Exploring the newly-defined Holme Granite beneath the UK Pennine Basin: geophysical and geological evidence

John A. Donato[1], Christopher P. Pullan[2] & Georgina E. V. Lockham[1]

[1] *Merlin Energy Resources Ltd., Newberry House, New Street, Ledbury, Herefordshire, HR8 2EJ*
[2] *CP Exploration, Butts Farm Barn, The Butts, Potterne, Devizes, Wiltshire, SN10 5LR*
January 2025

Abstract

Gravity modelling studies crossing the Carboniferous northern England Pennine Basin have identified a residual gravity low with an amplitude of up to 12 mGal and dimensions of approximately 40 km by 30 km. It is suggested that the anomaly is produced by a buried granite-cored block located partially beneath the Holme and Heywood structural highs. The gravity low has flanking positive magnetic anomalies in common with similar features seen in association with other known northern England granites. Seismic data across the area show shallow pre-Carboniferous basement located over and to the southwest of the residual gravity low. In addition, the seismic data show the development of massive Lower Carboniferous platform carbonate sequences above the southern flank of the postulated buried granite block. There is some evidence for local pre-Upper Paleozoic maturity enhancement within the area of the proposed granite. The proposed granite lies within the fault bounded northwest-southeast trending Burnley-Stamford Magnetic Anomaly (BSMA) which may have influenced its emplacement position. Large granites within the Pennine Basin, such as those at Weardale and Wensleydale, are thought to have provided significant tectonic influence during the extensional phases of the early Carboniferous. The Holme Granite by comparison, being significantly smaller in size, may have offered a reduced, but nevertheless significant, tectonic influence on the regional structural high.

Introduction

The Pennine Basin is a Carboniferous sedimentary basin extending across northern England between the Wales-Brabant Massif in the south and the Southern Uplands in the north. During early Carboniferous times, phases of rifting and associated extensional tectonics occurred, thought to be caused by back-arc extension, located north of a subducting Rheic Ocean (Leeder, 1982). Structurally high and low areas formed during this period, commonly described as the development of early Carboniferous 'block' and 'basin' features (Phillips, 1836; Bott, 1967; Johnson, 1967; Fraser & Gawthorpe, 2003). The high areas are characterised by relatively thin, often stratigraphically incomplete, shallow water carbonate-dominated, occasionally reefal, sedimentary deposits, whereas the basinal areas contain deeper-water argillaceous-dominated sequences, which are much thicker and more stratigraphically complete. Later, during the Namurian and Westphalian, subsidence was of a more regional nature being related to post-rifting thermal relaxation (McKenzie, 1978). Namurian deposition was associated with a large southerly-prograding river delta complex leading to the deposition of the Millstone Grit Group sediments. Eventually, a flat landscape of lakes and rivers developed during which the Westphalian Pennine Coal Measures sequence was deposited. The red beds of the Warwickshire Group brought the Carboniferous deposition to a close during a period of drier climate. Table 1 provides a simplified summary of the Carboniferous stratigraphy.

Due to the generally poor seismic resolution at depth, the interpretation of gravity data has played a significant role in helping to understand pre-Carboniferous basement configuration and in particular

Period	Epoch	Groups/Formations	Lithology	Tectonics
Permian				
Variscan Unconformity				
Carboniferous	Stephanian	Warwickshire Group	mudstone, sandstone, siltstone	
		Symon Unconformity		
	Westphalian	Pennine Coal Measures Group	mudstone, sandstone, siltstone, coal	Thermal Relaxation
	Namurian	Millstone Grit Group, Edale Shale and Bowland Shale Groups	sandstone, mudstone	
	Visean	Chatburn and Clitheroe Limestone Groups, Worston Shale Group	limestone (structural highs) mudstone, minor limestone, sandstone (structural lows)	Rifting
	Tournaisian			
Late Devonian				
Acadian Unconformity				

Table 1 *Simplified stratigraphy of the Pennine Basin after Aitkenhead et al. (2002) and Pharaoh et al. (2011)*

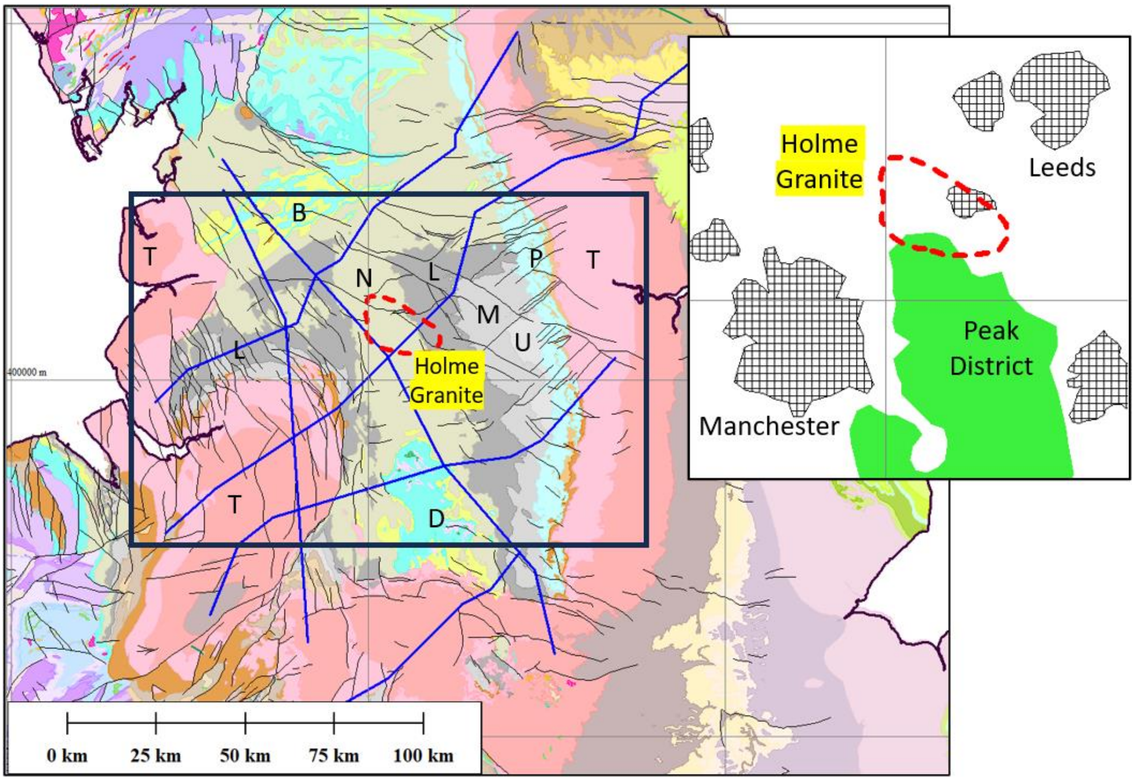


Figure 1 *Solid geology map reproduced with permission from the British Geological Survey (BGS) with the locations of modelled gravity and magnetic cross-sections shown by blue lines. The area of the well and seismic database map of Figure 2 is shown by the black rectangle. Within the rectangle, principal stratigraphic intervals that outcrop are labelled as follows: - T-Triassic, P-Permian, U, M and L – Upper, Middle and Lower Coal Measures, N- Namurian, D – Dinantian (Visean and Tournaisian) and B-Bowland High Group and Craven Group. Contains British Geological Survey materials ©UKRI 1991. The approximate position of the proposed buried granite pluton is outlined with the red dashed polygon on both the geology map and the inset summary location map. urban areas are cross hatched*

the location of possible granite plutons. Specifically, and within the general area of this study, the gravity fields over various proven and postulated granites have been reviewed, such as the Lake District (Lee, 1990; Woodcock, et al., 2019), Weardale and Wensleydale (Bott, 1967), Market Weighton (Bott, et al., 1978), Hornsea (Donato & Megson, 1990), Newark (Allsop, 1987; Evans & Allsop, 1987) and Bingham (Donato, 2019). The Lake District Granite is seen in outcrop. The Weardale Granite is proven by drilling in the Rookhope (Dunham et al., 1965; Johnson & Nudds, 1995) and Eastgate (Manning, et al., 2007) boreholes with the Wensleydale Granite being confirmed in the Raydale Borehole (Dunham, 1974; Pashley et al., 2021). The Market Weighton, Hornsea, Newark and Bingham Granites are inferred from gravity interpretation coupled with reflection seismic data. Several of the studies have suggested a strong link between areas of platform stability, massive Lower Carboniferous Limestone development, and the locations of large granite intrusions (Bott, 1967; Bott, et al., 1978; Donato, 2019; Howell, et al., 2019). Although the Blocks or Highs are cored by the granites, they are set within larger regional highs or blocks, whose margins are controlled by pre-existing faults or tectonic lineaments. This study further extends the use of gravity data in conjunction with well and reflection seismic information to suggest the location of a previously unrecognised buried granite pluton.

The Pennine Basin (Kirby, et al., 2000; Aitkenhead, et al., 2002; Pharaoh, et al., 2011) provides an example of a classic area where the influence of granite blocks has played a significant role in the style and distribution of early Carboniferous sedimentation (Bott, 1967). Age dating shows some of the granites of the area to have been intruded during Lower Devonian and others in Ordovician times (Woodcock, et al., 2019). Following intrusion, the large low-density granite masses are thought to

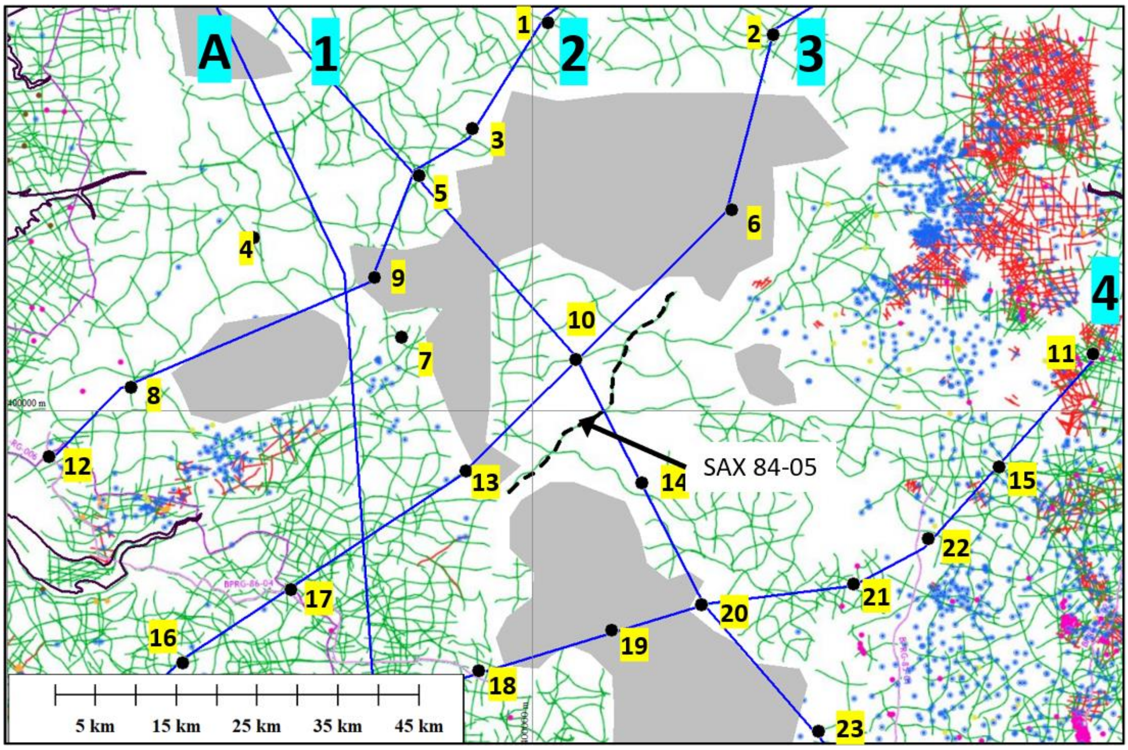


Figure 2 *Well and seismic database map. Profiles 1-4 were modelled by Donato and Pullan (2022). Profile A is an additional cross-section run for the purposes of this study. Well control points on the modelled profiles are shown by the black dots with wells labelled as follows:- 1-Low Bradley-1, 2-Weeton-1, 3- Boulsworth-1, 4-Roddlesworth-1, 5-Holme Chaple-1, 6-Willow Farm BH, 7-Heywood-1, 8-Upholland-1, 9-Fletcher Bank-1, 10-Wessenden-1, 11-Hatfield-1, 12-Croxteth-1, 13-Lingard Pit BH, 14-Alport-1, 15-Tickhill BH, 16-Bowyers Waste BH, 17-Knutsford-1, 18-Bosley-1, 19-Woo Dale BH, 20-Eyam-1, 21-Bramley Moor-1, 22-Kiverton Park-1 and 23-Highoredish-1. Green and red lines show the existing seismic database (UKOGL website). Seismic line, SAX 84-05, highlighted with the black dashed line is illustrated in Figure 10(a). Areas of no coverage and poor-quality seismic data are coloured grey.*

have produced flexural uplift (Howell, et al., 2019) and localised structural highs over which shallow water Lower Carboniferous sedimentation took place. The highs were uplifted utilising peripheral normal faulting produced or reactivated during the early Carboniferous extensional phases (see Discussion section for further explanation). At these times, Carboniferous syn-rift sedimentation patterns were strongly influenced by the granite-cored blocks or domes and by the intervening basinal areas.

