Trip#5 The influence of geology on scenery, oil and beer in the East Midlands. AAPG Birmingham 99 Field Guide

T C Pharaoh, N J Riley and J N Carney

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AAPG Excursion #5 The influence of geology on scenery, oil and beer in the East Midlands Sunday 12 September 1999

Leaders: Tim Pharaoh, Nick Riley and John Carney, British Geological Survey

Excursion itinerary

Excursion leaders (3) meet Chauffeurs coach at Curdworth garage and depart (08.00).

Collect participants (maximum 22) and depart Birmingham ICC Century Square entrance (08.30). 56 miles via M6 (J15), A500 and A52.

Brown End Quarry, Waterhouses (09.45–10.15). Dinantian deep water limestone turbidites and megabreccia of the Widmerpool half-graben. 5 miles via minor roads Thorpe Cloud (10.30–11.30). Waulsortian mud-mound complex within the Dinantian reef belt on the southern flank of the Peak District National Park. Very pleasant scenery. 36 miles via A52

Nottingham Castle (12.30–13.40). Reservoir characteristics of the Sherwood Sandstone Group, an important oil reservoir in southern Britain, and aquifer in the East Midlands, the quality of whose water plays a key role in the quality of the beer produced in this region. Buffet lunch and reservoir test in historic excavated cave system. Sample of 'formation fluids' courtesy of Tracs International, Aberdeen. 10 miles via A60

Rempstone Village (14.00–15.00). Production from oilfield discovered by BP on the southern margin of the deep Carboniferous Widmerpool half-graben and now operated by Pentex Oil kGas. Reservoired in Namurian turbidite sands. Display of 3D seismic data by Steve Trueman of Tracs International, courtesy of Pentex Oil & Gas. Display of selected borehole cores from the region by BGS. 10 miles via A6006, B588, B5330

Beacon Hill, Charnwood Forest (15.30–16.00). Precambrian marginal basin metamorphosed volcaniclastic sedimentary rocks. Exhumed desert landscape of Triassic age. Very pleasant scenery. 9 miles via B5330, A512 and minor roads

Cloud Hill Quarry, Breedon (16.15–16.45). Dinantian dolomitised limestones affected by strong Variscan inversion at the southern margin of the Widmerpool half-graben.

Breedon Hill Quarry (16.50–17.15). Pleasant scenery, with overview of the day's trip, if time permits. 30 miles via M42. Return to Birmingham ICC (18.00 sharp) in time for ice-breaker party.

Tim Pharaoh 9/09/99

Basin Analysis & Stratigraphy Group, British Geological Survey

Introduction

Our excursion today (Figure 1) will visit 6–7 localities displaying representative geology of the East Midlands region, covering about 160 miles (250 km). During the excursion, your leaders hope to show you (weather permitting!!) some of the most beautiful scenery in this region — in particular the Peak District and Charnwood Forest. We hope to demonstrate that some elements of this landscape are derived from a much older (c. 240 Ma old) desert landscape of Triassic age. Largely concealed beneath Permo-Triassic cover, the East Midlands hydrocarbons province (Figure 3) comprises a number of relatively small oil fields which have been discovered since the 1940's. These fields are generally associated with inversion structures located near to the margins of major Dinantian half-graben structures, such as the Widmerpool half-graben or 'Gulf. We will examine the exposed Dinantian geology at the southern margin of the Peak District, which forms the carbonate ramp and platform occupying the top of the half-graben tilt-block (localities 1 and 2). Then we will examine the Triassic cover itself, exploring the interesting history of the caves underlying Nottingham Castle (locality 3), where we will enjoy a buffet lunch. The Sherwood Sandstone Group is an important reservoir in southern England, most significantly at Wytch Farm. In the Midlands, it is an important aquifer whose attributes play a key role in the quality of beer produced locally. In the afternoon, our first stop will be in Rempstone village (locality 4), at the production facility of Pentex Oil & Gas. Steven Trueman of Tracs International will display data from a 3D survey across this field. Cores from deep boreholes from the region will be displayed, held in the national archive, are representative of the strata deposited in deeper water. Just south of Rempstone we cross the southern, major bounding fault of the Widmerpool half-graben, crossing onto the adjacent Hathern Shelf. The basement of the latter is exposed in the Charnwood Massif. Here we will examine probable deep-water volcaniclastic facies of Neoproterozoic age, at Beacon Hill (locality 5). This locality provides an insight into some of the tectonic basement grain which may have controlled the orientation of subsequent Dinantian rift-structures. Finally, we visit the spectacular inlier of Dinantian strata at Cloud Hill Quarry (locality 6), near Breedon, which provides important information on the history of the shelf. Again we will see evidence for the nearby Triassic erosion surface. If time permits, we may climb to the top of Breedon Hill (locality 7) where the viewpoint (given good weather!!) will allow us to put the excursion in perspective.

Acknowledgements

This excursion is sponsored by the AAPG and the British Geological Survey. Liquid refreshment at lunchtime (1 round!) is sponsored by Tracs International, Aberdeen. Access to the Rempstone site is by kind permission of Pentex Oil & Gas, and the demonstration of 3D seismic is courtesy of Tracs International. The core display is provided by BGS. We thank Breedon Quarry Company for access to their quarry. All of these companies are thanked for their support, with particular thanks to Steve Trueman and Mark Graham (Tracs), Alastair Tweedie (Pentex) and Stuart Hollyer (BGS). Keith Ambrose (BGS) contributed the description of the Breedon Hill locality. Dave Evans and Karen Shaw helped in the production of this guide. The Geological Society kindly granted approval for the reproduction of several diagrams from the various papers produced by Al Fraser and other members of the BP team in 1990.

Geological history

Precambrian and Early Palaeozoic

The Charnwood Forest region of north-western Leicestershire is one of the few parts of England where there are exposures of 'basement' rocks dating back to Precambrian time. The maximum elevation attained is only 271m, on Bardon Hill, but because the surrounding terrain is principally a subdued, dissected Triassic plain these uplands form a landmark visible for many miles. Within Charnwood Forest the topography is locally rugged due to the basement rocks forming numerous craggy exposures that protrude through a covering of Triassic Mercia Mudstone strata and Quaternary drift deposits. Past workers have viewed Charnwood Forest as a 'fossil' hill range, dissected by erosion between the late Carboniferous and early Triassic and now in the process of being exhumed from beneath its cover.

The lithostratigraphy of the Charnwood Forest succession was formalised after the detailed mapping and 1979 thesis of J. Moseley, and a subsequent paper by the latter author and T. D. Ford in 1985. The Charnian is divided into three principal groupings along with their component formations and members. The precise or absolute age of the Charnian Supergroup, is not well constrained. It is certainly late Precambrian, on the basis of its fossils which are comparable to Ediacaran assemblages elsewhere in the world, and is currently thought to be slightly older than 603 Ma. This figure however, based on long-range correlations with chemically similar Precambrian rocks that have been radiometrically dated (U-Pb method) at Nuneaton. It is in conflict with the current value of 580 Ma, which is considered to be the oldest possible age for rocks bearing these types of Ediacaran fossils. An added complication is that some or the entire upper unit of the Charnian — the Brand Group (Figure 23) — is Lower Cambrian rather than Precambrian.

The Charnian Supergroup is a volcaniclastic succession. This is an 'umbrella' term for bracketing strata containing varying proportions of grains derived from the erosion of pre-existing volcanic successions (epiclastic origin), as well as material incorporated into the rock directly from volcanic eruptions (pyroclastic origin). Pyroclastic material may consist of unabraded glass shards, crystals or angular 'cognate' volcanic fragments. In this account the qualifying term tuffaceous is commonly used, meaning lithologies thought to be a mixture of epiclastic and pyroclastic grains, where the latter's abundance is more than 25 and less than 75 per cent of the rock. The rocks of the Maplewell Group are all tuffaceous sediments, with a significant pyroclastic component. As (Figure 23) shows it displays a lateral change on going north-westwards, from the stratified volcaniclastic rocks of the Beacon Hill Formation into the thickly-developed volcanic breccias of the Charnwood Lodge Volcanic Formation which indicate close proximity to the pyroclastic centres of Charnian volcanism. Rocks that may have formed within the volcanic centres are typically massive or autobrecciated, and because they do not form part of a stratified sequence they are known as the volcanic complexes, of Bardon and Whitwick.

There is a rarity of well-organised sedimentary structures like cross bedding, such as commonly indicate reworking at shallow depths, and wave ripples have been tentatively identified only in a few places. It can therefore be suggested that much of the succession was deposited below the limit of storm-wave influence. Fairly deep-water, offshore environments are in keeping with the more prevalent sedimentary structures, which include parallel bedding or lamination, various types of grading, load structures and slump-induced disruption of bedding. Such structures indicate that virtually the whole of the stratified Charnian, regardless of its pyroclastic content, has been modified to varying degrees by the action of submarine debris flows and turbidity currents. These were probably triggered by tectonic instability or pyroclastic eruptions originating on the more distant flanks of basins marginal to the active volcanoes.

The palaeoenvironment of the Charnian rocks, and their tectonic setting, can be partly deduced from their geochemical attributes. These indicate that the parental magmas were calc-alkaline, generated above a subduction zone, and similar to those of modern evolved volcanic arcs founded upon oceanic or attenuated continental crust. Many modern intra-oceanic arc systems are largely submerged and consequently it is the fragmental material, either eroded or ejected from the volcanic axis, that is the most likely to be preserved in the depositional basins that surround the arc. This is the type of environment envisaged for the Charnian Supergroup.

Recent work has indicated that the Charnian sequence was folded and mildly metamorphosed as a result of the Acadian deformation phase of the Caledonian Orogeny, which in Charnwood has been dated (unpublished work) to the late Silurian/Early Devonian. The same event imposed the highly penetrative cleavage that is everywhere seen transecting the Charnian rocks.

Deep boreholes on the northern edge of the Widmerpool half-graben, encounter low-grade metasedimentary rocks of Tremadoc and older age, which are considered to lie off the Midlands Microcraton, within the concealed Caledonide fold-thrust belt of eastern England (Pharaoh et al., 1987). Rempstone 1 encountered a granodiorite of presumed Ordovician age, in the footwall of the Hoton Fault. The high magnetic susceptibility of this rock'is iriferred to be the cause of the prominent aeromagnetic anomalies underlying the Hathern Shelf.

Late Palaeozoic

The region lies at the south-east end of the Carboniferous basin complex of the East Midlands, on the north-western edge of the London-Brabant Massif (Figure 2). The basin complex comprises a mosaic of half-graben structures, with dip-slopes tilting to south-west and north-east, controlled by major syndepositional faults with a broadly north-west strike. The latter are believed to reflect Carboniferous reactivation of fundamental faults (thrusts or shear-zones) within the Caledonide basement of eastern England (Soper et al, 1987; Fraser et al, 1990; Lee et al, 1990).

The evolution of the Carboniferous basin complex of the East Midlands is now well understood as a result of detailed seismostratigraphic studies of reprocessed high quality seismic reflection data (Ebdon et al, 1990; Fraser et al, 1990).

These studies have demonstrated that Dinantian sedimentation in this region is characterised by alternating phases of rift-related tectonism and quiescence. In the Widmerpool Gulf (Figure 9), 6 sequence units (EC1–6) are recognised within the Dinantian syn-rift phase, and 2 sequences (LC1–2) within a late Brigantian to late Westphalian C post-rift phase (Figure 4); (Figure 5); (Figure 6). Sequences EC1, 3 and 5 show wedge-shaped geometries thickening onto the basin-bounding fault and thinning up the hangingwall dip-slope (Figure 7). Associated phenomena include strong onlap, coarse clastic wedges, drowning of hangingwall carbonate margins and footwall uplift (Ebdon et al, 1990). They are interpreted as tectonically driven sequences arising from periods of lithospheric extension. Boreholes indicate that mudstones and interbedded carbonate turbidites are the dominant lithologies in the central parts of the half-graben. Intervening sequences, EC2, 4 and 6 reflect the development of prograding carbonate ramps, typically thinning towards basin-marginal faults (Figure 7). They are interpreted as stillstand or regressive sequence tracts deposited during tectonically quiescent periods. Following EC6 in late Brigantian times there was,,a minor inversion event along faults with a NNW–SSE trend (Ebdon et al 1990) prior to deposition of sequence LC1, controlled by thermal subsidence. The initiation of the Eakring inversion anticline and other comparable structures dates from this time.

The Widmerpool Gulf is a major half-graben trending NNW, controlled by a major syndepositional fault on its southern side (Normanton Hills or Hoton Fault). The half graben contains a thick Dinantian sequence (>3000 m). As noted earlier, most of this thickening appears to have been achieved by late Arundian times. Significant footwall erosion was recognised by Ebdon et al. (1990) along the southern margin of the half-graben during the EC3 rift phase. Fraser & Gawthorpe (1990) recognised that the greatest Dinantian syndepositional throws occurred on WNW and NW oriented faults, e.g. the Hoton and Askern-Spital Faults (Figure 9). In the Grantham district, the Barkston Fault exhibits analogous behaviour. Variscan inversion produced long wavelength inversion anticlines in the hanging-wall blocks of these faults (Figure 7); (Figure 10). By contrast, NNW trending faults e.g. the Eakring-Denton Reverse Fault and Ironville Thrust (Figure 9) show less Dinantian syndepositional growth and are characterised by shallower detachments and tight inversion anticlines adjacent to the faults e.g. at Eakring and Welton.

In Dinantian times the Breedon — Ticknall area formed part of the Hathern Shelf (e.g. Ebdon et al., 1990), a structural province which was bordered to the south by a landmass that included Charnwood Forest. This palaeogeographic configuration is indicated by pebble beds with Charnian clasts occurring in Early Chadian and Brigantian age rocks exposed in the various inliers. The Breedon area formed part of a carbonate ramp, between the shelf and the half-graben provinces, on which limestones were mainly deposited. Later in the Carboniferous, substantial reverse movements occurred on the graben-bounding faults and other structures transecting the Hathern Shelf. During the main end-Carboniferous (Variscan) deformation the basins that accumulated the Carboniferous sequences, up to and including the Westphalian Coal Measures, were inverted and at this time the steep dips seen in the two Breedon quarries were imparted. Movements also occurred in post-Triassic times along many of the major faults. Dolomitisation and mineralisation of the Carboniferous Limestone is thought to have occurred during the Variscan movements. The principal mineral *seen* at Breedon Hill is calcite. Other minerals found include galena, chalcopyrite, malachite, cuprite, sphalerite, wulfenite and cinnabar (e.g. King 1968). Karstification leading to cave formation was initiated after the uplift had occurred and the available evidence suggests that much of the present system of voids was formed by early Triassic times.

Permian–Mesozoic

Strata of Permian and Triassic age unconformably overlie the Carboniferous structural elements identified above, and are in turn overlain by Jurassic strata, forming part of the Eastern England Platform marginal to the North Sea Basin.

During the early Triassic, the Breedon inliers stood out as residual hills (inselbergs), rising above a broad, low-lying plain. A major river system flowed across this plain, initially depositing pebble beds and pebbly sands (Polesworth Formation and Nottingham Castle Sandstone Formation of the Sherwood Sandstone Group), followed by generally finer sand (Bromsgrove Sandstone Formation). The river system did not encroach far onto Breedon Hill, however, and its deposits are probably only present on the northern flanks. The succeeding Mercia Mudstone Group represents deposition under predominantly arid, semi-desert conditions and it was the accumulation of these sediments that eventually buried Breedon and Cloud hills, and the Charnwood Massif.

Some of the Variscan faults were reactivated and show minor amounts of normal movement affecting Permo-Triassic strata. Some faults with a north-westerly orientation show minor throw of Permo-Triassic strata, but do not affect Jurassic strata. Most of the faults affecting Jurassic strata have a more east-west orientation.

