



A review of the Carboniferous shale gas potential of northern England: a data-based analysis of why it won't work

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Abstract: The recent shale gas revolution originated in the USA in the late 1990s with the exploration of the Carboniferous Barnett Shale in Texas. Success in a number of additional basins in North America, such as the Marcellus, Eagle Ford and Bakken basins, stimulated a search for similar opportunities elsewhere around the world. Among the shales and basins targeted by industry was the Carboniferous Bowland Shale (and equivalents) in northern England. The initial premise that the Barnett Shale represented an excellent analogue for the Bowland Shale led to over-optimistic reserve estimates that have since been shown to be largely incorrect. On the basis of visual inspection of wellbore cores, the Carboniferous Barnett and Bowland shales appear to be very similar. Unfortunately, it is there that the similarity ends. Research carried out for the UK Unconventional Hydrocarbons project has highlighted important differences adversely impacting prospectivity. These can be summarized as basin type/continuity and structural complexity. The total organic carbon, maturity, mineralogy and thickness of the Bowland Shale and equivalents are broadly similar to the successful US examples. Our conclusion is that the Bowland Shale in the UK does not represent a technically significant resource, and in hindsight did not merit the considerable industry and media attention that has been associated with it. One key learning is that fundamental research based on heritage data and modern analytical and modelling techniques should have preceded drilling and fracking operations in northern England.

Supplementary material: Tabulated data recording the mineralogical and geochemical analysis carried out for this study on BGS core samples by EGI in Utah are available at <https://doi.org/10.6084/m9.figshare.c.7027899>

The shale gas and oil revolution in the USA has transformed their energy market (Stephenson 2015). A seminal moment in October 2014 saw the USA produce more oil per day than Saudi Arabia. The potential for the technology developed in the USA to be applied to shale basins elsewhere in the world including the UK (Selley 2012) has energized geologists and engineers over the past 10 years.

The initial part of the research presented here was carried out in a joint Energy and Geoscience Institute (EGI)/Imperial UK shales study. This was largely industry funded and was designed to provide an independent assessment of UK shale potential, bringing together the joint expertise of the EGI at the University of Utah and Imperial College London. The project involved sampling analysis of over 100 Carboniferous core samples from basins in northern England, including many from the Bowland Shale and equivalents. A broad coverage was chosen reflecting core availability and the wish to screen for organic-rich intervals over several stratigraphic

intervals. At the time of sampling, the new boreholes drilled by industry had not been released and have not been included in this study. However, further data collection and analysis in the past 5 years funded by the Natural Environment Research Council/Economic and Social Research Council (NERC/ESRC) UK Unconventional Hydrocarbons research project has added to this earlier study and is reported elsewhere in this volume, e.g. Lodhia *et al.* (2023), Hennissen *et al.* (2024), Sims *et al.* (2024) (Fig. 1).

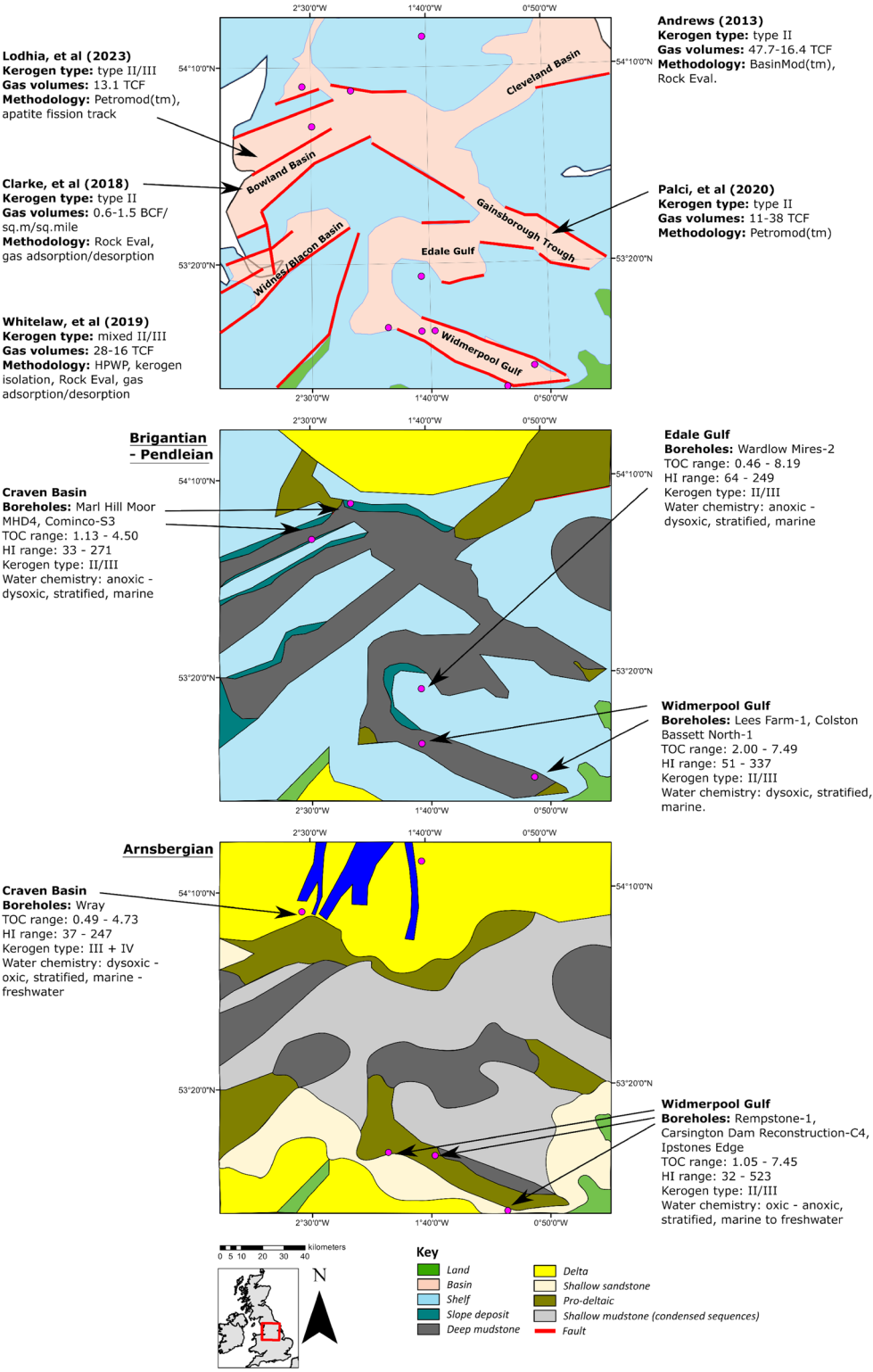
An extensive core sampling programme was undertaken at the British Geological Survey (BGS) Core Store facilities in Keyworth in Nottinghamshire. Although the Bowland Shale can be observed at outcrop in Lancashire and Derbyshire, it was felt that archive core material would produce more reliable results than weathered outcrop samples. During the initial part of the study, the core chips were transferred to EGI in Salt Lake City for detailed geochemical and petrological/mineralogical analyses using programmed pyrolysis (HAWK), X-ray diffraction

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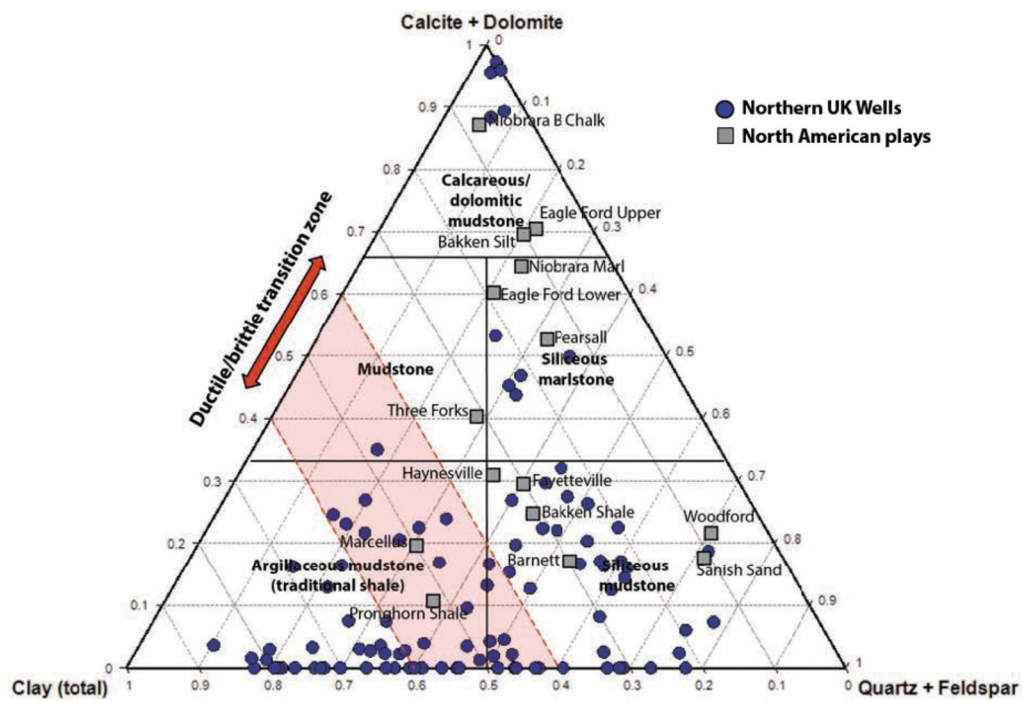


