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Structural Geothermal Plays in the Lower Carboniferous Limestone, East Midlands, UK: Insights from Legacy Geophysical Data

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Key Points:

- Integrated seismic and potential field data reveal distinct fault domains within the Lower Carboniferous Limestone
- Late Carboniferous inversion caused localised uplift and erosion with potential enhanced fracturing and palaeokarst development
- Fault corridors alongside relay systems and fault intersections define three conceptual structural geothermal plays

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Abstract

Lower Carboniferous Limestone (LCL) is a promising geothermal target in Britain, but uncertainty in subsurface structure and permeability limits resource assessment. Here, we use the Welton area of the East Midlands, where legacy hydrocarbon exploration data provide detailed subsurface coverage, to investigate the controls on LCL geothermal prospectivity. We integrate 3D seismic reflection, well, gravity and aeromagnetic data with gravity forward and inverse modelling to characterise the geometry and structural evolution of the LCL. Seismic interpretation reveals a heterogeneous reservoir partitioned into a western rift-bounding fault corridor, an eastern relay system and a northern fault-intersection zone, together with fault-tip and segment-linkage structures. Seismic-stratigraphic relationships record late Carboniferous reactivation of this inherited extensional architecture, expressed by localised LCL doming and erosion, Namurian absence and onlap, and onlap within the lowermost Westphalian. These relationships indicate variable inversion and possible weathering or palaeo-karst development on uplifted LCL highs. Gravity and magnetic lineaments reproduce and extend seismic-scale structural trends, while source-depth estimates indicate that parts of the fault network were localised above deeper inherited fabrics. Gravity modelling shows that plausible LCL density variations alone cannot explain the observed gravity field, requiring deeper or unmodelled density heterogeneity. The integrated results define three conceptual structural geothermal plays: a fault-damage-zone play, a relay/linkage play and a fault-intersection play. These settings may favour secondary permeability through fracturing, augmented by inversion-related deformation and possible palaeokarst development, although present-day transmissivity remains unconstrained. This study demonstrates how legacy seismic and potential-field datasets can support geothermal targeting in structurally complex carbonate reservoirs.

Plain Language Summary

Geothermal energy, which uses heat stored beneath the Earth’s surface, could provide a reliable source of low-carbon heating in the UK. However, identifying suitable underground rocks remains challenging because extracting heat efficiently requires water to circulate through connected fractures and openings in the rock. This study investigates deeply buried limestone in the East Midlands of England to understand how its geological history may influence its geothermal potential. We combine existing data collected during oil and gas exploration with measurements of Earth’s gravity and magnetic fields to reconstruct the underground geology. Our results reveal a complex network of ancient faults that divide the limestone into distinct structural zones. Some faults were reactivated during later geological events, causing parts of the limestone to rise, fracture and undergo erosion. These processes may have created pathways for water circulation, particularly where faults intersect or overlap. We identify three geological settings that could offer favourable conditions for geothermal development, although further testing is needed to confirm whether water can flow through them today. Our findings demonstrate how existing geological data can be reused to identify promising geothermal areas, helping reduce exploration uncertainty and support the development of low-carbon heating resources.

1 Introduction

Mississippian Lower Carboniferous limestones (LCL) are widely developed in the subsurface of central and southern Britain and form a regionally important aquifer (Allen et al., 1997). Across Great Britain, these limestones occur in two broad provinces separated by the Wales-Anglo-Brabant Massif (Pharaoh et al., 2021). In the central area, Mississippian extension produced a polygonal mosaic of deep-water basins, ramps and shallow-water platforms; in the southern province, limestones accumulated on a shelf along

the northern margin of the Rheic Ocean before later Variscan deformation, folding and erosion (Pharaoh et al., 2021).

In the East Midlands and adjoining Pennine region, the structural architecture of the LCL was strongly controlled by syn-rift tectonics and subsequent inversion. Fault-bounded depocentres such as the Widmerpool Gulf and Gainsborough Trough developed alongside structural highs including the East Midlands Platform and Derbyshire High, and later experienced varying degrees of late Carboniferous shortening and inversion. This tectono-stratigraphic inheritance governs both the preserved geometry of the limestone succession and its present-day compartmentalisation in the subsurface (Fraser & Gawthorpe, 2003).

The importance of accurately mapping the LCL extends beyond stratigraphic reconstruction. Lower Carboniferous limestones in Britain form a productive aquifer in places, host active hydrothermal systems, and are increasingly recognised as a potentially important deep geothermal target (Allen et al., 1997; Pharaoh et al., 2021; Jones et al., 2023). However, their permeability is highly heterogeneous and is thought to be concentrated along faults, fractures, bedding planes and karstified zones, rather than being controlled by primary matrix porosity alone (Allen et al., 1997; Jones et al., 2023). As a result, prediction of LCL fluid flow and geothermal potential depends fundamentally on understanding the geometry, stratigraphy and structural framework of the carbonate bodies at depth (Jones et al., 2023).

Jones et al. (2023) estimated a total LCL heat-in-place of approximately 1,415-1,528 EJ across central and southern Britain, with substantial potential in the East Midlands. This theoretical resource does not establish the heat that can be recovered at individual sites. Resource prediction remains sensitive to uncertainty in the depth, thickness and distribution of the limestone interval, particularly its basal geometry, because available interpretations rely heavily on legacy seismic datasets and relatively sparse bore-hole control (Jones et al., 2023).

That limitation is especially relevant in structurally complex areas where the LCL is deeply buried beneath younger cover and where seismic imaging may be insufficient to resolve basement relief, basin margins and fault architecture. In such settings, potential-field methods offer an important complementary dataset. Gravity and magnetic data have already been shown to help map structural-geological elements, including basins, highs and intrusive bodies, and to provide guidance for carbonate mapping in areas with limited or no seismic data (van Heiningen et al., 2018; van Heiningen, 2020).

Mature oilfields provide both legacy subsurface datasets and opportunities to recover geothermal heat from co-produced water (Gluyas et al., 2018). The Welton field, discovered in 1981, has already been assessed for geothermal heat utilisation using its existing oilfield infrastructure (Hirst et al., 2015; Hirst, 2017). Hirst et al. (2015) estimated a formation temperature of 52.5°C at 1,500 m and approximately 1.6 MW of thermal power for a 30°C cooling scenario that included oil- and water-bearing intervals. These estimates concern the assessed field intervals rather than a dedicated LCL resource. Their well-record analysis also documented weathering of the limestone surface and fracture-related fluid occurrence, providing a local geological basis for investigating the deeper carbonate succession. The spatial distribution of favourable LCL structures nevertheless remains insufficiently constrained.

We therefore integrate legacy 3D seismic reflection, well, gravity and aeromagnetic data to characterise the LCL in the Welton area of the East Midlands, on the East Midlands Shelf immediately south of the Gainsborough Trough. Here, Lower Carboniferous limestones are preserved beneath younger Carboniferous strata, and hydrocarbon exploration has generated extensive seismic and deep-well coverage. We investigate how the combined datasets can potentially constrain the 3D stratigraphic and structural archi-

Across Britain, LCL developed in two provinces separated by the WABM (Figure 1, Waters et al., 2009). In the southern province, limestones accumulated on a relatively continuous southward-deepening shelf extending from Ireland to the Rhineland (western Germany), later fragmented into discrete minibasins by Variscan deformation and post-Carboniferous erosion. In the northern province, which includes northern England, Mississippian extension affected the heterogeneous pre-Carboniferous basement with inherited Caledonian structural fabrics, and produced a mosaic of deep-water basins, ramps and carbonate platforms. Carbonate deposition in this province was therefore structurally partitioned from the outset, and was further modulated by glacioeustatic sea-level fluctuations that generated complex carbonate system tracts, repeated emergence surfaces and strong facies contrasts between platform tops, margins and basin floors (Waters et al., 2009; Pharaoh et al., 2021).

In northern England, the LCL architecture was mainly inherited from the Caledonian structural fabric with dominant NW-SE and NE-SW fault trends (Figure 1), repeatedly reactivated during Carboniferous extension and later shortening events (Fraser & Gawthorpe, 1990). The Carboniferous basin evolution is best described in terms of syn-rift, post-rift and inversion megasequences linked to the Variscan cycle. During the syn-rift, tectonic subsidence outpaced clastic sediment supply across much of the southern part of the province, allowing carbonate platforms and rimmed shelf margins to develop on fault-block crests and hanging-wall slopes, while adjacent half-grabens accumulated fine-grained basinal sediments and calciturbidites. This resulted in a structurally segmented carbonate system whose thickness, facies and preservation vary according to basin position and fault-controlled palaeotopography (Fraser & Gawthorpe, 1990).

Within this northern province, the East Midlands Shelf formed a major structural high, flanked by the Gainsborough and Edale troughs to the north and the Widmerpool Trough to the south (Figure 1, Waters et al., 2009; Ford & Worley, 2016). A SE-trending fault system parallel to the northern margin of the Wales-Brabant High defined this platform domain, and carbonate deposition became concentrated on the East Midlands Platform and Hathern Shelf, where the LCL are assigned to the Peak Limestone Group (Waters et al., 2009). In contrast, neighbouring half-grabens such as the Gainsborough Trough developed as deeper-water depocentres in which carbonate platforms fringed the basin margins and basinward facies passed into hemipelagic mudstones, debris flows and calciturbidites (Waters et al., 2009).

This regional framework places the Welton study area (Figure 1) within a tectonically controlled shelf-to-basin transition, where the geometry and subsurface continuity of the LCL are closely tied to pre-existing Caledonian fault architecture, Carboniferous extension and subsequent inversions.

3 Data and methods

This study integrates four complementary, publicly available datasets to characterise the geometry, depth and structural architecture of the Lower Carboniferous Limestone in the Welton area. These comprise 3D seismic reflection and velocity data, borehole data from exploration and appraisal wells, and regional gravity and aeromagnetic data.

3.1 Seismic and well datasets

The study area is covered by three overlapping 3D seismic surveys, Welton-96, Fiskerton-98 and Branston-00, acquired during hydrocarbon exploration and subsequently reprocessed and merged by Geo-X Systems Ltd. in 2000. The merged seismic volume was obtained through the UK Onshore Geophysical Library (UKOGL; <https://ukogl.org.uk/>). Available acquisition and processing information of the seismic volumes is summarised

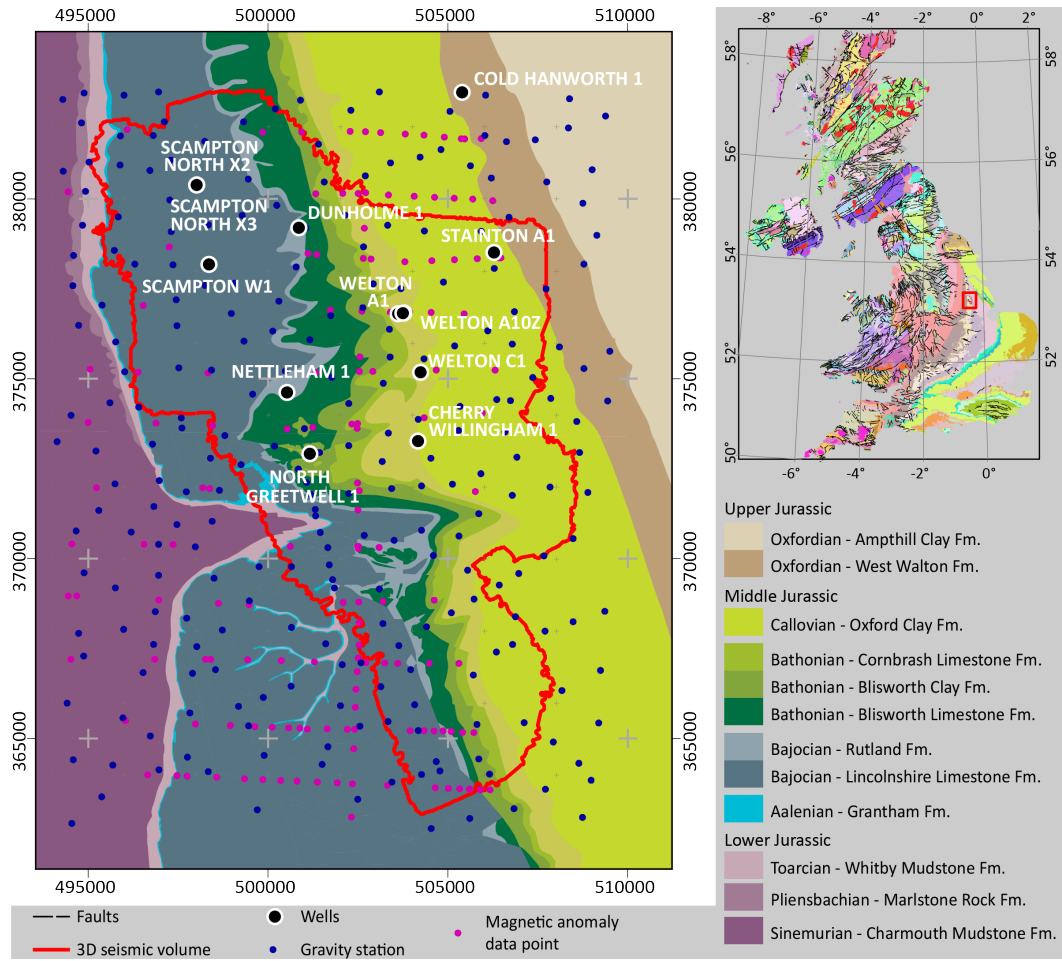


Figure 2. Geological and geophysical data coverage across the study area. Simplified bedrock geology map (based on 1:50,000 BGS geological maps) is overlain by the extent of the 3D seismic volume (red outline), wells used for stratigraphic control (white circles), gravity stations (blue dots), and aeromagnetic data points (magenta dots). The inset shows the location of the study area (red rectangle) within Great Britain.

in Text S2 and Table S1 of the Supporting Information. We use the merged seismic cube (Figure 2) to interpret subsurface stratigraphy and fault architecture in the time domain, and the associated stacking-velocity cube for depth conversion.

The well dataset used in this study comprises 11 hydrocarbon exploration and appraisal wells (Figure 2), compiled from the UKOGL (<https://ukogl.org.uk/>). The wells provide stratigraphic tops and associated depth and two-way-travel-time values used to calibrate seismic horizon interpretation. Most wells penetrate only the upper part of the LCL, whereas Welton A1 penetrates approximately 1,041 m of limestone before encountering Lower Carboniferous volcanic rocks and Precambrian basement. Well data were therefore used principally to constrain stratigraphic markers, calibrate seismic interpretation and provide depth control on the LCL and overlying succession.

3.2 Seismic interpretation and depth conversion

Seismic interpretation was undertaken in Petrel 2024 by integrating the merged 3D seismic volume with borehole stratigraphic control. Seven key stratigraphic intervals were recognised: Middle-Upper Triassic, Lower Triassic, Upper Permian, Lower Permian, Westphalian, Namurian and Lower Carboniferous Limestone (LCL); their lithostratigraphic description is summarised in Text S1 of the Supporting Information. Eight horizons defining these intervals were mapped throughout the seismic volume: top Middle-Upper Triassic, top Lower Triassic, top Upper Permian, top Lower Permian, top Westphalian, top Namurian, top LCL and base LCL.

Welton A1 encounters an approximately 60-m-thick volcanic and volcanoclastic interval beneath the LCL. The interpreted base LCL was tied to the top of this interval, thus, the calculated LCL thickness excludes the volcanic rocks. Because the volcanic interval was not represented as a separate unit, base LCL was also used as the upper boundary of the modelled basement unit.

Faults were initially identified from discontinuities in the interpreted horizons and subsequently refined using discontinuities in seismic reflections. The fault traces shown at top and base LCL are intersections of the same interpreted 3D fault surfaces with the respective horizons. Interpretation confidence decreases near base LCL as seismic resolution deteriorates; reduced fault displacement may also contribute to poorer fault and fault geometry definition at depth.

A seismic-well tie was performed at Welton A1 using deterministic wavelet extraction to calibrate the principal stratigraphic markers against their seismic responses. The synthetic seismogram shows good correspondence with the observed seismic character at the interpreted horizons (Figure S1); further details are provided in Text S2 of the Supporting Information.

The seismic volume, horizons and faults were converted from time to depth using the reprocessed stacking-velocity cube. Stacking velocities were first converted to interval velocities using the Dix equation (Dix, 1955; Yilmaz, 2001), then stratigraphically partitioned using the interpreted horizons and smoothed to suppress short-wavelength velocity fluctuations. The resulting interval-velocity model was applied to the seismic cube and interpretations. Details about time-depth conversion, interval velocity-depth relationships and regression parameters for each stratigraphic interval can be found in Text S3 and Figure S2 of the Supporting Information.

3.3 Potential field datasets

Publicly available regional aeromagnetic and land-gravity data were obtained from the BGS (British geological survey: <https://www.bgs.ac.uk/datasets/>) and used to provide independent constraints on subsurface structure (Figure 2). The aeromagnetic dataset comprises digitised airborne surveys acquired mainly between 1955 and 1965, typically along ~ 1.6 -km-spaced flight lines with ~ 10 -km tie-lines and a nominal terrain clearance of ~ 305 m. The gravity data provide complete coverage of onshore Britain at an average density of about 1.6 stations per km^2 . Bouguer gravity and magnetic anomaly observations were gridded using minimum curvature at cell sizes of 290 and 350 m, respectively. The magnetic anomaly was subsequently processed in Oasis montaj using Differential Reduction to the Magnetic Pole (DRTP), which accounts for spatial variations in geomagnetic-field inclination and declination across the input grid (Arkani-Hamed, 1988, 2007); further details are provided in the Supporting Information Text S4.

3.4 Potential field analysis and modelling

Gravity and magnetic data were processed in Geosoft Oasis montaj to identify structural trends, estimate source depths and constrain subsurface density structure. The workflow comprised density-constrained gravity modelling, wavelength-domain filtering, derivative-based anomaly enhancement, automated lineament extraction and source-depth estimation using tilt-derivative and Euler-deconvolution methods.

3.4.1 Density analysis and gravity modelling

Bulk-density constraints for gravity modelling were derived from available bore-hole density logs. Density measurements were grouped by stratigraphic interval and analysed to determine representative mean values and observed density ranges for the principal tectonostratigraphic units. These well-derived values provided the starting density constraints for both forward and inverse gravity modelling.

3D gravity modelling was performed in GM-SYS 3D using the depth-converted seismic interpretation to define model geometry. The geological model was discretised at 100×100 m horizontal resolution, and each stratigraphic unit was initially assigned its mean well-derived density. The calculated gravitational response was compared with the observed Bouguer anomaly, and residuals were defined as observed minus calculated gravity.

Separate density inversions were subsequently undertaken for the LCL and basement while all other stratigraphic geometries and densities remained fixed. LCL density was permitted to vary between 2.60 and 2.70 g/cm³ from an initial value of 2.666 g/cm³, whereas basement density was allowed to vary between 2.60 and 3.00 g/cm³ from an initial value of 2.693 g/cm³. Model geometry remained fixed and no regional gravity correction or additional density-constraint grid was applied. Full model and inversion parameters are provided in Table S1.

3.4.2 Wavelength separation and anomaly enhancement

Radially averaged power spectra were used to identify characteristic wavelength domains within the Bouguer gravity anomaly (GBA) and DRTP magnetic anomaly (DRTP-Mag) datasets (Figure S3) (e.g., Spector & Grant, 1970). Spectral breaks defined long-, medium- and short-wavelength components of 7-60, 2.4-7 and <2.4 km for the GBA, and 8-60, 2.7-8 and <2.7 km for DRTP-Mag. Cosine roll-off filters (Pilkington & Cowan, 2006; Seequent, 2025) were applied to isolate these components on regional grids before cropping to the seismic study area (Figure S4). Long- and medium-wavelength components were retained for subsequent analysis, whereas the shortest wavelengths were excluded as predominantly reflecting shallow sources and/or acquisition and processing noise. Because wavelength depends on both source geometry and depth, the filtered components are treated here as spatial-scale domains rather than direct depth intervals.

