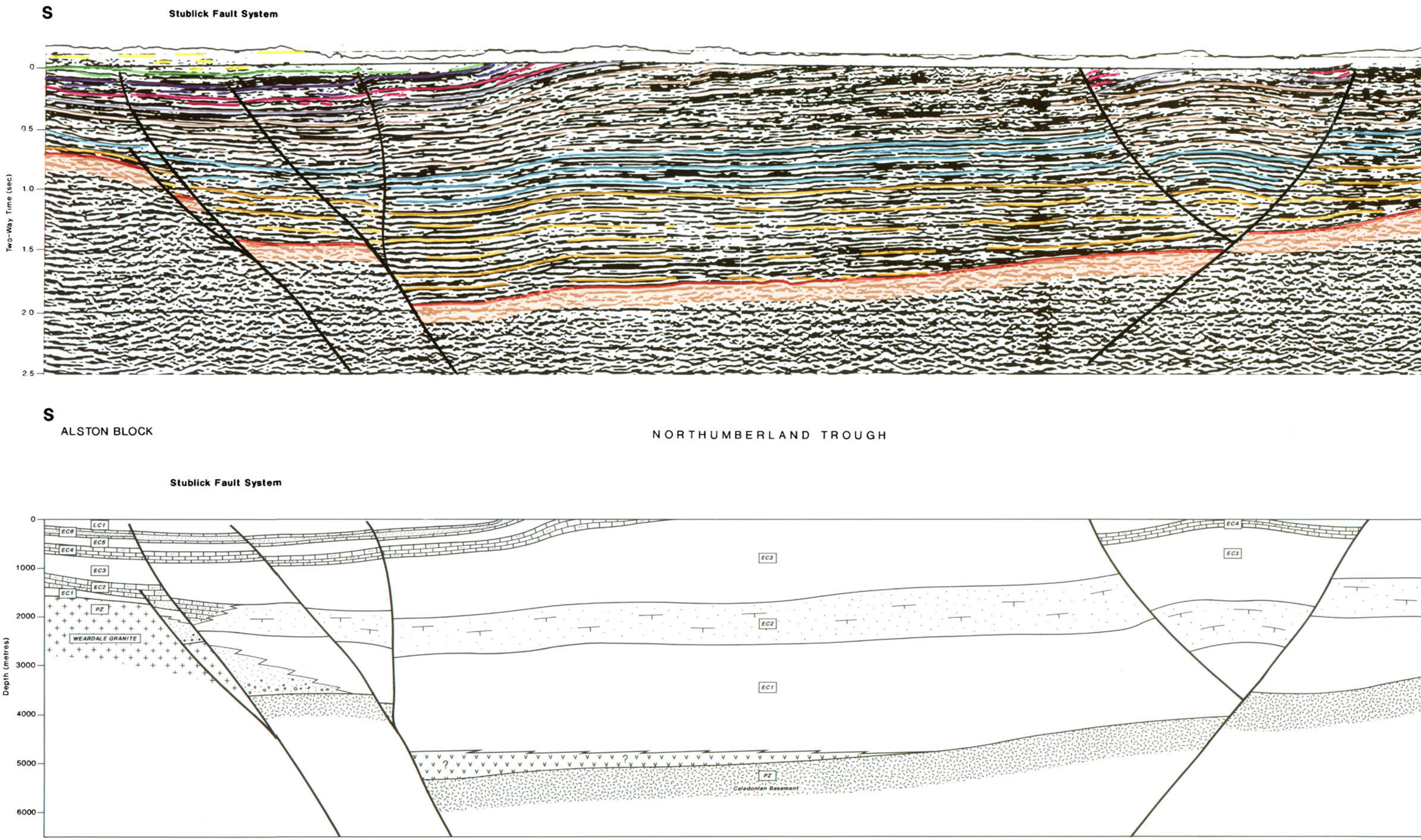
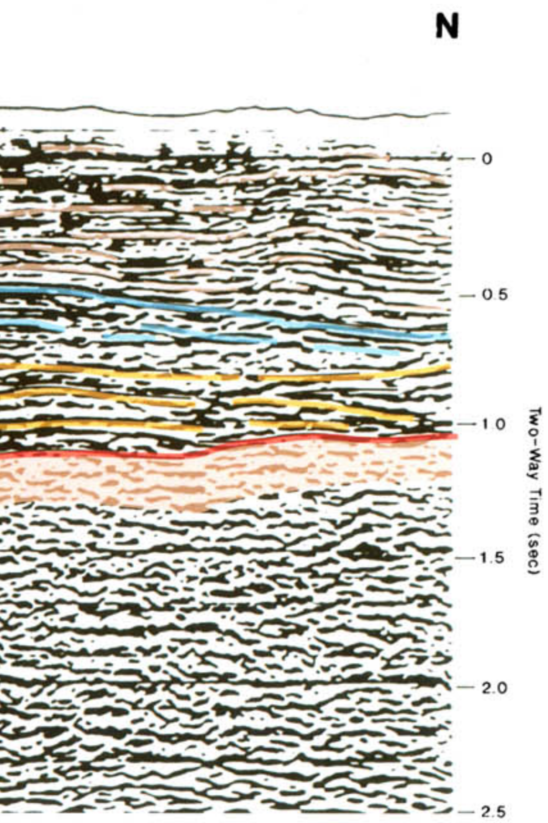
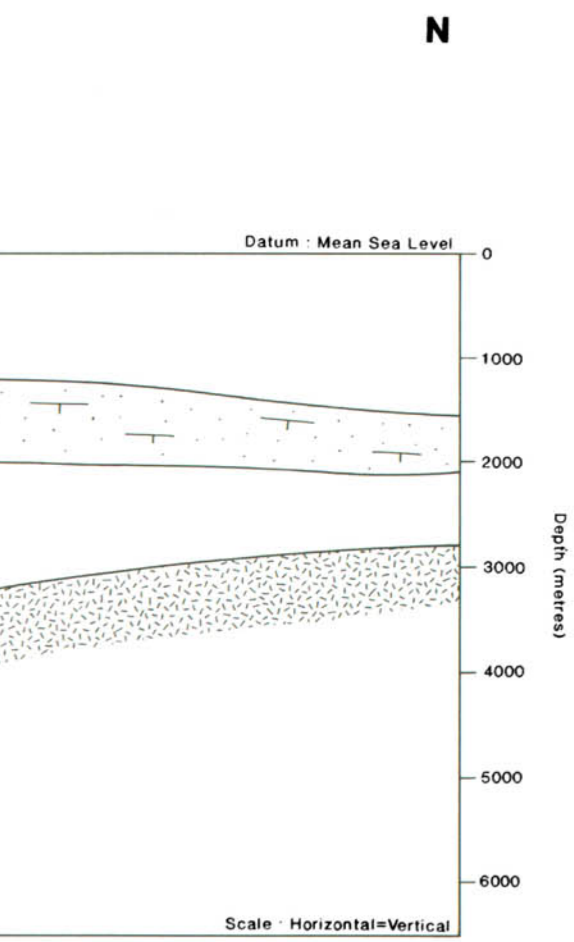


Fig. 22. Composite 2D seismic line and interpreted geological cross section across the Northumberland Trough (after Kimbell *et al.* 1989; see Fig. 10 for location of the seismic).


N
0
0.5
1.0
1.5
2.0
2.5
Two-Way Time (sec)


N
Datum : Mean Sea Level
0
1000
2000
3000
4000
5000
6000
Depth (metres)
Scale : Horizontal=Vertical

except for facies changes associated with better developed marine conditions towards the SW. Lack of exposure of the lower part of the Dinantian sequence in the centre of each basin previously prevented a full comparison of the thickness of Dinantian strata. The regional seismic data confirm that both basins underwent similar amounts of Dinantian extension with some 4–5 km of early Carboniferous sediments deposited in the central parts of the basins (e.g. Fig. 22).

Rift initiation occurred during the late Devonian–Courceyan (EC1) with the eruption of the alkaline basaltic Birrenswark/Kelso/Cockermouth lavas, imaged as a series of high-amplitude reflectors on the regional seismic profile (Fig. 22). Early syn-rift sedimentation was dominated by influxes of mature fluvial siliciclastic detritus from the Southern Uplands, interbedded with the widespread Cementstone facies of fluvio-lacustrine origin (Leeder 1974) forming the Lower Border Group and its correlatives. Regional seismic reflection data across the Northumberland Trough indicate an extremely thick Lower Border Group (EC1 sequence) in the hanging-wall of the Stublick–Ninety Fathom fault system (Fig. 22).

The Courceyan–Chadian (EC1/EC2) Lower Border Group of Bewcastle and Liddesdale comprises numerous peritidal carbonate and clastic deltaic cycles formed by the periodic advance of lobate deltas from the NE (Leeder 1974, Leeder *et al.* 1989). On regional seismic data these facies are represented by a series of stacked, laterally continuous, high-amplitude events, thought to reflect the interbedded nature of the interval (Fig. 22).

The diachronous advance of a major axial braided fluvial system, also from the NE, is recorded in the Arundian to Holkerian Middle Border Group (EC3). On seismic data the sequence thickens to the north in the Northumberland Trough, suggesting that basin polarity switched between EC1 and EC3 rifting (Fig. 22). Conversely the EC3 sequence appears to thicken into the southern bounding fault of the Solway Basin. Outcrop studies indicate the presence of multistorey fluvial channel belts within intra-basin lows defined by the Antonstown and Beckhead/Binky Linns Faults, suggesting syn-depositional tectonic control on the alluvial architecture (Day 1970, Leeder 1987*b*). These sandbodies split and intercalate with marine facies to the SW (Day 1970), although the Thirlstane Sandstone, a suspected correlative to the SW, retains its fluvial signature into the Solway Basin (Ord *et al.* 1988).

The Asbian Upper Border Group (EC4) is composed of Yoredale-type cycles in southwestern areas (Lumsden *et al.* 1967). In contrast, the central intra-basin lows around Bewcastle and Bellingham contain over 2000 m of deltaic facies, again deposited as axial drainage systems derived from the NE (Day 1970; Frost & Holliday 1980; Leeder 1987*b*; Leeder *et al.* 1989). In Berwickshire and NE Northumberland the equivalent Scremerston Coal Group is very much thinner and largely composed of delta-top fluvial facies with numerous thick coals. During the late Asbian, deltaic cycles of Yoredale type were deposited over the whole basin. These conditions continued into the Brigantian (EC5–EC6) when some increase of cycle thickness from the Alston footwall into the basin suggests continued differential subsidence during EC5 times.

The Namurian–Westphalian (LC1–LC2) post-rift fill of the basin was characterized by further Yoredale type, Millstone Grit and Coal Measures sedimentation. The Upper Carboniferous succession shows marked differences between the Northumberland and Solway Basins. Not only are there major thickness changes but there appear to have been differences in the duration of phases of subsidence and inversion/erosion (Johnson 1984). Slower subsidence and deposition in the Solway Basin as compared to the Northumberland Trough in the Namurian was compensated by continued subsidence well into the Westphalian D (V1) with the formation of a thick red-bed succession.

Intense inversion in the late Carboniferous resulted in the removal of Upper Carboniferous sediments from most of the Northumberland Trough (Fig. 22) and the generation of a marked angular unconformity at the base of the Permian in the Solway Basin. Central and southeastern parts of the basin are characterized by open folds striking approximately north–south. Around the northern and western margins asymmetric anticlines with steep west-facing limbs are often reverse faulted, e.g. the Bewcastle anticline. Normal displacements of Permian strata on faults such as the Ninety Fathom reflect renewed extensional faulting in the Permo-Triassic.

Tectono-sedimentary synthesis

The Variscan plate cycle can be divided into syn-rift, post-rift and inversion megasequences (Fig. 8). These describe a late Devonian–Dinantian rift-controlled subsidence, a Namurian–Westphalian thermally driven subsidence, and a late Westphalian to early Permian inversion or foreland basin phase. These in turn can be broken down into a series of depositional cycles or tectono-stratigraphic sequences which describe the late Devonian–Carboniferous fill of the northern England basin.

The syn-rift megasequence exhibits a characteristic wedge-shaped geometry that is exemplified by a four-fold increase in sediment thickness across the major basin-bounding fault of half graben such as the Gainsborough Trough, Bowland Basin and Stainmore Trough (Figs 12, 18 and 21). Isopachs for the upper part of this interval show the thickest sections to be confined to the individual fault-bounded half graben (Fig. 23). The border fault zones bounding these are segmented, forming en echelon arrays, but the sparse 2D seismic coverage and poor imaging of the earliest syn-rift inhibits detailed analysis of their growth and linkage history during rifting. However, by earliest Dinantian times the basins had become well defined, suggesting that the faults had essentially propagated laterally and linked to form their final lengths and, thereafter, largely grew by increasing their displacement. The relatively fixed fault lengths throughout the syn-rift megasequence and rapid localization of displacement onto the border fault zones may be a result of reactivation of basement fault lineaments (see page 10). Similar fault growth histories, involving rapid attainment of fault lengths, have been suggested for fault populations from the East African Rift (e.g. Morely 1999), Timor Sea (Meyer *et al.* 2002) and Suez Rift (Gawthorpe *et al.* 2002). However, there is evidence for migration of fault activity between major fault zones, for example the hanging-wall migration of fault activity from the Thringstone–Sileby Faults to the Hoton Fault during the EC3 rifting event. This type of basinward migration of fault activity is recorded from a number of rift basins, such as the East African Rift, central Greece, Suez Rift (see Gawthorpe & Leeder 2000 for a discussion) and may be a general feature of fault population evolution.

Within the constraints offered by independent biostratigraphic data (Ebdon *et al.* 1990), the three rift pulses (EC1, EC3 and EC5) are broadly synchronous across the northern England basins. The differing magnitudes of extension and timing of the main rift phase in each basin appears to be a function of the trend of the rift-bounding faults with respect to the direction of maximum extensional stress as it rotated from north–south during EC1 to NE–SW during EC5 (Fraser 1995). This may account for the pronounced rifting during EC5 times on the NE–SW-trending Hoton Fault, Widmerpool Gulf (Fig. 12).

Two main syn-rift depositional systems can be identified: (i) clastic fluvial-deltaic and (ii) carbonate platforms (Fig. 9). During the syn-rift phase, tectonic subsidence generally exceeded the rate of sediment supply to the basin and the clastic deltas remained confined to the north of the region. As a consequence, the south of the area (Bowland, Edale and East Midlands basins) became sediment starved and carbonates accumulated on the footwall crests giving rise to the development of carbonate rimmed shelf margins (Figs 12, 17 and 18). The half-graben were infilled by calciturbidite and fine-grained hemipelagic deposits. In the shallower half graben, carbonate sedimentation was able to keep pace with subsidence thus precluding the development of rimmed shelves and sediment-starved depocentres (e.g. the Leeds Basin, Fig. 19).

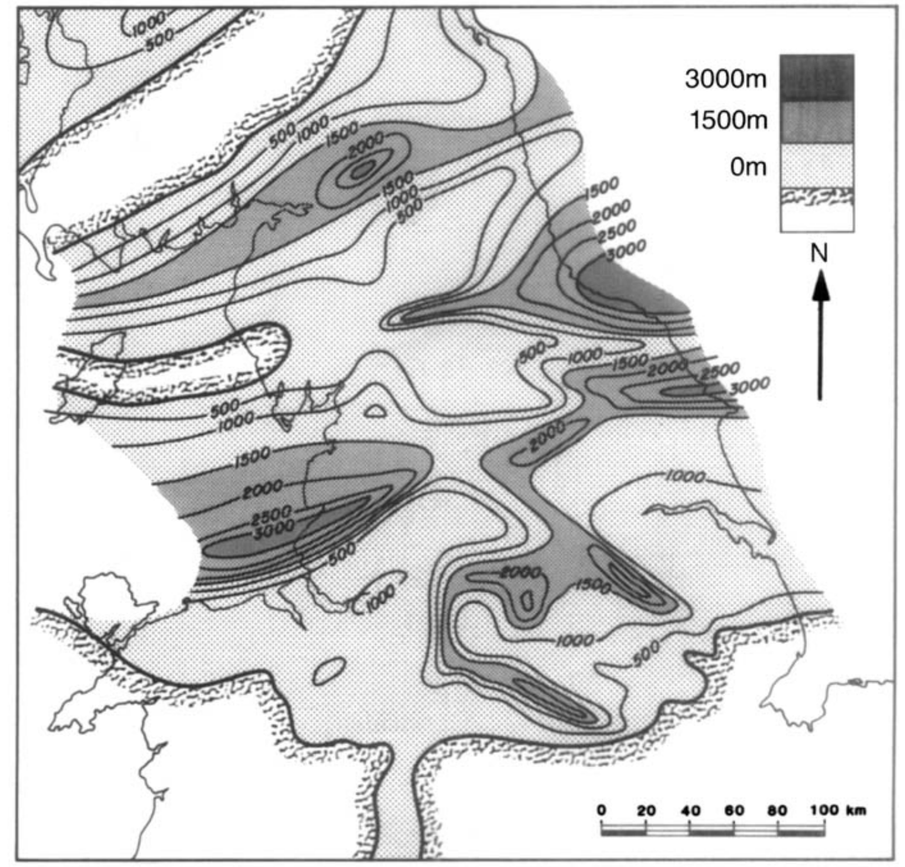


Fig. 23. Restored isopachs for the syn-rift sequences EC2–EC6 (Chadian–early Brigantian). Modified from Fraser & Gawthorpe (1990).

During the early post-rift phase, sediment supply overtook subsidence for the first time, allowing a marked southwards progradation of the fluvio-deltaic system which had, until this time, been mainly restricted to the north of the Alston and Askrigg Blocks (Fig. 9). This resulted in burial of the last vestiges of the northern England carbonate system in the late Brigantian–early Pendleian and infilling of the remnant rift topography with fluvio-deltaic sediments.

The onset of Carboniferous compressional tectonics, on a regional scale, was diachronous from south to north. Foreland basin development in the south Wales Coalfield started in the early Namurian (Gayer & Jones 1989), whereas compressional tectonics leading to basin inversion north of the Wales–London–Brabant Massif occurred much later during the Westphalian C. In northern England, the effects of the Variscan compression are marked on the reflection seismic data by the presence of large-scale inversion anticlines in the hanging-walls of the Dinantian basin-bounding normal faults (e.g. Fig. 18). Early Permian peneplaination of these anticlines created a pronounced angular unconformity at the base Permian over all northern England basins. The degree of uplift and subsequent erosion of syn- and post-rift Carboniferous sediments appears to be controlled by the orientation of the basin-bounding faults with respect to the direction of maximum compressive stress. Basins such as the Bowland Basin (Fig. 18) and the Northumberland Trough (Fig. 22) that are interpreted as lying orthogonal to the NW–SE direction of maximum compressive stress were intensely inverted during the Variscan orogeny. In contrast, NW–SE-trending basins such as the Widmerpool Gulf and Gainsborough Trough were only mildly inverted (Fig. 12). The inversion megasequence is characterized by the accumulation of continental red-beds and molasse in intermontne troughs. Sediment was largely sourced from the evolving Variscan mountain front in southern England with some local drainage networks sourced from inversion structures (Besly 1988; Glover & Powell 1996).

Chapter 4

Palaeogeography and facies evolution

Overview

Having discussed the broad-scale tectono-stratigraphic subdivision of the north of England Carboniferous in the previous section, we now use the megasequences and tectono-stratigraphic sequences to determine the spatial and temporal evolution of depositional systems using sequence palaeogeographies.

By late Devonian times, rifting had begun in northern England with sedimentation occurring in incipient half graben under an arid climate. The remnant Caledonian mountain belt to the north acted as a major sediment source (e.g. Gilligan 1920; Leeder 1988; Gawthorpe *et al.* 1989) and, in the study area, Caledonian structures were reactivated and also acted as local sediment sources.

The northward drift of European Pangaea during the Dinantian led to a change to humid climatic conditions by the late Dinantian (Duff, 1980). This, together with regional transgression, caused a change from red-bed style deposition to fluvio-deltaic deposition in the north of the area, close to the major sediment source, and predominantly carbonate depositional systems in the south of the area, particularly on footwall highs starved of clastic sediment. The development of high-frequency cyclicity in late Dinantian times (e.g. Walkden 1987; Leeder & Strudwick 1987) signifies the growing importance of glacio-eustasy as a control on stratigraphic development; a control which became dominant in the Silesian.

There is general agreement that northern Britain occupied an equatorial position during the Namurian (Scotese *et al.* 1979; Smith *et al.* 1981), and the occurrence of coal and bauxitic soil horizons in Scotland indicates a humid, tropical climate (Cope *et al.* 1992). The increasing rainfall, and associated increase in sediment supply, may in part have been responsible for the southward progradation of a delta system of Brahmaputra scale in earliest Namurian times. However, Morton & Whitham (2002) have suggested uplift in the Norwegian–Greenland Sea region created widespread erosion and diverted a major northerly flowing fluvial systems southward into the UK. On a more local scale, an additional factor influencing the marked southerly progradation in early Namurian times on is likely to have been the change in tectonic regime from rapid, local fault-controlled subsidence of the syn-rift megasequence to slower, regional subsidence of the post-rift megasequence. The mineralogy of the delta system suggests a provenance in the Scottish/Scandinavian Caledonides (Gilligan 1920; Leeder 1988) and transportation is thought to have been via braided river systems flowing generally southward. Namurian sedimentation was initially controlled by the inherited Dinantian rift topography and caused local diversion of regional sediment transport pathways with axial flow along the Dinantian rift basins. With continued infilling of the sediment-starved Dinantian basins and broad thermal subsidence, more widespread deposition occurred over most of northern England through to Westphalian C times.

Recent provenance studies (e.g. Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000), whole-rock Sm–Nd isotopic data (Glover *et al.* 1996; Leng *et al.* 1999) and U–Pb dating of detrital zircon and monazite (Drewery *et al.* 1987; Cliff *et al.* 1991; Evans *et al.* 2001) have helped to determine the characteristics of the northern source and have highlighted the importance of other sediment sources to the Namurian and Westphalian of northern England. Overall sediment derived from areas of Larentia–Baltica affected by Caledonian orogeny dominates Namurian depositional systems. During the latest Namurian, westerly sources become more important (e.g. Collinson & Banks 1975; McLean & Chisholm 1996) and dominate the mid Westphalian A to mid Westphalian B of the Yorkshire Coalfield (e.g. Hallsworth & Chislom 2000; Hallsworth *et al.* 2000). The location of this westerly source is still problematic as zircon ages cannot be reconciled with derivation from the Appalachians–Newfoundland–Labrador area (Hallsworth *et al.* 2000). Southerly sources, probably derived from the uplift and erosion in the Variscan orogenic belt to the south and SE became important from mid/late Westphalian B times onwards (Glover *et al.* 1996; Leng *et al.* 1999; Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000; Evans *et al.* 2001). Local uplift and erosion, presumably related to inversion, in the Westphalian D-?Stephanian, is suggested by clasts of Dinantian carbonates and chert (Glover & Powell 1996).

During late Westphalian C times, the thermal subsidence regime was modified by inversion tectonics related to the progressive northwards movement of the Variscan deformation front. In addition, continued northwards drift of Pangea led to a return to arid conditions by late Westphalian times. Sedimentation was initially confined to internally drained molasse basins which were eventually swamped by increasing amounts of sediment shed northwards from the evolving Variscan orogen lying to the south, although east to west axial transport of sediment from the central European Variscides has been suggested for SW England (Sherlock *et al.* 2000).

Syn-rift megasequence

The syn-rift meagasequence can be divided into six tectono-stratigraphic sequences on the basis of three phases of rifting (EC1, EC3 and EC5). Figure 23 presents a summary isopach map for the EC2-EC6. The lack of well control and poor seismic definition of the top basement reflector mean that EC1 could not be mapped regionally with confidence. The thickest syn-rift sections occur in discrete depocentres located in the immediate hanging-wall of the major basin-bounding normal fault zones. Over 3 km of syn-rift stratigraphy is preserved in these structural locations (e.g. Cleveland and Bowland Basins), which contrasts with < 500 m of stratigraphy preserved on the footwall highs (e.g. Alston and Askrigg blocks) (Fig. 1).

Sequence EC1: early syn-rift I (late Devonian–earliest Dinantian)

There are very few data to constrain the palaeogeography of northern England during the late Devonian. By this time, the mountainous topography of the Old Red Sandstone continent, particularly over northern Britain, was much subdued. Conglomerate deposition developed along newly active fault-scarps, such as the Gamblesby–Melmerby–Ousby fans along the Deep Slack, Fellside and Swindle Beck Faults and the Mell Fell Conglomerate, along the Eden–Pennine Fault in east Cumbria (Fig. 24). The Whita and Annan Sandstones in the Northumberland Trough (Leeder 1974) are interpreted as examples of more sheet-like hanging-wall derived fan systems.

In the East Midlands area approximately 275 m of coarse breccias, consisting of pebbles of quartzite, metasediments and igneous rocks, rest on Lower Palaeozoic phyllites in Eakring-146. These are interpreted to reflect deposition in close proximity to an active fault-scarp. Other boreholes penetrating siliciclastic rocks of probable late Devonian age are Caldon Low (*c.* 170 m red-brown pebbly sandstone) situated on the footwall of the Widmerpool Gulf, and Whittington Heath (*c.* 1 m pebbly sandstone) in the hanging-wall of the Birmingham Fault (see Figs 2 and 24).

Further evidence for early syn-rift sedimentation in the East Midlands area comes from gravity and seismic data. Late Devonian sedimentary basins are generally localized around gravity lows e.g. the Eakring-Foston and Gainsborough troughs (Fig. 24).

Sequence EC1: late syn-rift I (Courceyan)

A marine transgression occurred across much of northern England during the Courceyan. Basinal areas such as Northumberland, Cleveland–Stainmore and Bowland–Craven, were already subsiding and receiving siliciclastic sediment (Fig. 25). The main topographic highs, e.g. Southern Uplands, Manx–Cumbria–Alston–Askrigg ridge and Mercian Massif, remained emergent and in some cases persisted as highs throughout the Dinantian.

Coastal sabkhas developed around the northern margin of the Mercian Massif, with approximately 100 m of anhydrite and dolomite proven in Hathern-1 (Falcon & Kent 1960; Llewellyn & Stabbins 1968, 1970), suggesting restricted marine influence on the Hathern Shelf at this time (Fig. 25). Palynological analysis (Llewellyn *et al.* 1969) indicates a Courceyan age equivalent to the CM Zone of Clayton *et al.* (1977). Thicker evaporitic deposits are inferred for the Widmerpool Gulf. Thin (*c.* 80 m) transgressive siliciclastics were proven in the Eyam borehole in Derbyshire (Dunham 1973; Strank 1985). Other wells such as Caldon Low (Institute of Geological Sciences 1978, Welsh & Owens 1983) and Eakring-146 encountered nearshore or alluvial plain siliciclastics (see Figs 2 and 25). Dolomitic carbonates with subordinate siltstones and mudstones in Grove-3, Caldon Low, Welton-A1 and Gun Hill-1 boreholes represent the initial stage of a widespread carbonate ramp development in northern England (see Figs 2 and 25).

Sabkha evaporites accumulated along the northern flank of the Bowland Basin (Gawthorpe 1986, 1987*a*, Arthurton *et al.* 1988) and in the Northumberland Trough (Johnson 1984) (Fig. 25). Elsewhere, evaporites and restricted-shelf carbonates are proposed for nearshore environments around the margins of developing half graben, such as the Rossendale, Huddersfield and Edale Basins and the Stainmore Trough (e.g. Evans & Kirby 1999). Courceyan strata tentatively identified at the base of the Seal Sands-1 borehole in the eastern Stainmore Trough comprise siliciclastics, possibly derived from the emergent Alston Block to the north.

Alluvial fans developed in fault-bounded lows within the Manx–Cumbria–Alston–Askrigg Ridge (Fig. 25), for example the Shap Red Beds (Kimber & Johnson 1986). These include conglomerates derived from the Silurian greywackes to the south and SW, grading up into cross-bedded sandstones. Similar conglomerates at Sedbergh to the south were probably derived from

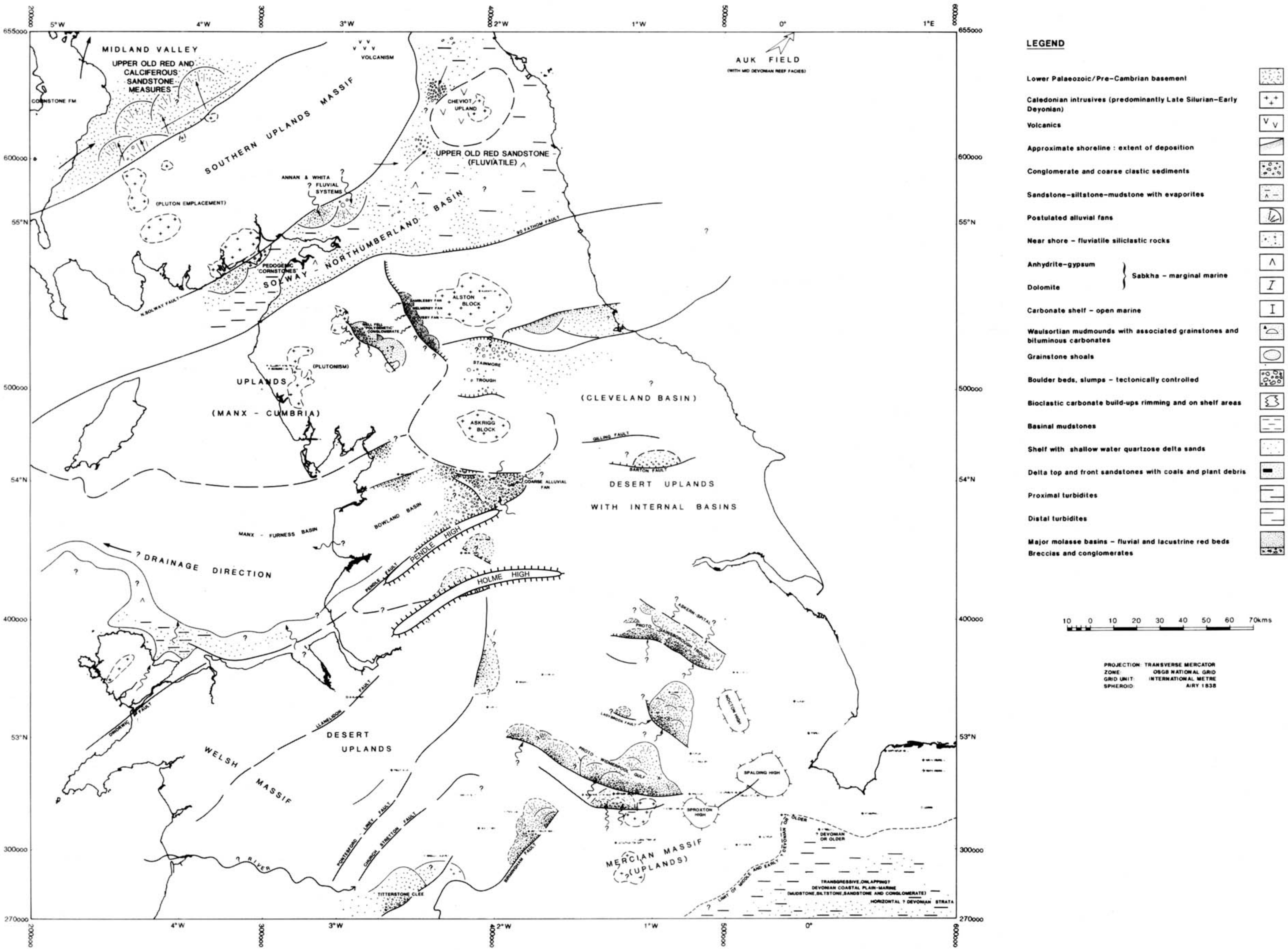


Fig. 24. Palaeofacies map for the early part of syn-rift sequence EC1 (late Devonian–earliest Dinantian; predating marine transgression).