Fig. 2. Overview of mineralogical data derived from X-ray diffraction (XRD) analysis for northern England Carboniferous wells. The XRD ternary plot uses gross mineralogical parameters as axes, with lithological rock types shown. The ductile/brittle transition zone and potentially analogous Northern American plays are shown for reference. Readers should note that North American plays are a gross average of XRD mineralogical data.

(XRD) mineralogy and optical and scanning electron microscope (SEM) petrological investigation techniques. The results of these analyses have been combined with an extensive literature and 2D seismic-based regional mapping project to derive play risk maps providing a relative assessment of shale gas potential in the UK (Palci *et al.* 2020).

An initial assessment of the shale oil and gas potential in the onshore UK (Andrews 2013) suggested that considerable potential existed for gas in the Carboniferous basins of northern England. The new research presented in this paper has shown that earlier estimates of shale gas potential in the Bowland Shale were over optimistic, perhaps by an order of magnitude (Whitelaw *et al.* 2019; Hennissen *et al.* 2024). On initial inspection of the laboratory results there was some optimism that rocks of the Bowland Shale exhibited organic carbon contents

consistently in excess of 2% and on occasions over 10% in discrete bands. Analyses also indicated that from a mineralogical point of view, the Bowland Shale shared similar silica and carbonate content to the Barnett and Marcellus shales of the USA (Fig. 2).

Recent research carried out at Imperial College and in collaboration with colleagues at the BGS and Manchester, Bristol, Heriot-Watt, Leicester and Nottingham universities focused on merging the sample analyses from heritage core material with a basin-wide understanding of the tectonostratigraphic setting of these shale deposits. Much of this research is presented in this volume (e.g. Lodhia *et al.* 2023; Hennissen *et al.* 2024; Sims *et al.* 2024). Extensive use was made of the excellent UK Onshore Geophysical Library (UKOGL) seismic database and access to released onshore borehole data from across the northern England

Fig. 1. Maps of the Carboniferous annotated with regional specific details adapted from Andrews (2013), Fraser and Gawthorpe (2003) and Lodhia *et al.* (2023). (a) The specific areas published Bowland Shale resource estimates are associated with. (b) The general environmental interpretation of boreholes used in the current study for different basins, which were specially selected on the basis of the presence of Brigantian to Pendleian stratigraphy. (c) Similar to (b) but for Arnsbergian strata and data. TOC, total organic carbon; HI, hydrogen index.

Carboniferous. This has allowed us to generate detailed maps of the distribution, thickness and facies, focused on the organic-rich Bowland Shale. We have used a combination of simple 1D basin modelling and more sophisticated 2D and 3D basin modelling techniques to describe the Bowland Shale petroleum system and predict maturity and generation volumes (both expelled and retained) (Palci *et al.* 2020). Each basin has undergone significantly different post-deposition burial, faulting and uplift, and this is reflected in the relative potential of each basin.

More recent volumetric estimates have been provided by several authors using Rock-Eval techniques rather than analogues. For example, the estimated in-place shale gas and oil resources in the Carboniferous Bowland Shale in the Gainsborough Trough was estimated by Palci *et al.* (2020) using 3D petroleum systems modelling as 11–38 trillion cubic feet (TCF) of gas and 8–26 billion barrels of oil; Lodhia *et al.* (2023) estimated 13.1 TCF of gas in the Bowland/Craven Basin using petroleum systems modelling with burial and uplift calibrated by apatite fission track analysis (AFTA); Clarke *et al.* (2018) used Rock-Eval to estimate 0.6–1.5 billion cubic feet (BCF), again in the Bowland/Craven Basin (Fig. 1).

Regional geology

Area of interest

The area covered by this review incorporates all the half graben identified in the northern England Carboniferous rift system (Fig. 3).

The Early Paleozoic Southern Uplands and Wales–Brabant Massif represent the northern and southern geological limits of the study area. The main Carboniferous basins assessed are the Bowland (Kirby *et al.* 2000; Clarke *et al.* 2018; Anderson and Underhill 2020), Blacon (Widnes) Basin (Emmings *et al.* 2023; Hennissen *et al.* 2024), Cleveland Basin (Hughes *et al.* 2018), Edale Gulf (Hennissen *et al.* 2017; Waters *et al.* 2020), Gainsborough Trough (Palci *et al.* 2020) and Widmerpool Gulf (Könitzer *et al.* 2016; Hennissen and Gent 2019; Sims *et al.* 2024). The Midland Valley of Scotland has not been included in this study. The Midland Valley shales are of similar Carboniferous age, but the depositional environment and later tectonic modification and burial history are very different, being largely delta top rather than pro-delta environments (Underhill *et al.* 2008).

Stratigraphy

A total of 270 key wells, which have penetrated Lower Carboniferous strata in northern England,

have been incorporated in this study. Details of the wells used in the study including stratigraphy, logs and well reports can now be accessed via the BGS. The well data, such as lithology, age, thickness and so on, have been used to control palaeogeographic maps, generate isopachs and as fence posts in seismic stratigraphic interpretation in the Widmerpool Gulf, Gainsborough Trough, Edale Gulf, Bowland and Cleveland basins.

Detailed biostratigraphy carried out by BP and published by Ebdon *et al.* (1990) was used to constrain the chronostratigraphic framework within which this study is set. Their use of conodonts, microflora and fauna and the traditional goniatite stratigraphy (Ramsbottom 1973, 1977) provides a high-resolution (equivalent to ammonite zone) framework. The key observation is that the organic-rich Bowland Shale and equivalents young southwards in advance of the southwards progradation of the Pennine Delta. This led to an earlier, probably erroneous, conclusion by Fraser *et al.* (1990) that the deltas were directly responsible for introducing organic matter into the basins. It now seems clear that organic matter enrichment in the Bowland Shale is attributed to the development of pervasive bottom-water anoxia in moderately restricted basins. Development of anoxia was potentially associated with weakly stratified, nutrient-rich conditions (Emmings *et al.* 2020a), the development of warm, saline bottom waters (Li *et al.* 2023) or some combination of the two mechanisms. While freshwater input from the major deltas potentially contributed to water column stratification, none of the established palaeoredox models favour development of a freshwater lid as a driver for anoxia in the Bowland Shale, and all favour normal marine to weakly hypersaline water column conditions in the photic zone and/or bottom waters (Gross *et al.* 2015; Emmings *et al.* 2020a; Li *et al.* 2023). Instead, the evidence shows anoxia developed most intensely during sea-level high-stands and became weakened during sea-level regression and delta progradation. Based on geochemical analysis, Sims *et al.* (2024) reported that shale samples from the Bowland (Craven), Widmerpool and Edale basins exhibit marine characteristics (Fig. 1). For example, parameters such as pristane/phytane ratios <1 indicate a marine, rather than terrestrial, origin for the organic matter.

Biostratigraphic data proved to be critical in the dating and correlation of sequence boundaries between isolated half graben and with the numerous outcrop-based studies that exist in the literature for the Carboniferous. Much well data, including summary biostratigraphic data, are now in the public domain and can be accessed via the BGS. Similarly, all the seismic reflection data can be accessed through the UKOGL website.