The retained grids were further analysed using first vertical derivative, horizontal gradient and tilt-derivative transformations to enhance anomaly gradients and source boundaries (Miller & Singh, 1994; Salem et al., 2007, 2008). More details about potential-field wavelength separation and filtering can be found in Text S5 of the Supporting Information.

3.4.3 Lineament extraction and orientation analysis

Potential-field lineaments were extracted independently from the long- and medium-wavelength GBA and DRTP-Mag grids using CET Grid Analysis plug-in in Oasis montaj (Kovesi, 1999; Holden et al., 2008). Phase congruency was used to identify anomaly edges and potential source boundaries, whereas phase symmetry was used to identify elongated

gated anomaly ridges/troughs (Kovesi, 1999; Holden et al., 2008). This produced eight lineament populations representing the two datasets, two wavelength domains and two extraction methods. Extracted lineaments were subsequently compared spatially with faults interpreted from the seismic data.

Lineament orientations were analysed as axial data over 0-180° using 10° bins and weighted by mapped lineament length. Bin values were normalized to the total mapped length of each population, and rose-diagram radii were square-root transformed so that sector area is proportional to the percentage of total mapped length (Nemec, 1988). Fault traces mapped from the seismic volume were analysed using the same orientation procedure. Further details of the extraction and orientation analysis are provided in the Supplementary Information (Text S6).

3.4.4 Potential-field source-depth estimation

Source depths were estimated independently for the long- and medium-wavelength GBA and DRTP-Mag components using tilt-derivative depth estimation and Euler deconvolution. Tilt-depth estimation uses the spatial relationship between characteristic tilt-angle contours around anomaly boundaries to estimate source depth (Miller & Singh, 1994; Verduzco et al., 2004; Salem et al., 2008).

Euler deconvolution was applied independently to the four retained filtered grids using a structural index of 0.5, selected to target contact- to fault-like source geometries (Thompson, 1982; Reid et al., 1990). Accepted solutions were compared spatially with the potential-field lineaments, seismic-derived LCL fault network and mapped top and base LCL surfaces. Additional informations and processing parameters are provided in Text S6 and Table S1 of the Supporting Information.

4 Results

4.1 Structural and stratigraphic architecture

Correlation of the principal stratigraphic markers between wells provides the vertical framework for the seismic interpretation and highlights substantial lateral variations within the Carboniferous succession (Figures 3). Along the NW-SE well section (Figures 3), the Middle-Upper Triassic, Lower Triassic and Permian tops are laterally continuous and show relatively modest changes in depth between Scampton North X2, Dunholme 1, Welton A1 and Welton C1. In contrast, greater variability occurs below the top Westphalian. The top LCL rises from approximately 1.7 km (SSTVD: Sub-Sea True Vertical Depth) at Scampton North X2 to ~1.5 km at Welton A1, whereas the overlying Namurian succession changes markedly in thickness. It is several hundred metres thick at Scampton North X2 but becomes very thin towards Dunholme 1 and disappears in Welton A1. Welton A1 provides the deepest stratigraphic control and penetrates the complete LCL succession to reach the basement at approximately 2.5 km subsea, indicating an LCL thickness of approximately 1 km at the well. The NE-SW correlation between Nettleham 1, Welton A1 and Stainton A1 shows a comparable architecture (Figures 3). The top LCL deepens northeastward from Nettleham 1 through Welton A1 to Stainton A1, while the Namurian remains comparatively thin around Stainton A1 and thins out completely towards the south. In contrast, the Westphalian forms a relatively thick and laterally persistent succession across both sections. The well correlations therefore indicate that the strongest short-wavelength stratigraphic variability occurs within the LCL and Namurian intervals, whereas the overlying Westphalian and Permian-Triassic succession is comparatively more uniform.

Mapping of the well-constrained horizons within the 3D seismic volume reveals that this stratigraphic variability is superimposed on a strongly asymmetric, fault-bounded

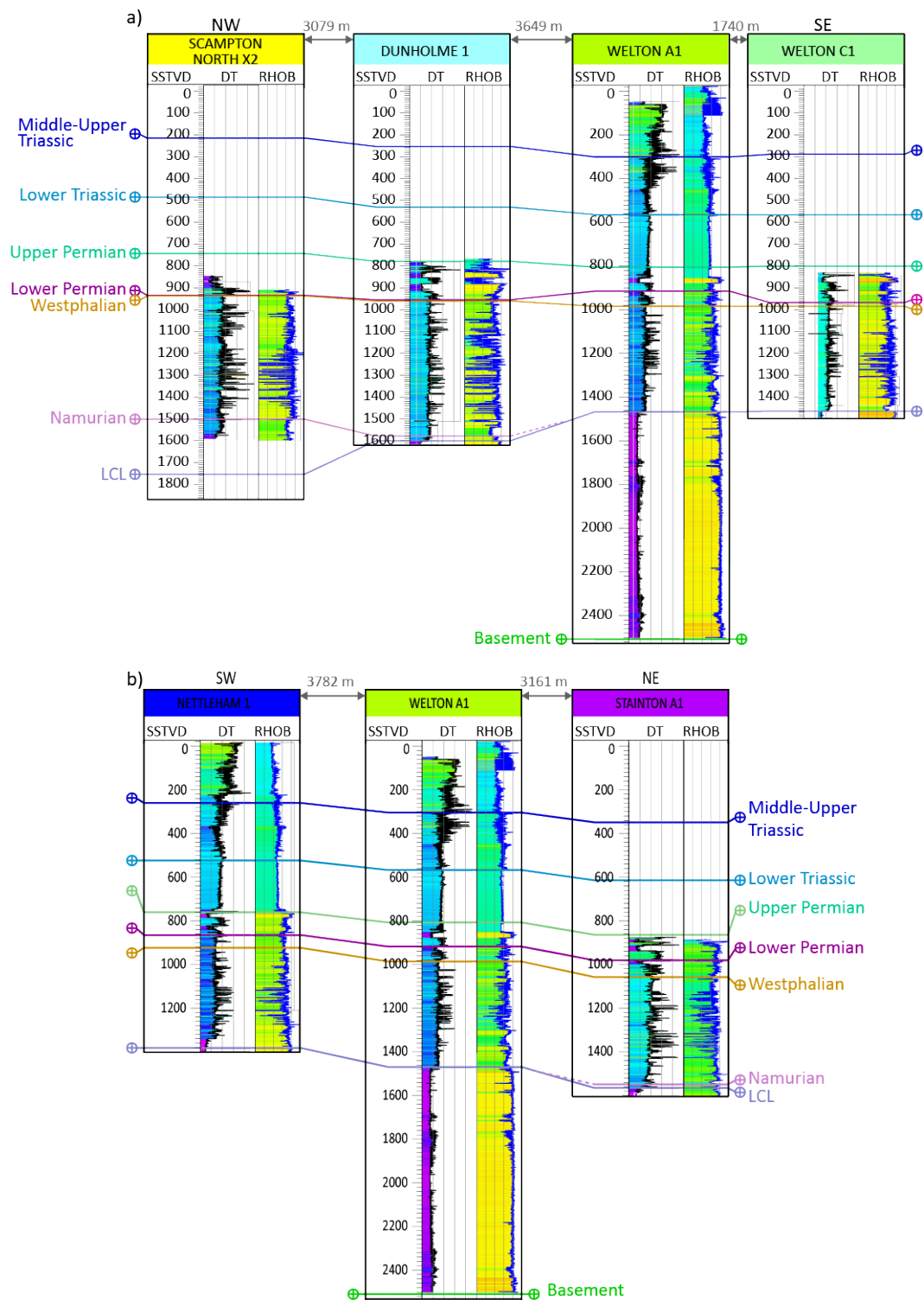


Figure 3. Stratigraphic correlation between selected wells across the study area. a) The upper panel shows a NW-SE correlation through Scampton North X2, Dunholme 1, Welton A1 and Welton C1. b) The lower panel shows a NE-SW correlation through Nettleham 1, Welton A1 and Stainton A1. Tracks show true subsea vertical depth (SSTVD), sonic transit time (DT) and bulk density (RHOB). Coloured correlation lines mark the interpreted Middle-Upper Triassic, Lower Triassic, Upper Permian, Lower Permian, Westphalian, Namurian, Lower Carboniferous Limestone (LCL) and basement horizons. Distances between the wells are indicated.

structural depression (Figures 4-6). The first-order structure is a broadly NW-SE-oriented graben whose western margin is defined by the most prominent fault system in the study area. This western boundary comprises a series of subparallel NW-SE-trending normal faults that dip predominantly eastward towards the graben interior. The faults are segmented along strike and locally overlap or step laterally. They accommodate the largest structural relief within the seismic volume and produce an abrupt transition from the relatively elevated western margin into the deeper central part of the graben. The western side of the structure is therefore comparatively steep and sharply fault-controlled.

The eastern side of the graben has a contrasting structural style (Figures 4-6). NW-SE-trending faults are also present but are generally fewer and of smaller apparent displacement than those along the western boundary. These faults occur together with a prominent population of approximately E-W to ENE-WSW-trending structures. The interaction between the two fault sets produces a more distributed and segmented eastern margin. In several locations, E-ENE-trending faults occur between overlapping or laterally offset NW-SE fault segments and delimit gently inclined structural blocks. These blocks progressively deepen towards the central part of the graben and define relay-ramp geometries through which structural relief is transferred between neighbouring fault segments. Consequently, the overall graben is markedly asymmetric: displacement is concentrated along the steep, east-dipping western boundary fault system, whereas the eastern side is characterised by smaller faults, distributed structural gradients and relay zones that step progressively towards the graben axis.

A third, subordinate fault orientation is present in the northern part of the study area, where several structures trend NE-SW (Figure 6). These faults are most clearly expressed on the base LCL depth map and can also be recognised, although less prominently, at the Top LCL level. They are oblique to both the dominant NW-SE fault system and the E-ENE-trending structures farther east, and locally intersect or terminate against the NW-SE faults. Their restricted spatial distribution gives the northern part of the graben a more complex, intersecting fault pattern than that observed farther south. The mapped fault network therefore comprises three principal orientations: dominant NW-SE structures, subordinate NE-SW faults concentrated in the north, and E-W to ENE-WSW structures that are most evident in the eastern part of the study area.

The seismic sections illustrate both the asymmetry of the graben and the vertical distribution of faulting (Figures 4-5). The NE-SW profiles intersect the western boundary fault system as a relatively dense array of steep normal faults associated with abrupt changes in the elevation of the base- and top-LCL horizons. Towards the graben interior and eastern margin, the structural style becomes more distributed, with smaller offsets, broader structural gradients and relay geometries. The NNW-SSE section provides a complementary view of the graben interior and shows that the base- and top-LCL surfaces are considerably more structured than the overlying succession. Most mapped faults affect the LCL and some can be traced into the overlying Carboniferous succession. Several interpreted fault traces extend below base LCL, but their geometry and extent at depth are less confidently resolved because of the decrease in seismic imaging quality.

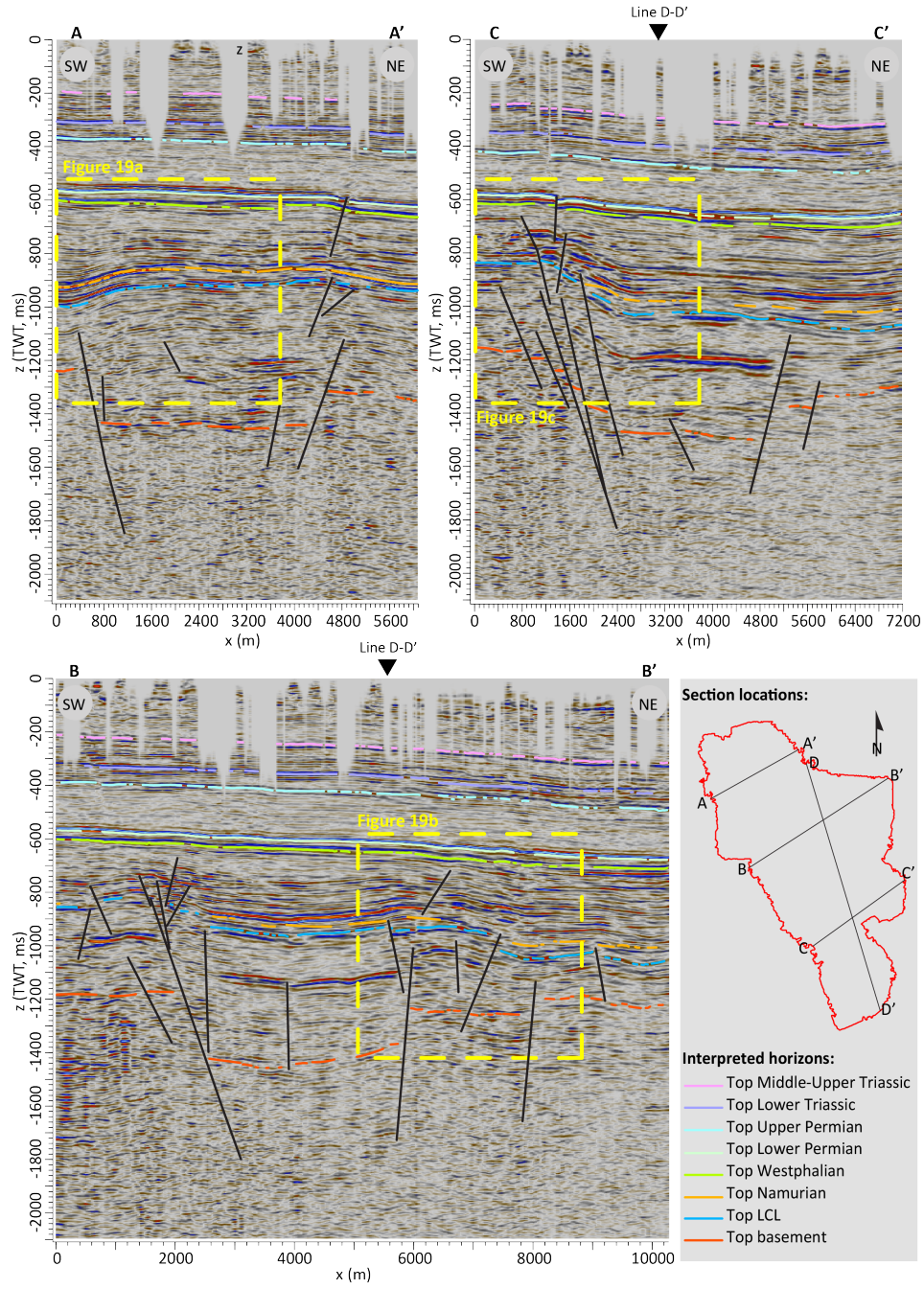


Figure 4. Interpreted NE-SW-oriented seismic sections across the study area. Interpreted horizons are the tops of the Middle-Upper Triassic, Lower Triassic, Upper Permian, Lower Permian, Westphalian, Namurian, Lower Carboniferous Limestone (LCL) and basement; interpreted faults are shown in black. Yellow dashed boxes identify inversion examples discussed in Section 5.2. Section locations are shown in the inset map. Vertical axis is in two-way-time (TWT).

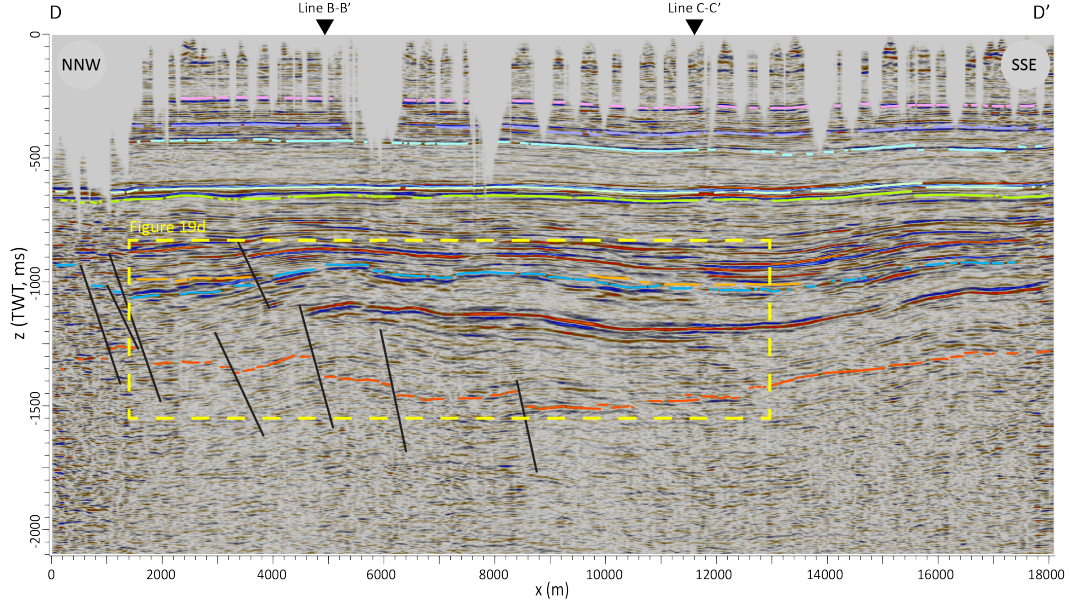


Figure 5. Interpreted NNW-SSE seismic section across the study area. Interpreted horizons are the tops of the Middle-Upper Triassic, Lower Triassic, Upper Permian, Lower Permian, West-phalian, Namurian, Lower Carboniferous Limestone (LCL) and basement, with interpreted faults shown in black. The yellow dashed box indicates the interval enlarged in Figure 14D. Section location is shown in the inset map of Figure 4. Vertical axis is in two-way-time (TWT).

Fault displacement generally decreases upwards, and the Permian-Triassic reflections are comparatively continuous and only weakly affected by discrete offset.

The contrasting structural styles are also expressed in the depth maps of the top and base LCL (Figure 6). The top LCL varies from approximately 1.2 to 1.8 km below sea level and displays a combination of regional relief and abrupt fault-related steps. The surface is shallowest across the south-central part of the seismic volume and becomes substantially deeper towards the eastern and northeastern parts, while additional local structural highs and lows occur throughout the area. The base LCL has considerably greater relief, ranging from approximately 1.6-2.0 km along parts of the graben margins to locally around 3 km within its deeper central domains. The strongest depth gradients occur adjacent to the western NW-SE fault system, whereas the eastern part of the structure is characterised by a broader transition into the graben interior. In the north, the NE-SW faults locally disrupt the otherwise dominant NW-SE structural grain and contribute to additional segmentation of the base LCL surface. Farther east, the orientation of depth contours is locally modified across the E-ENE-trending faults and relay zones. Fault intersections with base LCL are more extensive across the mapped area than those with top LCL, where traces are concentrated along particular corridors (Figure 6).