As part of the ongoing studies of the Beneath Britain Group in association with the UK Onshore Geophysical Library (UKOGL), a series of cross-sections were constructed across northern, central and eastern England (Donato & Pullan, 2022). Four of these cross-sections are located over the Pennine Basin and one additional profile has been constructed for the purposes of this study (Line A). As shown in Figure 1, Carboniferous rocks outcrop over the Pennine Basin and the profiles are based upon an integration of stratigraphic well tops combined with published structure contour maps incorporating reflection seismic data interpretations. The seismic and well database is shown in Figure 2. Seismic coverage is highly variable with significant areas unconstrained by seismic control. Deep borehole penetrations are also limited with only five (Wessenden-1, Boulsworth-1, Holme Chapel-1, Roddlesworth-1 and Eyam-1) reaching pre-Carboniferous strata. The cross-sections have been converted to a series of simplified 2.5D gravity and magnetic model profiles, and the calculated anomalies have been compared to observed gravity and magnetic variations derived from maps published by the British Geological Survey (BGS) (Chacksfield & Edwards, 2006; Chacksfield et al., 2006). Assumed densities for the models are based upon an evaluation of well log data combined with published information. Magnetic susceptibility model values have been derived from published information. The gravity modelling has allowed the gravity effect of the better understood, shallower

No	Well	Date	TD Depth (m)		TD Formation Age	Lower Carboniferous Facies
			md	ss		
1	Low Bradley-1	1991	613.5	344.7	Middle Carboniferous	NR
2	Weeton-1	1984	1979.3	1928.5	Lower Carboniferous	Shale
3	Boulsworth-1	1963	1922.9	1493.8	Devonian	Limestone
4	Roddlesworth-1	1987	2509.0	2273.1	Devonian	Limestone
5	Holme Chapel-1	1974	1982.3	1710.8	Lower Ordovician	Limestone
6	Willow Park-1	1971	656.5	573.9	Upper Carboniferous	NR
7	Heywood-1	1984	1619.0	1499.0	Lower Carboniferous	Limestone
8	Upholland-1	1956	1522.4	1439.5	Middle Carboniferous	NR
9	Fletcher Bank-1	1958	1681.0	1434.1	Middle Carboniferous	NR
10	Wessenden-1	1987	1127.7	630.6	Lower Palaeozoic/Precambrian?	Limestone
11	Hatfield-1	1965	1604.8	1599.7	Middle Carboniferous	NR
12	Croxteth-1	1953	1285.0	1260.3	Lower Carboniferous	Limestone
13	Lingard Pit BH	1925	369.1	288.3	Upper Carboniferous	NR
14	Alport-1	1939	778.8	495.3	Lower Carboniferous	Shale
15	Tickhill BH	1958	1710.5	1681.5	Middle Carboniferous	NR
16	Bowyers Waste BH	1958	193.2	116.0	Lower Triassic	NR
17	Knutsford-1	1973	3045.7	3000.0	Upper Carboniferous	NR
18	Bosley-1	1986	2006.4	1564.0	Lower Carboniferous	Shale
19	Woo Dale BH	1947	312.1	69.6	Lower Ordovician	Limestone
20	Eyam-1	1970	1851.0	1621.0	Lower Ordovician	Limestone
21	Bramley Moor-1	1987	1146.9	925.9	Lower Carboniferous	Limestone
22	Kiverton Park-1	1940	1415.4	1312.2	Lower Carboniferous	Limestone
23	Highoredish-1	1955	184.5	158.2	Lower Carboniferous	Limestone

***Table 2** Summary results for the wells located and numbered in Figure 2. NR=Not reached*

geological structure to be removed, leaving residual anomalies thought to be derived from deeper, more poorly understood features. Following an initial 2.5D gravity modelling phase, magnetic anomalies were also modelled and incorporated.

The profiles revealed a significant residual negative gravity anomaly of up to 12 mGal located between Manchester and Leeds and spanning the northern edge of the Peak District. The anomaly has approximate dimensions of 40 km by 30 km. Donato & Pullan (2022) have tentatively suggested that the residual anomaly is associated with a previously unrecognised buried granite pluton, the Holme Granite, located beneath the Holme and Heywood structural highs. In this paper, this feature is examined in greater detail using supplementary 2.5D gravity and magnetic modelling, a 3D four-layer gravity model and detailed seismic interpretation.

2.5D Gravity and magnetic modelling and residual Gravity Anomaly

Five profiles extend across the area of interest, and three of these are illustrated in Figure 3 (Profiles 1, 2 and 3). The profiles are constructed using the 2.5D grav/mag modelling software (Pedley, et al., 1993) of the British Geological Survey (BGS) and are extracted with slight modification from Donato & Pullan (2022) where detailed profile descriptions are provided. For the initial gravity calculation, model layers representing five stratigraphic intervals were constructed including: - (i) Jurassic, (ii) Permo-Triassic, (iii) Stephanian and Westphalian (including Pennine Coal Measures), (iv) Namurian (including the Millstone Grit) and (v) Visean and Tournaisian (see Table 1). The lowermost layer, Visean and Tournaisian, is separated into two parts depending on the predominant lithology, one where platform limestones predominate and another where basinal shales predominate. The layer polygons are controlled by the numerous well ties coupled with published BGS depth structural contour maps (Kirby et al., 2000, Smith et al., 2005, Pharaoh et al., 2011). Assumed layer densities are listed in the profile figure captions and are defined by an evaluation of density logs from the Longhorsley-1, Errington-1, Whitmoor-1, Swinden Tipanheck-1, Boulsworth-1, Holme Chapel-1, Wessenden-1, Heywood-1, Croxteth-1, Roddlesworth-1 and Hesketh-1 wells and by summaries of rock density measurements provided by Kimbell et al. (2006).

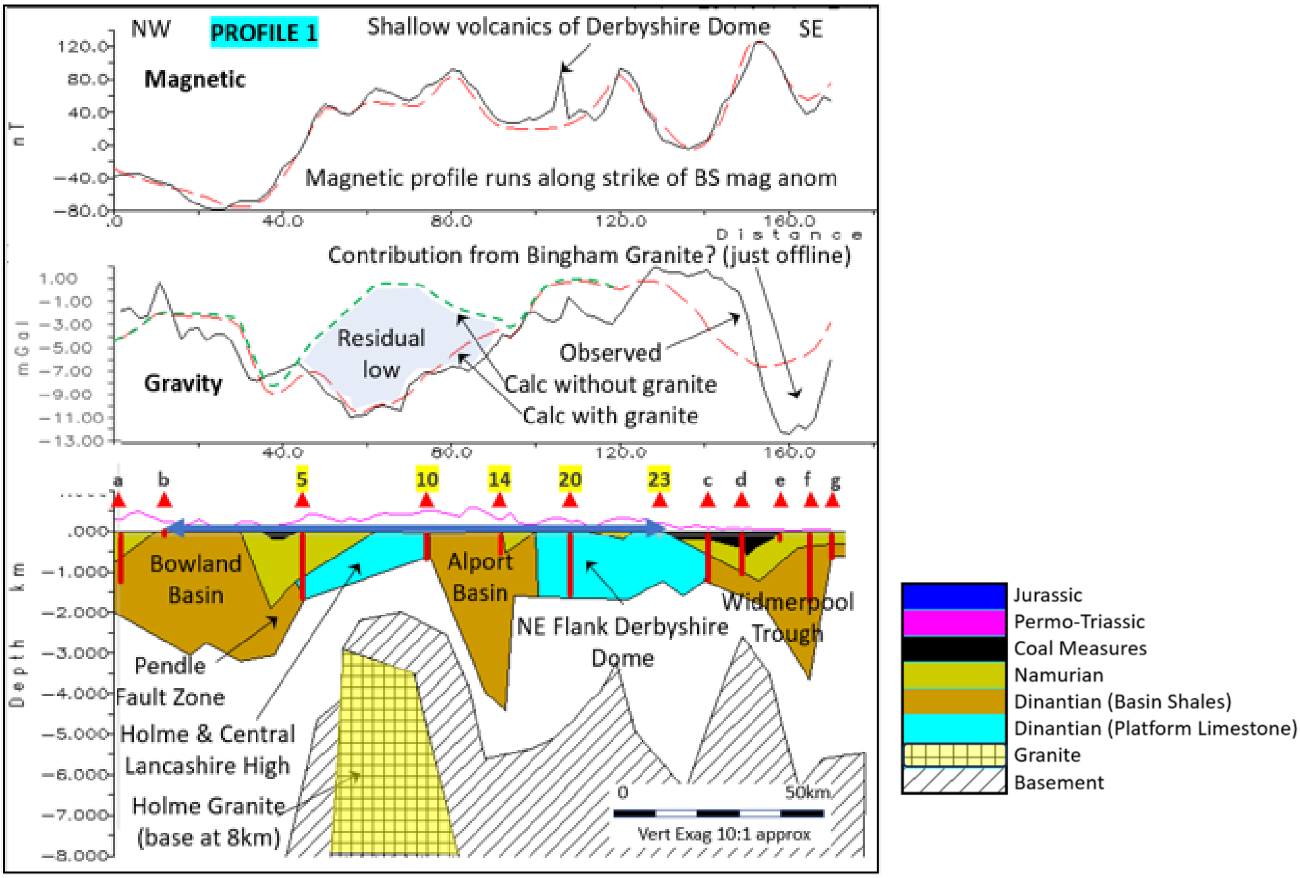
As discussed in Donato & Pullan (2022), 2.5D gravity and magnetic modelled profiles are usually constructed as straight lines crossing features at right angles to the apparent strike direction. The models created here do not satisfy this norm and, therefore, have additional limitations with respect to the more normal, orthogonally-intersecting profiles. The purpose of constructing the profiles is to attempt to identify areas where significant residual anomalies exist and, therefore, to highlight areas where further investigations may be worthwhile. Donato & Pullan (2022) estimated that differences greater than 5 mGal suggest further investigation to be merited.

Profile 1 (Figure 3) passes from northwest to southeast commencing within the Bowland Basin with deformed and inverted Namurian rocks at outcrop. Southwards, beyond the Pendle Fault, the profile passes over Lower Carboniferous shelf carbonate sediments. Shelf carbonate facies are proven in the Holme Chapel-1 (well number 5), Wessenden-1 (well number 10), Heywood-1 (well number 7) and Boulsworth-1 (well number 3) wells and are confined to the area of complex, positive structural features including the Central Lancashire, Heywood and Holme Highs (Evans & Kirby, 1999). Farther south, the profile crosses the Alport Basin, a Lower Carboniferous (Visean and Tournaisian) basinal area, as proved by the Alport-1 well (well number 14), before reaching the East Midlands Shelf and the northeastern flank of the Derbyshire Dome. The southeastern end of the profile continues across the Widmerpool Trough, another major Lower Carboniferous basinal area, beyond the area of interest considered here. The modelled gravity calculation, based upon the Carboniferous and younger layers, reveals a residual gravity low with an amplitude of approximately 12 mGal located between 40 and 95 km along the profile (shaded light blue in Figure 3, Profile 1). A possible explanation for this significant gravity residual anomaly, and also for the associated magnetic anomalies, is offered by the inclusion in the model of a non-magnetic Holme Granite block intruded into slightly magnetic basement. This is shown by the lower model prisms of Figure 3 (Profile 1).

Profile 2 (Figure 3) extends from southwest to northeast. Namurian to Westphalian section outcrops to the northeast of the Croxteth-1 well (well number 12) and the profile crosses the Lancashire Coalfield before passing onto the Holme and Central Lancashire Highs. A residual gravity low of approximately 8 mGal may be seen located over the structural high area between 30 and 55 km along the profile. This gravity low and its associated flanking magnetic anomalies may be explained, as for Profile 1, by the inclusion in the model of a non-magnetic Holme Granite block.

Profile 3 (Figure 3) crosses the deep gravity low associated with the thick Permo-Triassic sediments of the Cheshire Basin and then passes onto the Holme and Central Lancashire Highs. Beyond the High, the profile crosses the north-westerly extensions of the Huddersfield Basin and Gainsborough Trough. In agreement with Profiles 1 and 2, Profile 3 shows a significant residual gravity low located primarily over the structurally high area of the Holme High. In this case, it has an amplitude of approximately 10 mGal, is located between 80 and 100 km along the profile and, in a similar manner to Profiles 1 and 2, may be explained by the presence of the Holme Granite.