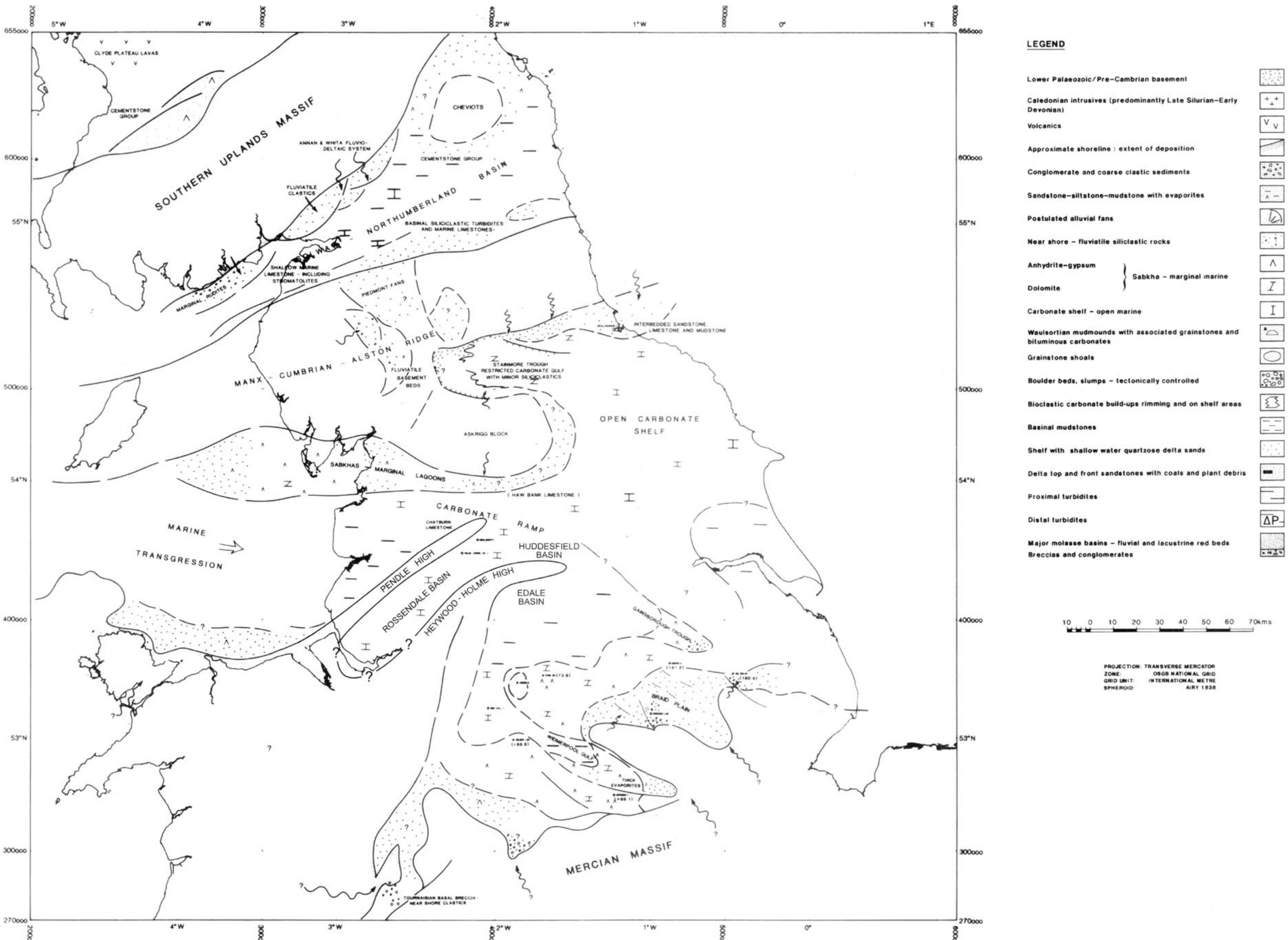


Fig. 25. Palaeofacies map for the late part of syn-rift sequence EC1, (Courceyan; post-dating marine transgression).

the northwestern side of the Askrigg Block.

Cementstone-type facies were established during the early Dinantian in the Scottish Borders in fluvio-lacustrine and hypersaline lake environments. Widespread drainage from the Southern Upland Massif provided coarse siliciclastic sediments to the Northumberland Trough, e.g. Rerrick, Annan and Whita alluvial systems (Leeder 1974; Johnson 1984). In Kirkudbrightshire, the northern Solway Fault was active and the Criffel Granite unroofed, leading to localized alluvial fan and fan delta deposition along the fault-controlled northern margin of the Solway Basin. By the end of the Courceyan, marine facies and faunas were prevalent in the Northumberland Trough Solway Basin.

The subsidence of the Northumberland Trough was accompanied by extensive alkaline fissure basalts (Birrenswark/Kelso/Cockermouth Lavas) along its northern bounding fault (Leeder *et al.* 1989). Igneous activity is also recorded in the East Midlands by tuffaceous sediments of Courceyan age encountered in Welton-Al and Grove-3 (see Figs. 2 and 25).

Sequence EC2: post-rift I (Chadian)

During Chadian times, low-angle carbonate ramps developed peripheral to the Mercian Massif and along the southern margin of the Manx–Cumbrian–Alston Ridge, Askrigg Block and around the Pendle and Holme Highs (Fig. 26). In contrast, north of the Manx–Cumbrian–Alston Ridge, the Chadian succession is dominated by siliciclastics.

In the East Midlands, EC2 has been penetrated in Hathern-l on the footwall of the Hoton Fault (see Figs 2 and 26). Here the sequence is developed as shallow-water limestones (Llewellyn & Stabbins 1968, 1970) which are dated as no older than the CF4 Zone of Conil *et al.* (1979). Restricted basinal facies are interpreted for the Widmerpool Gulf and Gainsborough Trough half graben. On the adjacent East Midlands Platform EC2 is the oldest of the Dinantian sequences preserved, and is developed as shelf limestones (Strank 1987), with the topographic highs of Sproxton, Stixwold, Nocton, Foston and Woo Dale preserving no Chadian sediments. Nearshore siliciclastics and dolomitic carbonates are recorded from boreholes in the East Midlands area (e.g. Bardney-l, NCB Bassingham, Hathern-l, Eakring-146, Ironville-5, Strelley-1, Grove-3 and the Eyam borehole) (see Figs 2 and 26).

The Chadian was a time of major carbonate production in the Bowland Basin (Gawthorpe 1986, 1987*a*; Riley 1990). The Clitheroe Limestone Formation and equivalents, exposed in the Bowland Basin, reflect deposition on a southwest dipping carbonate ramp. Carbonate grainstone shoals were developed above wave base on the shallower parts of the ramp and these grade basinwards into interbedded argillaceous limestones and mudstones. To the southeast of the Bowland Basin, the lowermost Dinantian in Holme Chapel-l, Boulsworth-l, Roddlesworth-l and Wessenden-l comprises carbonates of probable Chadian age that form ramp/shelf carbonates with poorly defined shelf margins that fringe developing fault controlled highs (see Figs 2 and 26) (Evans & Kirby 1999).

Waulsortian buildups are also characteristic of EC2 in the in the southern half of the northern England rift province. Miller & Grayson (1982), Grayson & Oldham (1987) and Riley (1990) report Waulsortian facies of Chadian age from the central part of the Bowland Basin, and in Dovedale, on the Derbyshire Dome, an elongate Waulsortian complex is reported by Bridges & Chapman (1988) (Fig. 26). In contrast to the carbonate-dominated environments to the south, marine pro-delta mudstones accumulated in the Northumberland and Cleveland basins (Fig. 26). However, in the northeastern part of the area, delta-front and alluvial deposition was already established, for example the Fell Sandstone delta system.

Sequence EC3: syn-rift II (late Chadian–Holkerian)

The late Chadian–Holkerian EC3 sequence comprises a series of carbonate ramps with associated basinal mudstones south of the Manx-Cumbrian Ridge and Alston Block, with fluvio-deltaic deposition dominant in the Northumberland Trough (Fig. 27). Locally, the base of EC3 is a pronounced angular unconformity in the footwall of fault blocks.

The palaeofacies map for the early part of EC3 (late Chadian–Arundian) shows clear evidence of a major transgression from the west, although delta top siliciclastics persist in the eastern Northumberland Trough and northern Cleveland Basin (Seal Sands-1 borehole) (see Figs 2 and 27). Both the Alston and Askrigg Blocks were increasingly subject to marine incursions. The conodont fossils recorded from Ravenstonedale (Higgins & Varker 1982) indicate increasing water depths during the Arundian, consistent with regional transgression. During this transgressive phase, extensive carbonate shelf areas developed and onlapped upland areas. The Manx–Cumbrian Ridge was apparently separated by shallow shelf seas from the Alston and Askrigg 'islands'. In the central Pennines, around the Pendle, Rossendale and Holme Highs, Arundian shelf margins backstepped towards footwall crests compared to the older Chadian margins (Evans & Kirby 1999).

Renewed extensional tectonic activity at the end of the Chadian is indicated by boulder beds and slumping (olistostromes) observed in outcrops in the Bowland Basin (e.g. Gawthorpe 1987*a*; Riley 1990) (Fig. 27). Here EC3 is represented by the Worston Shale, a mudstone-dominated succession with thinly bedded hemipelagics and calciturbidites. During the rifting, seismic shocks associated with slip events on the major normal faults triggered synsedimentary slumps and slides in sediments of EC3 age (Gawthorpe & Clemmey 1985). A similar mechanism has been suggested for major dewatering horizons within fluvial sediments of the Solway and Northumberland basins (Leeder 1987*b*; Leeder *et al.* 1989). The tectonism was also accompanied by some alkali volcanism, e.g. the Cockermouth Lavas in west and north Cumbria (Johnson 1984) (Fig. 27).

Alluvial and nearshore facies of Arundian age crop out in the Mold district of North Wales (Somerville & Strank 1984). Arundian limestones onlap earlier Carboniferous sequences and, in places, overstep onto Lower Palaeozoic rocks along the northern margin of the Wales–Brabant High. Non-depositional highs persisted to some extent in the East Midlands, but the Woo Dale high in Derbyshire was finally submerged (Woo Dale borehole; Cope 1973) (Fig. 27).

There was no major tectono-stratigraphic break between the Arundian and Holkerian with continued deepening and progressive onlap. This interval marked the maximum extent of the Dinantian transgression, with shelf limestones more extensive during the Holkerian than at any other time in the Dinantian (Strank 1987). Carbonates with minor siliciclastics accumulated across the East Midlands, and the Nocton, Foston, Stixwold and Askern–Spital highs were all submerged (Strank 1987). Shelf-ramp carbonates extended northward beyond the Alport-l borehole in the Edale Gulf (Fig. 27).

In places, on the Derbyshire Dome, the Holkerian is thin or absent, representing local emergence or non-deposition (e.g. Dovedale). Highly porous dolomitised shelf limestones (Woo Dale Limestone) have been described by Schofield & Adams (1985) who interpreted the environment of deposition as a shallow subtidal carbonate shelf which experienced varying degrees of restriction from open marine conditions. Carbonate shelf environments persisted around the islands and uplands to the north (Fig. 27).

Despite the retreat of the Fell delta system due to the Holkerian transgression, it still covered most of the Northumberland and Cleveland basins. Coal swamps developed on the upper delta plain and provided structured woody plant material to the pro-delta organic-rich mudstone facies deposited in the southern Cleveland and Solway basins (Fig. 27).

Sequence EC4: post-rift II (late Holkerian–mid Asbian)

Considerably more data are available to constrain the EC4 palaeogeography compared to the older syn-rift tectono-stratigraphic sequences. Over 200 boreholes penetrate late Holkerian to mid Asbian strata and outcrops of shelf, shelf margin and basinal facies are present in the Derbyshire Dome, Bowland Basin, North Wales, Cumbria and across the Alston and Askrigg Blocks.

The Holkerian–Asbian (EC3/EC4) boundary is poorly defined biostratigraphically (Ebdon *et al.* 1990), but can be observed seismically as strong downlap of the prograding shelf margins (e.g. Fig. 12). In the East Midlands rimmed shelf margins are resolved on regional seismic lines, and in basinal settings high-amplitude reflectors represent an increase in carbonate within an otherwise mudstone-dominated succession (e.g. Fig. 12). The progradational and aggradational clinoforms identified on the basin margins are believed to represent the development of carbonate ramp to rimmed shelf facies, although none of the clinoforms have been penetrated by wells. Shelfward of these features, and confirmed by borehole data, shallow marine shelf carbonate grainstones and packstones accumulated (Fig. 28).

By EC4 times, the extensive Arundian–Holkerian shelf and ramp systems had evolved into a series of land-attached (e.g. North Wales) and isolated (e.g. Derbyshire Dome, Pendle and Holme highs) carbonate platforms with well developed shelf-slope breaks (Fig. 28). In the Pendle and Holme areas, carbonate platforms were drowned and backstepped so that they are less aerially extensive than their Arundian counterparts (Evans & Kirby 1999). In areas of shallow water, starved of clastic sediment, shoaling-upward cyclic shelf carbonates were deposited; for example the Great Scar Limestone and equivalents in western Stainmore and on the Alston and Askrigg Blocks. Typically these shelf cycles are 5–30 m thick and are interpreted to reflect high frequency glacio-eustatic sea-level fluctuations (e.g. Walkden 1987; Horbury 1989). Where the platforms are land-attached, pronounced fluvial lowstand incised valley fills are developed (e.g. North Wales, Walkden & Davies 1983), otherwise these high-frequency sequences are dominated by shoaling upward deposits of the highstand systems tract capped by palaeosols marking interfluve sequence boundaries (e.g. Horbury 1989).

In the East Midlands and Bowland Basin, shelf carbonates pass basinwards through platform margin facies into hemipelagic lime mudstones and calciturbidites of the foreslope. This carbonate slope facies association shows a coarsening upward trend, reflecting overall progradation of the rimmed shelf. Shelf margin complexes are exposed in the Derbyshire Dome, Bowland Basin and North Wales. There was a general absence of framework building organisms during the Dinantian and boundstone reefs were not usually formed. Instead, the platform margins commonly comprise bioclastic shoals with abundant fauna including crinoids, productids and other brachiopods and solitary corals.

Along the exposed section of the northern margin of the Derbyshire platform, the depositional talus slope attained angles of up to 30° (Broadhurst & Simpson 1973). These steep angles would have been maintained by early cementation. This footwall margin was weakly progradational, but did not extend significantly beyond the controlling fault (see Edale Gulf seismic line, Fig. 17). The form and location of the rimmed shelf margins were largely controlled by faulting and the margins can be extrapolated around the fault-controlled East Midlands basins (Widmerpool Gulf, Edale Gulf and Gainsborough Trough) (Fig. 28). The angle of slope and amount of progradation were greatly affected by the amount of throw on the fault and whether the shelf margin developed on the footwall or hanging-wall dip slope. The marginal facies were also controlled by their leeward or windward position as recognised in the Derbyshire Dome (Schofield 1982), with grainstone facies apparently developed on the north-facing windward margins. Slope facies

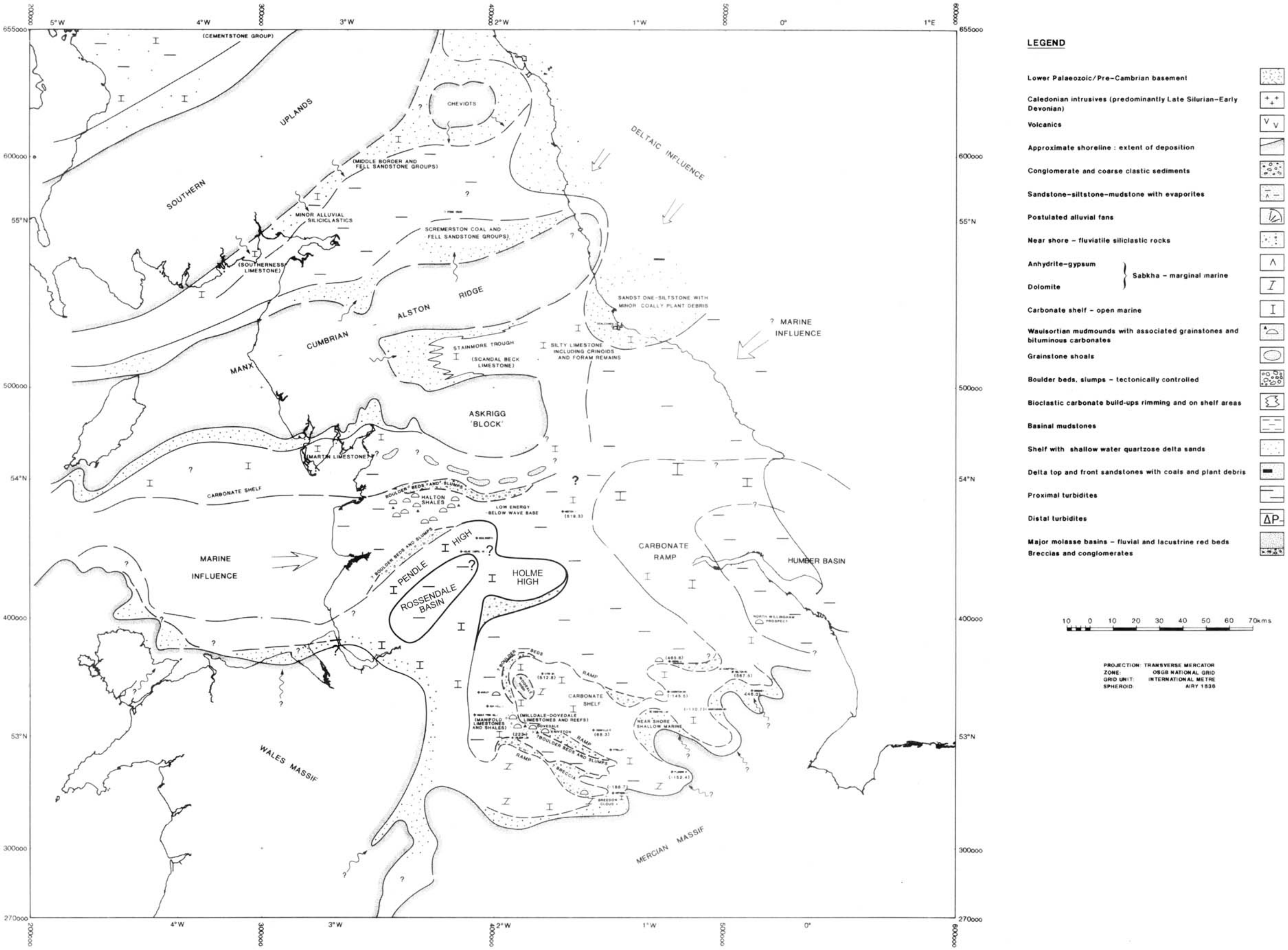


Fig. 26. Palaeofacies map for syn-rift sequence EC2 (Chadian).

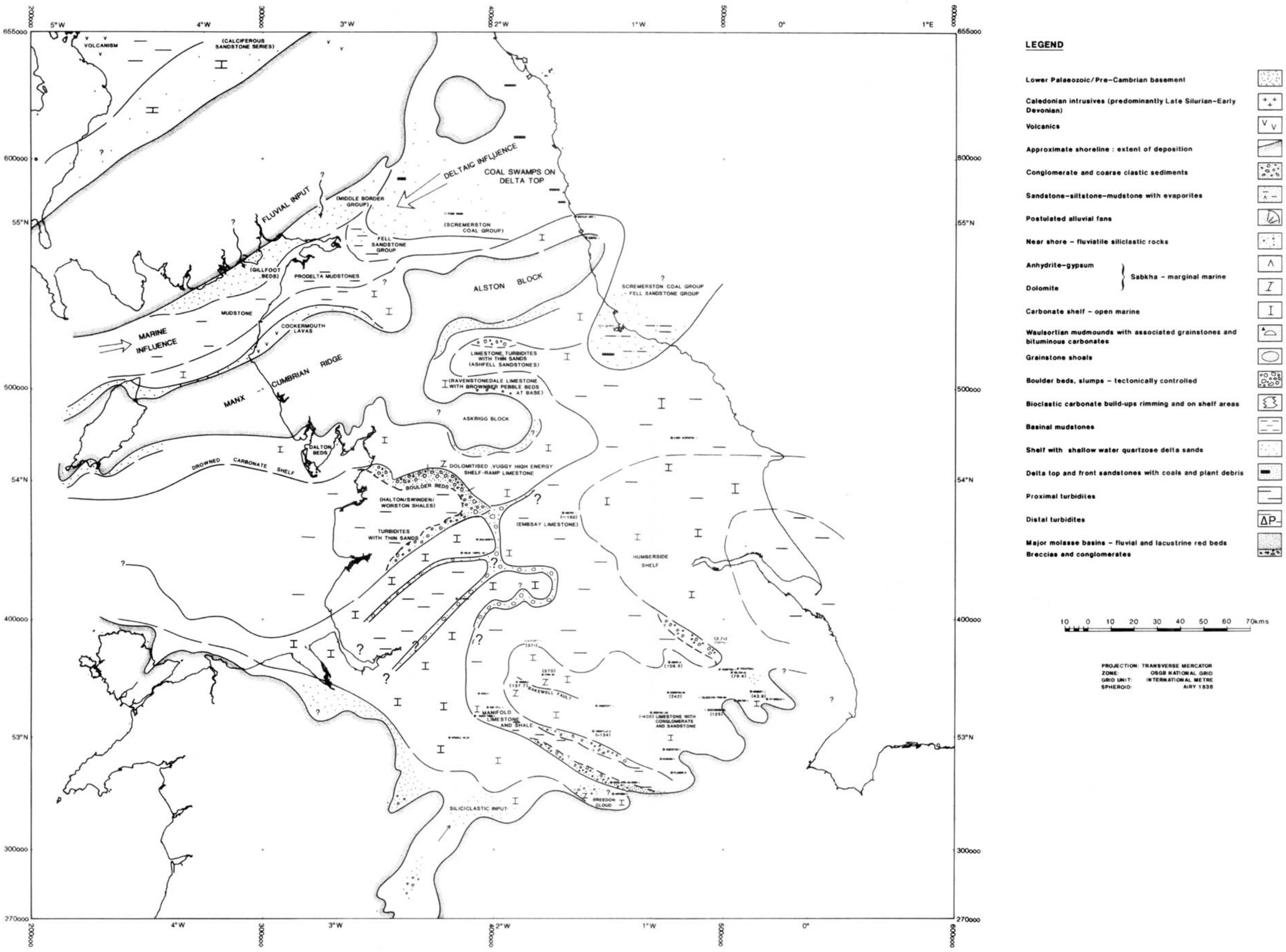


Fig. 27. Palaeofacies map for syn-rift sequence EC3 (late Chadian–Holkerian).

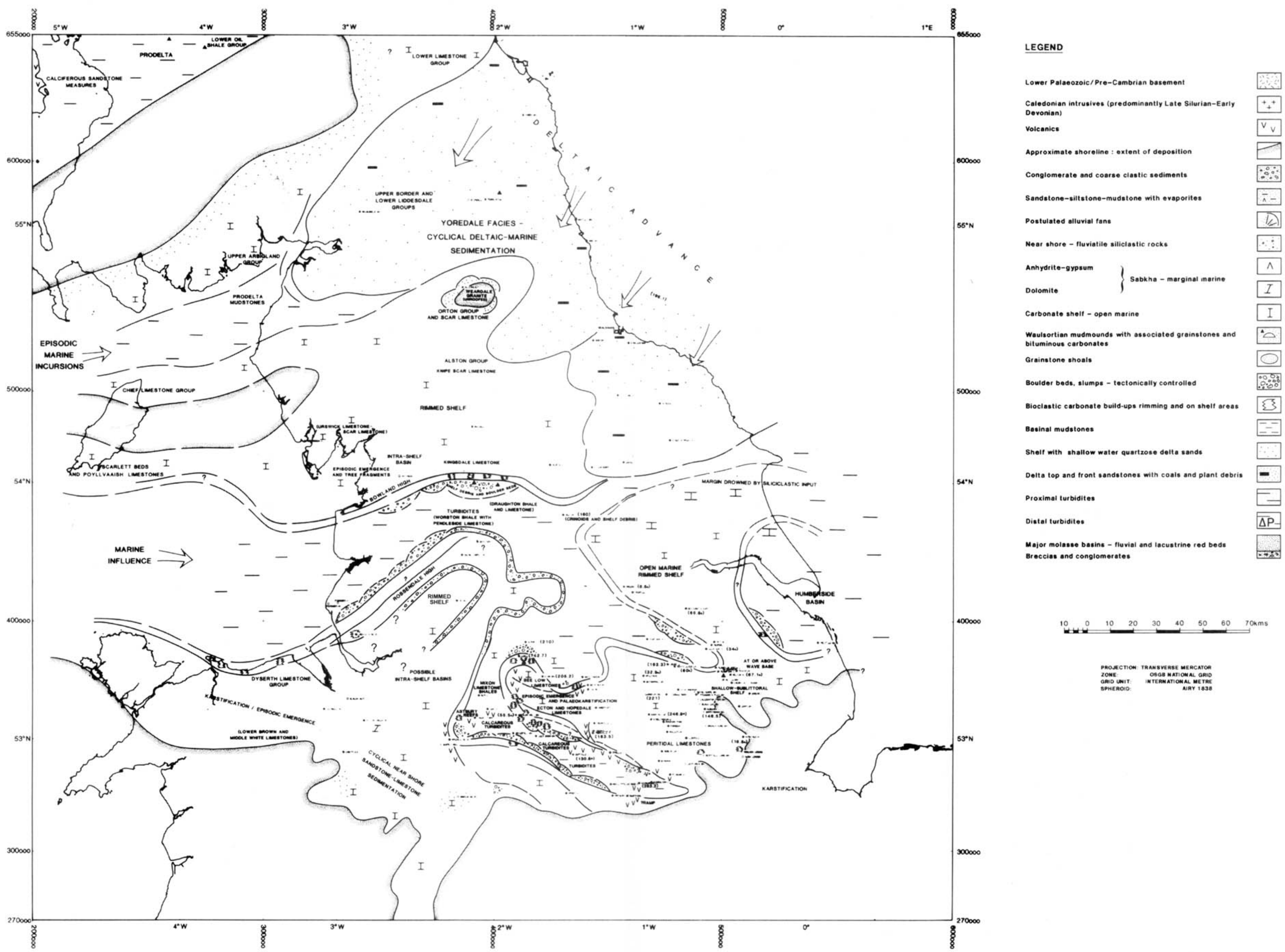


Fig. 28. Palaeofacies map for syn-rift sequence EC4 (late Holkerian–mid Asbian).

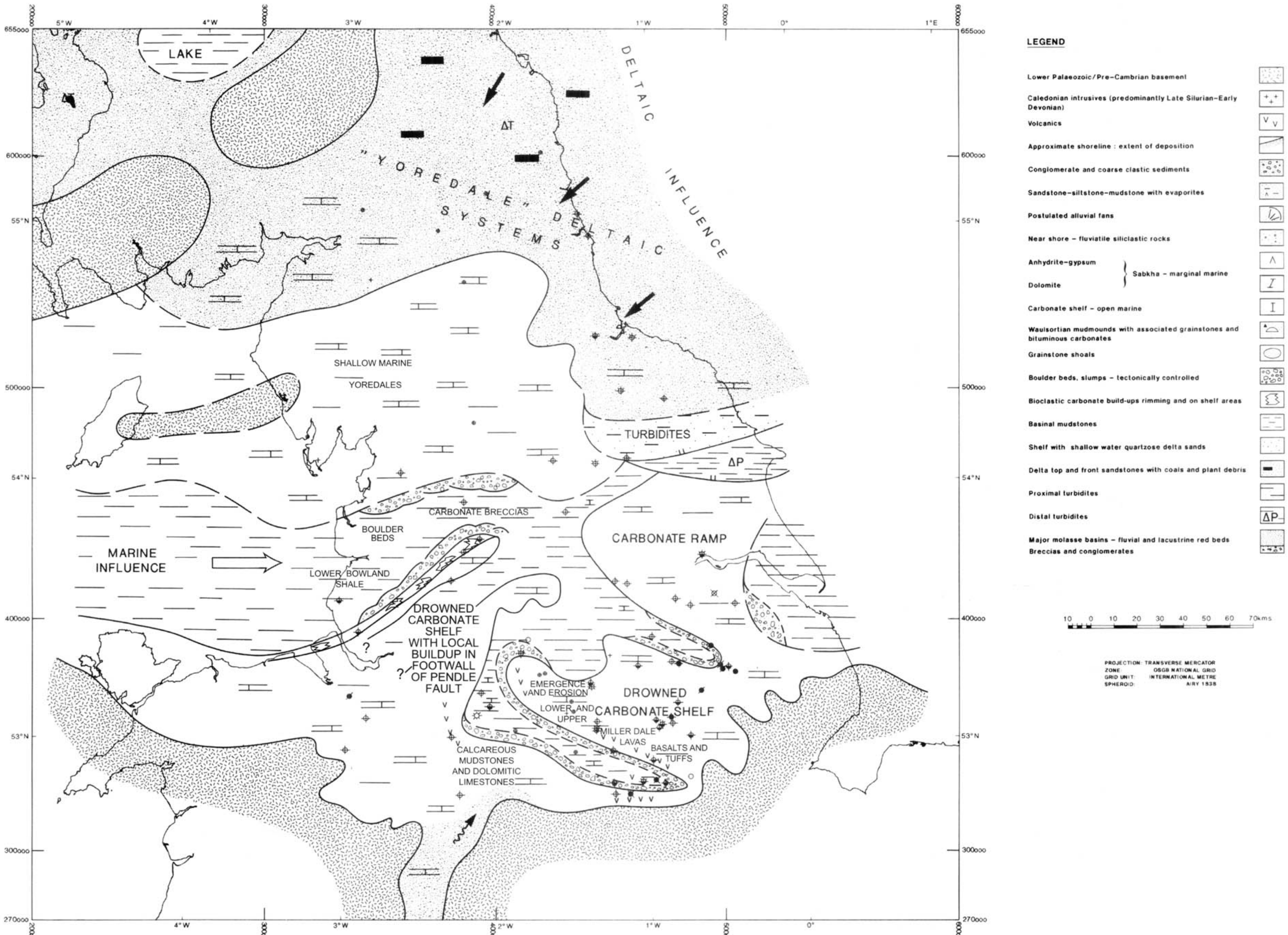


Fig. 29. Palaeofacies map for syn-rift sequence EC5 (late Asbian–early Brigantian).

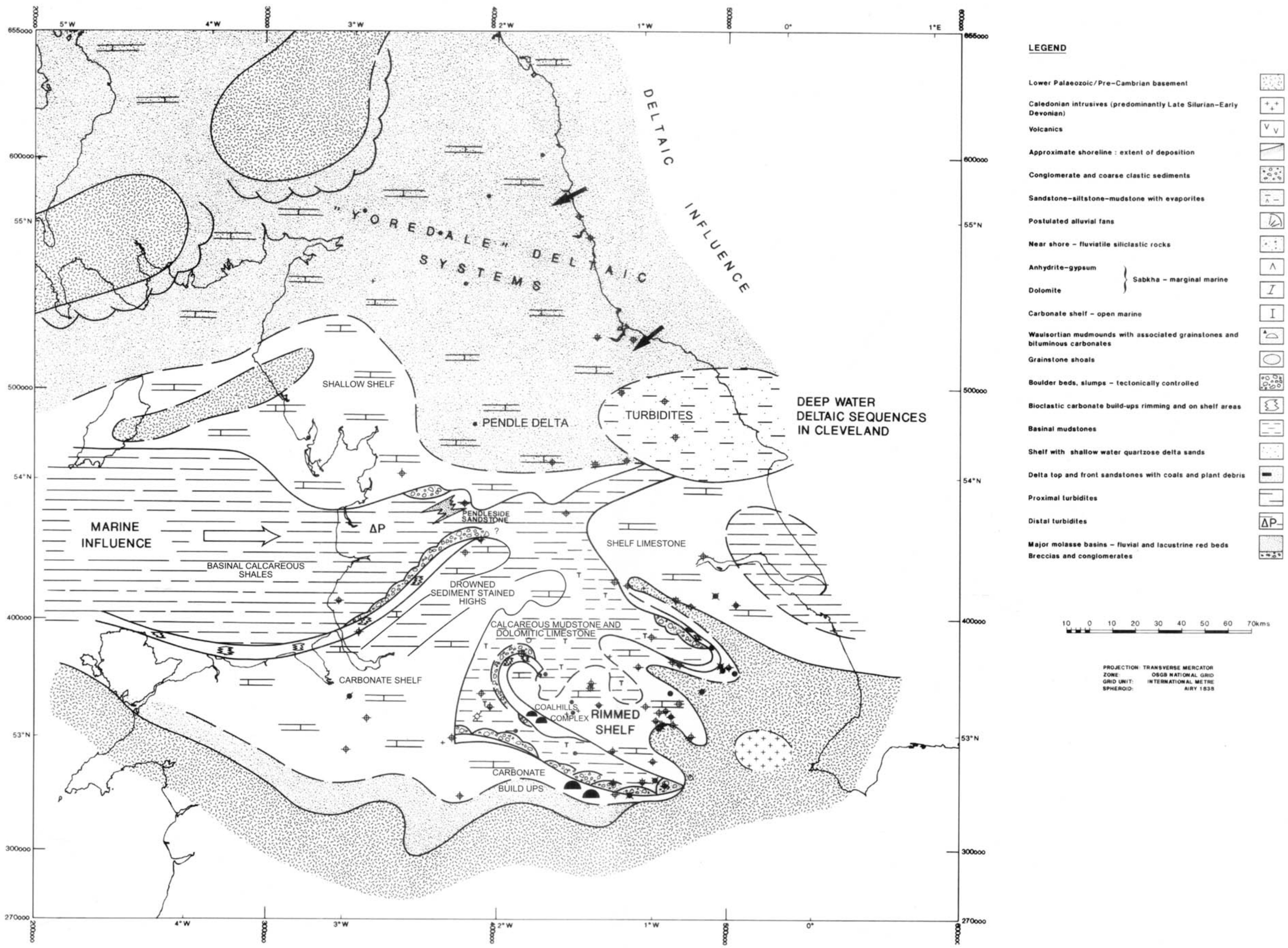


Fig. 30. Palaeofacies map for syn-rift sequence EC6 (early–mid Brigantian).