The difference in relief between the top and base LCL produces pronounced lateral variation in LCL thickness (Figure 6). The interval ranges from approximately 200 m to as much as 1.3-1.4 km across the seismic volume. The thickest LCL occupies broad domains within the interior of the graben, where thickness commonly exceeds 1 km and locally reaches >1.25 km. In contrast, substantially thinner LCL occurs towards the structural margins. The western boundary is particularly abrupt, with steep thickness gradients occurring adjacent to the main NW-SE fault system. The transition towards the eastern margin is more distributed and locally follows the stepped and relay-ramp ge-

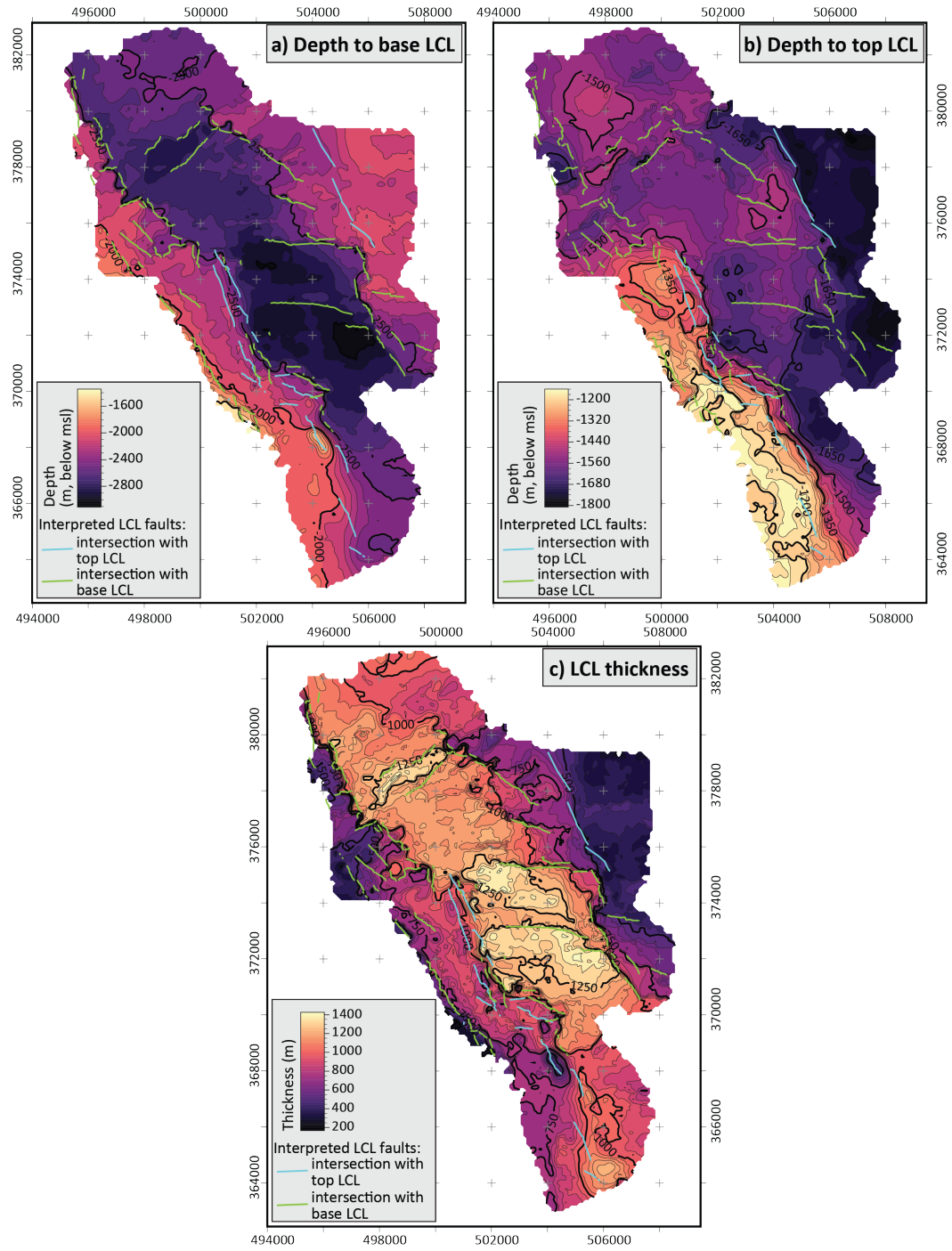


Figure 6. Depth and thickness (isochore) of the Lower Carboniferous Limestone (LCL) derived from the depth-converted seismic interpretation. (a) Depth to the base LCL (i.e., top basement), (b) depth to the top LCL, and (c) LCL thickness. Black lines are contours. Cyan and green lines show interpreted faults at their intersections with the top and base LCL, respectively. Depths are expressed in metres below mean sea level.

ometry defined by the intersecting NW-SE and E-ENE fault populations. Individual fault segments therefore commonly separate domains with contrasting LCL thickness, while the largest-scale thickness pattern broadly follows the asymmetric graben geometry defined by the base-LCL structure.

The Namurian succession differs markedly from the underlying LCL (Figure 7). It is considerably thinner, generally ranging from zero to approximately 200-250 m, and displays a more discontinuous thickness distribution. Very thin intervals occur across substantial parts of the central and northern study area, consistent with the close spacing of the top Namurian and top LCL observed in the well correlations and seismic sections. Thicker Namurian accumulations occur locally along parts of the western and eastern margins and within discrete belts through the central part of the graben. Although several thickness gradients coincide spatially with the inherited LCL fault network, the Namurian isochore pattern does not simply reproduce that of the LCL; i.e., domains of maximum LCL thickness are not systematically overlain by the thickest Namurian. The transition from the LCL to the Namurian therefore corresponds to a substantial change in both the magnitude and spatial distribution of stratigraphic thickness.

The Westphalian succession is substantially more laterally continuous and exhibits broader thickness variations (Figure 7). Thickness generally ranges from approximately 300 to >650 m. The succession is thinnest across the southern and south-central parts of the seismic volume and generally thickens northwards, with local maxima in the northern and northeastern areas. Unlike the LCL, the principal Westphalian thickness gradients are not systematically bounded by individual faults. Nevertheless, local thickness anomalies and changes in reflection geometry occur above parts of the inherited Carboniferous fault network. On the seismic sections, Westphalian reflections extend across many of the underlying LCL faults and show substantially less structural relief than the deeper horizons, although local deformation is retained above some of the larger structures.

A further change in architectural style is observed across the Permian succession (Figure 7). The combined Permian interval is approximately 250-450 m thick and displays broad, smooth thickness variations rather than the sharply compartmentalised pattern characteristic of the LCL. The succession is generally thickest across the northern part of the survey, where values reach approximately 400-450 m, and thins towards the south, where thickness locally falls below 300 m. The mapped thickness contours show little correlation with individual Carboniferous faults. This geometry is consistent with the seismic sections, on which the Lower and Upper Permian reflections remain comparatively continuous across the faulted Carboniferous substrate and largely record longer-wavelength structural relief.

The Triassic and younger succession is similarly characterised by smooth regional thickness variation, although its spatial pattern differs from that of the Permian (Figure 7). Thickness ranges from approximately 480 m in the west and northwest to almost 700 m in the eastern part of the seismic volume. The dominant feature is a broad eastward increase in thickness, with relatively minor short-wavelength variability superimposed upon this regional gradient. The Middle-Upper and Lower Triassic seismic horizons are correspondingly continuous and display little direct expression of the underlying Carboniferous fault segmentation. The Triassic and younger cover therefore contrasts strongly with the fault-controlled thickness domains and structural relief of the LCL.

Overall, the integrated well and seismic interpretation defines an asymmetric NW-SE-oriented graben whose architecture is principally expressed within the lower Carboniferous succession. The graben has a sharply defined western margin controlled by segmented, east-dipping NW-SE normal faults, whereas its eastern margin is broader and structurally more distributed, comprising smaller NW-SE faults together with E-ENE-trending faults and associated relay-ramp geometries that deepen towards the graben interior. In the northern part of the study area, a subordinate set of NE-SW-trending

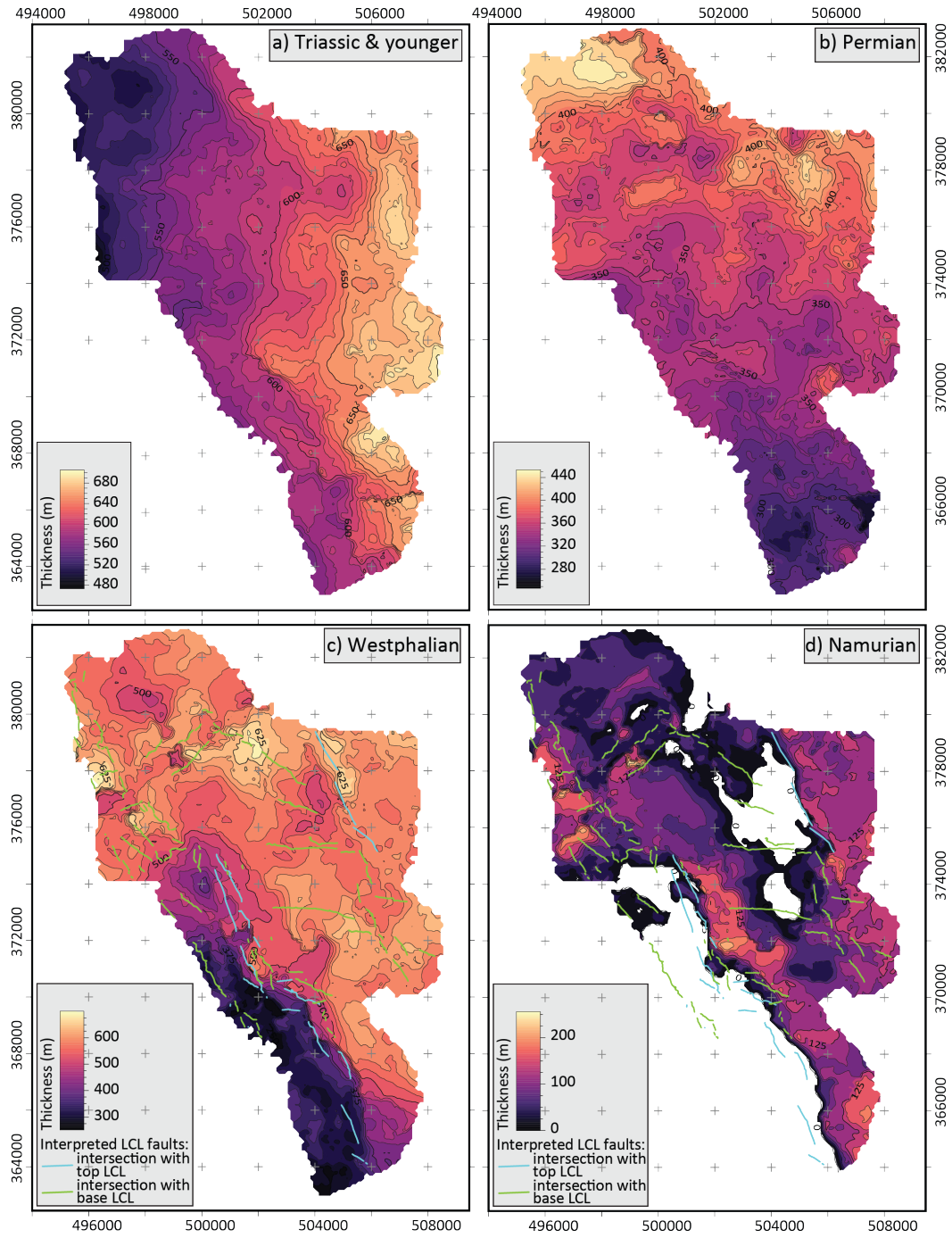


Figure 7. Isochore maps of the principal post-LCL stratigraphic intervals: (a) Triassic and younger strata, (b) Permian, (c) Westphalian and (d) Namurian. Thicknesses were calculated from the depth-converted seismic horizons and illustrate spatial variations in post-LCL sediment accumulation, erosion and preservation. Cyan and green lines show interpreted LCL faults at their intersections with the top and base LCL, respectively.

faults further segments the graben and locally disrupts the dominant structural grain. This structural organisation is most clearly recorded by the base LCL surface and by the strong lateral variation in LCL thickness. The overlying Namurian retains a heterogeneous but substantially different thickness pattern, whereas the Westphalian becomes more laterally continuous and is dominated by broader regional thickness variations. The Permian and younger successions progressively smooth the underlying Carboniferous relief and show little direct correspondence with individual faults. The structural and stratigraphic architecture therefore records a pronounced upward decrease in the expression of the fault-bounded graben framework, from strong compartmentalisation within the LCL to broad regional geometries within the Permian-Mesozoic cover.

4.2 Density-constrained gravity modelling

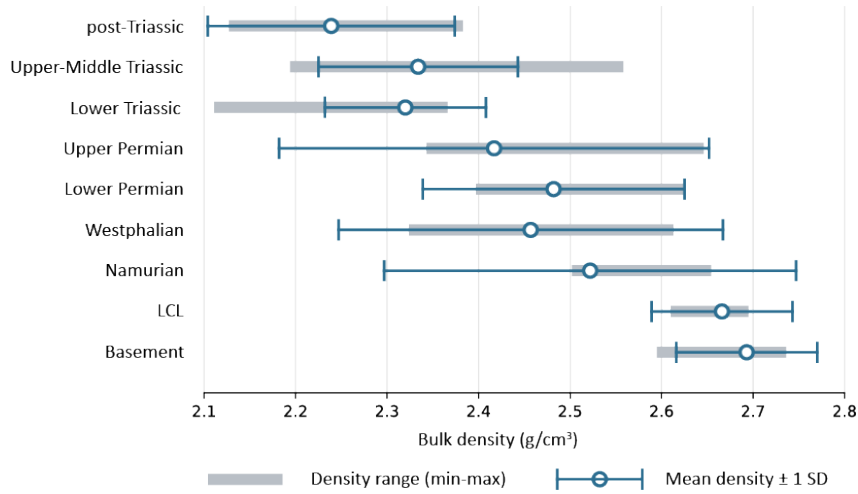


Figure 8. Bulk-density statistics derived from available well density logs for the main stratigraphic intervals in the study area. Grey bars show the observed minimum-maximum density range, while open circles and blue error bars indicate mean density and ± 1 standard deviation (SD), respectively. Density values are expressed in g/cm^3 .

Analysis of the available well density logs shows a general increase in bulk density with stratigraphic depth, although substantial overlap occurs between several of the post-Carboniferous and Upper Carboniferous units (Figure 8). Mean densities increase from 2.239 g/cm^3 in the post-Triassic succession to 2.334 and 2.320 g/cm^3 in the Upper-Middle and Lower Triassic intervals, respectively. The Upper and Lower Permian have mean densities of 2.417 and 2.482 g/cm^3 , while the Westphalian and Namurian intervals yield mean values of 2.457 and 2.522 g/cm^3 , respectively. The LCL is distinctly denser, with a mean density of 2.666 g/cm^3 and a comparatively narrow measured range of $2.610\text{--}2.695 \text{ g/cm}^3$. The highest mean density is recorded for the basement at 2.693 g/cm^3 , with measured values ranging between 2.595 and 2.736 g/cm^3 . The LCL and basement also show relatively low standard deviations of 0.077 g/cm^3 compared with the overlying stratigraphic intervals.

These mean formation densities were assigned to the corresponding units of the sub-surface 3D geological model to calculate its gravity response. The resulting forward model reproduces the first-order regional variation of the observed Bouguer anomaly (Figure 9a), including the transition from lower gravity values in the northwest to progressively higher values towards the south of the study area. However, comparison between the observed and calculated gravity fields reveals a pronounced, spatially coherent residual. The resid-

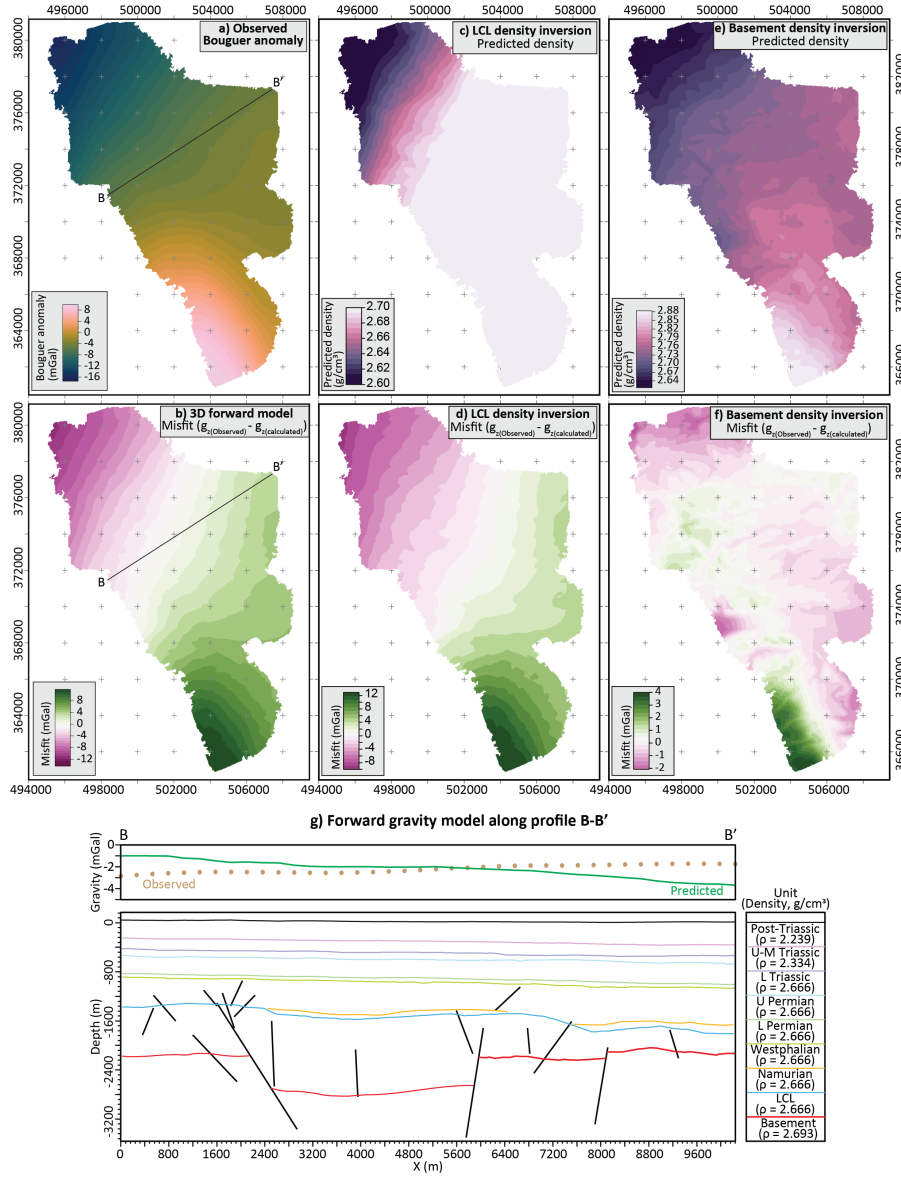


Figure 9. Gravity forward- and inverse-modelling results for the seismic-constrained 3D geological model. (a) Observed Bouguer gravity anomaly and (b) residual from the constant-density forward model, calculated as observed minus modelled gravity. (c) Recovered Lower Carboniferous Limestone (LCL) density and (d) corresponding residual following LCL density inversion. (e) Recovered basement density and (f) corresponding residual following basement density inversion. LCL density was constrained between 2.60 and 2.70 g/cm³, whereas basement density was allowed to vary between 2.60 and 3.00 g/cm³. The RMS residual decreases from 4.92 mGal for the forward model to 4.02 mGal for the LCL inversion and 0.49 mGal for the basement inversion, showing that plausible lateral density variation within the LCL alone cannot account for the observed gravity field, whereas deeper density heterogeneity substantially improves the fit.

ual, calculated as: $g_z(\text{observed}) - g_z(\text{calculated})$, ranges from -5.44 to +11.13 mGal, with a mean of +3.25 mGal and a root-mean-square (RMS) misfit of 4.92 mGal, is strongly negative in the northwestern part of the model, approaches zero across the central area and becomes increasingly positive towards the south (Figure 9b, g). Thus, the constant-density model systematically overpredicts the observed gravity response in the northwest and underpredicts it in the south, indicating that the density distribution represented by the mean well-log values alone cannot reproduce the observed gravity field.