The East Midlands Oil and Gas Province

Hydrocarbons have been produced from the Carboniferous strata of northern England since the 1920s (Falcon & Kent, 1960). There have been 30 discoveries to date, most located in the East Midlands. Field sizes are mostly small (typically 1–2mm bbls recoverable) but the relatively low exploration and development costs make these an attractive commercial proposition. 280 exploration wells have been completed to date, of which 60% encountered shows. Recoverable reserves are 75 M barrels of oil and 27 bcf of gas (Fraser & Gawthorpe, 1990). The first discovery at Hardstoft, Derbyshire in 1919 was in tightly folded and fractured Dinantian strata. The first significant discovery, was by D'Arcy in 1939 at Duke's Wood near Eakring, in a Namurian delta-top channel and mouthbar sandstone (7 mmbls oil). Subsequently BP discovered Beckingham/Gainsborough (13 mmbbls oil, 6.5 bcf gas) in 1939: Welton (>20 mmbbls oil) in 1981, both in Namurian and early Westphalian A delta top sandstones.

Beer brewing in the Midlands

Burton Abbey near Burton-on-Trent was founded in 1002 and the monks were quick to recognise the special quality of well water in the vicinity, whose high sulphate content made it excellent for use in brewing. By 1850 most major British brewers had a satellite brewery in the town, and in 1888 more than 8000 people were employed by the industry in some 30 breweries, mostly family owned. The big companies included Bass, Charrington, Worthington and Ind Coope, and in addition to the traditional 'bitter' and sweeter 'stout' ales, bottle conditioned, lighter 'pale' ales were produced for export to India and the rest of the British empire (hence Indian Pale Ale or 'I.P.A.').

Locality descriptions

1. Brown End Quarry, Waterhouses [SK 086 502]

This outcrop preserves 97m of bedded limestones and claystones. The limestones contain allochthonous grain types derived from the carbonate ramp edge to the north and transported gravitationallly into the Widmerpool Gulf. Much of the narrow and probably steep ramp which shed the carbonate is no longer preserved due to intra-Dinantian unconformity, hence the limestones at this quarry provide clues to the phantom stratigraphy of the southern margin of the Derbyshire cratonic block which existed during the early Visean.

Sedimentology

The limestones are mainly fine to coarse grained packstones, with some grainstone units. Bed thickness varies, but averages less than lm thick. Grain types are dominated by crinoids and peloids, carbonate lithoclasts also occur. Other bioclasts include brachiopods, bryozoans, corals, echinoids, ostracodes, molluscs, foraminifera, trilobites, dasyclad algae (e.g. *Koninckopora*) and cyanobacterial tubules (e.g. *Girvanella*). Grain micritisation and boring is common. Grain types and pre-depositional preservation reflect the different environments on the ramp which exported sediment gravitationally into the Widmerpool Gulf. Most of the large bioclasts are fragmentary, with the majority of brachiopods being disarticulated. Beds show some internal lamination (clinoform and subparallel to parallel) scour and vertical grading. Sharp erosive bases are prevalent and some beds are lenticular. Multistorey beds are common. Some beds comprise debris flows containing brecciated clasts of ramp and reef facies. One large block, over lm across, is a megaclast of reef limestone with inverted geopetals (DANGER! do not attempt to climb the face to observe this). Many beds show only subtle or no internal architecture and this is due to reworking of the sediment by bioturbation.

Claystones are slightly calcareous and are a dark grey/greenish/blue in colour. Their mineralogy and chemistry has not been studied.. Conspicuous is the large amount of bioturbation with "chondritiform" and *"Planolites"* type burrows being common. Bioclasts, which are mainly brachiopods and crinoids, but also include ostracodes, trilobites, hashed bryozoans and molluscs, tend to be jumbled by bioturbation, but long crinoid stringers can be found. Solitary corals occur including the cold water tabulate *Amplexus coralloides.* Ammonoids are rare.

Depositional environment

The limestones reflect gravitational flow. Deposition probably lay close to the base of storm wave base at the foot of the ramp. The lack of *in situ* photic algae suggests water depths close to, or below the local limit of the photic zone (probably –200m). Bioturbation indicates oxygenation of the substrate, but oxygen tensions were probably low, as the claystone biota includes weaniid trilobites, which were specialised for dysaerobic hemi-pelagic environments. The presence of rare ammonoids (*Ammonellipsites*) demonstrates proximity to deeper water ammonoid facies.

Age

Interpretation of the age of the Waterhouses section has had a controversial history. Morrris (1963) recognised the presence of the conodont *Scaliognathus anchoralis.* Until the work of Riley (1982) this conodont was always interpreted as indicative of latest Tournaisian. Riley (1982) demonstrated, using trilobite stratigraphy, that records of *Sc anchoralis* from the Frankenwald of Germany and the Genicera Fm of Spain, which both contain the short ranging trilobite *Weania colei* (originally described by Gand (1973, 1977) as species of his genus *Gitarra,* now recognised as synonymous with *Weania colei*.), actually belong to the earliest Visean. This is borne out by the subsequent discovery (Riley in Aitkenhead et al 1988) of the definitive foraminiferan *Eosparastaffella* and bilaminar examples of the dasyclad *Koninckopora* at Waterhouses. Direct correlation with the Whitemore Limestone of the Hodder Mudstone Fm. in the Craven Basin (Riley 1990) as well as Germany and Spain is possible. W *colei* is also known from Rathkeal (Co.Limerick) in Ireland. Waterhouses quarry represents the most northerly occurrence of *Sc. anchoralis* and its associated conodonts in Europe, despite rocks of equivalent age (lacking *Sc anchoralis* but having other conodonts) being present in N. England. This demonstrates the palaeobiogeographic problems with conodonts (not acknowledged by some conodont workers, e.g at the Mississippian/Pennsylvanian boundary in the USA).

Lithostratigraphy

Aitken and Chisholm (1979) placed this section in the Milldale and Hopedale Limestones. Neither is correct. The Milldale Limestones are older (Tournaisian age) and are inner to mid-ramp carbonates deposited by storm and traction currents (coeval with the Caldon Low limestones attached to the Charnian basement visible to the S.) The limestones at Waterhouses quarry are different in age lithology and origin. They would more appropriately be placed in the Widmerpool Fm.

2. Thome Cloud [SK 152 510]

Thorpe Cloud is a microbial Waulsortian reef lying on the southern margin of a carbonate ramp (Milldale Limestones). A late Tournaisian Waulsortian reef complex occupies the valley sides of Dovedale to the N., with Thorpe Cloud lying at its S. margin. This site coincides with the N. margin of the Widmerpool Gulf, bounded by the W. extension of the Cinderhill Fault. Bridges & Chapman (1988) produced a reconstruction of the reef complex, but failed to realise that the reefs are not all the same age within the late Tournaisian. Thorpe Cloud is the youngest of all the reefs (based on trilobite and ammonoid biostratigraphy derived from the Craven Basin by Riley 1982 & 1990). It contains a distinct and biostratigraphically significant fauna including the trilobite *Phillibollina worsawensis* (first discovered here by John Tilsley) and the ammonoid *Polaricylcus minimus* (type locality). The older reefs to the N. contain the trilobite *Phillipsia gemmulifera* and the ammonoid *Fascipericyclus fasciculatus* (making this reef the same age as Breedon Cloud — which will be seen at a later stop today) characteristic of the zone below. The present reef topograpy is a combination of factors, with the original reef shape being modified by intra-Dinatian erosion at the end Tournaisian and again prior to deposition of the Asbian (a combination of footwall uplift and eustatic sea level changes).

The reef top and sides contain spectacular microbial wackestones. These lime muds were precipated (actively or passively) by microbes. Lithificaton began early resulting in lithified crusts which, due to dewatering, pulled apart from the overlying lime muds. This happened repeatedly resulting in subhorizontal cavities now filled with burial cements (sheet spars). In the USA and former USSR significant commercial hydrocarbon finds have been made where early oil invasion occurred. Unfortunately in the Derbyshire examples oil generation of underlying source rocks was not happening at the time of deposition and early burial.

There seems to be a correlation between basement faults and the siting of microbial reefs at several times during the late Palaeozoic. One theory is that hydrocarbon seeps seeded the microbial reefs. Certainly they could thrive in aphotic conditions (Miller & Lees 1985). The seeps need not have been oil, or free gas, modern sour gas seeps with gas in solution seed microbial mats to this day. It should be noted that Waulsortian; reefs are restricted to the late Tournaisian and are subtly distinct from the late. Dinantian platform rim reefs described by Mundy (1993) which he termed Cracoeian.:,'

3. Nottingham Castle [SK 569 393]

The old medieval castle was burnt down by Chartist rioters in1825. The present building, built in the mid-19thC, serves as a civic museum and art gallery. The castle is located on cliffs of sandstone which are the type locality of the Nottingham Castle Sandstone Formation, the local representative of the Sherwood Sandstone Group (Triassic, Scythian). The cliffs, and manmade caves dug into them, provide excellent exposures of the sandstone. We shall inspect these during lunch which will be taken in the famous hostelry known as 'Ye Olde Trippe to Jerusalem' (more colloquially, 'The Trip') claimed to be the oldest 'pub' in the world, allegedly founded in 1189 AD! The pub gets its name from its function as a meeting place for knights and men at arms gathering at the foot of the royal stronghold before departing with King Richard the First, the 'Lionheare, for the Third Crusade to the Holy Land. Unfortunately there is little documentary evidence before the 17th Century to support this legend. It is however likely that beer was brewed in the adjacent 'Brewhouse Yard' for consumption in the castle since the 11th Century.

The foundations of buildings in the city of Nottingham contain hundreds of caves, which have been used for shelter since prehistoric times. In Saxon times, caves in the basement of the nearby pub 'The Salutation' were being used as a shelter for farm animals. When the Normans arrived, they found the 'Hamlet of Snod', or 'Snodingham' comprised about 200 buildings. They recognised its important strategic significance controlling the crossing of the River Trent and rapidly fortified the cliffs. In the following centuries the cave systems were extended for the storage of food and water. A major investigation of the caves was carried out as part of the remapping of the Nottingham geological map by BGS.

4. Rempstone Village [SK 581 241]

Rempstone village is located just to north of Hoton, where the southern major bounding fault of the Widmerpool half-graben is located. The Rempstone structure is a relatively small inversion anticline located just to north of the fault. The field was discovered by BP in 1985 (Rempstone 1). BP subsequently sold the field on to Pentex Oil & Gas, who are the current operators. Oil is produced from two relatively clean sands (C and H sands) of the Retnpstone Formation, lying near the base of the Namurian (Pendleian). Steven Trueman of Tracs International will present results from the latest 3D seismic survey of this structure, and give more information on the discovery and production history of the field.

A core display of material from the national archive at Keyworth will be presented by the British Geological Survey. These are representative of producing sands (Namurian) at Rempstone, and deepwater Dinantian facies.

Long Eaton 1

Core 1 (5871–5902') Box 1 (5871–5874')

This well is the deepest penetration of Dinantian in the Widmerpool half-graben, terminating in evaporite-bearing Tournasian strata. The cored interval comprises strata no older than Arundian in age (N.Riley, pers. comm. 1999). They are limestone turbidites of sequence EC3. Graded beds of siltstone, calcisiltite and fine to very coarse grained packstones and grainstones are interbedded with hemipelagic claystones. Concretions are well developed in some horizons. Bases are sharp and erosional, and 'rip-up' lithoclasts are present. There is abundant evidence for loading and dewatering. Ripple and parallel lamination are commonly developed. They are interpreted as limestone turbidites, derived from a carbonate platform or ramp, probably storm-triggered.

Old Dalby 1

Core 2 (1437–1455 m) Box 34 (1452–1453 m)

Limestone turbidites of the Widmerpool Formation (Asbian-Brigantian) forming part of sequence EC5. Coarse bioclastic well-graded turbidites with sharp erosional bases and affected by slump structures.

Rempstone 2

Core 2 (727.0–731.0 m) Box 14 (730 m) H Sand

Core 3 (786.0–789.0 m) Box 34 (788 m) Unit D

Core 4 (803.4–810.0 m) Box 54 (807 m) C Sand

Core 4 (803.4–810.0 m) Box 55 (808 m) C Sand

This borehole was deviated at a steep angle through the reservoir horizon which is of Pendleian age. The Rempstone Formation occurs at the base of LC1A, representing the onset of the thermal subsidence phase. Production is from the lower, C Sand. The following description is from the BP completion report.

The upper, H Sand has a gross thickness of 13.8 m (TVT) with 10.8 m of net sandstone (723.5–737.2 m BRT). It is predominantly fine to medium grained, quartzose, and poor to moderately sorted. It contains abundant interbeds of siltstone and mudstone. From core analysis, average porosity is 18% and horizontal permeability about 0.7 Md.

Intervening strata of units G-E comprise dark grey to brown carbonaceous mudstones and siltstones, with thin sandstones in places.

The lower, C Sand (803.6–816.0 m BRT) has a gross thickness of 12.6 m (TVT) and a nett sand thickness of 10.3 m. It is the best developed sandstone horizon in the Pendleian. The quartzose, pale brown sandstone has an average porosity of 16% and a mean horizontal permeability of about 20 Md.

The samples in the core display show the following features:

Box 14: Thin debris flows and locally syn-sedimentary faulting.

Box 34: Debris flow of Unit D, containing disrupted clasts and folded beds of sandstone at 787.5 m.

Box 54: Debris flow, containing wisps and streaks of siltstone and sandstone in a grey matrix at 806.9 m.

Box 55: Sands are separated by thin shaly units.

A possible interpretation is that the clean, rather structureless C and H sands were sourced from the adjacent high of the Anglo-Brabant Massif, rather than from the northern British Caledonides, as was most of the Namurian sediment. They may have Been emplaced as grain-flows disturbed by storms. On the other hand, the debris-flow units are inferred to represent periodic incursions of sediment slumperd down the delta-slope into the pro-delta environment.

5. Beacon Hill, Charnwood Forest [SK 510 148]

Beacon Hill is a local landmark and public viewpoint, with excellent exposures that serve as the type section for the Beacon Tuffs Member of the Beacon Hill Formation. This member, about 740 m thick, occupies a significant stratigraphical position since it is in part contemporaneous with the Charnwood Lodge Volcanic Formation farther NW (Figure 23), which contains the principal record of primary pyroclastic activity in the Charnian Supergroup. At Beacon Hill the sequence is finer grained and the range of sedimentary structures suggests a considerable degree of secondary reworking. Accessibility of the exposures, and the occurrence of well-polished rock surfaces, are special features of Beacon Hill important for demonstrating the relative significance of pyroclastic and epiclastic sedimentation processes during a period of raised volcanic activity in the Charnian arc.

Rock samples from Beacon Hill, when viewed in thin section, show acicular and y-shaped glass shards indicating that some of these beds have a significant juvenile pyroclastic content. Some of the youngest beds are exposed on the prominent crag by the footpath to the west of the Trig Point.. In this predominantly fine-grained sequence, the lowest bed, at least 2.8 m thick, consists of white-weathering, very fine-grained tuff or tuffaceous mudstone; it is devoid of bedding or lamination, but careful examination of favourable surfaces suggests that such features may have been obliterated by liquefaction ('slurrying') prior to consolidation. Extensive sedimentary load structures characterise a prominent undulating bedding plane in the middle part of these crags, and are continued a few metres to the south where completely detached, ball-shaped masses of sediment are enclosed within a lower bed. The overlying bed is 0.2 m thick and shows slight grading from tuffaceous siltstone at the base to a porcellanous, white-weathering mudstone at the top. The uppermost, laminated beds have highly lenticular geometries, due to a combination of large-scale slumping and intraformational scouring. The overlying strata are best seen around and to the east of the Trig Point; they are thinly bedded to laminated, with many small-scale examples of undulatory bedding, rafted or truncated lamination, normal grading and load structures. A possible *disc-like fossil* has been found on a bedding plane exposed to the south of the Trig Point.