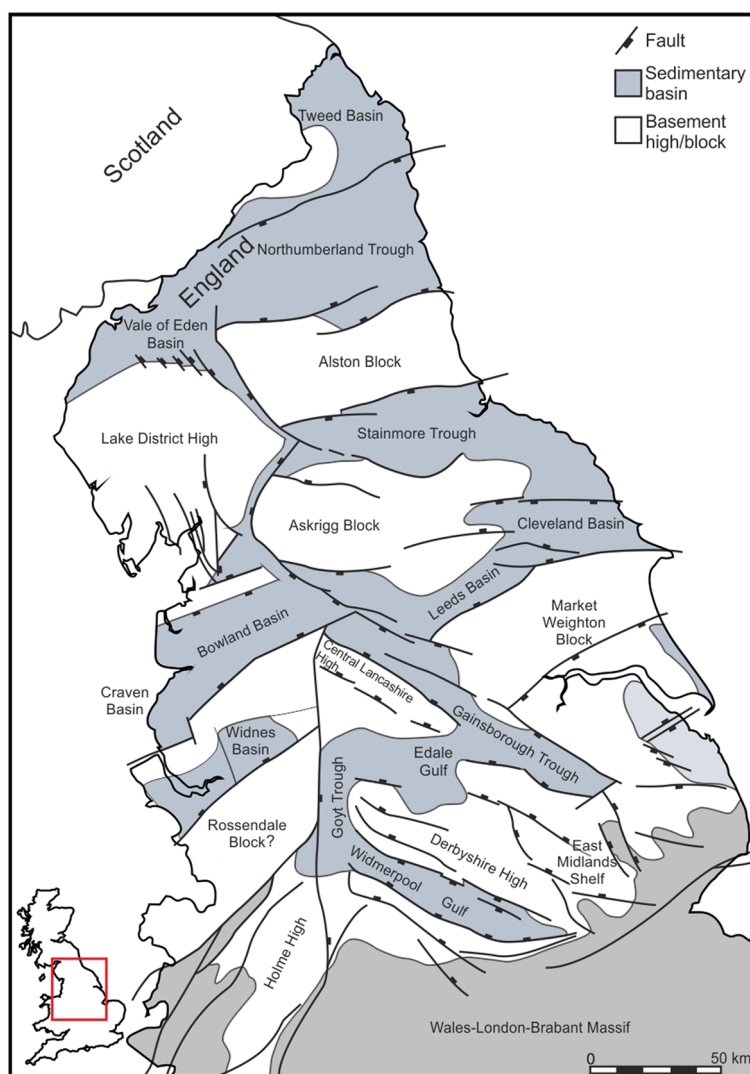


Fig. 3. Carboniferous rift basins of the onshore UK adapted from [Fraser and Gawthorpe \(1990\)](#). The basinal areas potentially containing the Bowland Shale and equivalent facies are represented by the grey shaded areas.

Tectonostratigraphic evolution of the Carboniferous

The structural configuration of the northern England Carboniferous rift system has its origins in the earlier Caledonian orogeny ([Coward 1993](#); [Pharoah *et al.* 1987](#)). NW–SE- and NE–SW-trending extensional faults can be directly related through seismic and outcrop analysis to pre-existing Caledonian faults, e.g. the Dinorwic Fault in Wales and the Pendle Fault forming the southern boundary of the Bowland Basin.

Carboniferous basin evolution in northern England can be characterized as a series of three

megasequences. Each megasequence represents a particular phase of basin evolution and is characterized by a dominant basin-forming process related to plate margin processes in the evolving Variscan Orogeny to the south ([Knott *et al.* 1993](#)). Megasequences can in turn be broken down into a series of tectonostratigraphic sequences that describe the Upper Devonian–Carboniferous fill of the basins in more detail ([Fig. 4](#)).

The boundaries of the tectonostratigraphic sequences presented in this study may vary markedly around the basin owing to spatial variations in accommodation development and/or sediment

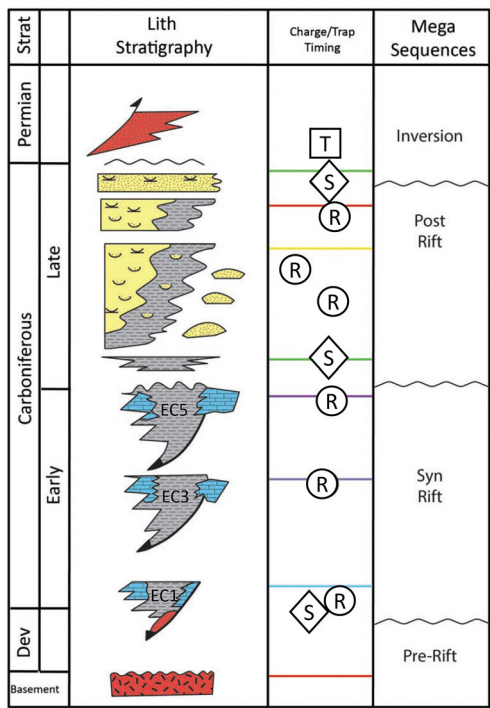


Fig. 4. Summarized stratigraphy of the Carboniferous in the Edale Gulf, Gainsborough Trough and Widmerpool Gulf showing megasequence and sequence development (after Fraser and Gawthorpe 1990). The three rift cycles (EC1, EC3 and EC5) described by Fraser and Gawthorpe (1990) are highlighted on the diagram. Abbreviations in the charge/trap timing column: R, reservoir; S, source; T, trap. Coloured horizontal lines represent mapped seismic horizons in Figure 5.

supply (cf. Gawthorpe *et al.* 1994; Church and Gawthorpe 1997); thus they are not necessarily depositional sequence boundaries *sensu* Van Wagoner *et al.* (1990). This spatial variability is most pronounced in the synrift megasequence where the interplay between clastic and carbonate deposition is controlled by active rifting. Locally, the boundary of a tectonostratigraphic 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.

The synrift megasequence ranges in age from the Late Devonian to the late Dinantian and is characterized by marked facies and thickness variations around major normal fault zones that bound half graben depocentres. It is composed of six

tectonostratigraphic sequences (designated EC1–EC6 by Fraser and Gawthorpe 1990, 2003). Applying this stratigraphic framework across northern England, two main synrift depositional systems can be identified: (1) clastic fluvio-deltaic; and (2) carbonate platforms (Fig. 1).

The clastic depositional systems dominate the north of the study area (e.g. Northumberland Trough) owing 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 synrift 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; Könitzer *et al.* 2014, 2016; Newport *et al.* 2018; Emmings *et al.* 2020b). The sediment-starved half graben were key to the accumulation and preservation of organic-rich shales (the Bowland Shale and equivalents). 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. Fluvio-deltaic sandstones, siltstones, mudstones and coals dominate the stratigraphy, 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 long been recognized (Bott and Johnson 1967; Ramsbottom 1973, 1977), and more recently these cycles have been understood to form high-frequency depositional sequences and component systems tracts (e.g. Wignall and Maynard 1996; Church and Gawthorpe 1997; Hampson 1997; Hampson *et al.* 1997; Jones and Chisholm 1997; Waters and Condon 2012). In recent years, major changes in provenance and source area compositions in the upper Namurian and Westphalian of the Pennine Basin have been recognized, suggesting extra-basinal controls on sediment source areas and sediment transport pathways (e.g. Glover *et al.* 1996; Hallsworth and 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 synrift 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 associated with the evolving Variscan mountains to the south. The inversion megasequence can locally be subdivided into two tectonostratigraphic sequences; however, the lack of preserved stratigraphy due to progressive uplift and erosion precludes the development of a regional framework.

Synrift basin formation. As described above, the northern England Carboniferous can be divided into synrift, post-rift and inversion megasequences (Fig. 4).

The synrift megasequence exhibits a characteristic wedge-shaped geometry that is characterized by a significant increase in sediment thickness across the major basin-bounding faults of half graben such as the Widmerpool Gulf, Gainsborough Trough and Bowland Basin (Fig. 5). Isopachs generated from well data (Fraser and Gawthorpe 1990) and regional seismic lines such as presented above show the thickest sections to be confined to the individual fault-bounded half graben (Fig. 3). The individual synrift basins are connected via narrow openings, allowing continuous marine connection even during low sea-levels. However, the Bowland Shale and equivalents deposited during the syn- to post-rift transition in northern England are confined to the original synrift depocentres and do not represent a regionally continuous deposit as is the case for the US analogues the Bowland is often compared to, e.g. Barnett and Marcellus.

Within the constraints offered by independent biostratigraphic data (Ebdon *et al.* 1990), the three rift pulses (EC1, EC3 and EC5; Fig. 4) are synchronous across the northern England basins. This is as expected given an overriding regional plate tectonic control. 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 & Gawthorpe 2003). This may account for the pronounced rifting during EC5 times on the NE–SW-trending Hoton Fault, Widmerpool Gulf (Fig. 5).