To assess whether this residual could be accommodated by lateral density variations in the two deepest units, separate inversions were performed for the LCL and basement (Figure 9c-f). In each case, the densities of all other stratigraphic units were retained at their mean well-log-derived values. The LCL density was constrained between 2.6 and 2.7 g/cm³, consistent with the range observed in the density logs (Figure 8). Basement density was allowed to vary over a wider interval of 2.6-3.0 g/cm³. The broader basement density range reflects the limited penetration of basement by the available wells and hence the poorer constraint on its possible lithological and density variability.

The LCL inversion produces a strong northwest-to-southeast density gradient but only a limited improvement in the gravity fit (Figure 9c-d). The RMS residual decreases from 4.92 to 4.02 mGal, equivalent to an 18.3% reduction, while the mean absolute error decreases from 4.19 to 3.28 mGal. Residuals remain strongly asymmetric, ranging from -3.88 to +10.08 mGal, with a mean of +2.63 mGal. The recovered LCL densities range from 2.60 to 2.70 g/cm³, with a mean of 2.684 g/cm³ and a median of 2.700 g/cm³. The density distribution is strongly skewed towards the imposed upper constraint: 67.3% of model cells reach the upper bound of 2.7 g/cm³, and 71.1% lie within 0.01 g/cm³ of this value. In contrast, only 2.1% of cells reach the lower density bound. The lowest predicted LCL densities, approaching the imposed lower bound of 2.6 g/cm³, occur in the northwest. Density increases rapidly southeastwards and reaches values close to the upper inversion bound of 2.7 g/cm³ across most of the central and southern parts of the study area. Despite this variation, the resulting residual retains the broad spatial pattern observed in the constant-density forward model, with negative residuals in the northwest and increasingly positive residuals towards the south.

In contrast, the basement inversion produces a markedly improved fit to the observed Bouguer anomaly (Figure 9e-f). The RMS residual decreases from 4.92 to 0.49 mGal, corresponding to a 90.1% reduction relative to the constant-density forward model, and the mean absolute error decreases from 4.19 to 0.37 mGal. The mean residual is reduced to +0.31 mGal, and residual values range from -0.69 to +1.98 mGal. Recovered basement densities vary between 2.600 and 2.891 g/cm³, with a mean of 2.745 g/cm³ and a median of 2.752 g/cm³. They are lowest in the northwest, where values are approximately 2.64-2.70 g/cm³, and increase progressively towards the central and southern parts of the model. Densities commonly exceed ~2.75-2.80 g/cm³ across the central and southeastern areas and reach their highest values at the southern end of the model. Introducing this lateral variability substantially reduces the gravity misfit (Figure 9f). Unlike the LCL inversion, the recovered basement-density distribution is not concentrated at the imposed model limits. Only 0.18% of cells reach the lower bound of 2.6 g/cm³, while no cells reach the 3.0 g/cm³ upper bound. The central 90% of recovered basement densities lies between 2.637 and 2.845 g/cm³, indicating that most of the modelled density variability is resolved within, rather than at the limits of, the permitted density range.

The contrasting inversion results show that lateral density variations within the range measured for the LCL are insufficient to account for the long-wavelength gravity residual generated by the constant-density geological model. Allowing the less well-constrained basement density to vary, however, removes much of this regional mismatch and provides a substantially closer fit to the observed Bouguer anomaly.

4.3 Potential-field structural analysis

Wavelength filtering of the Bouguer anomaly (GBA) and reduced-to-pole magnetic anomaly (DRTP-Mag) separates broad regional anomalies from shorter-wavelength variations associated with shallower sources (see Text S5 and Figure S4). The long-wavelength components are characterised by smooth, spatially extensive gradients across the study area, whereas the medium-wavelength components resolve shorter-scale anomaly variations and sharper gradients. In contrast, the shortest-wavelength components are low amplitude and spatially irregular and were therefore shallow sources and/or acquisition/processing noise. The medium- and long-wavelength components were subsequently used for structural enhancement and source-depth analysis.

Tilt-derivative depth estimates show that the filtered wavelengths sample different depth ranges (Figure 10). Medium-wavelength solutions are generally shallower and are commonly spatially associated with gradients that coincide with, or occur close to, mapped LCL faults. Long-wavelength GBA tilt depths are substantially deeper, whereas the DRTP-Mag tilt depths show a broader overlap between the two wavelengths.

Euler deconvolution provides a clearer quantitative separation (Figure 11). Medium-wavelength GBA solutions ($2.4 < \lambda < 7\text{ km}$) have a median source depth of 1.24 km (interquartile range, IQR = 1.04-1.77 km; $n = 229$), while medium-wavelength DRTP-Mag solutions ($2.7 < \lambda < 8\text{ km}$) have a median depth of 1.44 km (IQR = 1.17-1.81 km; $n = 231$). Long-wavelength solutions are substantially deeper, with median depths of 3.08 km for the GBA ($7 < \lambda < 60\text{ km}$; IQR = 2.75-3.47 km; $n = 223$) and 2.82 km for DRTP-Mag ($8 < \lambda < 60\text{ km}$; IQR = 2.04-3.52 km; $n = 410$) (Figure 11).

Comparison of the Euler solutions with the independently mapped top and base of the LCL further supports this vertical partitioning (Figure 11). For the medium-wavelength GBA, 69.9% of solutions occur above the top LCL and 29.7% within the LCL interval, with only 0.4% located below its base. The medium-wavelength DRTP-Mag solutions show a similar, although slightly deeper, distribution, with 57.6% above the top LCL, 37.2% within the LCL interval, and 5.2% below its base. The distribution is reversed for the long-wavelength components. Approximately 85.7% of long-wavelength GBA solutions occur below the mapped base of the LCL, compared with 5.4% within and 9.0% above the LCL interval. Long-wavelength DRTP-Mag solutions are more vertically dispersed but remain predominantly deeper, with 61.2% occurring below the base LCL, 31.7% within the LCL, and 7.1% above its top. The distinction between the medium- and long-wavelength source populations is therefore particularly pronounced in the gravity data.

Phase-based extraction of lineaments from the filtered potential-field datasets identifies 85 features with a combined mapped length of 169.4 km (Figure 12). The length-weighted orientation distribution is dominated by a N150-160° trend and has a length-weighted axial mean of N160.3°. At the scale of the study area, NW-SE lineaments account for 42.3% of the total mapped length and N-S lineaments for 35.6%, whereas NE-SW and E-W orientations represent 12.6% and 9.5%, respectively. The pooled populations nevertheless show systematic differences according to dataset, wavelength, and extraction method (Figure 13). GBA lineaments ($n = 52$) are predominantly N-S, with 51.1% of their total length falling within the N-S family and a dominant N000-010° trend (Figures 13a), whereas DRTP-Mag lineaments ($n = 33$) show a stronger NW-SE orientation, which accounts for 55.6% of mapped length and has a dominant N140-150° trend (Figures 13b).

Wavelength also influences the orientation distribution. Medium-wavelength lineaments ($n = 54$) contain approximately equal N-S and NW-SE components, representing 37.7% and 36.1% of mapped length, respectively, although the dominant trend is N150-160° (Figures 13c). Long-wavelength lineaments ($n = 31$) show a clearer NW-SE preference, with 52.7% of mapped length within this orientation and a dominant N140-150°

trend (Figures 13d). A comparable contrast is observed between the two phase-based extraction methods. Phase-congruency edges ($n = 33$) are dominated by N-S orientations, which represent 44.5% of total edge length and define a dominant N000-010° trend; NE-SW orientations form a secondary component accounting for 28.8% (Figures 13e). In contrast, phase-symmetry ridges ($n = 52$) are predominantly NW-SE, representing 55.2% of total ridge length and defining a dominant N150-160° trend (Figures 13f).

Separating the lineaments simultaneously by dataset, wavelength, and extraction method shows that these pooled trends are not uniformly distributed among the indi-

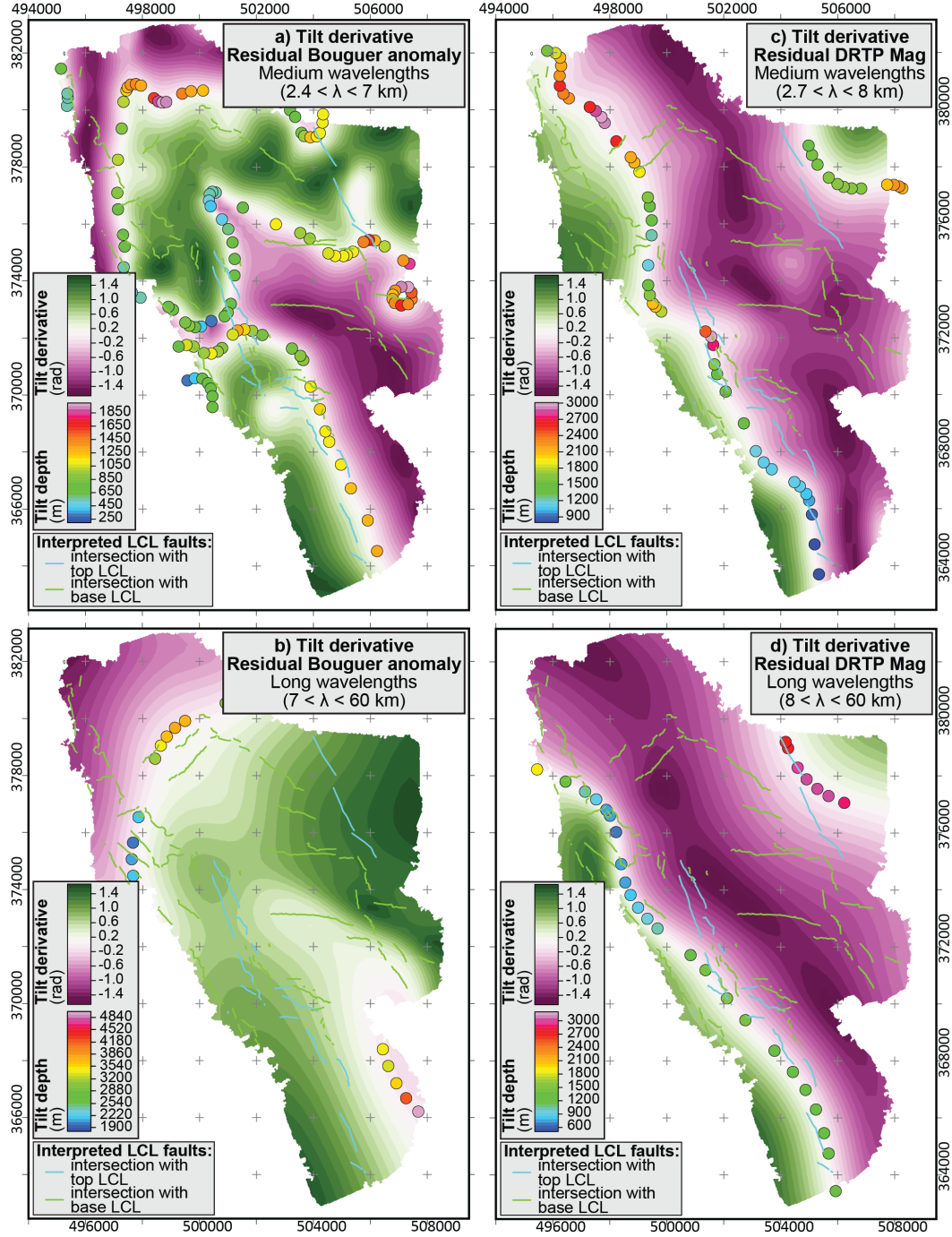


Figure 10. Tilt-derivative maps and associated source-depth estimates for the wavelength-filtered potential-field anomalies. (a) Medium-wavelength residual Bouguer gravity anomaly ($2.4 < \lambda < 7$ km), (b) long-wavelength residual Bouguer gravity anomaly ($7 < \lambda < 60$ km), (c) medium-wavelength residual reduced-to-pole magnetic anomaly ($2.7 < \lambda < 8$ km), and (d) long-wavelength residual reduced-to-pole magnetic anomaly ($8 < \lambda < 60$ km). Coloured symbols show estimated source depths. Cyan and green lines show interpreted faults at their intersections with the top and base LCL, respectively.

vidual populations (Figure 13g-n). The N-S signal in the GBA is particularly associated with phase-congruency edges (Figure 13g-h): N-S lineaments account for 72.6% of the mapped length of the medium-wavelength GBA edges ($n = 12$; dominant bin N000-010°) and 77.5% of the long-wavelength GBA edges ($n = 6$; dominant bin N0-10°). GBA ridges are more heterogeneous (Figure 13i-j). Medium-wavelength ridges ($n = 22$) contain both NW-SE and N-S components, representing 45.0% and 39.8% of mapped length, respectively, with a dominant N150-160° trend. Long-wavelength GBA ridges ($n = 12$) are similarly distributed between N-S and NW-SE orientations, which account for 44.2% and 39.6% of mapped length, respectively.

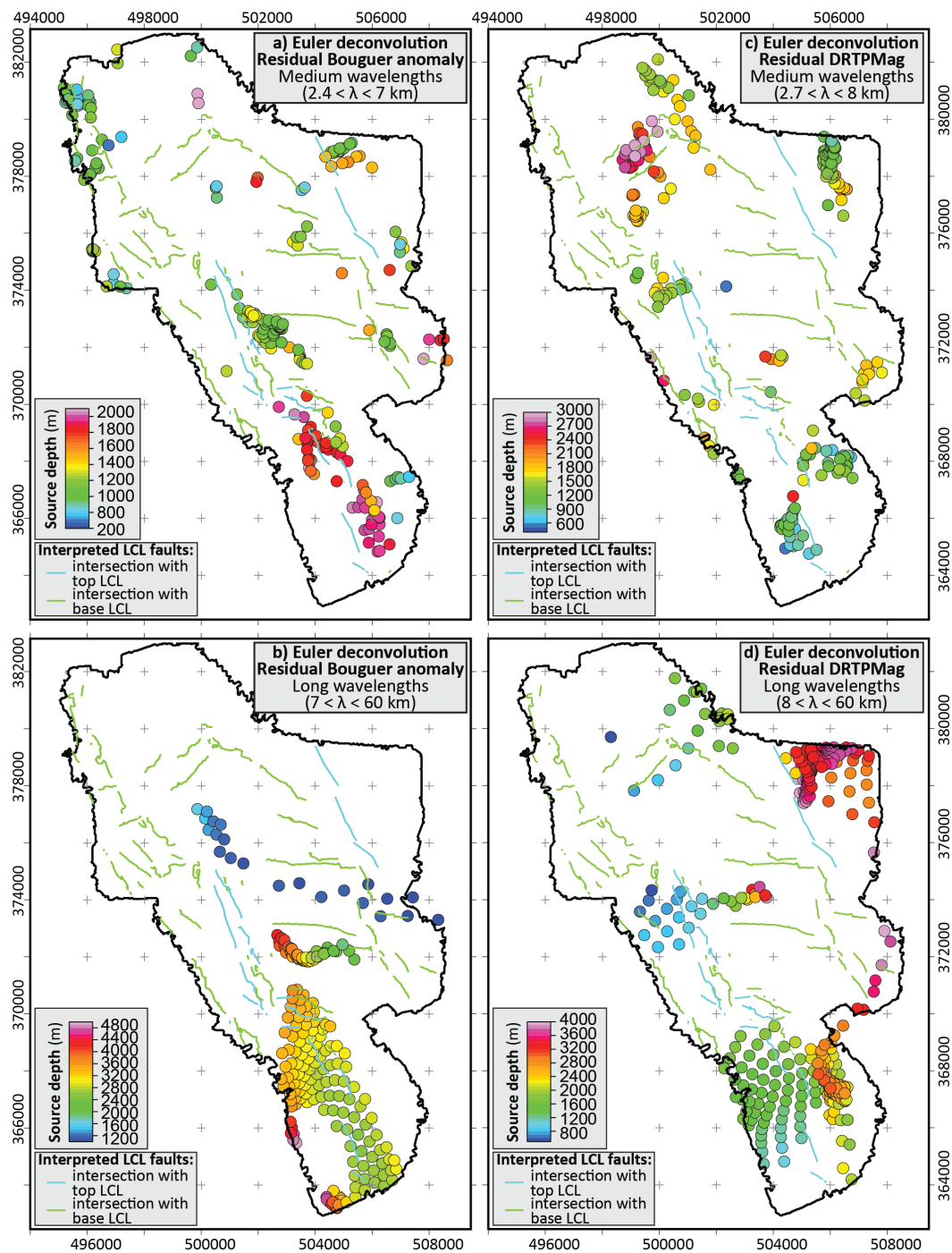
The NW-SE character of the DRTP-Mag dataset is principally expressed by the phase-symmetry ridges. Medium-wavelength DRTP-Mag ridges ($n = 9$) have a dominant N150-160° trend, with 52.2% of their mapped length belonging to the NW-SE family (Figure 13k). This orientation becomes particularly pronounced in the long-wavelength DRTP-Mag ridges ($n = 9$), for which 95% of the mapped length is NW-SE and the dominant trend is N140-150° (Figure 13l). DRTP-Mag edges are substantially more dispersed. Medium-wavelength edges ($n = 11$) have a dominant N040-050° trend and contain NE-SW, NW-SE, and E-W components (Figure 13m), whereas the long-wavelength edge population comprises only four lineaments distributed among several orientations and therefore does not define a robust preferred trend (Figure 13n).

Spatial comparison with the seismic interpretation shows that several NW-SE potential-field lineaments are parallel to, or locally coincide with, the mapped LCL fault system, particularly through the central and southern parts of the study area (Figure 12). Other potential-field lineaments extend beyond the seismically mapped fault traces or display N-S to NE-SW orientations that are less clearly expressed in the LCL fault interpretation. Together, the potential-field results therefore identify a multiscale structural fabric dominated by NW-SE and N-S components, while also showing that their relative expression varies systematically with potential-field dataset, anomaly wavelength, and whether anomaly edges or ridges are analysed.

5 Discussion

5.1 Structural domains

The structural architecture resolved at the Welton area is part of the broader tectonic framework of the Carboniferous basins of northern England, where basin development was strongly influenced by reactivation of pre-existing structures in the underlying pre-Carboniferous basement. Regional seismic and geological studies identify prominent NW-SE and NE-SW structural grains inherited from pre-Carboniferous deformation and repeatedly reactivated during subsequent basin evolution (Leeder, 1982; Fraser & Gawthorpe, 1990, 2003). In the East Midlands, Late Devonian to Viséan extension exploited this inherited structural fabric to generate a mosaic of fault-bounded blocks, platforms and asymmetric graben to half-graben basins, including the Gainsborough Trough, Widmerpool Gulf and Edale Gulf (Figure 1; Ebdon et al., 1990; Fraser & Gawthorpe,



Stratigraphic distribution of Euler deconvolution solutions

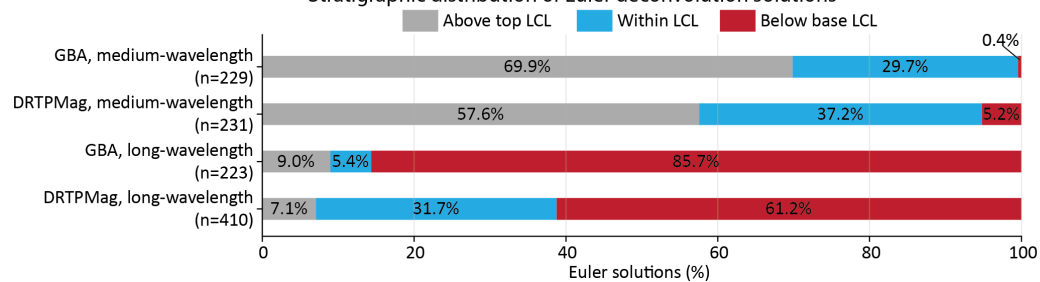


Figure 11. Euler deconvolution solutions for the wavelength-filtered potential-field anomalies. (a) Medium-wavelength residual Bouguer gravity anomaly ($2.4 < \lambda < 7$ km; $n = 229$), (b) long-wavelength residual Bouguer gravity anomaly ($7 < \lambda < 60$ km; $n = 223$), (c) medium-wavelength residual reduced-to-pole magnetic anomaly ($2.7 < \lambda < 8$ km; $n = 231$), and (d) long-wavelength residual reduced-to-pole magnetic anomaly ($8 < \lambda < 60$ km; $n = 410$). Symbols are coloured according to estimated source depth. Cyan and green lines show interpreted faults at their intersections with the top and base LCL. The lower bar chart summarises the proportion of Euler solutions located stratigraphically above the top LCL, within the LCL interval and below the base LCL.