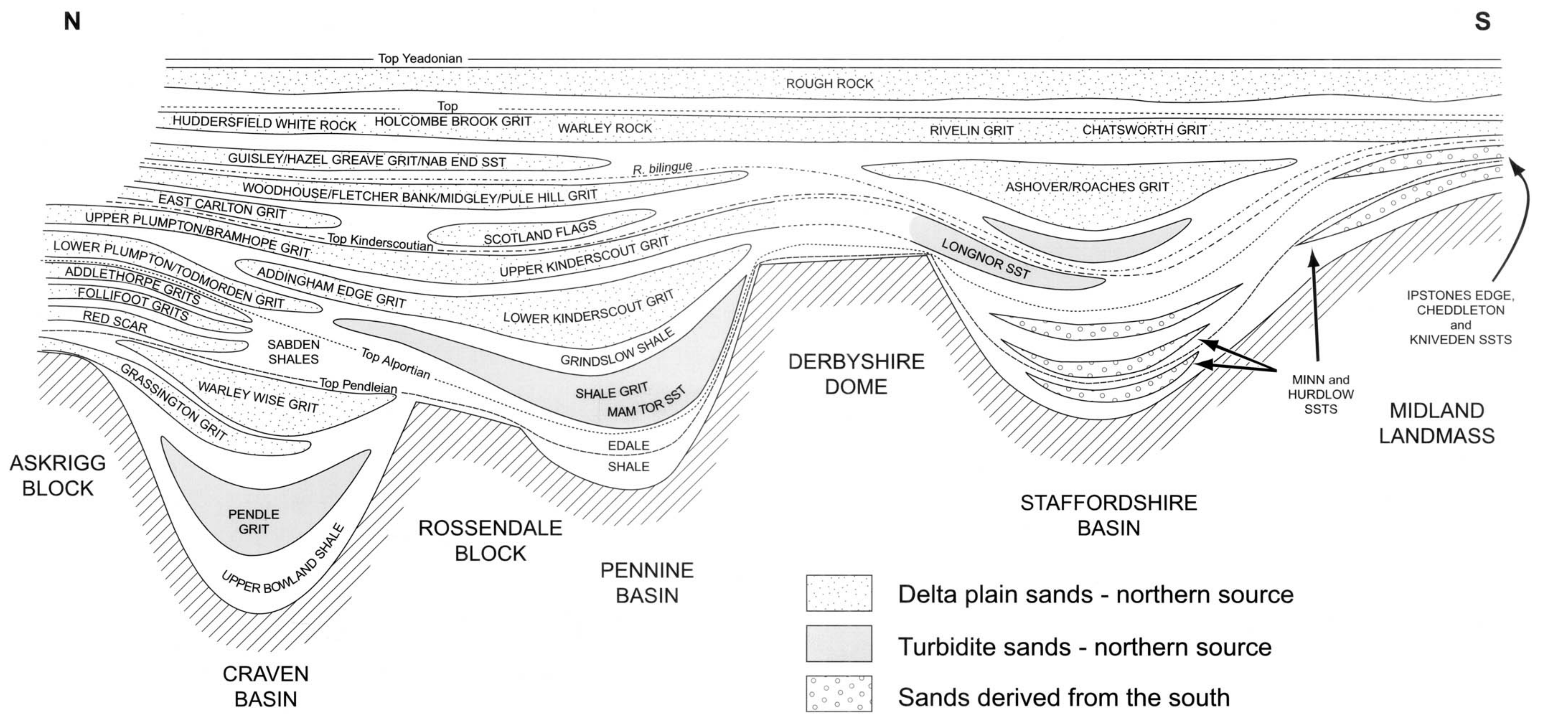


Fig. 31. Schematic regional north–south cross section illustrating the diachronous development of basin-filling turbidites and fluvio-deltaic sandstones across the Pennine Basin from the Bowland Basin in the north to the Widmerpool Gulf/Goyt Trough in the south. Note that the first phase of coarse-clastic infill is dominated by turbidites in each major depocentre. After Collinson (1988).

grade from proximal talus through coarse grainstone turbidites and mass flows, into hemipelagic and pro-delta mudstones of the lower slope and basin. These slope and basinal facies associations are well developed in the Bowland Basin (e.g. Gawthorpe 1986, 1987*a*, *b*; Riley 1990) and imaged on seismic from the adjacent subsurface (Evans & Kirby 1999).

Deltaic conditions prevailed in the northeast with the development of the Yoredale delta system, with pro-delta mudstones providing some potential hydrocarbon source rocks in the Northumberland/Solway and Cleveland basins (Fig. 28). The delta system had advanced considerably southwards, infilling much of the Northumberland and Cleveland basins with cyclical deltaic siliciclastics. Cyclicity in the mixed carbonate–clastic Yoredales involved fluvial channel belts and overbank deposits with minor coals, and interbedded marine limestones and mudstones. The cyclicity is interpreted to reflect high frequency glacio-eustatic sea-level changes, like the carbonate cyclicity developed in shelf settings to the south.

Sequence EC5: syn-rift III (late Asbian–early Brigantian)

Renewed tectonic activity in late Asbian times again reactivated and rotated fault blocks causing inundation of the shelf margins, footwall erosion and slumping and boulder bed deposition in hanging-wall settings within the Bowland Basin and the main basins of the East Midlands (Fig. 29). The exact timing of this end-Asbian event is difficult to ascertain due to rapid facies-related faunal variations. The record of palynofloras belonging to the ME Subzone (Clayton *et al.* 1977) of the NM Zone (Neves *et al.* 1972) is consistent with the late Asbian age assigned to the base of the sequence (Ebdon *et al.* 1990).

Shallow-marine shelf limestones accumulated on the East Midlands Platform and Hathern Shelf (Fig. 29). In the basinal setting borehole evidence (Ratcliffe-on-Soar-1; Fig. 14) indicates that EC5 consists of a monotonous series of calcareous mudstones and thin dolomitic limestones (Fig. 29). As with earlier rift phases, debris flow horizons, carbonate breccias and sedimentary slides are present (e.g. Bowland Basin; Gawthorpe 1986, 1987*a*). During EC5 times siliciclastics advanced further south, reaching the Bowland Basin for the first time to form the pro-delta Lower Bowland Shale (Fig. 29). Shallow-water carbonates in the footwall of the Pendle Fault continuded to be restricted to the crest of the fault block, whereas the Holme High became a drowned, sediment-starved high (Evans & Kirby 1999).

Gutteridge (1987) identifies two periods of emergence and karstic erosion on the Derbyshire Dome in the late Asbian and early Brigantian. These may correspond to two pulses of extension in the area during EC5 times, leading to footwall uplift and erosion. In the Widmerpool Gulf, carbonate production ceased either as the EC5 transgression inundated the shelf margins (hanging-wall setting) or the marginal platforms became emergent (footwall setting).

In Stainmore and on the Alston and Askrigg Blocks, where shallower water conditions prevailed close to the clastic source, cyclic Yoredale sedimentation was dominant (Johnson 1960) (Fig. 29). The Yoredale cycles can be interpreted as high-frequency depositional sequences. The marine limestones within the cycles are the equivalent of condensed sections associated with maximum flooding surfaces, formed when the rate of relative sea-level rise outpaced clastic sediment supply. The overlying coarsening and shoaling upward fluvio-deltaic units are highstand systems tracts, with local erosionally based, multistorey fluvial sandstones representing lowstand incised valley fills. As with the depositional sequences developed on the carbonate platforms further south, transgressive systems tracts are thin. The regional extent of the Yoredale cycles suggests a glacio-eustatic control; however, Leeder & Strudwick (1987) also highlight the role of local tectonics and sediment supply.

Rifting in EC5 is also associated with renewed igneous activity. In Derbyshire this phase of igneous activity is represented by the Lower and Upper Millers Dale Lavas (Walkden 1977, Walters & Ineson 1981, Macdonald *et al.* 1984). In the East Midlands, basalts and tuffs in Strelley-1 (Fig. 14) are associated with a series of NW–SE-trending faults, the Cinderhill Fault, which bounds the northern margin of the Widmerpool Gulf (e.g. Fraser & Gawthorpe 1990) (Fig. 29).

Sequence EC6: post-rift III (early–mid Brigantian)

It seems likely that, by Brigantian times, basinal sedimentation was continuous from the Dublin Basin to the Bowland Basin, and eastwards to the Widmerpool and Gainsborough basins (Fig. 30). In contrast, shelf limestone facies were now widespread across the East Midlands Shelf (Strank 1987) (Fig. 30). The top of the tectono-stratigraphic sequence EC6 is well constrained by the top of the *G. bilineatus* conodont Zone of Metcalfe (1981) (Ebdon *et al.* 1990). Conodont assemblages are rich and diverse throughout and resemble those present in the underlying EC5 sequence. The EC6 sequence belongs exclusively to the NC Zone (Neves *et al.* 1972), the top of the sequence falling within the biozone.

The interval is characterized by carbonate ramp to rimmed shelf development in the Widmerpool Gulf and Gainsborough Trough where water depths in the basins were up to 300 m (Fig. 30; also see Fig. 12). In the basin this interval comprises thinly bedded, dark grey, calcareous mudstones and brown, dolomitic muddy limestones. The EC6 hanging-wall margin along the north of the Widmerpool Gulf established itself shelfward of the Asbian margins and subsequently prograded basinward. Facies changes across these Brigantian margins are rapid as exposed at Wirksworth in Derbyshire (Walkden 1982). Here, over a distance of roughly 1 km, shelf grainstones, packstones and wackestones pass southwards through stacked grainstone shoal complexes and into slumps and slides. Prominent carbonate buildups also developed along the hanging-wall dip slope, for example the Coal Hills complex described by Walkden (1982) (Fig. 30).

During EC6, the Pendle delta system prograded southwards from the NE and NW resulting in the deposition of siliciclastic turbidites (Pendleside Sandstone) in Bowland, effectively precluding further carbonate production in this basin (Fig. 30). To the SE, the carbonate platforms fringing the footwall of the Pendle fault finally drowned (Evans & Kirby 1999). Further north, cyclic Yoredale sedimentation continued in Stainmore and across the Alston and Askrigg Blocks (Fig. 30).

The onset of siliciclastic turbidite deposition in the Bowland and Cleveland Basins marks a major change in depositional style in the central Pennines and East Midlands which continued into the early part of the post-rift megasequence. In all of these areas, the first major siliciclastic-dominated sequences contain prominent turbidites reflecting the influence of local antecedent syn-rift bathymetry and sediment bypass on sequence development (Fig. 31).

Post-rift megasequence

The post-rift megasequence can be divided into two tectono-stratigraphic sequences, LC1 and LC2. The boundary between these two tectono-stratigraphic sequences represents a major change from lower to upper delta-plain environments throughout most of northern England. Seismic data show the post-rift megasequence to have been deposited regionally across northern England (e.g. Fig. 12). Isopachs for the post-rift section exhibit a classic bullseye pattern interpreted by Leeder (1982) as resulting from a phase of passive thermal subsidence (Fig. 32). A similar thermal sag has been identified further east in the Southern North Sea (Leeder & Hardman, 1990).

During the early part of the post-rift megasequence, sediment supply overtook subsidence for the first time, allowing marked southward progradation of the fluvio-deltaic system and the infill of the remnant rift topography with deltaic sediments (Fig. 31). Backstripping of the top syn-rift reflector in the Widmerpool Gulf indicates water depths of around 300 m for the sediment starved half graben at this time. The observed thickening of the Namurian and Westphalian (post-rift) isopachs into the Widmerpool Gulf (Kent 1966) can partly be explained in terms of infilling of antecedent bathymetry in a starved rift by deltaic systems (Fig. 32).

Sequence LC1a: post-rift (late Brigantian–early Pendleian)

By the end of the Brigantian, deltaic influence covered most of northern England and the carbonate platforms were restricted to south of the central Pennines, with most of the former carbonate-producing shelf areas being sediment starved or drowned by deltaic or shallow marine clastics (Fig. 33). Brigantian strata belonging to sequences EC6 and LC1a are not encountered on the palaeotopographic highs of Nocton, Foston and Stixwold (Fig. 33). This is interpreted as non-deposition due to uplift related to the earlier mid-Brigantian inversion event. The Brigantian is also absent over large parts of the Widmerpool Gulf where mid-Brigantian inversion is thought to have been strongest.

Renewed subsidence, following shortly after the mid Brigantian inversion event, caused inundation of the shelf margins and development of new intrashelf basins, for example the Welbeck Low and across the Derbyshire Dome (Gutteridge 1987). Pro-delta basinal mudstones and turbidites accumulated in inherited starved syn-rift depocentres to the south of the advancing Yoredale delta system (Fig. 33). More proximal quartz-rich turbidite sandstones derived from the London-Brabant Massif are evident in several Goyt Trough and Widmerpool Gulf boreholes (e.g. Bosley, Nooks Farm-1A, Widmerpool-1 and Duffield; Figs 2 and 33). At Welton in the East Midlands, the top Dinantian includes quartzose channel sands, with a probable

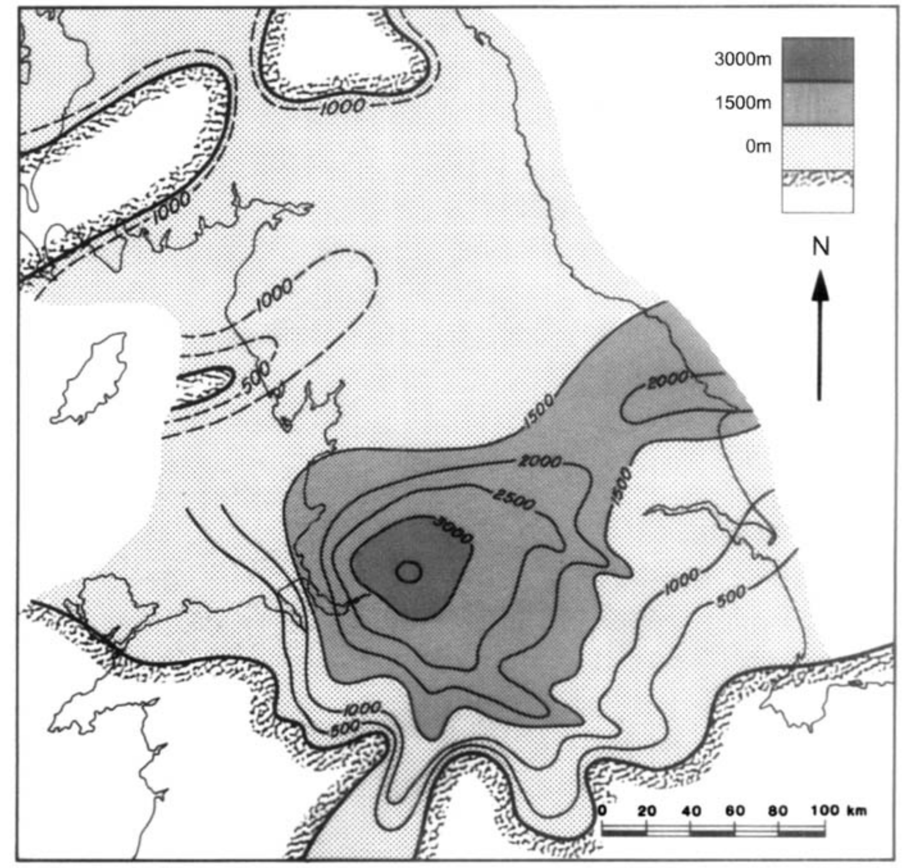


Fig. 32. Restored isopachs for the post-rift megasequence (late Brigantian to late Westphalian C). Modified from Fraser & Gawthorpe (1990).

southeasterly provenance. These low sinuosity channels are considered analogous to outcrops in Anglesey (Walkden & Davies 1983).

By the end of the Dinantian, the last vestiges of a once-extensive carbonate platform south of the central Pennines and East Midlands were disappearing. The earliest Namurian (Pendleian) was characterized by progradation of delta and turbidite systems westwards from Cleveland and southwards across Cumbria into the Bowland Basin (Fig. 33). North of Craven Fault Zone, high frequency Yoredale sequences continued to develop, generally in shallow water, low subsidence settings (e.g. Askrigg Block). South of the fault zone, the earliest coarse-grained siliciclastic deposition is represented by stacked deep water turbidites of the Pendle Grit, marking sediment by-pass and basin floor deposition associated with the Pendle delta system (Martinsen 1993; Fig. 33). South of the Pendle Fault, pro-delta shales onlapped and overstepped the late Dinantian platform on the crest of the fault block (Evans & Kirby 1999). After Pendle Grit deposition, shallower-water, deltaic deposits accumulated, especially in the Skipton area, represented by the Grassington, Skipton Moor, Warley Wise and Beamsley Grits.

To the south and SE of the Bowland Basin, sediment-starved conditions prevailed and basinal mudstones, rich in terrigenous plant debris, accumulated in sub-basins of the central Pennines (e.g. Huddersfield Basin), the Edale Gulf and Gainsborough Trough (e.g. Edale Shales) and, to a lesser extent, across depositionally lower parts of the Humberside area (thin Gamma Active Shales, Fraser *et al.* 1990; Fig. 33). These mudstones are proven rich potential hydrocarbon source rocks. The main Pendle delta advance was prevented from entering the central Pennines and East Midlands area by the Pendle Fault with

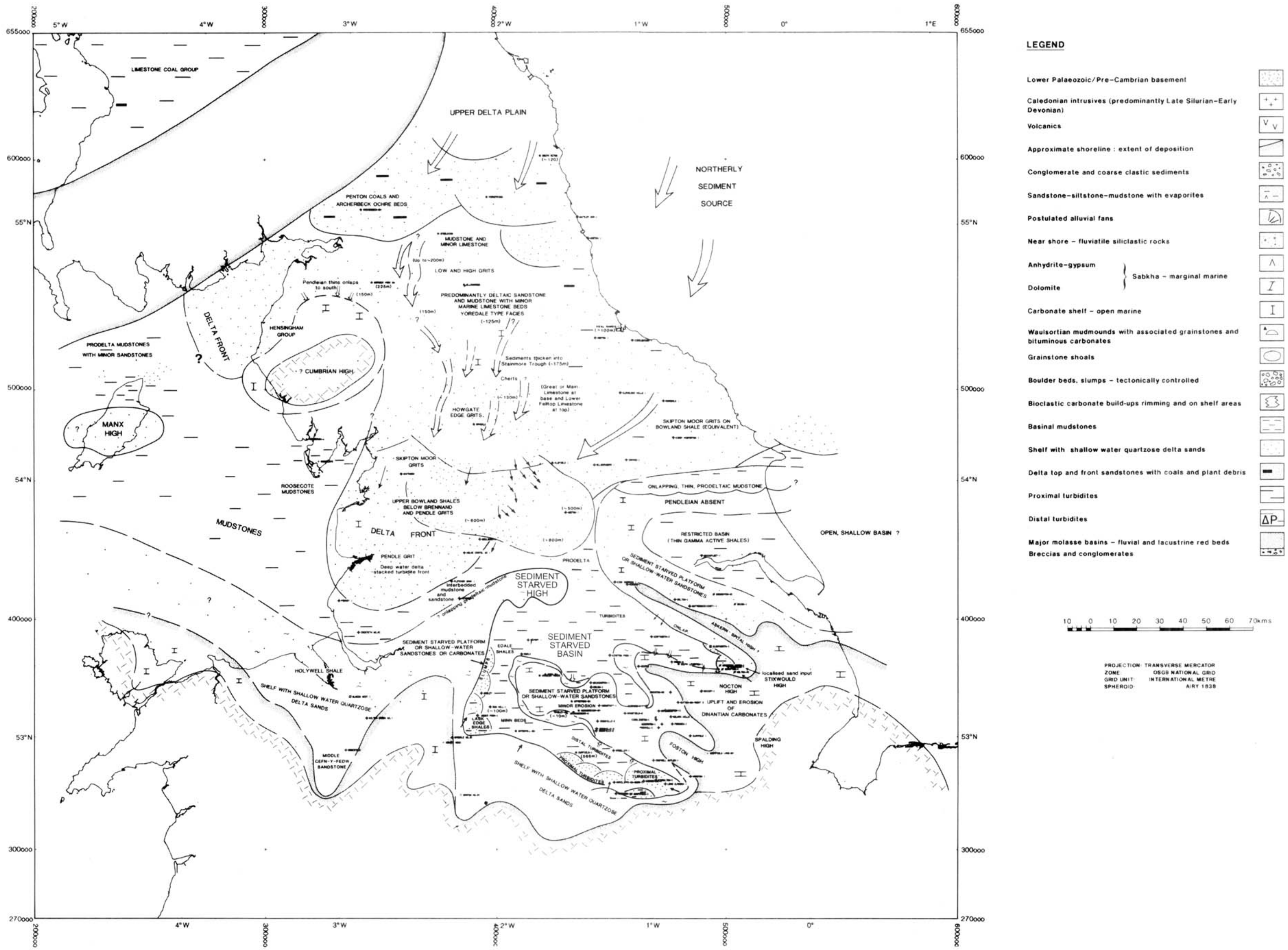


Fig. 33. Palaeofacies map for post-rift sequence LC1a (late Brigantian–early Pendleian).

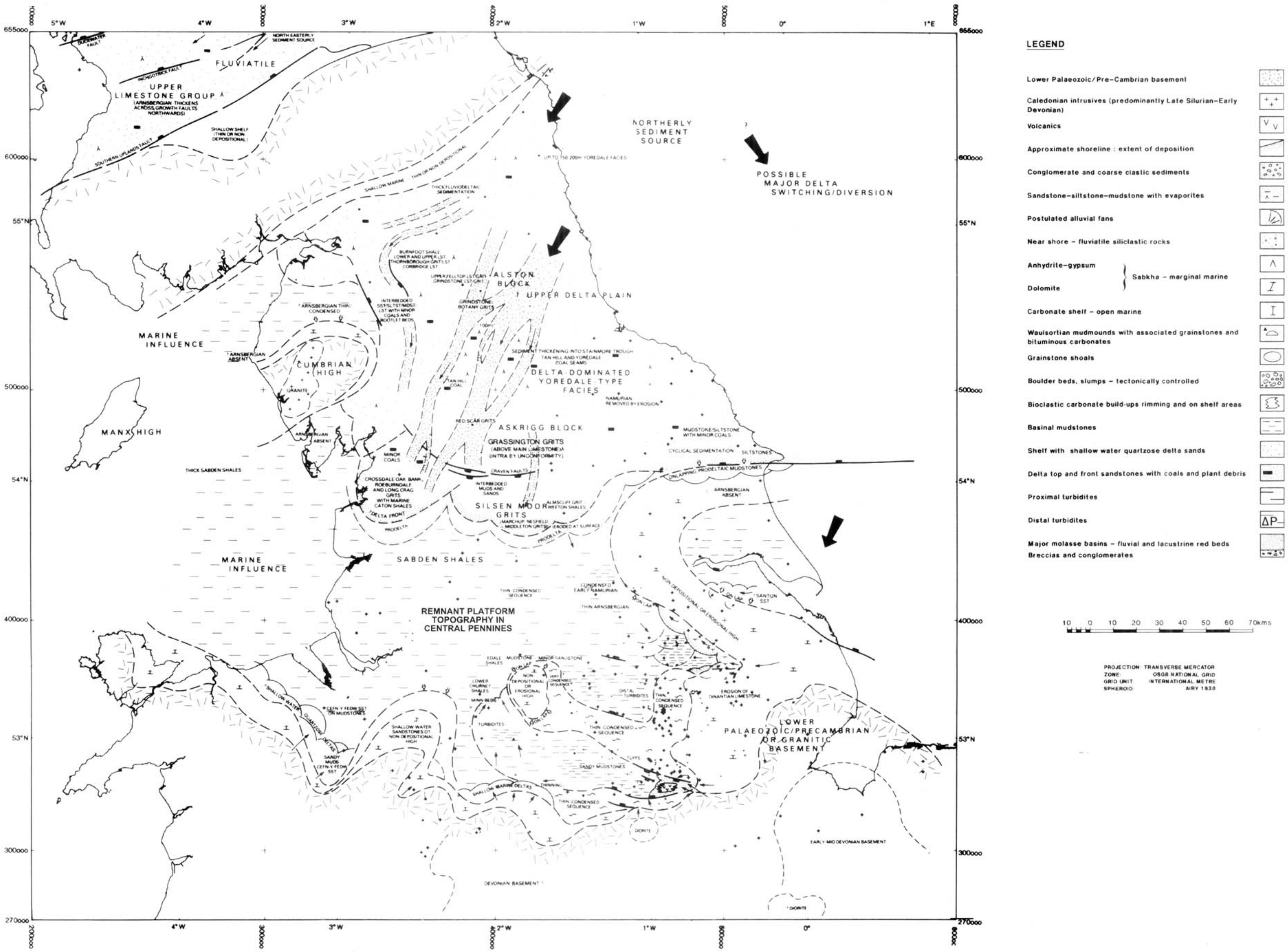


Fig. 34. Palaeofacies map for the early part of post-rift sequence LC1b (late Pendleian–Arnsbergian).

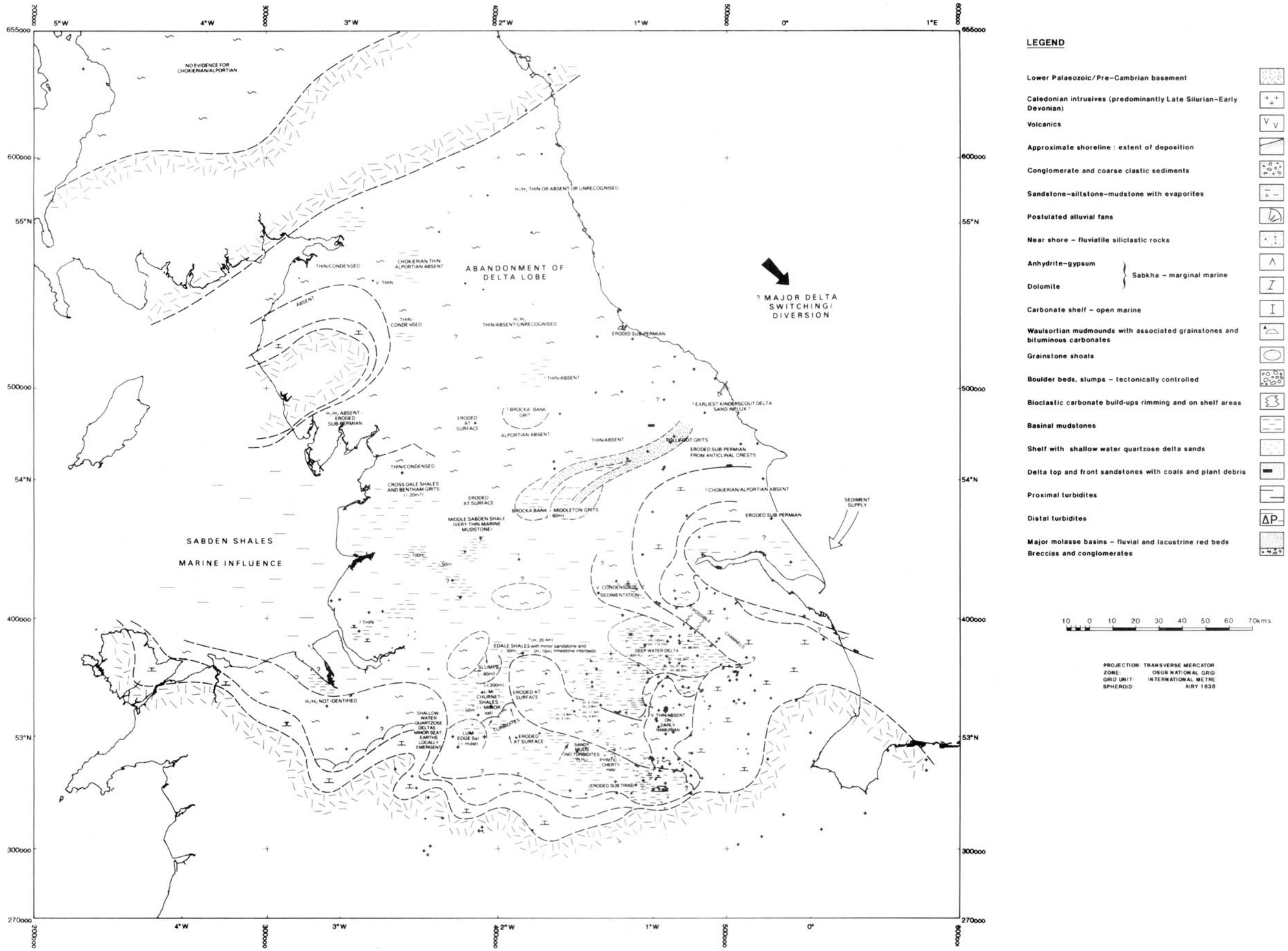


Fig. 35. Palaeofacies map for the late part of post-rift sequence LC1b (Chokierian–Alportian).

former carbonate platforms to the southeast being sites of non-deposition or erosion (e.g. Holme High) (Fig. 33). Southerly-derived, proximal turbidites, with quartzitic petrography, continued to accumulate at the head of the Gainsborough Trough and Widmerpool Gulf, with only minor distal turbidites entering from the north. Proximal turbidites and minor slumps developed around the margins of the East Midland basins, perhaps indicating some minor extensional fault movements in the Pendleian. The former Dinantian shelf areas became sediment-starved platforms or areas of non-deposition. Minor quartzose deltas formed on the shallow shelf areas along the Mercian Massif shoreline.

Sequence LC1b: post-rift (late Pendleian–Alportian)

After the major turbidite-fronted delta advance across the Bowland Basin during the early Pendleian (LC1a), the Arnsbergian was a time of turbidite sandstone and mudstone deposition over much of the central Pennines (Fig. 34). Interbedded delta-top sandstones and mudstones of the Roeburndale Grit Group were deposited in the Lancaster Fells and the Silsden Moor Grits prograded southwards from the Askrigg Block into the Leeds-Bradford area (Arthurton *et al.* 1988). To the south and west Lower Sabden Shales deposition was dominant, as encountered in outcrops and also in boreholes (e.g. Croxteth, Upholland, Heywood, Fletcher Bank and Holme Chapel; Figs 2 and 34).

Across the Northumberland Trough and the Alston and Askrigg Blocks, Yoredale-type sedimentation persisted throughout the Arnsbergian (e.g. Leeder *et al.* 1989; Fig. 34). Sedimentation kept pace with subsidence in the Stainmore Trough as evidenced from increased thickness in the absence of any major facies variation. Fluvio-deltaic sandbodies (e.g. Thornborough, Grindstone, Botany, Red Scar Grits) are interbedded with shallow marine mudstones and limestones, reflecting the continued influence of glacio-eustatic sea-level fluctuations on high-frequency sequence development. The Cumbrian non-depositional/erosional high was onlapped by thin or condensed marine mudstones and interbedded deltaic siliciclastics of the Upper Hensingham Group (Fig. 34).

Across the central Pennines and East Midlands areas, non-deposition or erosion of earlier Dinantian carbonate shelf areas persisted, such as the Holme High and Askern-Spital High, where no pre-Kinderscoutian sediments are proven. Thin, condensed mudstone-dominated sequences onlap these shelf areas. The thickest Arnsbergian sections occur in the previously starved and thermally subsiding Gainsborough Trough, Edale Gulf, Widmerpool Gulf and Goyt Trough depocentres (Fig. 34). Turbidites and shallow marine siliciclastics derived from the Mercian Massif to the south were channelled longitudinally along the southern-most gulf areas, as proven in the Rempstone-1 and Duffield boreholes (Figs 2 and 34).

The Chokierian–Alportian stages are both poorly represented (condensed) across most of northern England and North Wales (Fig. 35). Across the Northumberland Basin and southwards to the Craven faults, Chokierian/Alportian sediments comprise thin mudstones or are absent or unrecognised. In the Colsterdale area, this interval is represented by mature palaeosols (ganister), intercalated with minor marine limestones and mudstones. In Yorkshire, these stages are represented by less than 30 m of mudstones and siltstones in the Cowling area and a slightly greater thickness in Wharfedale (Fig. 35). In the latter, fluvial sandstones of the Upper Follifoot Grit up to 18 m thick occur at the top of the succession, heralding the subsequent progradation of the Kinderscout delta system. Similar sandstones have been identified in boreholes in the Cleveland Basin (e.g. Kirby Misperton-1; Figs 2 and 35).