Post-rift basin fill. Two main synrift depositional systems can be identified: (1) clastic fluvio-deltaic; and (2) carbonate platforms (Fig. 1). During the synrift 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, Gainsborough and Widmerpool basins) became sediment starved and carbonates accumulated on the footwall crests, giving rise to the development of fairly widespread carbonate

platforms (Fraser and Gawthorpe 1990, 2003). During the early post-rift phase, sediment supply overtook subsidence for the first time, allowing a marked southwards progradation of the fluvial-deltaic system that had, until this time, been mainly restricted to the north of the study area (Fig. 1). This resulted in the drowning of the last vestiges of the northern England carbonate system in the late Dinantian–early Namurian and the infill of the remnant rift topography with fluvio-deltaic sediments (Collinson 1988).

Variscan inversion. In northern England, the effects of ‘far-field’ Variscan compressional tectonics 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. 5). Early Permian peneplanation of these anticlines created a marked angular unconformity at the base of the Permian observed across 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 (Corfield *et al.* 1996). Basins such as the Bowland Basin (Fig. 3) 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 (Corfield *et al.* 1996). This difference in uplift has had a profound impact on the relative structural complexity and Bowland Shale preservation in these basins with generally negative implications for shale gas potential. The inversion megasequence is characterized by the accumulation of continental red beds and molasse in intermontane 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 and Powell 1996).

Post-Carboniferous tectonics

Permo-Triassic extension. The presence of major Permo-Triassic basins on the western side of the Pennine High exerts two important controls on shale gas potential. Firstly, the additional burial matures the Bowland Shale well into the gas window to depths required for successful shale gas production (Fig. 6). On the downside, the pervasive and repeated rifting throughout the Permo-Triassic fragmented the source depocentres, introducing a degree of structural complexity that is likely to downgrade shale prospectivity (Anderson and Underhill 2020). Examples of significant post-Bowland Shale structural

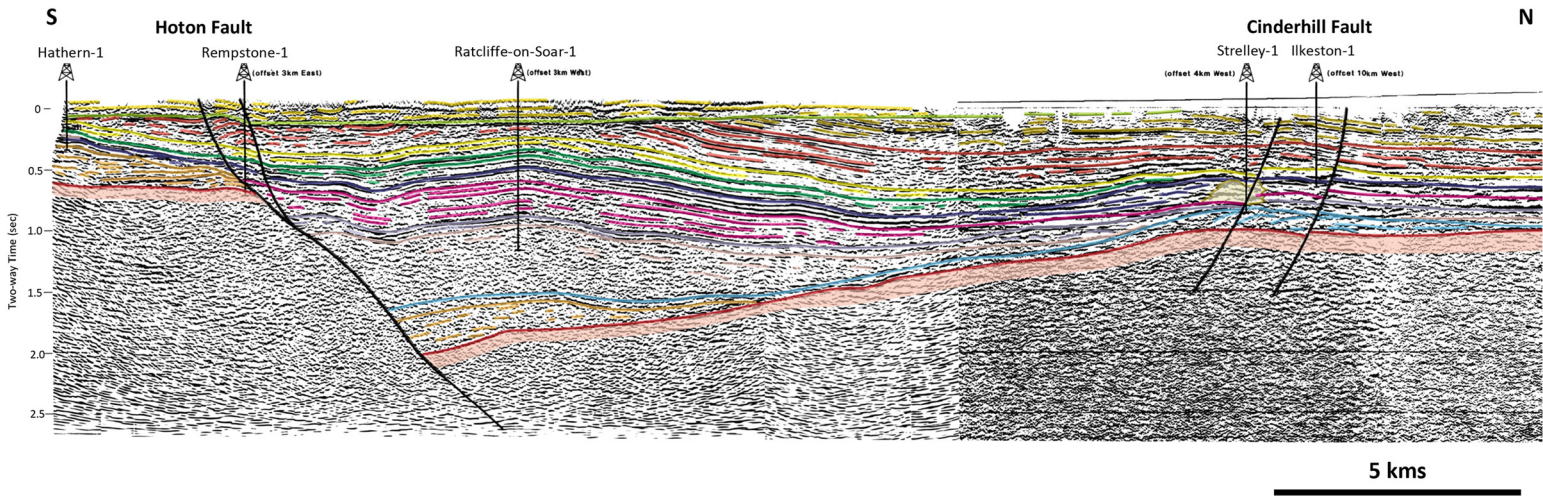


Fig. 5. SW–NE seismic profile across the Widmerpool Gulf. See [Figure 4](#) for a key to the seismic horizon interpretation.

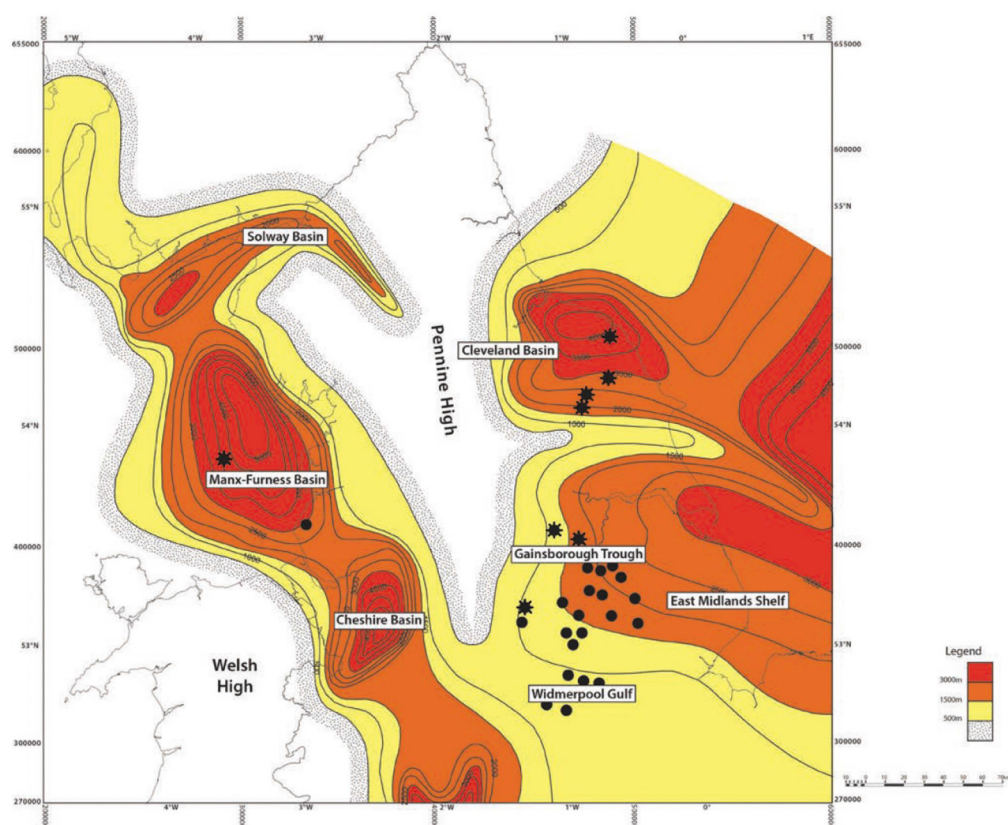


Fig. 6. Post-Variscan deposition in northern England. Map compiled from an interpreted regional dataset of vitrinite reflectance (% R_o) values collected by Fraser (1995). This is essentially a maximum burial map constrained by vitrinite reflectance values, which record maximum temperature and hence maximum burial, modelled 1D burial history profiles (Palci *et al.* 2020) and apatite fission track analysis (AFTA) (Lodhia *et al.* 2023). Thickness contours are in metres. Black dots with crosses indicate gas fields and black dots oil fields, modelled 1D burial history profiles (Palci *et al.* 2020) and apatite fission track analysis (AFTA) (Lodhia *et al.* 2023). Thickness contours are in metres. Black dots with crosses indicate gas fields and black dots represent oil fields.

modifications at this time occur in the Formby–Fylde area (onshore Manx–Furness Basin) and in parts of the Cheshire Basin (Fig. 6).

The main phase of oil and gas generation commenced in the major depocentres towards the end of the Triassic, and continued until uplift in the early Cenozoic effectively froze further generation (Fig. 7).

Jurassic–Cretaceous subsidence and local inversion. The later Mesozoic history of NW England is highly conjectural, but it has been suggested from AFTA that some 1–1.5 km of Jurassic and Cretaceous sediments were deposited (Lewis *et al.* 1992; Lodhia *et al.* 2023). 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.