The underlying beds, exposed on the middle series of crags consist of thinly bedded to parallel-laminated tuffaceous siltstones with minor sandstones. An unusual occurrence, in the northern part of this exposure, consists of a 0.2 m thick bed displaying what appear to be either profiles through asymmetrical ripples or complex sediment loading phenomenon.

Time may allow us to visit the base of the type section, where about 6 m of strata consist of white to grey, very fine-grained sedimentary rocks. These are mostly massive, but when bedding planes are seen they are in places highly irregular and convoluted; in one case the contorted strata are truncated at the base of the overlying bed. Near the top of this section, parallel-laminated tuffaceous mudstones and siltstones show laminae disrupted into pencil-like rafts. Other laminae show evidence of incipient slumping in the presence of asymmetric drag-folds, whose direction of vergence is consistently towards the west.

Interpretation

The Beacon Hill exposures provide an opportunity to examine lithologies which are clearly of a distal facies with respect to the volcanic centres known to be active at that time in NW Charnwood Forest. Contemporary volcanism is strongly suggested by the occurrence of juvenile pyroclastic material (glass shards) at Beacon Hill. In thin sections of such fine-grained lithologies it is commonly assumed that the unresovable matrix surrounding the shards, and constituting most of the rock, represents the highly comminuted, fine ash-grade equivalents of the shards, and that consequently the rock is a vitric tuff. Unfortunately, however, subsequent devitrification and silicification of the glassy material have masked the delicate textural details necessary to confirm such an origin. This process produced the extremely hard, porcellanous texture of these rocks and also perhaps their high silica content (79.81% in one sample).

The distinctive, very thick beds of fine-grained tuff in the sequence appear to be internally structureless, but it is possible that an earlier lamination may have been obliterated by liquefaction consequent upon large-scale movement within a water-saturated sequence. Such a complex pre-diagenetic history, in subaqueous environments, is suggested by soft-sediment deformation structures such as: undulatory and lenticular bedding, the extensive downward penetration of load structures, and incipient asymmetric slump folding of laminae. Normal grading suggests that at least some of the detrital material in these rocks was brought in by the action of low-density turbidity currents. Nevertheless, the abundance of fine-scale parallel lamination, as seen close to the Trig Point, may indicate a significant contribution of pyroclastic material in the form of fine-ash that settled through the water column after being carried in ash clouds from the volcanic source region(s)'. Turbidity currents generally come to rest in basins with moderately deep waters, but the Beacon Hill exposures contain one very rare example of possible ripples. This type of sedimentary structure could be indicative of oscillating wave action, and may suggest that at times the depositional basin had shoaled to relatively shallower depths, above storm wave base.

6. Cloud Hill Quarry. Breedon [SK 412 215]

This magnificent viewpoint overlooks the most important of the Dinantian sections occurring south of the River Trent. Together with Breedon Hill, crowned by its distinctive church and seen in the background to the north of this quarry, Cloud Hill is one of a series of Carboniferous Limestone inliers that have been extensively quarried for roadstone over several decades. The other grouping of Carboniferous Limestone inliers around Ticknall, to the west-north-west of Breedon, contain strata that lie unconformably beneath the Namurian (Millstone Grit). The same relationship was proved by BGS with the drilling of the Worthington Borehole at a site 700 m west (to the left) of this viewpoint. There, the strata are gently dipping and the sequence shown was: Lower Coal Measures (18 m); Namurian (115 m); Carboniferous Limestone (Brigantian) (44+ m).

Background

In Dinantian times the Breedon — Ticknall area formed part of the Hathern Shelf, a structural province bordered to the south by a landmass that included Charnwood Forest. About 7 km NE of here, Dinantian shelf sedimentation terminated at the margin of a deep-sea trough trending WNW–ESE, known as the Widmerpool Gulf or half-graben. The principal structure at this southern margin of the trough was the Normanton Hills Fault (Hoton Fault of some workers), its movements controlling sedimentation as the half-graben periodically subsided throughout early Carboniferous (Dinantian) times, enabling up to 5.5 km of mudstones and carbonate turbidites to accumulate. The Dinantian sequence in the Cloud Hill-Breedon area was by contrast highly attenuated, and is possibly no more than 500–700 m thick hereabouts. It formed part of a ramp, between the shelf and the half-graben provinces, on which limestones were mainly deposited.

Later in the Carboniferous, substantial reverse movements occurred on the graben-bounding faults and other structures transecting the Hathern Shelf. During the main end-Carboniferous (Variscan) deformation the basins that accumulated the Carboniferous sequences, up to and including the Westphalian Coal Measures, were inverted. The westerly dip of strata in this quarry was formed at this time; it steepens progressively going east, probably because the strata were rotated against a reverse fault located immediately east (to the right of) the quarry and now concealed beneath the Triassic. Dolomitisation and mineralisation of the Carboniferous Limestone is thought to have also occurred during the Variscan movements.

During the Triassic, the inliers stood out as residual hills (inselbergs), rising above a broad, low-lying plain. The Mercia Mudstone Group, seen as the red strata in cuttings at the top of the quarry, to the left of this viewpoint, represents deposition under predominantly arid, semi-desert conditions and it was the accumulation of these sediments that eventually buried Breedon and Cloud hills.

Stratigraphy

Cloud Hill Quarry has been exploited to a depth of more than 120 m, the lowest part of the quarry now being below sea level. It exposes a thick and varied sequence of carbonate rocks that have virtually all been dolomitised. The sequence comprises Early Chadian strata assigned to the Milldale Limestone Formation, which crop out in the eastern part of the quarry. These are overlain unconformably by the Cloud Hill Dolostone Formation, of ?Holkerian to Late Asbian age. The youngest beds in the quarry, seen in the highest level to the west (right) of us, are correlated with the Late Asbian and Brigantian-age Ticknall Limestone Formation.

Looking northwards along the length of the quarry, the oldest strata forming the steeply dipping beds to the east (right) are correlated with the Mil!dale Limestone of North Derbyshire. They comprise thinly bedded dolostones with common, undulating, non-sutured stylolites, which tend to enhance clay or shaly mudstone partings. The beds appear moderately fossiliferous, with brachiopods and crinoids the most commonly seen. The former includes *Levitusia* (*Productus*) *humerosus*, an Early Chadian form for which this quarry is the type area in Europe. Other fossils noted in this part of the sequence include solitary and colonial corals, gastropods and the echinoid *Archaeocidaris*. Chert nodules occur in discrete layers or within beds of dolostone. They have preserved the original structure of the rock and have yielded a microfauna also indicating an Early Chadian age. The cherts provide good evidence that the dolomitisation in this quarry is secondary; they segregated after deposition of the host sediment, but because original structures are preserved in the nodules, dolomitisation could not have occurred before their formation. In the higher exposed beds of the Milldale Limestone, sandy dolostones and dolomitic sandstones contain a few pebbles of porphyritic, glassy volcanic rock that chemically is very similar to dacitic tuffs from the Precambrian of Charnwood Forest.

The Milldale Limestones of Cloud Hill are thought to represent accumulations of carbonate sand (shell detritus, ooids, peloids) in a shelf sea. The absence of any emergent features suggests moderately deep waters and an outer shelf rather than an inner shelf environment. The shell pavements, seen in the quarry, are typical products of storm events, with the interbedded mudstones and siltstones representing suspensiOn sedimentation in quieter periods. The more abundant fauna and the local clastic component, seen near the exposed top, indicates that these beds represent deposition in a shallower, more proximal to shore setting compared to those of Breedon Hill Quarry.

The exposed thickness of the Milldale Limestone here is 400 m, but its base is not seen and its top surface is a major unconformity — termed the Main Breedon Discontinuity — across which the rest of the Chadian, the Arundian and at least part of the Holkerian are missing. On current geochronological scales this represents a time gap of between 7 and 10 million years. Towards the southern end of the quarry, down to the left of the viewpoint, the beds above the unconformity dip less steeply to the west than those below and a slight angular truncation may be seen if the lighting is good. This indicates there was a slight tectonic tilting of the shelf region in the intervening period, but no evidence has been observed for emergence and/or karstic development along the unconformity. Comparisons of the rocks above and below the unconformity suggest they are of similar lithology, but they are radically different farther north as will be explained below.

The supra-unconformity beds, of the Asbian to ?Late Holkerian Cloud Hill Dolostone, are exposed on the western (right-hand) upper quarry levels. They are interpreted as marking a return to carbonate shelf depositional environments.

Farther along the western face, the Cloud Hill Dolostone is faulted and the beds to the north of the displacement (which is difficult to see from here) are rather different in type, as can be seen in the spectacular exposures on the northern upper quarry levels. The sequence there consists of a basal unit of grey to red- or orange-stained beds representing the *Cloud Wood Member,* which rests upon the continuation of the Main Breedon Discontinuity. A typical package in this member consists of a basal mudstone overlain by thinly interbedded mudstones, siltstones and dolostones. Many of the mudstone beds have a strong shear-induced foliation, and tight folding is outlined by the pale grey dolostone beds. No dateable macro- or microfossils have been recovered from these beds, but palynomorphs indicate a Late Holkerian to Early Asbian age. Overlying the Cloud Wood Member are largely unbedded dolostones which have been interpreted as a type of reef. This lithology is finely crystalline and fossiliferous dolostone, and although many fossils have been destroyed during dolomitisation, those that have survived include brachiopods, crinoids, corals including *Amplexus,* gastropods, nautiloids and ammonoids including the genus *Goniatites,* the latter a type of ammonoid denoting a Late Asbian age. There are common cavities in this reef rock, some showing a concentric fill of calcite ('stromotactis'). The reef facies dolostones represent a particular type of mud-mound (cracoean buildup) that formed as a fringing reef on the outer margin of the Hathern Shelf, probably in waters up to 100 m deep.

Interpretation of deformation at the base of the Cloud Wood Member

The style of this deformation recalls descriptions of sequences in which there has been penecontemporaneous, large-scale slumping of whole packages of strata. In this quarry the limestone beds, being the first to have achieved lithification, behaved relatively competently and thus were fractured rather than sheared. Folds are asymmetric, with axial planes reclined to the south-west. Possibly therefore the Main Breedon Discontinuity, on which the slumping was initiated, sloped to the east or north-east at this time. The underlying Early Chadian rocks are also folded, or at least variably tilted, and the possibility of some tectonic influence on these structures cannot be discounted. The mud-mound reef limestone facies overlies the folded and sheared beds, but slivers of it are also caught up in the disturbance and are tectonically repeated, indicating that slumping occurred no older than the Late Asbian.

7. Breedon Hill Ouarry [SK 405 233]

This quarry has a maximum depth of about 90 m and is almost entirely excavated into the Milldale Limestone Formation, of Early Chadian age. This unit is estimated to be around 400 m thick hereabouts, but no base is seen. The younger Cloud Hill Dolostone Formation, of ?Holkerian–Asbian age, is only exposed in the upper part of the northwest face. The Triassic unconformity is clearly visible at the northern end of the quarry, here overlain by a coarse breccia.

A major fault runs approximately north - south through this quarry and has produced a broad shatter zone. Neither the direction nor the amount of throw of this fault can be determined from the exposed sections, but it can be traced northwards away from the quarry in the overlying Triassic rocks where it downthrows to the east. The Carboniferous Limestone beds on either side of the fault are steeply dipping, locally folded and overturned in places.

The roadway down into the quarry exposes what are thought to be the oldest beds in the quarry. They are assumed to young to the west, but no evidence for their way-up has so far been found. One geopetal structure has been found in the north-west of the quarry, however, and indicates the beds there young to the west. The beds at the roadway are part of a sequence at least 170 m thick of grey to buff, locally red, purple or ochreous stained, fine to coarsely crystalline dolostone. The individual beds are generally massive, although some show evidence of internal lamination. They are commonly separated by thin, undulating grey or red shaly mudstone or silty mudstone partings that have been enhanced or exaggerated by stylolitisation. The sequence is very poorly fossiliferous, with only crinoids noted. Locally these are common, particularly near to the eastern side of the main fault. Chert nodules occur at some levels.

The bedded dolostones are thought to represent distal storm deposit gravity flows, possibly turbiditic, deposited in comparatively shallow water on the carbonate ramp. The muds and silts settled out from suspension in quieter periods. Due to the intense dolomitisation of these rocks, however, precise environmental interpretation remains speculative. The equivalent beds in the nearby Cloud Hill Quarry were deposited in shallower water on the platform/shelf.

Breedon Hill Quarry contains some spectacular caves, none more so than the one viewed here. The visible dimensions of the cave are approximately 60 m in length and 10 m in height. Observations indicate that the roof here is dipping at around 40^2 into the quarry, giving a thickness of about 9 m for the exposed sediment fill, the base of which has not yet been proved. The cave sediments are of presumed Triassic age and comprise red and green, matrix-supported breccias, massive siltstones and mudstones, and a laminated bed of clay-silt/sand couplets. The clasts in the breccias are almost exclusively of Mercia Mudstone lithologies but a few dolostone clasts may be visible. Boulders up to 0.5 m across have been noted in these breccias, but tend to be confined to the outer part of the fill. Samples of the green mudstone have been submitted for palynological analysis but all have failed to yield any evidence of age. Detailed mapping of the surrounding Mercia Mudstone strata indicates, however, that Gunthorpe Formation occurs where the projected cave mouth intersects the surface of the Breedon Hill inselberg. This suggests that the infill is early Middle Triassic (Anisian–Ladinian) in age, and that cave formation at Breedon occurred well before this time. Ford and King (1966) and Simms (1990) have also described caves at Breedon Hill Quarry. The former authors regarded them as isolated dissolutional caverns of unknown age. Simms dated the cave development as Late Triassic (Carnian), partly based on a mid to late Carnian monsoonal event proposed by Simms and Ruffell (1990).

On the opposite quarry face, more caves are visible. Some are voids, some have partial infills of dolostone debris, which has probably collapsed from the cave walls and roof, and many are lined with dog-tooth spar calcite. One small void has been noted with a dog-tooth spar lining and a later fill of Triassic mudstone. Examination of the cave walls has shown both smooth and etched surfaces. The latter may be associated with hydrothermal action or could have resulted from the in situ formation of sulphuric acid from the oxidation of sulphides. Smooth cave walls may result from blocks falling from the cave roof, or abrasion by moving water, with or without a sediment load. The cave deposits are assumed to have been deposited by debris flow processes (breccias) and sudden discharge of sediment-laden water that was rapidly slowed (siltstones). The laminated bed indicates a period of standing water in the cave, the coarser and finer laminae possibly indicating a seasonal influx of sediment.

To the north of the cave, the beds comprise least 100 m of massive, unbedded, generally fine to very finely crystalline dolostone, overlain by similar but better-bedded dolostones. They are more fossiliferous than the beds along the roadway into the quarry and contain a diverse fauna of brachiopods, crinoids, corals, nautiloids and ammonoids (goniatites). The fauna collected includes the solitary coral *Amplexus coraloides* and the goniatite *Fascipericyclus fasiculatus,* which indicates an Early Chadian age. Past workers noted the brachiopod *Levitusia humerosus* in these beds, supporting an Early Chadian age. The structureless dolostone is thought to represent the core of a mud-mound 'reef, with the bedded dolostones forming on the reef flanks. Analogy with mud-mound reefs of similar age in North Derbyshire suggests it is a Waulsortian reef. These formed in water depths of 220–280 m and are composed of an accretion of calcite mud produced by bryzoa and sponge spicules (Bridges et al., 1995). A pronounced fabric of elongate voids can be seen in the rocks; some of these formed close to the sediment-water interface during deposition and others represent the casts of bioclasts.

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Figures

(Front cover)

(Figure 1) Excursion route, plotted on a display from the Geoscience Data Index developed by the British Geological Survey. Geological data, extracted from 1:625,000 Geological Map © NERC. Topography: Ordnance Survey, © Crown Copyright reserved.

