

Gravity modelling across two postulated granite batholiths within the UK onshore East Midlands Shelf

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Abstract

Six UK onshore 2D composite seismic lines have been reprocessed, interpreted and published (Butler and Jamieson, 2013). These lines provide a series of long regional seismic lines crossing England. The work described here focuses on one of these lines (UKOGL-RG-005) passing with EW orientation from the Welsh Borders to the Lincolnshire Coast. A simple polygonal 2.5D model based upon the Butler and Jamieson (2013) seismic interpretation has been created to predict the expected gravity and magnetic variations along the line. These model calculated values, when compared to the observed BGS gravity field data, indicate a significant discrepancy over the East Midlands Shelf between the Carboniferous Basins of the Gainsborough Trough and the Widmerpool Gulf. Such a difference may be explained in two possible ways. Firstly, by the presence of a thick remnant Old Red Sandstone basin. Secondly, by the existence of two adjacent, buried granite batholiths of presumed late Caledonian (Acadian) age. The first option is considered unlikely as the area of the gravity discrepancy lies within the Acadian Fold Belt with an Acadian subcrop showing little evidence for thick Lower Devonian rocks and comprising mainly older metamorphic sediments or igneous rocks. There is also no evidence on the seismic data for the presence of thick Devonian sediments within the area of the discrepancy. The second option involving the presence of buried granite batholiths is preferred. One of the two granites, the Newark Granite, has been proposed before but the other granite, here called the Bingham Granite, has not been previously recognised. Their locations may have contributed to the early Carboniferous tectonic stability of this part of the East Midlands Shelf.

Introduction

Gravity modelling has been undertaken along composite seismic line UKOGL-RG-005. The location of the line is shown within Figure 1 together with the British Geological Survey (BGS) solid geology mapping. Detailed images and description of the seismic line, the associated well ties and the full seismic interpretation are available (Butler and Jamieson, 2013, and on the United Kingdom Onshore Geophysical Library (UKOGL) website, www.ukogl.org.uk). The line passes with EW orientation across central Britain starting on the outcropping Permian rocks and then passing eastwards over the Triassic rocks, thickly preserved within the Cheshire Basin. It heads further eastwards, passing to the south of the Derbyshire Dome, and then crosses over the Carboniferous Basin of the Widmerpool Gulf before heading north-eastwards over the East Midland Shelf. Continuing to the north-east, the line passes onto the easterly-dipping Triassic and Jurassic outcrops before terminating on the North Sea coast at Sutton-on-Sea on Cretaceous Chalk outcrop. To the west of the eastern margin of the Derbyshire Dome, line UKOGL-RG-005 is interpreted as having a gently deformed sequence of Cambrian to Lower Devonian rocks beneath the Acadian Unconformity. To the east, no recognisable events relating to rocks of these ages can be mapped. This change is taken as the boundary of the Acadian Fold Belt.

The main area of interest for this study is the central area of the line between the Widmerpool and Gainsborough Carboniferous Basins. An additional line, 'AB', has been constructed and modelled across these two basins. The locations of both lines are shown within Figure 1.

Gravity and magnetic data published by the BGS (BGS, 1998) and downloaded from the BGS website (www.bgs.ac.uk) have been used for the evaluation. A contoured Bouguer Anomaly Map is shown within Figure 2 covering the identical area to Figure 1. Thick Carboniferous sediments within the Gainsborough Trough and Widmerpool Gulf are represented on the gravity data by two WNW-ESE trending gravity lows (white lines). Between these gravity features are two en-echelon lows (red lines), both with approximately N-S trend. Line UKOGL-RG-005 crosses the southerly of these lows and the additional profile, 'AB', passes with NNE-SSW trend approximately across the centre of both lows. Numerous other gravity lows shown on the map are thought to be associated with the existence of buried granite batholiths. To the north-east, lows are situated over the Market Weighton Granite (Bott et al, 1978) and Hornsea Granite (Donato and Megson, 1990). To the south-east, four smaller, adjacent lows are associated with the proposed Wash Granites (Allsop, 1987). At the southern limit of the map, the northern edge of the proposed Hollowell Granite (Allsop et al, 1987) is also shown. To the west, a significant NNE-SSW trending gravity low is formed by the thick Triassic sediments within the Cheshire Basin.