The residual gravity anomaly defined by the 2.5D gravity profiles has been mapped and is illustrated in Figure 4. The anomaly has a maximum amplitude of 12 mGal and extends over an area of approximately 1200 sq km. This paper attempts to further define this gravity anomaly. As a first step in this more detailed examination, a local 3D gravity model has been constructed, the extent of which is shown by the red-dashed rectangular outline of Figure 4.



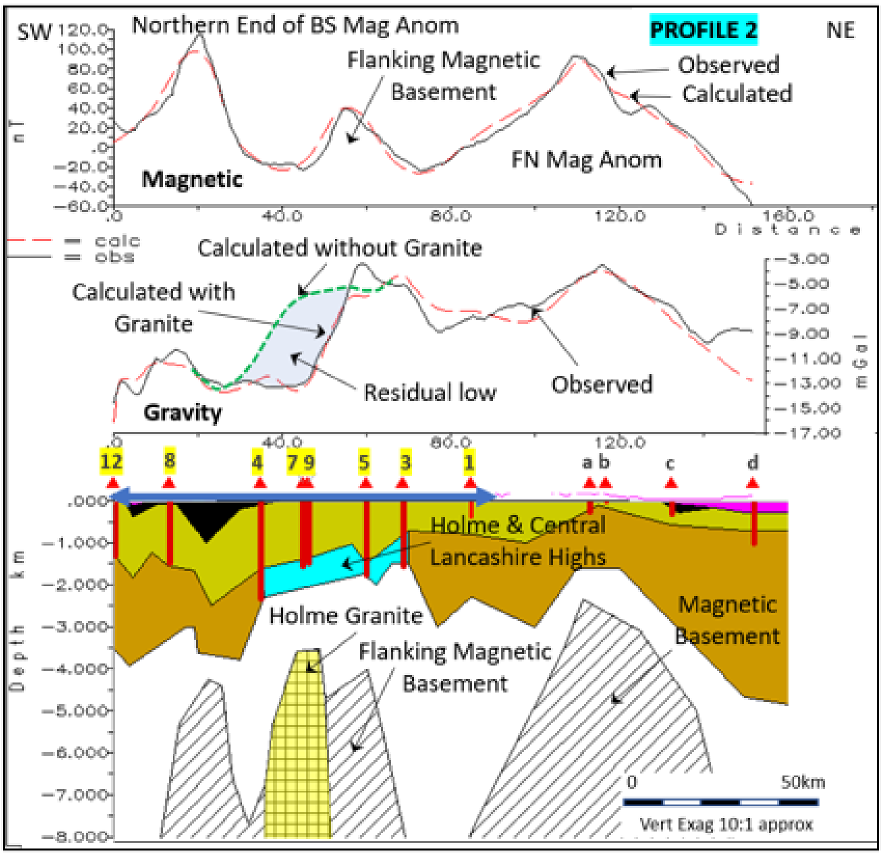


Figure 3 continued below

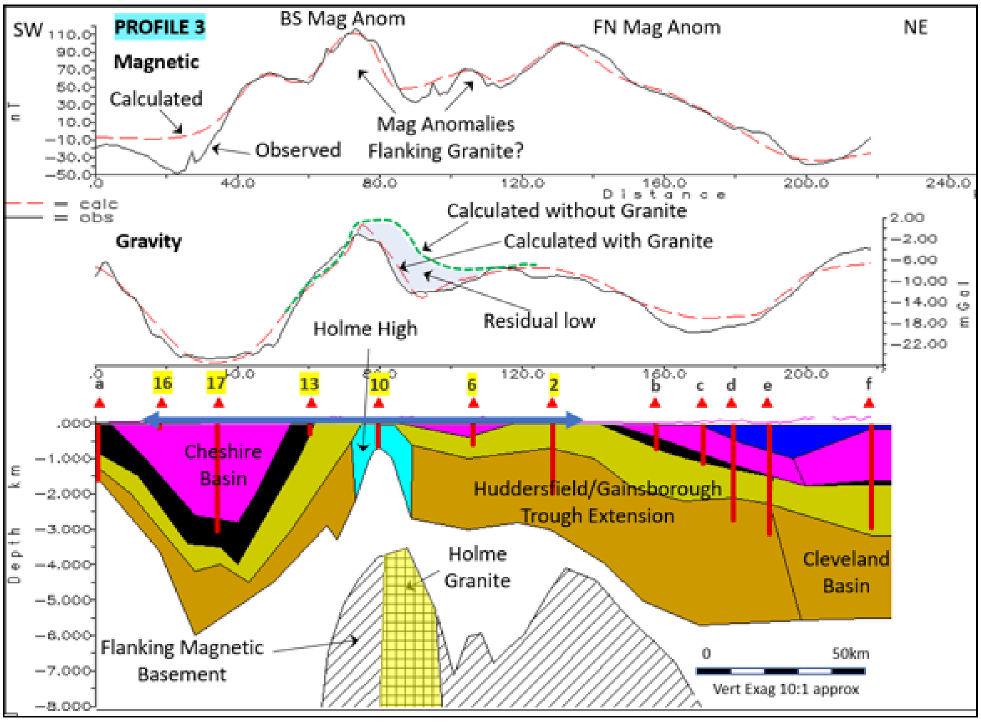


Figure 3 *Profiles 1, 2 and 3 reproduced with slight modification from Donato and Pullan (2022). The yellow shaded granite block is the postulated Holme Granite. Abbreviations used are FN- Furness to Norfolk and BS-Burnley to Stamford magnetic anomalies. The extent of the profiles within Figure 2 is shown by the blue horizontal line. In this area the wells are labelled with numbers in accordance with Figure 2. Outside of this area the wells are labelled with letters. Profile model parameters and well tie points are listed below: -*

Profile 1 *Assumed densities are Triassic 2.55, Westphalian 2.6, Namurian 2.6, Visean and Tournaisian 2.7 (Bowland and Edale Basins), Visean and Tournaisian 2.68 (Widmerpool Trough), Visean and Tournaisian 2.73 (carbonates), Granite 2.65. A background density of 2.72 has been assumed. Magnetic basement 2.72, 0.019 SI. The well locations are numbered as a Whitmoor-1, b Brennand BH, 5 Holme Chapel-1, 10 Wessenden-1, 14 Alport-1, 20 Eyam BH, 23 Highoredish BH, c Ironville-5, d Ilkeston-1, e Stapleford-1, f Ratcliffe on Soar-1 and g Hathern-1*

Profile 2 *Assumed densities are Permo-Triassic 2.45, Westphalian 2.6, Namurian 2.6, Visean and Tournaisian Sst/Sh 2.67, Visean and Tournaisian Lmst 2.73, Granite 2.65, Magnetic Basement SW of granite 2.72, 0.018 SI, Magnetic Basement NE of Granite 2.735, 0.01 SI, Magnetic Basement NE end of profile 2.72, 0.014 SI. The well locations are numbered as 12 Croxteth-1, 8 Upholland-1, 4 Roddlesworth-1 (offset), 7 Heywood-1 (offset), 9 Fletcher Bank-1, 5 Holme Chapel-1, 3 Boulsworth-1, 1 Low Bradley-1, a Sawley-1, b Aldfield-1, c Kirklington BH and d Harsley-1.*

Profile 3 *Assumed densities are Jurassic 2.6, Permo-Triassic 2.55/2.65(Cleveland Basin inverted), Westphalian 2.6, Namurian 2.6/2.7 (inverted), Visean and Tournaisian Sst/Sh 2.68/2.72 (inverted), Visean and Tournaisian Lmst 2.75, Granite 2.62, 0.005 SI, Magnetic Basement SW of Granite 2.73, 0.015 SI, Magnetic Basement NE of Granite 2.72, 0.017 SI. The well locations are numbered as a Milton Green-1, 16 Bowyers Waste BH, 17 Knutsford-1, 13 Lingard Pit BH, 10 Wessenden-1, 6 Willow Farm BH, 2 Weeton-1, b New Parks BH, c Thornton le Clay-1, d High Hutton-1, e Kirby Misperton-8 and f Cloughton-1*

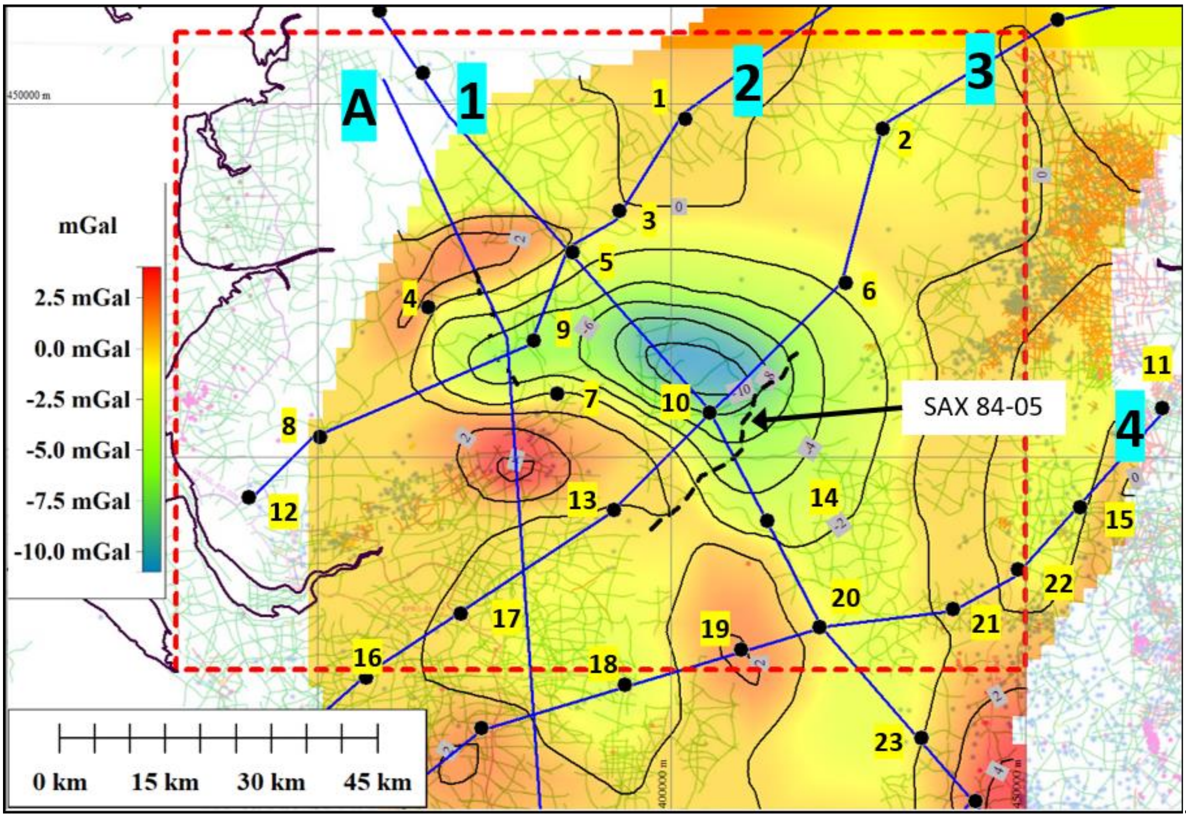


__Figure 4__ Residual gravity map derived from the gravity modelling of Profiles 1-5 and A. The map has a contour interval of 2 mGal. The main anomaly of interest is the area of low residual gravity values located close to the intersections of Profiles 1, 2 and 3. The red dashed rectangle shows the location of the 3D gravity modelling study. Wells are shown by black dots and are numbered as Figure2. The UKOGL seismic database is shown by the green and red lines.

3D Gravity Modelling

A four-layer 3D gravity model, using a grid interval of 2 km, has been constructed based upon simplified versions of the series of depth contour structure maps published by Kirby, et al. (2000), Aitkenhead, et al. (2002) and Smith, et al. (2005). The depth surfaces shown in Figure 5 were used to define the following four intervals: Permo-Triassic, Westphalian, Namurian and Dinantian (Visean and Tournaisian). Assumed densities were similar to those used for the 2.5D profiles but were refined following an evaluation of density logs in the Wessenden-1 (well number 10), Roddlesworth-1 (4) and Heywood-1 (7) wells. Based on well information, Dinantian (Visean and Tournaisian) densities were varied across the area with higher values ascribed to areas of thicker platform carbonates. Values used are listed in the Figure 5 caption. This model allows an attempt to be made to calculate the gravity effect from all sediments above the base Carboniferous/top Caledonian Unconformity. The calculated results of the 3D model were subtracted from the observed gravity field of Figure 6(a). A regional background gravity field, following that proposed by Donato et al. (2024), was also removed. The resulting residual gravity anomaly produced by this stripping process is shown in Figure 6(c). These results are compared to the residual fields obtained from the 2.5D profiles (Figure 6(b)) and also to the work of Kimbell, et al. (2006) (Figure 6(d)) who undertook a similar evaluation extending over the northern part of the area of the red dashed rectangle. The three slightly different methods all reveal a residual gravity low in approximately the same location and highlighted by the three black dashed outlines. The feature appears to comprise an approximately east-west trending low with the minimum gravity values located within the eastern part. Grey shading highlights areas of no or poor seismic coverage. In these areas, the geological structure is poorly defined hence the gravity modelling is less reliable. The observed gravity field of Figure 6(a) shows a strong regional westerly increase in gravity values superimposed upon the gravity effects of this structurally complex area. It is only when the regional variation and structurally related gravity effects are removed by the stripping process that the low residual anomaly may be clearly identified.