(Figure 2) Early Carboniferous structural elements. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

(Figure 3) East Midlands hydrocarbon province: structural elements and field distribution. reproduced from Fraser and Gawthorpe (1990) with permission © Geological Society of London.

(Figure 4) Sequence stratigraphy of the Variscan cycle in the Central England rift system. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

(Figure 5) Summarised stratigraphy of the Variscan plate cycle in the East Midlands showing megasequence and sequence development. AT delta top, AF delta front, AP pro-delta. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

(Figure 6) Dinantian seismo-stratigraphic summary, Widmerpool half-graben. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.

(Figure 7) Composite sketch of seismo-stratigraphic interpretation, western Widmerpool half-graben. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.

(Figure 8) Delta advance during the middle to late syn-rift and early post-rift and its relationship with source rock distribution and age in northern England. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

(Figure 9) East Midlands Dinantian structural elements. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

(Figure 10) Composite seismic and interpreted geological section across the Widmerpool half-graben and Hathern shelf, East Midlands. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.

(Figure 11) Sequence architecture, southern margin of the Widmerpool half-graben. LC1c delta slope; LC1b prodelta turbidites; LCla distal prodelta; EC6' shelf carbonates and mudstones; EC6 basinal carbonates; EC4' carbonate rimmed shelf margin; EC4 basinal carbonate; EC3 basinal carbonate and mudstone; EC2 shelf carbonate; EC1 evaporite/ carbonate slope deposits; Pz Basement; PT Permo-Triassic. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.

(Figure 12) Sequence architecture, northern margin of the Widmerpool half-graben. LC2 delta top; LC1c delta slope; LC1b prodelta turbidites; LCla distal prodelta; LCla' carbonate shelf/condensed mudstone sequence; EC6' carbonate rimmed shelf margin; EC6 basinal carbonates; EC5 basinal mudstone; EC4 basinal carbonate; EC3 basinal carbonate and mudstone; EC2 shelf carbonates; EC1 evaporite/ carbonate slope deposits. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.

(Figure 13) Devono-Carboniferous basin development: Widmerpool half-graben and Hathern shelf, East Midlands. Adapted from Ebdon et al. (1990) Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

(Figure 14) Isopach and facies maps for the syn-rift megasequence. (a) Restored isopachs for syn-rift sequences EC2-EC6 (Chadian-early Brigantian) Data from George (1958), Leeder (1974) (b) Palaeofacies map for syn-rift sequence EC4 (late Holkerian-mid Asbian) AT delta top, AF delta front, AP pro-delta. Incorporates data from Stevenson & Gaunt (1971), Leeder (1974), Miller & Grayson (1982), Smith et al. (1985), Aitkenhead et al. (1985), Gawthorpe 1987a and Grayson & Oldham (1987). Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

(Figure 15) Isopach and facies maps for the post-rift megasequence. (a) Restored isopachs for post-rift sequences LC1-LC2 (Namurian-Westphalian C). Data from Wills (1951), Kent (1966), Calver (1968), Leeder (1982), Guion & Fielding (1988). (b) Palaeofacies map for post-rift sequence LC1c (Kinderscoutian to late Westphalian A). Data from Collinson et al. (1977), Reading (1964) and Guion & Fielding (1988). Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

(Figure 16) Intra-Carboniferous play fairway summary. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

(Figure 17) Carboniferous clastic delta system play fairway summary. AT delta top, OF delta front, AP pro-delta. Reproduced from Fraser & Gawthorpe (1990) with permission. 0 Geological Society of London.

(Figure 18) Early syn-rift clastic play fairway summary. S source, C seal, R reservoir. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

(Figure 19) Dinantian carbonate shelf margin play fairway summary. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

(Figure 20) Porosity against depth plot for Namurian-early Westphalian channel sandstone facies from wells in the East Midlands. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

(Figure 21) East Midlands oil/source rock correlation. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

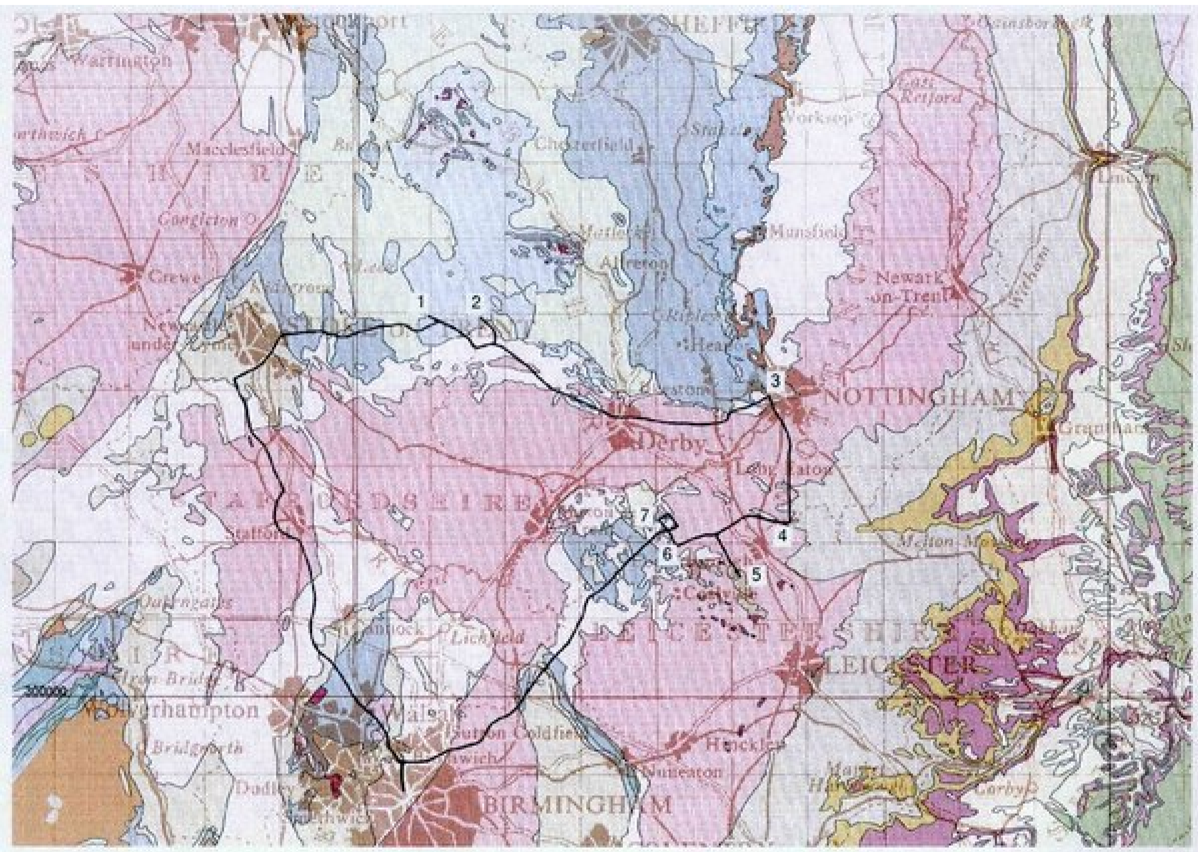
(Figure 22) Maturity against depth profile for the well Bardney 1 in the East Midlands based on vitrinite reflectance data. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

(Figure 23) Pre-Triassic geological map of Charnwood Forest. Reproduced from Carney (in press). © NERC.

(Figure 24) Geology of Cloud Hill Quarry (UBD=Upper Breedon Discontinuity, MBD=Main Breedon Discontinuity, LBD=Lower Breedon Discontinuity). From Carney & Ambrose (1999). ©NERC

(Figure 25) Comparative stratigraphical terminology for the Carboniferous Limestone of the Breedon on the Hill and Cloud Hill inliers. From Carney & Ambrose (1999). ©NERC

(Plate 1) Composite seismic and interpreted geological section across the Widmerpool Gulf and Hathern Shelf, East Midlands. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.



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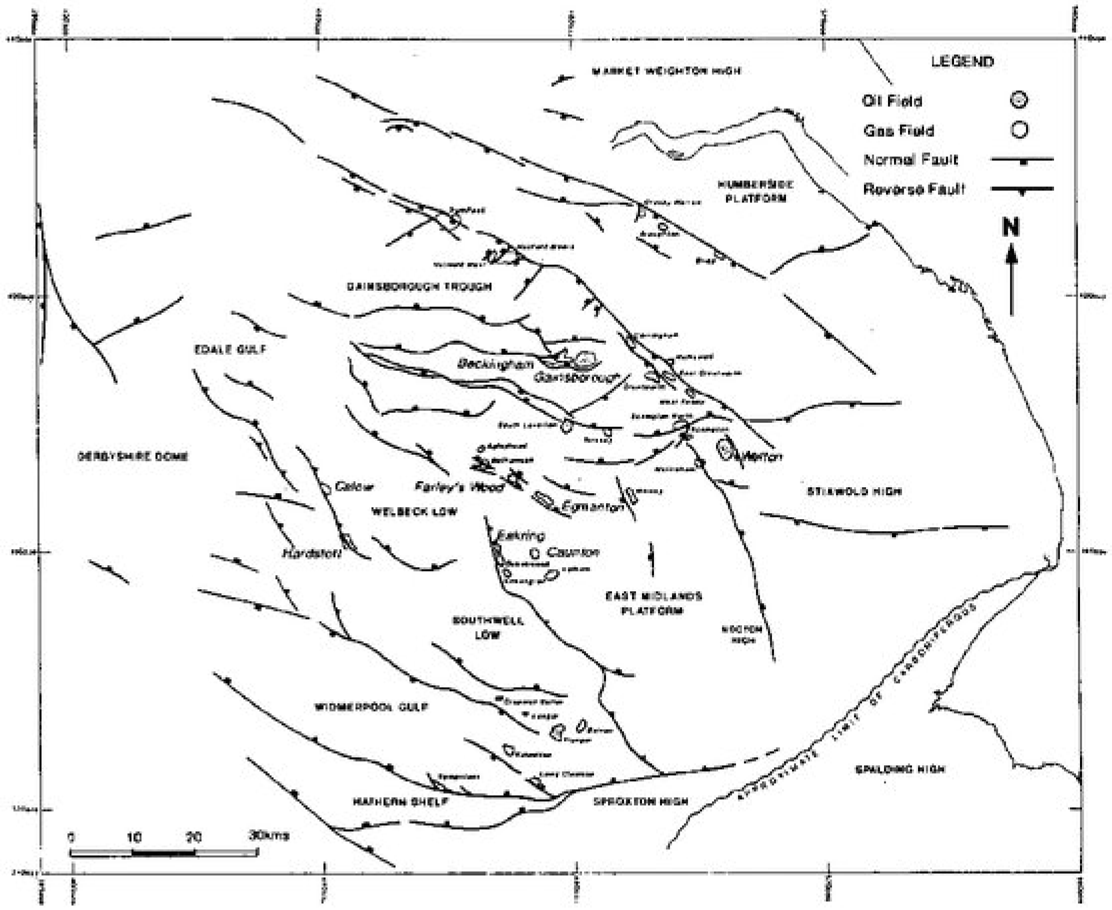

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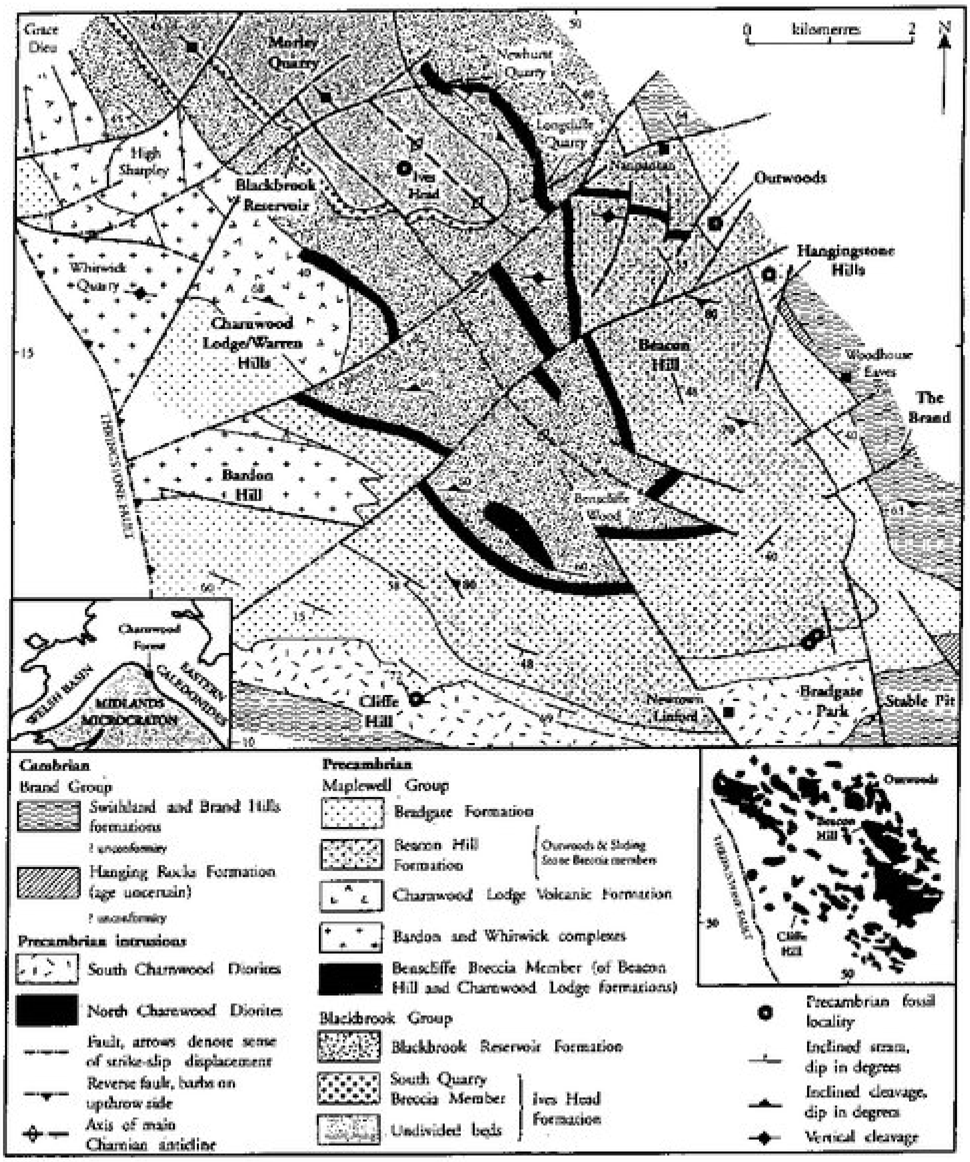