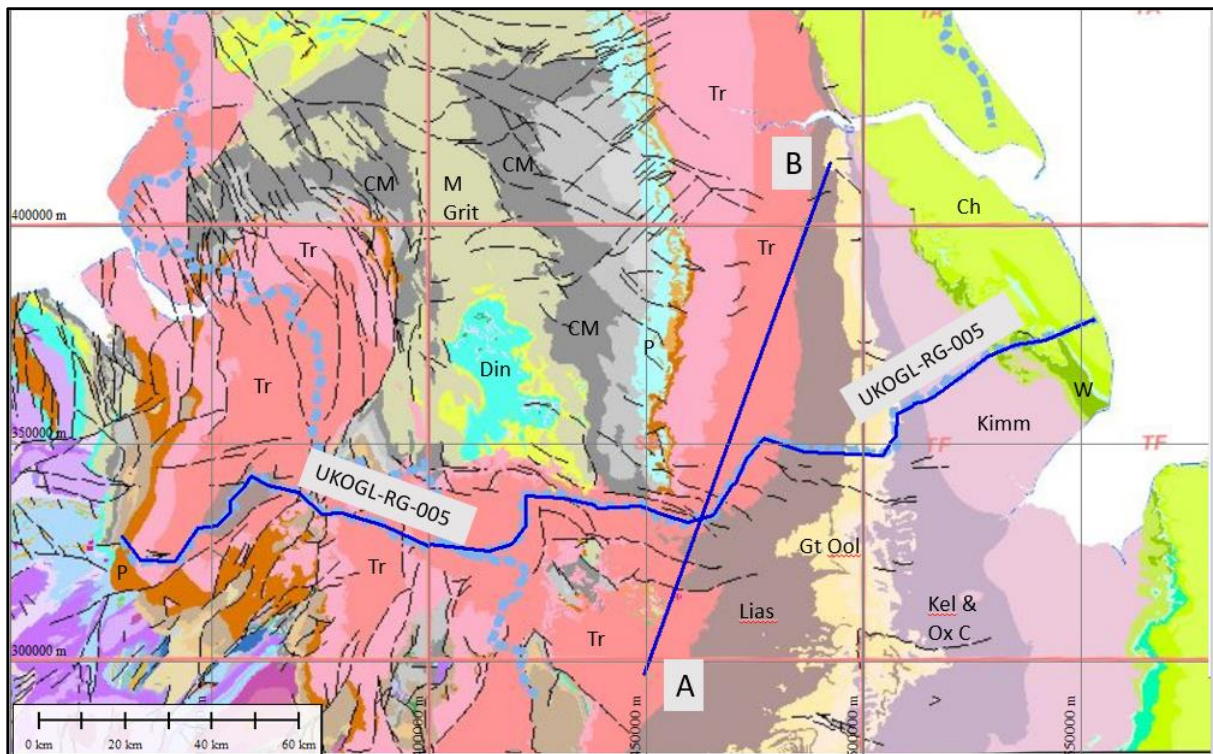


Figure 1 British Geological Survey Solid Geology from UKOGL website (www.ukogl.org.uk). The locations of the two profiles illustrated in Figure 3 (UKOGL-RG-005) and Figure 4 ('AB') are also shown. Labelled geological outcrops are simplified and abbreviated as follows:- Ch-Chalk, Kimm - includes Kimmeridge Clay, Kel & Ox C – Kellaways and Oxford Clay, Gt Ool – Great and Inferior Oolites, Lias – Lias, Tr – Triassic (undifferentiated), P – Permian, CM – Coal Measures, M Grit – Millstone Grit, Din – Dinantian.

Gravity and Magnetic Models

It is important to be aware that the model created here based upon line UKOGL-RG-005 is slightly unusual in its construction and consequently has limitations. The profile is not a straight line and the gravity and magnetic data have been extracted along the slightly irregular path of the composite seismic traverse. Polygonal features incorporated into the structural model are not generally orthogonal (nor symmetric) to the model 'line'. Detailed agreement between observed and calculated gravity and magnetic values cannot therefore be expected. For the gravity data, it is estimated that agreement to within 2-3 mGal is acceptable. Differences of greater than 5 mGal merit further consideration and may suggest the influence of additional sources not revealed by the seismically-derived sedimentary structure. In summary therefore, the UKOGL-RG-005 model should be considered as approximate and preliminary and has been used mainly as a method to highlight areas where additional features, other than those shown on the seismic data, may be required to explain more fully the observed gravity anomalies.

