Gravity modelling across the UK Solway Basin and Northumberland Trough - a possible basic igneous intrusion buried beneath the Solway Basin

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August 2020

Abstract

A 2.5D gravity and magnetic model cross-section has been produced along an ENE trending profile passing across the Solway Basin and Northumberland Trough within northern England. The profile is based upon a composite regional seismic line, UKOGL-RG-002, one of six lines reprocessed, interpreted, and published by Butler and Jamieson (2013). The seismic profile, with a total length of over 150 km, begins on the west coast, west of Carlisle, and extends to the east coast, just to the north of Blyth. The simple polygonal 2.5D model predicts the expected gravity and magnetic variations along the profile. A discrepancy of approximately 20 mGal is observed between predicted and observed gravity values over the central part of the Solway Basin. This discrepancy occurs within the vicinity of a circular positive magnetic anomaly of approximate amplitude 100 nT. The presence of a deeply-buried mafic intrusion, located beneath the Solway Basin, is proposed to explain the gravity discrepancy and the associated magnetic anomaly. It is also suggested that the intrusion may be of early Mississippian (?Tournaisian) age. The mass excess associated with the dense intrusion may have influenced later subsidence geometry within this part of the Solway Basin.

Introduction

2.5D gravity and magnetic modelling has been undertaken along a profile following the path of composite seismic line UKOGL-RG-002. The position of the profile can be seen within Figure 1 together with the British Geological Survey (BGS) solid geology outcrop mapping. Images of the seismic line and detailed descriptions of the interpretation are available on the United Kingdom Onshore Geophysical Library (UKOGL) website (www.ukogl.org.uk) and in Butler and Jamieson (2013). As shown in Figure 1, the line passes with ENE orientation across northern Britain. In the west, the line commences over the Permo-Triassic basin of Cumbria. It passes eastwards to cut obliquely across the Solway Basin containing Permo-Triassic rocks underlain by a thick sequence of Carboniferous sediments, with the bulk of the thickness comprising rocks of Dinantian age. Immediately to the west of Carlisle, the line crosses an exposure of Liassic strata preserved within the core of the Solway Basin syncline. To the east of the Solway basin, the line crosses a broad anticline, located to the north of the Pennines, with Dinantian rocks at outcrop. East of the anticline, the strata dip to the east allowing Namurian and then Westphalian rocks to outcrop. The Pennsylvanian (Stephanian) Whin Sill intrusion is present along this part of the profile and the sill outcrops a few kilometres to the north. The line terminates on Middle Westphalian Coal Measures at the North Sea coast approximately 10 km north of the town of Blyth. The primary area of interest described here relates to that part of the profile crossing the Solway Basin.

The study has utilised gravity and magnetic data published by the BGS (BGS, 1998) with gridded data downloaded from the BGS website (www.bgs.ac.uk). A contoured Bouguer Anomaly Map is shown in shaded relief within Figure 2. This figure covers the identical area to Figure 1.