Figure 7 provides a summary Bouguer anomaly gravity map with the gravity lows previously interpreted by other workers as being related to granite masses highlighted by black dashed contours. The residual gravity low (7) calculated here for the proposed Holme Granite has been inserted for comparison. Examples of granite plutons within central and northern England shown on the map include:- the Lake District Granites (1) (Lee, 1990; Woodcock, et al., 2019) involving two phases of granitic intrusions of Upper Ordovician age including the Ennerdale Granophyre and Eskdale Granite and early Devonian age including the Shap and Skiddaw Granites, the Weardale Granite (2) (Bott, 1967) within the Alston Block, the Wensleydale Granite (4) (Bott, 1967) within the Askrigg Block, the Market Weighton Granite (5) (Bott, et al., 1978) and its possible offshore extension including the Hornsea Granite (6) (Donato & Megson, 1990), the Newark (9) (Allsop, 1987; Evans & Allsop, 1987) and Bingham (10) (Donato, 2019) Granites within the East Midlands Shelf.

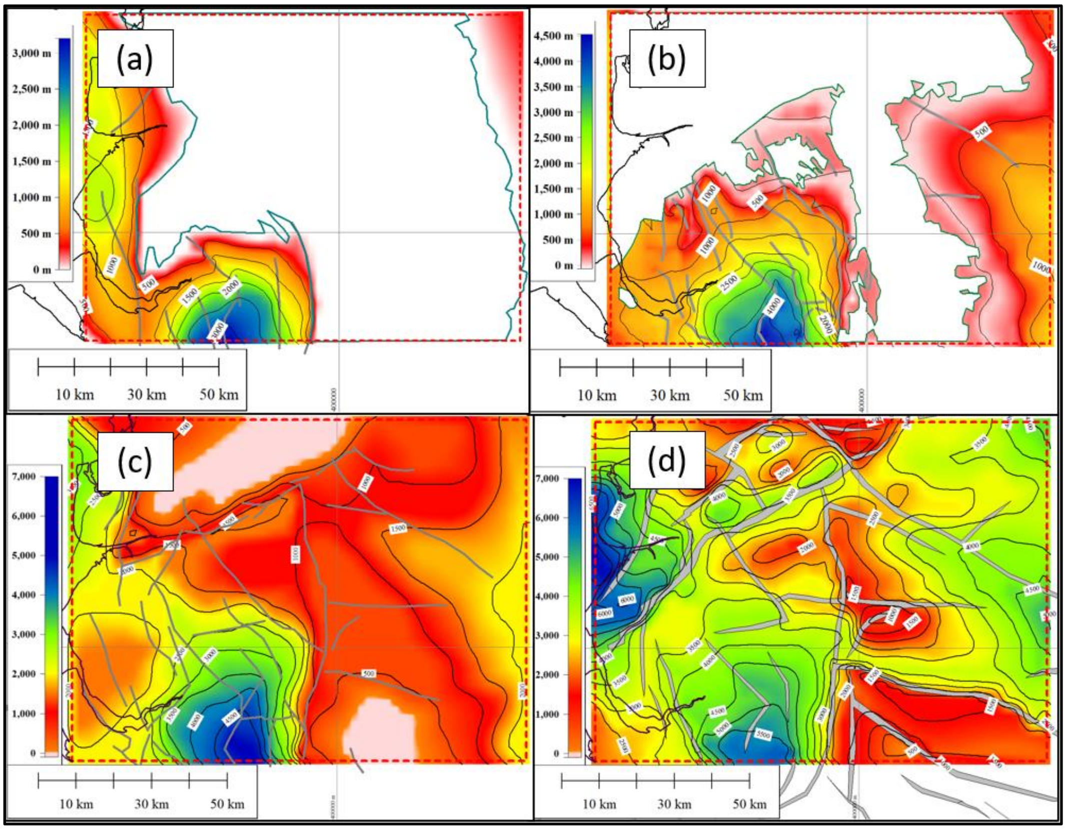


Figure 5 *Depth structure maps derived, simplified and slightly modified from Aitkenhead, et al. (2002), Kirby, et al., (2000) and Smith, et al., (2005) and used for the construction of a four-layer 3D gravity model,* ***Figure 5 (a)*** *Variscan Unconformity,* ***Figure 5 (b)*** *Base Westphalian,* ***Figure 5 (c)*** *Top Dinantian (Visean and Tournaisian), and* ***Figure 5 (d)*** *Base Carboniferous/Caledonian Unconformity. The area of the maps is shown by the red dashed rectangle in Figure 4. Assumed densities are Permo-Triassic 2.52, Westphalian 2.55, Namurian 2.6 and Dinantian (Visean and Tournaisian) 2.68 (basinal areas, argillaceous) and 2.73 (platform areas, limestones).*

In Figure 8(a) the three residual gravity outlines of Figure 6 are superimposed upon the total magnetic anomaly map derived from Chacksfield, et al. (2006). An arcuate positive magnetic anomaly with an amplitude of approximately 150nT is located along the southern flank of the residual negative gravity anomaly, interpreted here as associated with the buried Holme Granite. The magnetic anomaly appears associated with the easterly, deeper part of the residual gravity anomaly and not its possible westerly extension.

Granites frequently appear to have low magnetic susceptibility and consequently often display peripheral positive magnetic anomalies associated with the more magnetic surrounding basement. The flanking magnetic anomalies may result from topography on the magnetic basement in proximity to the granites as modelled in Donato & Pullan (2022) (for example see Profiles 1, 2, 3, 10, 12, 15, 16, 17 and 18). In addition, or as a possible alternative explanation, the anomalies may be related to mineralisation/alteration of the basement adjacent to the granitic intrusions. Examples of peripheral magnetic anomalies from central and northern England include the Wensleydale (Askrigg Block), Market Weighton and Wash Granites. At Wensleydale, positive magnetic anomalies lie along the southwestern flank of the gravity low caused by the granite (Bott, 1961) with magnetic amplitudes rising to just over 160nT. The Beckermonds Scar borehole, drilled on the southwestern flank of the granite, encountered steeply-dipping, magnetite-rich siltstones, mudstone and greywacke sandstones of Ordovician age (Wilson & Cornwell, 1982). These sediments abut the gravity low of the non-magnetic granite and are considered capable of producing the observed flanking magnetic anomalies. The Market Weighton Granite (Bott, et al., 1978) shows two positive magnetic anomalies of amplitude 100 and 150nT located on the southern and western flanks of the associated gravity low. Bott (1961) interpreted the anomalies as related to magnetic basement flanking the non-magnetic granite block. The Wash Granites (Allsop, 1987), most notably the Boston Granite, have positive magnetic anomalies with amplitudes approaching 170nT located on the flanks of the granite masses. By analogy, therefore, the association between the residual gravity low and the arcuate positive magnetic anomalies, as shown in Figure 8(a), lends support to an interpretation of the features being related to the postulated buried Holme Granite.

A spectral decomposition of magnetic data (Beamish, et al., 2016) reveals possible deeper basement magnetic features (Figure 8(b)). This shows the proposed Holme Granite and its associated magnetic anomaly as centrally located within the northern end of the large northwest-southeast trending Burnley-Stamford Magnetic Anomaly (BSMA) (Figure 8(b)) (Donato & Pullan, 2022). The Bingham Granite is also located along the line of the BSMA but the Market Weighton, Newark and Hollowell Granites do not follow this trend. Suggestions for a deep source for the BSMA include the presence of Ordovician intrusive rocks, possibly associated with subduction of the Tornquist Ocean (Allsop, 1987; Pharaoh et al., 1993), or the presence of a Precambrian magnetic basement (Wills, 1978; Cornwell & Walker, 1989). The Burnley-Stamford Anomaly is complex however, and also incorporates significant sources with shallower origins, such as Dinantian volcanics and volcanic centres of the Derbyshire Dome (Cornwell & Walker, 1989), Westphalian volcanics seen at the Strelley Volcanic Centre (Pharaoh, et al., 2011) and Ordovician granodiorite intrusions (Evans & Maroof, 1976; Allsop, 1987; Lee et al., 1990). The early Carboniferous Basins of the Gainsborough Trough and Widmerpool Gulf lie at an oblique angle to the BSMA with the Bingham Granite (Donato, 2019) appearing to extend beneath the northern faulted margin of the Widmerpool Gulf (Figure 8(b)). In the region of the proposed Holme Granite the BSMA anomaly is bounded by a series of deformation/fault zones, the Todmorden Smash Belt to the north-east, the Pendle Fault to the northwest and the Derwen Valley Faults to the southwest (Figure 8(b)).

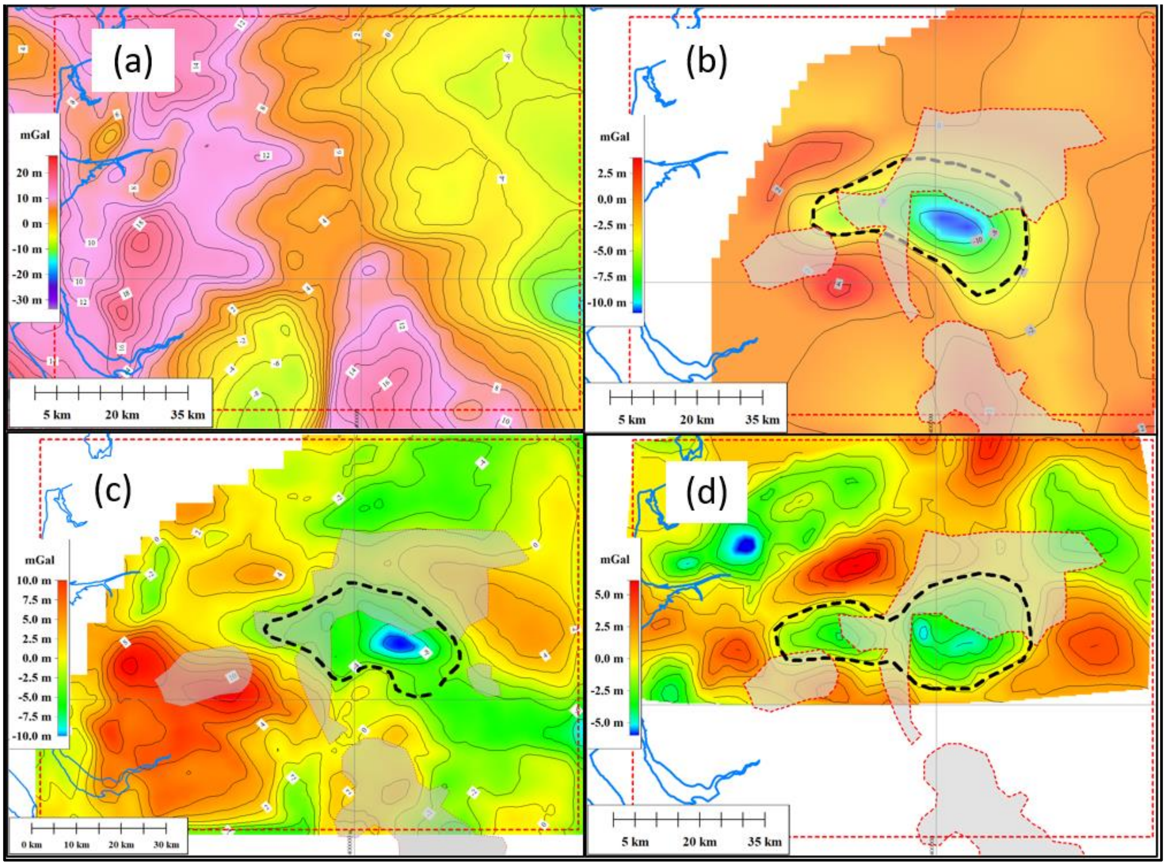


Figure 6 *Gravity anomaly comparisons. The four maps all cover the area of the red dashed rectangle shown in Figures 4 and 5**. Figure 6 (a)** Observed Bouguer anomaly gravity map derived from Chacksfield & Edwards (2006)* ***Figure 6 (b)*** *Residual gravity anomaly obtained from the 2.5D models of Profiles 1-4 and A.* ***Figure 6 (c)*** *Residual gravity anomaly derived from the four-layer 3D model**. Figure 6 (d)** 10th order residual gravity anomaly following removal of the gravity effect of Carboniferous and younger rocks redrawn from Kimbell, et al., (2006). In (b), (c) and (d) the anomalies are interpreted as related to the postulated Holme Granite and are highlighted by the black dashed outlines. The contour interval for (a), (b) and (c) is 2 mGal and that for (d) is 1 mGal. Grey shading highlights areas of no or poor seismic coverage where the geological structure and hence gravity modelling will be less reliable.*