Prior to Early Jurassic times the Carboniferous basins in NE England and the East Midlands (and their offshore extensions into the Southern North Sea) had undergone similar burial and thermal histories. Both areas had been strongly structured in the Late Carboniferous Variscan Orogeny and had been subject to gentle regional subsidence during the Permo-Triassic. The contrast between basins in NE England and the East Midlands commenced in Early Jurassic times and continued into the Cenozoic 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 and Boegner 1981). This had essentially two effects. Source rock continuity was severely disrupted due to renewed fault movements and successive phases

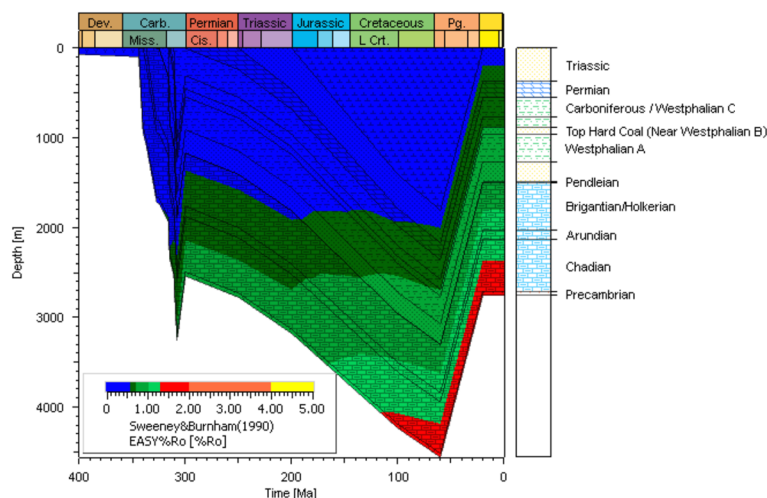


Fig. 7. Example burial curve for Bowland Shale from the Grove-3 well in the Gainsborough Trough. Oil and gas generation commenced during Triassic burial with generation being frozen in the early Cenozoic due to the significant Cenozoic uplift (maturity scale after Sweeney and Burnham 1990).

of basin inversion during the Late Cretaceous–Cenozoic. In addition, localized deep burial, principally as a product of Early Cretaceous rifting in northern Cleveland and the Southern North Sea, buried the Bowland Shale and equivalent source rocks into the gas generation window. Vitrinite reflectance (% Ro) is the percentage of light reflected from the surface of polished vitrinite. Vitrinite is a common type of organic matter occurring in shales whose reflectance increases with increasing temperature and is therefore commonly used by the petroleum industry as an indicator of the maturity of hydrocarbon source rocks. High vitrinite reflectance values (0.9–1.2% Ro) in the Whitwell on the Hill-1 borehole, if correct, appear to support this observation (Supplementary appendix 2). The East Midlands basins attained significantly lower levels of maturity (0.5–0.8% Ro) (Supplementary appendix 2).

Cenozoic uplift and erosion. From the end of Upper Cretaceous chalk deposition, the northern England Carboniferous basins experienced strong uplift and erosion, with a consequent ‘freezing’ of hydrocarbon generation and build-up of overpressure. A regional heating event, which has elevated present-day geothermal gradients in parts of NW England and the East Midlands, may have been associated with early Cenozoic volcanism in the North Atlantic province (Fraser and Gawthorpe 2003). However, these elevated heat flows are unlikely to have significantly retriggered generation from source rocks in the study area. Regional estimates of uplift and erosion range from 1100–3000 m in NW England to 1000–2000 m in the East Midlands, which imposed a

regional easterly tilt to eastern England of 1–2° (Fraser *et al.* 1990).

Northern England shale gas and oil potential

The main aim of this section is to integrate the geological observations and analytical data into a focused play evaluation of the Carboniferous Bowland Shale and provide some comparison of the relative prospectivity of the various Carboniferous basins of northern England. Much as in the case of conventional play analysis, the key inputs are a series of spatially varying attributes that can be mapped and convolved to produce a relative risk map. The conventional traffic light colours of green = low risk, yellow = moderate risk and red = high risk have been used.

Bowland Shale success factors

The key success factors in US shale gas exploration and production are described by Charpentier and Cook (2011) and with a few modifications can be summarized as follows:

- Basin type: foreland, passive margin
- Original total organic carbon (TOC): >2%
- Source rock facies (kerogen type, marine Type II)
- Thickness: net shale (100 m minimum, laterally consistent unit)
- Maturity: ($T_{\max}$ data, vitrinite reflectance values of 1.2–1.5% Ro)
- Brittleness (XRD and Vclay: <40% Vclay (Vclay represents the clay fraction of a shale))

- Depth: >1000 m
- Overpressure: required to sustain commercial gas flow rates
- Minimal faulting and structural complexity (e.g. fault density)
- Data density: interpretation confidence based on outcrop, wells and 3D seismic

These variables have been considered in our UK shale gas risk assessment.

Laboratory-based analysis of the mineralogical, petrological and geochemical characteristics of the Bowland Shale (Supplementary appendices 1 and 2) have been used to compare the UK Carboniferous shale basins with the successful shale basins in the USA (Fig. 2). UK shale data from this study compares well with that of Clarke *et al.* (2018, fig. 7). An excellent summary of the location and characteristics of the main US shale basins can be found in Jarvie (2012) and Stephenson (2015).

Shale presence and lateral continuity

The basic structural elements map of the Carboniferous is the key to understanding and mapping the presence of the Bowland Shale and equivalents over northern England (Fig. 3). The organic-rich shales were deposited around the Dinantian/Namurian boundary as the basins transitioned from synrift to post-rift subsidence. The shales were deposited in the remnant bathymetry in the latest part of the synrift/early post-rift between the rimmed carbonate platforms present on the footwall and hanging wall dip slopes of the synrift half graben (Fig. 5). Clinoforms observed on 2D seismic data over the carbonate margins indicate palaeowater depths of *c.* 500 m. The shales themselves are *c.* 300 m thick in the basin centre. Regional seismic profiles tied to well data show that the shales (Sequence EC1a) are only present within the depocentres. This is confirmed by the presence of oils with a very different signature (Type III) on the platform areas in fields such as Eakring (Fraser *et al.* 1990). TOC contents within the Bowland Shale and equivalents interval average *c.* 3–5% and show a remarkable consistency throughout the Cleveland, Bowland, Edale and Gainsborough/Widmerpool basins (Supplementary appendix 2).

As highlighted in the structural elements and palaeogeographic maps, the Bowland Shale and equivalents are preserved as a series of relatively narrow (25 km), finger-like bodies trending NW–SE in the East Midlands (Gainsborough Trough = 5000 km²) and NE–SW in Lancashire and Cheshire. This is in marked contrast to the continuous and regional nature of the organic-rich shale intervals in the Barnett (13 000 km²), Marcellus (250 000 km²) and Eagle Ford (20 000 km²) plays in the USA.

Another aspect to the Carboniferous source presence story is the potential for deeper Lower Carboniferous shales to contribute to the shale gas resources of northern England. However, there is a degree of debate around this additional potential. This is largely due to an absence of data below the topmost Dinantian across northern England. Geochemical data presented by Clarke *et al.* (2018) for the Beconsall-1z, Preese Hall-1 and Grange Hill-1z wells provide recent data for the Lower Bowland and Hodder shales in the Bowland Basin. The BGS/Department of Energy and Climate Change analysis (Andrews 2013) claimed a potential mean resource of 1329 TCF to be present in these lower units. This was on the basis of the elevated organic carbon content of the Hodder shales in the Preese Hall well (Clarke *et al.* 2018). With limited data and well penetrations (e.g. Ratcliffe-on-Soar and Long Eaton in the Widmerpool Gulf, which showed no elevated TOC), it is difficult to justify extrapolation of the Preese Hall results beyond the western Bowland Basin.

It is the contention of the authors of this study that minimal gas resources should be ascribed to this Lower Carboniferous interval until further supporting borehole evidence is available. This study will therefore focus on the proven source potential of the overlying late synrift–early post-rift Bowland Shale and equivalents. However, we accept there may be deeper synrift potential in the western Bowland Basin.

Source rock facies

The geochemical analyses of the Bowland Shale and equivalents (Fig. 8) indicate the presence of a marine Type II transitioning to Type II/III kerogen through time, i.e. with significant input of terrestrial material from the southward-advancing Pennine Delta in the upper part of the interval. The Lower Bowland shales are thoroughly marine, sitting between the emergent carbonate platforms in a series of linked but partially isolated troughs.