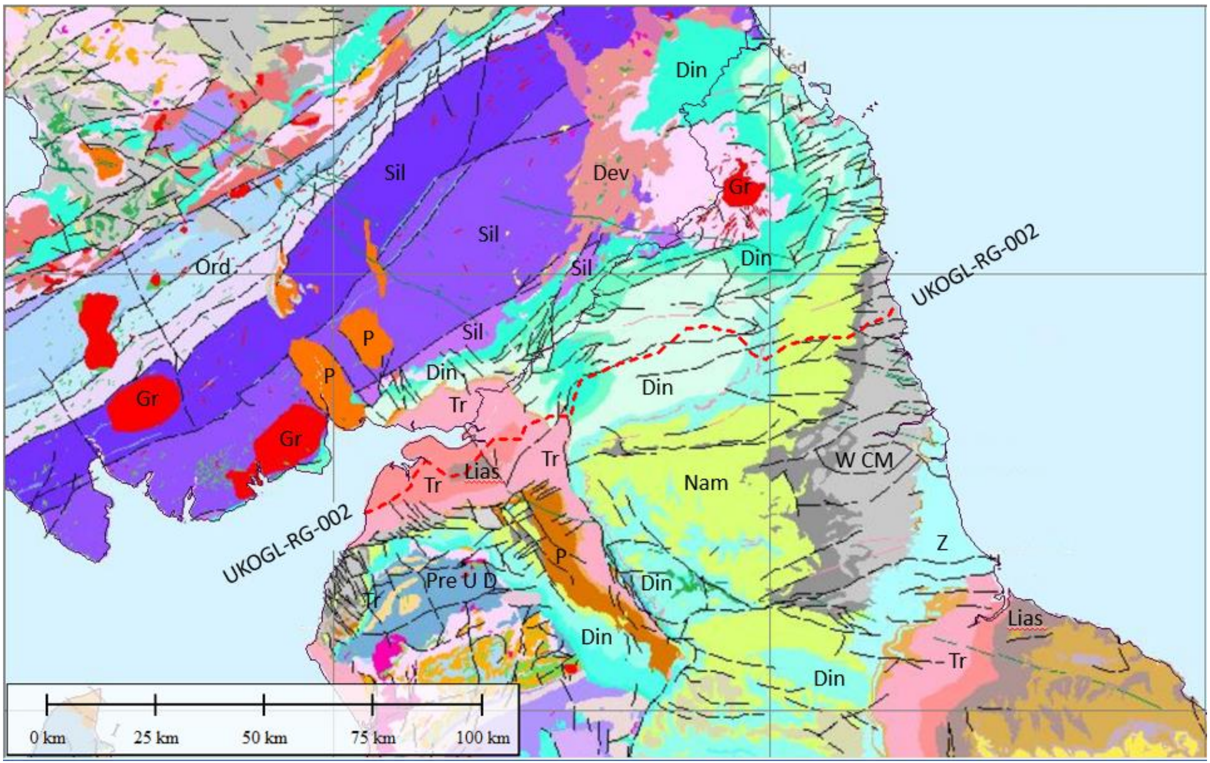

Figure 1 British Geological Survey (BGS) Solid Geology Map taken from UKOGL website (www.ukogl.org.uk). The location of line UKOGL-RG-002 is shown by the red dotted line. Labelled geological outcrops are identified as follows: Lias – Lias, Tr – Triassic, Z - Zechstein, W CM – Westphalian Coal Measures, Nam - Namurian, Din – Dinantian, Dev – Devonian, Sil – Silurian, Ord – Ordovician, Pre U D – Pre-Upper Devonian of the Lake District and Gr - Granite

The most prominent features on the gravity map relate to the distribution of low-density granite intrusions. Marked gravity lows are associated with the Tweeddale (Lagios and Hipkin, 1979), Cheviot (Bott, 1967; Lee, 1983; Kimbell et al, 2006), Weardale (Bott et al, 1957; Kimbell et al, 2006; Howell et al, 2019) and Teeside (Donato et al, 1983) granites. On the western side of Figure 2, smaller lows are linked to the presence of the Criffel (Bott et al, 1960) and Fleet granites. To the south, lows correspond to the Lake District Batholith (Bott 1974; Lee, 1984; 1986; 1989; 2000; Kimbell et al, 2006) and to the Shap and Skiddaw culminations.

Gravity lows are also associated with sedimentary basins. NW-SE trending gravity lows occur notably over the Vale of Eden Basin and also over the smaller Dumfries (Bott et al, 1960) and Lochmaben Basins. Of interest here are the gravity features associated with the Solway Basin and the Northumberland Trough. The Solway Basin is a symmetrical syncline with NE-SW trend (Chadwick et al, 1995). It does not, however, appear as such in the gravity data where it is shown as two separated gravity lows (Figure 2). Curiously, the slightly elevated gravity values between the two lows lie over the deepest part of the basin. This unexpected relationship is discussed in the modelling section below. The Northumberland Trough appears as a significant gravity low with ENE trend extending offshore until being terminated by a N-S trending gravity ridge. Onshore, the Northumberland Trough lies between the Cheviot and Weardale granite-cored basement blocks. Offshore, the easterly extension of the Northumberland Trough lies to the north of the Teeside Granite basement block.