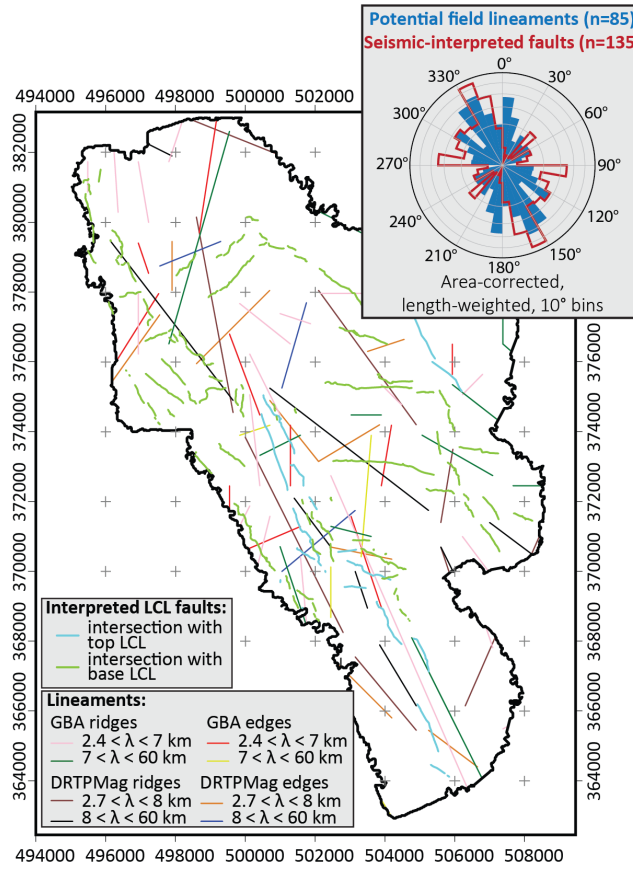


Figure 12. Spatial distribution of lineaments extracted from the wavelength-filtered Bouguer gravity anomaly (GBA) and reduced-to-pole magnetic anomaly (DRTP-Mag). Lineaments derived from ridge and edge detection are shown separately for the long- and medium-wavelength components. Cyan and green lines show interpreted faults at their intersections with the top and base Lower Carboniferous Limestone (LCL), respectively, allowing comparison between potential-field lineaments and the seismic-derived fault network. Top right corner inset shows rose diagrams of potential field lineaments (in blue) and seismic-interpreted faults (in red).

1990). Syn-rift deformation was episodic, with successive extensional phases producing wedge-shaped stratigraphic packages adjacent to active basin-bounding faults, while carbonate platforms developed preferentially on relatively elevated footwall blocks and structural highs.

The fault architecture mapped in the Welton area (Figures 4, 5, and 6) is consistent with this regional structural framework but also demonstrates substantial along-strike and across-basin heterogeneity. The dominant NW-SE-trending, predominantly east-dipping faults along the western part of the study area define a relatively coherent fault corridor and broadly parallel the principal structural grain of the East Midlands Carboniferous rift system. In contrast, the eastern part of the study area contains a more distributed network in which NW-SE faults interact with E-ENE-trending structures, while subordinate NE-SW-trending structures are particularly evident farther north (Figure 6). The recurrence of these orientations in both the seismic interpretation and the gravity and magnetic lineament analysis suggests that at least part of the mapped LCL

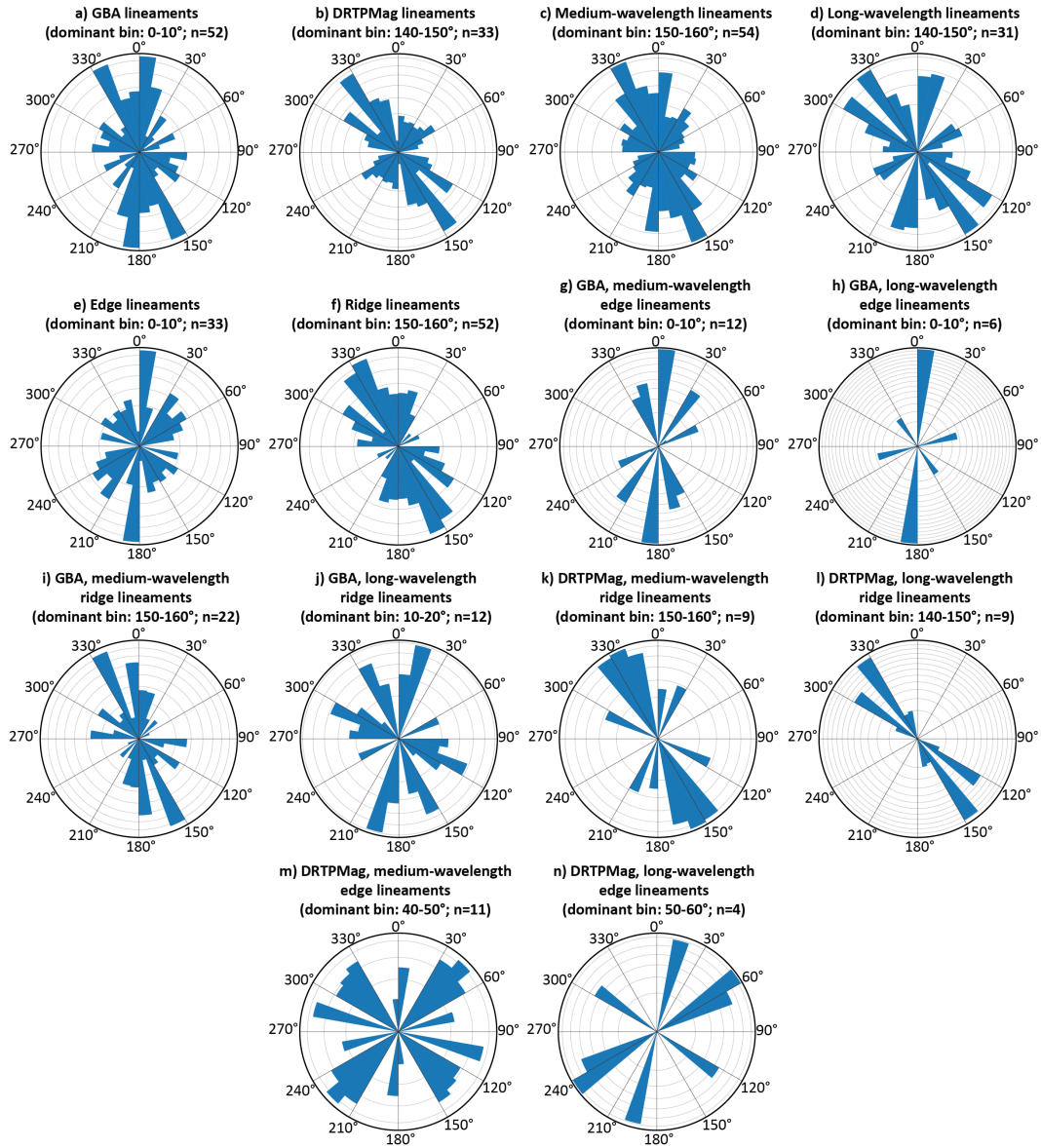


Figure 13. Rose diagrams showing orientations of lineaments extracted from wavelength-filtered Bouguer gravity anomaly (GBA) and reduced-to-pole magnetic (DRTP-Mag) data. (A-H) Lineaments separated by dataset, wavelength domain and extraction method: long-wavelength DRTP-Mag ridges (a) and edges (b), long-wavelength GBA ridges (c) and edges (d), medium-wavelength DRTP-Mag ridges (e) and edges (f), and medium-wavelength GBA ridges (g) and edges (h). Panels I-N show pooled orientations by wavelength domain (i-j), potential-field dataset (k-l), and extraction method (m-n). Orientations are treated as axial data, grouped into 10° bins, and weighted by mapped lineament length. Bin values are normalized to the total mapped length of each population, and sector radii are square-root scaled so that sector area is proportional to the percentage of total mapped lineament length (Nemec, 1988). The dominant orientation bin and number of lineaments (n) are indicated for each population.

fault network reflects a deeper and more regionally extensive structural template rather than faulting confined to the Carboniferous sedimentary succession.

This inherited and multidirectional structural fabric provides an important framework for understanding the spatial organisation of deformation within the LCL. Rather than representing the response of an initially homogeneous crust to a single extensional stress field, the Welton fault system likely developed through selective reactivation, propagation and interaction of differently oriented pre-existing discontinuities during successive stages of Carboniferous extension. This provides a plausible explanation for the marked contrast between the localised western fault corridor, the more distributed eastern relay system, and zones of fault intersection and segment linkage elsewhere in the study area. These structural domains are considered separately below because their contrasting fault geometries and degrees of structural interaction are likely to exert different controls on fracture development and connectivity, and hence on the geothermal prospectivity of the LCL.

5.1.1 *Rift-bounding fault corridor*

The western part of the Welton area is characterised by a relatively narrow corridor of predominantly NW-SE-trending, east-dipping normal faults that accommodates much of the structural relief across the study area (Figures 4, 5, and 6). Collectively, these faults define the western margin of the Welton asymmetric graben, separating the structurally elevated western block from the deeper basin interior. The concentration of faulting, together with the abrupt changes in depth and LCL thickness across this margin, suggests that extension was preferentially localised within a relatively persistent structural corridor rather than distributed uniformly across the basin. Although individual fault traces are segmented and locally overlap or step laterally, their broadly consistent orientation and dip direction indicate that they form components of a larger, kinematically linked fault system.

The NW-SE orientation of this corridor closely matches one of the dominant inherited structural trends recognised throughout the Carboniferous basins of northern England. Regional studies have shown that Late Devonian-Viséan extension preferentially exploited pre-existing basement structures, producing fault-controlled half-graben and tilted-block geometries across the East Midlands (Leeder, 1982; Fraser & Gawthorpe, 1990, 2003; Ebdon et al., 1990). The western Welton fault corridor is therefore interpreted as the expression of this inherited extensional framework rather than a fault system nucleated entirely within the Carboniferous succession, although its connection to individual pre-Carboniferous structures is not directly resolved. This interpretation is supported by the potential-field analysis, in which several NW-SE-trending gravity and magnetic

lineaments are parallel to, or spatially coincide with, the mapped LCL faults (Figures 10, 11, and 12). The recurrence of similar structural orientations at different wavelengths is consistent with structural continuity at depth and suggests that at least some faults within the western corridor may be rooted in the pre-Carboniferous basement.

Such localisation of repeated displacement has important implications for the LCL fracture network. Major faults are likely to represent structurally heterogeneous fault zones comprising discrete slip surfaces, fault cores, subsidiary faults and variably fractured damage zones (e.g., Caine et al., 1996; Faulkner et al., 2010). Where displacement is partitioned between closely spaced fault strands, as observed along the western corridor, these damage zones may overlap and generate a broader volume of fractured rock than would be predicted from the mapped fault surfaces alone. Consequently, the western corridor is likely to contain higher fracture intensities and greater potential for vertically and laterally connected fracture networks than the comparatively weakly faulted blocks away from the basin margin. Repeated movement along inherited structures may further enhance this heterogeneity by exploiting existing discontinuities and promoting successive generations of subsidiary fracturing.

5.1.2 *Relay-controlled rift margin*

The eastern margin of the Welton graben is characterised by a more distributed fault architecture in which NW-SE-trending faults occur together with a prominent population of E-W to ENE-WSW-trending structures (Figures 5, and 6). Rather than defining a discrete basin-bounding fault zone, these structures form a stepped fault system across which structural relief is progressively transferred towards the graben interior. In several locations, E-ENE-trending faults occur between overlapping or laterally offset NW-SE fault segments and delimit gently inclined blocks that deepen towards the basin centre (Figure 6). The corresponding depth and thickness patterns of the LCL follow this stepped geometry, with broader structural gradients and more gradual changes in LCL thickness than across the sharply fault-controlled western margin (Figure 6). These relationships indicate that displacement along the eastern side of the graben was distributed between multiple interacting fault segments and intervening relay zones.

Such geometries are characteristic of segmented normal-fault systems in which displacement is transferred between overlapping fault segments through relay ramps (e.g., Peacock & Sanderson, 1991; Childs et al., 1995; Peacock et al., 2017). Relay structures develop as initially discrete faults that propagate laterally and begin to interact, with deformation within the intervening rock volume accommodating the displacement deficit between neighbouring segments. Continued extension may progressively rotate and deform the relay block and ultimately lead to breaching and hard linkage of the original fault segments. The geometry observed at Welton is therefore consistent with a fault system that developed through progressive propagation and interaction of segmented normal faults rather than through displacement on a single continuous eastern boundary fault. The preservation of several stepped blocks suggests that different parts of the system may record different degrees of fault interaction and linkage.

The relationship between the NW-SE and E-ENE fault populations may reflect strain partitioning within an oblique extensional or transtensional system. The NW-SE faults are compatible with the inherited structural grain that influenced regional Carboniferous rifting and may have accommodated most of the displacement, while the E-ENE-trending structures could have acted as accommodation faults, transferring displacement between NW-SE segments and enabling bulk N-S extension. Their systematic association with changes in the geometry and continuity of the NW-SE faults is consistent with such a kinematic role. These transverse structures may have exploited pre-existing weaknesses, developed during fault interaction, or combined both processes. Regardless of their

origin, the E-ENE-trending faults appear to have contributed to displacement partitioning and the organisation of the eastern rift margin.

The distributed nature of deformation within relay systems has important implications for fracture architecture within the LCL. Strain within an intact relay is accommodated not only by slip on the bounding faults but also by rotation, flexure and subsidiary faulting within the intervening block (Nixon et al., 2019; Rotevatn et al., 2007; Imber et al., 2004; Fossen & Rotevatn, 2016). As relay systems evolve, deformation may become increasingly localised around fault tips and eventually across breached linkage zones, creating spatially heterogeneous fracture networks rather than damage confined to the mapped major fault surfaces (e.g., Fossen & Rotevatn, 2016). Consequently, the eastern rift margin is likely to comprise a mosaic of relatively intact relay blocks, distributed deformation zones and locally more intensely fractured areas associated with progressive fault interaction. These variations are not resolved directly by seismic-scale fault mapping but are important when considering the potential distribution and connectivity of fractures within the LCL.

5.1.3 *Fault interaction and linkage zones*

Superimposed on the first-order rift architecture are localised domains in which faults of different orientations intersect, terminate, overlap or change orientation (Figure 6). These geometries occur throughout the mapped fault network but are particularly evident in the northern part of the study area, where subordinate NE-SW-trending faults cut obliquely across the dominant NW-SE structural grain. These structures are most clearly expressed at the base LCL and locally disrupt or segment the NW-SE fault system (Figure 6). Similar interaction occurs farther east where E-ENE structures link or terminate against NW-SE fault segments, while the western rift-bounding system itself comprises overlapping and laterally stepping fault strands. The mapped fault network therefore contains numerous structural discontinuities at which displacement must either terminate, be transferred to neighbouring faults, or be accommodated by deformation of the intervening rock volume.

The subordinate NE-SW faults in the north are particularly significant in the context of the inherited regional structural framework. Their orientation broadly coincides with the second major basement trend recognised across the Carboniferous basins of northern England (Leeder, 1982; Fraser & Gawthorpe, 1990, 2003; Ebdon et al., 1990), suggesting that the Welton fault network may record interaction between two inherited structural fabrics rather than development along a single rift-parallel trend. The potential-field lineaments reinforce this interpretation by identifying multiple structural orientations beyond those resolved directly by the seismic interpretation (Figures 12, 13). However, spatial coincidence alone does not demonstrate that individual LCL faults are basement-rooted. A more cautious interpretation is that the intersection of NW-SE and NE-SW structures defines zones where differently oriented components of the inherited structural grain may have interacted during Carboniferous extension.

Fault intersections and segment terminations are mechanically distinct from the relatively simple portions of individual fault surfaces. Stress and strain become concentrated around propagating fault tips, within overlap zones and where faults interact, commonly producing subsidiary faults, fractures and distributed damage before through-going linkage is established (Peacock & Sanderson, 1991; Childs et al., 1995; Kim et al., 2004). As fault segments propagate towards one another, progressive interaction may therefore transform initially isolated damage zones into interconnected fault-fracture networks. This process is consistent with the range of geometries observed in the Welton area, from apparently isolated or terminating segments to overlapping faults, relay structures and more complex intersections (Figure 6). The present-day structural pattern likely preserves different stages of this progressive interaction and linkage rather than representing a net-

work in which all mapped faults developed simultaneously or were continuously connected from inception.

These interaction zones may be particularly important for the fracture architecture of the LCL because deformation is likely to extend beyond the seismically resolvable fault surfaces. Fault-tip damage, subsidiary fracturing and the overlap of damage zones around neighbouring structures can locally increase fracture density and establish connections between faults of different orientation. Where differently oriented fault systems intersect, such connectivity may also provide three-dimensional pathways linking otherwise compartmentalised structural blocks or stratigraphic levels. Comparable relationships between fault interaction, fracture development and focused fluid circulation have been documented in hydrothermal systems, where fault tips, intersections and accommodation zones commonly localise fluid pathways (e.g., Curewitz & Karson, 1997). These structural positions therefore represent plausible zones of enhanced fracture connectivity within the LCL.

5.2 Structural inversion and palaeo-karst development

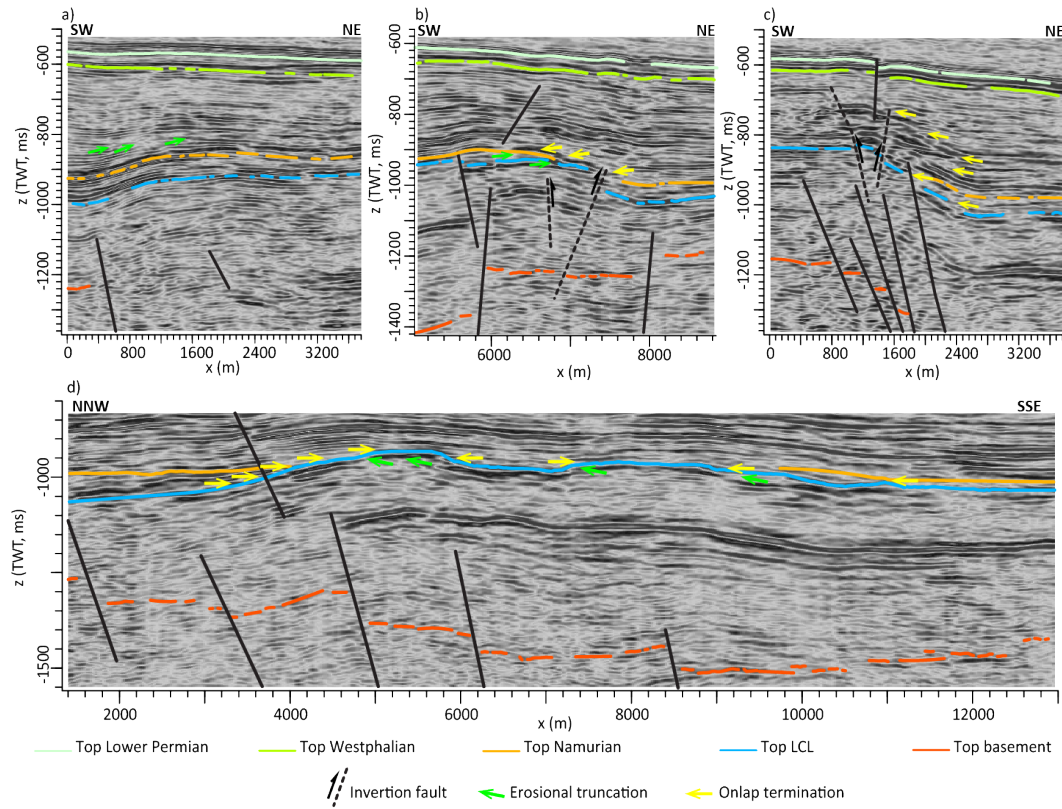


Figure 14. Seismic examples illustrating inversion-related deformation and associated stratigraphic terminations above the Lower Carboniferous Limestone (LCL). Panels (a-c) are extracted from the NE-SW seismic sections in Figure 4 and panel (d) from the NNW-SSE section in Figure 5. Solid black lines mark interpreted faults and dashed black lines indicate inferred inversion-related faults. Green arrows identify erosional truncation and yellow arrows onlap terminations. Vertical axis is in two-way-time (TWT).