The apparent link between the age of the deltas prograding southwards and the younging of the source rocks from the Cleveland to Bowland to Edale and Gainsborough/Widmerpool basins was explained previously by Fraser *et al.* (1990) as the distal pro-delta facies of the deltas. New geochemical data gathered for this study (Supplementary appendix 2) and analysis by Sims *et al.* (2024) show that the shales were strongly Type II (marine) before the Pennine Delta reached the basins (Fig. 1). XRD analysis also indicates the presence of thin carbonate layers in the Bowland Shale interval at this time. This is consistent with the association of the organic-rich Bowland Shale and the rimmed carbonate margins (Clarke *et al.* 2018; Palci *et al.* 2020).

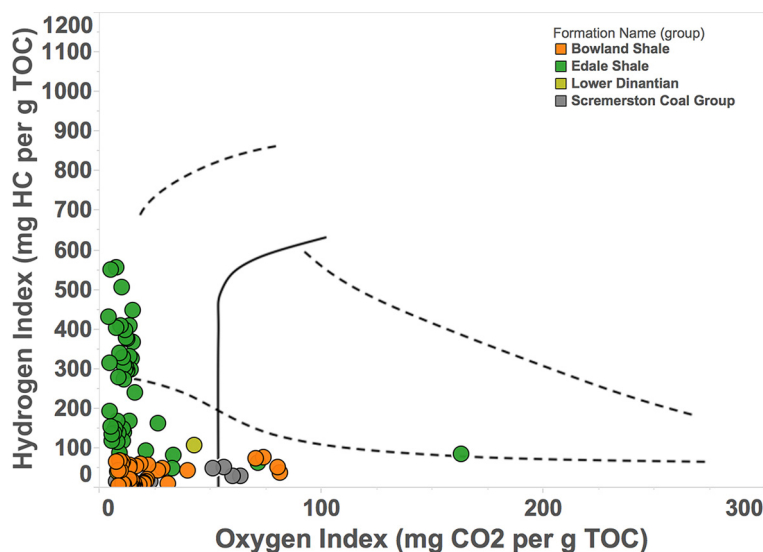


Fig. 8. Pseudo van Krevelen diagram for northern UK shales samples. The Bowland Shale displays a strong Type II kerogen signature. Higher maturity samples from the Carboniferous limestone plot in two regions, one at the base of the Type II curve and the other in the Type III–Type IV region. Dashed lines represent boundaries between Type I (top left), Type II (middle) and Type III (base) kerogens. The solid line approximates the boundary between immature shales on the left and mature shales on the right. This boundary is curved, being a function of both kerogen type and temperature.

Thickness and TOC

Well correlation in the Gainsborough Trough coupled with a regional geoseismic cross-section over the East Midlands demonstrates the presence of a 300 m thick sequence (LC1a) comprising the organic-rich Bowland Shale (Fig. 9).

The shales are observed to thin and pinch out against the carbonate margins on either side of the basin (Palci *et al.* 2020). These were originally referred to as the gamma active shales by Fraser *et al.* (1990). The highest gamma ray unit is at the top of the sequence, but our analysis shows a TOC content consistently in the 2–5% range throughout the interval and across the different depocentres (Supplementary appendix 2). Seismic and well data from the Widmerpool and Edale basins confirm these findings (Gross *et al.* 2015; Yang *et al.* 2016; Sims *et al.* 2024). In the Bowland Basin the results of the Cuadrilla Preese Hall-1 well suggest a thicker development, with two units of organic-rich shale preserved as the Lower and Upper Bowland Shale (Clarke *et al.* 2018). Stratigraphic data presented by Ebdon *et al.* (1990) and Fraser and Gawthorpe (1990) suggest the Upper Bowland Shale in the Bowland, Craven and Cleveland basins and the Edale Shale in the East Midlands basins are time equivalents. Further south in the Widmerpool Gulf, the organic-rich shales continue into the later Pendleian–Arnsbergian (Morridge Formation) (Sims

et al. 2024), an observation consistent with the southward younging of the organic-rich shales.

Maturity and petroleum yields

The burial history plot for the Bowland Shale at the Grove-3 well location (Fig. 7) shows two main burial events: the first in the Late Carboniferous prior to Variscan uplift and erosion, and the second in the Late Cretaceous prior to Cenozoic uplift, erosion and tilting (Bray *et al.* 1992; Green *et al.* 1997; Besly 2018). This is consistent with the studies of Fraser *et al.* (1990) and Fraser and Gawthorpe (1990). The main phase of oil and gas generation commenced during Triassic burial, with generation being frozen in the early Cenozoic owing to significant regional uplift. The 2D petroleum systems model for the East Midlands based on the geological cross-section shown in Figure 9 highlights the subtle difference in maturity between the largely immature Widmerpool Gulf to the south and the oil to early gas mature Gainsborough Trough to the north (Fig. 10). The model successfully predicts all the conventional oil and gas accumulations in the East Midlands area apart from the Eakring field, which requires out-of-plane oil migration from the Edale Gulf to the west. To have predicted this correctly would have required a 3D petroleum systems model rather than the 2D model presented in Figure 10.

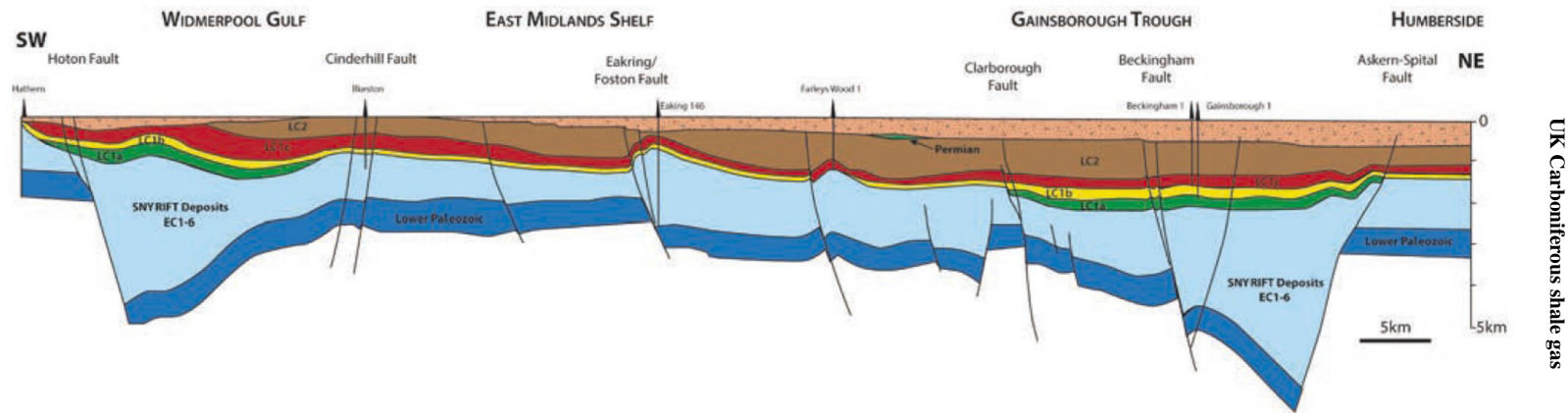


Fig. 9. SW–NE structural cross-section across the East Midlands hydrocarbon province. The organic-rich Bowland shales are shaded green. These are confined to the late synrift and early post-rift section of the major fault-bounded half graben. Note the 5× vertical exaggeration. See [Figure 4](#) for key to stratigraphy.