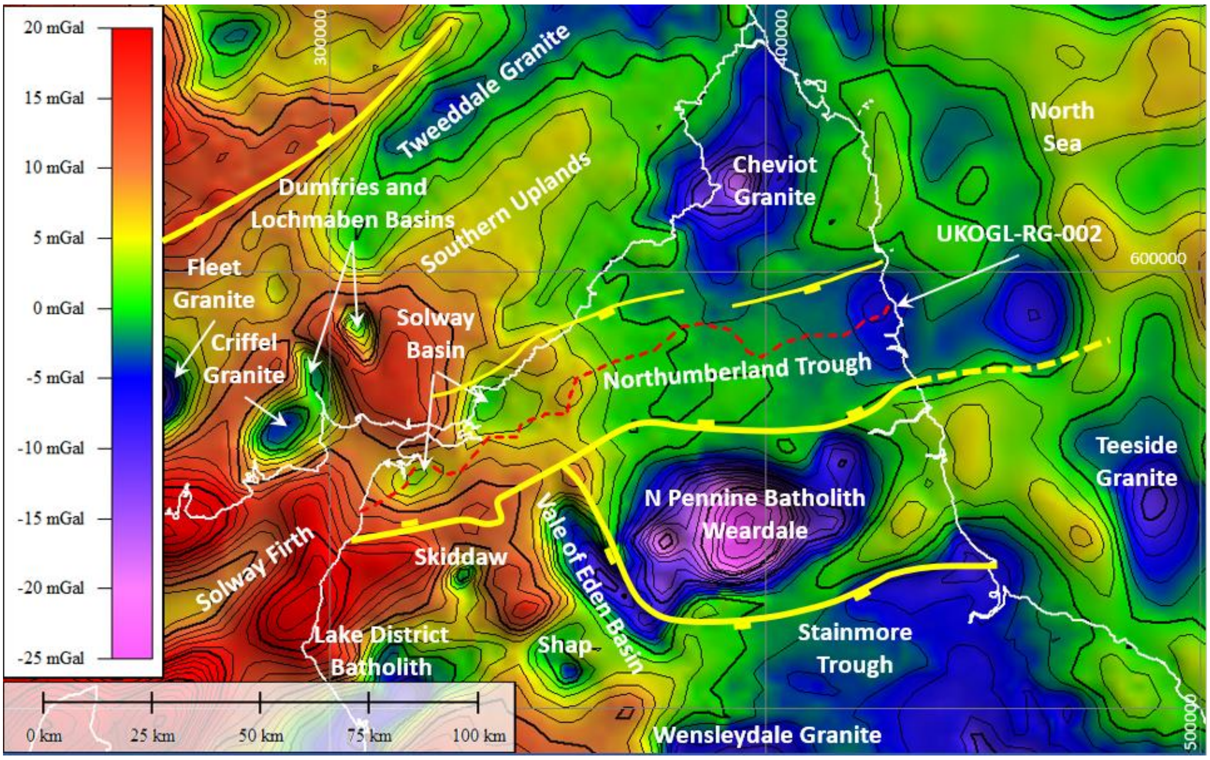

Figure 2 Bouguer Anomaly Gravity Map shown in shaded relief with the main structural features added. Contour lines are at 2 mGal interval. The location of the gravity and magnetic profile follows line UKOGL-RG-002, as shown by the red dotted line. Pronounced gravity lows are associated with the presence of granitic intrusions as at Weardale, Cheviot, Tweeddale, Criffel, Fleet, Lake District, Skiddaw, Shap and Teeside. The Carboniferous Solway and Northumberland Basins are also associated with gravity lows as are the small basins at Dumfries and Lochmaben.