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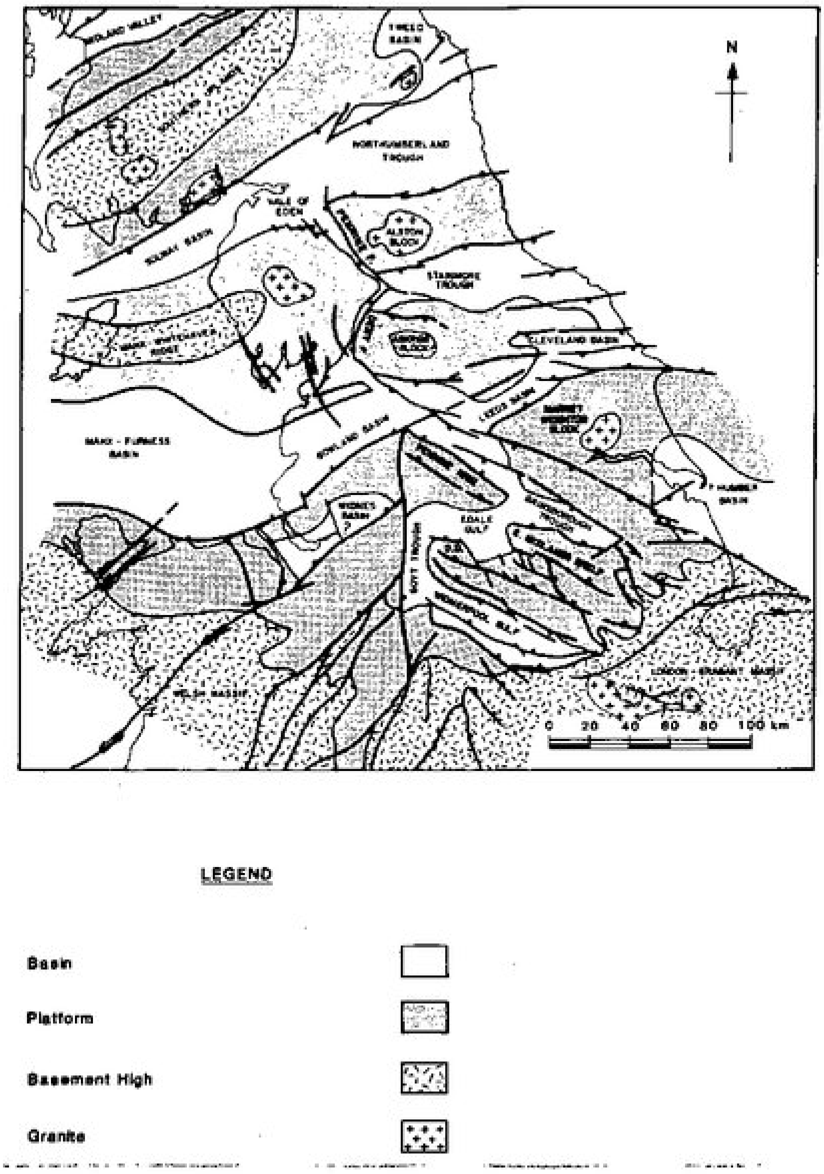
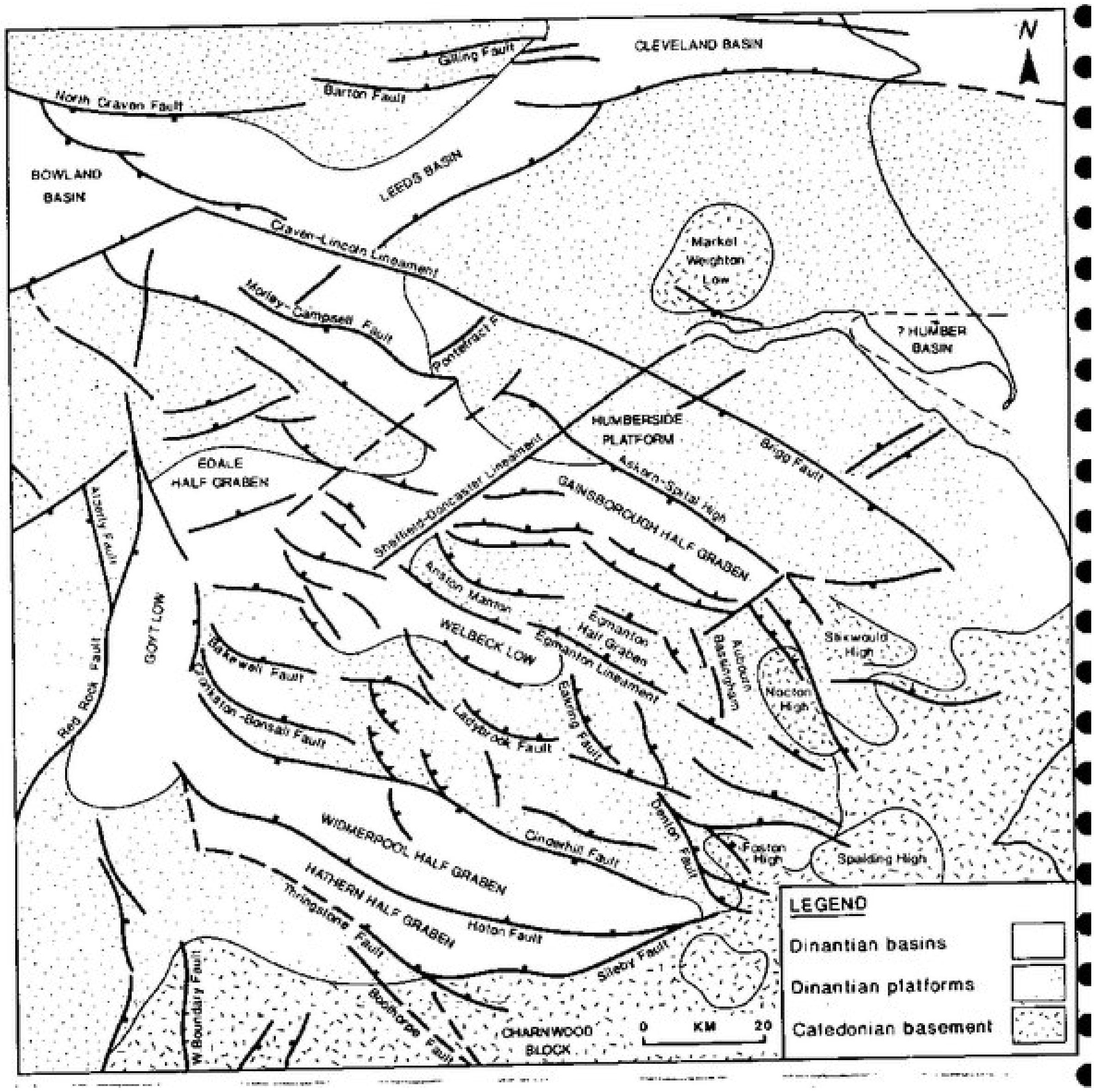


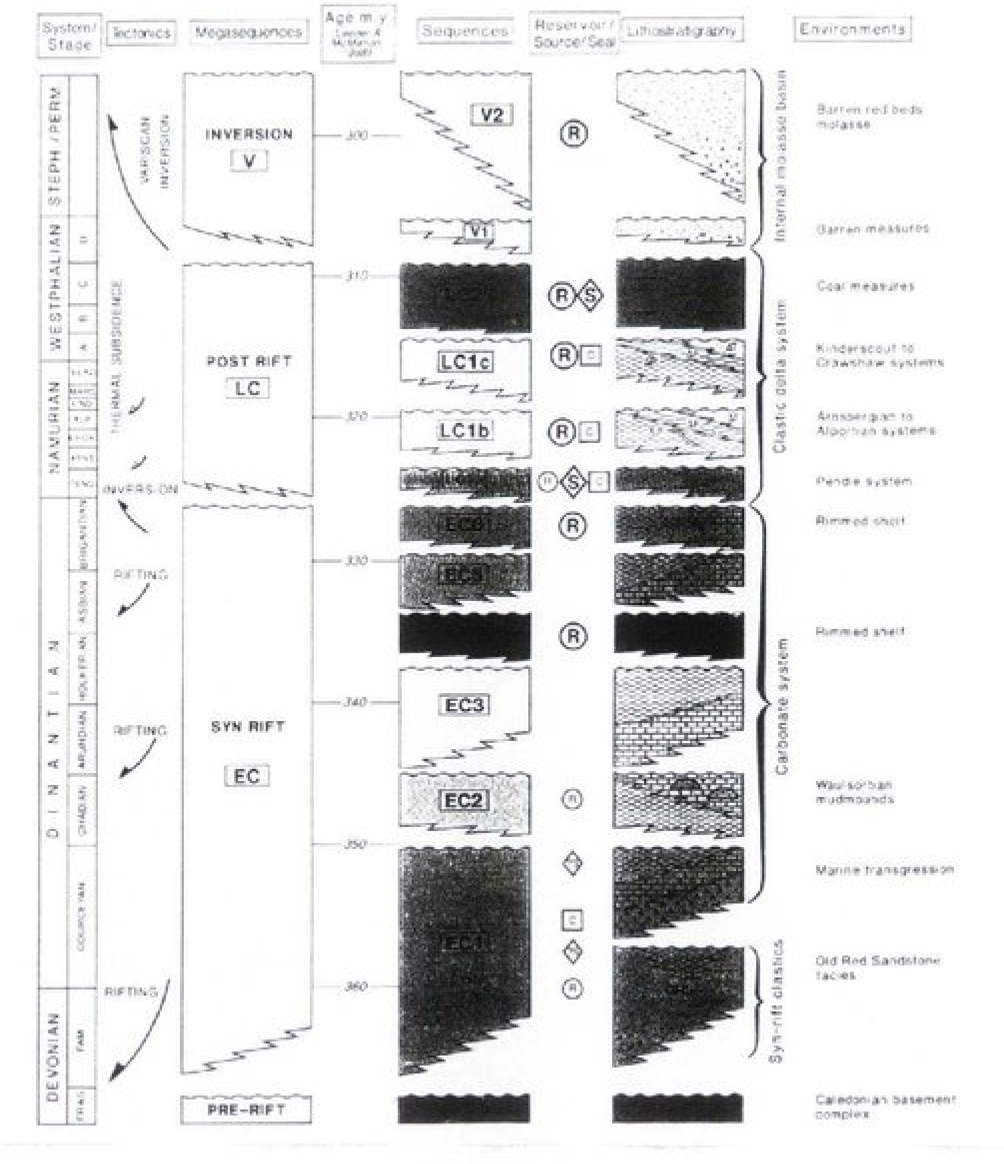
(Figure 2) Early Carboniferous structural elements. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.



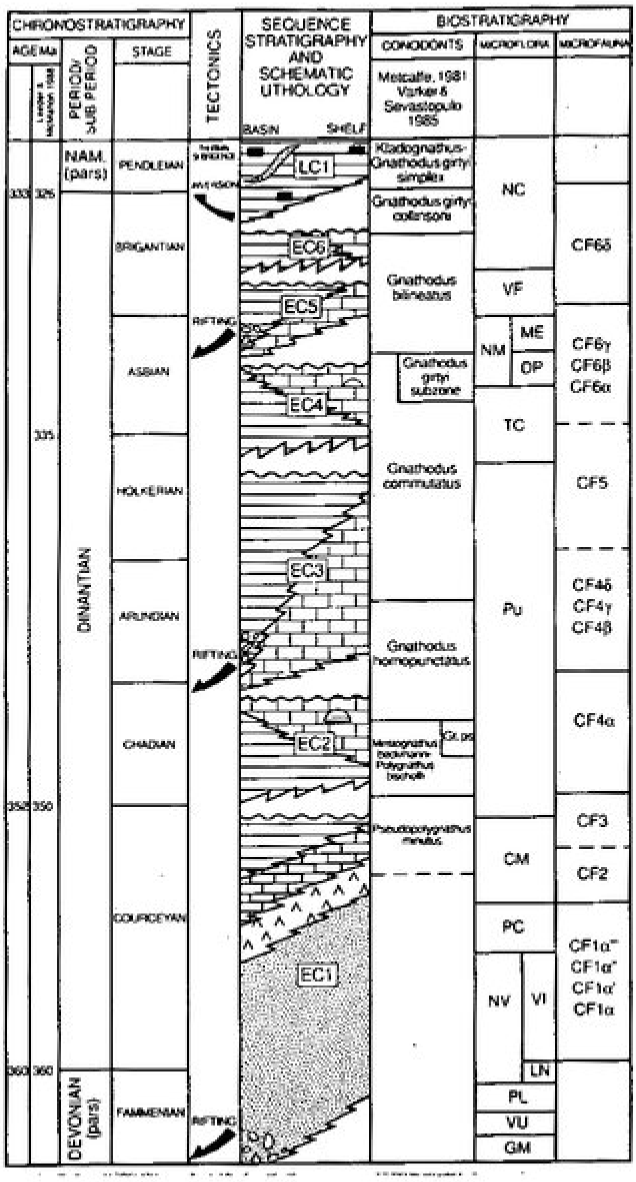
(Figure 9) East Midlands Dinantian structural elements. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

Megasequence		Sequence	Age	Tectonics/Facies Description
Inversion		VI	Late Westphalian C–Stephanian	Strong uplift and erosion of syn-rift depocentres. Accumulation of barren red beds and coarse pebbly sands and fanglomerates in internally drained molasse basins.
Post-rift		LC2	Early Westphalian A–late Westphalian C	Thermal subsidence. Establishment of upper delta plain, coal swamp conditions over much of Northern England. Progradation of Pennine delta southwards across Wales–Brabant massif.
		LC1	Late Brigantian–early Westphalian A	Onset of post-rift thermal subsidence. Drowning of shelf margins and development of intra-shelf basins (see Gutteridge 1987) following marine transgression over inverted topography. Progressive advance of deltaic systems from northeast drowning carbonate platforms.
Syn-rift	III	EC6	Early–mid Brigantian	Basin inversion event resulting in a regressive phase. Carbonate ramp to rimmed shelf development in the East Midlands with margins both aggradational and progradational.
		EC5	Late Asbian–early Brigantian	Reactivation of extensional fault regime with significant back-stepping of fault system in Widmerpool Gulf (Fig. 6). Renewed footwall rotation and erosion and development of boulder beds and slumps basinward of drowned margins.
	II	EC4	Late Holkerian–mid Asbian	Stillstand or regressive phase. Carbonate ramp to rimmed shelf development with margins both aggradational and progradational.
		EC3	Late Chadian–late Holkerian	Rejuvenation of extensional faults causing rotation of fault blocks and significant footwall erosion. Development of boulder beds and slumps (see Gawthorpe 1987) and drowning of carbonate shelf margins.
	I	EC2	Chadian	Stillstand or regressive phase. Carbonate ramp to rimmed shelf development with the growth of Waulsortian-type mud mounds on the upper part of ramp.
		EC1	Late Devonian–Courceyan	Initial development of half graben. Downlapping subaerial fan sequence developing into Old Red Sandstone fluvial plain deposits. Marine transgression marked by progressive onlap of basement by carbonate slope deposits.
Pre-rift		PZ	Pre–late Devonian	Caledonian granite and folded lower Palaeozoic basement complex.

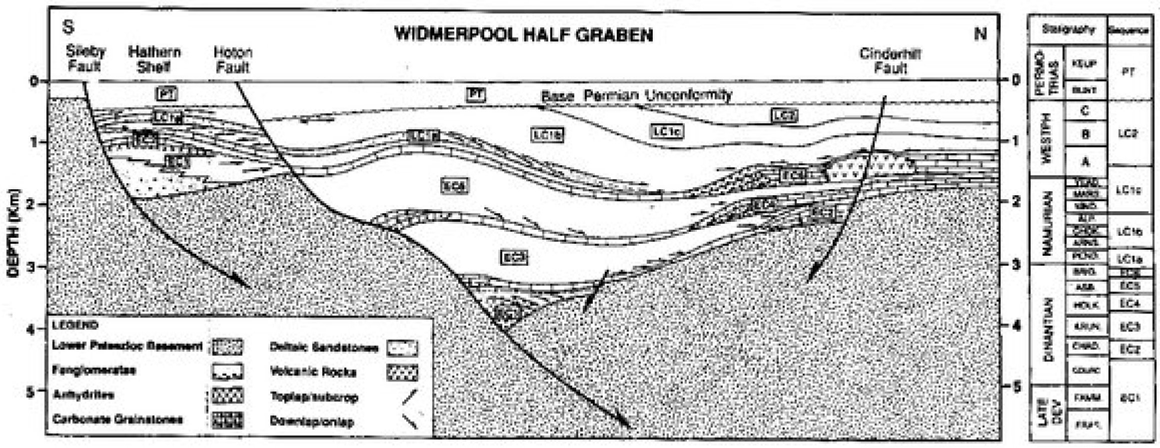
(Figure 4) Sequence stratigraphy of the Variscan cycle in the Central England rift system. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.