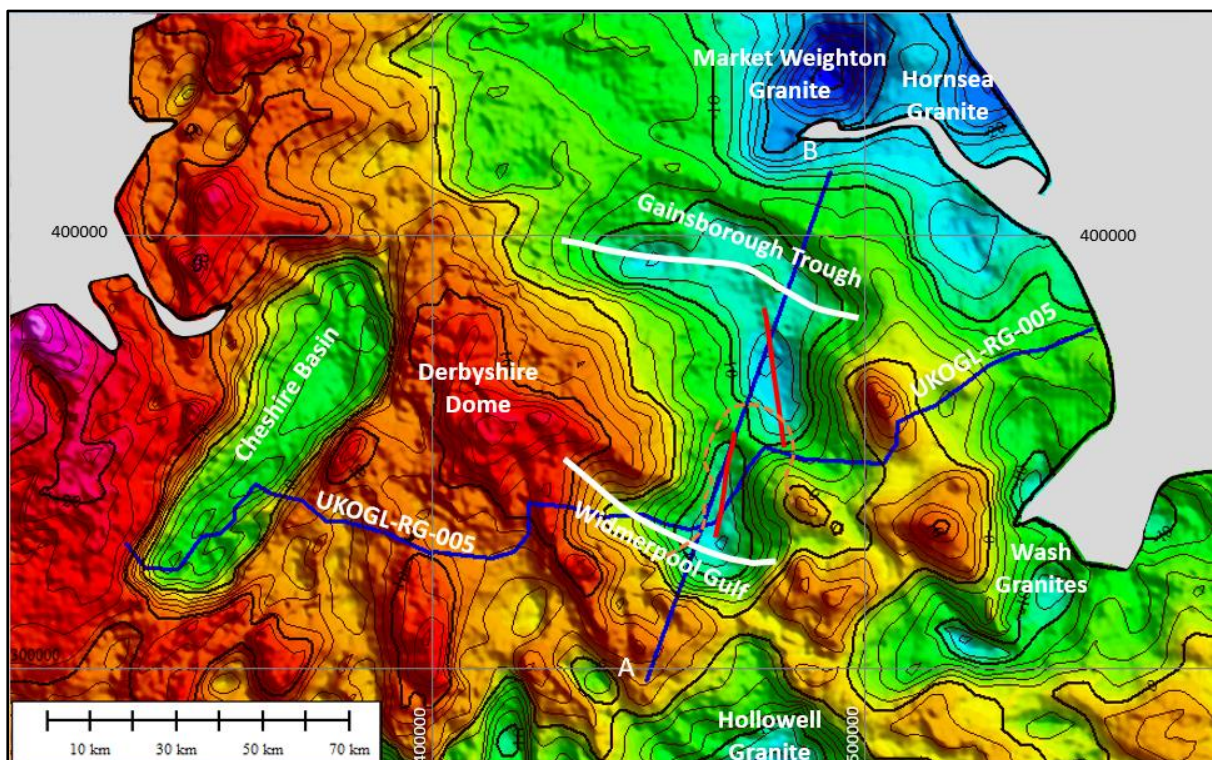


Figure 2 Bouguer Anomaly Gravity Map shown in shaded relief. Low gravity areas are coloured blue and high gravity areas yellow and red. 2mGal contour lines have been superimposed. The locations of the two profiles (UKOGL-RG-005 and 'AB') illustrated in Figures 3 and 4 are also shown. The Gainsborough Trough and Widmerpool Gulf Carboniferous Basins are associated with WNW-ESE gravity lows, highlighted by the two white lines. Between these two basins, two N-S trending gravity lows (red lines) form the focus area for this study. Carboniferous sills (Falcon and Kent, 1960) occur mainly to the south of the thin orange dashed line.

Additional uncertainty arises in association with the assumed rock layer density data. Density values used here are based upon measurements described in Maroof (1975), Rollin (1978), Allsop (1987), Arter (1982) and Busby et al (2006). A background basement density of 2.72 gm/cc has been assumed. Density values will be dependent on several factors associated with, for example, lithological changes within individual rock sequences and the magnitude and extent of phases of uplift. For the Dinantian section, density values will vary laterally, with limestone platform sequences having slightly greater

density than deeper, more argillaceous, basin sections. However, to retain model simplicity, a single average value has been assumed here for the complete Dinantian sequence. If a slightly higher density were to be assumed for local areas of limestone facies, the residual gravity anomaly discussed below would increase slightly in magnitude. Consequently, this simplification is not thought to result in any significant change to the general conclusions described below.

The results of the 2.5D gravity and magnetic model along line UKOG-RG-005 are shown within Figure 3. The polygonal model (c) is based upon the horizons interpreted by Butler and Jamieson (2013). Their horizon time picks have been converted to depth using a mean of the two depth scales provided by them on the western and eastern ends of the seismic section. A simple depth conversion method, such as this, is considered adequate for the modelling undertaken in this study.

Calculated model gravity values (blue dashed curve) are compared to the BGS observed values within Figure 3 (b). Agreement is acceptable along the profile apart from the section between 140 and 220km. Here, the calculated gravity values are too high by as much as 18 mGal. A difference of this magnitude is significantly outside the expected errors of the modelling method and requires explanation. When the additional gravity effect of two postulated granite blocks shown in the figure are included (red dashed curve), agreement is considerably improved. Consequently, it is suggested that the two NS trending gravity lows shown in Figure 2 (red lines) may be caused by two adjacent granite batholiths. The profile of Figure 3 passes centrally over the southerly gravity low, here attributed to the Bingham Granite, and over the southern flank of the northerly gravity low, the Newark Granite (Allsop, 1987). The two gravity lows merge together suggesting only limited separation between the two proposed granite masses. The northern and southern boundaries of the two gravity lows also merge smoothly with the WNW-ESE gravity anomalies associated with the thick sediments within the Gainsborough and Widmerpool Basins. It would appear, therefore, that the gravity effect of the two basins is similar in magnitude to the gravity effect of the granites resulting in no clear gravity differentiation of the boundary between the granites and basins (Figures 3 and 4). However, the extent of both basins is well controlled by existing seismic data (Andrews, 2013).

Part (a) of Figure 3 provides the observed magnetic profile along the line. The magnetic features of the area are complex with many anomalies associated with the various intruded and extruded Carboniferous volcanic rocks. Consequently, no detailed magnetic modelling has been undertaken. However, a simple illustrative sill model has been included, with sills constrained to occur within the area indicated by Falcon and Kent (1960) and Pharaoh et al (2011).