Figure 3 shows an image of the total magnetic field (Kimbell et al, 2006) displayed with illumination from the north-east. The inset to this figure shows contours (BGS, 2004) of a circular, positive anomaly (labelled 'a' in the figure) and located within the centre of the Solway Basin. The feature has previously been named the Carlisle Magnetic Anomaly (Kimbell et al, 2006). The anomaly occurs over the deepest part of the Solway Basin where the gravity values appear to be anomalously elevated. It is circular in shape with a diameter of approximately 40 km and with an amplitude of just over 100 nanoTesla (nT). An associated low magnetic area with amplitude of approximately 20 nT exists just to the north of the positive high. The long wavelength of the feature implies a deep-seated source and Lee (1989) suggests that it may be related to a magnetic, intrusive body beneath the Solway Basin. Line UKOGL-RG-002 passes just to the south of the peak magnetic amplitude and it has been modelled in this study.

Other marked features on the magnetic map include a series of NW-SE trending linear anomalies. These are labelled 'b', 'd', and 'e' and are related to the Cleveland-Armathwaite, Acklington and Blyth Cenozoic dykes respectively. The Acklington and Blyth anomalies can be traced eastwards into the North Sea and here they are imaged on offshore reflection seismic data (Kirton and Donato, 1985). The magnetic anomalies are primarily of negative amplitude indicating reversed magnetisation. A similar feature is the High Green Dyke ('f') which is of north-easterly strike, of probable Permo-Carboniferous age and displays a positive anomaly form. The complex and short wavelength anomalies around the area labelled 'g' are related to the extent of the buried Pennsylvanian (Stephanian) Whin Sill. Early Mississippian (Tournaisian) intrusive and extrusive features may also be seen. These include the Kelso ('i') and Birrenswark ('k') Lavas indicated by a contorted magnetic anomaly pattern. Similarly-aged Cockermouth Lavas also occur but their presence on the magnetic data is masked by the strong feature ('h') related to the exposed lavas of the Ordovician Eycott Volcanic Group. Strong positive anomalies are associated with the Cheviot Complex ('c') with maximum amplitudes surrounding the central granite and associated with marginal rocks and hornfels (Lee, 1983).