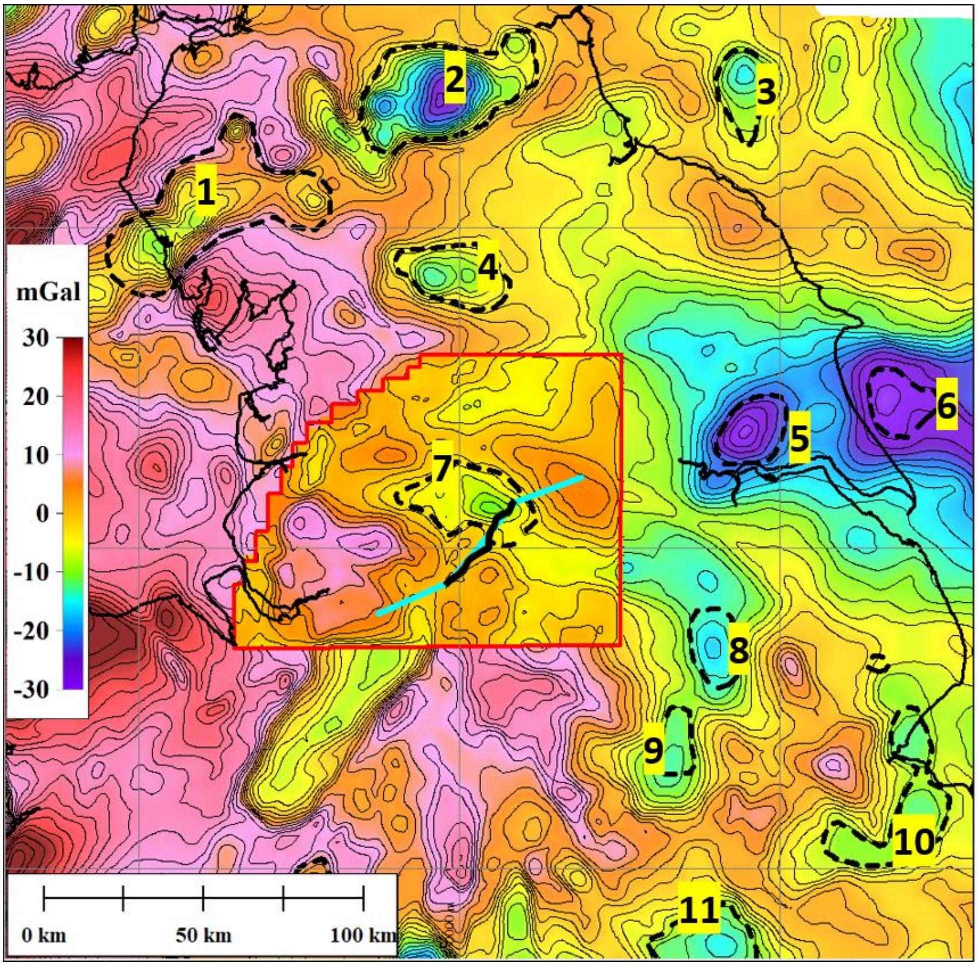
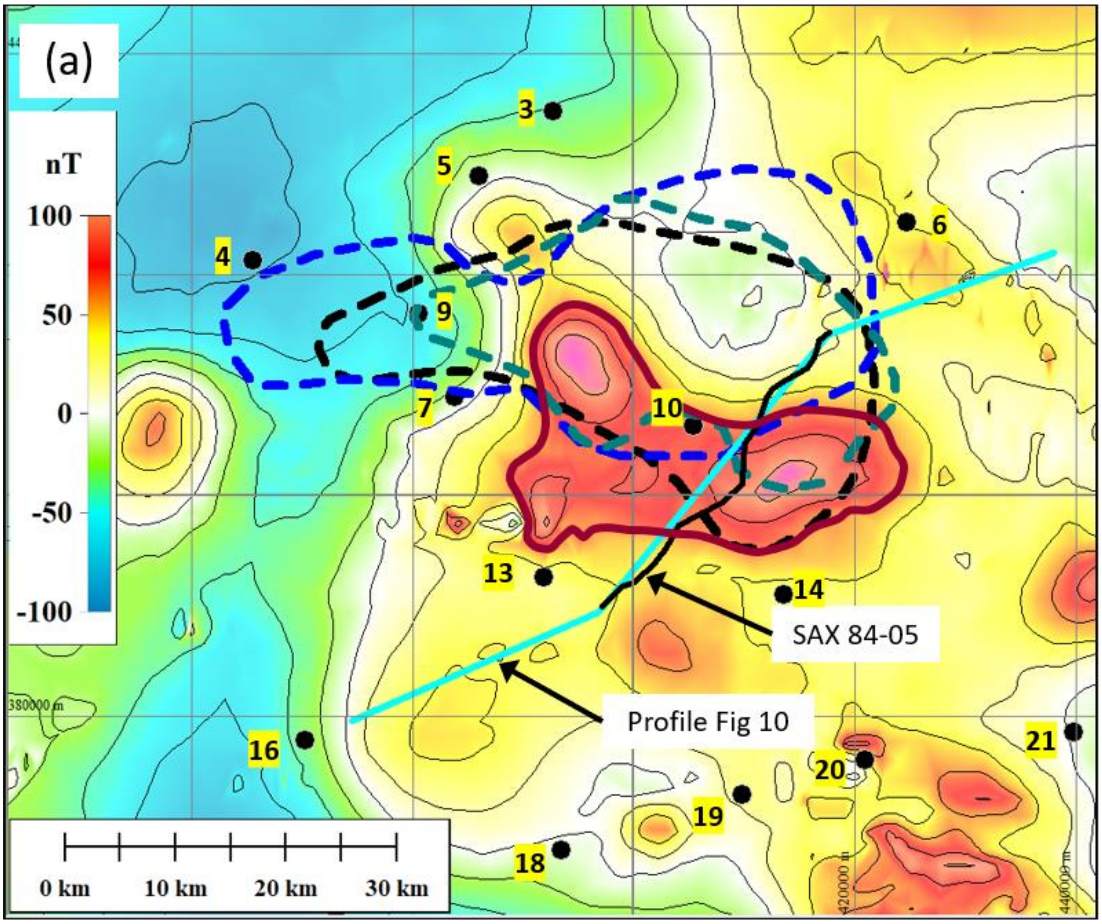


Figure 7 *Bouguer anomaly gravity map produced by digitising contours from Chacksfield & Edwards (2006) and then gridding and contouring with GlobalMapper software. The residual gravity anomaly of Figure 6(c) has been inserted within the red polygon. The contour interval is 2 mGal for both datasets. Black dashed outlines show the locations of postulated granite blocks labelled as follows:- 1-Lake District, 2-Weardale (Alston Block), 3-Tyne, 4-Wensleydale (Askrigg Block), 5- Market Weighton, 6-Hornsea, 7- Holme (as proposed here), 8-Newark, 9-Bingham, 10-Wash and 11- Hollowell. The solid black line shows the location of SAX84-05 and the cyan line shows the position of Profile B illustrated in Figure 10.*



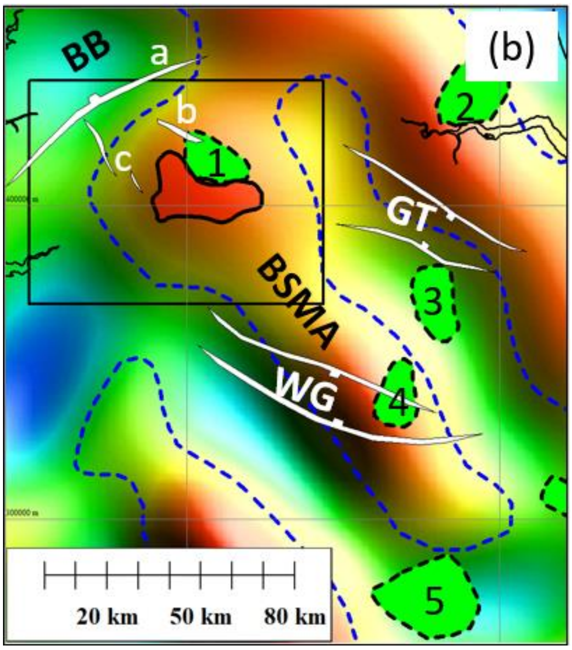


Figure 8 (a) *Map showing the residual gravity outlines of Figure 6 superimposed on the Total Magnetic Anomaly redrawn from Chacksfield et al. (2006). An arc-shaped positive magnetic anomaly, highlighted with the solid dark red line, lies on the southern flank of the eastern, deeper component of the low residual gravity anomaly. The location of seismic line, SAX 84-05, is shown by the labelled black line and the location of the Profile B of Figure 10 by the cyan line. Well locations are shown by black dots and are labelled as Figure 2.* ***Figure 8 (b)*** *shows the long wavelength spectral decomposition of the magnetic field reduced to pole (Beamish, et al., 2016). The positive magnetic feature of the Burnley-Stamford Magnetic Anomaly (BSMA) (Donato and Pullan, 2022) is labelled and outlined with the body boundaries shown by the blue dashed line (Beamish et al., 2016) as estimated by a tilt derivative analysis. Granites are labelled 1- Holme, 2 - Market Weighton, 3 - Newark, 4 – Bingham and 5 – Hollowell, sedimentary basins as -GT - Gainsborough Trough, WG - Widmerpool Gulf and BB - Bowland Basin and faults as a – Pendle Fault, b – Todmorden Smash Belt and c – Derwen Valley Fault. The red polygon with black outline shows the location of the positive magnetic anomaly. The black rectangle shows the extent of Figure 8(a).*

Seismic Interpretation

Following the 3D gravity modelling exercise, DUG Technology Ltd. (DUG, 2024) kindly made available their seismic interpretation software package to the Beneath Britain Group under an academic licence. This enabled a seismic interpretation to be undertaken using the seismic data provided by the UK

Geophysical Library (UKOGL) loaded to the DUG Insight software (v5.1, 2024). Seismic acquisition across the area is varied, with patches of very limited or non-existent coverage (Figure 2) and with several lines displaying poor data quality. The area of interpretation spanned the Holme High and extended north-westwards to include the Central Lancashire High. Interpretation was focused upon mapping the Base Namurian and Base Carboniferous reflectors with key well ties obtained from the Boulsworth-1, Roddlesworth-1, Holme Chaple-1, Heywood-1, and Wessenden-1 wells. The two resulting time maps are shown in Figure 9 with areas of no or poor-quality seismic data shown by grey shading. The Base Namurian map (Figure 9(a)) shows a prominent NNW-SSE trending ridge following the Namurian surface outcrop with flanking Westphalian strata and reflecting post-Carboniferous inversion along the Pennine Axis. The Base Carboniferous map (Figure 9(b)) is more heavily faulted with faults generated during early Carboniferous phases of extensional tectonics. An example of one of the better-quality lines, SAX 84-05, is shown in Figure 10(a) with horizon identification as follows:- brown – Base Coal Measures, green – Near Base Namurian (Top Dinantian (Visean and Tournaisian)), blue – Top Platform Carbonates with a transparent seismic character, various yellow – wedge-like 'stripy' appearance representing Dinantian (Visean and Tournaisian) basinal facies, red – Base Carboniferous/Top Lower Paleozoic Basement. The south-western end of the line commences on the upthrown, southern side of the Alport Fault. The line then passes into the Alport Basin and rises north-eastwards to the Holme High. Towards the north-eastern end, the line passes beyond the Holme High and into the southern flank of the Huddersfield Basin.

In general, the Base Namurian reflector may be followed with reasonable confidence, but the Base Carboniferous event shows marked variability with some areas of strong, clear reflections and other areas with very poor reflector strength and weak lateral continuity. Within the Dinantian (Visean and Tournaisian) interval, a strong event may be seen locally over structural highs. This is thought to originate from massive platform carbonate sequences identified in the Holme Chapel-1 (well number 5), Wessenden-1 (10), Heywood-1 (7) and Boulsworth-1 (3) wells. These carbonate sequences are confined to two main areas, the Holme and the Central Lancashire Highs. as shown in Figure 9(b) by the cyan polygons.