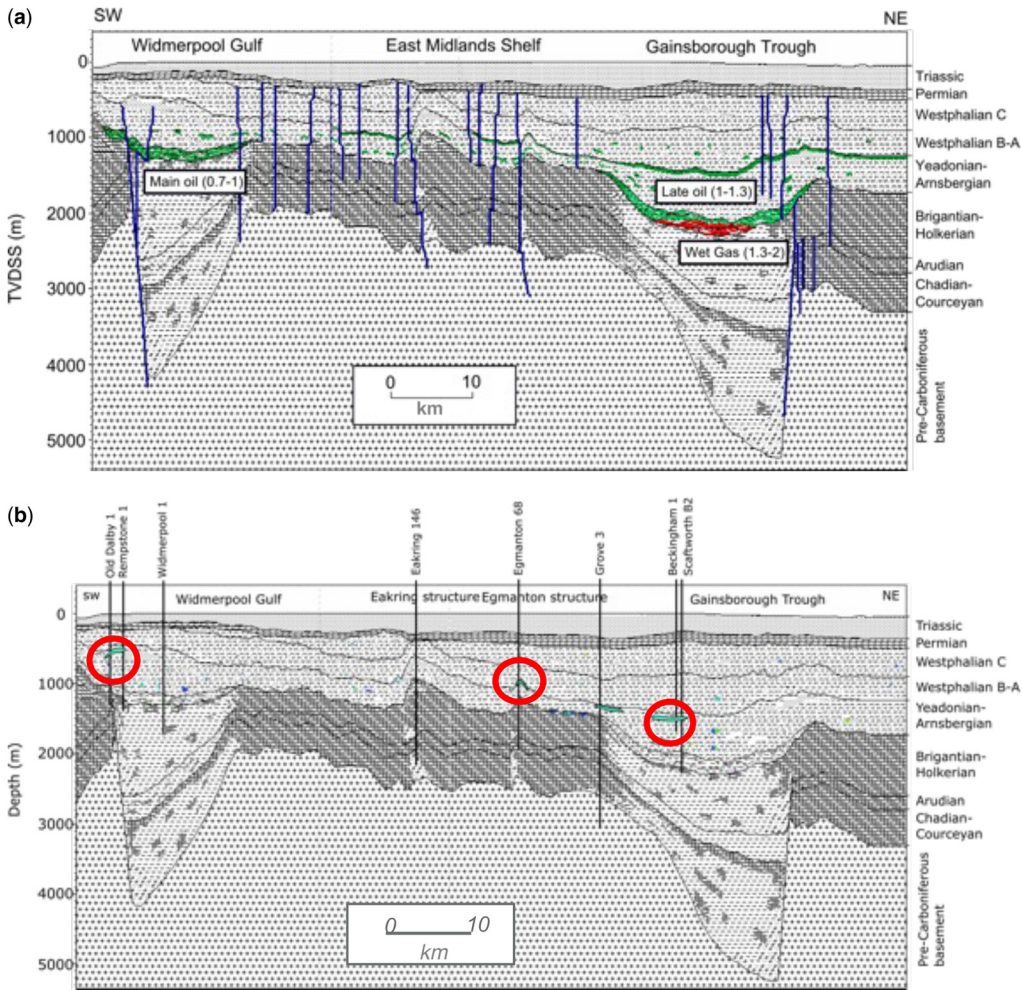


Fig. 10. East Midlands present-day Bowland Shale maturity model (after [Palci *et al.* 2020](#)). (a) Present-day maturity model showing Widmerpool Gulf to be mature for oil only and Gainsborough Trough mature for oil and wet gas in the centre of the basin. These levels are not sufficient for a dry gas product from fracking and well completion. TVDSS, true vertical depth below sea-level. (b) Oilfields at Rempstone, Egmonton and Beckingham/Gainsborough correctly predicted by model.

The maximum burial of the Bowland Shale across northern England is shown in [Figure 11](#), with the deeper buried areas of the Cleveland, Bowland, Cheshire Basin and Gainsborough Trough being mature for gas and the more mildly buried area of the Widmerpool Gulf being mature for oil generation. Owing to the significant uplift of the central Pennines since the Miocene ([Fraser and Gawthorpe 1990](#)), the Edale shales in the Edale Gulf and the Bowland Shale in the eastern Bowland Basin are now at surface or near-surface burial depths and cannot be considered as viable targets.

In terms of the geochemistry, the final area analysed is the petroleum yield. Over most of the Bowland Shale interval we have recorded petroleum yields reaching 20 kg/tonne. However, the key research here is by [Whitelaw *et al.* \(2019\)](#), who used hydrous pyrolysis analysis of core data to demonstrate that the Bowland Shale and equivalents were not capable of delivering the volumes originally estimated using conventional dry pyrolysis techniques. This implies the presence of economically less significant gas resources in the Carboniferous of northern England.

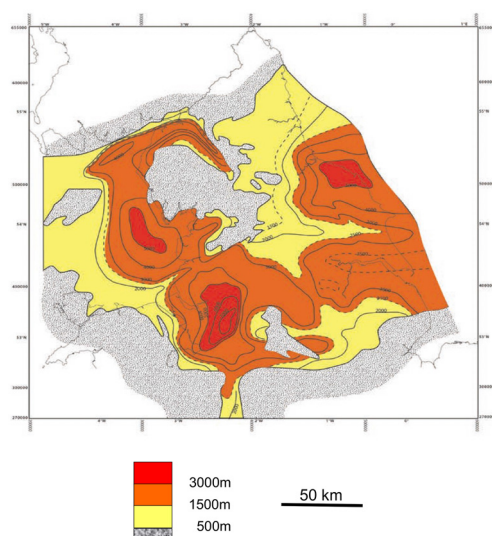


Fig. 11. Maximum burial of the Bowland Shale based on vitrinite reflectance data compiled by [Fraser \(1995\)](#), apatite fission track analysis ([Green *et al.* 1997](#)) and basin modelling ([Palci *et al.* 2020](#)). Depth contours are in metres.

Brittleness

Mineralogical data compiled for the Bowland Shale core samples is detailed in [Supplementary appendix 1](#). When compared on a ternary diagram ([Fig. 2](#)) of clay, carbonate and silica content, it is clear that on this metric the UK shales sit in fields comparable to the major shale gas and oil producing basins of the USA e.g. Bakken, Eagle Ford, Haynesville, Barnett and Marcellus.

The Bowland Shale samples exhibit clay fractions below 40% (generally accepted upper stimulation limit) and a predominantly silica fraction with some carbonate. The carbonate fraction is almost certainly related to the location of the shales in the depocentre between the carbonate platform margins ([Clarke *et al.* 2018](#)).

Overpressure

There is no recorded overpressure in the numerous conventional Carboniferous fields in northern England despite up to 500 m of uplift post-Miocene ([Fraser and Gawthorpe 1990](#)). The shales are modelled to retain some degree of remnant overpressure, but this has yet to be established by production testing of these inherently tight intervals. Data from [Jarvie \(2012\)](#) indicate all successful North American shale basins show at least some degree of overpressure.

Faulting

Depositionally, the Bowland shales are situated in the latest synrift/early post-rift where syn-depositional faulting was absent or minimal. The passive depositional setting contrasts with the deeper Hodder shales that are highly slumped, faulted and contorted as evidenced at outcrop ([Fraser and Gawthorpe 1990](#)). However, the main cause of poor connectivity in Carboniferous shales of northern England is the Mesozoic rift-related faulting in the region. This has resulted in considerable post-depositional faulting, segmentation and deformation of the Bowland Shale interval in the Bowland Basin ([Anderson and Underhill 2020](#)). The other basin significantly impacted by later rifting is the Cleveland Basin where Jurassic and Early Cretaceous rifting along the Dowsing Fault zone extends onshore into north Yorkshire and reactivates faults in the Cleveland Basin. The Permian Zechstein evaporites largely detach the severe deformation in the shallow cover from deeper events, but rifting and compression will also impact the pre-Permian evaporite section.

Relative prospectivity

Combining the elements outlined above, we have been able using an approach similar to that in [Palci *et al.* \(2020\)](#) to generate a relative risk or common risk segment (CRS) map for the Bowland Shale interval across northern England ([Fig. 12](#)) that represents an attempt to highlight the key areas for shale gas and oil exploration in the Carboniferous of northern England ([Hennissen *et al.* 2017](#); [Clarke *et al.* 2018](#); [Palci *et al.* 2020](#); [Lodhia *et al.* 2023](#)). The low-risk (green) segments represent areas where the main elements required for a successful shale gas play are interpreted to be present and correspondingly where the main shale gas resources are predicted to be found. The key areas are the Bowland Basin and the Gainsborough Trough. The Cleveland Basin is also assessed as low risk, but this basin has been shown to represent a hybrid gas play relying on tight sandstone interbedded with Bowland Shale ([Hughes *et al.* 2018](#)). The Widmerpool Gulf, which lacks post-Carboniferous burial, has been modelled as lying in the early oil window. The Bowland Shale in the Edale Basin to the west of the Gainsborough Trough lies at depths between the surface outcrop and 500 m and, although mature owing to pre-Permian burial, is considered too shallow to represent a viable target.