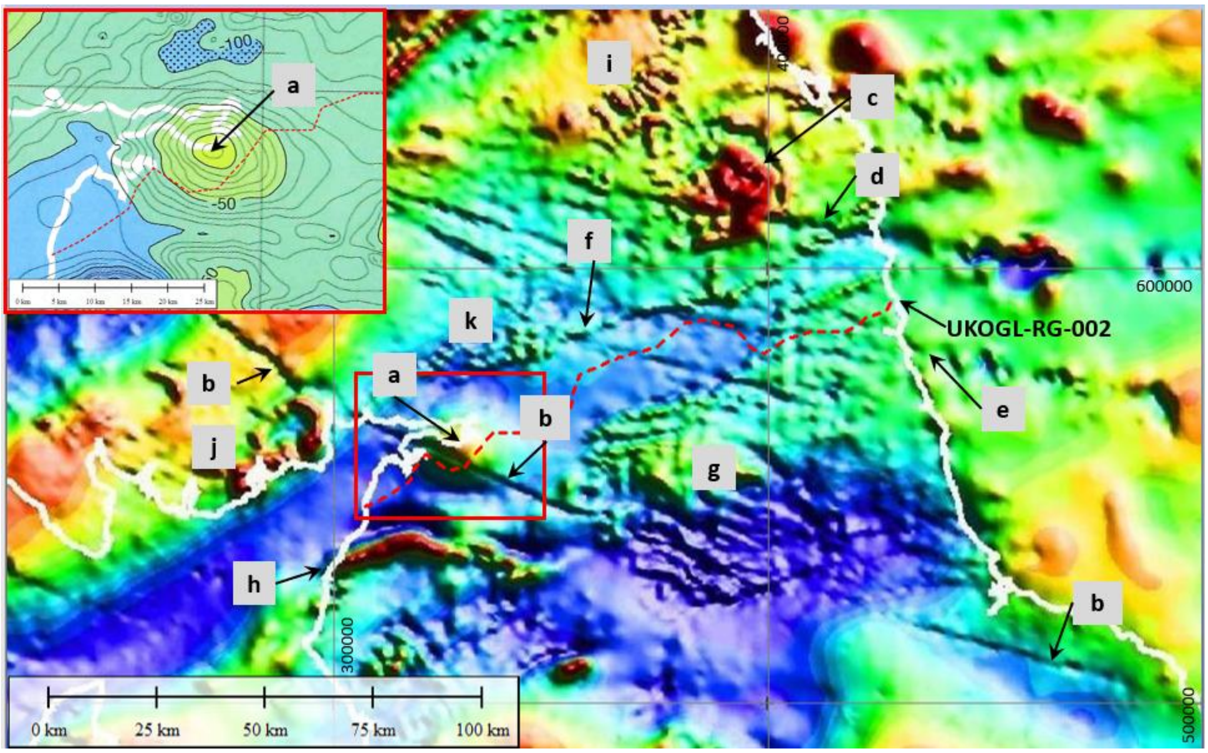

Figure 3 Total Magnetic Anomaly Map with NE illumination (Kimbell et al, 2006) and with features labelled as follows:- 'a' – Carlisle Magnetic Anomaly, 'b' – Cleveland-Armathwaite Tertiary Dyke, 'c' – Cheviot Granite, 'd' – Acklington Tertiary Dyke, 'e' – Blyth Tertiary Dyke, 'f' – High Green Permo-Carboniferous Dyke, 'g' - Whin Sill, 'h' – Eycott Volcanic Group, 'i' – Kelso Lavas, 'j' – Bengairn Complex extending to Black Stockarton Moor Complex and 'k' – Birrenswark Lavas. The inset shows contours at 10 nT interval (BGS 2004) of the Carlisle Magnetic Anomaly, labelled 'a'.

Gravity and Magnetic Models

The 2.5D gravity and magnetic profile produced here follows exactly the path of seismic line UKOGL-RG-002 (see Figure 1 for location). As such, it is unusual in its construction. The profile is not a straight line and polygonal features built into the model are not generally orthogonal (nor symmetric) to the model 'line'. In addition, the profile follows the strike of the Northumberland Trough and this will introduce potential errors. In an attempt to minimise this effect, the half width of polygons has been set to 20 km to mimic the average width of the Northumberland Trough. Sediments are generally thicker to the south of the profile and thinner to the north. Fortunately, this will result in a cancelling effect and the values calculated for the average thickness along the strike line will be a reasonable estimate. For these reasons, close agreement cannot be anticipated between calculated and modelled values. It is estimated that agreement to within 5 mGal is acceptable. As will be shown later, a difference approaching 20 mGal has been discovered along the model line. This is considerably outside the range of predicted errors and requires explanation.

In summary, therefore, the purpose of the modelling has not been to produce a highly-accurate match between calculated and observed values but to test the predictions of the seismic interpretation against the potential field data. In this way, to attempt to identify areas where predicted, modelled values are in significant disagreement with observed values. In such areas, the presence of additional geological features, not revealed on the seismic data, may be necessary for an improved overall interpretation to be achieved.

As for all gravity and magnetic modelling studies, the selection of appropriate density and susceptibility values presents uncertainty. Fortunately, in this case, an excellent summary of relevant density and magnetic data is available in Kimbell et al (2006). This publication provides a comprehensive review of rock property data. The density and magnetic values used for the modelling presented here are based mainly upon this compilation. In particular, however, the selected density values have been biased towards nearby well control at Silloth-1A, Broadmeadows-1, Long Horsley-1 and Errington-1. A background basement density of 2.75 Mg m^{-3} has been assumed.