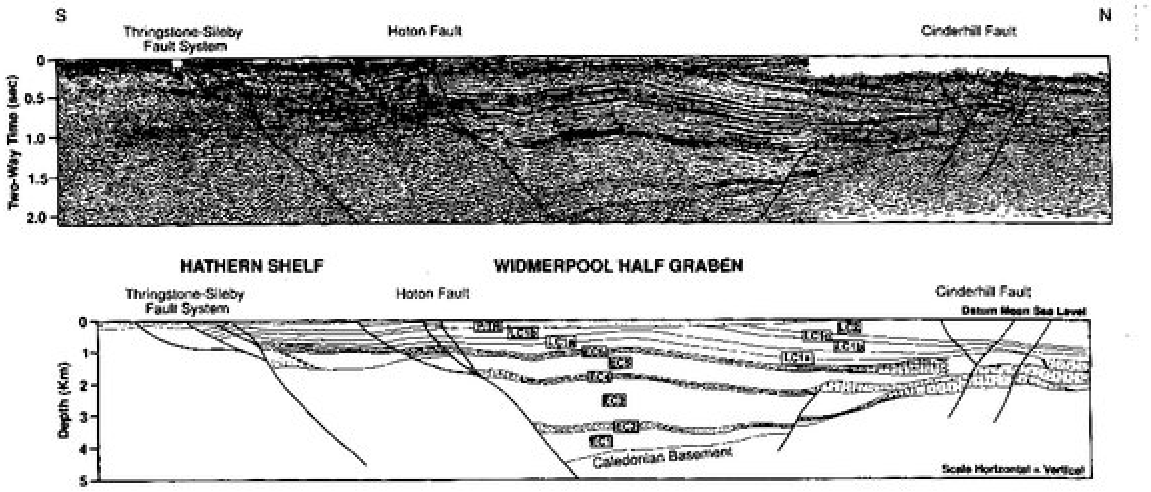
(Figure 5) Summarised stratigraphy of the Variscan plate cycle in the East Midlands showing megasequence and sequence development. AT delta top, AF delta front, AP pro-delta. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.



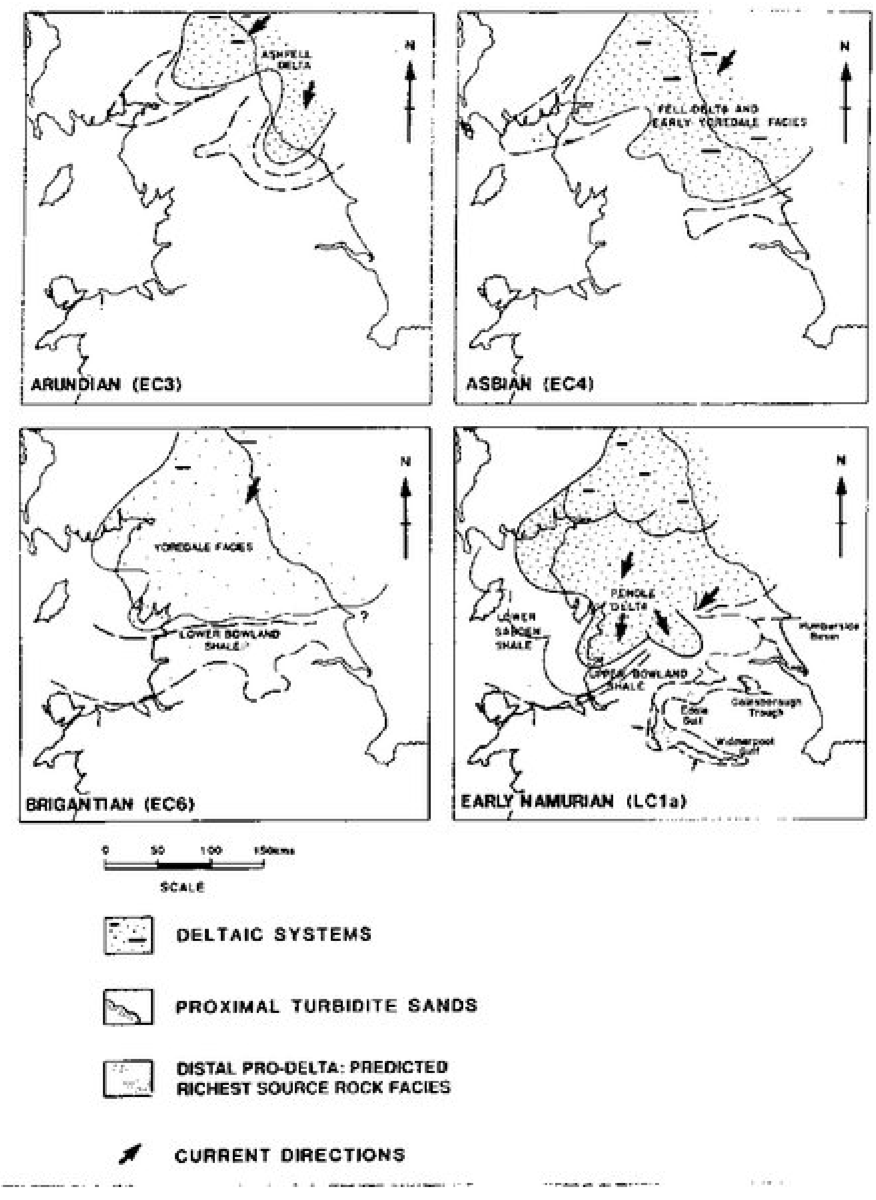
(Figure 6) Dinantian seismo-stratigraphic summary, Widmerpool half-graben. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.



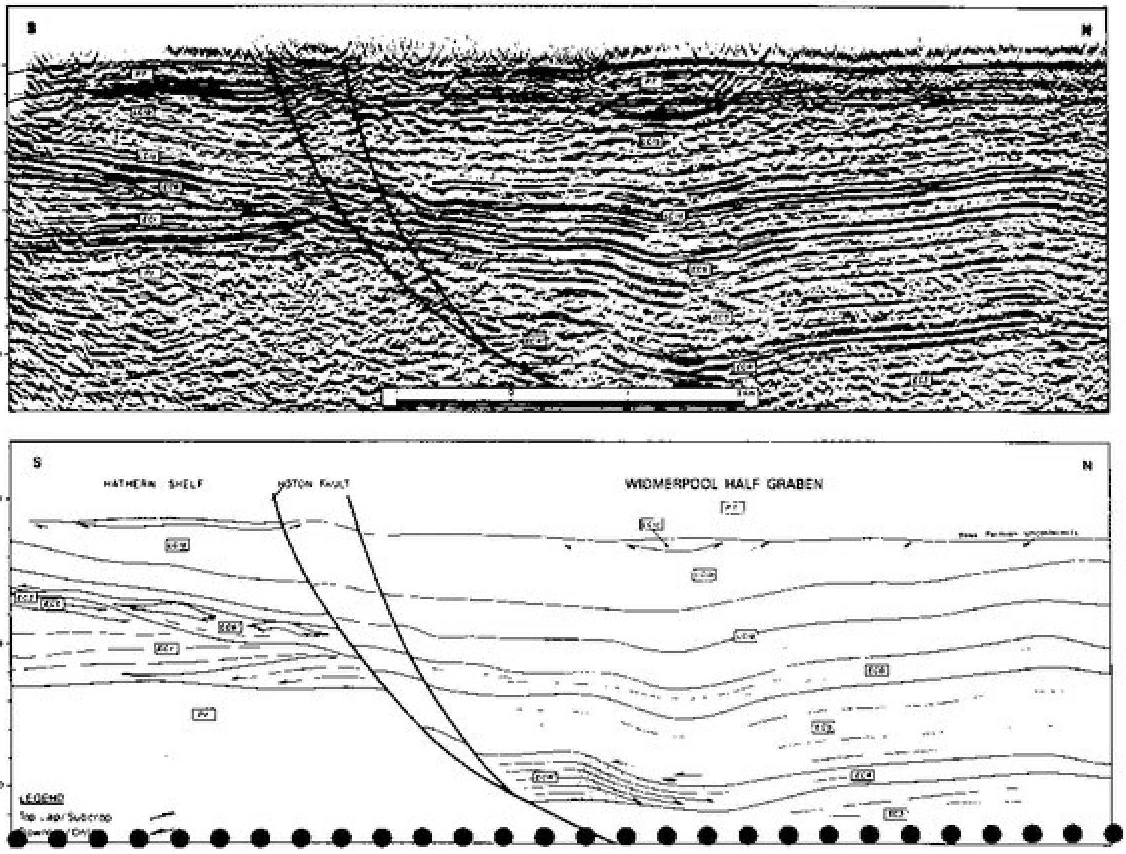
(Figure 7) Composite sketch of seismo-stratigraphic interpretation, western Widmerpool half-graben. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.



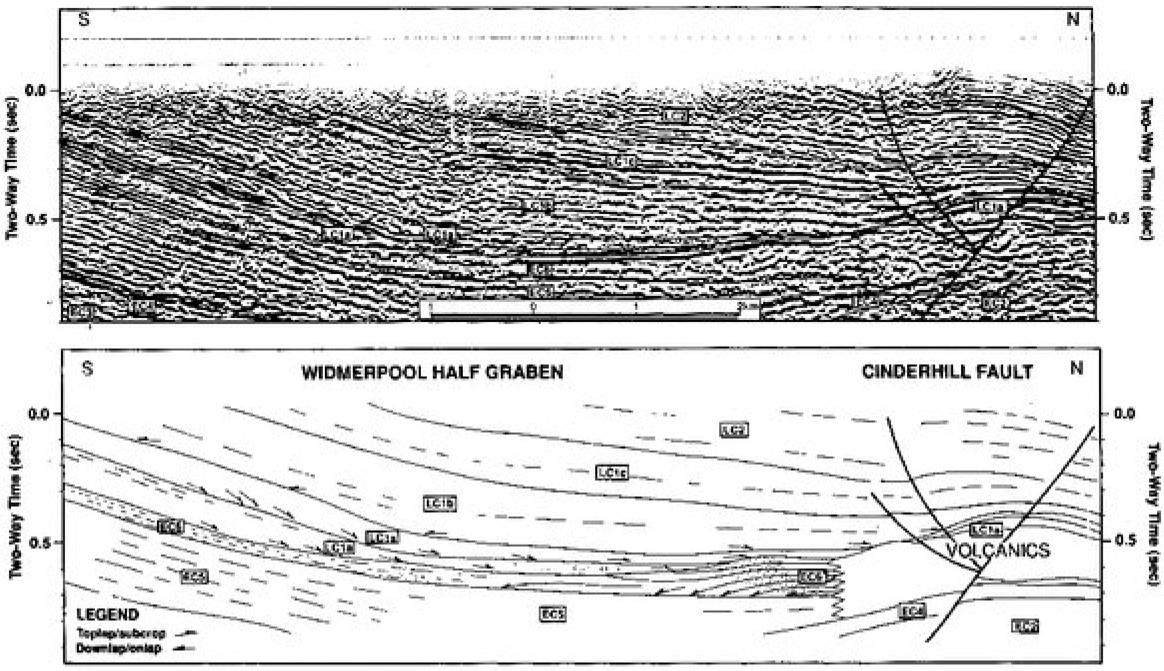
(Figure 10) Composite seismic and interpreted geological section across the Widmerpool half-graben and Hathern shelf, East Midlands. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.



(Figure 8) Delta advance during the middle to late syn-rift and early post-rift and its relationship with source rock distribution and age in northern England. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.



(Figure 11) Sequence architecture, southern margin of the Widmerpool half-graben. LC1c delta slope; LC1b prodelta turbidites; LCla distal prodelta; EC6' shelf carbonates and mudstones; EC6 basinal carbonates; EC4' carbonate rimmed shelf margin; EC4 basinal carbonate; EC3 basinal carbonate and mudstone; EC2 shelf carbonate; EC1 evaporite/ carbonate slope deposits; Pz Basement; PT Permo-Triassic. Reproduced from Ebdon et al. (1990) with permission. © Geological Society of London.



(Figure 12) Sequence architecture, northern margin of the Widmerpool half-graben. LC2 delta top; LC1c delta slope; LC1b prodelta turbidites; LCla distal prodelta; LCla' carbonate shelf/condensed mudstone sequence; EC6' carbonate rimmed shelf margin; EC6 basinal carbonates; EC5 basinal mudstone; EC4 basinal carbonate; EC3 basinal carbonate and mudstone; EC2 shelf carbonates; EC1 evaporite/ carbonate slope deposits. Reproduced from Ebdon et al. (1990)