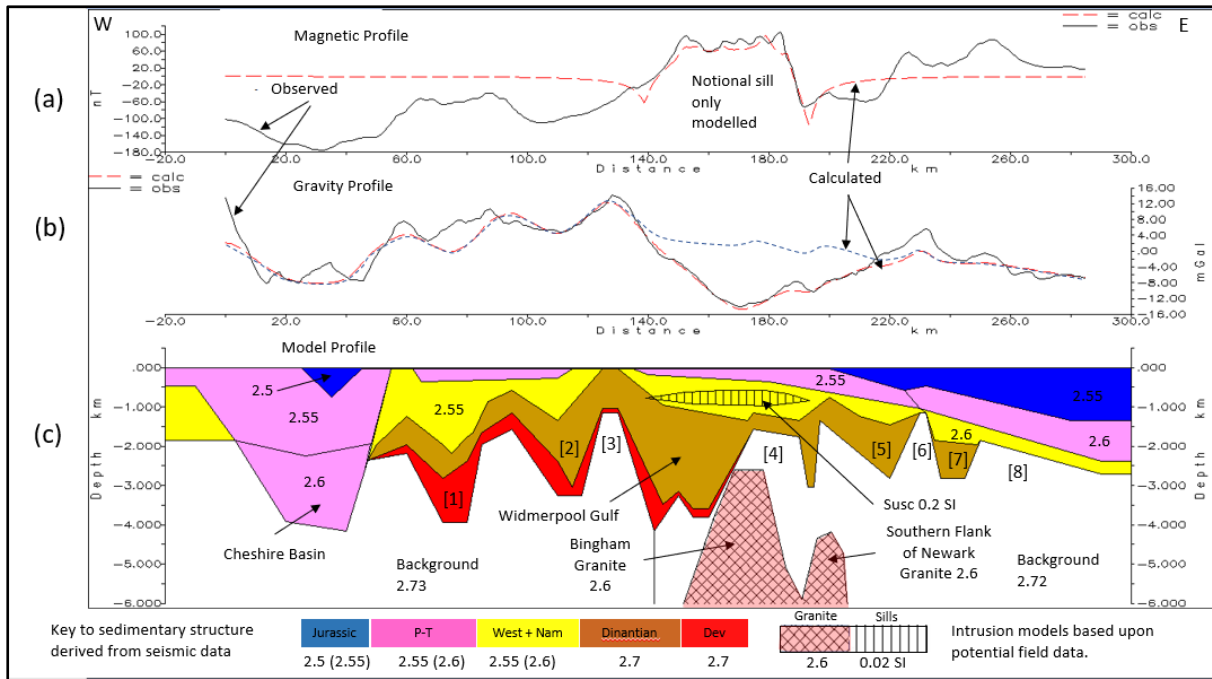


Figure 3 Polygonal Model (c) along line UKOGL-RG-005 (see Figures 1 and 2 for location). The modelling has been undertaken using the BGS GRAVMAG software (Pedley et al, 1993). The model is based upon the interpretation of line UKOGL-RG-005. Features identified by number are as follows:- [1]-Stafford Basin, [2]-Needwood Basin, [3]-Derbyshire Dome, [4]-Nottingham Platform, [5]-Sleaford Half-Graben, [6]-Nocton High, [7]-Coningsby Half-Graben and [8]-Stixwold High. There are two calculated gravity profiles in (b). The blue dotted profile is calculated using only the sedimentary structure as defined on the seismic line interpretation. The red dotted profile also includes the gravity effect of the two postulated granite blocks. The calculated magnetic curve in (a) is based solely on the estimated magnetic effect of sills intruded within the Carboniferous succession. A regional gravity background has been assumed along the 280km profile with values from W to E varying from 14 to 10 mGal. To the west of 140km, the background density of 2.72 g/cc has been raised slightly to 2.73 g/cc, suggesting a slight increase in basement density associated with the Midlands Microcraton.

To consider a profile more centrally located through both gravity lows, an additional profile, 'AB', with NNE-SSW orientation, was created (Figure 4). Profile 'AB' is more conventional in its construction, being a straight-line model. Nevertheless, the limitations of 2.5D modelling apply, especially when, as for the gravity lows here, observed anomalies are more circular in nature. Horizons were extracted from the published depth maps of Pharaoh et al (2011). These depth surfaces enabled the construction of the sedimentary structure along profile 'AB' as shown within Figure 4(c).