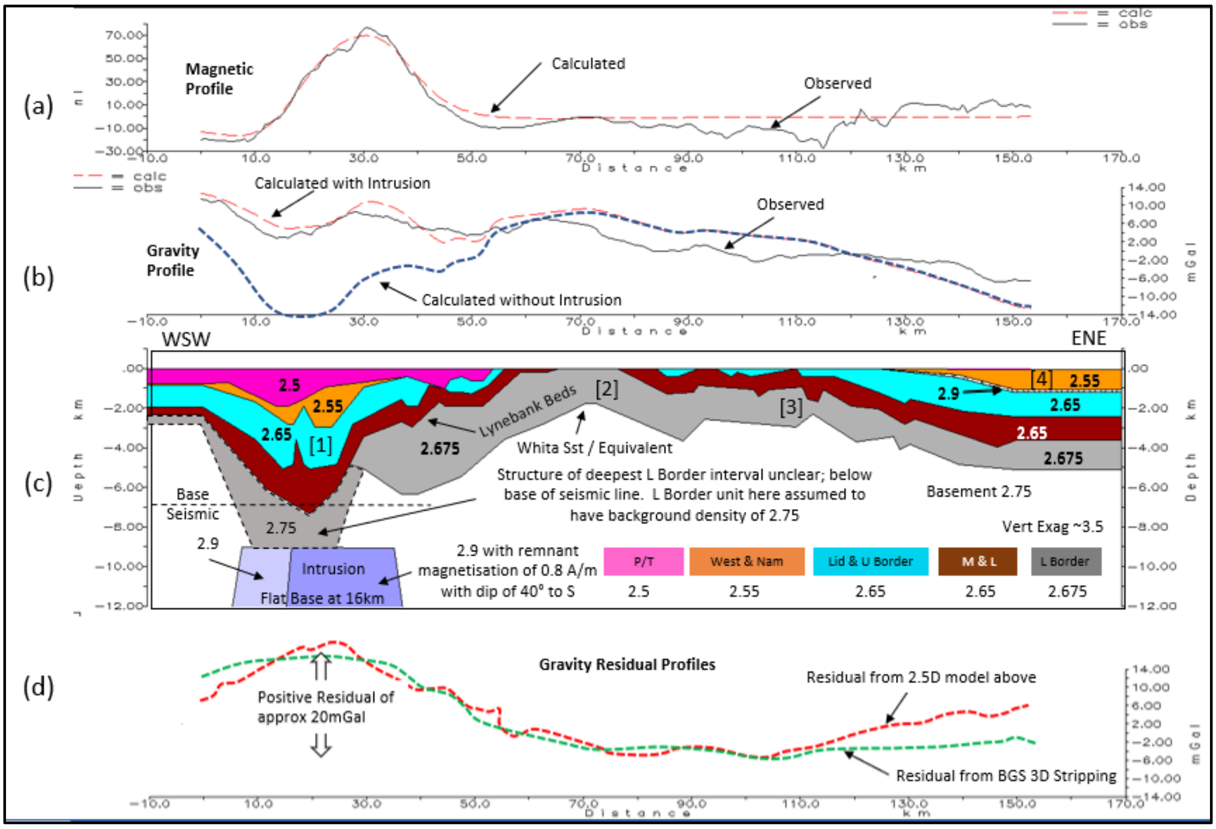

Figure 4 Polygonal 2.5D model (c) along line UKOGL-RG-002 (see Figures 1, 2 and 3 for location). The model is based upon the seismic interpretation of line UKOGL-RG-002. Modelling has been undertaken using the BGS GRAVMAG software (Pedley et al, 1993). Features identified by number are:- [1] - Solway Basin, [2] - Northern continuation of the Pennine High, [3] - Northumberland Trough and [4] - Northumberland Coalfield. The assumed 2.5D polygonal model is shown in (c) with assumed density values (Kg m^{-3}) annotated. There are two calculated gravity profiles in (b). The blue dotted profile is calculated using the estimated effect of the sedimentary structure as defined by the seismic line interpretation. The red dotted profile also includes the gravity effect of an assumed buried mafic intrusion beneath the Solway Basin. The calculated magnetic curve in (a) is based solely on the estimated magnetic effect of this assumed intrusion. The two profiles in (d) are both residual gravity profiles with the gravity effect of the Carboniferous and younger section removed. The red curve is that obtained from the 2.5D profile in (c) and the green curve is that obtained by 3D basin modelling of Kimbell et al, 2006. A regional gravity background has been assumed along the 150 km profile with

values from W to E varying from 20 to 8 mGal. This agrees with the general regional westerly rise in gravity values.