Where present at all, Chokierian–Alportian sedimentation is thin and condensed over much of the East Midlands area. However, thick sequences are reported from the central Gainsborough Trough (c. 280 m from Scaftworth-2) and Goyt Trough (up to 200 m; Figs 2 and 35). Minor volcanism and tuffs may be of Chokierian–Alportian age in the vicinity of the Long Clawson-1 borehole in the Widmerpool Gulf (Figs 2 and 35). Mudstones and siltstones, with minor turbiditic sandstones, dominated deposition in the North Staffordshire Basin (e.g. Lower and Middle Churnet Shales).

Sequence LC1c: post-rift (Kinderscoutian–early Westphalian A)

The influx of coarse-grained sediment from the north recommenced some time during the early to mid Kinderscoutian leading to major deltaic progradation and infilling of the northern part of the Pennine Basin (Figs 36 and 37). The whole Kinderscoutian stage exceeds 500 m in north Derbyshire in contrast to a mere 30 m in the Woodland borehole on the Alston Block.

During the early part of LC1c (early–mid Kinderscoutian) deposition of Yoredale-type facies persisted in the Northumberland Trough–Alston Block area, with quartzose sandstones containing brachiopods and shelly fauna indicative of very shallow water developed on the southern edge of the Alston Block in Wharfedale-Nidderdale (e.g. Cayton Gill Shell Bed). In contrast, coarse-grained fluvial sandbodies developed across the Askrigg Block, for example the Libishaw and Brimham Grits (Ramsbottom *et al.* 1978) (Fig. 36). These prograded over the Craven Fault Zone as various deltaic lobes, such as the Cobden and Caley Crags Grits of the Lancaster Fells and West Yorkshire (Ramsbottom 1974; Ramsbottom *et al.* 1978; Fig. 36). Mudstone deposition persisted across most of the Pennine Basin from Lancashire to the East Midlands (e.g. Upper Sabden and Upper Churnet Shales), including local turbidites (e.g. Mam Tor Sandstones) (Fig. 36).

By late Kinderscoutian times (Fig. 37), the southward advance of a major delta from the north dominated northern England. The Kinderscout delta complex comprises a number of high frequency sequences, the oldest dominated by basin floor and slope turbidites of the Mam Tor Sandstone and Shale Grit and equivalents. Palaeocurrents within these initial coarse-grained basinal sediments highlight the reduction in inherited bathymetric control as the sediment starved basinal areas were infilled. For example, initial turbidites of the Mam Tor Sandstone flow to the west parallel to the trend of the Dinantian carbonate platform margin, whereas towards the top of the formation the flow is dominantly to the south across the underlying syn-rift basin margin (Allen 1960). The turbidites were followed by slope deposits of the Grindslow Shales which form a delta front coarsening-up package underlying the main fluvial sandbodies of the lower Kinderscout Grit. (Walker 1966; Collinson 1968; McCabe 1978). Although the Edale Shale to Lower Kinderscout Grit succession was originally interpreted as a series of genetically related environments from basinal through turbidite fans and slope to delta top, several major candidate sequence boundaries and marine flooding surfaces within this succession suggest the presence of a number of depositional sequences (e.g. Hampson 1997). In contrast to the Lower Kinderscout Grit, the Upper Kinderscout Grit is a sheet-like sandbody that was deposited following a short-lived abandonment, represented by the Butterly Marine Band maximum flooding surface. The Upper Kinderscout Grit may be traced northwards into the Upper Brimham Grits (McCabe 1977) (Fig. 37).

The various high-frequency sequences that comprise the Kinderscout Grits effectively filled the Pennine and other Central Province basins by the end of the Kinderscoutian resulting in widespread shallow water and delta-top conditions in these areas (Fig. 37). Minor, shallower-water, coarsening upward deltaic cycles occurred across the Gainsborough Trough area throughout the Kinderscoutian (Steele 1988) and thin shallow water sandstones and mudstones typify the entire Kinderscoutian of North Wales and the Lancashire shelf area. The remaining topographic lows to be infilled following the deposition of the Kinderscout delta lay to the south in Derbyshire, north Staffordshire and the East Midlands and to the west in the Manx-Furness Basin (Fig. 37).

By early Marsdenian times (Fig. 38), the Kinderscout delta was effectively abandoned, leading to the *R. gracile* maximum flooding surface. The sedimentary facies and sequence stratigraphy of the Marsdenian have been studied in detail over the East Midlands area (Church & Gawthorpe 1994, 1997; Fig. 15), and in parts of the adjacent outcrops in Derbyshire and North Staffordshire (Jones & Chisholm 1997) and the central Pennines (e.g. Wignall & Maynard 1996). Major channel systems were established from the east and NE across the East Midlands area by the middle Marsdenian forming the Ashover–Roaches delta. This represents the last deep water turbidite-fronted system and infilled the Widmerpool Gulf axially from the SE (Fig. 38). The Roaches Grit of north Staffordshire represents the corresponding turbidite deposits on the delta front in the deep Goyt Trough (Jones 1980; Jones & Chisholm 1997) (Fig. 38). Following progradation of this delta, all of the sediment starved basinal areas in northern England had been infilled.

Across the Gainsborough Trough, Ashover Grit equivalents included coarse pebbly channel sandstones (e.g. Trumfleet Grit) with sedimentation dominated by shallow-water delta deposition (Steele 1988) (Fig. 38). In general, the East Midlands Platform succession is thinner, with few thin fluvial channel sandstones that grade westwards into pro-delta mudstones and siltstones. Abandonment of the Ashover-Roaches delta system is interpreted to have resulted from relative sea-level rise, culminating in the *R. superbilinque* maximum flooding surface (Church & Gawthorpe 1994; Jones & Chisholm 1997; Fig, 15).

By late Marsdenian times shallow-water delta-top conditions were established across most of northern England (Fig. 39). The late Marsdenian and Yeadonian, like much of the Namurian, is characterized by high frequency cyclicity, comprising goniatite-bearing marine mudstones passing upwards through delta-front mudstones and siltstones, into mouth bar and fluvial channel sandstones and delta-top deposits associated with coals and palaeosols. Typically these 'shallow water delta' cycles are 10 to 50 m thick in the East Midlands and each cycle is characterized by a major fluvial sandbody such as the Chatsworth Grit-Huddersfield White Rock (e.g. Figs 15 and 39), Lower Haslingden Flags, and Rough Rock–Upper Haslingden Flags. The major sediment transport direction was to the west and SW, although the syn-rift basin morphology continued to influence transport pathways with axial transport inferred along the Widmerpool Gulf into the Yeadonian (Church & Gawthorpe 1997) (Fig. 39). However, sediment supply from the west and northwest occurred during deposition of the Yeadonian Lower and Upper Haslingden Flags (Collinson & Banks 1975) and provenance studies suggest a different source area to the northern source that had dominated up until now (e.g. McLean & Chisholm 1996). This westerly source area became dominant during the overlying Westphalian A (e.g. Hallsworth & Chisholm 2000).

It is generally accepted that these cycles result from high frequency glacio-eustatic sea-level changes (e.g. Ramsbottom 1977; Leeder 1988; Holdsworth & Collinson 1988; Maynard & Leeder 1992; Church & Gawthorpe 1994; Hampson *et al.* 1995, 1997). The goniatite-bearing marine mudstones (marine bands) reflect maximum flooding surface condensed sections and the overlying delta-front to delta-top succession, progradation of the highstand systems tract. Many of the major fluvial sandbodies, e.g. the Rough Rock, display marked incision into underlying sequences and are interpreted as incised valley fills (Church & Gawthorpe 1994, 1997; Fig. 15).

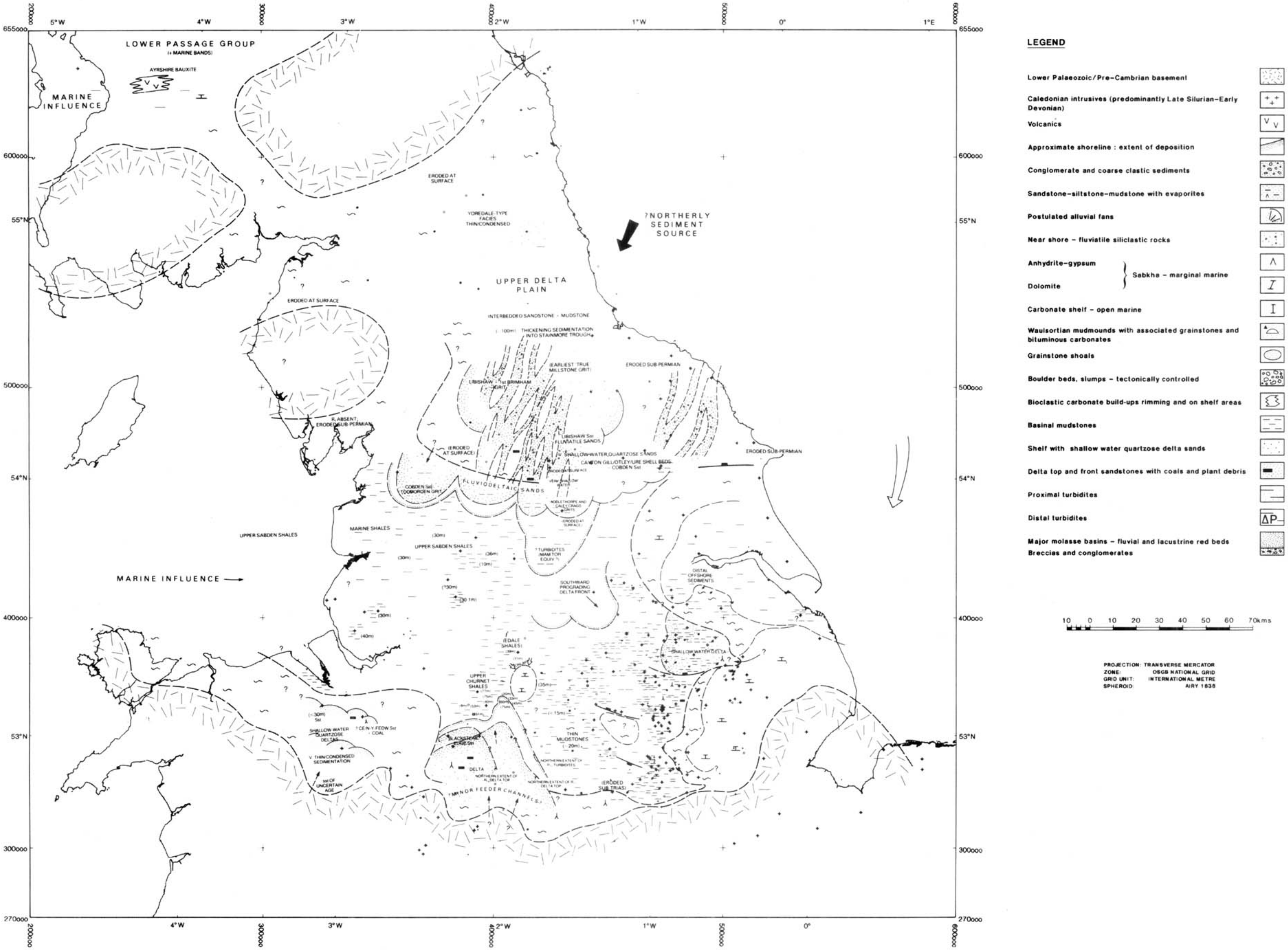


Fig. 36. Palaeofacies map for the early part of post-rift sequence LC1c (early–mid Kinderscoutian).

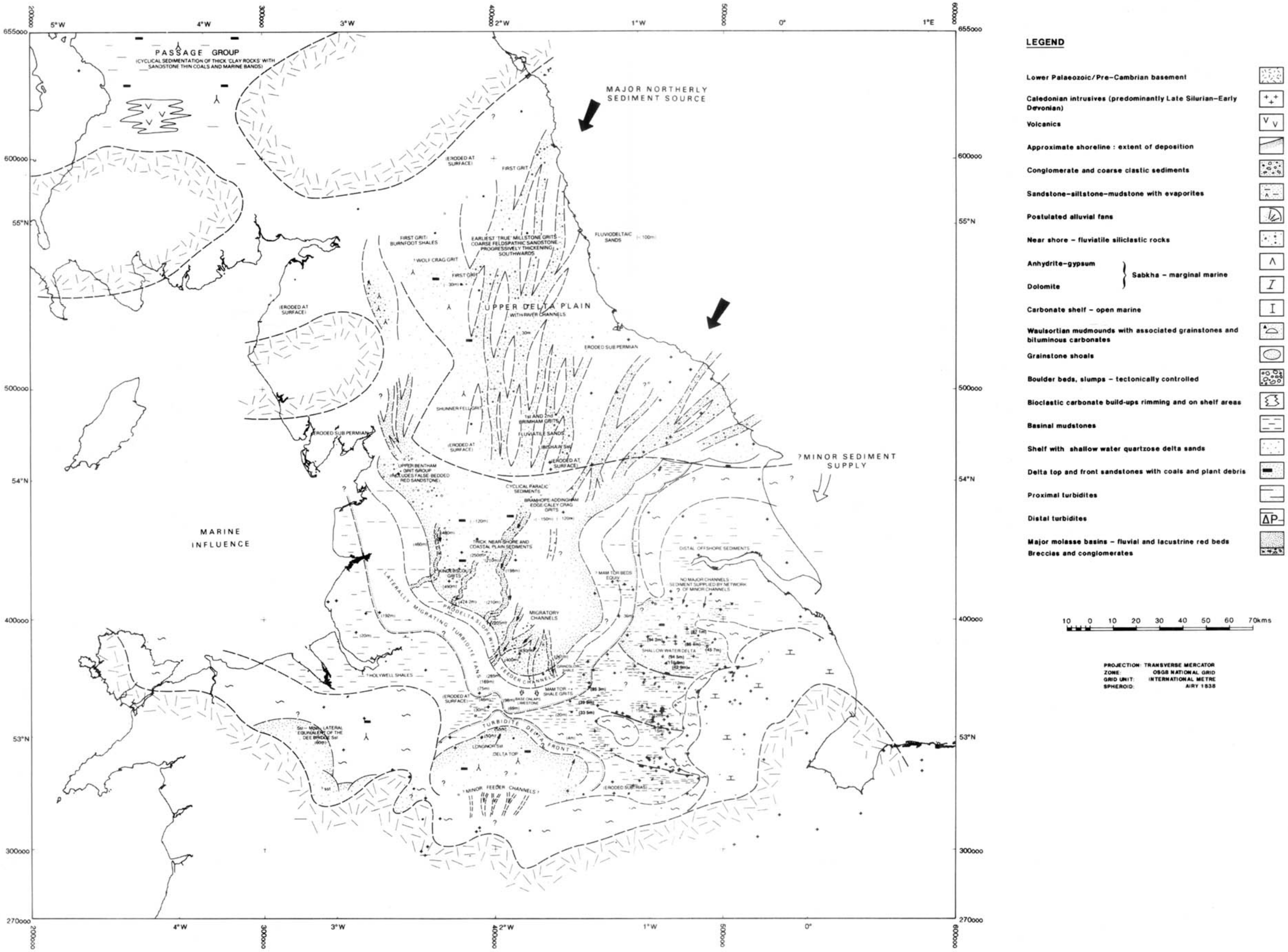


Fig. 37. Palaeofacies map for the middle part of post-rift sequence LC1c (mid–late Kinderscoutian).

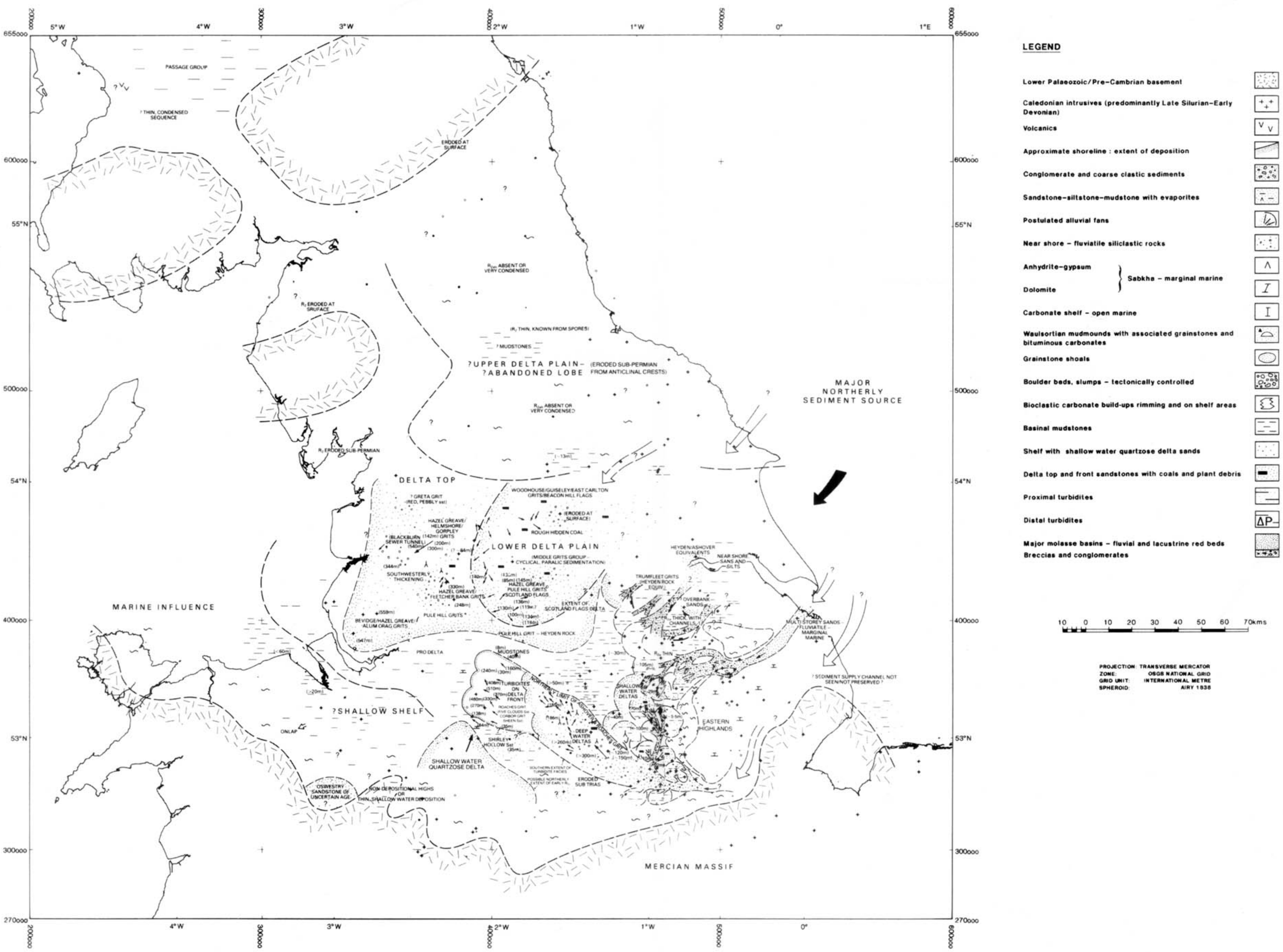


Fig. 38. Palaeofacies map for the late part of post-rift sequence LC1c (middle Marsdenian).

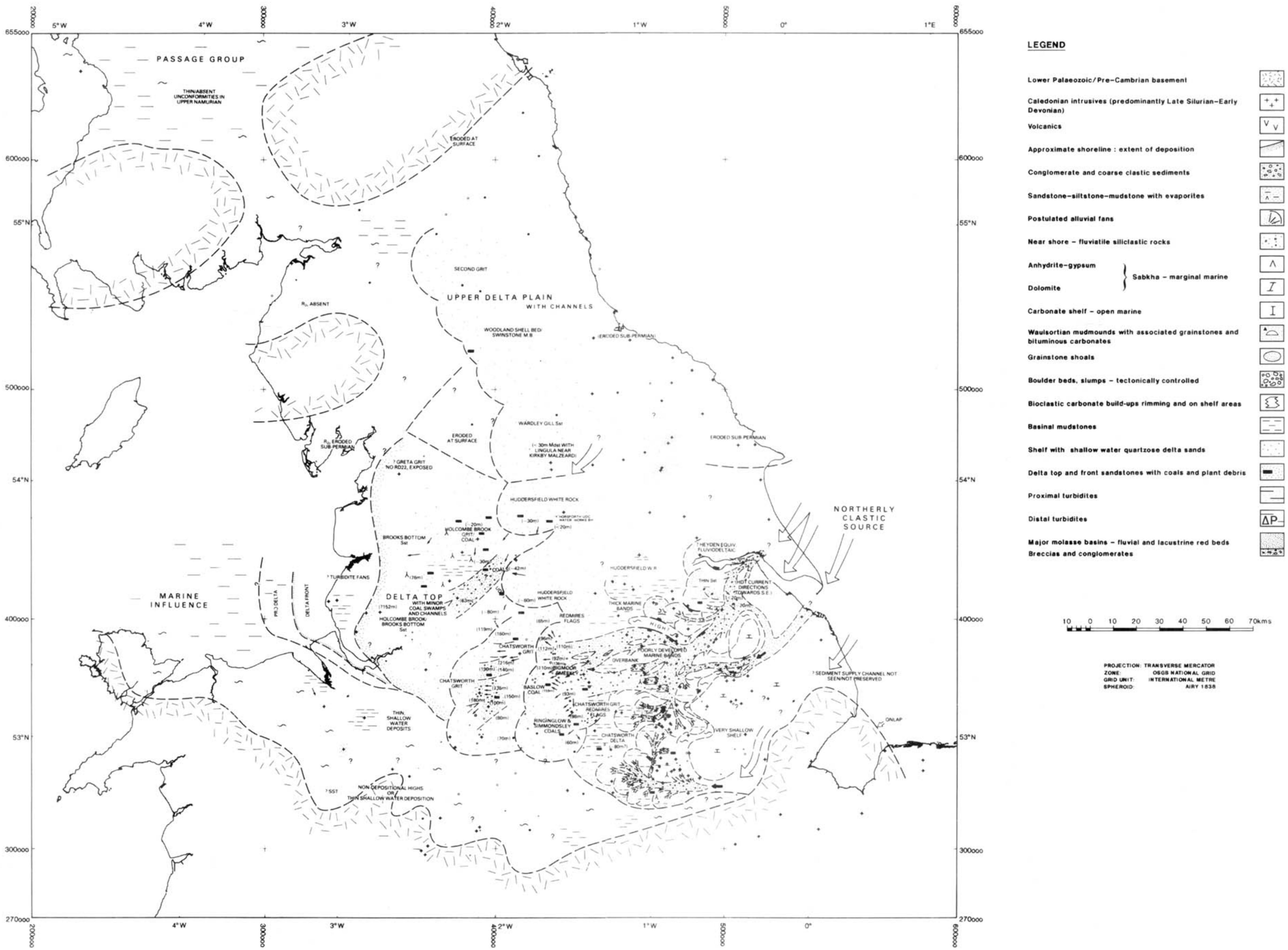


Fig. 39. Palaeofacies map for the late part of post-rift sequence LC1c (late Marsdenian).

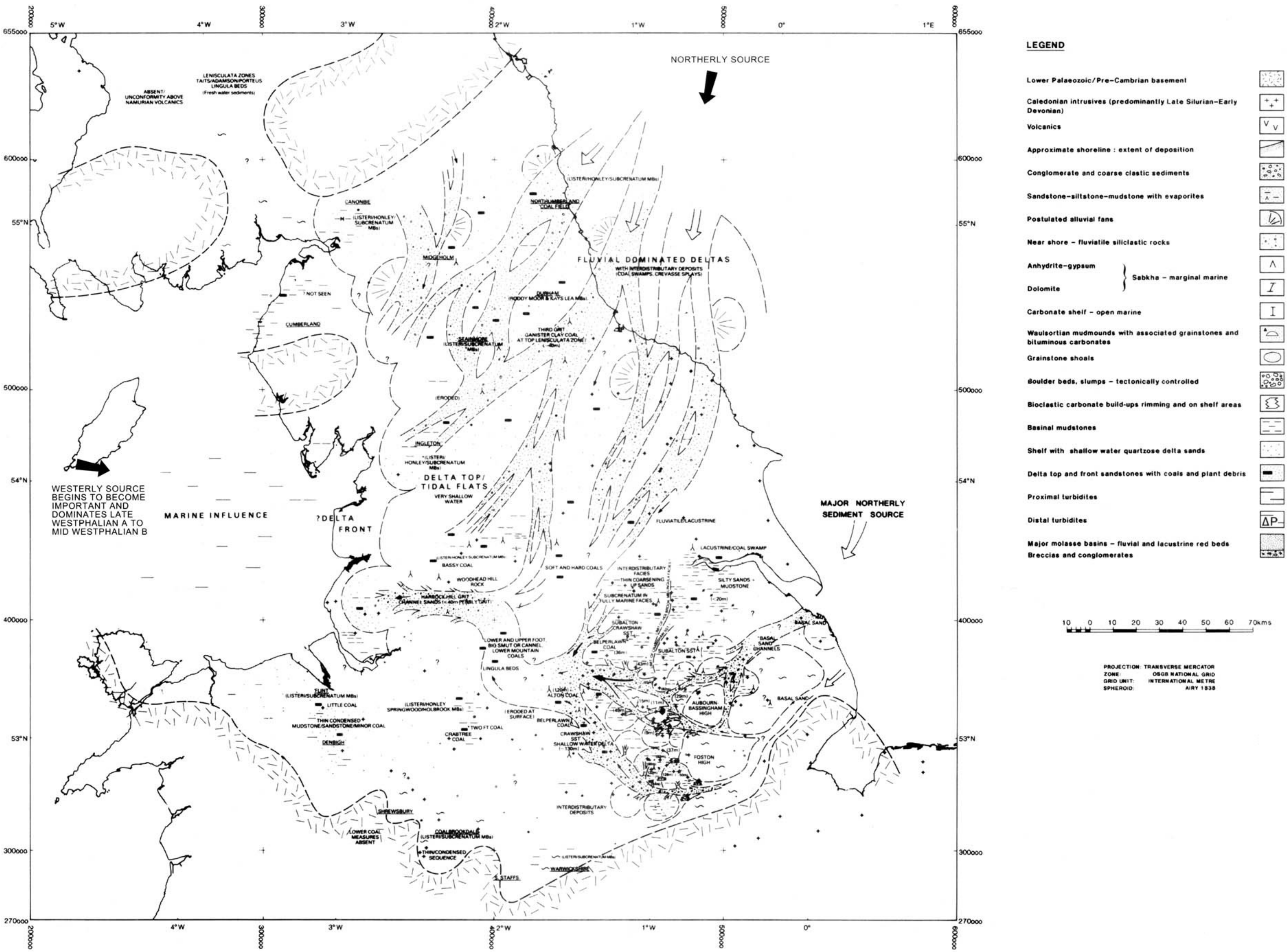


Fig. 40. Palaeofacies map for the late part of post-rift sequence LC1c (earliest Westphalian A).

By Westphalian A times, the Namurian deltas had established a low lying coastal plain over northern England (e.g. Guion & Fielding 1988). Sedimentary environments were dominated by swamps and brackish and fresh water lagoons where mudstones, siltstones and coals accumulated, and distributary and crevasse channels formed the main sandbodies. The 'Coal Measures' show a cyclicity with black and dark grey mudstones coarsening upwards into siltstones and sandstones generally with the development of a seatearth and coal at the top. The thin marine bands are important for correlation particularly in Westphalian A times. As with the late Dinantian and Namurian cyclicity, glacio-eustasy was a dominant control.

The Crawshaw shallow water delta dominated the East Midlands and Derbyshire during early Westphalian A times (Fig. 40). The Crawshaw channels flowed westwards across the East Midlands either reflecting differential compaction, controlled by underlying structures or constraints imposed by the Wales-Brabant Massif to the south forcing the rivers to drain into the remaining depocentre in the Irish Sea to the west (Guion & Fielding 1988).

The thickest depocentre for the entire Westphalian A is around the Goyt Trough to Rossendale High (central Pennine Basin). This appears to be the focus of all channel systems draining across northern England at this time. South of the Craven Fault system the facies is dominated by shallow-water, lower delta plain environments (Fig. 40). Northwards this grades into the upper delta plain. In the East Midlands, the Foston and Bassingham highs persisted, but these became swamped by later Westphalian sediments (Fig. 40).

Sequence LC2: post-rift (late Westphalian A–Westphalian C)

The depositional setting of the late Westphalian A, north of the Variscan Front, has generally been interpreted in terms of upper delta plain environments (Fielding 1984*a*, *b*, 1986; Fulton & Williams 1988; Guion & Fielding 1988; Read 1988; Kirk 1989). Important depositional elements include distributary channels and shallow fresh to brackish lakes that were filled by lacustrine deltas, crevasse splays and overbank deposits. The westerly source that became increasingly important in early Westphalian A times formed the dominant source area until mid Westphalian B (e.g. Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000). Depositional gradients were low and thus palaeocurrents in many cases represent local depositional conditions rather than regional palaeoslopes (Cope *et al.* 1992). However, in certain areas minor contemporaneous tectonic activity did influence the pattern of sedimentation. Fielding (1984*a*), Fielding & Johnson (1987), Guion & Fielding (1988) and Aitken *et al.* (1999) suggest that a number of faults, including the Ninety Fathom, Butterknowle and Morley-Campsall Faults influenced sedimentation. However, much of this fault activity may be due to differential compaction over earlier structures now at depth.

The amount of data available for the Westphalian is immense as a result of the extensive coal mining activity (e.g. Ramsbottom *et al.* 1978; Wills 1956; Guion & Fielding 1988). Thicknesses of up to 3 km are estimated for the Lancashire Coalfield. Local lithostratigraphic nomenclature for coals, sandstones and marine bands seriously hinders regional correlation. Distributary channels were of a highly migratory nature and splitting, pinching-out or washing-out of coal seams is common. These factors, together with high frequency cyclicity, render the construction of a single meaningful LC2 palaeogeography virtually impossible.

After the early Westphalian fluvial-dominated delta systems, typical Coal Measures facies were established across the whole of northern England. The intermittent marine bands are still of importance for correlation, but non-marine bivalves and fish beds become increasingly abundant with time reflecting the establishment of upper delta-plain environments. The area was dominated by coal swamps and meandering fluvial channels. Sedimentation was less controlled by the underlying structure, and the ancient basins such as the Widmerpool Gulf and Gainsborough Trough ceased to influence the location of major distributary channels. Abrupt changes in sandstone petrography occur in the Yorkshire Coalfield associated with the Westphalian B Woolley Edge Rock and are interpreted to reflect a change from westerly to southerly provenance (e.g. Hallsworth and Chisholm 2000). This major provenance change is also associated with up to 50 m of incision at the base of the Woolley Edge Rock in the East Midlands (Aitken *et al.* 1999) and is interpreted to reflect an intra-LC2 inversion event in northern England (e.g. southeast Gainsborough Trough; Fig. 16). However, the association of local inversion and the major change to a southern provenance suggests a clear link to tectonic events in the Variscan organic belt to the south. The southerly-derived sediment dominates the rest of the Westphalian (e.g. Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000).

As the Westphalian progressed conditions became increasingly non-marine, evolving into an internally drained basin. Red beds became more prominent in later Westphalian times, partly due to the orographic effects of the developing Variscan mountain belt to the south and to the northward drift of the British Isles (Besly 1988; Glover & Powell 1996).

Inversion megasequence

The inversion megasequence marks a major change in basin configuration, sediment source areas and depositional systems associated with extensive uplift of the former rift depocentres during Westphalian C to early Permian times. The onset of Carboniferous compressional tectonics, on a regional scale, was diachronous from south to north. Foreland basin development in the South Wales Coalfield started in the early Namurian (Gayer & Jones 1989), whereas compressional tectonics leading to basin inversion north of the Wales–London–Brabant Massif occurred much later during the Westphalian C.

The inversion megasequence is mainly associated with the accumulation of continental red bed molasse facies within growth synclines associated with inversion of the syn-rift normal faults (Figs. 41 and 42). In addition to sediment sourced from uplifting growth anticlines, sediment was derived from the evolving Variscan orogen to the south (e.g. Glover & Powell 1996; Hallsworth & Chisholm 2000; Hallsworth *et al.* 2000). As a consequence of basin inversion, post-Carboniferous rocks of various ages rest upon Carboniferous rocks across an angular unconformity (see Figs 12 and 20 from the East Midlands and Cleveland Basin).