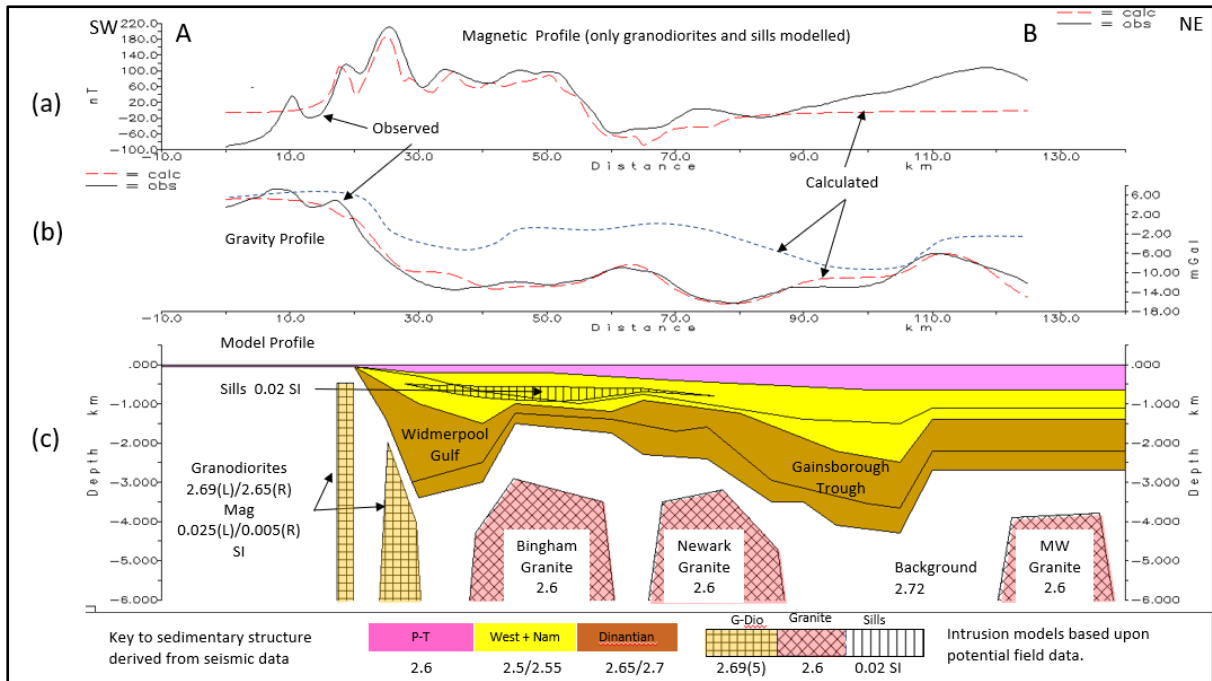


Figure 4 Polygonal Model (c) along line 'AB' (see Figures 1 and 2 for location). The sedimentary structure model is based upon the BGS depth structure maps provided in Pharaoh et al (2011). The Dinantian section is divided into upper (Visean) and lower (Tournaisian) polygons. There are two calculated gravity profiles in (b). The blue dotted profile is calculated using only the sedimentary structure as defined by the BGS interpretation. The red dotted profile also includes the gravity effect of the two postulated granite blocks (Bingham and Newark) and the Market Weighton Granite located just off the northern end of the profile. Also included in the red curves in both (a) and (b) are the gravity and magnetic effects of the two granodiorite blocks and the sills intruded within the Carboniferous sediments. A regional gravity background has been assumed along the 125km profile with values from SW to NE varying from 7 to 10 mGal.

Calculated model gravity values (blue dashed curve) are compared to observed values within Figure 4 (b). Using a similar background value as for the UKOGL-RG-005 profile, a significant residual anomaly occurs along the profile between 20 and 90km. When the additional gravity effect of the postulated Newark and Bingham Granite blocks is included (red dashed curve), closer agreement to the observed values is achieved. The observed gravity values dip at the north-eastern end of the profile. This is thought to be due to the profile approaching the location of the Market Weighton Granite. Consequently, a very simple polygon has been included at the end of the profile to simulate this reduction in gravity values.

Part (a) of Figure 4 provides the complex magnetic profile along the line. As for profile UKOGL-RG-005, simple illustrative magnetic models have been included. The southern end of profile 'AB' crosses a NW-SE trend of positive magnetic anomalies thought to be associated with the presence of granodiorites (Lee et al, 1991). Allsop (1987) has modelled a magnetic profile across a granodiorite (proven in the Kirby Lane borehole) near Melton Mowbray. Using similar parameters, two granodiorite blocks have been added to the southern end of profile 'AB'. In addition, and as for profile UKOGL-RG-005, notional sills intruded into the Carboniferous sediments have also been included. The magnetic modelling is not considered to be an accurate representation of magnetic bodies in the subsurface but merely to be illustrative of the types of feature possibly related to the observed anomalies. Granites, such as those proposed at Bingham and Newark, appear to be generally non-magnetic but occasionally

have weak peripheral magnetic anomalies (as seen for some of the Wash Granites) presumably caused by the slight magnetic contrast between the non-magnetic granite and the surrounding bedrock.

Discussion

Bott et al (1958), in a study of the gravity field of SW England, proposed a tectonic stabilising and isostatic buoyancy effect to be associated with large, low density granite batholiths. Since then, numerous studies have provided support and refinements to this general concept. Notably, and within the broad area of this study, interpretations of the Weardale and Wensleydale Granites (Bott, 1987; Howell et al, 2019), the Market Weighton Granite (Bott et al, 1978), the Hornsea Granite (Donato and Megson, 1990), the Cleaver Bank Granites (Donato, 1993), the Reading Granites (Rabae et al, 1997) and the Central North Sea area (Milton-Worsell et al 2010) have played a part in relating areas of platform stability to the locations of large granite masses. Howell et al (2019) have modelled the influence of granite blocks in terms of an initial lithospheric flexural bulge followed by a more local uplift as the granite blocks seek to achieve a more Airy-like isostatic equilibrium during subsequent extensional tectonism. Basin depocenters, especially those associated with periods of extensional subsidence, are considered to occur generally away from, or on the periphery of, granite-cored stable platform areas. Faults existing prior to extensional phases are thought to play an important role in defining the detailed locations and orientations of the peripheral basin sedimentary accumulations. Smaller granite masses have a greatly reduced initial flexural bulge. However, the mass deficit associated with both large and small granites may influence peripheral basin locations during any subsequent extensional phase, with faulting allowing closer approach to Airy isostasy.

In line with these suggestions, an interpretation is proposed here in terms of two adjacent buried granite batholiths (the Newark and Bingham Granites) associated with the two N-S trending gravity lows located between the Widmerpool and Gainsborough Basins (Figure 2). Figure 5 provides a summary of various proposed granite batholith locations (Bott et al, 1978; Allsop, 1987; Allsop et al, 1987; Donato and Megson, 1990) together with a simplified Dinantian structural framework (after Fraser and Gawthorpe, 1990 and Pharaoh et al, 2011). The proposed Newark and Bingham Granites are located within the Midland Platform between the Gainsborough and Widmerpool Carboniferous Basins. The Edale Gulf is located to the west with the Sleaford and Conningsby sub-basins located to the east. As discussed above, the two granites may have contributed to the stability of this part of the East Midlands Shelf particularly during early Carboniferous phases of extensional subsidence. The Gainsborough and Widmerpool Basins are both of half-graben form, each being tilted away from the granite-supported central shelf area (see Figure 4). A basement structural high, the Nocton High, is offset to the east of the Newark Granite. The Foston-Boston basement ridge is offset to the east of the Bingham Granite with the location of this ridge perhaps influenced by the location of the Wash Granite Batholith to the southeast.