Discussion

On visual inspection of drill cores, the UK Bowland Shale and equivalents look similar to many US

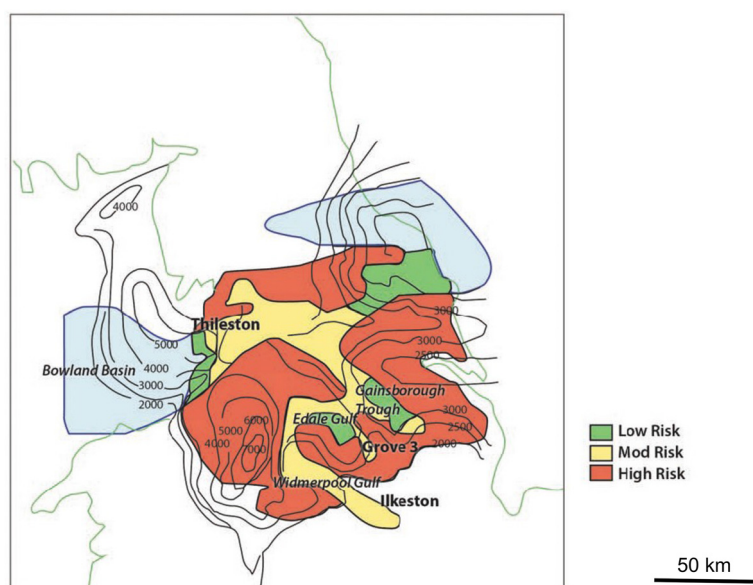


Fig. 12. Map highlighting relative prospectivity for Carboniferous shale gas exploration in northern England. Interestingly, a simple analysis of existing conventional oil and gas discoveries would have resulted in a very similar map. Green indicates areas where all or most of the components required for a successful shale gas play are present. Red shows areas where at least one shale gas play element is absent. Yellow is moderate risk. Blue colour fill indicates parts of the Bowland and Cleveland basins that extend offshore and are not included in this analysis. Depth contours in metres.

shales e.g. Barnett and Marcellus. However, that is where the similarity ends. Our analysis has highlighted two areas of critical difference between the prospectivity of UK and US shales that adversely impact UK prospectivity. Firstly, in the USA the main shale basins, e.g. Barnett and Marcellus, are essentially broad foreland basins with laterally continuous shale deposition. In the UK the organic-rich Bowland shales are confined to individual fault-bounded basins and lack any degree of lateral continuity and thickness, with the shale thinning markedly towards the margins of the basins. Secondly, the complex and polyphase tectonic history of the UK and the resulting structural complexity of the basins in the UK containing the organic-rich Carboniferous Bowland shales downgrades shale gas potential.

The other areas of differentiation relate to the relatively shallow depths of burial of the Bowland Shale interval. This is particularly true of the East Midlands, an established conventional oil province, where the shale is barely in the gas window in the deeper basinal areas and is largely mature for oil. This is reflected in the dominance of oil over gas in the conventional field distribution (Fraser and Gawthorpe 2003; Palci *et al.* 2020). The basins where the shales have been buried deeper, Bowland (due to Permo-Triassic rifting and burial) and

Cleveland (Early Cretaceous rifting and burial), are in the gas window but unfortunately located in structurally complex areas. This fragments the shale layers into a ‘shattered glass’ pattern, making accurate horizontal drilling on a large scale problematic and importantly contributing to poor 3D seismic imaging. 3D seismic is key to accurate fault identification and the successful landing of horizontal wells. The density of natural faults and fractures ultimately becomes an issue in these areas during fracking operations.

The TOC, maturity, mineralogy and thickness of the Bowland Shale and equivalents are broadly similar to the successful US examples.

Resources

There are several methods of shale gas resource estimation depending on the maturity and the presence or absence of production data. This is described in some detail by Jarvie (2012), Charpentier and Cook (2011) and Stephenson (2015). In conventional oil and gas plays, a simple volumetric calculation is carried out based on the volume of the trap and the hydrocarbon pore space available. Although still an estimation, this method generates a range of either in-place or, with a recovery factor, recoverable reserves. However, with resource plays such as

shale gas this is not practical. The method outlined above is geared to field-scale volume estimation, not basin-scale estimates. Large uncertainties over resource size, pore volume and ultimately recovery factor, which are key inputs to the estimation, render this type of approach unreliable.

In this study we have used regional risk mapping for the Bowland Shale and equivalents, taking into account the presence/absence of the key success factors presented above. This allows us to make predictions regarding where the likely resources lie (green) and conversely where they do not (red). This is also a methodology more suited to basin and resource play analysis. This immediately focuses our attention towards the Bowland Basin, Cleveland Basin, Gainsborough Trough and Edale Gulf (Fig. 12). In terms of resource estimates associated with these 'low risk' areas, we have compiled estimates reported by other authors, including research presented in this volume by Lodhia *et al.* (2023) (Fig. 1). There is only one detailed total volume for the Bowland Shale in northern England published by Andrews (2013) of 16.4–47.7 TCF. Whitelaw *et al.* (2019) reported volumes of 16–28 TCF for the Bowland Basin and Widmerpool Gulf combined. Other published estimates are restricted to individual basin areas identified as low risk in the above risk analysis.

For the Bowland Basin, Clarke *et al.* (2018) reported a resource density of 0.6–1.5 TCF/square mile. Given the area of the low-risk segment in the west of the basin (50 square miles) this amounts to some 30–75 TCF. Lodhia *et al.* (2023) reported more pessimistic gas volumes of 13.1 TCF for this area. In the Gainsborough Trough, Palci *et al.* (2020) estimated resources of 11–38 TCF. To directly quote the abstract of Whitelaw *et al.* (2019), 'Extrapolating our findings to the whole Bowland Shale, the maximum gas in place equates to potentially economically recoverable reserves of less than 10 years of current UK gas consumption.'

Conclusions

Roughly 12 years ago, industry and academia enthusiastically embarked on UK shale gas research with the premise that the organic-rich Bowland Shale and equivalents in northern England would provide UK shale gas resources that could fill an ever-widening gas supply gap from rapidly declining North Sea production. Initial in-place estimates published by the BGS (Andrews 2013) based on a possibly over-optimistic interpretation of the organic content of the deeper basin fill (Bowland, Hodder and equivalents) appeared to support the general optimism. However, our research involving geochemical, mineralogical and petrological analysis of over 100 core samples for this study and

complimentary sampling for other studies, e.g. Hennissen *et al.* (2024), Sims *et al.* (2024), suggests a markedly different and more pessimistic resource outlook. To summarize, the key negative factors are the wrong type of basins (rift rather than foreland) and post-depositional structural complexity.

In summary, technical support for the resumption of fracking in the UK is not provided by the research reported here. We conclude that some gas could be produced from the Bowland Basin, which has the required maturity levels for dry gas, but feel that resources are unlikely to justify further activity. Some oil and gas could also be produced from the less-structured Gainsborough Trough, but the most prospective area is small (in the area of the existing Beckingham–Gainsborough Field) and of marginal maturity for gas (Palci *et al.* 2020). Oil is probably a more likely product here.

Our main conclusion is that the Bowland Shale and equivalents in the UK do not represent a technically significant resource and in hindsight did not merit the considerable industry and media attention that has been associated with it. A key learning is that fundamental research based on heritage data and modern analytical and modelling techniques could usefully have preceded drilling and fracking operations in northern England.

In 2010, when Cuadrilla drilled the Preese Hall-1 shale gas exploration well in Lancashire, the UK was in an excellent position to develop a sound technical shale gas resource evaluation and investment strategy. This would build on a 50 year history of North Sea oil exploration and production, an academic community with recognized expertise in petroleum-related teaching and research and a world-class archive of heritage core, seismic and well data hosted by the BGS at Keyworth in Nottinghamshire.

Several factors contributed to shale gas operations commencing before the fundamental research was in place. The major North Sea operators such as Shell and BP, with access to critical expertise and data, declined to take up exploration licences for UK shale gas. This left the field open to a dominance of underfunded and technically inexperienced exploration companies whose business objectives did not necessarily align with the public interest and who were slow to fund the necessary research in UK universities. It was not until 2014 that the government, through NERC and ESRC, actively funded research into UK shale gas resources. Before this, the void was largely filled by an underfunded geological survey that was slow to identify and respond to the issues and out of its depth when it was allocated the shale gas resource evaluation task.

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Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions **AJF**: investigation (equal), project administration (lead), resources (lead); **BHL**: data curation (lead), formal analysis (equal), software (lead); **MJES**: formal analysis (equal), investigation (equal), resources (supporting).

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Data availability The datasets generated during and/or analysed during the current study are available in the Core Store and NERC data repository, BGS, Keyworth, Nottinghamshire. Excel spreadsheets containing the geochemical (rock-eval pyrolysis) and mineralogical (XRD) data analysis of core samples are available at <https://webapps.bgs.ac.uk/services/ngdc/accessions/index.html#item182109> and <https://webapps.bgs.ac.uk/services/ngdc/accessions/index.html#item182111>, respectively.

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