Sequence V: inversion (late Westphalian C–early Permian)

During mid–late Westphalian C times, a major phase of basin inversion commenced to the north of the Mercian (London–Brabant) Massif, radically changing the sedimentary depocentres and facies patterns across northern England. Dinantian and Namurian basinal areas became inverted, creating highs that supplied sediment to local growth synclines (Fig. 42). The orientation of the syn-rift basin-bounding fault zones with respect to the NW to NNW direction of maximum shortening determined the severity of uplift (Corfield *et al.* 1996). As a consequence, NE–SW-trending rift basins were strongly inverted, resulting in erosion of much of the Silesian post-rift fill

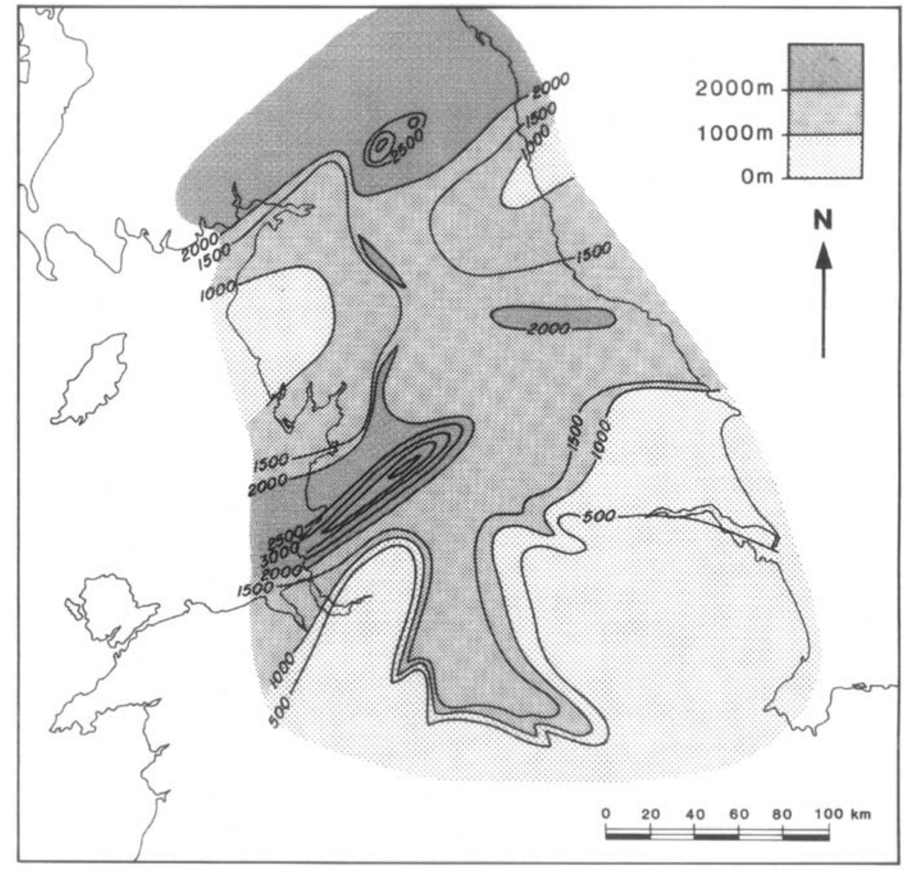


Fig. 41. Map showing estimated Variscan erosion compiled from a combination of regional seismic data and burial/uplift estimates from vitrinite reflectance, sonic velocities and apatite fission-track data (from Fraser & Gawthorpe 1990).

(e.g. Bowland Basins; Fig. 41). In contrast, the north–south- and NW–SE-trending rift basins (e.g. North Staffordshire Basin, Widmerpool Gulf/Gainsborough Trough) were oriented more obliquely to the direction of maximum shortening and, as a consequence, display significant strike slip. In general, the north–south- and NW–SE-trending rift basins were less strongly inverted and the Silesian post-rift fill has been retained (Fig. 41).

The lack of preserved section associated with the inversion megasequence across much of northern England precludes detailed palaeogeographic analysis. However, reconstruction of inverted faults, coupled with uplift estimates and extrapolation of data from the West Midlands allows an overall palaeogeography for the inversion megasequence to be determined (Fig. 42). Data from the East and West Midlands suggest two phases of inversion; a mid-late Westphalian C phase, and a later, more major, Westphalian D-Stephanian phase (e.g. Wills 1956; Besly 1988; Fraser & Gawthorpe 1990; Corfield *et al.* 1996). However, condensed stratigraphy over the crests of inversion anticlines in north Staffordshire and the Gainsborough Trough suggests localized inversion pulses may have commenced much earlier in the Westphalian.

The complex stratigraphy of the inversion megasequence has been collectively referred to as the Westphalian C–D molasse (Corfield *et al.* 1996). Alternative terms commonly applied are the Barren Red Measures (Leeder & Hardman 1990) and Barren Red Beds (Besly *et al.* 1993). However, these names are inappropriate as the Westphalian C–D is neither wholly red nor barren (of coal). In central England, the Westphalian C–D molasse is composed of three distinct lithostratigraphic units; (i) Etruria Formation (late Westphalian C to early Westphalian D), (ii) Newcastle and Halesowen

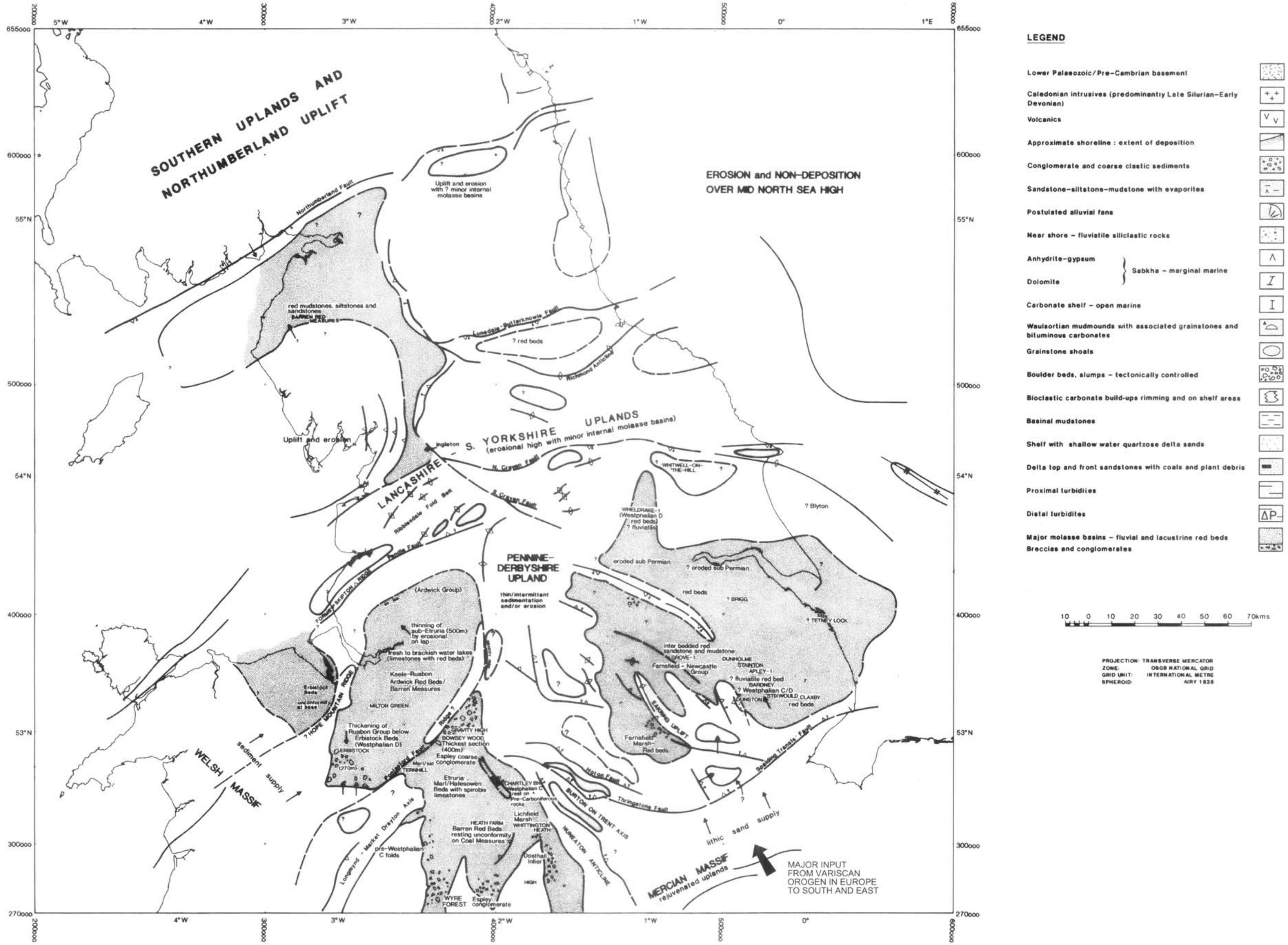


Fig. 42. Palaeofacies map for the early part of the Inversion meagasequence (late Westphalian C–Westphalian D).

Formations (early Westphalian D), and (iii) Keele and Enville Formations (late Westphalian D–early Stephanian).

The Etruria Formation (late Westphalian C to early Westphalian D) is interpreted by Besly (1988) as the product of intra-Westphalian tectonic uplift, and is locally unconformable upon gently folded coals of late Westphalian B age (e.g. the Symon unconformity in the Coalbrookdale Coalfield, central England). The Etruria Formation is composed of a range of facies including alluvial fan complexes and lateritic palaeosols (Besly 1988) that were developed around inversion anticlines. In central England, the Etruria Formation has a southerly derivation from contemporaneously uplifted parts of the London–Brabant Massif. In contrast, red beds of this age in northern England and Scotland are northerly derived, in common with the underlying coal-bearing Westphalian.

The Newcastle and Halesowen Formations (early Westphalian D) are locally unconformable upon older Westphalian sediments or, in the case of the Oxfordshire Coalfield, upon Devonian and older rocks. They reflect a temporary return to a humid coal-forming environment and are the time equivalents of the coal-bearing Middle Pennant Sandstone of South Wales. Provenance studies (e.g. Glover & Powell 1996) suggest a major input from the Cornubian-Amorican highlands. The southerly thickening of these sediments in the Oxfordshire Coalfield is interpreted to reflect the flexural subsidence of the southern margin of the London-Brabant Massif due to crustal loading. The Keele (late Westphalian D) and Enville Formations (late Westphalian D–early Stephanian) are southerly-derived clastics of red bed facies (Besly 1988, Foster *et al.* 1989). They are interpreted as the erosion products of Variscan nappes to the south of the British Isles and can be thus considered as a regional molasse (Besly *et al.* 1993), but also have local provenance sourced from unroofing of Lower Palaeozoic rocks (Glover & Powell 1996).

It is probable that the Westphalian D was originally more extensive and that a thick Stephanian succession was deposited in many of the growth synclines associated with inversion. Thermal modelling of the Ratcliffe-on-Soar-1 borehole in the Widmerpool Gulf suggests deposition and erosion of some 600 m of post-Westphalian B sediments prior to basal Permian sedimentation (Fraser 1995). However, the base Permian unconformity cuts across the late Carboniferous stratigraphy of northern England and much of the evidence for the deposition of these sediments has been removed

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Chapter 5

Play fairway analysis

Introduction

Integrated structural and sequence stratigraphic analysis, such as that described in this Memoir (specifically Chapters 3 and 4), represents a powerful tool for analysing a petroleum system by identifying hydrocarbon plays and constraining the regional distribution of the key elements of a play. A play is a combination of reservoir, source and seal facies which, together with a trap, may lead to hydrocarbon accumulations at a specific stratigraphic level. The geographic area over which a play is thought to extend is known as the play fairway and is usually determined by the depositional and erosional limits of the reservoir. This need not always be the case, however; play fairways based on the regional extent of a hydrocarbon source rock system or particular structural style are equally valid.

Play fairway analysis is essentially an assessment of exploration risk at a basin scale. In the past the petroleum industry has applied the concept of risk mainly at a prospect-specific level. On a larger scale, applying risk analysis to the play fairway level in frontier basins permits channelling of exploration effort into the most prospective parts of a basin. Furthermore, by combining the risks for individual plays within a basin, different basins can be ranked, allowing exploration to be focussed towards particular basins. In more mature areas, the technique can highlight new plays in under-explored parts of the basin or, equally, provide an indication that the basin has very little remaining prospectivity and that it may be time to withdraw.

Figure 43 illustrates an idealised model of the main potential Carboniferous plays recognised in northern England: (i) early syn-rift clastics, (ii) syn-rift carbonate platform margins and (iii) clastic delta systems. Many of the key elements of these plays, with the exception of early syn-rift continental clastics, can be seen at outcrop in the Castleton area of Derbyshire and are illustrated in the frontispiece. The photograph looks east along the Hope Valley and shows the exhumed southern margin of the Edale Gulf, with the Asbian- to Brigantian-aged carbonate platform margin forming the right (southern) hillslope. The platform margin grainstones and foreslope breccias had high initial porosity; much of this is now occluded but traces of bitumen are found. Direct evidence of the validity of the carbonate platform margin play is provided by a breached hydrocarbon accumulation exposed at Windy Knoll nearby. Here highly degraded hydrocarbons infill primary, secondary and fracture porosity within late Dinantian shelf carbonates that were sealed by overlying Namurian pro-delta mudstones.

In the foreground of the photograph, forming the solid geology of the valley floor, are pro-delta, organic-rich Edale Shales. These are of early Namurian age and preceded the southward progradation of the main Kinderscoutian delta systems. Pro-delta marine mudstones are considered to be the source for the hydrocarbons for the Windy Knoll accumulation and, more generally, the oil fields in the East Midlands. The initial deep water turbiditic fill of the basin is poorly represented on the photograph, which was taken from Mam Tor. In the field, the Mam Tor exposure reveals a coarsening upward succession of progressively more proximal turbidites. This progressive infilling culminated in the progradation of the Kinderscout delta and establishment of fluvial channels of the Kinderscout Grit. Capping the hills in the distance are younger Marsdenian fluvial facies of the Chatsworth Grit, reflecting further phases of deltaic progradation. It is fluvial sandbodies like these that form the major

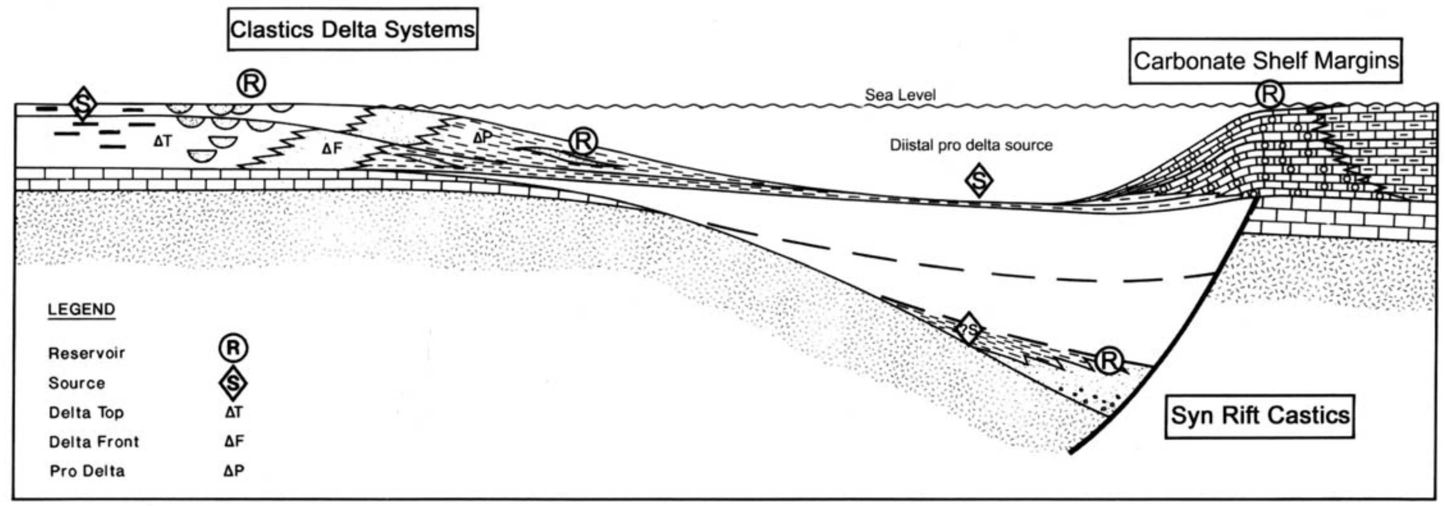


Fig. 43. Summary of potential plays in the Carboniferous of northern England (after Fraser *et al.* 1990; Fraser & Gawthorpe 1990).

proven reservoirs in the East Midlands oil fields.

In the offshore Southern North Sea Carboniferous gas province, one further play is present – molasse/red bed clastics of late Westphalian-Stephanian age (e.g. Besly *et al.* 1993; Corfield *et al.* 1996). As discussed in Chapter 4, alluvial reservoir sandstones that form this play were deposited primarily at the margins of growth synclines that developed during Variscan inversion (Fig. 42). However, the inversion megasequence is poorly preserved below the base Permian unconformity in northern England, thus the molasse/red bed clastic play is not considered further in this analysis.

Early syn-rift clastic play (Fig. 44)

Late Devonian–Courceyan syn-rift alluvial conglomerates and sandstones form a potential play in the rifted half grabens throughout northern England. Well data, for example Caldon Low (Institute of Geological Sciences 1978) and Hathern-1 (Falcon & Kent 1960, Llewellyn & Stabbins 1968, 1970) (Fig. 2), suggest that sandstones of this age could be sealed by overlying Courceyan evaporites associated with early marine transgression into the basins. The early rifts may contain lacustrine source rocks such as have been tentatively identified in Gun Hill-1 in the Goyt Trough (Lees & Tait 1945) (Fig. 2).

Critical factors that reduce the prospectivity of this play are reduction of reservoir quality and overmaturation of early syn-rift source rocks due to deep burial in the immediate hanging-wall of basin-bounding normal faults. The prospectivity of this play is much greater where early syn-rift reservoir facies are preserved in the footwall of major syn-rift border faults, thus minimizing burial depths. Studies of normal fault zone evolution suggest that migration of the locus of faulting is common in the development of rift basins, and several well-studied active and ancient rifts show pronounced basinward migration of active faulting with time (e.g. central Greece and Gulf of Suez; Gawthorpe & Leeder 2000). Thus it is possible for early syn-rift deposits to have been uplifted in the footwall of late syn-rift fault zones such as in the Widmerpool Gulf, where a wedge of early syn-rift clastics (EC1) is preserved in the footwall of the Hoton Fault (Fig. 45). In this situation, the early syn-rift clastics are in juxtaposition with early Namurian oil-prone basinal mudstones and an early syn-rift lacustrine source is not needed for the play to be successful. The most prospective areas for this play are interpreted to be the southern margin of the Widmerpool Gulf, the northern margin of the Gainsborough Trough and the margins of the Cleveland Basin.

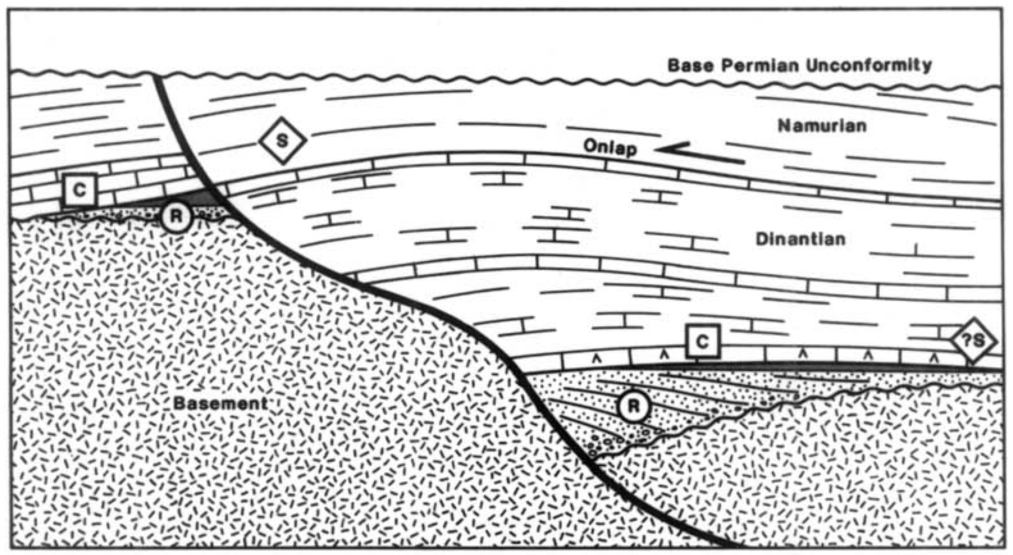
Syn-rift carbonate plays (Fig. 46)

Carbonate platform margin play

Outcrop studies of the Derbyshire Dome and the Bowland Basin suggest that Dinantian carbonate reservoirs are most likely to be found in the Chadian (EC2), Asbian (EC4) and Brigantian (EC6) sequences, when rimmed shelves were developed around the margins of the major half graben. Outcrop and subsurface data indicate that the carbonate platform margins are restricted to clastic-starved areas such as the Widmerpool Gulf, Goyt Trough, Edale Gulf, Gainsborough Trough and Bowland Basin (Fig. 46). The internal facies of the margins comprise bioclastic grainstone shoals, algal buildups, peri-platform talus, debris flows and turbidites — all potential reservoir facies. In addition, megabreccias were developed on the platform margins during the late Chadian to early Arundian (EC3) and late Asbian (EC5), associated with slope instability caused by tectonic activity (Gawthorpe 1987*a*).

The platform margins can be identified in the subsurface on seismic reflection data (e.g. Fig. 47). The margins are characterized by complex oblique-sigmoidal clinoforms that pass down-dip (basinward) through

SYN-RIFT SANDSTONES



RESERVOIR: Upper Devonian - Courceyan syn-rift fanglomerates and fluvial sandstones

SEAL: Courceyan evaporites and shales

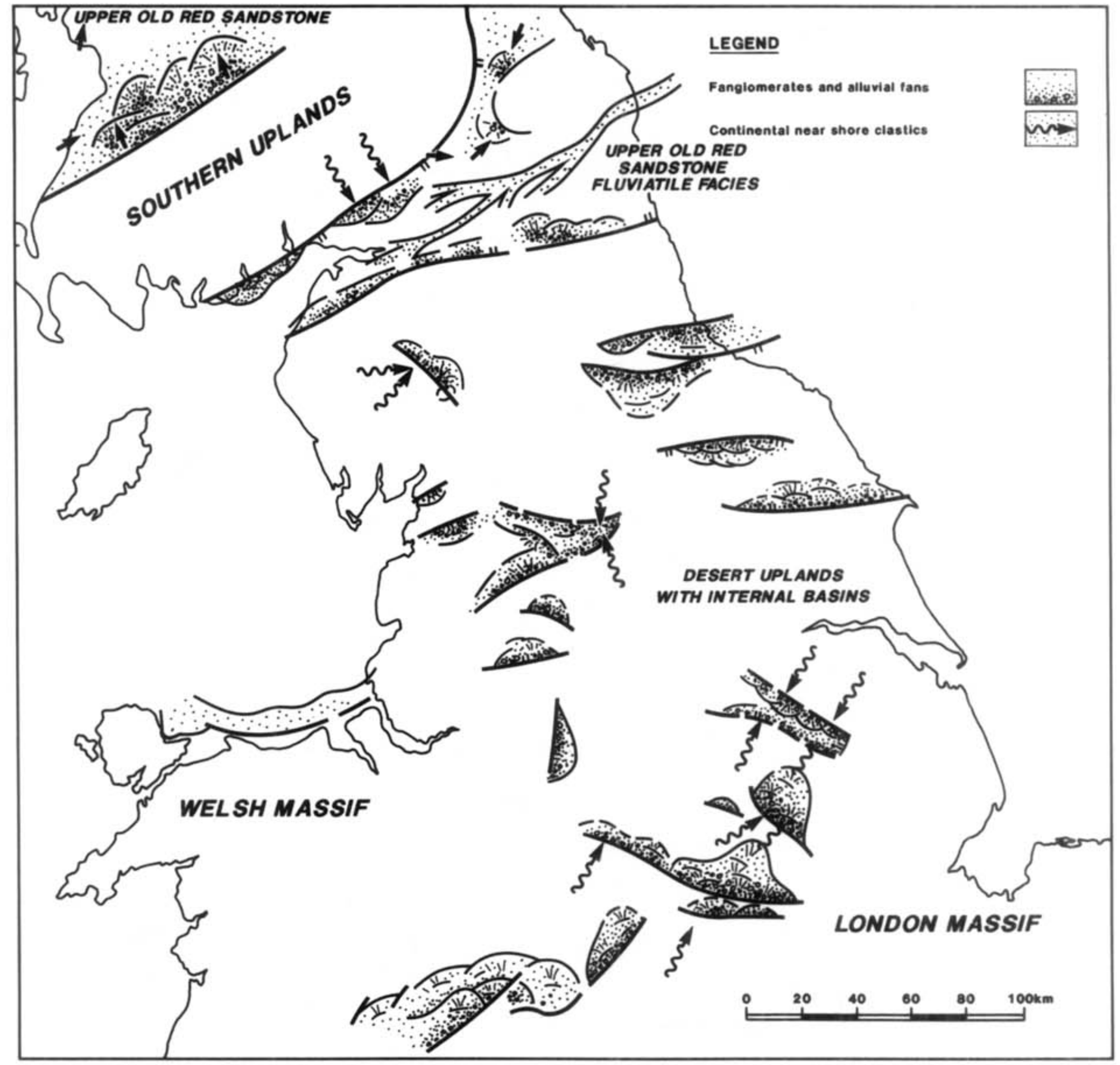
SOURCE: Early syn-rift (Courceyan) basinal shales - not proven
Cross fault juxtaposition with pro delta shales
Carboniferous and Mesozoic charge

CRITICAL FACTORS: (i) Excessive depth of reservoir burial in hanging wall
(ii) Limited distribution
(iii) Play relies heavily on unproven early syn-rift source

DISTRIBUTION: Immediate hanging wall of early syn-rift fault systems and along hanging wall dipslopes

STATUS: Unproven

STATISTICS: Number of valid tests - ?1 (Eakring 146)
Discoveries - None



Distribution of Upper Devonian - Courceyan (O.R.S. facies) Sands

S = Source

C = Seal

R = Reservoir

Fig. 44. Critical factors and distribution of the early syn-rift clastic play fairway.

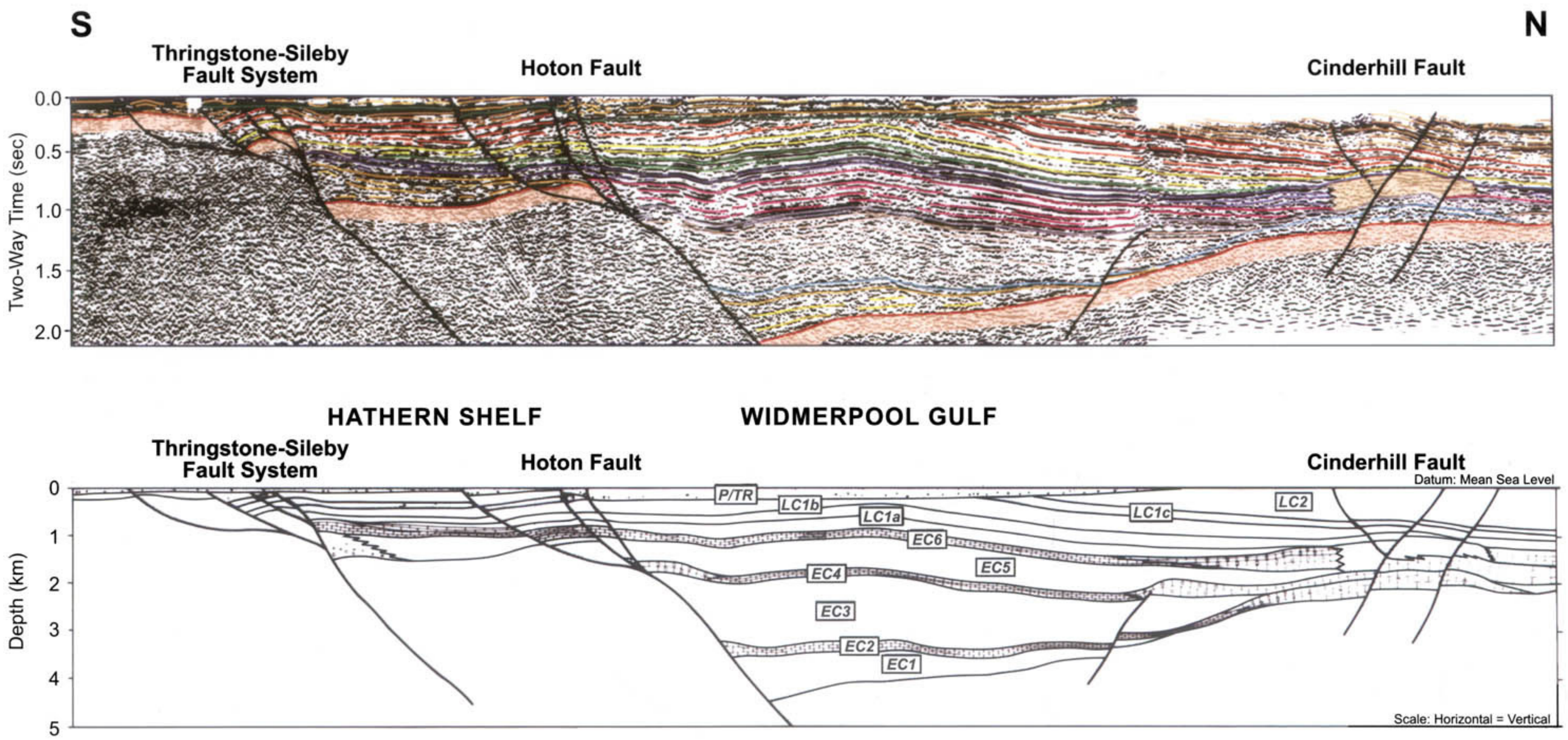


Fig. 45. Composite 2D seismic line and interpreted geological cross section across the Widmerpool Gulf illustrating preservation of early syn-rift clastics in the footwall of the Hoton Fault (after Fraser *et al.* 1990). These syn-rift clastics were deposited in the immediate hanging-wall of the Thringstone-Sileby Fault during earliest syn-rift times, but were subsequently preserved in a relatively shallow position, due to migration of fault activity onto the Hoton Fault.

hummocky clinoforms into a series of parallel reflections. By analogy with exposures in the Bowland Basin (Gawthorpe 1986), the hummocky and parallel reflections are interpreted to represent distal calciturbidite facies and interbedded basinal mudstones and distal turbidites. The spatial distribution of the carbonate platform margin play is limited to a 0.5–2 km wide fairway which rims the margins of the half graben (Figs 26–30 and 46). The narrowness of the play fairway highlights the need to identify the margins on seismic, since present well control is of insufficient density to map the location and extent of the platform margins in the subsurface.

Schofield & Adams (1985) and Gawthorpe (1987b) suggest that basinal mudstones acted as sources of fluids for burial dolomitisation and secondary porosity generation. Burial dolomitisation and leaching played a crucial role in controlling reservoir quality. Field and core petrographic studies indicate that, although primary porosity is occluded by early calcite cement, subsequent dolomitisation and leaching created secondary porosity prior to hydrocarbon generation (e.g. Walkden 1987; Gawthorpe 1987*b*). Onlapping late Brigantian to early Namurian pro-delta mudstones not only provide a source of fluids for dolomitisation and leaching, but are also the top seal and hydrocarbon source rock for the play. The success of this play also requires lateral seal. This may be provided by the facies change from the high energy platform margin reservoirs into low porosity and low permeability shelf wackestones and peritidal mudstones, or by faulting against basal Namurian or Holkerian mudstone facies.

The most prospective areas for this play occur where late Dinantian–early Namurian source rocks, matured during Mesozoic burial, directly onlap Dinantian platform margins (Fig. 46). The four main areas where the carbonate margin play is developed are as follows (Fig. 48).

Widmerpool Gulf (northern margin). Seismic and outcrop data have highlighted the presence of Asbian/Brigantian hanging-wall margins along the northern rim of the Widmerpool Gulf (Figs 12 and 47).

Gainsborough Trough (north and south margins). Seismic and well data have confirmed the presence of platform margins of Asbian and Brigantian age in both footwall and hanging-wall settings (Fig. 12).

Edale Gulf. Field and seismic data suggest the presence of well developed Asbian/Brigantian margins surrounding the Edale Gulf (Fig. 17). Maturation and migration of hydrocarbons into the margin are indicated by bitumen around Castleton (southern footwall margin).