It is possible to estimate the mass deficit of individual granite masses by integrating the associated gravity anomaly. In this way, and for example, Bott et al (1958) calculated a mass deficit of $11.5 * 10^{14}$ kg for the Dartmoor Granite in Devon. A similar calculation undertaken here using the gravity anomaly associated with the Weardale Granite (No 18 of Figure 6) reveals a mass deficit of approximately $5.3 * 10^{14}$ kg. The gravity anomalies associated with the proposed Bingham and Newark Granites are not isolated features but merge with the gravity lows derived from the thick sediments of the adjacent Widmerpool and Gainsborough Basins. Consequently, a calculation of the Bingham and Newark mass deficits cannot be confidently found. Nevertheless, an attempt has been made to isolate the granite anomalies and, in this way, it has been estimated that the combined mass deficit for the two granites is likely to lie between 2.0 and $3.0 * 10^{14}$ kg. Isostatic uplift, associated with the low-density granites, will be proportional to the magnitude of the mass deficit. Consequently, although it would be

expected that the Bingham and Newark Granites would offer a stabilising effect, the influence of the Weardale Granite, for example, would be significantly greater.

It is interesting to note the location of the significant Eakring Fault. This fault passes with NW-SE trend between the two granite blocks. Profile UKOGL-RG-005 (Figure 3) shows an approximately 5km wide wedge of thickened Dinantian sediments at 190km along the profile. This downthrown wedge may have been controlled by the adjacent granites located to either side. Profile 'AB' (Figure 4) shows no such wedge. However, examination of BP seismic data (UKOGL website, www.ukogl.org.uk) along the line of this profile offers the opportunity to propose a slightly revised interpretation with a similar, narrow wedge of thickened Dinantian section also located between the two granites.

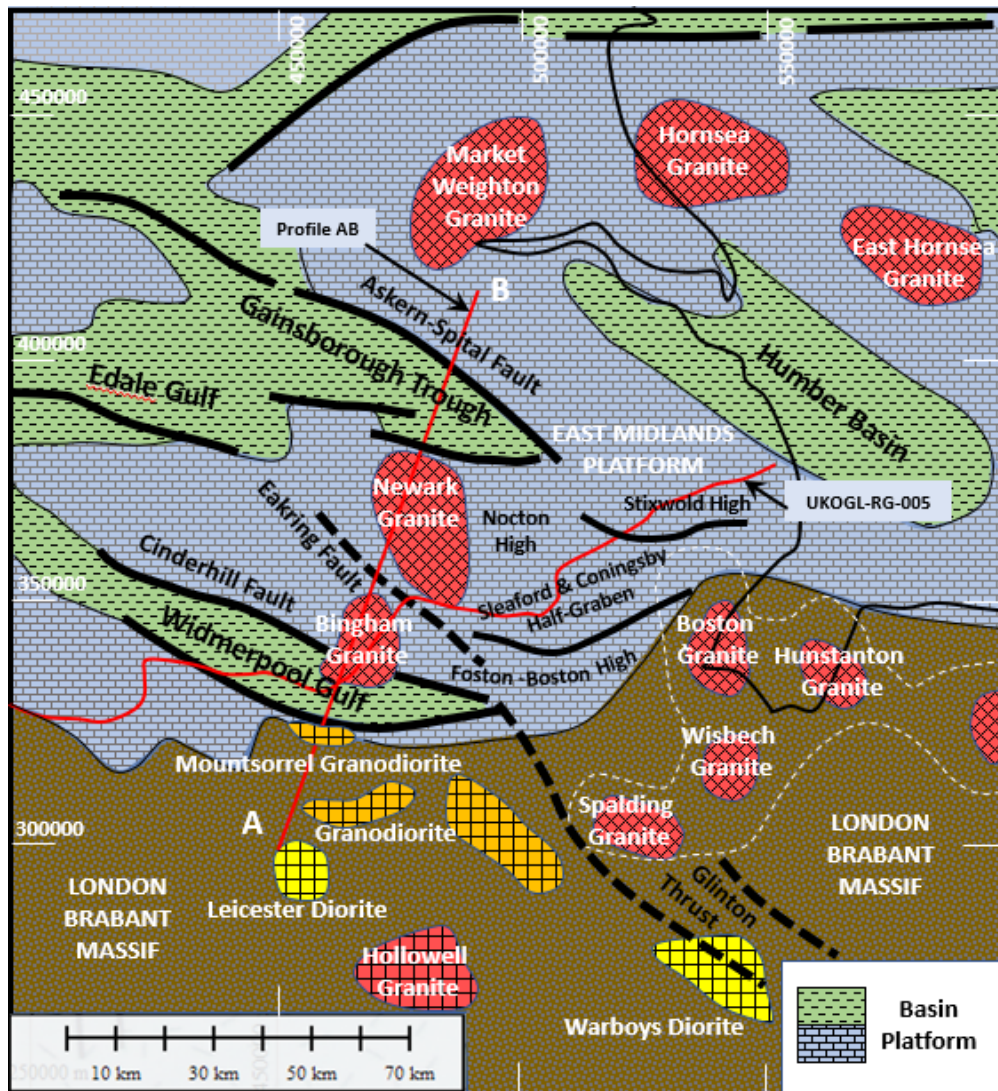


Figure 5 Summary map showing the Dinantian structural framework after Fraser and Gawthorpe (1990), Pharaoh (2011) and Andrews (2013). The locations of various intrusions are also shown as are the locations of the two profiles, UKOGL-RG-005 and 'AB'. The proposed Newark and Bingham Granite blocks are situated within the East Midlands Platform between the Gainsborough Trough to the north and the Widmerpool Gulf to the south. Two possible locations for the south-easterly continuation of the Glington Thrust are shown (black dashed lines). The southerly option follows Chadwick et al (2005) and the northern option follows Woods et al (2012).