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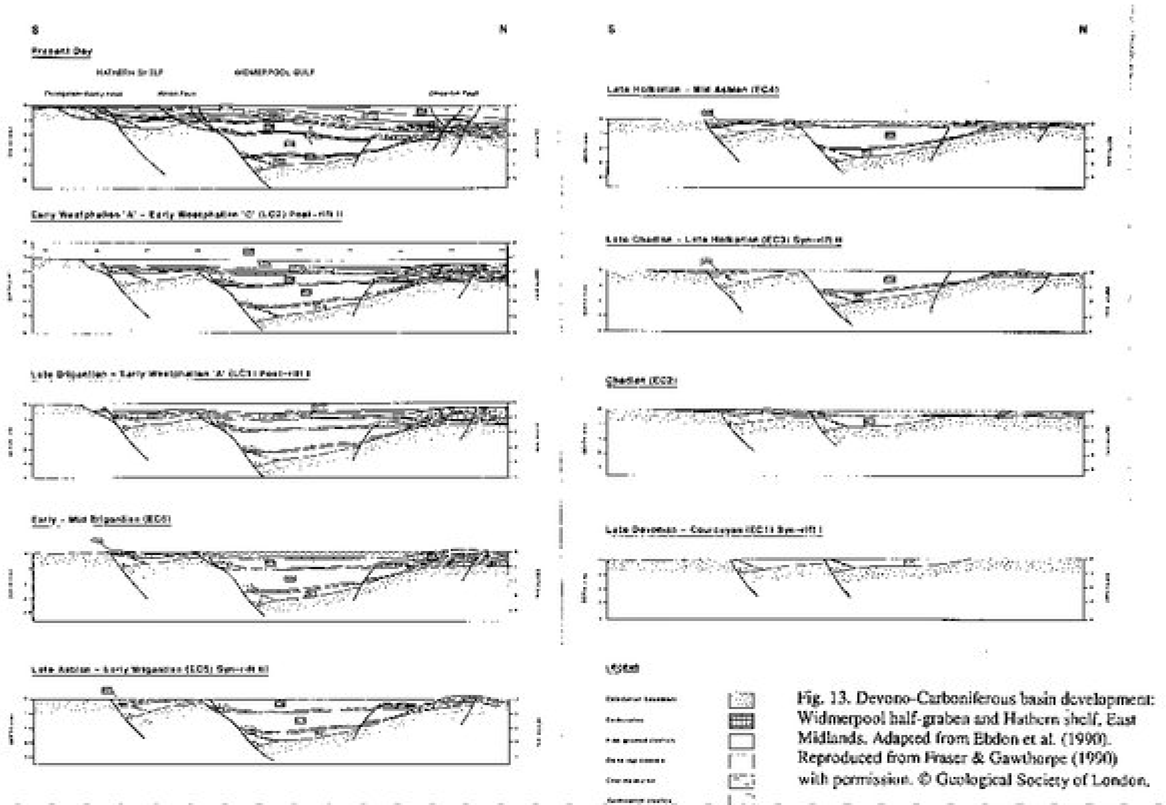
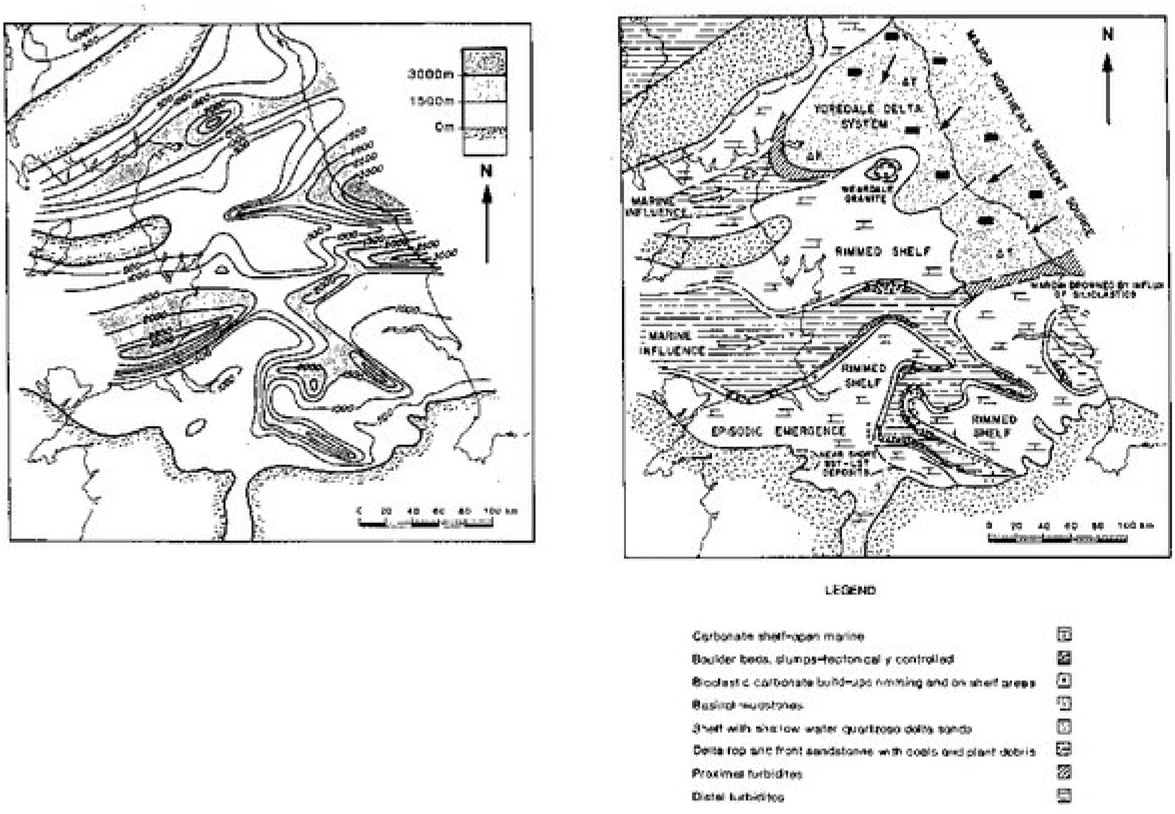
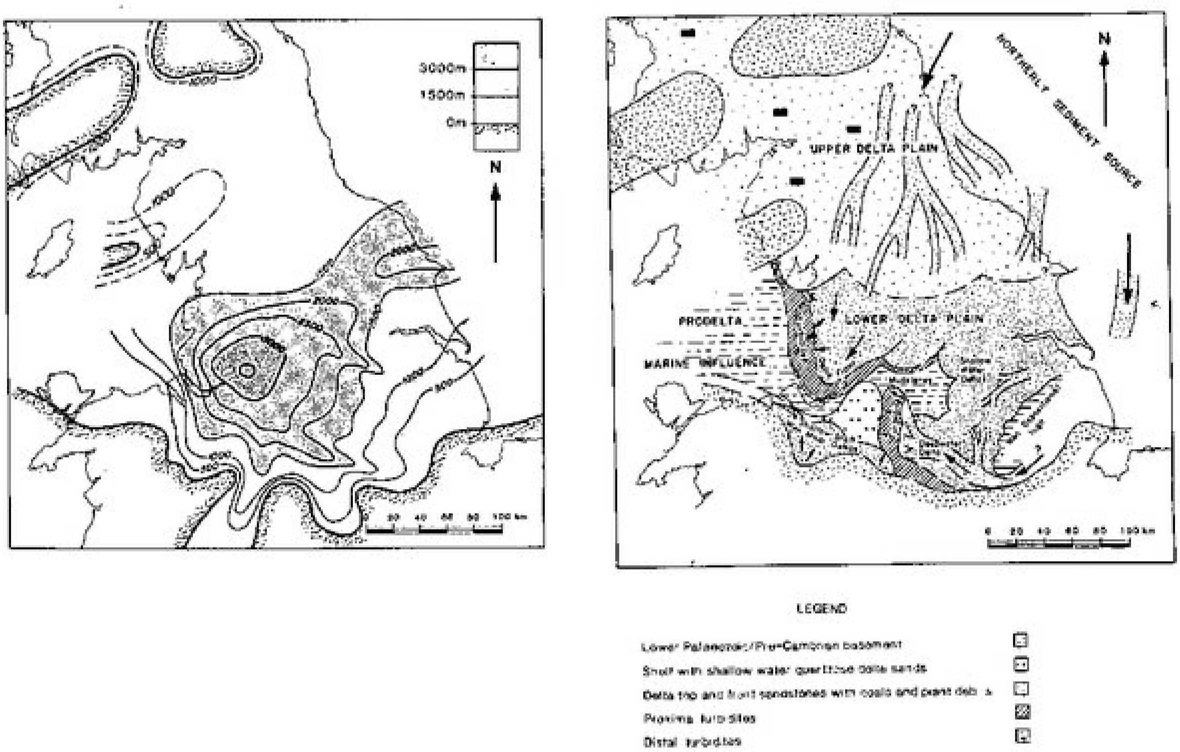


(Figure 13) Devono-Carboniferous basin development: Widmerpool half-graben and Hathern shelf, East Midlands. Adapted from Ebdon et al. (1990) Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

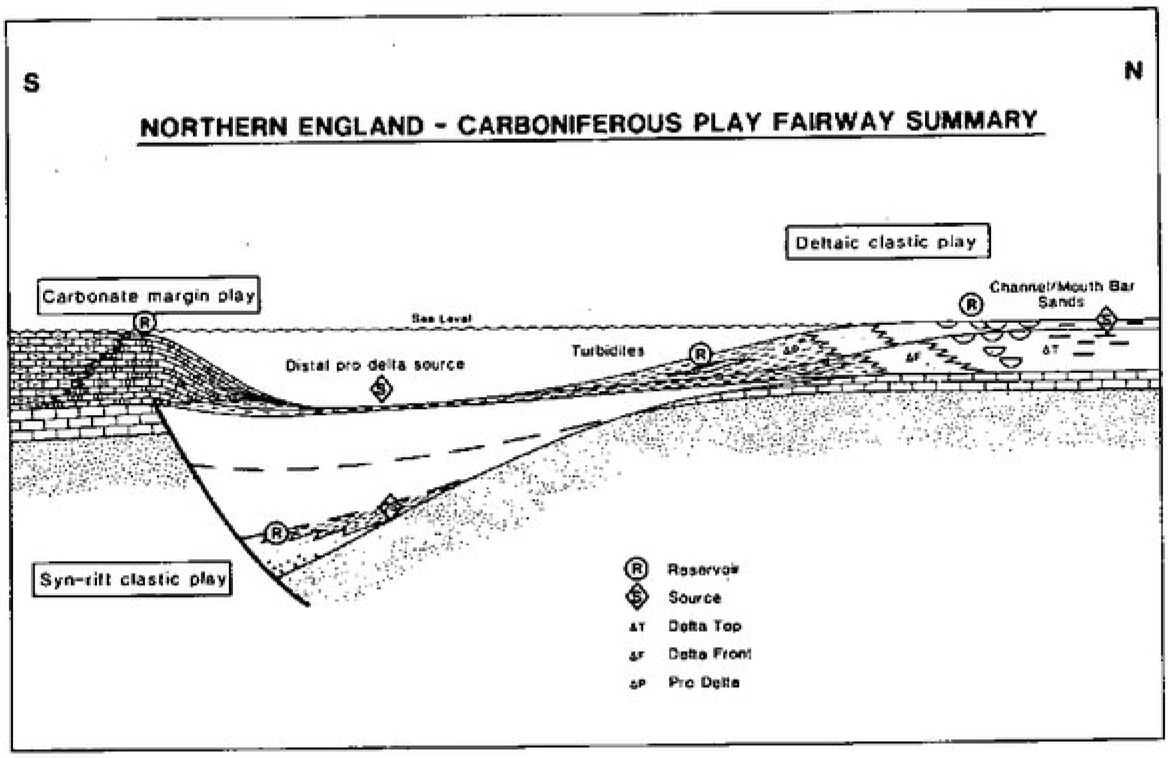


(Figure 14) Isopach and facies maps for the syn-rift megasequence. (a) Restored isopachs for syn-rift sequences EC2-EC6 (Chadian-early Brigantian) Data from George (1958), Leeder (1974) (b) Palaeofacies map for syn-rift sequence EC4 (late Holkerian-mid Asbian) AT delta top, AF delta front, AP pro-delta. Incorporates data from Stevenson & Gaunt

(1971), Leeder (1974), Miller & Grayson (1982), Smith et al. (1985), Aitkenhead et al. (1985), Gawthorpe 1987a and Grayson & Oldham (1987). Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.

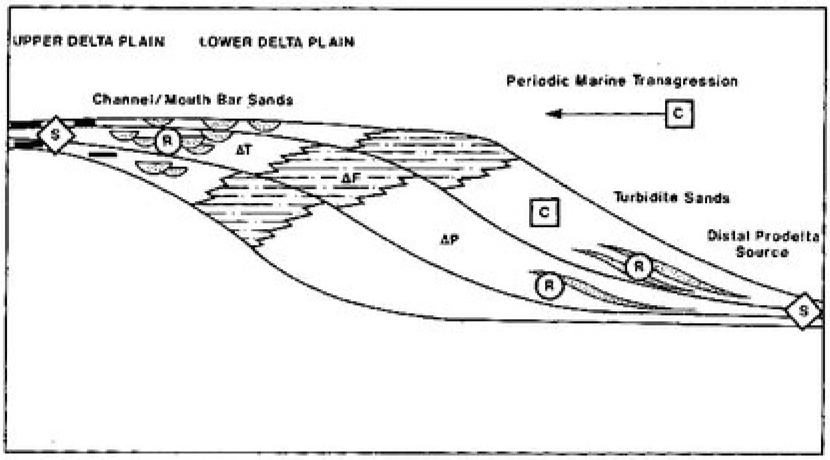


(Figure 15) Isopach and facies maps for the post-rift megasequence. (a) Restored isopachs for post-rift sequences LC1-LC2 (Namurian-Westphalian C). Data from Wills (1951), Kent (1966), Calver (1968), Leeder (1982), Guion & Fielding (1988). (b) Palaeofacies map for post-rift sequence LC1c (Kinderscoutian to late Westphalian A). Data from Collinson et al. (1977), Reading (1964) and Guion & Fielding (1988). Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.



(Figure 16) Intra-Carboniferous play fairway summary. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.

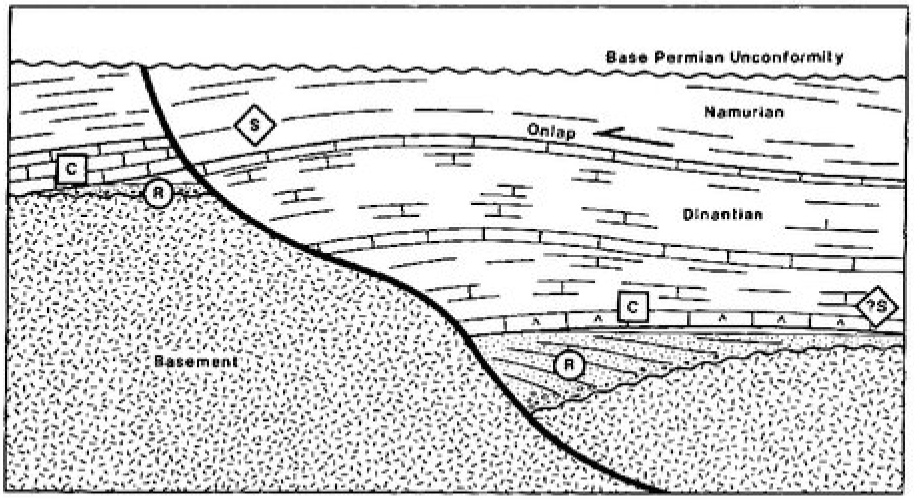
CLASTIC DELTA SYSTEMS



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.

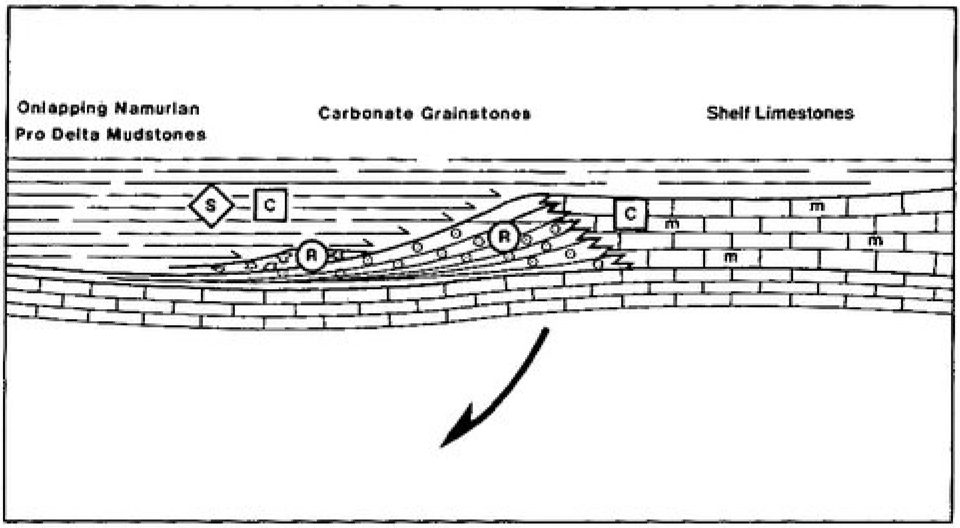
(Figure 17) Carboniferous clastic delta system play fairway summary. AT delta top, OF delta front, AP pro-delta. Reproduced from Fraser & Gawthorpe (1990) with permission. 0 Geological Society of London.

SYN–RIFT SANDSTONES



RESERVOIR :	Upper Devonian - Courceyan syn-rift conglomerates 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 depths of reservoir burial in hanging wall. (ii) Limited distribution. (iii) Play relies heavily on unproven early syn–rift source.

(Figure 18) Early syn-rift clastic play fairway summary. S source, C seal, R reservoir. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.