Figure 9 displays contour maps of two-way-time, and no depth conversion has been attempted. It may be worth considering however, how the structure in time may be distorted by velocity effects. The Wessenden-1 well (well number 10) penetrated almost 500m of platform carbonates with an interval velocity of 6.3 km/s. The average interval velocities of the sections above and below the carbonates were measured in the well as approximately 4 km/s and 5 km/s respectively. Consequently, the carbonates represent a high velocity interval and time 'pull-up' will be anticipated beneath the thicker units of carbonate. Depth conversion will therefore partially flatten the time structure beneath the two cyan polygons outlined in Figure 9(b).

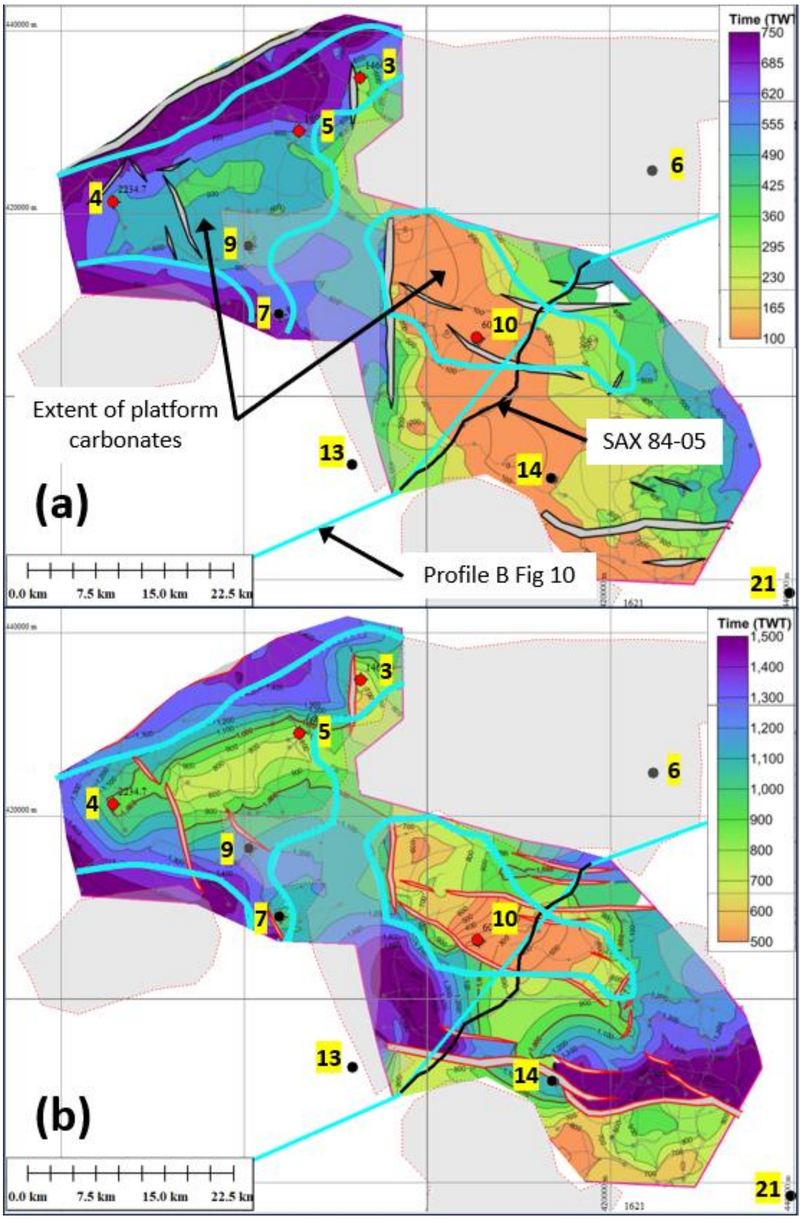


Figure 9 (a) *Time map of the Base Namurian reflector. The locations of line SAX 84-05 and Profile B of Figure 10 are shown by the black and cyan lines respectively. The two cyan polygons show the areas of platform carbonate development as proven in wells Holme Chapel-1 (well number 5), Wessenden-1 (well number 10), Heywood-1 (7) and Boulsworth-1 (3). Grey shading illustrates areas with no or poor-quality seismic coverage.* ***Figure 9 (b)*** *Time map of the Base Carboniferous reflector. Wells penetrating to the Base Carboniferous are shown by red dots and include Wessenden-1 (10), Boulsworth-1 (3), Holme Chapel-1 (5), Roddlesworth-1 (4) and Eyam-1 (located just off the map to the south.*

Despite the variable and often indifferent data quality, particularly for the Base Carboniferous reflector, there is broad, general agreement between our mapping and numerous independent interpretations including those of Evans & Kirby (1999), Chadwick & Evans (2005) and those of various oil company geoscientists whose interpretation are stored on the UK Onshore Geophysical Library (UKOGL) website (Saxon (1985); Enterprise (1987); Edinburgh (1988); Amoco (1991); Sovereign (1991).and Aurora (2014)).

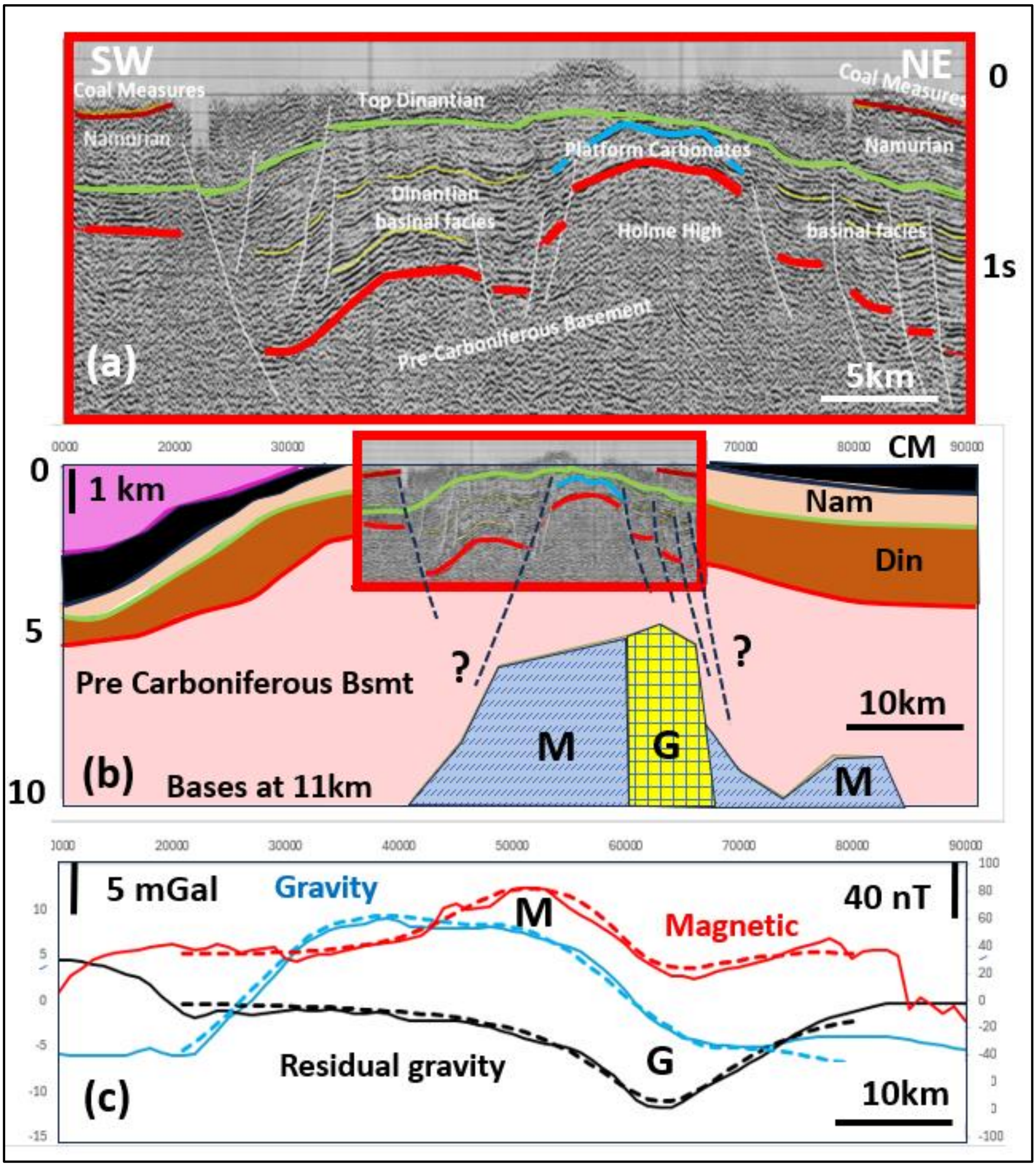


Figure 10 *Profile B with location shown in Figures 7, 8, 9 and 11.* ***Figure 10 (a)*** *Interpretation along line SAX 84-05 with horizons marked as follows:- brown – Base Coal Measures, green -Base Namurian/Top Dinantian (Visean and Tournaisian), blue – Top Platform Dinantian Carbonates, various yellow – wedge-like 'stripy' character representing Dinantian basinal facies – red – Base Carboniferous/Top Lower Paleozoic Basement.* ***Figures 10 (b) and 10 (c)*** *Speculative gravity and magnetic model. The profile is a combination of the 3D models of the Carboniferous and Permo-Triassic intervals described earlier plus a 2.5D model of the gravity and magnetic basement blocks (G and M). The granite block (G) has an assumed density of 2.55 gm/cc and zero susceptibility. The flanking magnetic basement has a density 2.72 gm/cc with susceptibility of 0.012 SI. A background density of 2.72 gm/cc has been assumed with a gravity regional following that described in Donato et al. (2024) with slight modification. A linear regional magnetic field has been assumed with values increasing north-eastwards by 0.1 nT/km.*

Figure 10 shows an integration of the seismic, magnetic and gravity data along Profile B (location shown in Figures 7, 8, 9 and 11). Figure 10(a) illustrates the interpretation of line SAX 84-05 described above. In Figure 10(b), this interpretation has been integrated into a geological cross-section based upon the Permo-Triassic and Carboniferous mapping described in Figure 5. It should be noted that in

Figure 10 (b) the seismic section has a vertical axis in two-way-time but it has been displayed so as to match approximately the depth section. The profiles of Figure 10(c) are a combination of the 3D models of the Carboniferous and Permo-Triassic intervals described earlier plus a 2.5D model of the gravity and magnetic basement blocks G and M. Assumed parameters are listed in the figure caption. Agreement for the gravity profiles was achieved by assuming a density of 2.55 gm/cc for the granite block, a value lower than the likely densities for Namurian or Dinantian sediments. The main mass of the proposed Holme Granite is located beneath the northern flank of the Holme High and the southern flank of the Huddersfield Basin. The granite is assumed to be intruded into the magnetic basement associated with the Burnley-Stamford Magnetic Anomaly (BSMA).

Discussion

Age dating shows the Crummock Water, Shap, Weardale and Skiddaw granites to have been intruded during Lower Devonian times (Woodcock, et al., 2019) with the Wensleydale and Eskdale granites and the Ennerdale Granophyre being intruded within the Ordovician (Aitkenhead, et al., 2002; Pashley, et al., 2021). A series of maturity studies have been undertaken by the BGS on the pre–Upper Paleozoic section for wells within the Pennine Basin (Merriman, et al., 1993; Molyneux, 2001). The work on the basal Lower Ordovician intervals in the Eyam-BH (Early Arenig), Holme Chapel-1 and Ironville-5 (Tremadoc – Arenig) wells showed maturities to be either in the anchizone or diagenetic zones. The results from the basal, undated interval in the Wessenden-1 well showed significant maturity enhancement with maturities reaching the epizone stage. The presence of a granite in the vicinity of the Wessenden-1 well may explain this higher maturity measurement. The age of the basal section in the well is unknown, although the BGS suggest a Precambrian?-Cambrian date (Aitkenhead, et al., 2002). This age would suggest a significantly older subcrop than the neighbouring wells (possibly reflecting doming over the intrusion). The absence of a significant temperature anomaly in the Wessenden-1 well may suggest that the granite is of Late Ordovician age (like the Wensleydale Granite (Pashley, et al., 2021)) rather than the Devonian age of the Weardale and Skiddaw granites which are characterised by a high heatflow (Aitkenhead, et al., 2002; Busby, et al., 2011).

In a study on the gravity field of Southwest England, Bott et al. (1958) proposed that large, low-density and rigid granite batholiths have a stabilizing effect on tectonics by seeking to achieve and then maintaining isostatic equilibrium, especially during phases of extensional tectonics. This concept has been supported and refined in numerous subsequent investigations (Bott, 1967; Bott, et al., 1978; Allsop, 1987; Evans & Allsop, 1987; Donato & Megson, 1990; Donato, 2019). Howell et al. (2019) modelled the influence of granite blocks, suggesting an initial lithospheric flexural bulge often followed by more localized and faulted uplift. This occurs as the granite blocks strive for a more Airy-like isostatic equilibrium during subsequent extensional tectonism. Basin depocenters, particularly those associated with periods of extensional subsidence, are generally considered to occur away from, or on the periphery of, granite-cored stable platform areas (Bott, 1967). Pre-existing faults are thought to play a significant role in determining the specific locations and orientations of peripheral basin sedimentary accumulations (Howell, et al., 2019).