The tectonic evolution of the study area was marked by positive inversion that was strongly localised along selected elements of the extensional fault network rather than

expressed as broad basin-wide shortening. Seismic evidence for inversion includes local doming of the LCL and overlying succession above reactivated faults, erosional truncation across the crests of these structures, and onlap of younger strata onto the resulting palaeorelief (Figure 14). Importantly, these relationships vary spatially and stratigraphically across the study area, indicating that inversion was episodic and partitioned between different structures through time. The lack of comparable deformation within the Lower Permian succession further indicates that the principal inversion recorded by the seismic data was completed during the Carboniferous.

The earliest and most pronounced inversion is observed in the southwestern part of the study area, along the central and southern segments of the western fault corridor, and farther east around the relay system (Figure 14B-D). Here, the Top LCL is folded into discrete fault-related structural highs and locally truncated by erosion. Namurian reflections onlap both flanks of these highs but are absent across their crests, indicating that positive relief had developed by Namurian time and that uplift was locally sufficient to prevent deposition and/or remove previously deposited strata. This interpretation is independently supported by the Namurian thickness map (Figure 7d), which shows complete removal of the Namurian along central and southern parts of the western fault corridor and above the eastern relay system. The lowermost Westphalian succession locally continues to onlap the LCL palaeohighs, but younger Westphalian reflections progressively become conformable with the underlying structure. The upward attenuation of this exhumation signal indicates that deformation and its associated palaeorelief persisted into the early Westphalian but progressively waned thereafter. The onset of this phase is therefore constrained to the latest stages of LCL deposition or early Namurian time, with the strongest uplift and erosion occurring before or during Namurian deposition.

This timing is consistent with evidence for late Brigantian-earliest Namurian inversion elsewhere in the East Midlands. Regional seismic-stratigraphic studies document local contractional reactivation following the final phase of Dinantian rifting, with uplift and erosion concentrated along selected inherited faults before deposition of the Namurian-Westphalian post-rift succession (Ebdon et al., 1990; Fraser & Gawthorpe, 1990, 2003; Pharaoh et al., 2011). Of particular relevance, Namurian strata are absent over the Welton Anticline, where Westphalian strata have previously been interpreted to unconformably overlie an eroded, and potentially karstified, Visean succession deformed during pre-Westphalian inversion (Fraser & Gawthorpe, 2003; Pharaoh et al., 2011).

A different stratigraphic expression of inversion occurs in the northwestern part of the study area, along the northern segment of the western fault corridor (Figure 14a). Here, the Namurian conformably drapes the LCL and the lowermost Westphalian similarly overlies the Namurian, with no evidence for the pronounced Namurian-age palaeorelief observed farther south. Instead, the LCL, Namurian and lowermost Westphalian succession is folded together into a broad structural high. Lowermost Westphalian reflections are truncated across its crest, defining an intra-Westphalian erosional unconformity, above which younger Westphalian reflections aggrade across the structure. This geometry requires deformation after deposition of the lower Westphalian and therefore records an inversion pulse younger than that expressed by the Namurian onlap relationships in the south and east. Intra-Westphalian inversion has also been recognised regionally, including within the Gainsborough Half-graben, where condensed Westphalian successions over inversion anticlines have been interpreted to record discrete pulses of contractional deformation (Fraser & Gawthorpe, 2003; Pharaoh et al., 2011).

These relationships favour episodic and spatially partitioned inversion rather than a single continuous inversion phase. Early deformation was preferentially accommodated by structures in the southern western fault corridor and eastern relay system, whereas a younger intra-Westphalian pulse is more clearly expressed along the northern western fault corridor. This spatial variation is unlikely to represent simple uniform inversion of

the original graben architecture. Instead, contractional strain appears to have been redistributed between selected elements of the inherited fault system through time. Such behaviour is consistent with regional observations showing that the magnitude and style of Carboniferous inversion in the Variscan foreland were strongly controlled by the orientation and geometry of pre-existing basement and extensional structures relative to the shortening direction (Corfield et al., 1996). NW-SE-, N-S-, and E-W-trending structures commonly experienced oblique and comparatively localised reactivation rather than complete inversion of their associated basins. The study area therefore preserves a structurally heterogeneous response to regional contraction, in which the inherited fault architecture established during extension subsequently governed the localisation of inversion-related uplift.

This history has important implications for the development of secondary porosity within the LCL. The strongest case for inversion-related palaeo-karst occurs above the early inverted structures in the southern western fault corridor and eastern relay system. There, uplift generated pronounced LCL palaeohighs, erosion locally removed the overlying Namurian succession, and younger Namurian and basal Westphalian strata on-lap directly onto the resulting relief. Where erosion reduced or completely removed the siliciclastic cover, the LCL may therefore have been exposed at, or brought sufficiently close to, the palaeosurface for meteoric groundwater circulation and carbonate dissolution. Reactivation of the underlying faults would simultaneously have increased fracture density and vertical hydraulic connectivity, further focusing fluid circulation within the uplifted limestone. Although karstification cannot be demonstrated directly from the seismic data, the combined structural and stratigraphic relationships identify these inversion-related palaeohighs as favourable sites for palaeo-karst development.

A palaeo-karst interpretation is supported by regional analogues. The pre-Westphalian Viséan surface at Welton has previously been interpreted as eroded and possibly karstified, while karstification and fracturing of Early Carboniferous limestones are recognised as potentially important controls on their present-day hydraulic transmissivity and geothermal prospectivity (Pharaoh et al., 2011, 2021). More generally, the permeability architecture of Early Carboniferous limestones in Britain reflects the combined effects of syn-depositional exposure and karstification, subsequent deformation and fracturing during inversion, and later phases of uplift and karst development (Pharaoh et al., 2021). The seismic data presented here provide a structural framework for predicting where such processes were most likely to have operated within the study area.

The two inversion phases are therefore likely to have produced different diagenetic consequences within the LCL. Early inverted structures in the south and east combine fault reactivation and enhanced fracturing with evidence for erosion down to the LCL, and therefore represent the most favourable settings for exposure-related meteoric palaeo-karst development. In contrast, the later inversion recorded along the northern western fault corridor occurred while the LCL remained buried beneath Namurian and lower Westphalian strata. Although this later deformation may have enhanced fracture connectivity and promoted deeper fluid circulation, the seismic stratigraphy provides no evidence for direct exposure of the LCL during this phase. palaeo-karst development associated with structural inversion was therefore likely to have been spatially heterogeneous and preferentially concentrated above the early inverted structural highs, particularly along the southern western fault corridor and eastern relay system.

5.3 Potential-field constraints on subsurface structure

The potential-field data provide an independent constraint on the structural framework interpreted from seismic reflection data. In particular, the dominant NW-SE structural grain is reproduced by both gravity and magnetic lineaments, several of which are spatially coincident with, or subparallel to, mapped LCL faults (Figure 12). This cor-

relation is strongest along the western fault corridor, where lineaments persist through much of the central and southern parts of the basin and are expressed across different wavelength bands (Figure 12). The coincidence between seismic faults and potential-field lineaments therefore supports the interpretation of the western margin as a through-going structural corridor rather than a set of isolated fault segments. The strong N-S component expressed particularly by GBA edges has a less obvious counterpart in the seismic-derived LCL fault network. These lineaments may therefore reflect deeper lithological or structural boundaries that were not significantly reactivated during Carboniferous extension.

The Euler-depth analyses of the different potential field wavelengths further suggest that this structural grain extends below the LCL succession (Figure 11). Medium-wavelength Euler solutions are concentrated predominantly within or above the LCL interval, whereas most long-wavelength gravity solutions, and a substantial proportion of the long-wavelength magnetic solutions, occur below the mapped base LCL. The recurrence of similar structural orientations at different characteristic depths is consistent with localisation of parts of the Carboniferous fault system above deeper inherited basement fabrics. This relationship is most obvious along the western fault corridor, where shallow and deeper potential-field expressions broadly overlap the seismic-defined fault system, supporting a significant component of basement inheritance.

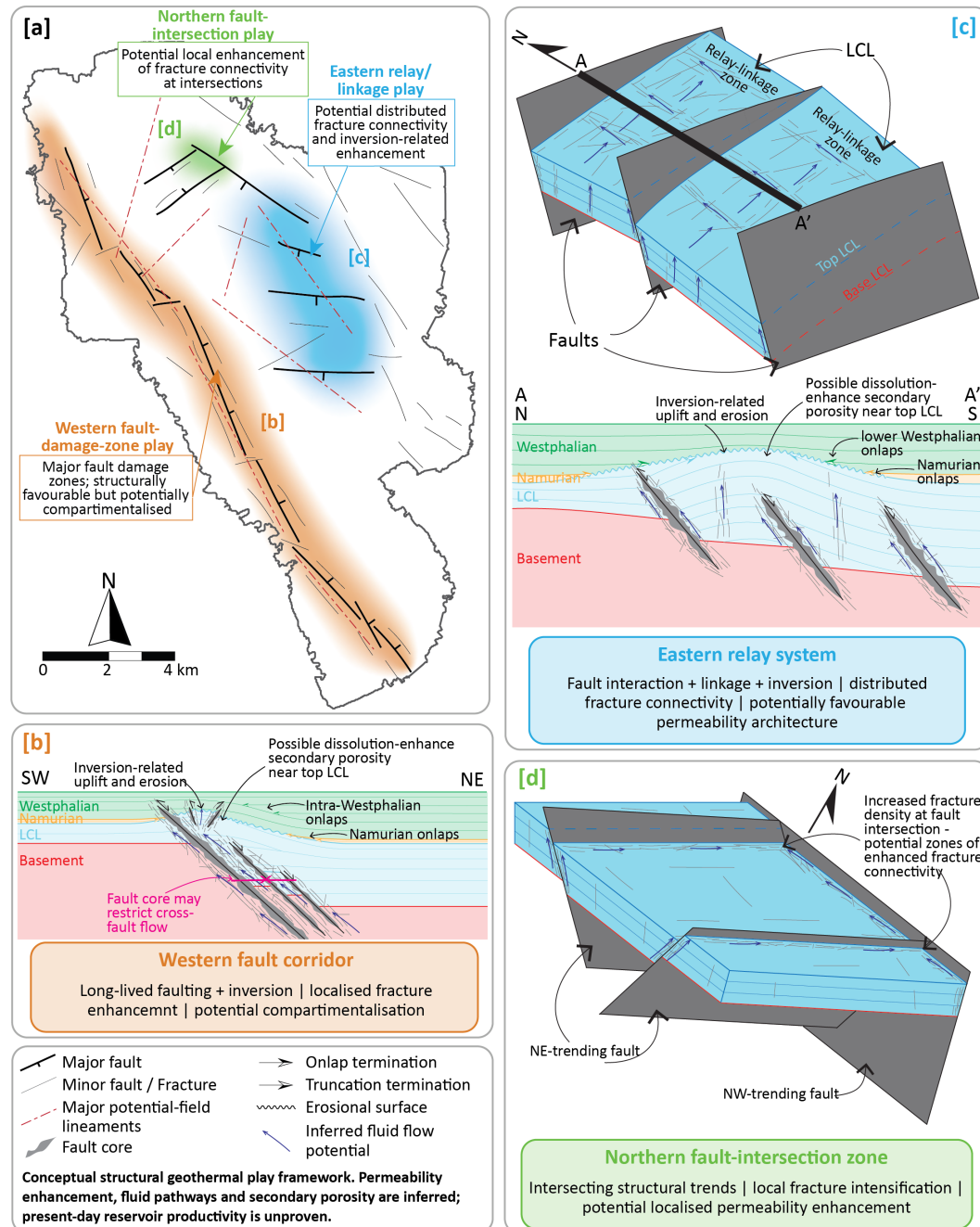
The gravity-modelling results independently indicate that the long-wavelength density structure cannot be explained by the LCL alone. Allowing LCL density to vary within the range constrained by the borehole logs reduces the RMS gravity misfit only from 4.92 to 4.02 mGal, and the recovered density distribution is strongly skewed towards the imposed upper bound. In contrast, inversion of basement density reduces the RMS misfit to 0.49 mGal, while the recovered densities remain largely within the permitted range rather than accumulating at its limits. This contrast indicates that plausible lateral density variation within the LCL is insufficient to reproduce the observed regional gravity field and that a substantial component of the residual must come from deeper and/or otherwise unmodelled density heterogeneity. Unmodelled Lower Carboniferous volcanic rocks are a plausible contributor to this deeper density heterogeneity, although lithological variability within the pre-Carboniferous basement and deeper regional sources may also contribute. The recovered basement-density pattern should therefore not be interpreted as a unique lithological map, but rather as an effective representation of the deeper density structure required by the gravity data.

By contrast, the eastern relay system has a more heterogeneous potential-field expression. Here, NW-SE trends are accompanied by E-W to ENE-WSW and locally N-S lineaments, several of which cross, terminate within, or occur oblique to the mapped relay faults (Figure 12). Rather than indicating direct downward continuation of individual relay faults, this pattern suggests that the relay system developed within a structurally heterogeneous substrate containing pre-existing fabrics of contrasting orientation. A similar relationship is observed in the northern fault-intersection zone, where multiple potential-field trends converge within the same area as the complex seismic fault geometry. The co-location of these contrasting fabrics suggests that structural heterogeneity at depth may have influenced the localisation and interaction of Carboniferous fault segments.

Although gravity and magnetic lineaments cannot uniquely be interpreted as faults, their spatial association with geometrically complex parts of the seismic-derived fault network suggests that deeper structural or lithological heterogeneity may have influenced fault propagation and linkage. Therefore, the potential-field data extend the seismic interpretation vertically and laterally. They support the dominant early Carboniferous structural framework, reveal deeper and transverse fabrics that are only partly resolved in seismic reflection data, and support a model in which the observed Carboniferous fault architecture was conditioned by deeper inherited basement structure, while the gravity data

additionally indicate substantial deeper density heterogeneity that is not captured by the seismic-constrained stratigraphic model.

5.4 Structural controls on geothermal prospectivity



The results of this study indicate that structural favourability for geothermal exploitation within the LCL is unlikely to be spatially uniform or controlled solely by reservoir depth and thickness. Instead, the distribution and connectivity of secondary permeability are likely to be strongly influenced by the inherited fault architecture and its subsequent reactivation. This is particularly important for deeply buried Carboniferous carbonates, where matrix permeability may be limited and economically viable fluid cir-

Figure 15. Conceptual structural geothermal play framework for the Lower Carboniferous Limestone (LCL). (a) Plan-view distribution of the three principal structural plays identified in the study area: the western fault-damage-zone play, eastern relay/linkage play and northern fault-intersection play. (b) Western fault-damage-zone play, illustrating long-lived faulting and inversion-related uplift and erosion, associated fault-damage zones, Namurian and intra-Westphalian onlap. Damage zones may enhance fracture permeability, while fault cores may restrict cross-fault flow and compartmentalise the reservoir. Dissolution or palaeokarst development near top LCL is a possible additional mechanism for enhancing secondary porosity. (c) Eastern relay/linkage play, showing how interacting fault segments may generate distributed fracture networks and enhanced connectivity. The accompanying section illustrates inversion-related uplift, Namurian and lowermost Westphalian onlap, and possible dissolution-related enhancement near top LCL. (d) Northern fault-intersection play, where intersecting NW- and NE-trending structures may locally intensify fracturing and enhance connectivity. Blue arrows represent conceptual possible fluid-flow pathways. The diagrams are schematic and not to scale; permeability enhancement, secondary porosity and flow pathways are inferred, and present-day transmissivity and reservoir productivity remain unproven.

culation can depend on fractures, faults and locally enhanced secondary porosity (Pharaoh et al., 2021; Jones et al., 2023; Aditama et al., 2026). Our integrated seismic and potential-field interpretation defines a conceptual structural geothermal play framework comprising a western fault-damage-zone play, an eastern relay/linkage play, a northern fault-intersection play, and fault-tip and segment-linkage zones (Figures 6 and 15). Each play groups a mapped structural setting with proposed mechanisms for enhancing secondary permeability and may exert a first-order control on reservoir connectivity (Figure 6). The significance of these structures extends beyond the seismically resolved faults, as potential-field lineaments suggest that some form part of larger and potentially deeper-rooted structural systems (Figure 12). Recent work on UK Mississippian carbonates similarly highlights the importance of structural inheritance and polyphase deformation in governing fracture-network connectivity and, consequently, geothermal reservoir behaviour (Aditama et al., 2026).

The three plays represent domains for further geothermal appraisal, with distinct proposed permeability architectures and exploration risks (Figure 15a). In the western fault-damage-zone play, the large, long-lived rift-bounding faults may have generated substantial damage zones and therefore locally enhanced fracture permeability (Figure 15b). However, mature fault zones can behave as conduits, barriers, or combined conduit-barrier systems depending on the relative development and hydraulic properties of fault cores and surrounding damage zones (Caine et al., 1996; Faulkner et al., 2010). Thus, the western fault corridor may offer significant permeability enhancement while also presenting a greater potential for hydraulic compartmentalisation. The eastern relay/linkage play is characterised by interacting fault segments, relay structures and associated fault-tip and linkage zones, in which deformation is likely to be distributed across broader volumes of fractured rock (Figure 15c). Relay zones progressively accumulate fractures and subsidiary faults as neighbouring fault segments interact and link (Fossen & Rotevatn, 2016), and analogous geothermal systems show a strong association between fluid circulation and fault stepovers, relay ramps, terminations and intersections (Faulds et al., 2011). The northern fault-intersection play focuses on the mapped convergence of NW- and NE-trending structures, where overlapping deformation zones may locally intensify fracturing (Figure 15d). Relay/linkage and intersection geometries therefore provide a basis for identifying areas of potentially enhanced fracture connectivity, although their present-day transmissivity cannot be established from structural geometry alone. Present-

day hydraulic behaviour will also depend on factors not resolved by the available data, including fracture aperture and connectivity, the contemporary stress state, mineral precipitation or sealing, and the effects of burial diagenesis.