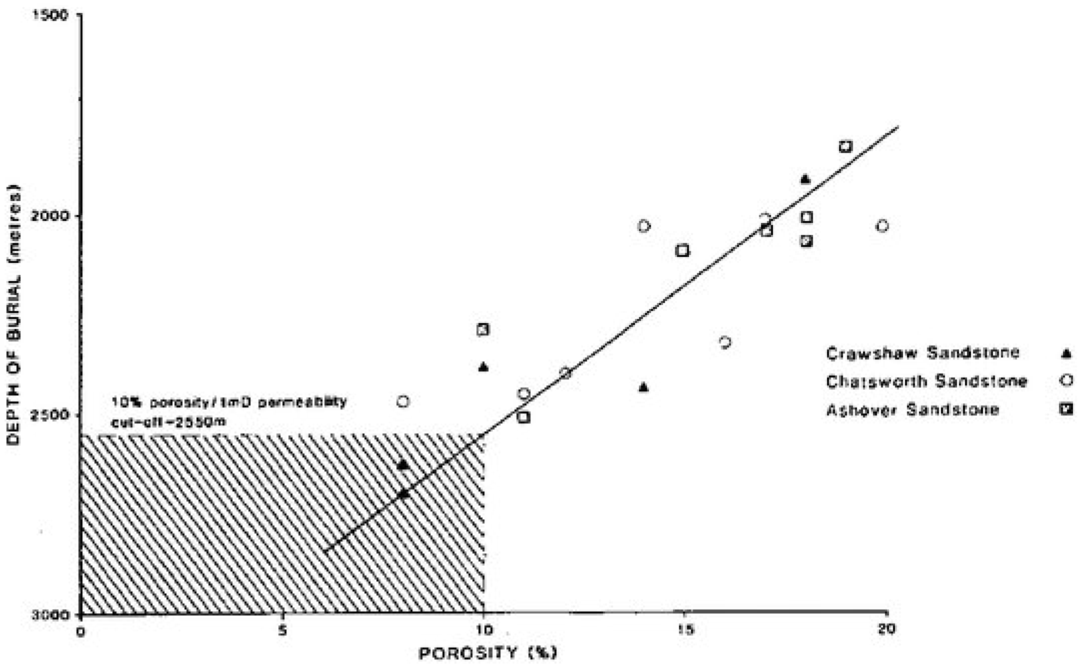
RESERVOIR : Chadian/late Asbian/early Brigantian grainstones

SEAL : Onlapping late Dinantian and Namurian pro-delta mudstones
Lateral facies change into tight shelfal limestones

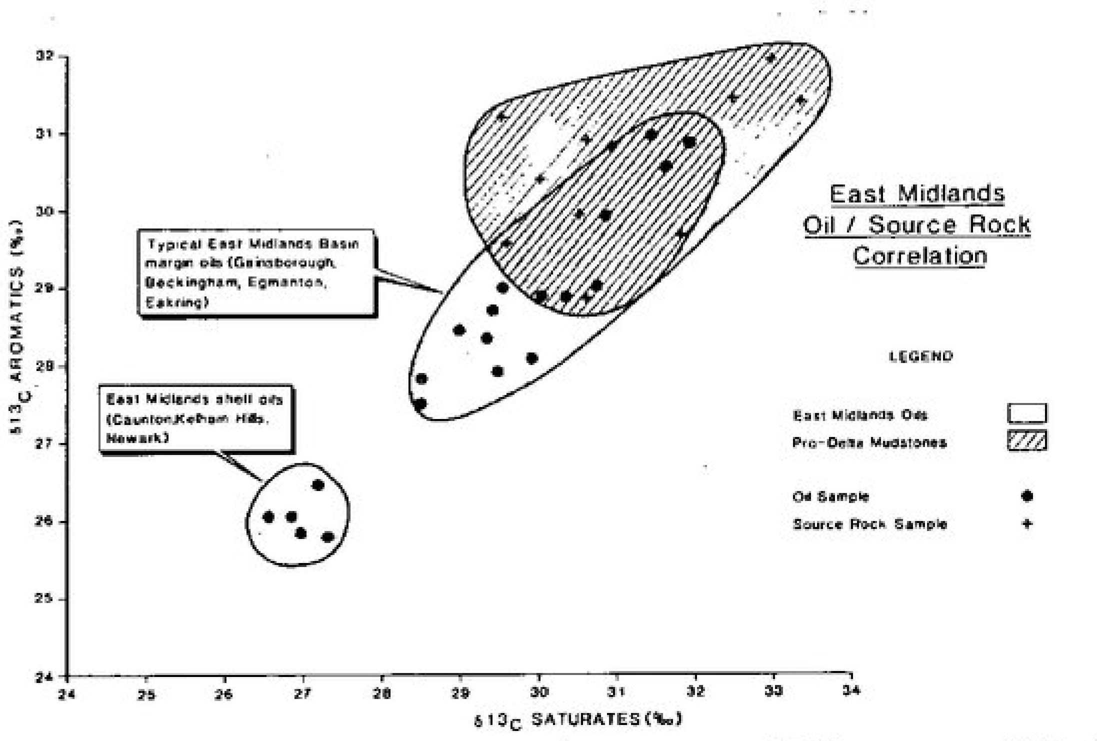
SOURCE : Interdigitating and onlapping late Dinantian/early Namurian mudstones
(Bowland Shales and equivalents)

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

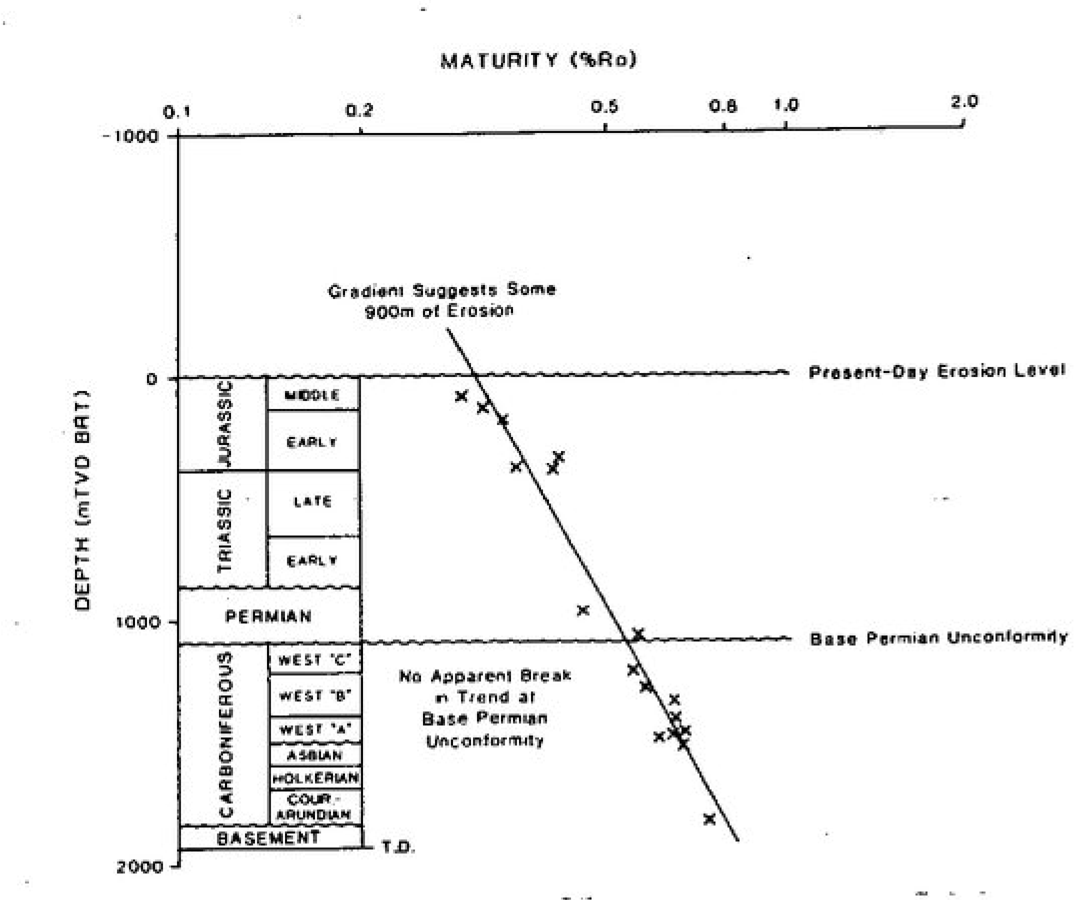
(Figure 19) Dinantian carbonate shelf margin play fairway summary. Reproduced from Fraser & Gawthorpe (1990) with permission. © Geological Society of London.



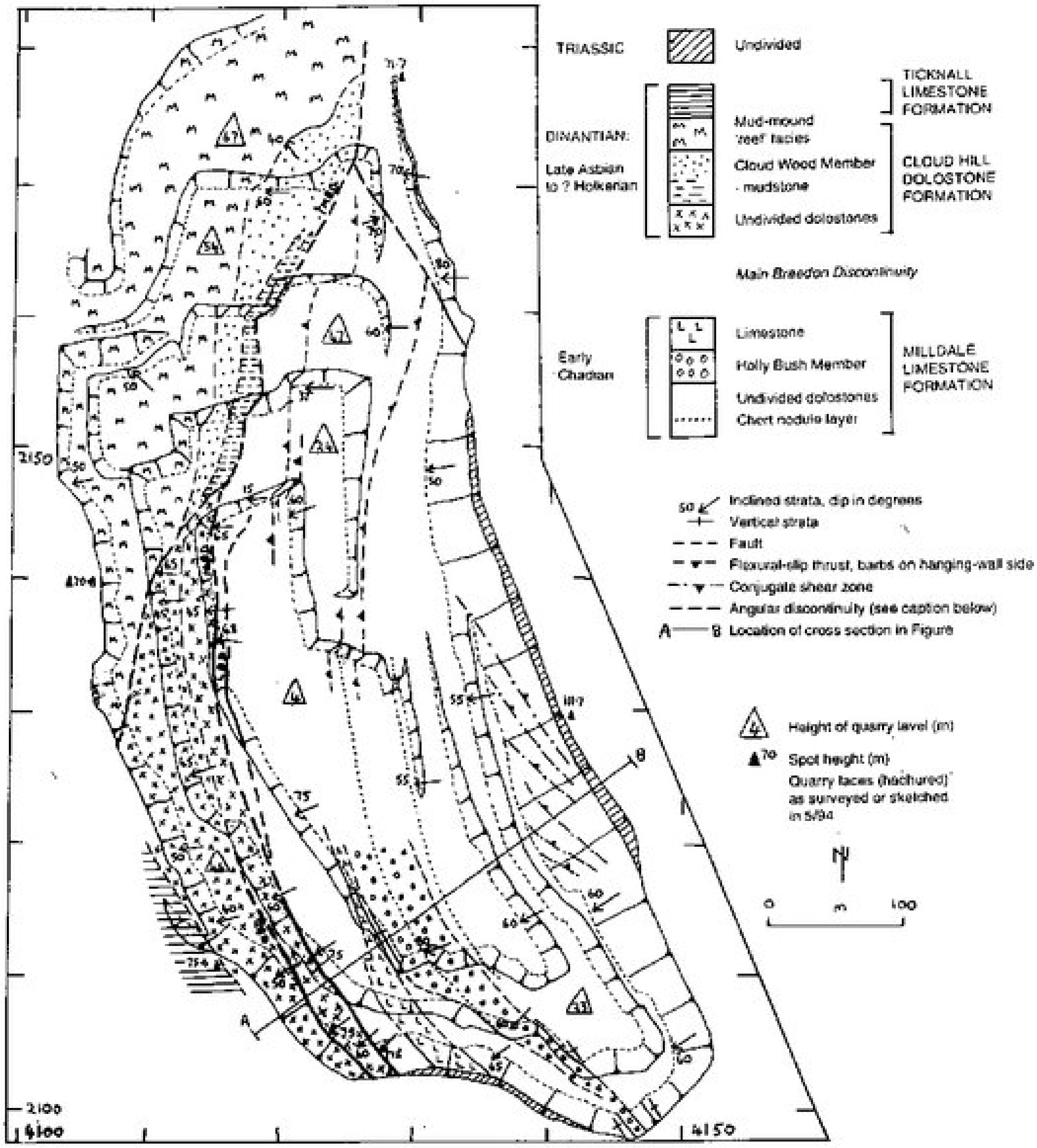
(Figure 20) Porosity against depth plot for Namurian-early Westphalian channel sandstone facies from wells in the East Midlands. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.



(Figure 21) East Midlands oil/source rock correlation. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.



(Figure 22) Maturity against depth profile for the well Bardney 1 in the East Midlands based on vitrinite reflectance data. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.



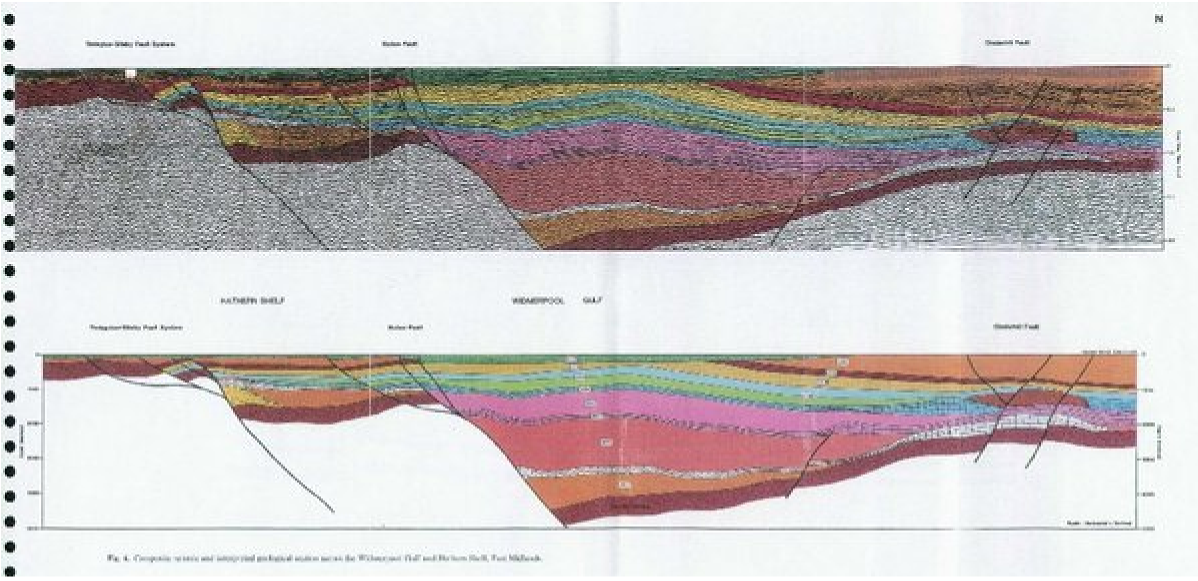
(Figure 24) Geology of Cloud Hill Quarry (UBD=Upper Breedon Discontinuity, MBD=Main Breedon Discontinuity, LBD=Lower Breedon Discontinuity). From Carney & Ambrose (1999). ©NERC

Parsons (1918)		Mitchell & Stubblefield (1941)		Monteleone (1973)			This Account			
		Upper Reef and bedded Limestones	B_2	CLOUD HILL DOLOMITE FORMATION	Bioherm Member	D_1		TICKNALL LIMESTONE FORMATION		
		Bedded Breccia	D_1					CLOUD HILL DOLOSTONE FORMATION	Late Asbian	D_1
		Upper Red Beds	D_1?							
		Lower Reef Limestones	B_1 or S_2?							
?—?—?—? Thinly bedded Red Dolomite with thin shale partings ?—?—?—?	? D_2-D_3 ?	Lower Red Bed and Pebble Bed Group (UNCONFORMITY)	C_2S_1		Red bed Member (FAULT)	C_2S_1	Cloud Wood Member	MAIN BREEDON DISCONTINUITY	Early Asbian - Late Holkerian	S_2-D_1
Yellow Dolomite with chert	D_2-D_3	Massive Bedded Dolomites with *L. humerosus*	C_2		Massive Bedded DolomiteMember with *L. humerosus*	C_2S_1	Holly Bush Member	MILLDALE LIMESTONE FORMATION	Early Chadian	C_1
?—?—?—? Yellow Dolomite with *Levitusia humerosus* and no chert	? D_1									

Coral/brachioped Zones
C_2, C_2S_1 Chadian - Arundian
S_2 Holkerian
D_1 Asbian
D_2-D_3 Brigantian

Ammonoid Zones
B_1, B_2 Asbian

(Figure 25) Comparative stratigraphical terminology for the Carboniferous Limestone of the Breedon on the Hill and Cloud Hill inliers. From Carney & Ambrose (1999). ©NERC



(Plate 1) Composite seismic and interpreted geological section across the Widmerpool Gulf and Hathern Shelf, East Midlands. Reproduced from Fraser et al. (1990) with permission. © Geological Society of London.