It is clear from profile 'AB' (Figure 4) and from Pharaoh et al (2011) that the Carboniferous sections above the proposed Bingham and Newark Granites differ. The Bingham Granite appears to have exerted considerable influence during Dinantian times with significantly thinner Dinantian section above the granite compared to the considerably thicker section seen southwards within the Widmerpool Basin. The Newark Granite appears to have exerted similar control, but to a lesser extent, with the western end of the Sleaford sub-basin extending partly over the area of the Newark Granite. The line of the Eakring Fault appears to be a significant controlling factor on Dinantian subsidence in this local area. This fault forms the north-western end of the Eakring-Glinton Lineament (Pharaoh, 2018). The lineament, trending from NW-SE, is a long-lived feature possibly originating as a thrust during Ordovician times and subsequently reactivated (Chadwick et al, 2005; Pharaoh, 2011 and Woods et al, 2012). The thrust is imaged on reflection seismic data (Chadwick et al, 2005) and dips at approximately 25° to the north-east. Well results suggest Ordovician aged sediments on the south-west, footwall side of the thrust with overthrust, older, Cambrian or Precambrian, aged sediments in the hanging wall. As such, the Newark and Bingham Granites, with locations straddling the thrust (see Figure 5), may be intruded into different age and density (Chadwick and Evans, 2005) basement rocks. The detailed isostatic effects of the granites within such a possibly heterogeneous basement morphology are likely to be complex.

It is tempting, but highly speculative, to suggest that, as well as the vertical displacements discussed above, there may have been dextral movement along the pre-existing line of the Eakring-Glinton Lineament, possibly in sympathy with the suggested dextral movement along the north-eastern edge of the Midlands Microcraton (Soper et al, 1987). Such movements may explain the slight present-day offset observed between the (originally joined?) Newark and Bingham Granites. Clearly, the detailed and complex relationship between the granites, the Eakring-Glinton Lineament and the geometry of the extensional formation of the early Carboniferous Basins remains to be more fully explained.

Heat flow anomalies within the United Kingdom (Lee et al, 1987) show high heat flow areas associated with the Cornubian Granite Batholith (up to approx. 120mW/m²) and the Lake District and Weardale Batholiths (up to approx. 90mW/m²) of northern England. Heat flow measurements over the Newark and Bingham Granites are sparse with no measurements recorded over the granites themselves. Measurements are available however close to the western margin of the Newark Granite and also near the eastern edge of the Bingham Granite. These measurements demonstrate a positive heat flow anomaly (of up to 90mW/m²) similar in magnitude to the Lake District/Weardale anomaly. Data measurements are even more sparse on and around the Market Weighton and Wash Granites and no heat flow anomaly has been recognised here even though there is one measurement point located above the Wisbech Granite. Although heat flow data points are sparse, there may be some slight evidence for the radiogenic heating effects of the Newark and Bingham Granite masses.

There are numerous igneous, mainly granitic, intrusions observed and proposed within the broader area and Figure 6 attempts to show all such occurrences to the northeast of the Midlands Microcraton. Many of the features, mostly based upon analyses of potential field and seismic data, are thought to be buried, some at considerable depth. Despite the lack of firm outcrop or well penetration data, evidence for some of these features is strong whereas others are much more speculative. No attempt has been made in the figure to differentiate the reliability of the proposed occurrences.

Age dating of the intrusions is scarce. However, a few date estimates do exist, and two main phases of magmatic activity are recognised, one at approximately 400my (Early Devonian, Acadian) and one at around 450my (Late Ordovician). To the North (see Figure 6), the Cheviot Granite (Thirwall 1988) at outcrop and the Weardale and Wensleydale Granites, as sampled in the Rookhope and Raydale boreholes, provide ages of approximately 400my. These dates are like those obtained for the younger

Lake District granites at Shap and Skiddaw (Woodcock et al 2018) and for the Southern Uplands Granites e.g. Loch Doon, Criffel and Cainsmoor of Fleet (Halliday et al 1980).