Manx-Furness Basin (including Formby–Fylde). The presence of platform margins to the north and south of the western Bowland Basin (i.e. Manx–Furness) is inferred mainly from outcrop in the south of the Askrigg Block and boreholes such as Croxteth and Formby (Fig. 2). Residual hydrocarbons were encountered in BP Minerals boreholes in this facies on the northern margin of the Bowland Basin (Fraser & Gawthorpe 1990).

Secondary carbonate plays

In addition to the main carbonate margin play, there are a number of other plays within Dinantian carbonate depositional systems, the main ones being: (i) carbonate buildups, (ii) Chadian grainstone shoals and (iii) shelf carbonates.

Carbonate buildups. A wide range of Dinantian carbonate buildups occur in northern England, including Waulsortian buildups that range from isolated mounds a few tens of metres high, to complexes hundreds of metres high that cover several square kilometres. In general, the buildups are not reefal frameworks and the core facies of all the buildups are largely micritic with vuggy porosity and low permeability. However, the marginal facies are often coarse-grained bioclastic grainstones that may act as potential reservoirs. By analogy with well-exposed Waulsortian buildups of the Sacramento Mountains in New Mexico (e.g. Kirkby & Hunt 1996), complex internal facies architecture, controlled by a combination of sea-level change, bottom-water anoxia, bottom currents and sea-floor bathymetry, is likely to result in marked reservoir heterogeneity.

Waulsortian buildups of Chadian age (EC2) form the main play, with basinal mudstones of Arundian age providing the top seal and the trap being mainly stratigraphic. However, source rocks are a major problem given the lack of potential source rock development in the overlying Arundian strata (Fraser *et al.* 1990). Carbonate buildups are also developed in the Brigantian (EC6), for example the Coalhills complex exposed along the southern margin of the Derbyshire carbonate platform. Top seal to these Brigantian buildups is provided by overlying and onlapping late Brigantian to early Namurian organic-rich mudstones which are also the source. Because of the major source problem with Chadian Waulsortian buildups, the Brigantian buildups are thought to be the more prospective.

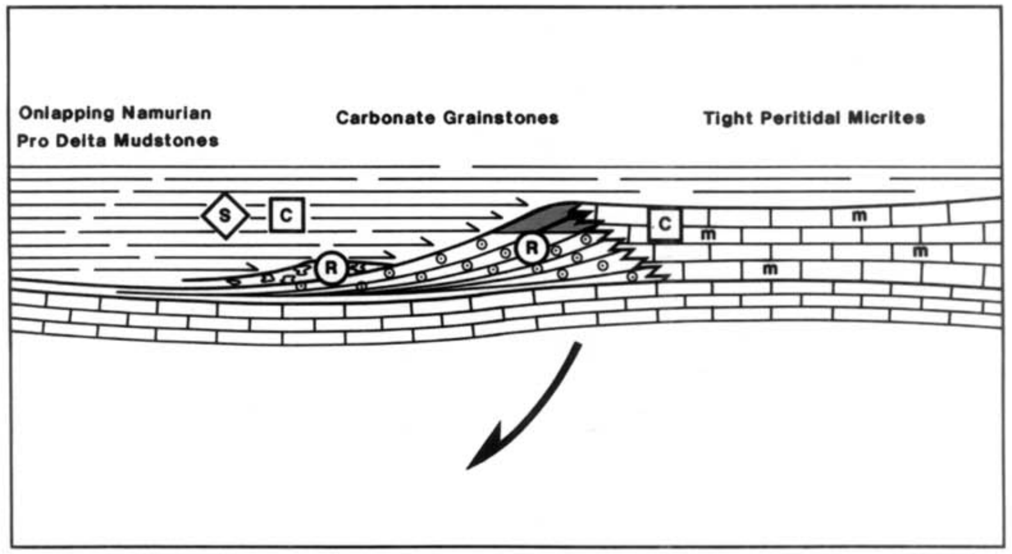
The carbonate buildup play is thought to be prospective in off-shelf locations in the Widmerpool Gulf, Hathern Shelf, Edale Gulf, Gainsborough Trough and Humber Basin, and mounded seismic facies originally drilled as reef prospects are now considered to be Dinantian carbonate buildups (e.g. Grove-1, Fig. 12). The majority of these areas have had access to oil generation during both Carboniferous and Mesozoic burial. Parts of the western Bowland Basin and Goyt Trough may still retain some exploration potential, but these areas rely solely on Carboniferous generation and underwent large amounts of uplift in both the late Carboniferous-early Permian and during the Tertiary.

Chadian grainstone shoals. Chadian grainstone shoals developed in proximal, above wavebase, portions of carbonate ramps. These facies can be observed at outcrop in the Bowland Basin south of the Askrigg Block and were proven to be oil bearing in Strelley-1 in the Widmerpool Gulf.

Commonly the grainstones are dolomitized and have good reservoir quality with moderate to high visible porosity. Onlapping Arundian basinal mudstones and lateral facies changes into low permeability peritidal carbonates should provide both top and lateral seal. Sourcing this intra-Dinantian play fairway is a problem; however, fault juxtaposition with the carbonate platform margin play fairway in Strelley-1 suggests a possible migration path from the basal Namurian pro-delta source rock (Fig. 12).

A major problem with the Chadian grainstone play is in predicting its distribution in the subsurface. Outcrop and well data suggest a very restricted fairway in terms of both its shoreline location and its apparent reliance on the

CARBONATE SHELF MARGINS



RESERVOIR: Chadian / Late Asbian / Early Brigantian grainstones

SEAL: Onlapping Late Dinantian and Namurian pro delta mudstones
Lateral facies change into tight micritic limestones

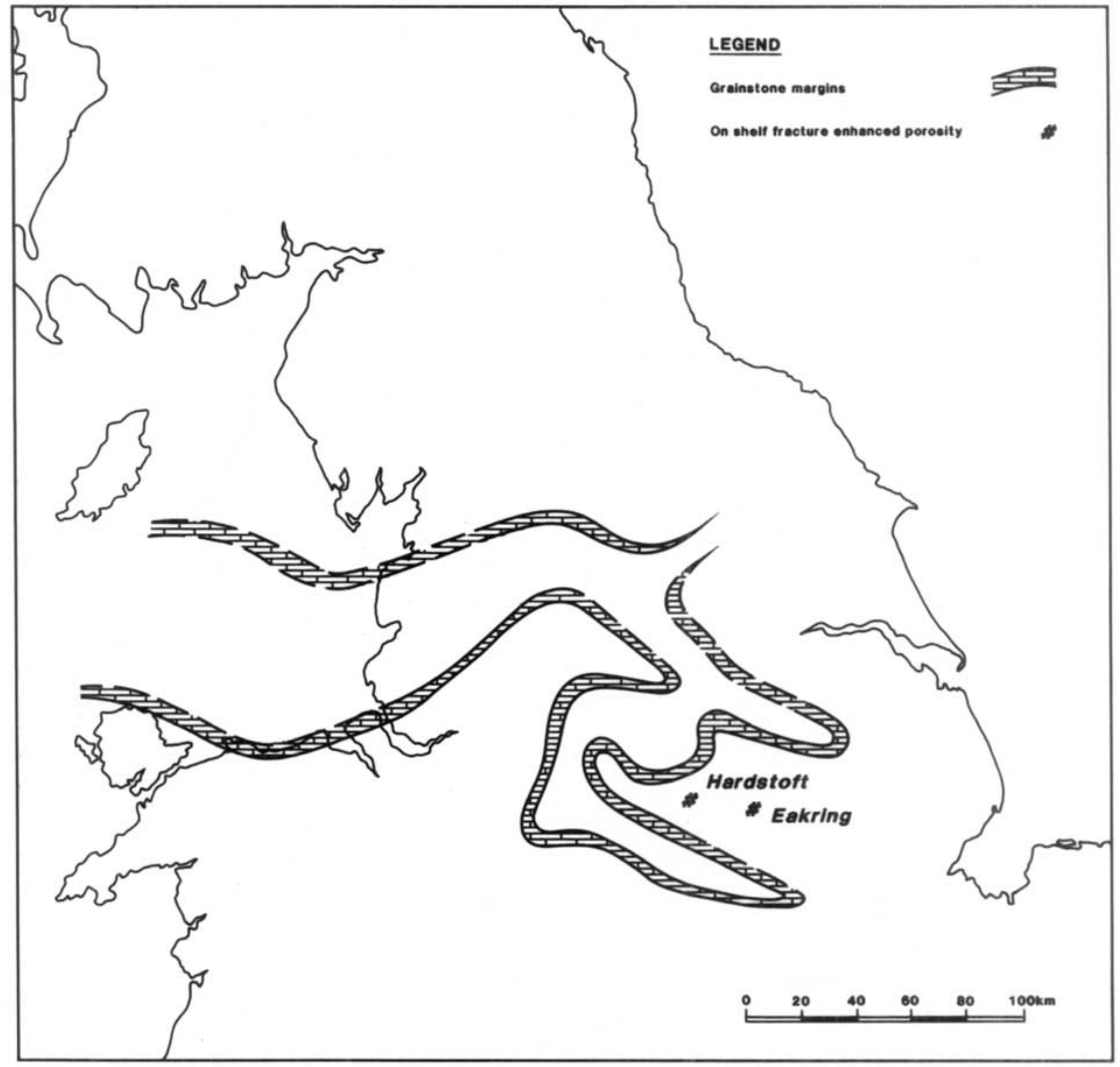
SOURCE: Interdigitating and onlapping Late Dinantian / Early Namurian mudstones (Bowland Shales and equivalent)

CRITICAL FACTORS: (i) Secondary porosity (dolomitisation) required
(ii) Lateral seal
(iii) Narrow belt, difficult to identify

DISTRIBUTION: Shelf margins of Bowland, Edale, Widmerpool and Gainsborough half grabens

STATUS: Unproven, although several wells have encountered hydrocarbon shows in proximity to shelf margin. Castleton blue john deposits thought to have been injected into hydrocarbon bearing shelf margin of this type.

STATISTICS: Number of valid tests - ?25 (most drilled in onshelf locations)
Discoveries - 2



Distribution of Dinantian Carbonate Shelf Margins

Fig. 46. Critical factors and distribution of the Dinantian carbonate platform margin play fairway.

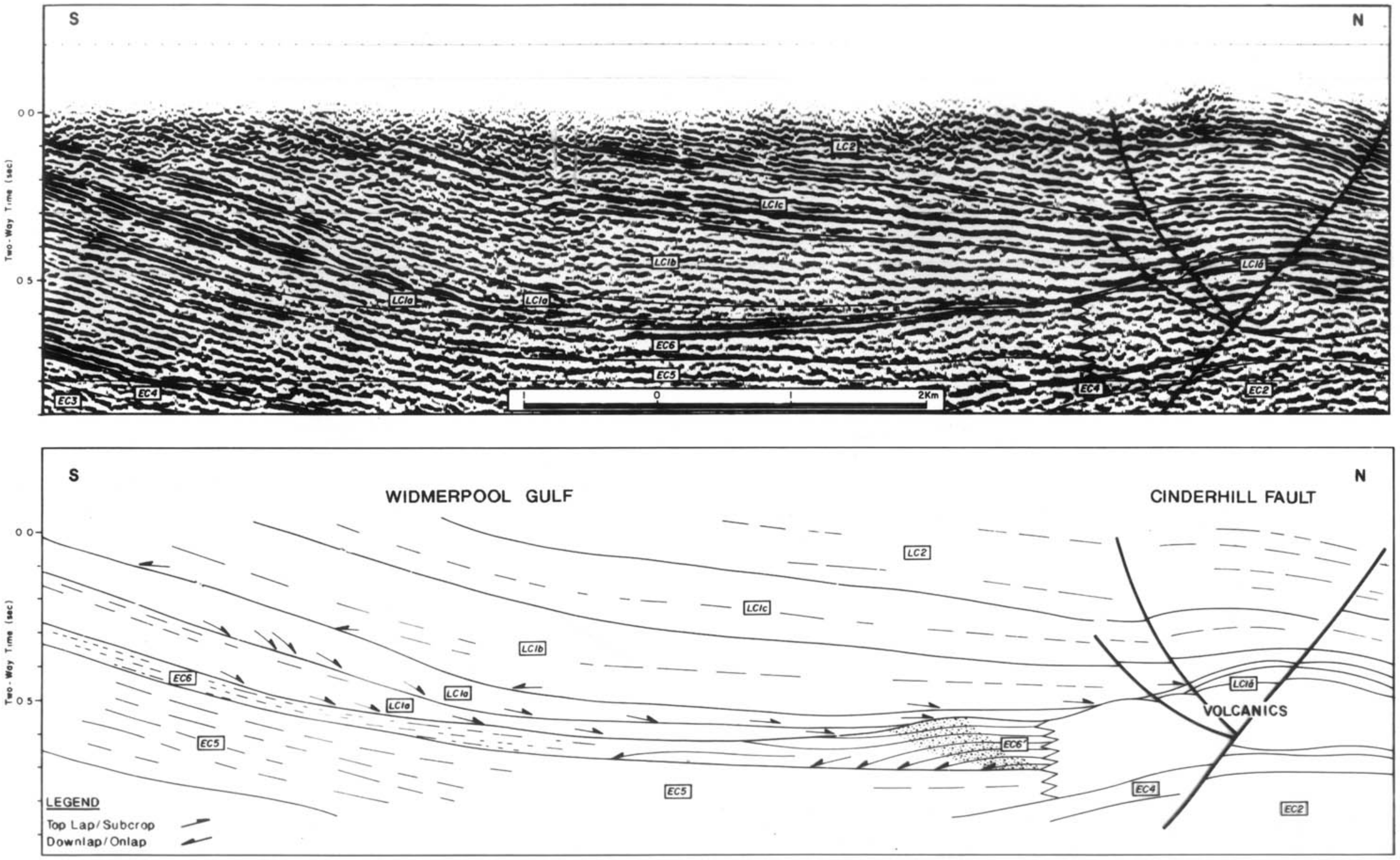


Fig. 47. Sequence architecture of the northern margin of the Widmerpool Gulf showing development of the EC6 hanging-wall dip-slope carbonate platform margin and associated clinoforms and reflector terminations. Note onlapping early LC1a succession, composed of pro-delta mudstone source rocks.

development of local highs (e.g. footwalls to intrabasin faults). The facies is not identifiable on seismic and strong emphasis would have to be placed on mapping facies-structural relationships around the basin margins. The fairway is likely to be most prospective in the Widmerpool Gulf and Gainsborough Trough.

Shelf carbonates. Shelf carbonates in the Dinantian preserve little primary porosity and only patchy secondary porosity is developed. In addition, the carbonate shelf areas are largely beyond the limits of hydrocarbon migration from basinal source kitchens and thus are unlikely to have received a hydrocarbon charge. Nevertheless, fractured shelf carbonates associated with Variscan folding have produced some 32 000 bbls (50 000 bbls reserves in place) of oil in Hardstoft in the East Midlands (Fig. 11; Table 2) indicating the potential for reservoir development in this play.

Clastic delta play (Fig. 49)

This play is by far the most important in the Carboniferous of northern England and contains the majority of the reserves discovered to date in the province (Table 2), with reservoirs developed in both delta-top/shallow marine and deep water turbidite facies (Fig. 49). In the southerly prograding delta systems, channel and mouth bar sandstones form the main producing reservoir facies, with channel sandbodies exhibiting the more favourable reservoir characteristics. Antecedent rift bathymetry exerted a significant control on the distribution of reservoir sandstones (e.g. Figs. 34 and 38), with delta-top and mouth bar reservoirs best developed where they axially infill remnant rift bathymetry (Fig. 50). Major lowstand incised valley fills form particularly thick, but often laterally restricted, fluvial reservoirs (e.g. the Rough Rock along the northern margin of the Widmerpool Gulf; Church & Gawthorpe 1994; Fig. 15). Turbidite sandstones sourced from the main delta systems to the north and the Wales–London–Brabant Massif in the south also form potential reservoirs in pro-delta settings (e.g. Longnor Sandstone; Fig. 37). In particular, basin floor turbidites associated with bypass across remnant steep half graben basin margins represent the most favourable turbidite targets. Outcrop examples of this type of bypass turbidite system include the Pendle Grit and equivalents in NW England (Fig. 33), the Mam Tor Sandstone and Shale Grit in the Edale Gulf (Fig. 37), and the Ashover/Roaches Grit equivalents in north Staffordshire (Fig. 38).

Additional important reservoirs are provided by southerly derived, quartzose fluvial sandbodies which form valleys incised into Dinantian carbonate platforms and abandoned delta plains during major lowstands. These are particularly well developed in the late Brigantian following the EC6 regional uplift and inversion event (e.g. Fig. 33). Oil-bearing sandstones of this age have been encountered in both Welton and Eakring/Dukes Wood (Figs 2, 12, 54 and 55), with flow rates of 570 bbls of oil per day from Welton-A4. However, problems exist in predicting the location of the palaeovalleys, and the location of the individual channels within them, because these sandbodies are generally below seismic resolution.

In addition to reservoir distribution, post-depositional modification of porosity and permeability (poroperm) during burial diagenesis is a major factor influencing reservoir quality. Based on over 1.5 km of core data from the East Midlands, relationships between log and core porosities, and porosities and permeabilities, permit the prediction of porosity in different facies to within one or two porosity units. For example, within Namurian fluvial channel sandstones the porosity cut-off for a commercially viable reservoir is estimated at 10%, corresponding to a permeability of *c.* 1 mD. This cut-off suggests that beyond a maximum depth of burial of 2550 ± 200 m reservoir quality is likely to be poor (Fig. 51). Therefore reservoir quality is likely to be significantly downgraded in the main depocentres in Cheshire and NW England/Irish Sea, and in the Cleveland Basin (Fig. 51) because of excessive burial.

Regional seal is provided by marine bands deposited during maximum flooding events. The marine bands have been shown to be adequate seals for oil accumulations, but are unreliable for gas (e.g. the Calow Field, Fraser *et al.* 1990). In the pro-delta environment, marine mudstones provide excellent seals for turbidite sandstone reservoirs.

The richest hydrocarbon source rocks identified are interpreted as distal pro-delta mudstones that were deposited in advance of the southerly prograding delta systems (Fig. 50). In the East Midlands the pro-delta source rocks are well developed in the basinal areas, but are poorly represented on the East Midlands Platform. The pro-delta source facies are predominantly oil prone. Biomarker studies and carbon isotope analyses clearly indicate a mixed marine/terrestrial derived kerogen (Fraser *et al.* 1990). Both the delta-top and turbidite reservoir systems prograded across and interfinger with the distal pro-delta source rocks forming hydrocarbon migration pathways. In addition, delta-top coal swamps developed regionally during the Westphalian (LC2) over northern England and the Southern North Sea. These provide gas and occasional oil prone source rocks which are likely to be in good communication with the delta-top channel and mouth bar reservoirs.

Assessment of reservoir distribution and quality, together with source rock distribution and the amount of Mesozoic burial, allows the main prospective areas for the clastic delta play to be identified (Fig. 52). In particular the East Midlands, with limited Mesozoic burial and good communication between source and reservoir is highlighted as the main oil-prone area for this play (Fraser *et al.* 1990; Fraser & Gawthorpe 1990).

Table 2. *Carboniferous oil and gas fields of northern England*

Field	Year	Province	Play Fairway	Sequence	Trap Age/Type	Oil (mmbbls)	Gas (bcf)	Total (mmboe)
Welton	1981	Gainsborough	Clastic delta/ Qtz channel	LC1c/LC2	Variscan inversion	27.00	0.00	27.00
Beckingham/ Gainsborough	1959	Gainsborough	Clastic delta	LC1c/LC2	Variscan inversion	13.20	6.50	14.36
West Firsby	1987	Gainsborough	Clastic delta	LC1c	Variscan inversion	7.00	0.00	7.00
Eakring	1939	E.M. Shelf	Carbonate/Clastic delta	EC6/LC1c/LC2	Variscan inversion	6.50	0.00	6.50
Glentworth	1961	Gainsborough	Clastic delta	LC2	Variscan inversion	4.10	0.00	4.10
Egmanton	1955	E.M. Shelf	Clastic delta	LC1c	Variscan inversion	3.50	0.00	3.50
Bothamsall	1958	E.M. Shelf	Clastic delta	LC1c	Variscan inversion	2.10	0.00	2.10
K. Misperton	1985	Cleveland Basin	Clastic delta	LC1b	Mesozoic extension	0.00	9.00	1.61
Scampton N.	1985	Gainsborough	Clastic delta	LC1c	Variscan inversion	1.80	0.00	1.80
Rempstone	1985	Widmerpool	Clastic delta	LC1b	Variscan inversion	1.15	0.70	1.27
Hatfield Moors	1981	Gainsborough	Clastic delta	LC2	Variscan inversion/ modified in Mesozoic	0.00	5.00	0.89
Long Clawson	1986	Widmerpool	Clastic delta	LC1c	Variscan inversion/ modified in Mesozoic	0.90	0.00	0.90
Corringham	1958	Gainsborough	Clastic delta	LC1c/LC2	Variscan inversion	0.70	0.00	0.70
Nettleham	1983	Gainsborough	Clastic delta	LC1c	Variscan inversion	0.60	0.00	0.60
Plungar	1953	Widmerpool	Clastic delta	LC1c	Variscan inversion	0.60	0.00	0.60
S. Leverton	1960	Gainsborough	Clastic delta	LC1c	Variscan inversion	0.60	0.00	0.60
Trumfleet	1957	Gainsborough	Clastic delta	LC1c	Variscan inversion/ modified in Mesozoic	0.00	2.70	0.48
Whisby	1985	E.M. Shelf	Clastic delta	LC1c	Variscan inversion/ stratigraphic	0.50	0.00	0.50
Crosby Warren	1986	Humberside	Clastic delta	LC1c	Variscan inversion	0.40	0.00	0.40
Kirklington	1985	E.M. Shelf	Clastic delta	LC1c	Variscan inversion	0.40	0.00	0.40
Caunton	1943	E.M. Shelf	Clastic delta	LC1c	Variscan inversion	0.30	0.00	0.30
Hatfield West	1983	Gainsborough	Clastic delta	LC1c	Variscan inversion/ modified in Mesozoic	0.00	1.30	0.23
Farley's Wood	1983	E.M. Shelf	Clastic delta	LC1c	Variscan inversion	0.20	0.00	0.20
Stainton	1984	Gainsborough	Clastic delta	LC1c	Variscan inversion	0.20	0.00	0.20
Malton	1970	Cleveland Basin	Clastic delta	LC1c	Variscan inversion	0.00	1.00	0.18
Cropwell Btlr	1984	Widmerpool	Clastic delta	LC1c	Variscan inversion	0.14	0.00	0.14
Kinoulton	1985	Widmerpool	Clastic delta	LC1c	Variscan inversion	0.13	0.00	0.13
Torksey	1962	Gainsborough	Clastic delta	LC1c	Variscan inversion	0.10	0.00	0.10
Calow	1956	Welbeck Low	Clastic delta	LC1c	Variscan inversion	0.00	0.50	0.09
Broughton	1984	Humberside	Clastic delta	LC2	Variscan inversion	0.08	0.00	0.08
Hardstoft	1919	Welbeck Low	Carbonate	EC6	Variscan inversion	0.05	0.00	0.05
Hemswell	1983	Gainsborough	Clastic delta	LC1c/LC2	Variscan inversion	0.05	0.00	0.05
Scampton	1985	Gainsborough	Clastic delta	LC1c	Variscan inversion	0.03	0.00	0.03
Nooks Farm	1982	Goyt Trough	Clastic delta	LC1c	Variscan inversion	0.00	0.37	0.07
Belvoir	1986	Widmerpool	Clastic delta	LC1c	Variscan inversion	0.02	0.00	0.02

Trap geometry

Focusing on the 36 or so oil and gas fields discovered in the Carboniferous of northern England, nearly all of which are part of the clastic delta play (Table 2), it is clear that Variscan deformation is a major factor in all the traps. Taking the East Midlands as an example, it can be seen that the oil and gas fields show a close relationship with the major fault trends (Fig. 11). Inspection of a depth converted regional seismic line across the province shows the major fields to lie in the hanging-walls of faults active during the Dinantian rift phase (Fig. 12). Sub-regional seismic lines with depth conversions are presented for several fields to illustrate the structural style associated with the trapping geometry. For the location of the individual fields refer to Figure 11.

Beckingham/Gainsborough (Fig. 53)
The Beckingham/Gainsborough Field was discovered by BP in 1959 in a faulted series of stacked reservoirs of Namurian and Westphalian age (sequences LC1c/LC2). Recoverable reserves from the field are assessed at 13 million barrels of oil, plus an additional 6.5 billion cubic feet of associated gas. The faulted anticlinal structure was formed by inversion on a series of early syn-rift faults lying at depth within the Gainsborough Trough. Closure is complicated by the presence of shallow, listric faults which apparently sole out within pro-delta early Namurian shales.

Welton (Fig. 54)
Discovered in 1981, Welton is, to date, the largest hydrocarbon accumulation in northern England. Reserves are now assessed at well over 20 million barrels. Production is mainly from delta-top channel sandstones within sequence LC1c (Rothwell & Quinn 1987). Seismic data show the field to be a Variscan inversion structure.

Eakring–Dukes Wood (Fig. 55)
The field occurs as a series of en echelon inversion anticlines adjacent to the NNW–SSE-trending Eakring-Foston Fault (Storey & Nash 1993). Recoverable reserves are assessed at 7 million barrels of oil, mainly reservoired in a stacked series of delta-top channel and mouth bar sandstones of Namurian–early Westphalian age (sequence LC1c).

Egmanton (Fig. 56)
The Egmanton Field is an inversion anticline formed on a NW–SE-trending fault to the south of the Gainsborough Trough. The field was discovered in 1955 and recoverable reserves are assessed at 3.5 million barrels. The main component of trap formation was again late Carboniferous (Variscan) inversion, as indicated by marked erosional truncation at the base Permian unconformity. However, the suggestion on seismic of subcropping Dinantian events at the base of the LC1 sequence may indicate a late Brigantian phase of inversion as well.

Calow (Fig. 57)
The Brimington anticline is perhaps the best example of a tight inversion fold

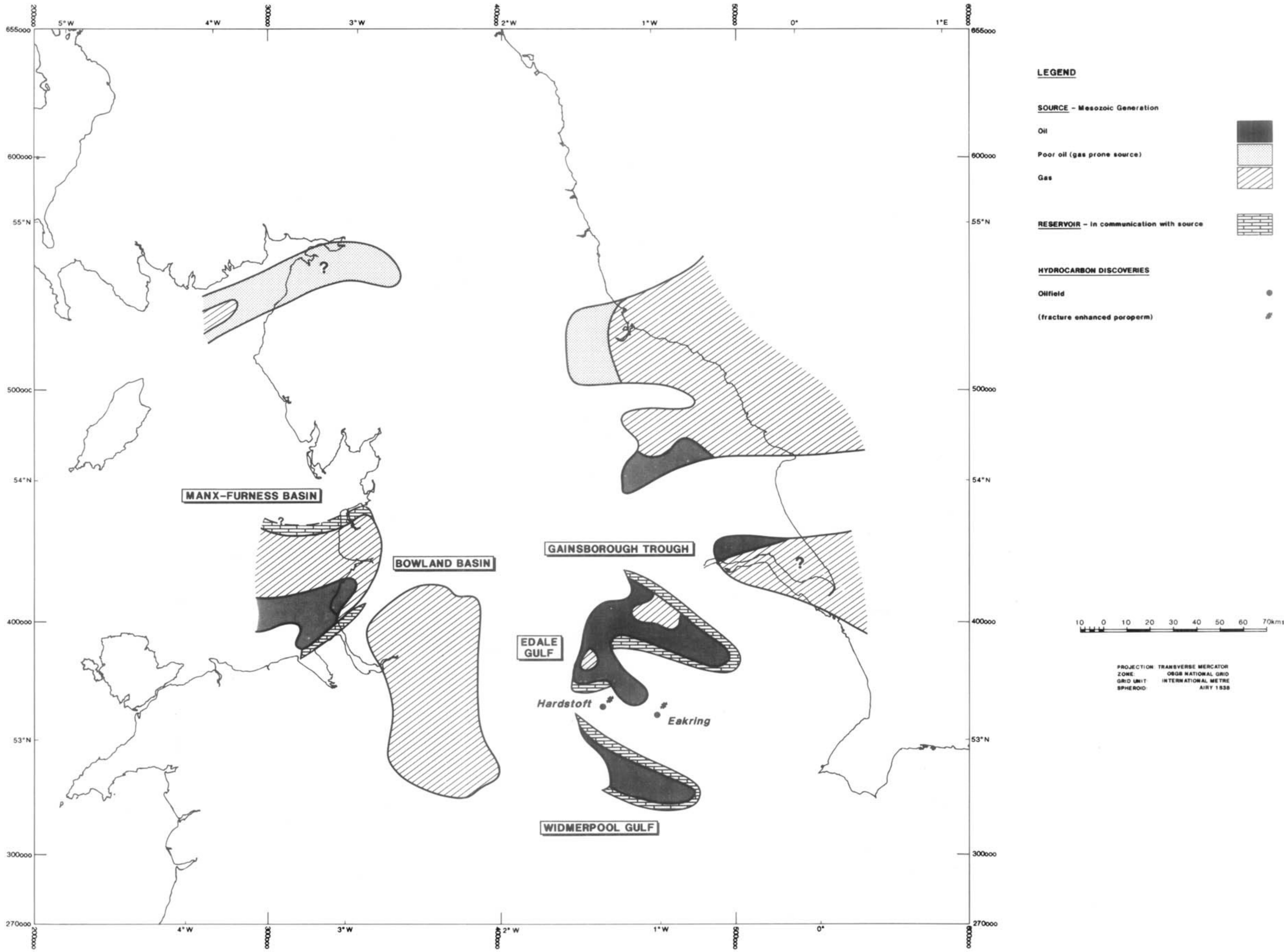
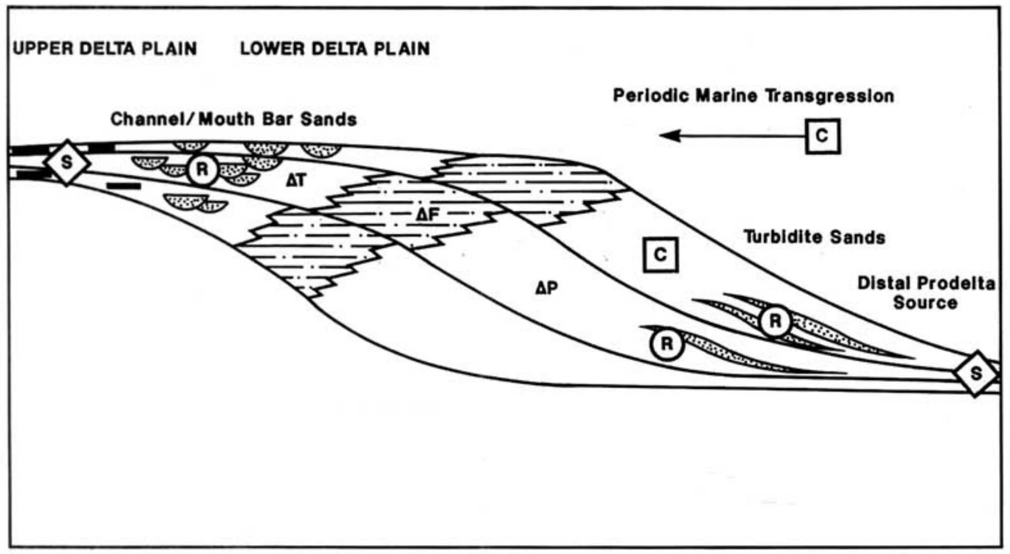


Fig. 48. Dinantian carbonate platform margin play assessment summary.

CLASTIC DELTA SYSTEMS



RESERVOIR: ΔT channel/mouth bar sands.
ΔP turbidite sands.

SEAL: ΔT marine bands - good; lacustrine/overbank muds - moderate/poor.
ΔP mudstones - good.