It is of interest to compare this general model for the possible tectonic influence of granite plutons to the proposed Holme Granite within the vicinity of the Holme High. Figure 11 shows the Dinantian (Visean and Tournaisian) time isochore illustrating the structural development during the extensional phases of the early Carboniferous. This is the period when the model would predict the granite to be active in influencing structural development. Two residual gravity contour lines at -3 and -5 mGal provide an approximate indication of the possible location of the granite mass. The granite is not positioned directly beneath the Holme High, as might be predicted by the general granite tectonic model, but is offset to lie beneath the northern edge of the high, extending beneath the southern flank of the Huddersfield Basin. Consequently, the granite tectonic concept appears not to be directly applicable in this instance and this is discussed further below. There is some uncertainty, however, regarding the structure of the Huddersfield Basin since, as shown in Figure 9, there is no seismic coverage in this area and consequently basin structure and associated gravity modelling will be uncertain.

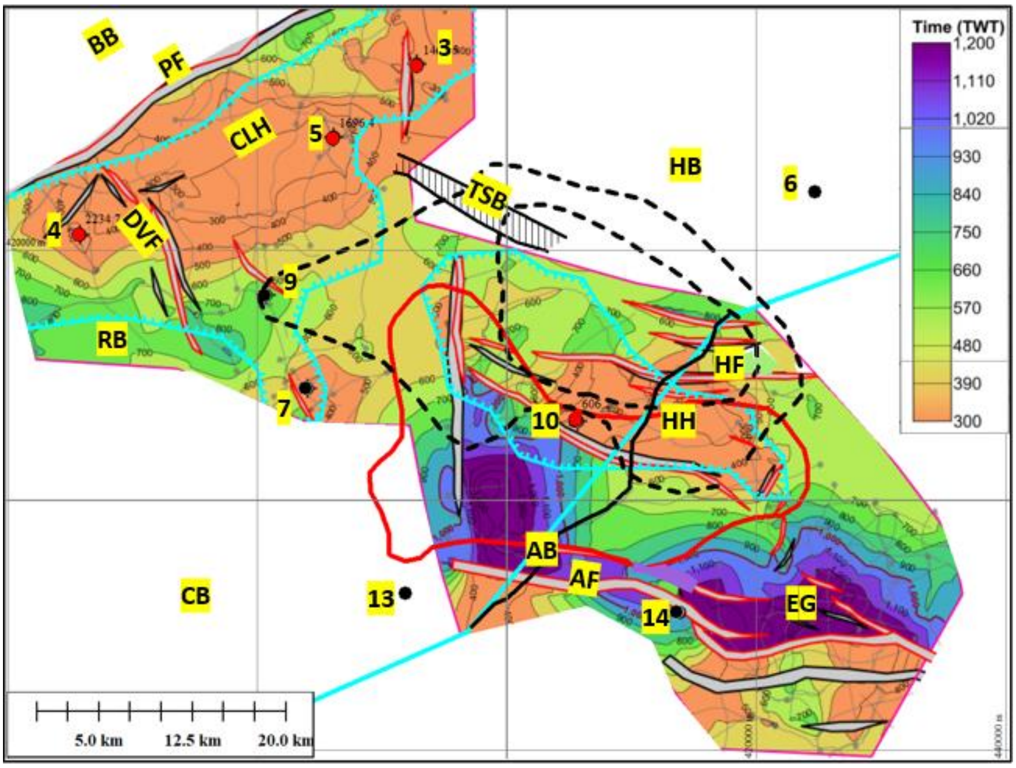


Figure 11 *Map showing the Dinantian (Visean and Tournaisian) time isochore with contour interval of 100ms TWT. Thinner areas are shaded orange with thicker areas shaded blue. Interpreted faults at Base Namurian and Base Carboniferous levels are both added to the map and are shown by the grey polygons with black outlines (Dinantian) and red lines (Base Carboniferous). Structural features are labelled as follows:- AB – Alport Basin, AF – Alport Fault, BB – Bowland Basin, CB – Cheshire Basin, CLH – Central Lancashire High, DVF – Darwen Valley Fault, EG – Edale Gulf, HB – Huddersfield Basin, HH – Holme High, HF – Holme Fault, PF – Pendle Fault and TSB – Todmorden Smash Belt. Well locations are shown by black dots and are numbered as in Figure 2. Red dots show those wells reaching the pre-Carboniferous. Two areas of platform carbonates are shown by the cyan polygons, one over the Holme High and one over the Central Lancashire High. The two black dashed outlines show the -3 mGal and -5 mGal residual gravity contours indicating the approximate location of the Holme Granite. The red polygon shows the location of the positive magnetic anomaly located over the southern flank of the proposed Holme Granite.*

The approximate size and mass deficit of the granites may be estimated from the dimensions and amplitude of the associated negative gravity anomaly. The largest gravity anomaly in this area is related to the Weardale Granite, approximately 30 km by 60 km, and Bott (1967) estimated a mass deficit for this pluton of approximately $5.0 * 10^{14}$ kg. By way of comparison, the much smaller residual gravity anomaly associated with the Holme Granite, approximately 15 km by 30 km, produces a mass deficit estimate of approximately $1.0 * 10^{14}$ kg. These estimates are likely to be minimum values and will be very approximate as the local regional gravity field is difficult to define with accuracy. Isostatic uplift potential and any associated tectonic stabilising effects will be proportional to the magnitude and dimensions of the granite block and its mass deficit. For example, assuming a flexural rigidity of

1.0E+21 Nm^2, the Weardale Granite will produce a flexural uplift over four times greater than that for the Holme Granite. As the granites approach Airy isostacy, this difference will reduce but the Holme Granite is buried beneath several kilometres of overburden so it may be difficult for Airy isostacy to be attained. Consequently, the smaller Holme Granite may only have been able to offer a reduced isostatic influence compared to that for other much larger granites such as that at Weardale. The reduced isostatic effect may explain the lack of a direct correspondence between the location of the granite and the structural high. An analogous situation appears to occur between the similarly-sized Bingham Granite and the northern edge of the Widmerpool Gulf (Figure 8(b)). Bott et al. (1978), in discussing the Market Weighton Granite, noticed a similar offset in the spatial relationship between the Market Weighton Granite and the associated Jurassic-aged stable block. This was explained by tilting of the block influenced by the granite buoyancy but utilising movements along pre-existing faults located away from the granite's margin. The same may be true for the Holme and Bingham Granites.

Following the syn-extensional phase during the early Carboniferous, the Pennine area underwent a wide regional subsidence with minor associated faulting. This period of post-rifting thermal relaxation (McKenzie, 1978) lasted from the mid-Brigantian to the Westphalian (Fraser & Gawthorpe, 1990) although an episode of transpression has been suggested during Westphalian B times (Howell, et al., 2021). Previous workers have shown that Lower Carboniferous Limestone development occurs over structural highs with shales developed in basinal areas. This work also shows that the structural highs reflect the influence of granites with many of the highs being bounded by fault zones.

The Central Lancashire High and Holme High both demonstrate the presence of shallow water Lower Carboniferous platform carbonates in the overlying section. No evidence of a granite has been recognised in the Central Lancashire High, although it is bounded to the north by the prominent Pendle Fault. Both of these features lie on the Burnley Stamford Magnetic Anomaly. This anomaly is bounded by a series of deformation/fault zones, including the Todmorden Smash Belt to the north-east, the Pendle Fault to the northwest and the Derwen Valley Faults to the southwest (Figures 8(b) and 11). These fault/deformation zones are the most significant within the local area (Wright et al. (1927)). The northwest-southeast trending Burnley Stamford Anomaly clearly has an Acadian phase of development although an earlier origin is very likely, probably Precambrian. The presence of this early structural trend may have influenced the emplacement locations of the Holme and Bingham Granites although the distribution of other granites in the local area do not follow the same orientation (Figure 8(b)).

In detail the Central Lancashire High and Holme High show a contrasting tectonic history. The Roddlesworth-1 well, located on the Central Lancashire High, shows Brigantian limestones overlain unconformably by Pendleian Upper Bowland Shales, with no significant time break. The Wessenden-1 well however, located on the Holme High, has carbonates of possible Asbian age beneath Kinderscoutian Edale Shales, indicating a 10–15 million year time break (Evans & Kirby, 1999). Consequently, the Holme High appears as a more prominent and longer-lived feature than the Central Lancashire High. This difference may reflect their different origins with the buried granite beneath the Holme High perhaps contributing to the creation of a more persistent stable high compared to the Central Lancashire High with no similar granite root. The Central Lancashire High was formed as an uplifted footwall fault block associated with extensional movements of the Pendle Fault, albeit periodically reactivated over time

Later, during the late Carboniferous to early Permian times, the area underwent NW-SE directed Variscan compression (Corfield, et al., 1996) and this led to reactivation of the basin bounding faults, with inversion seen along many of them. Locally, these movements are believed to be associated with a sinistral offset along the line of the Todmorden Smash Belt (Evans, et al., 2002). On this basis, the Burnley Stamford Magnetic Anomaly would underlie the compound basement block, including the Holme High, with the granite perhaps providing an additional element of tectonic rigidity and stability. It is a highly speculative suggestion, but it may be that the Holme Granite acted as a buttress to the north-westerly directed Variscan compression. In this way, sinistral movements occurred over the north-eastern flank of the rigid granite along the line of the Todmorden Smash Belt. In a similar way, dextral movements occurred along the south-western side of the granite block along the line of the Derwen Valley Faults. The Holme Granite, therefore, may have acted as a buttress allowing sinistral and dextral offsets on the northeastern and southwestern flanks respectively. In a similar way, Critchley (1984) suggests that the Weardale Granite intrusion of the Alston Block provided a rigid resistance to Variscan compressional movements.

Conclusions

Gravity modelling studies based upon mapped geological structure, revealed by seismic interpretations and well ties, have identified a residual gravity low with an amplitude of up to 12 mGal and dimensions of approximately 40 km by 30 km. This residual gravity low is interpreted as confirming the suggestion made by Donato & Pullan (2022) that it is related to a buried granite mass, the Holme Granite.

The initial emplacement location for the Holme Granite may have been influenced by faulting associated with the earlier basement structure related to the Burnley-Stratford Magnetic Anomaly. Subsequently, the tectonic influence of the granite may have reactivated the earlier faulting allowing a possible influence on the structural development during the early Carboniferous extensional tectonism.

The proposed granite is of small size when compared to some other granites within the area. The residual gravity low is located primarily over the northeastern flank of the Holme High formed during the early Carboniferous. It is suggested that the granite's small size may have limited its ability to provide a strong vertical isostatic tectonic control as seen for larger granites. Nevertheless, it may have exhibited horizontal structural control including the speculative possibility of it acting as a rigid buttress to Variscan north-westerly directed compression.

The presence of enhanced maturity of the pre-Upper Paleozoic sequence seen in the Wessenden-1 well may be related to the location of the underlying Holme Granite.

Acknowledgements

Doug Holiday, Ian Chisholm and Malcolm Butler kindly provided material, thoughts and helpful comments that greatly improved the content of the paper. Kostas Dimitropoulos is thanked for providing his 3D gravity modelling software. The British Geological Survey (BGS) kindly allowed access to their 2.5D grav/mag modelling software. SEGY seismic data and well log material were generously provided by the UK Onshore Geophysical Library (UKOGL). In an early phase of the seismic interpretation, Merlin Energy Resources Ltd. allowed access to their Kingdom workstation. We are very grateful to DUG Technology Ltd for providing the DUG Insight software (v.5.1, 2024) which was used to undertake the bulk of the seismic visualisation, interpretation and analysis. We would like to thank Peter Browning-Stamp for his assistance with initially setting up the DUG interpretation project.

References

Aitkenhead, N. et al., 2002. *British regional geology: the Pennines and adjacent areas (Fourth edition),* London: HMSO for British Geological Survey.

Allsop, J. M., 1987. Patterns of late Caledonian intrusive activity in eastern and northern England from geophysics, radiometric dating and basement geology. *Proceedings of the Yorkshire Geological Society,* Volume 46, pp. 335-353.

Amoco, 1991. *EXL011 Lancashire Technical Evaluation.* [Online]
Available at: https://ukogl.org.uk/map/php/seismic-interpretations.php?line=10872
[Accessed 1 3 2024].

Andrews, I. J., 2013. *The Carboniferous Bowland Shale gas study: geology and resource estimation,* London: British Geological Survey for Department of Energy and Climate Change.