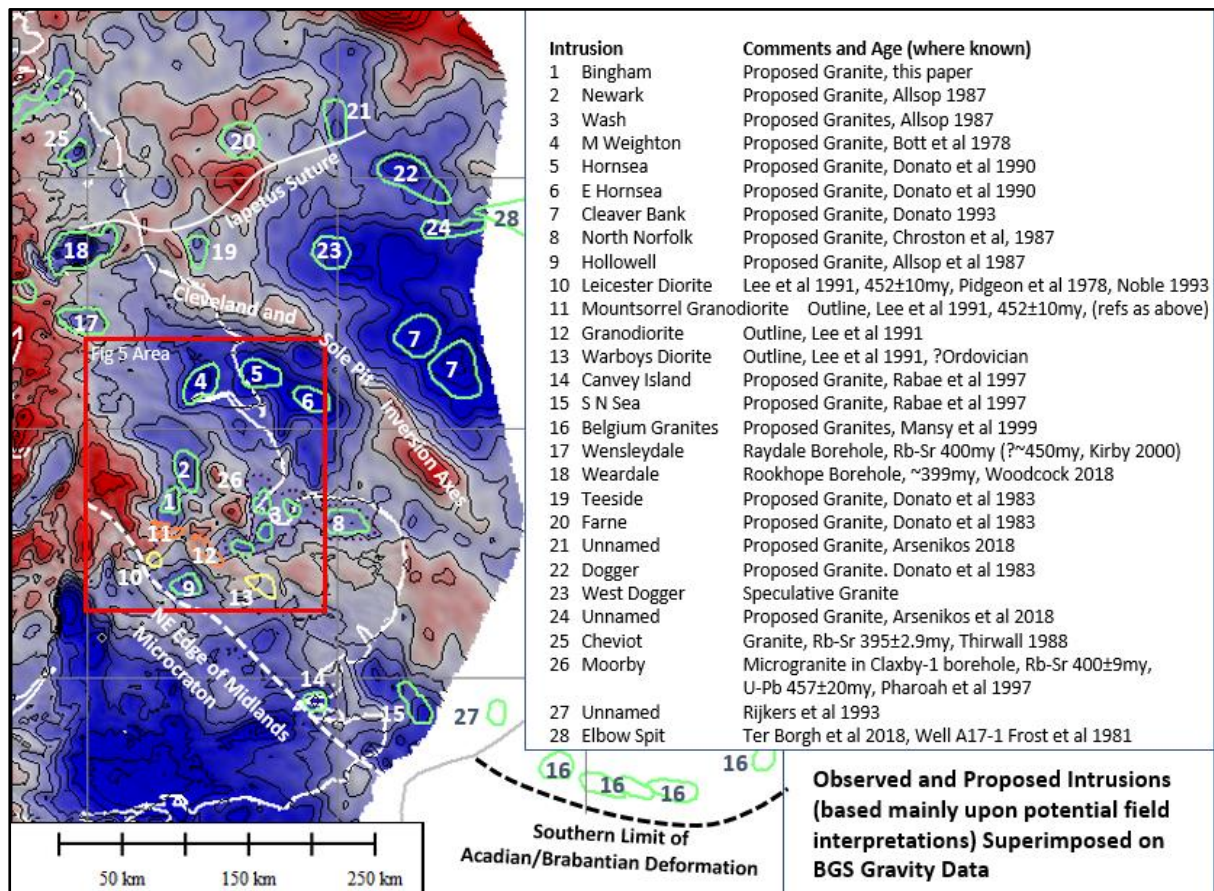


Figure 6 Summary map showing the approximate positions of various observed and proposed, mainly granitic, igneous intrusions. The thin black dotted line (around 3 and 8) shows the extent of the proposed Wash Batholith around the four suggested cupolas. Age dates, where available, are listed. Bouguer Anomaly gravity data are also shown with onshore data and offshore data downloaded from the BGS (www.bgs.ac.uk) and OGA (www.ogauthority.co.uk) websites respectively. Positive anomalies are coloured red and negative anomalies blue. 5 mGal contour lines are also displayed. The red box shows the extent of Figure 5

Further to the south, the Moorby Microgranite, located to the northwest of the Wash Granites and intersected in the Claxby-1 borehole, provides a U-Pb age of 457my with a younger Rb-Sr age of 400my (Pharaoh 1997), the age difference possibly being related to an Acadian phase of resetting. Like the Moorby Microgranite, the Wensleydale Granite may also have an earlier origin. Kirby et al (2000) suggest that Wensleydale, geochemically similar to the Moorby Microgranite, could be a member of the Ordovician group of intrusions with a later phase of Acadian resetting. Age dates are also available for the granodiorites and diorites located to the southwest of the proposed Bingham Granite. The Mountsorrel Granodiorite and South Leicester Diorite suite provide an age of approximately 450my (Pharaoh 2011). These dates agree with the age of the Lake District older granites, such as at Ennerdale and Eskdale (Hughes et al 1996). Within Belgium, a WNW-ESE trending line of five buried granites are suggested (Mansy et al 1999) with an interpreted age of late Ordovician to early Silurian.

Several buried granite masses have also been proposed beneath the southern North Sea. Netherlands well A17-1, drilled into the area of the Elbow Sit High (No 28 in Fig 6), is the only known granitic

penetration within the offshore area of Figure 6. This well provided an $^{40}\text{Ar}/^{39}\text{Ar}$ age for the granite of approximately 350my thought to indicate a Caledonian origin but with later influence by a mild intra-Carboniferous thermal event (Frost et al 1981). In summary therefore, the age of the proposed Newark and Bingham Granites cannot be confidently estimated but an approximate age of either 400my (Early Devonian, Acadian), or 450my (Late Ordovician) would seem most likely.

In conclusion therefore, the presence of two buried granite batholiths, Newark and Bingham, located within the East Midlands Shelf and of probable late Caledonian age are proposed. These granites may have influenced the location of early Carboniferous Basins within the area. The Newark Granite has been previously suggested (Allsop, 1987) but the Bingham Granite has not been previously recognised. The models presented here are simplistic, but nevertheless the conclusions are considered reliable. No doubt, further investigations involving more detailed seismic interpretation and 3D gravity modelling would be helpful and instructive.

Acknowledgements

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