The geothermal significance of these structures may have been further modified by later basin inversion. In the central and southern western fault corridor and, particularly, above the eastern relay system, seismic relationships indicate uplift and doming of the LCL, erosional truncation at its top, and onlap of Namurian and lowermost Westphalian strata onto the resulting structural highs (Figure 14). These relationships imply that inherited extensional structures were reactivated and that parts of the LCL experienced significant uplift and erosion before renewed burial. Reactivation may have enhanced pre-existing fracture networks or generated new fractures, while sufficiently shallow uplift or subaerial exposure could additionally have promoted meteoric dissolution and secondary porosity near the top of the carbonate succession. Although seismic data do not directly demonstrate palaeokarst, such an interpretation is consistent with regional assessments of Lower Carboniferous limestones, which identify exposure and karstification, Variscan inversion and fracturing, and later uplift as key controls on hydraulic transmissivity and geothermal prospectivity (Pharaoh et al., 2021). Possible palaeokarst enhancement is therefore an additional mechanism that may overlap the eastern relay/linkage and central-southern western fault-damage-zone plays (Figure 15b, c), rather than a separately demonstrated reservoir type.

These observations therefore provide a basis for defining structurally favourable areas as play concepts that can guide further geothermal appraisal (Figure 15a). Areas where fault interaction, segment linkage or fault intersections coincide with evidence for inversion-related uplift may therefore represent the most structurally favourable settings for connected secondary permeability. In contrast, the large-displacement faults of the western corridor may provide effective flow pathways locally but could also partition the reservoir, emphasising that proximity to a major fault is not, by itself, an adequate criterion for geothermal targeting. This distinction is important because regional assessments of the Lower Carboniferous Limestone recognise substantial geothermal heat potential in Britain but identify the availability of sufficient fluid flow through faults, fractures and karst as a key remaining uncertainty (Jones et al., 2023). The structural framework developed here identifies where permeability enhancement is geologically plausible and provides a basis for subsequent site appraisal and drilling-target selection. Quantitative resource evaluation and selection of individual drilling targets require integration with temperature data, fracture characterisation, petrophysical properties, hydrochemistry and well-test measurements of transmissivity.

5.5 Uncertainty and limitations

The integrated work presented here is subject to uncertainties associated with seismic imaging, depth conversion and the inherent non-uniqueness of potential-field data. Within the 3D seismic volume, the first order LCL architecture and principal fault corridors are relatively well constrained, whereas uncertainty increases for low-displacement faults, fault tips and areas of poorer seismic imaging. Confidence is lower near base LCL, where reduced seismic resolution, and possibly smaller displacement, limit fault definition. The lower endpoints of interpreted faults consequently mark the limits of confident interpretation and do not necessarily indicate geological termination. Likewise, absence of a fault trace at top LCL does not by itself demonstrate termination within the limestone. Depth conversion introduces additional uncertainty because the absolute depth and structural relief of the interpreted horizons depend on the velocity model. Nevertheless, many of the relationships central to our interpretation—including fault segmentation and linkage, relay geometries, local doming, erosional truncation and stratigraphic onlap—are directly expressed in the seismic data and are therefore less sensitive to uncertainty in absolute depth.

Potential-field interpretations carry greater ambiguity because gravity and magnetic anomalies represent the integrated response of sources with different geometries, depths and physical properties. The wavelength filtering applied here separates broad depth-related components of the anomaly but does not provide a unique correspondence between wavelength and source depth. Similarly, ridges and edges extracted from the filtered datasets identify anomaly axes and gradients rather than geological faults directly. Accordingly, individual potential-field lineaments should not be regarded as independent evidence for faulting. Confidence is greater where lineaments are reproduced across different wavelength bands, enhancement methods and datasets, and particularly where they coincide with faults independently mapped from seismic data. The variable degree of correspondence visible in the combined lineament interpretation illustrates this distinction between supported and uncertain structural features. The inferred influence of deeper inherited fabrics should therefore be distinguished from directly mapped fault continuity into pre-Carboniferous basement. Base LCL locally corresponds to the top of Lower Carboniferous volcanic rocks, further limiting attribution of deeper sources exclusively to older basement.

Similar caution applies to the gravity modelling. The recovered density distributions depend on the adopted geological geometry, imposed density bounds and the available well constraints, and therefore represent one set of models capable of explaining the observed gravity field rather than unique lithological solutions. This limitation is particularly relevant to the elevated recovered densities and positive gravity residuals identified locally. Lower Carboniferous volcanic rocks are documented within the regional Carboniferous succession of northern and central England (Walters & Ineson, 1981; MacDonald et al., 1984; Ebdon et al., 1990; Stephenson et al., 2003; Pharaoh et al., 2011), but were not represented explicitly in the gravity model. Unmodelled volcanic bodies, together with lateral variations in carbonate or basement properties, could therefore contribute to both gravity and magnetic anomalies and be expressed in the inversion as apparent density variations. Consequently, these density anomalies cannot be attributed uniquely to variations in basement and/or LCL geometry and properties. The gravity results are therefore most robust when used to assess the broad consistency of the seismic-derived geological model and to identify deviations from a simple layered-density architecture.

These uncertainties propagate differently into the geothermal interpretation. The first-order structural framework—including the western fault corridor, eastern relay system and northern fault-intersection zone—is supported by independent seismic and potential-field observations and is therefore relatively robust. Greater uncertainty concerns the geological significance of individual lineaments and, more importantly, whether mapped faults, intersections and inverted or potentially karstified zones presently retain enhanced permeability. The geothermal prospectivity discussed above should therefore be viewed as a relative geological favourability framework rather than evidence of demonstrated reservoir performance. Overall, confidence decreases from the regional structural architecture, through the interpretation of local lithological and density variations, to predictions of present-day hydraulic connectivity and permeability; resolving the latter will ultimately require direct subsurface constraints such as borehole, hydraulic and temperature data.

6 Conclusions

This study integrates 3D seismic reflection data, well constraints, gravity and magnetic datasets, and density-constrained gravity modelling to characterise the structural architecture of the Lower Carboniferous Limestone (LCL) and assess its implications for geothermal prospectivity. The results demonstrate that the LCL is not a structurally uniform reservoir, but is partitioned into distinct domains dominated by a western rift-bounding fault corridor, an eastern relay system, and a northern fault-intersection zone,

together with numerous fault interactions and linkages. These domains provide a structural framework for understanding the spatial distribution of deformation and, potentially, secondary permeability within the geothermal reservoir.

Seismic-stratigraphic relationships further show that parts of the extensional architecture were subsequently reactivated. Localised doming, erosion of the LCL crest, Namurian onlap and absence, and onlap within the lowermost Westphalian record spatially variable late Carboniferous uplift and inversion that had ceased before deposition of the Lower Permian succession. The spatial association of these features with major fault corridors, relay zones and fault intersections indicates that deformation was strongly controlled by the pre-existing rift architecture. Local erosion and possible exposure of uplifted LCL may additionally have promoted weathering and palaeo-karst development, providing a further mechanism for enhancing reservoir heterogeneity and permeability.

Potential-field analysis complements the seismic interpretation by identifying lineaments that broadly coincide with, extend, or connect seismic-scale structural trends, particularly around the principal fault corridors and linkage zones. Gravity modelling also demonstrates, however, that the observed gravity field cannot be explained solely by LCL and basement geometry. Significant lateral density heterogeneity is required, potentially reflecting variations within the Carboniferous succession, including volcanic rocks that are not explicitly represented in the geological model. Consequently, gravity-derived structure and density distributions should be interpreted jointly with seismic, well and magnetic constraints rather than as unique geological solutions.

From a geothermal perspective, these results define a conceptual structural play framework comprising a western fault-damage-zone play, an eastern relay/linkage play and a northern fault-intersection play (Figure 15). The western play combines possible damage-zone permeability enhancement with a risk of compartmentalisation by fault cores; the eastern and northern plays focus on potential fracture connectivity associated with fault interaction, linkage and intersections. Inversion-related fracturing and possible dissolution or palaeokarst development may locally augment these mechanisms, particularly in the eastern relay system and central-southern western corridor. The mapped domains provide areas for further geothermal appraisal based on plausible permeability mechanisms, without establishing a productivity ranking or precise drilling locations. This framework extends assessment beyond reservoir depth and thickness to the distribution and interaction of structure, reactivation and possible diagenetic modification. Temperature constraints, fracture characterisation and hydraulic testing are needed to determine whether the inferred connectivity supports effective fluid circulation and to select individual drilling targets.

Overall, the study demonstrates the value of integrating seismic interpretation with gravity and magnetic analysis for characterising structurally complex carbonate geothermal reservoirs. Although uncertainties remain concerning present-day in situ hydraulic behaviour, the distribution of palaeo-karst and the origin of deeper density variations, the integrated framework developed here identifies structural domains and plausible geological controls on geothermal prospectivity and provides a transferable approach for reducing subsurface uncertainty in Lower Carboniferous limestone systems in the UK and beyond.

Open Research Section

The seismic reflection data and associated velocity volume used in this study are publicly available through the UK Onshore Geophysical Library (UKOGL; <https://ukogl.org.uk/>). Well data, including stratigraphic information and geophysical logs, were also obtained from UKOGL. Regional gravity and aeromagnetic datasets were provided by the British Geological Survey (BGS) and are accessible through the BGS data portal (<https://>

www.bgs.ac.uk/datasets/). The Supporting Information provides additional details on data processing, interpretation procedures and modelling parameters.

Conflict of Interest disclosure

The authors declare there are no conflicts of interest for this manuscript.

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Supporting Information for “Structural Geothermal Plays in the Lower Carboniferous Limestone, East Midlands, UK: Insights from Legacy Geophysical Data”

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Contents of this file

1. Text S1 to S6
2. Figures S1 to S4
3. Tables S1 to S2

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Introduction

This Supporting Information provides additional methodological detail and supporting documentation for the seismic, well, gravity, and aeromagnetic analyses presented in the main manuscript.

It describes the seismic-stratigraphic framework used for interpretation and modelling, the provenance and available processing information for the merged 3D seismic volume, and the seismic–well tie and velocity-model construction used to calibrate and depth-convert the seismic interpretation. Supplementary figures (Figures S1 and S2) document the seismic–well calibration and interval velocity–depth relationships, while Table S1 summarises the acquisition and processing information available from the seismic SEG-Y textual header.

Additional sections document the provenance and preprocessing of the BGS land-gravity and legacy aeromagnetic datasets, including gridding of the Bouguer gravity anomaly and magnetic data and application of Differential Reduction to the Magnetic Pole (DRTP) to generate the DRTP magnetic anomaly used in subsequent analyses. The Supporting Information also provides details of wavelength-domain separation and filtering of the gravity and magnetic datasets, including the radial power spectra (Figure S3) used to define characteristic wavelength bands and the resulting filtered potential-field grids (Figure S4). Finally, the methodology used to extract and analyse potential-field lineaments is described, including the length-weighted, equal-area treatment of rose diagrams. Table S2 summarises the principal parameters used for potential-field gridding and preprocessing, gravity forward and inverse modelling, wavelength filtering, Euler deconvolution, and lineament mapping. These materials provide methodological context and reproducibility for the analyses presented in the main text, while the principal geological results and interpretations remain in the main manuscript.

Text S1: Seismic-stratigraphic sequences

The well data analysis identified seven stratigraphic sequences between the exposed Jurassic units and the pre-Carboniferous basement:

- Middle-Upper Triassic sequence: comprises the Penarth Group (Rhaetian of age, Audley-Charles, 1970) and the Mercia Group (Anisian - Rhaetian of age, Howard et al., 2008). It consists mainly of mudstones with subordinate limestones, sandstones, and siltstones. Halite-bearing units and thin beds of anhydrite/gypsum are encountered in some of the wells (e.g., Welton A1).
- Lower Triassic sequence: corresponds to the Sherwood Group (Induan - Anisian of age, Ambrose et al., 2014). It is made of sandstone with conglomerates at its base.
- Upper Permian sequence: comprises the Zechstein Group (Guadalupian - Lopingian of age, Smith et al., 1986). It consists of cyclical succession of marine dolomite, limestone, evaporites, mudstone, and siltstone.
- Lower Permian sequence: comprises the Rotliegend Group (Cisuralian - Lopingian of age, Johnson et al., 1994) and made of continental sandstones and conglomerates with minor mudstone and halite intercalations.
- Westphalian sequence: corresponds to the Pennine Coal Measure Group (Moscovian of age, Waters et al., 2009). The sequence comprises alternating sandstone, siltstone and mudstone, with frequent coal seams, ironstone nodules or beds and seatearth (palaeosol) horizons.
- Namurian sequence: includes primarily the Millstone Grit Group and the Craven Group (Serpukhovian - Bashkirian of age, Waters et al., 2009) and comprises cyclic sequences of sandstone, siltstone and mudstone.

- Lower Carboniferous limestone sequence: consists of the Carboniferous Limestone Supergroup (Tournaisian - Visean of age, Waters et al., 2011), which is dominated by limestone with interbedded shale and occasional sandstone/siltstone. Welton A1 shows a thin (ca. 60 m) extrusive igneous layer at the base of the LCL sequence made of volcanic and volcanoclastic rocks (i.e., lava, tuff, and sandstone/siltstone).

Eight seismic horizons, delineating the stratigraphic sequences, were picked and interpreted throughout the seismic cube, namely, top Middle-Upper Triassic, top Lower Triassic, top Upper Permian, top Lower Permian, top Westphalian, top Namurian, top LCL, and top basement. Because the basal Lower Carboniferous volcanic interval encountered in Welton A1 was not represented as a separate unit, the interpreted lower boundary of the LCL was tied to the top of the volcanic interval. For modelling purposes, this surface also defines the top of the underlying basement, which therefore locally incorporates the basal volcanic interval. Accordingly, calculated LCL thickness excludes the volcanic interval.

Text S2: Seismic data provenance and processing

The merged Fiskerton/Welton/Branston 3D seismic volume was obtained through UKOGL (<https://ukogl.org.uk/>). Available product-specific documentation comprises the SEG-Y textual header, which records processing by Geo-X Systems Ltd. for Cirque Energy (UK), dated 23 May 2000. No accompanying acquisition or full processing report was available for this study. Table S1 summarises the acquisition and processing information recorded in the SEG-Y header.

The processing sequence includes amplitude recovery, phase compensation and system minimum-phase conversion, surface-consistent signature deconvolution, static corrections, normal-moveout correction, T-P multiple attenuation and Gaussian-weighted stacking, followed by 3D one-pass phase-shift migration, F-X noise reduction, bandpass filtering and trace equalisation. The 30×30 m bin spacing describes spatial sampling rather than demonstrated resolving power. Similarly, the applied bandpass filter does not establish the dominant frequency or vertical resolution within the LCL interval.

The textual header does not provide numerical values for sample interval, record length or acquisition fold, nor does it specify source and receiver geometry.

Text S3: Seismic–well tie and velocity-model construction

A seismic–well tie was carried out at Welton A1 in Petrel 2024 to calibrate the borehole stratigraphy against the merged 3D seismic volume. A deterministic wavelet-extraction approach was used to account for phase differences between the processed seismic data and a synthetic seismogram generated from the available sonic and bulk-density logs. Acoustic impedance was calculated from the well-log data and used to derive reflection coefficients and the corresponding synthetic seismic response. The synthetic trace was then compared with seismic data extracted along the Welton A1 trajectory to establish the correspondence between principal stratigraphic markers and seismic reflections (Figure S1). This calibration provided the basis for propagating the interpreted horizons throughout the seismic volume.

Depth conversion used the reprocessed stacking-velocity cube associated with the merged seismic dataset. Stacking velocities were converted to interval velocities using the Dix equation (Dix, 1955; Yilmaz, 2001). The resulting interval-velocity samples were partitioned according to the interpreted stratigraphic framework and evaluated as a function of depth for the principal stratigraphic intervals. Linear least-squares relationships were fitted to the interval velocity–depth distributions, and smoothing was applied to suppress spurious short-wavelength variations in the velocity field (Figure S2). The re-

sulting stratigraphically constrained velocity model was subsequently used to convert the seismic volume, interpreted horizons and faults from time to depth.

Text S4: Potential-field data provenance and preprocessing

The gravity and aeromagnetic datasets used in this study were obtained from the British Geological Survey (BGS) as point-based legacy geophysical datasets referenced to the British National Grid. The BGS land-gravity dataset contains station coordinates and elevations together with observed gravity, free-air anomaly, terrain-correction information, Bouguer reduction density and Bouguer anomaly values. The accompanying documentation states that the gravity anomalies are referenced to the Geodetic Reference System 1967 (GRS67), International Gravity Standardisation Net 1971 (IGSN71) and National Gravity Reference Net 1973 (NGRN73). The supplied Bouguer anomaly values were used in this study and interpolated using minimum curvature with a grid-cell spacing of 290 m. The resulting grid is referred to hereafter as the Bouguer gravity anomaly (GBA).

The BGS aeromagnetic dataset is a digitised compilation of legacy airborne magnetic surveys acquired across Great Britain between 1955 and 1965. The standard BGS delivery preserves information on the original survey and flight-line segment, British National Grid coordinates, ground elevation, approximate mean terrain clearance and flying height, together with three magnetic-anomaly attributes corresponding to removal of the original Bullerwell regional field, IGRF1955 and a local variant of IGRF1990. In this study, the MAG_BUL attribute was used; this represents the magnetic field in nT after removal of the original magnetic reference field defined by Bullerwell.

The Welton study area lies within the 1955 East Midlands aeromagnetic survey. The original survey specifications indicate a nominal mean terrain clearance of 1,000 ft (approximately 305 m), E–W flight lines spaced at approximately 1 mile (approximately 1.6 km), and N–S tie lines spaced at approximately 6 miles (approximately 9.7 km). The survey documentation further indicates that flight height was intended to remain within approximately 100 ft (30 m) of the specified elevation, although drape flying was permitted over areas of strong relief. Total-field magnetic measurements were acquired using fluxgate magnetometers, with continuously recording base-station magnetometers used to monitor magnetic disturbances.

The aeromagnetic dataset should therefore be regarded as a regional legacy dataset rather than as a modern high-resolution airborne survey. The original flight-line spacing, navigation precision and subsequent digitisation place limits on the effective spatial resolution of the data. Accordingly, the 350-m grid-cell spacing adopted here represents the sampling interval of the interpolated magnetic grid rather than an equivalent geological resolving power. This distinction is particularly relevant when interpreting short-wavelength anomaly components. The data were interpolated using minimum curvature with a grid-cell spacing of 350 m before reduction to the pole.

Reduction to the pole was performed in Oasis montaj using the Differential Reduction to the Magnetic Pole (DRTP) filter implemented within MAGMAP. Conventional Fourier-domain reduction to the pole assumes a constant geomagnetic-field inclination and declination over the input grid and that the magnetisation direction is parallel to the inducing geomagnetic field. DRTP relaxes the constant-field assumption by allowing the geomagnetic-field direction, and correspondingly the assumed magnetisation direction, to vary spatially across the survey area. It represents the geomagnetic field as a mean field plus spatially varying perturbations and solves the resulting equations iteratively in the wavenumber domain following the perturbation approach of Arkani-Hamed (1988, 2007).

For a georeferenced input grid, the Oasis montaj DRTP implementation calculates spatially varying inclination and declination grids using the coordinate system and specified survey date. A survey date of 1 January 1955 was specified for the present analysis, consistent with the acquisition year of the East Midlands aeromagnetic survey. The default Northern Hemisphere amplitude-correction inclination of 20° was retained. This parameter is used by the DRTP implementation to stabilise the reduction-to-pole operator where magnetic inclinations approach low values. The resulting grid is referred to throughout this study as the differential reduced-to-pole magnetic anomaly (DRTP-Mag).

Text S5: Potential-field wavelength separation and filtering

Radially averaged power spectra were calculated independently for the Bouguer gravity anomaly (GBA) and reduced-to-pole magnetic anomaly (DRTP-Mag) datasets to identify characteristic wavelength populations (Table S2). Changes in spectral slope were used to define wavelength intervals representing signals at different spatial scales (Figure S3), following the general principle that potential-field spectra contain contributions from source populations with contrasting characteristic dimensions and depths (Spector & Grant, 1970).