Aurora, 2014. *14th Round Licence Application Rossendale Basin.* [Online]
Available at: https://ukogl.org.uk/map/php/seismic-interpretations.php?line=10872
[Accessed 1 03 2024].

Beamish, D., Kimbell, G. & Pharaoh, T., 2016. The deep crustal magnetic structure of Britain. *Proceedings of the Geologists' Association,* Volume 127, pp. 647-663.

Bott, M. H. P., 1961. Geological interpretation of magnetic anomalies over the Askrigg Block. *Quartely Journal of the Geological Society of London,* Volume 117, pp. 491-493.

Bott, M. H. P., 1967. Geophysical investigations of the Northern Pennine basement rocks. *Proceedings of the Yorkshire Geological Society,* Volume 36, pp. 139-168.

Bott, M. H. P., Day, A. A. & Masson-Smith, D., 1958. The Geological Interpretation of Gravity and Magnetic Surveys in Devon and Cornwall. *Series A. Mathematical and Physical Sciences,* 251(992), pp. 161-191.

Bott, M. H. P., Robinson, J. & Kohnstamm, M. A., 1978. Granite beneath Market Weighton, east Yorkshire. *Journal of the Geological Society (London),* Volume 135, pp. 535-543.

Busby, J., Kingdon, A. & Williams, J., 2011. The measured shallow temperature field in Britain. *Quarterly Journal of Engineering Geology and Hydrogeology,* Volume 44, p. 373–387.

Chacksfield, B. C. & Edwards, J. W. F., 2006. *1:1 000 000 UTM Series Gravity Anomaly Maps.* Nottingham: British Geological Survey.

Chacksfield, B. C., Edwards, J. W. F. & Royles, C. P., 2006. *1: 1 000 000 UTM Series: Magnetic Anomaly Maps,* Keyworth, Nottingham: British Geological Survey.

Chadwick, R. A. & Evans, D. J., 2005. *A seismic atlas of southern Britain : images of subsurface structure.* Occasional Publication 7 196pp ed. Nottingham: British Geological Survey.

Corfield, S. M. et al., 1996. Inversion tectonics of the Variscan Foreland of the British Isles. *Journal of the Geological Society, London,* Volume 153, pp. 17-32.

Cornwell, J. D. & Walker, A. S. D., 1989. Regional Geophysics. In: J. A. Plant & D. G. Jones, eds. *Metallogenic models and exploration criteria for buried carbonate-hosted ore deposits : a multidisciplinary study in eastern England.* Keyworth Nottingham: Institute of Mining Metallurgy, pp. 25-51.

Critchley, M. F., 1984. Variscan tectonics of the Alston block, northern England. *Geol. Soc. Special Pubs.,* Volume 14, pp. 139-146.

Donato, J. A., 2019. *Gravity modelling across two postulated granite batholiths within the UK onshore East Midlands Shelf.* [Online]
Available at: https://ukogl.org.uk/beneath-britain/100-Gpdf

Donato, J. A. & Megson, J. B., 1990. A buried granite batholith beneath the East Midland Shelf of the Southern North Sea. *Journal of the Geological Society of London,* Volume 147, pp. 133-140.

Donato, J. A. & Pullan, C. J., In Preparation. *A gravity and magnetic characterisation of the UK Midlands Platform.* [Online]
Available at: UKOGL

Donato, J. A. & Pullan, C. P., 2022. *The deep structure of England from gravity and magnetic profiling.* [Online]
Available at: https://ukogl.org.uk/beneath-britain/400-Dpdf

Donato, J. A., Pullan, C. P. & Dimitropoulos, K., 2024. *Moho structure beneath England and the regional gravity background field.* [Online]
Available at: https://ukogl.org.uk/beneath-britain/500-Mpdf

DUG, 2024. *DUG Insight (version 5.1). Windows/Linux/Mac.,* Perth, Western Australia: DUG Technology Ltd.

Dunham, K. C., 1974. Granite beneath the Pennines in North Yorkshire. *Proc. Yorkshire Geol. Soc,* Volume 40, pp. 191-194.

Dunham, K. C., Dunham, B. L., Hodge, B. L. & Johnson, G. A. L., 1965. Granite beneath Visean sediments with mineralisation at Rookhope. *Q. Jl. geol. Soc. Lond.,* Volume 121, pp. 386-417.

Edinburgh, 1988. *2nd Round Licence Application Bleaklow Derbyshire.* [Online]
Available at: https://ukogl.org.uk/map/php/seismic-interpretations.php?line=13741
[Accessed 1 03 2024].

Evans, A. M. & Maroof, S. I., 1976. Basement controls on mineralisation in the British Isles. *Mining Magazine,* Volume 134, pp. 401-411.

Evans, C. J. & Allsop, J. M., 1987. Some geophysical aspects of the deep geology of eastern England. *Proceedings of the Yorkshire Geological Society,* 46(4), pp. 321-333.

Evans, D. J. & Kirby, G. A., 1999. The architecture of concealed Dinantian carbonate sequences over the Central Lancashire and Holme highs, northern England. *Proceedings of the Yorkshire Geological Society,* 52(3), pp. 297-312.

Evans, D. J., Walker, A. S. D. & Chadwick, R. A., 2002. The Pennine Anticline, northern England - a continuing enigma?. *Proceedings of the Yorkshire Geological Society,* 54(1), pp. 17-34.

FINA, 1987. *Second Round Licence Application for conversion of XL184b - Report D79,* s.l.: UKOGL .

Fraser, A. J. & Gawthorpe, R. L., 1990. *Tectono-stratigraphic development and hydrocarbon habitat of the Carboniferous in northern England.* Special Publication No 55, pp49-86 ed. London: Geological Society of London.

Fraser, A. J. & Gawthorpe, R. L., 2003. *An Atlas of Carboniferous Basin Evolution in Northern England.* Volume 28 ed. London: Geological Society.

Fraser, A. J., Lodhia, B. H. & Sims, M. J. E., 2024. A review of the Carboniferous shale gas potential of northern England: a data-based analysis of why it won't work. *From: Emmings, J.F., Parnell, J., Stephenson, M. H. and Lodhia, B. H. (eds). The Bowland Shale Formation, UK: Processess and Resources, Geological Society of London, Special Publications,* Volume 534, pp. 19-38.

Gawthorpe, R. L., Gutteridge, P. & Leeder, M. R., 1989. Late Devonian and Dinantian basin evolution in northern England and North Wales. *Yorkshire Geological Society,* Occasional Publications(6), pp. 1-23.

Green, P. F., Westaway, R., Manning, D. A. C. & Younger, P. L., 2012. Cenozoic cooling and denudation in the North Pennines(northern England, UK) constrained by apatite fission-track analysis of cuttings from the Eastgate Borehole. *Proceedings of the Geologists Association,* 123(3), pp. 450-463.

Holliday, D. W., 1993. Mesozoic cover over northern England: interpretation of apatite fission track data. *Journal of the Geological Society,* Volume 150, pp. 657-660.

Howell, L. et al., 2021. Seismic and borehole-based mapping of the late Carboniferous succession in the Canonbie Coalfield, SW Scotland: evidence for a 'broken' Variscan foreland?. *Scotish Journal of Geology,* Volume 57, pp. 1-18.

Howell, L., Egan, S., Leslie, G. & Clarke, S., 2019. Structural and geodynamic modelling of the influence of granite bodies during lithospheric extension: Application to the Carboniferous basins of northern England. *Tectonophysics,* Volume 179, pp. 47-63.

Howell, L. P. et al., 2021. 'Block and basin' style rift basins: sedimentological insights from the Mississippian Fell Sandstone Formation. *Journal of the Geological Society,* 179(4), pp. jgs2021-083.

Johnson, G. A. L., 1967. Basement control of Carboniferous sedimentation in northern England. *Proceedings of the Yorkshire Geological Society,* Volume 36, pp. 175-194.

Johnson, G. A. L. & Nudds, J. R., 1995. Carboniferous biostratigraphy of the Rookhope Borehole, Co. Durham. *Transactions of the Royal Society of Edinburgh: Earth Sciences,* 86(3), pp. 181-226.

Kimbell, G. S., Carruthers, R. M., Walker, A. S. D. & Williamson, J. P., 2006. *Regional Geophysics of Southern Scotland and Northern England, Version 1.0 on CD-ROM,* Nottingham: British Geological Survey.

Kirby, G. A. et al., 2000. *Structure and evolution of the Craven Basin and adjacent areas, Subsurface Geology Memoir,* Keyworth, Nottinham: British Geological Survey.

Leeder, M. R., 1982. Upper Palaeozoic basins of the British Isles-Caledonide inheritance versus Hercynian plate margin processes. *J. geol. Soc. London,* Volume 139, pp. 479-491.

Lee, M. K., 1990. *Geophysical investigations in the English Lake District.* Open University: PhD Thesis.

Lee, M. K., Pharaoh, T. C. & Soper, N. J., 1990. Structural trends in central Britain from images of gravity and aeromagnetic fields. *Journal of the Geological Society, London,* Volume 147, pp. 241-258.

Manning, D. A. C. et al., 2007. A deep geothermal exploration well at Eastgate, Weardale, UK: a novel exploration concept for low-enthalpy resources. *Journal of the Geological Society,* 164(2), pp. 371-382.

McKenzie, D. P., 1978. Some remarks on the development of sedimentary basins. *Earth and planetary Science Letters,* Volume 40, pp. 25-32.

Merriman, R. J., Pharaoh, T. C., Woodcock, N. H. & Daly, P., 1993. The metamorphic history of the concealed Caledonides of eastern England and their foreland. *Geol Mag,* 130(5), pp. 613-620.

Molyneux, S., 2001. *Biostratigraphical ages and thermal maturity: Cambrian-Silurian successions in boreholes of the English Midlands and Welsh Borderland,* NERC: BGS Internal Report IR/01/065.

Pashley, V., Thomas, C. & Tapster, S., 2021. *Uranium-lead (U-Pb) dating of the Wensleydale Granite, Yorkshire Dales, UK.,* (Dataset): NERC EDS National Geoscience Data Centre.

Pearson, M. J. & Russell, M. A., 2000. Subsidence and erosion in the Pennine Carboniferous Basin, England: lithological and thermal constraints on maturity modelling. *Journal of the Geological Society,* Volume 157, pp. 471-482.

Pedley, R. C., Busby, J. P. & Dabek, Z. H., 1993. *GRAVMAG Interactive 2.5D Gravity and Magnetic Modelling.* Nottingham: British Geological Survey.

Pharaoh, T. C., Brewer, T. S. & Webb, P. C., 1993. The concealed Caledonide basement of Eastern England and the southern North Sea. *Geological Magazine,* Volume 39, pp. 330-346.

Pharaoh, T. C. et al., 2011. *Structure and evolution of the East Midlands region of the Pennine Basin,* Keyworth: Subsurface memoir of the British Geological Survey.

Phillips, J., 1836. *Illustrations of the geology of Yorkshire.* Part 2 The Mountain Limestone District ed. London: John Murray.

Quintana Petroleum, 1974. *Holme Chapel-1 Well Report,* London: DTI Release.

Rabae, A. M. & Kearey, P., 1997. Granites of the western Anglo-Brabant Massif. *Annales de la Société géologique de Belgique,* 120(2), pp. 217-226.

Saxon, 1985. *2nd Round Licence Application Central Pennines.* [Online]
Available at: https://ukogl.org.uk/map/php/seismic-interpretations.php?line=13741
[Accessed 1 03 2024].

Smith, N. J. P., Kirby, G. A. & Pharaoh, T. C., 2005. *Structure and evolution of the south-west Pennine basin & adjacent areas, Subsurface Memoir,* Keyworth, Nottingham: British Geological Survey.

Waters, C. N., Holliday, D. W. & Chisholm, J. I., 2020. The contribution of publications of the Yorkshire Geological Society to the understanding of the geological development of the Carboniferous Pennine Basin, northern England. *Proceedings of the Yorkshire Geological Society,* Volume 63, pp. 1-32.

Wills, L. J., 1978. *A Palaeogeological Map of the Lower Palaeozoic Floor below the cover of Upper Devonian, Carboniferous and Later Formations with inferred and speculative reconstructions of Lower Palaeozoic and Precambrian outcrops in adjacent areas.* London: Geological Society Memoir.

Wilson, A. A. & Cornwell, J. D., 1982. The Institute of Geological Sciences Borehole at Beckermonds Scar, North Yorkshire. *Proceedings of the Yorkshire Geological Society,* Volume 44, pp. 59-88.

Woodcock, N. H., Soper, N. J. & Miles, A. J., 2019. Age of the Acadian deformation and Devonian granites in northern England: a review. *Proceedings of the Yorkshire Geological Society,* Volume 62, pp. 238-253.

Wright, W. B. et al., 1927. *The geology of the Rossendale Anticline,* Sheet 76 (England and Wales): Memoir of the Geological Survey.