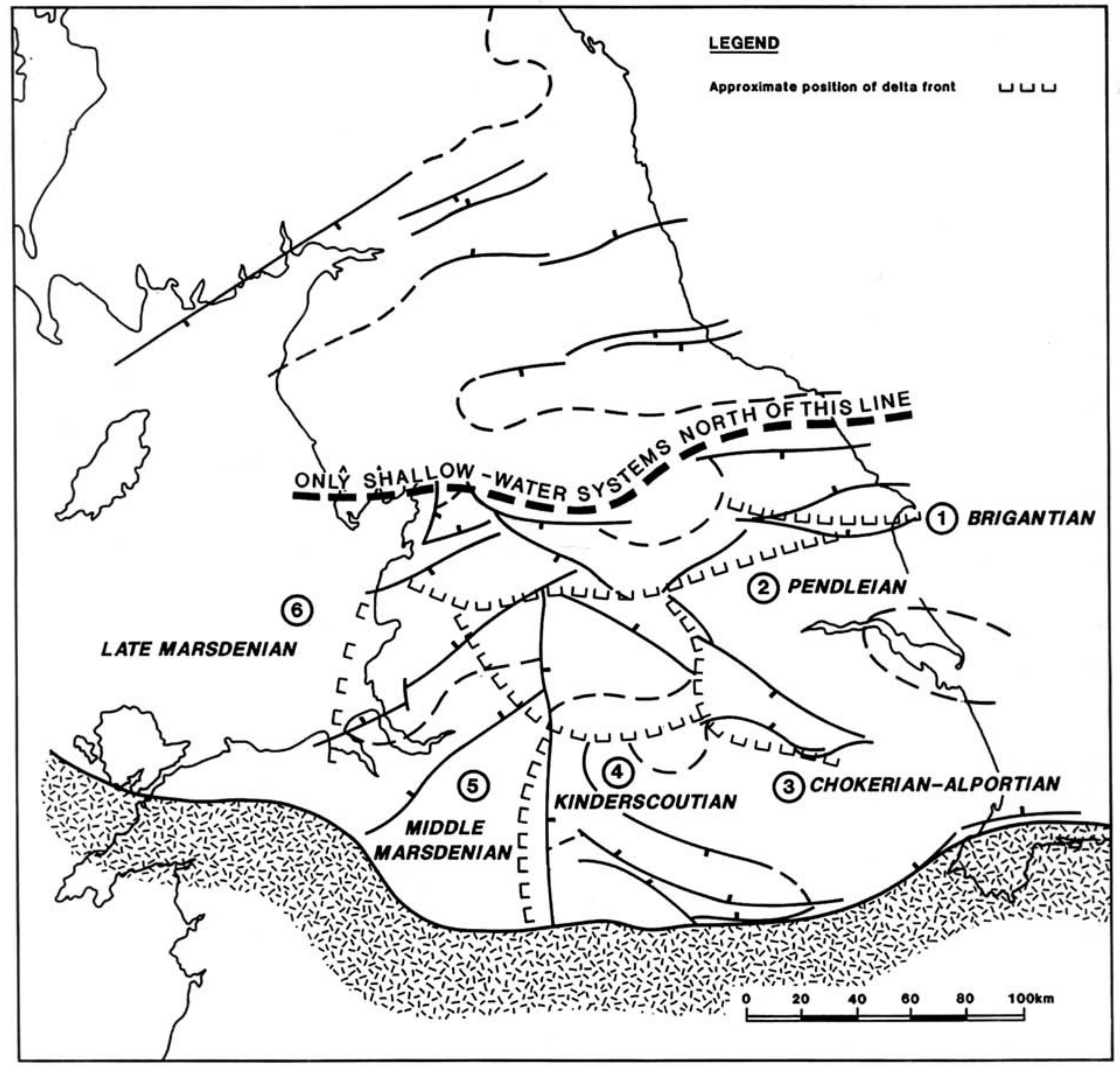
SOURCE: ΔT and ΔP reservoirs prograde over distal pro delta source rocks.
- Delta top coals.
- Late Carboniferous/Mesozoic charge.

CRITICAL FACTORS: (i) Reservoir quality downgraded beyond 2500m burial depths.
(ii) Dinantian pro delta source tends to be gas prone.
(iii) ΔT seals poor for trapping gas.

DISTRIBUTION: Persistent throughout Northern England Province.

STATUS: Namurian shallow water deltas form most prolific hydrocarbon play fairway in Northern England. Dinantian deep water deltas as yet unproven.

STATISTICS: Number of valid tests - 134. Discoveries - 39
Historical success rate - 1 in 3.5.
Overall recoverable reserves - 75 mmbbls. 27 bcf



Distribution of Dinantian - Namurian Delta Systems in Northern England

Fig. 49. Critical factors and distribution of the clastic delta system play fairway.

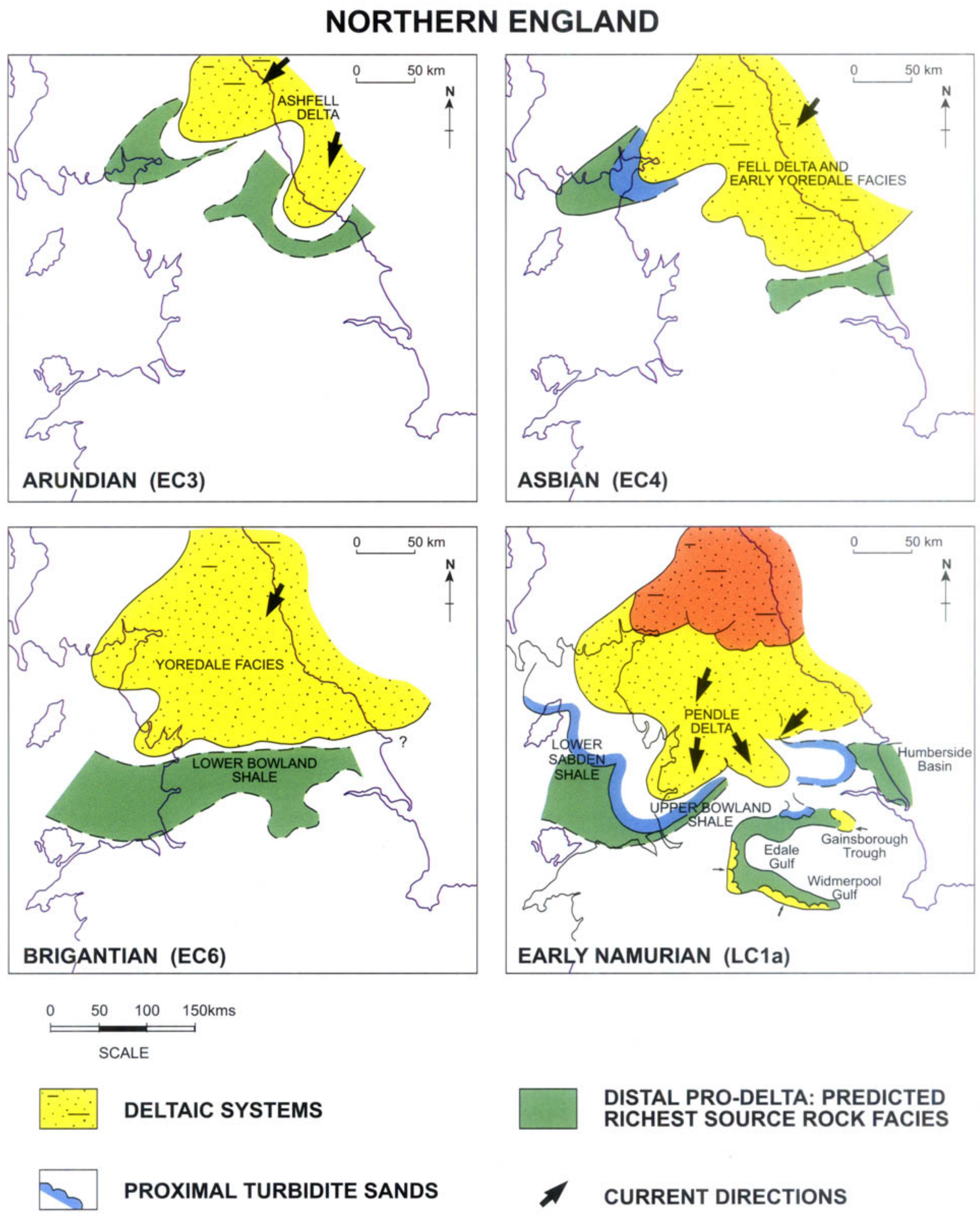


Fig. 50. Summary maps illustrating the advance of the major deltaic system during the Dinantian and early Namurian and the associated link to the age and distribution of pro-delta source rocks (after Fraser & Gawthorpe 1990).

in the East Midlands. The structure is that of a ramp anticline formed on a shallow detachment within the Dinantian. The Calow Field is a small gas accumulation (0.5 billion cubic feet) reservoired in channel and mouth bar sandstones in sequence LC1c.

Trap–hydrocarbon charge timing relationships

An understanding of the relationship between the timing of trap formation and hydrocarbon charge is critical to predicting the distribution of oil and gas accumulations in all hydrocarbon provinces. In the Carboniferous of northern England there are several key factors that controlled trap–charge timing relationships and these also affected the distribution and quality of the main reservoirs.

Post-rift Carboniferous factors

Two key factors critically affect the potential of the Carboniferous plays at this time.

Restricted distribution of basinal shales. Gross depositional facies maps demonstrate the volumetric importance of the early Namurian pro-delta mudstones as source rocks to an effective source kitchen. This generally limits the play fairway to within a few kilometres of the early Carboniferous depocentres. In the East Midlands the maximum horizontal migration distance from this source kitchen is 12 km; the average is 5 km.

Silesian depocentres: impact of pre-Variscan burial. Fraser *et al.* (1990) analysed maturity data from over 40 wells and suggested that the top and the base of the oil window would be 1900 m and 3600 m respectively, with maximum gas generation at 3400 ± 200 m. Thus the pro-delta mudstones located in the central Pennine Basin and the northwest England province were probably mature and producing hydrocarbons during the late Carboniferous (Fig. 32), thereby reducing their potential to generate oil following Variscan trap formation. Dinantian and Lower Namurian reservoir quality would also have been adversely affected at this time.

End Carboniferous Variscan inversion

Variscan inversion has been identified as the dominant trap-forming event in northern England (Fraser & Gawthorpe 1990). Variscan inversion also led to the 'freezing' of oil generation from source rocks throughout the province. The hydrocarbon system was essentially reset at this time, necessitating a second, Mesozoic, phase of burial and hydrocarbon generation post-dating the formation of Variscan traps. Areas where significant post-Carboniferous hydrocarbon generation occurred are highlighted in Figures 58 and 59.

Furthermore, the main clastic delta play was locally removed by end-Carboniferous erosion related to Variscan inversion (see Fig. 41). The areas where significant erosion of the main clastic delta play occurred include the Derbyshire Dome, parts of the Bowland Basin and extending along the Pennine–Dent line and the Cleveland Basin. In the Northumberland Trough removal of the clastic delta play is only partial.

Permo-Triassic extension

The presence of major Permo-Triassic basins on the western side of the Pennine High substantially downgraded the hydrocarbon potential of this area for two main reasons. Firstly, in the major Permo-Triassic depocentres (Cheshire Basin and parts of Manx–Furness), maximum burial cut-offs for both reservoir quality and oil generation were exceeded (Figs 51 and 58). Secondly, pervasive and repeated rifting throughout the Permo-Triassic fragmented earlier traps and reactivated trap-bounding faults. Examples of trap modifications at this time occur in the Formby–Fylde area (onshore Manx–Furness Basin) and in parts of the Cheshire Basin.

Gas generation commenced in the major depocentres towards the end of the

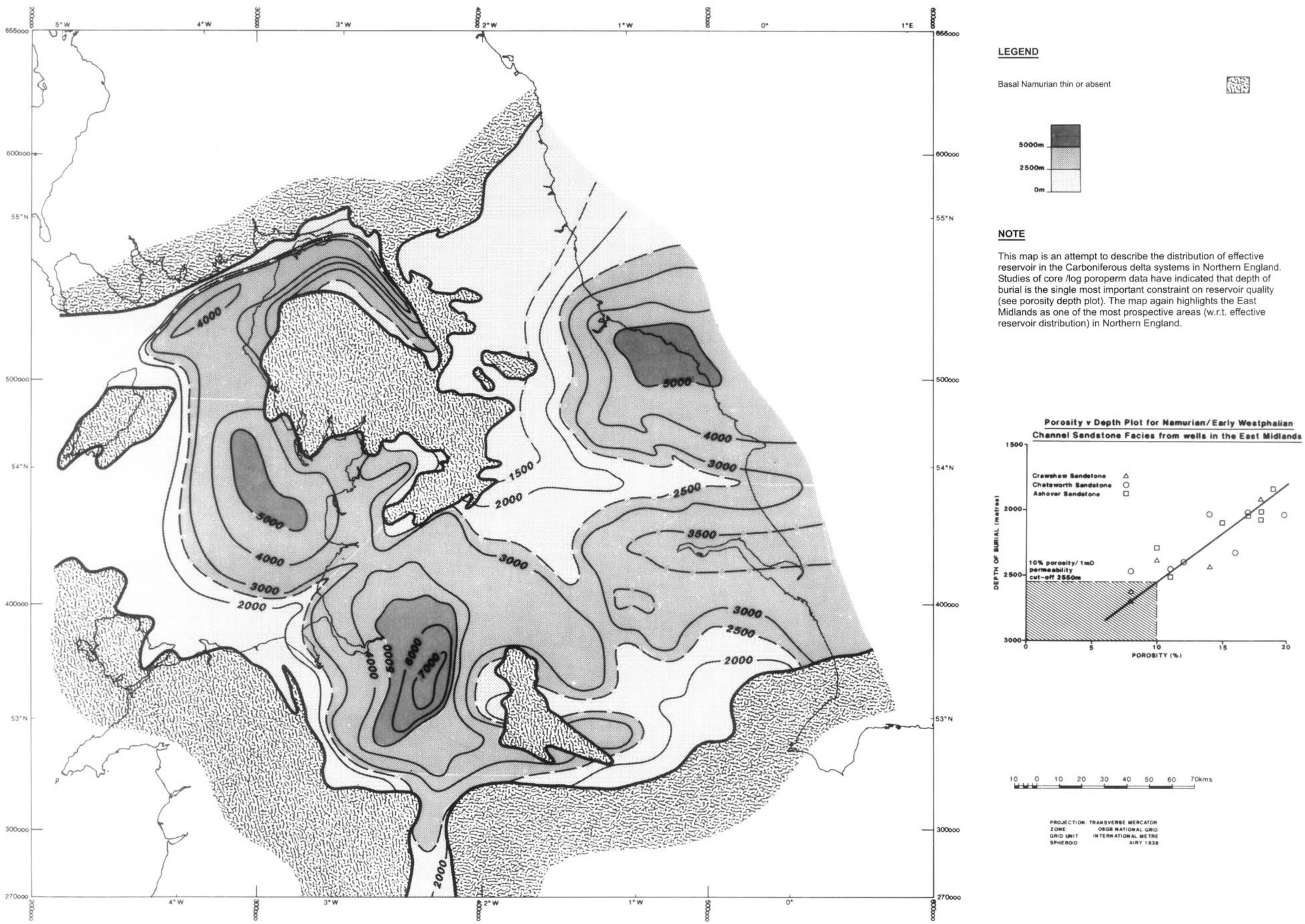


Fig. 51. Reservoir quality for the clastic delta play. Porosity depth relationships for Namurian and early Westphalian fluvial channel sandstone facies indicating 10% porosity/1 mD permability cut-off associated with a burial depth of 2550 m. Map shows reconstructed maximum palaeo-burial for basal Namurian.

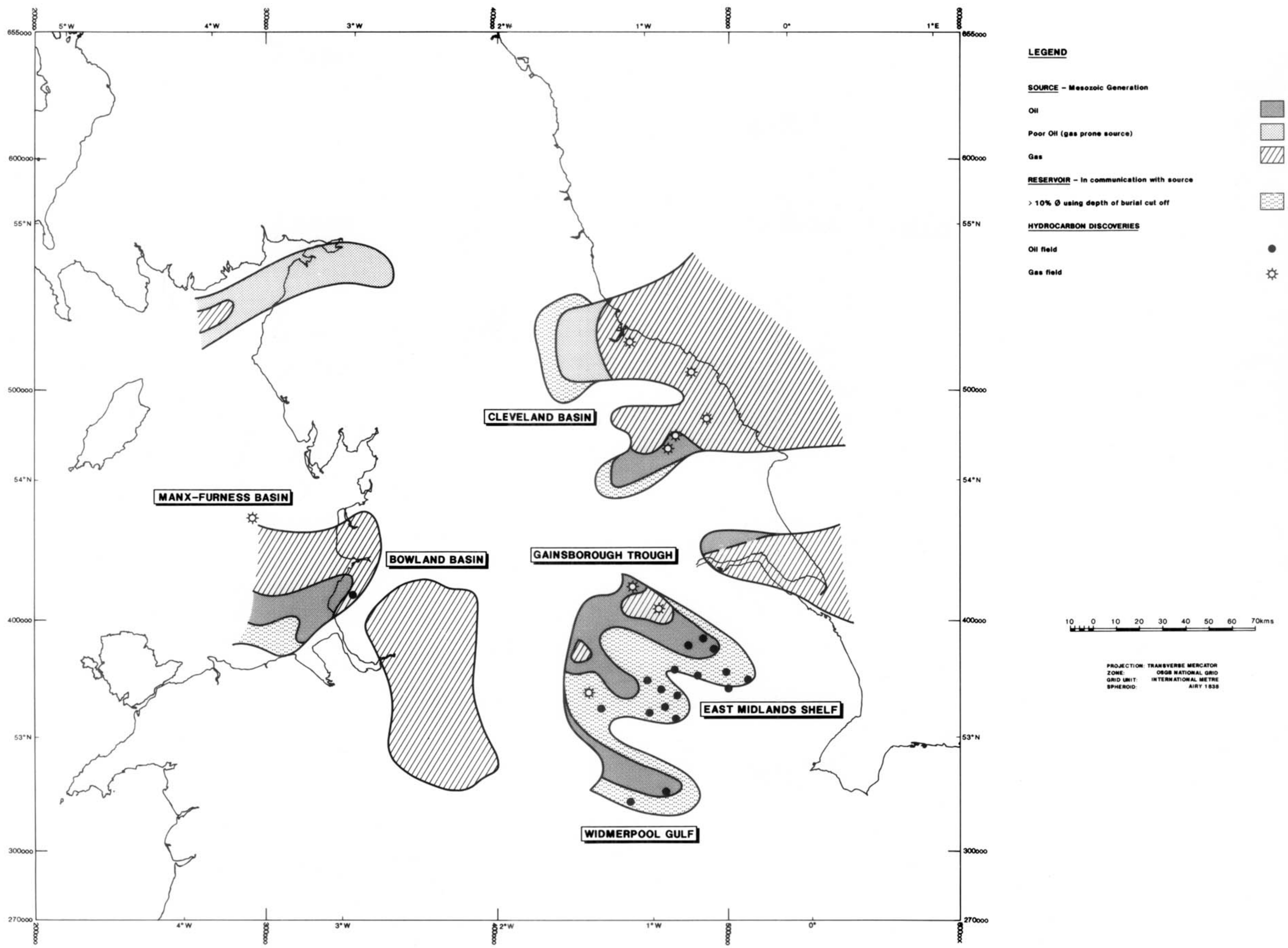


Fig. 52. Clastic delta system play assessment summary.

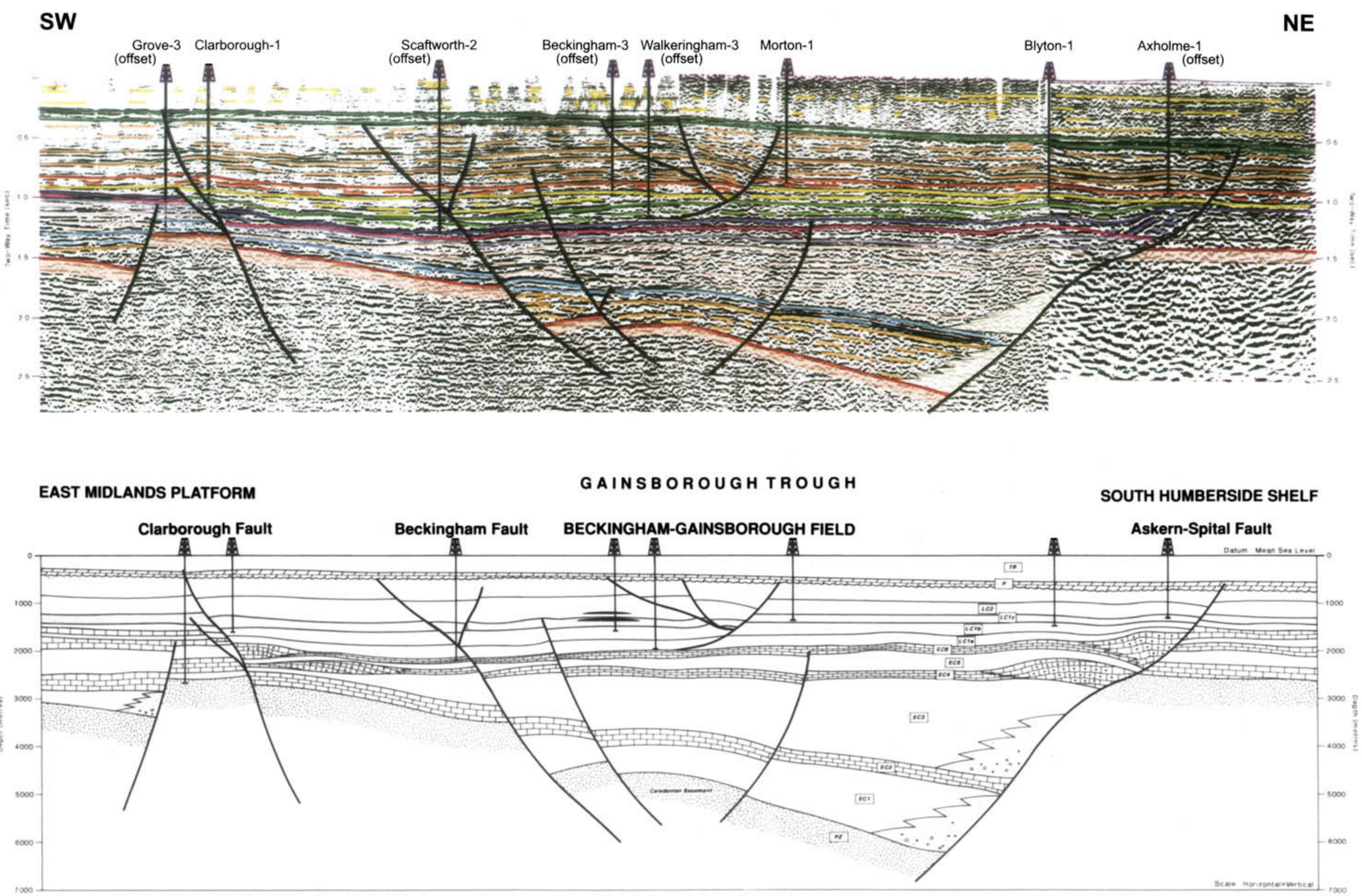


Fig. 53. Composite 2D seismic line and interpreted geological cross section across the Gainsborough Trough illustrating the location and geometry of the Beckingham/Gainsborough Field (see Fig. 11 for location).

Triassic, but trap modification and repeated faulting of marine band seals make prospects in basins lying in NW England unsuitable for gas retention. With continued gas generation, flushing of oil accumulations becomes an additional risk. In contrast, basins lying east of the Pennine High underwent gradual burial at this time, with renewed oil generation in the basinal areas and little trap modification.

Jurassic–Cretaceous subsidence and local inversion

The later Mesozoic history of northwest England is highly conjectural but it has been suggested from fission track analysis that some 1-1.5 km of Jurassic and Cretaceous sediments were deposited (Lewis *et al.* 1992). This continued burial left only minor onshore areas in the south of the Formby–Fylde area above the oil maximum for basal Namurian shales. Gas generation from Westphalian coals, where preserved following Variscan uplift and erosion, was widespread, particularly in the Cheshire Basin (Fig. 59).

Prior to early Jurassic times the Carboniferous basins in NE England and East Midlands (and their offshore extensions into the Southern North Sea) had undergone remarkably similar burial and thermal histories. Both areas had been strongly structured in late Variscan times, forming an array of anticlinal and fault-related traps, and had been subject to gentle regional subsidence during the Permo-Triassic. The contrast between basins in northeast England and the East Midlands commenced in early Jurassic times and continued into the Tertiary as the Cleveland and Stainmore basins became involved in rifting and inversion related to the Sole Pit fault system in the Southern North Sea (Glennie & Boegner 1981). This had essentially two effects. Traps were disrupted due to localized fault movements and successive phases of basin inversion during the late Cretaceous–Tertiary. In addition, localized deep burial, principally as a product of early Cretaceous rifting in northern Cleveland and the Southern North Sea (Fig. 58), took source rocks into the gas generation window (Fig. 59) with consequent flushing of liquid hydrocarbons from existing traps.

Cenozoic uplift and erosion

From the end of late Cretaceous chalk deposition onwards, the northern England basins experienced strong uplift and erosion, with a consequent 'freezing' of hydrocarbon generation. Offshore in the Southern North Sea, basins have experienced continued subsidence and hydrocarbon generation to the present day. A regional heating event which has elevated present day geothermal gradients in parts of northwest England and the East Midlands may have been associated with early Tertiary volcanism in the North Atlantic province. However, these elevated heat flows are unlikely to have significantly retriggered generation from source rocks in these areas, which were already in an advanced stage of maturity. Regional estimates of uplift and erosion range from 1100–3000 m in the northwest England to 1000–2000 m in the East Midlands, which imposed a regional easterly tilt to eastern England of 1–2^{o} (Fraser *et al.* 1990) (Fig. 60). The effects of uplift and tilting on existing accumulations are clearly demonstrated in many of the East Midlands fields, where palaeo oil–water contacts can be related back to pre-tilt closures.

Play assessment: summary

An assessment of the main Carboniferous plays in northern England is illustrated in Figures 61 and 62 (also see Figs 48 and 52). From the description of the hydrocarbon system described here, it is clear that the geological history of the East Midlands, compared to the rest of northern England, is most favourable for the development of an oil province. There are several critical factors that combine to achieve this.

(1) The East Midlands includes several isolated early Carboniferous rift basins containing thick basal Namurian source rocks, that became mature for oil generation in the Mesozoic, after Variscan trap formation.
(2) There is an abundance of reservoir–seal pairs providing reservoir–seal 'back-up' with burial depths over most of the area shallower than the critical threshold for an effective reservoir.
(3) The area was tectonically quiescent following Variscan trap formation with passive burial accompanied by a mild easterly tilting.

The presence of gas within the Carboniferous is likely to be more extensive, particularly in NE England and the offshore Southern North Sea (e.g. Leeder & Hardman 1990). However, gas potential may be hampered by poor reservoir quality and, particularly in NW England, by contemporaneous trap reactivation and the increased need for an effective sealing facies.

In most other areas in northern England, several factors have contributed to the lack of success in the Carboniferous play fairways.

- Excessive burial of Dinantian and Namurian sediments has resulted in loss of reservoir quality in both the syn-rift clastics and clastic delta play fairways below burial depths of 2500 m (e.g. Cheshire Basin).
- The carbonate platform margin play forms narrow zones around

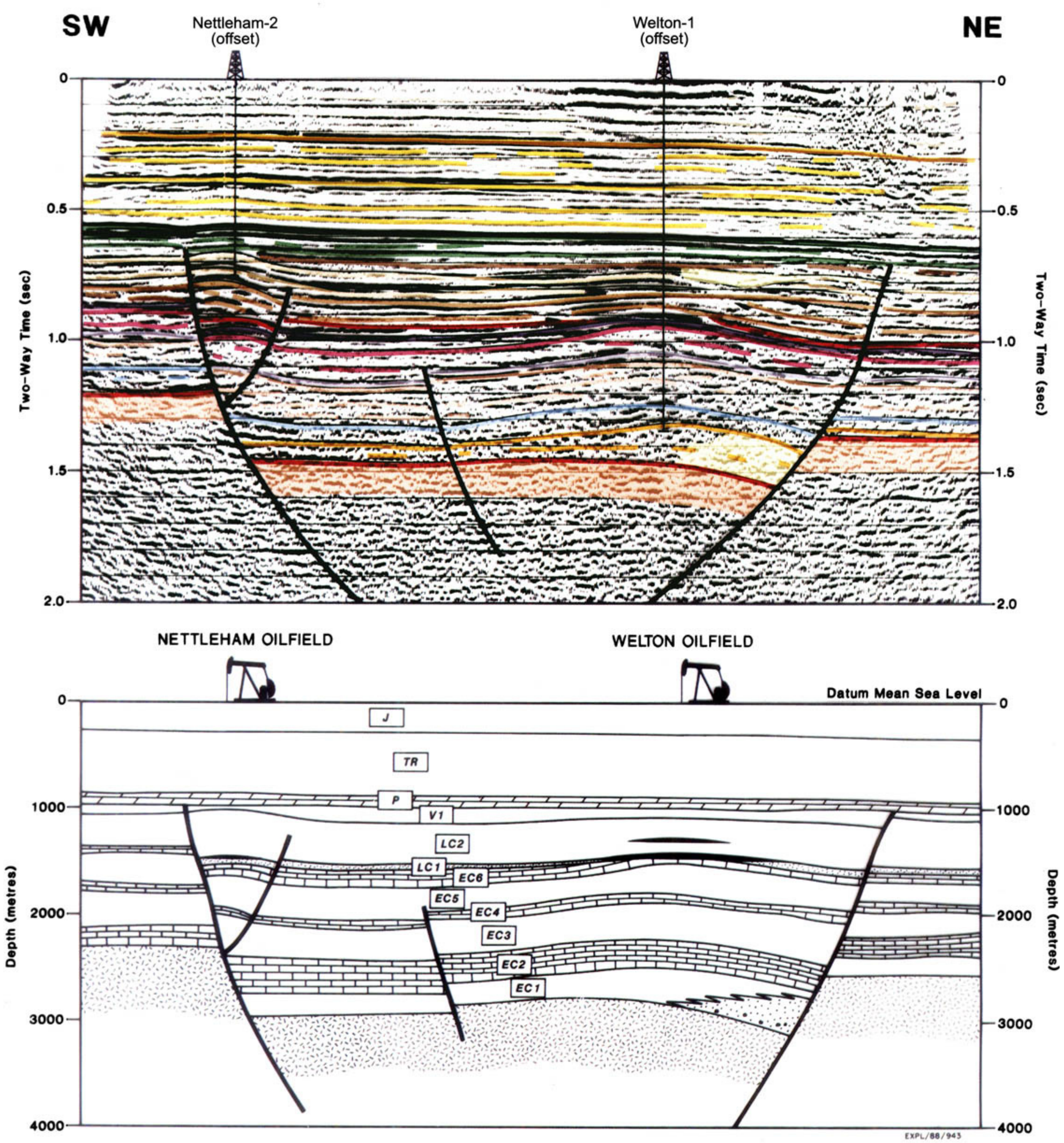


Fig. 54. Composite 2D seismic line and interpreted geological cross section across the Welton Field (see Fig. 11 for location).

basement highs, restricted to the southern half of the study area. In addition, the margins are difficult to image on regional 2D seismic data and their poroperm characteristics are unpredictable.

- Dinantian pro-delta mudstones, which dominate the northern part of the study area, are not as rich as their early Namurian equivalents and they also tend to be gas prone.
- The north of the study area (e.g. Northumberland and Bowland basins) suffered strong Variscan inversion and little Mesozoic burial.

Outside the East Midlands, the most prospective areas for the Carboniferous clastic delta play fairway are in the Solway, southern Manx–Furness and Cleveland basins (Figs 49 and 52). These areas are likely to have Dinantian–early Namurian pro-delta and Westphalian delta-top coal source rocks, with fluvio-deltaic reservoirs distributed throughout the Carboniferous succession. Traps formed during Carboniferous extension, Variscan inversion and Mesozoic extension structures may have been charged by late Mesozoic hydrocarbon generation. Perhaps the main barrier to success in the play is the excessive depth of burial of the reservoir in these basins. This is likely to result in poor reservoir quality, gas as the main hydrocarbon phase and hence reliance on intra-Carboniferous mudstone and basal Permian evaporite seals. The carbonate platform margin play still remains largely untested in the East Midlands and elsewhere in northern England.