For the GBA, spectral breaks defined long-wavelength components of 7–60 km, medium-wavelength components of 2.4–7 km and short-wavelength components below 2.4 km. Corresponding DRTP-Mag wavelength intervals were 8–60 km, 2.7–8 km and <2.7 km, respectively (Figure S4). Spectral analysis was undertaken on regional grids extending beyond the seismic study area to preserve wavelengths substantially longer than the dimensions of the 3D seismic volume.

The identified wavelength boundaries were subsequently used to construct cosine roll-off band-pass filters in Oasis montaj. Filtering was applied to the larger regional grids before the resulting components were cropped to the seismic study area for comparison with the seismic interpretation (Figure S4). Long- and medium-wavelength components were retained for derivative analysis, lineament extraction and source-depth estimation. The shortest-wavelength components were excluded from further interpretation because they were spatially irregular and considered likely to contain a substantial contribution from very shallow sources and/or acquisition and processing noise.

The filtered components are interpreted as spatial-scale domains rather than direct depth intervals, because anomaly wavelength depends on both source depth and source geometry. Their depth significance was therefore evaluated independently using tilt-derivative and Euler-deconvolution methods.

Text S6: Lineament orientation analysis

Potential-field lineaments were extracted independently from the long- and medium-wavelength components of the Bouguer gravity anomaly (GBA) and reduced-to-pole magnetic anomaly (DRTP-Mag) using the CET Grid Analysis tools in Oasis montaj (Table S2). Phase congruency was used to identify anomaly edges, representing spatial discontinuities and potential source boundaries, whereas phase symmetry was used to identify ridges corresponding to the axes of elongated anomaly features.

Lineament azimuths were analysed as axial orientations over (0 – 180°), because the mapped features have no directional polarity. Orientations were grouped into (10°) bins and weighted by the mapped length of each lineament rather than by feature count. Length weighting reduces the influence of numerous short extracted segments relative to longer, spatially persistent features and therefore provides a measure of the proportion of the mapped structural fabric represented by each orientation. For each population, the summed length

within each orientation bin was normalised by the total mapped length of that population and expressed as a percentage. The same procedure was applied to the pooled populations and to the seismic-interpreted fault traces used for comparison in the main manuscript.

Rose diagrams were plotted using an equal-area rather than a linear radial convention. For bins of constant angular width, sector area varies with the square of sector radius; consequently, plotting radius directly proportional to percentage would visually exaggerate strongly populated orientation classes. Sector radii were therefore scaled to the square root of the length percentage, such that the area of each sector is proportional to the percentage of total mapped lineament length represented by that bin (Nemec, 1988). Axial distributions are displayed bidirectionally in the rose diagrams, so opposing sectors represent the same structural orientation rather than independent populations. This convention preserves the histogram property that graphical area is proportional to the quantity represented and facilitates comparison between populations with different numbers and lengths of extracted lineaments.

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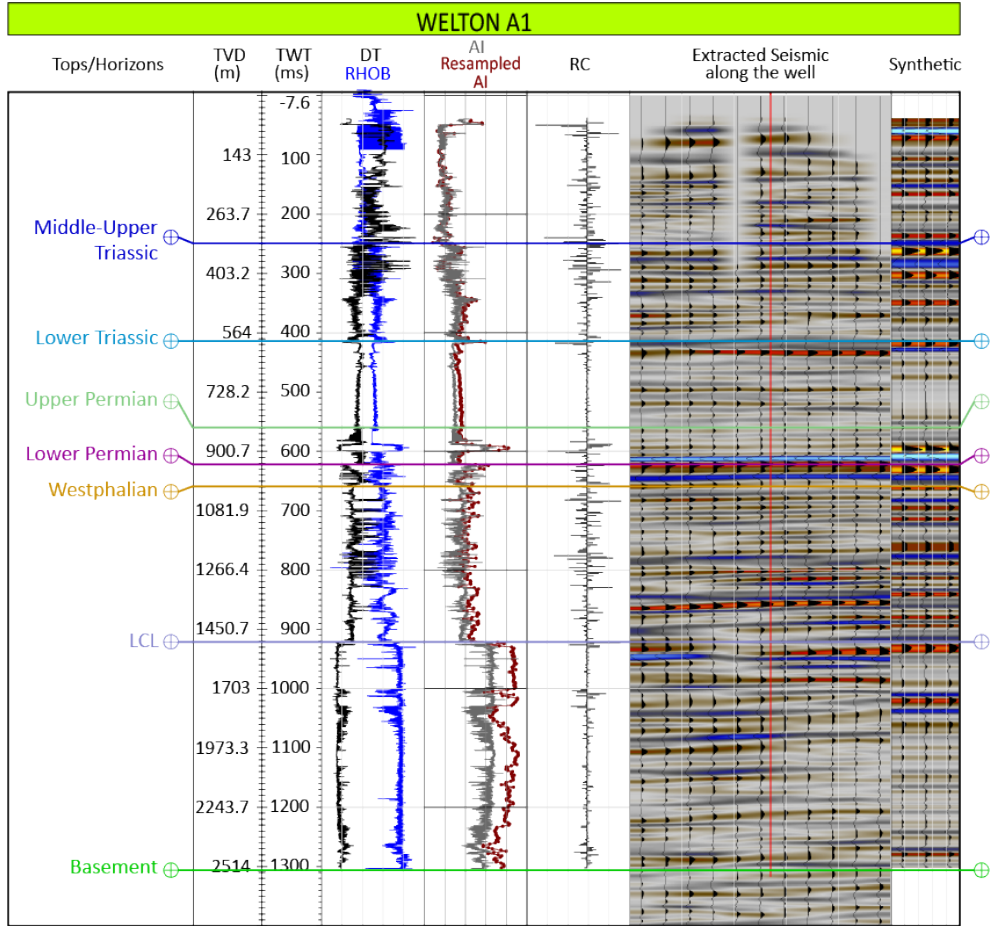


Figure S1. Seismic–well tie at Welton A1. From left to right, tracks show interpreted formation tops, true vertical depth and two-way travel time, sonic transit time (DT) and bulk density (RHO_B), acoustic impedance (AI) and resampled acoustic impedance, reflection coefficient (RC), seismic data extracted along the well trajectory, and the synthetic seismic trace. Coloured markers indicate the interpreted stratigraphic horizons and illustrate the correspondence between the synthetic and observed seismic responses.

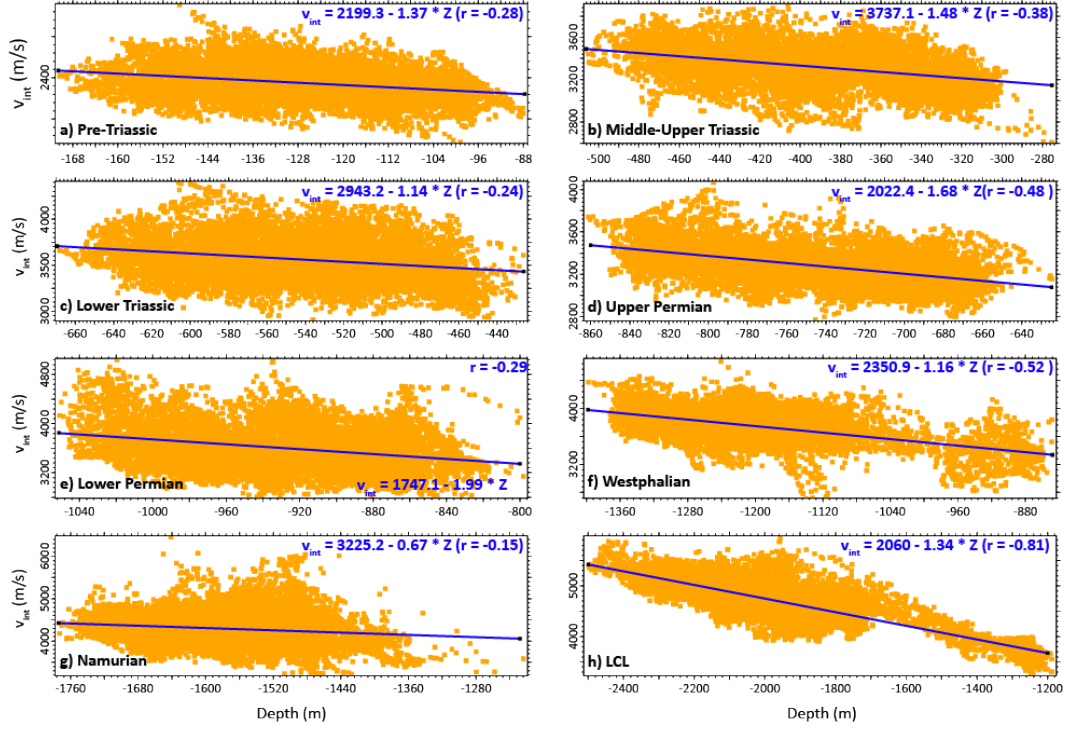


Figure S2. Interval velocity–depth relationships used to construct the seismic velocity model. Relationships are shown for (a) pre-Triassic, (b) Middle–Upper Triassic, (c) Lower Triassic, (d) Upper Permian, (e) Lower Permian, (f) Westphalian, (g) Namurian and (h) Lower Carboniferous Limestone intervals. Points represent interval-velocity samples derived from the stacking-velocity cube, and lines show the corresponding linear least-squares regressions. Regression equations and correlation coefficients are shown for each interval.

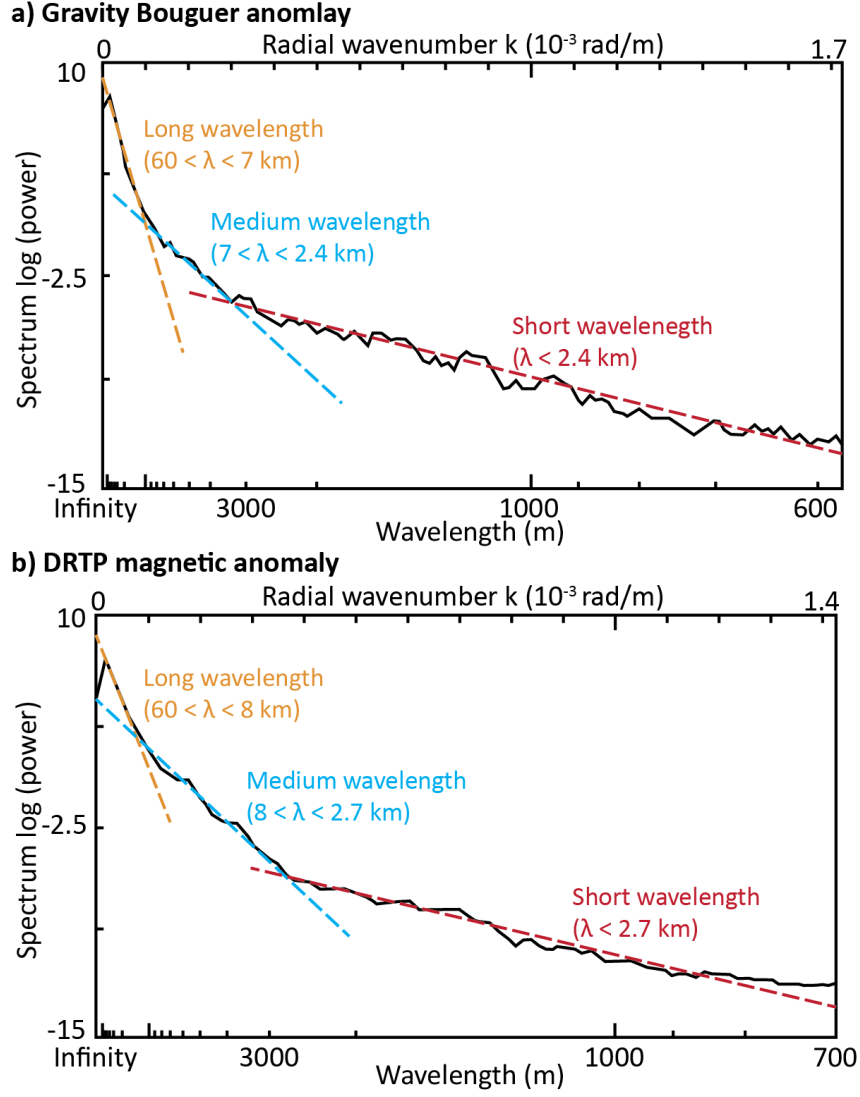


Figure S3. Radially averaged power spectra of the potential-field datasets. Power spectra for (a) the Bouguer gravity anomaly (GBA) and (b) the reduced-to-pole magnetic anomaly (DRTP-Mag). Linear segments fitted to changes in spectral slope were used to define characteristic wavelength domains for subsequent filtering. Selected GBA intervals are 7–60 km, 2.4–7 km and <2.4 km; corresponding DRTP-Mag intervals are 8–60 km, 2.7–8 km and <2.7 km.

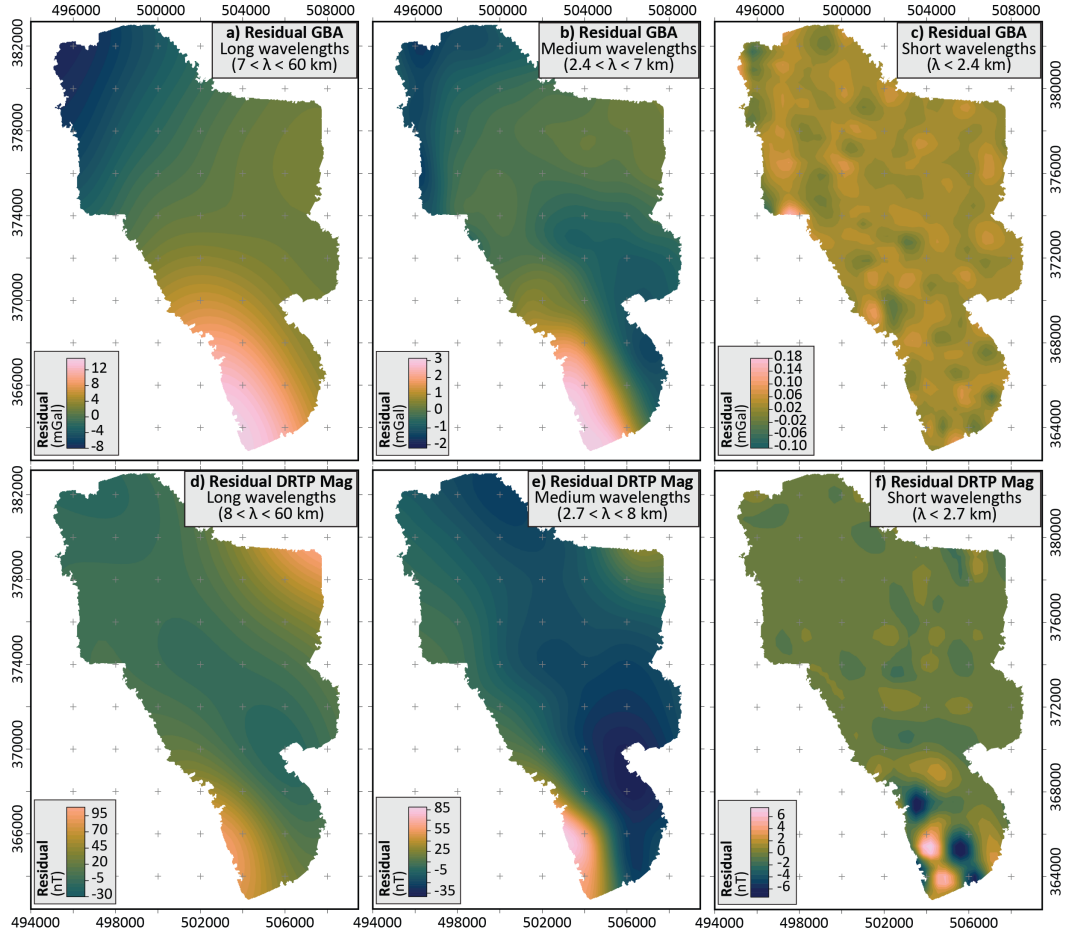


Figure S4. Wavelength-filtered potential-field anomalies across the study area. Band-pass-filtered Bouguer gravity anomaly (GBA) showing (a) long-wavelength (7–60 km), (b) medium-wavelength (2.4–7 km) and (c) short-wavelength (<2.4 km) components, and reduced-to-pole magnetic anomaly (DRTP-Mag) showing (d) long-wavelength (8–60 km), (e) medium-wavelength (2.7–8 km) and (f) short-wavelength (<2.7 km) components. Gravity and magnetic anomalies are expressed in mGal and nT, respectively.

Table S1. Acquisition and processing information for the merged Fiskerton/Welton/Branston seismic volume, extracted from its SEG-Y textual header.

Parameter / processing step	Header information
Client	Cirque Energy (UK)
Processor and date	Geo-X Systems Ltd.; 23 May 2000
Source types	Dynamite/Vibroiseis
Bin spacing	30×30 m
Grid dimensions	452×680 ; 307,360 nominal bins
Grid rotation	0° east of north
Processing datum	0 m elevation
Replacement velocity	2,200 m/s
Initial processing	Reformatting and amplitude recovery
Phase treatment	Phase compensation; system minimum-phase conversion
Deconvolution	Five-component surface-consistent signature deconvolution
Statics	Structure statics, surface-stack residual statics and cross-correlation statics
Moveout correction	Normal-moveout velocity correction
Multiple attenuation	T-P multiple attenuation; 600–2,400 ms window
Stacking	Gaussian-weighted stack
Migration	3D one-pass phase-shift migration
Noise reduction	F-X filtering; 300 ms windows, 100 ms overlap, 60% mix; 9×9 trace prediction filter and 20×20 trace block
Bandpass filter	10/14–90/100 Hz
Trace equalisation	Mean window of 750–1,300 ms

Table S2. Gravity modelling and potential-field processing parameters

Analysis	Parameter	Value
Gravity gridding	Input attribute	Bouguer anomaly
	Interpolation method	Minimum curvature
	Grid-cell size	290 m
Magnetic gridding	Input attribute	MAG_BUL
	Interpolation method	Minimum curvature
	Grid-cell size	350 m
Differential RTP	Software	MAGMAP Filtering, Oasis montaj
	Method	Differential Reduction to the Magnetic Pole (DRTP)
	Survey date	1955/01/01
	Amplitude-correction inclination	20°
Gravity filtering	Software	MAGMAP Filtering plug-in, Oasis montaj
	Long wavelength	7–60 km
	Medium wavelength	2.4–7 km
	Short wavelength	< 2.4 km
Magnetic filtering	Software	MAGMAP Filtering plug-in, Oasis montaj
	Long wavelength	8–60 km
	Medium wavelength	2.7–8 km
	Short wavelength	< 2.7 km
3D gravity model	Software	GM-SYS 3D, Oasis montaj
	Grid dimensions	281 × 341 cells
	Horizontal cell size	100 × 100 m
	Model base	5 km
	Background density	2.70 g/cm ⁻³
Density inversion	Software	GM-SYS 3D, Oasis montaj
	Maximum iterations	40
	Convergence criterion	Change in SD of gravity misfit < 0.1 mGal
LCL inversion	Initial density	2.666 g/cm ⁻³
	Density bounds	2.60–2.70 g/cm ⁻³
	Iterations to convergence	3
Basement inversion	Initial density	2.693 g/cm ⁻³
	Density bounds	2.60–3.00 g/cm ⁻³
	Iterations to convergence	5
Euler deconvolution	Software	Euler 3D plug-in, Oasis montaj
	Structural index	0.5
	Maximum depth tolerance	5%
	Maximum acceptance distance	5000 m
	Window size	3
Lineament mapping	Software	CET Grid Analysis plug-in, Oasis montaj
	Cell size (GBA / DRTP-Mag)	290 m / 350 m
	Smallest filter wavelength	3 cells
	Number of filter scales	8
	Symmetry robustness	5