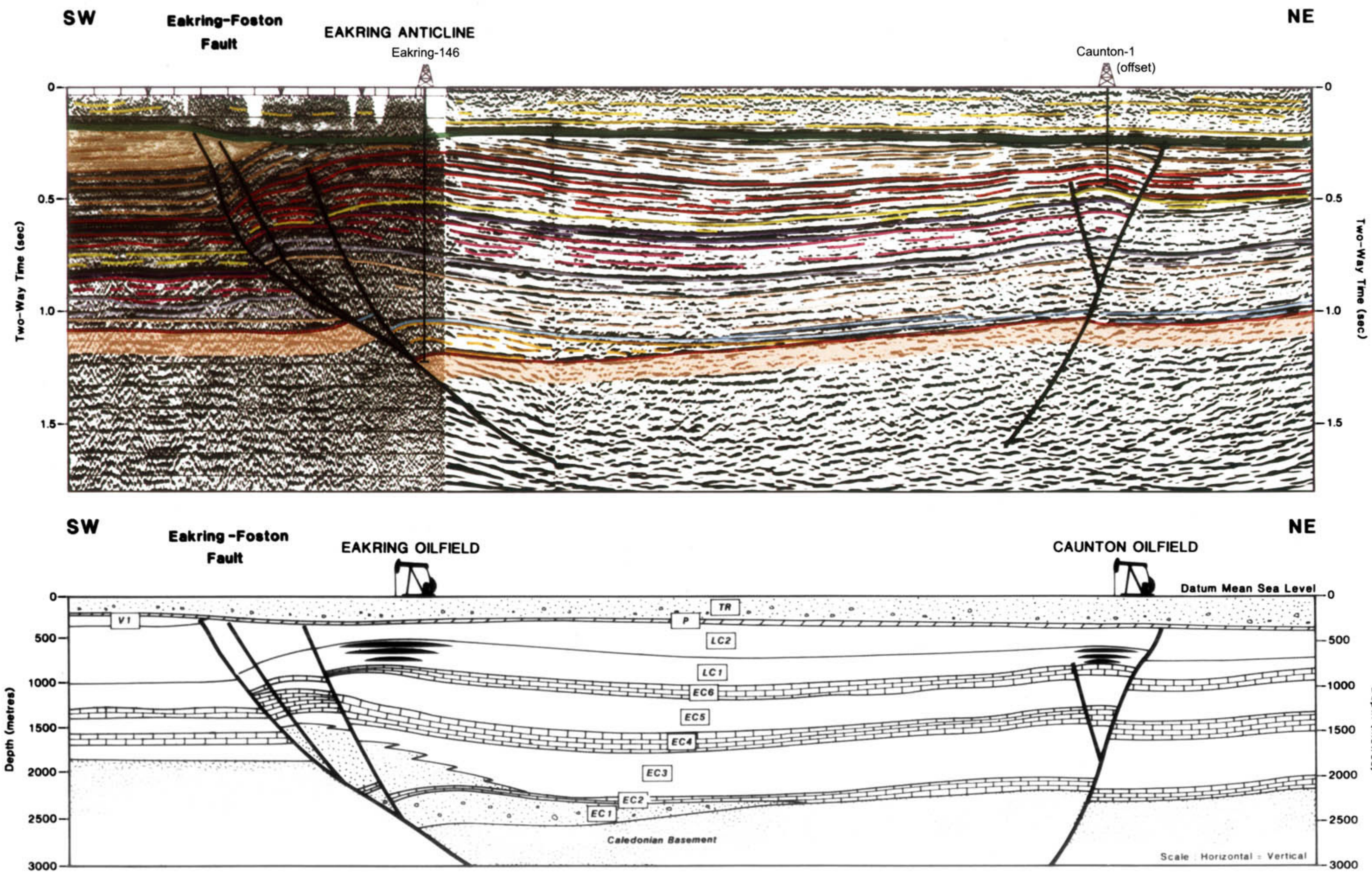


Fig. 55. Composite 2D seismic line and interpreted geological cross section across the Eakring-Dukes Wood Field (see Fig. 11 for location).

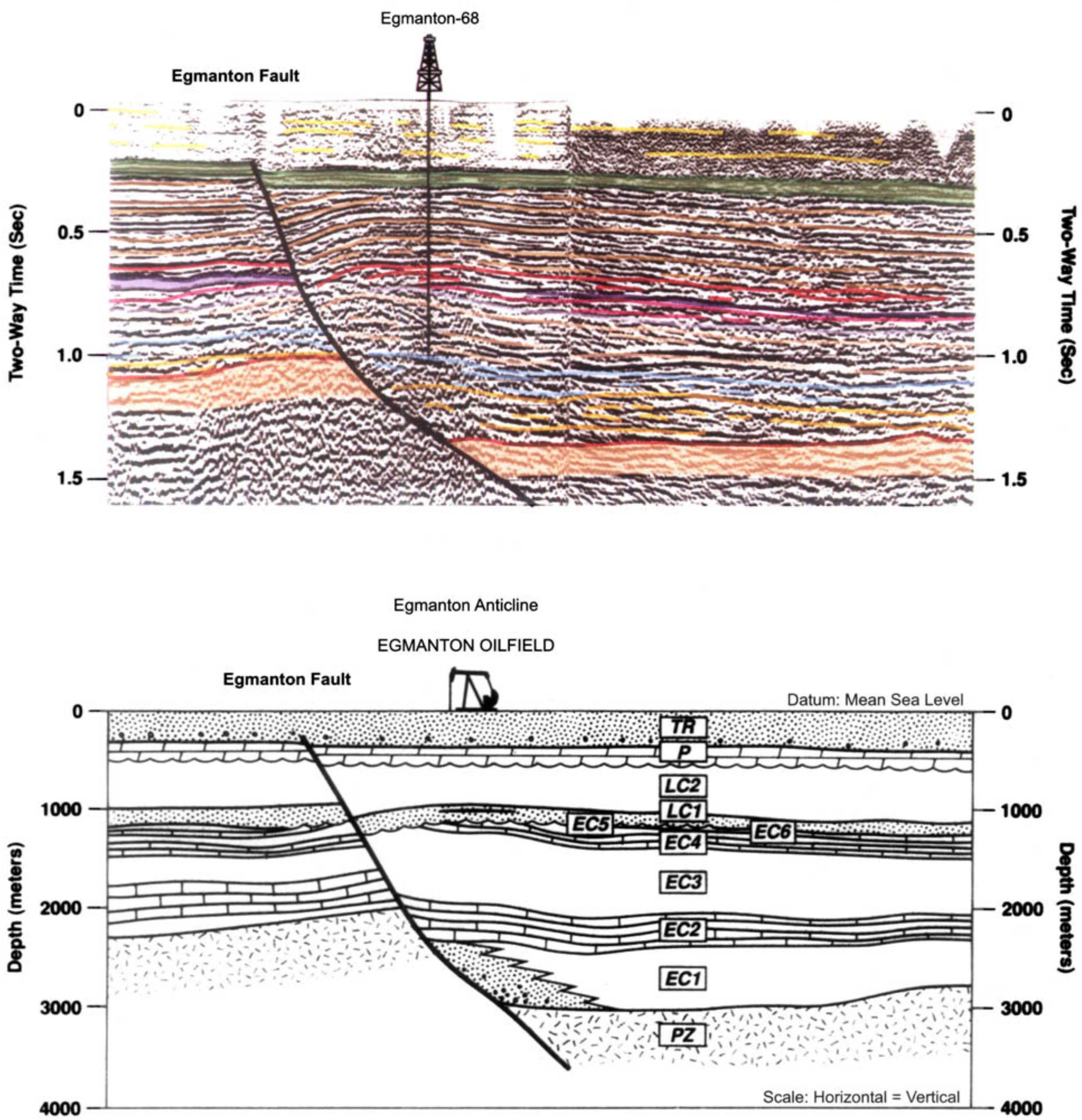


Fig. 56. Composite 2D seismic line and interpreted geological cross section across the Egmanton Field (see Fig. 11 for location).

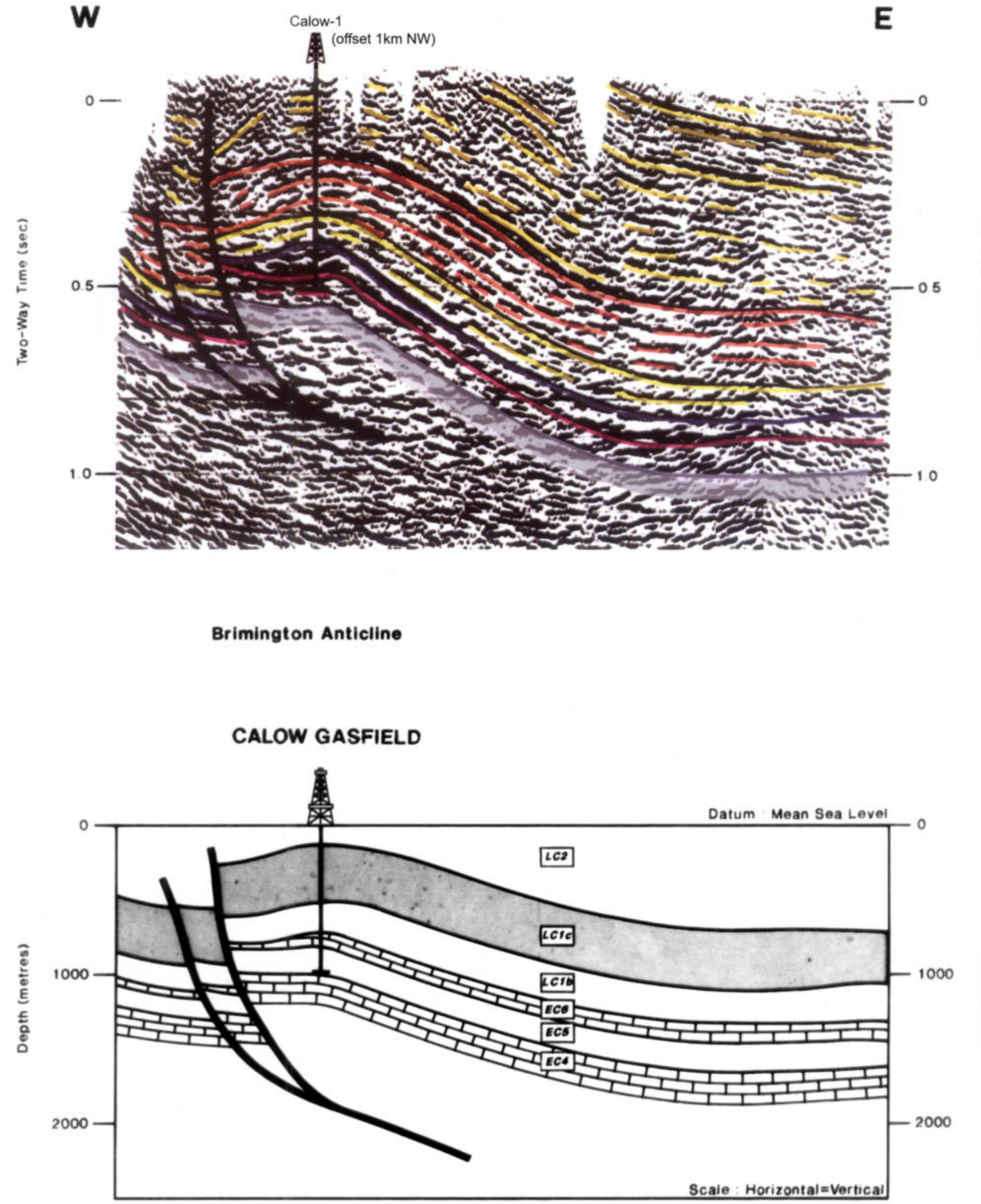


Fig. 57. Composite 2D seismic line and interpreted geological cross section across the Calow Field (see Fig. 11 for location).

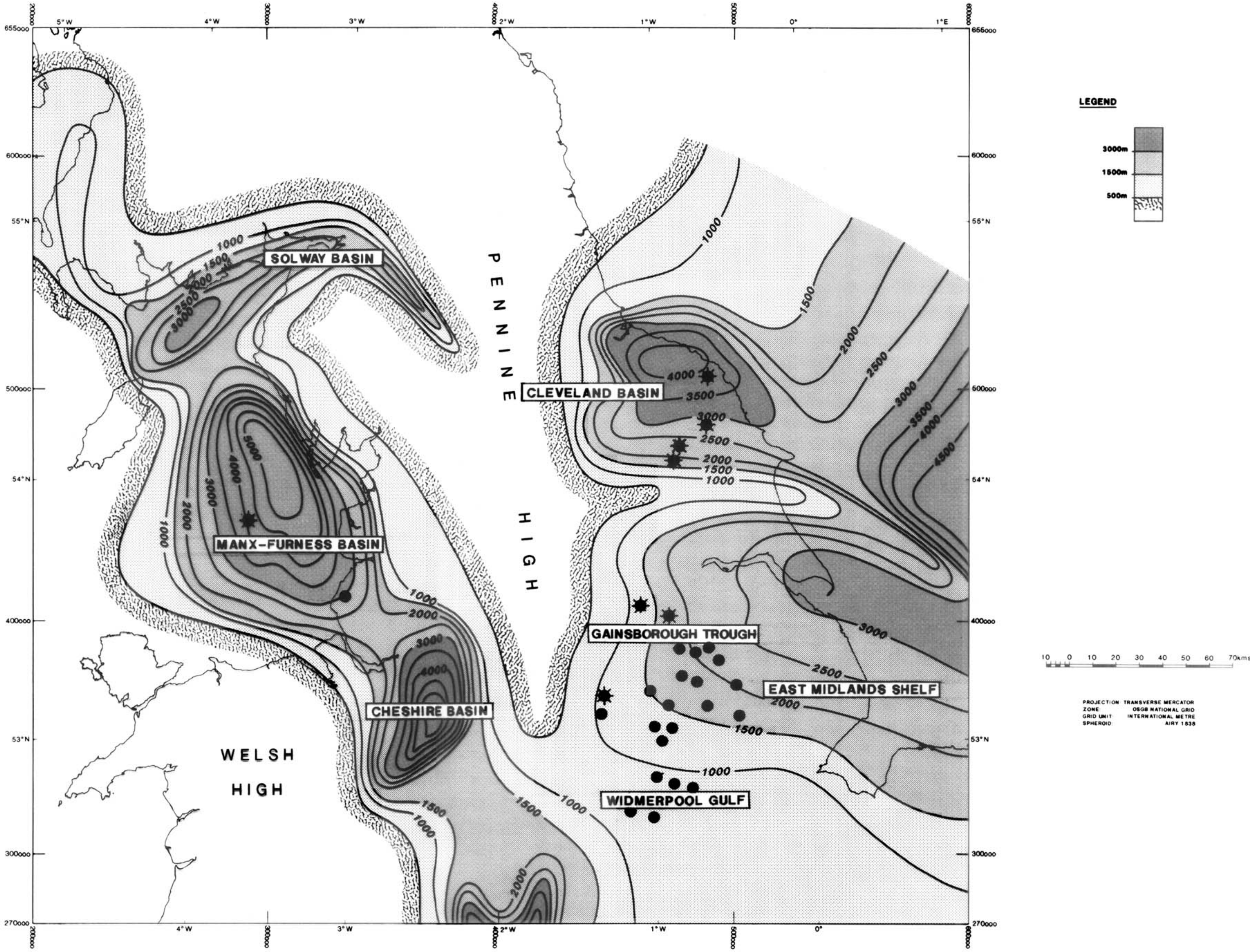


Fig. 58. Restored post-Carboniferous isopachs (after Fraser & Gawthorpe 1990).

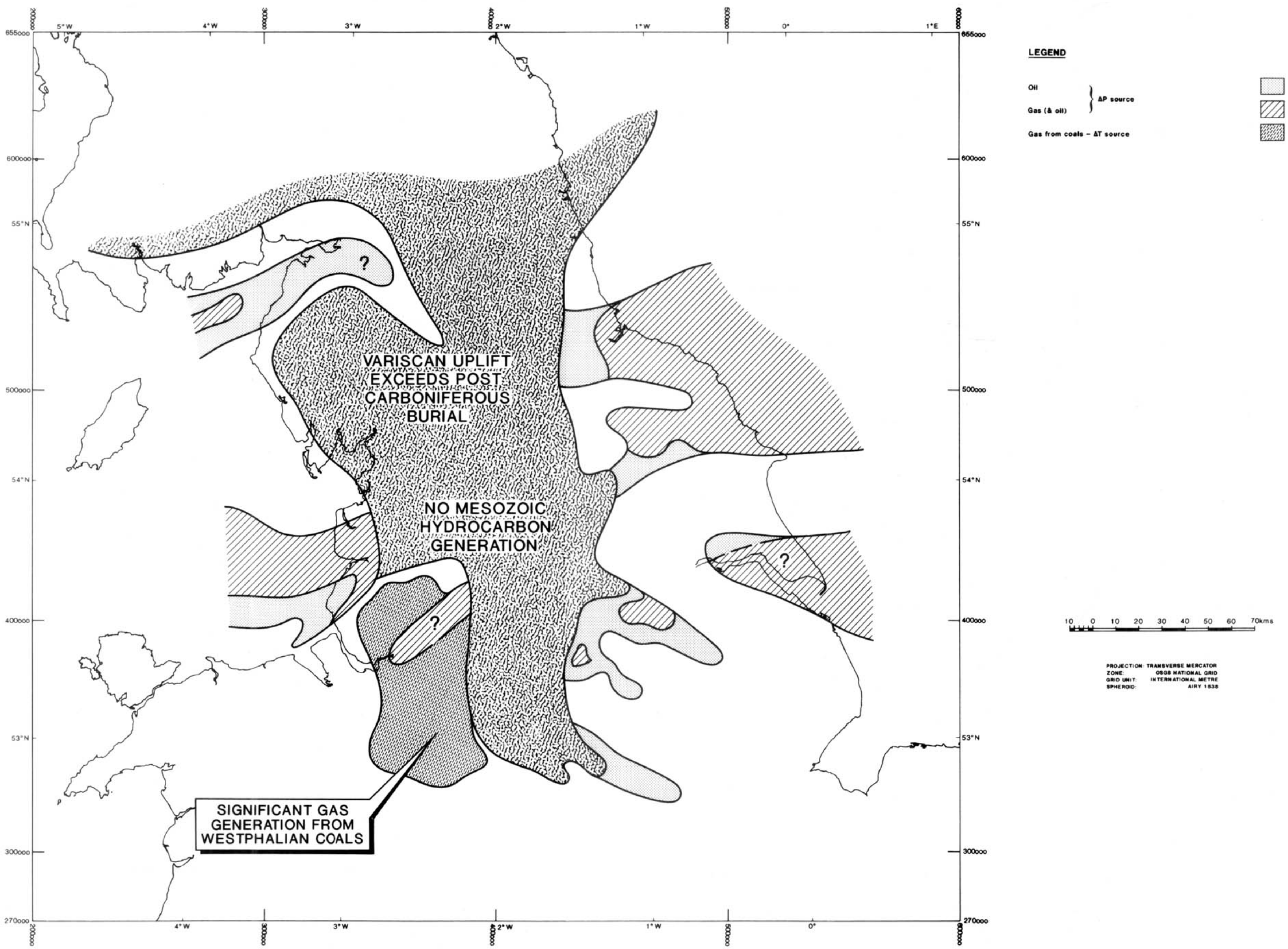


Fig. 59. Summary of late Mesozoic hydrocarbon generation (post-Variscan trap formation) (after Fraser *et al.* 1990).

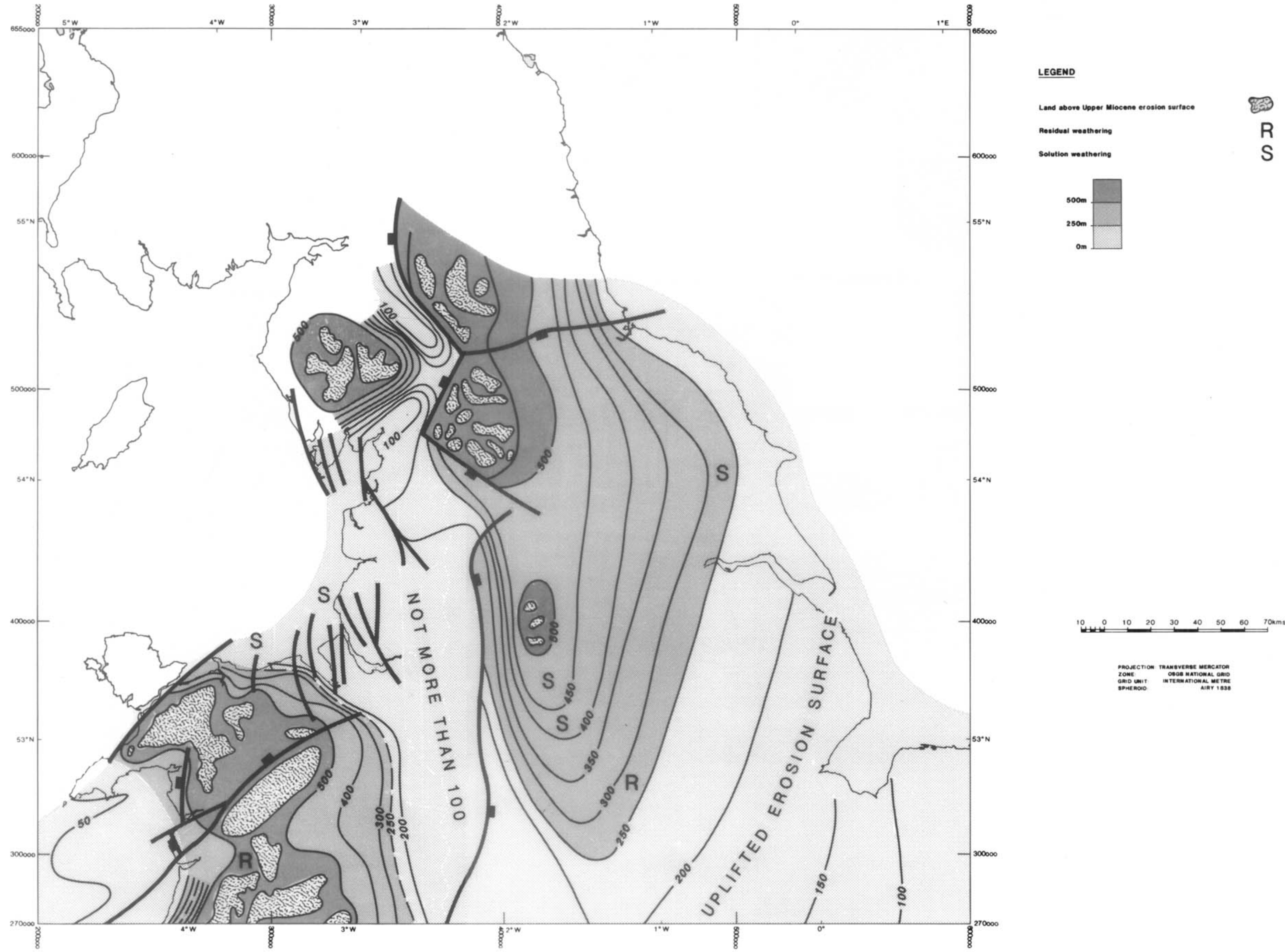


Fig. 60. Estimated Neogene and Quaternary uplift (after Fraser *et al.* 1990)

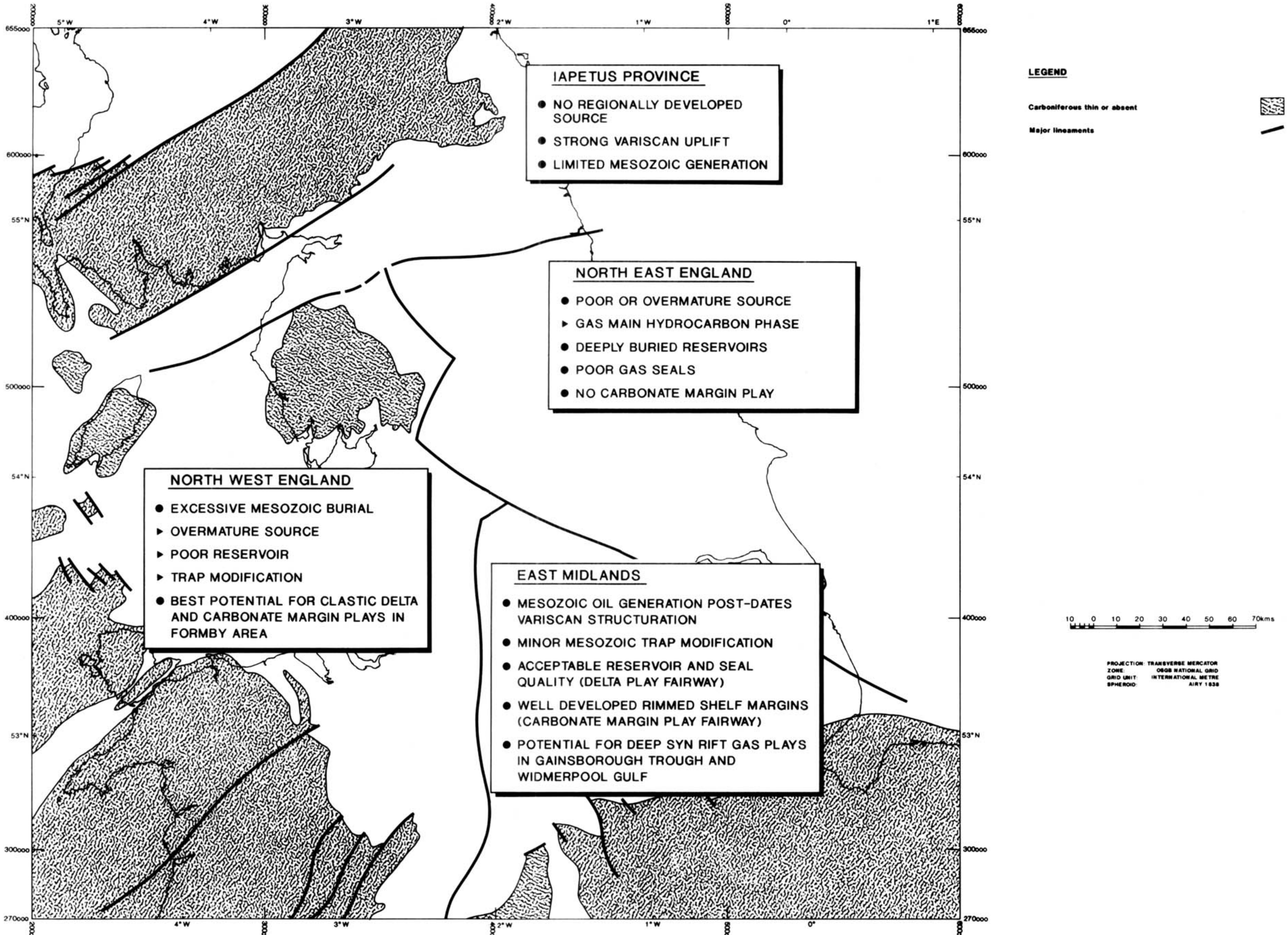


Fig. 61. Carboniferous play fairway summary (after Fraser *et al.* 1990)

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Chapter 6

Summary

The structures that controlled the Carboniferous tectonic and stratigraphic development of northern England were inherited from the earlier Caledonian orogeny which imparted a strong NW–SE and NE–SW tectonic grain that is evidenced on surface and subsurface data throughout northern England. The subsequent Variscan plate cycle, which involved the closure of the Rheic and Rheno-Hercynian oceans, controlled the development of syn-rift, post-rift and inversion megasequences from late Devonian to early Permian times. Regionally extensive, seismically resolvable sequences developed within the Carboniferous were controlled by episodic rifting and fault reactivation, with eustatic sea-level changes providing a high frequency control on depositional sequences that are generally below seismic resolution.

In the south of the province during the Dinantian, carbonate environments were extensively developed in syn-rift basins starved of terrigenous clastics. The north of the region was dominated from early Dinantian times onward by a southward prograding terrigenous clastic delta system. The carbonate environments in the south were finally drowned in the early post-rift (Pendleian) when the supply of terrigenous clastic sediments outpaced subsidence for the first time. Following this, rapid southward progradation of the delta systems occurred as a series of pulses largely controlled by eustatic sea-level changes, but with important local controls, namely antecedent rift physiography. By the early Westphalian, delta top conditions had been established over most of northern England. These conditions were progressively disrupted from late Westphalian C times by inversion related to the Variscan orogeny.

Over 70 years of exploration in northern England has resulted in the discovery of 75 million barrels of recoverable reserves. All hydrocarbon discoveries to date within the Carboniferous have shown some element of Variscan deformation in their trap geometry. Tectonics have also exerted a subtle, but important control on play fairway evolution (Fig. 62). The main source rocks, developed in distal pro-delta environments, are restricted to the syn-rift depocentres. Syn-rift siliciclastic reservoirs, associated with the early rift phase are located within the isolated, rifted, half graben. Carbonate reservoirs are controlled by the rift topography and the most prospective rim the margins of the deeper half graben in the south of the province. Delta top channel and mouth bar reservoirs are best developed where they axially infill remnant rift bathymetry.

Mesozoic burial, ensuring hydrocarbon generation post-dating Variscan trap formation, is considered to be the main control on the present day distribution of hydrocarbons in northern England (Fig. 62). Areas such as the central Pennines and Northumberland and Stainmore basins which received limited Mesozoic burial are considered to have poor hydrocarbon potential. The Cleveland, Manx–Furness and Cheshire basins where Mesozoic burial was excessive have gas as the major hydrocarbon phase. The East Midlands, where Mesozoic burial and post Variscan trap modification have been moderate, has therefore emerged as the most successful oil province in northern England.

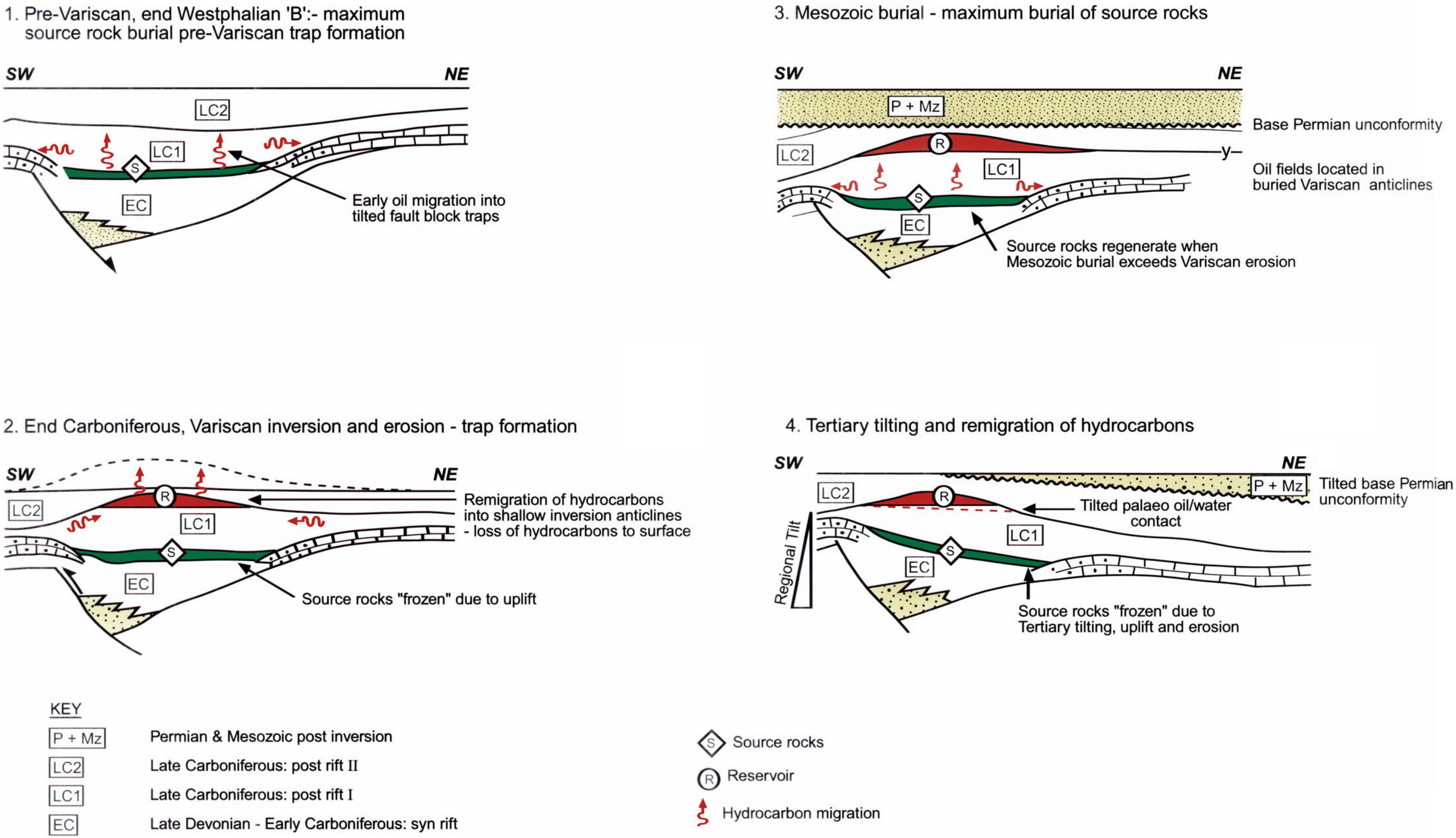

Fig. 62. Summary evolution of the Carboniferous play fairways, based on the East Midlands.

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