The results of the 2.5D gravity and magnetic model along line UKOG-RG-002 are shown within Figure 4. The polygonal model of Figure 4(c) is based upon selected horizons interpreted by Butler and Jamieson (2013) including Base Permo-Trias Unconformity, Top Dinantian, Lynebank Beds (within Lower Border Group) and the Whita Sst/Equivalent (near basal Mississippian horizon, stratigraphically above the Kelso/Birrenswark Lavas). The time picks of Butler and Jamieson (2013) have been converted to depth using a function based upon the time/depth scales shown on their interpreted profile:-

Depth(m) = 300*TWT(s)^2+2000*TWT(s) (applied to a TWT of 1.24s with constant 5000m/s beneath)

A simple depth conversion method, such as this, is considered acceptable for the gravity modelling undertaken here.

Calculated model gravity values based upon the seismic interpretation are shown by the blue dashed curve (b). From the southwest end of the profile to a distance of 50 km, there is a significant difference of up to 20 mGal between this blue curve and the observed gravity values. This difference is located over the central part of the Solway Basin and is of a magnitude significantly outside the expected errors within the 2.5D modelling method. Figure 4(d) displays two residual gravity curves after the effect of the Carboniferous and younger sediments has been removed. The red curve is that obtained from the 2.5D profile in (c) and the green curve is that obtained by the 3D modelling of Kimbell et al (2006). The two independent residual estimates are comparable, both revealing a positive 20 mGal residual high over the Solway Basin. Agreement for the rest of the profile, although not exact, lies within the expected error range and is therefore acceptable. One possible explanation for the 20 mGal divergence may be the presence of a dense body buried deeply beneath the Solway Basin. The profile of Figure 4(c) shows a possible location and depth for such a dense intrusion. In this case, the revised calculated gravity values, incorporating this body and the seismically-defined sedimentary structure, are shown by the red dashed curve, achieving acceptable agreement

In addition to the gravity model, a simple magnetic model has been undertaken. This assumes that the proposed deep intrusion, as well as producing a residual gravity high, produces a magnetic signature. Details of the magnetic block model are shown in Figure 4(c) with the results plotted in 4(a). The base at 16 km is well above the Curie depth thought to lie below 30 km in this area (Kimbell et al, 2006). A resultant magnetisation of 0.8 A/m has been assumed and best agreement is achieved with the vector dipping to the south at 40°. In this way, the existence of the Carlisle Magnetic Anomaly may also be explained. Assuming the intrusion cooled in a normally magnetised earth's field and with a Koenigsberger Ratio of 1, then a location at a latitude of 0°-20°S is implied. This is not inconsistent with an early Mississippian age for the intrusion but, on the basis of the data used here, this estimate must be regarded as uncertain. Clearly more detailed modelling is required before any firm conclusions may be drawn.

In summary therefore, the positive residual gravity anomaly of 20 mGal and the Carlisle Magnetic Anomaly of 100 nT may both be explained by the existence of a dense, mafic intrusion located deeply beneath the Solway Basin.

Discussion

The age of the proposed, deep mafic intrusion beneath the Solway Basin is unknown. There may, however, be some relevance to the distribution of outcropping Dinantian (Tournaisian) volcanic rocks as shown within Figure 5. These volcanic rocks, a mixture of both intrusive and extrusive origin, are thought to be related to tensional fracturing contemporaneous with the initiation of the main basin margin faults of the Northumberland Trough (Chadwick et al, 1995). The outcrops include four significant basaltic lavas (Figure 5) of Tournaisian age. The Birrenswark Lavas are located just to the north of the Solway Basin and are up to 90 m in thickness. The Kelso Lavas are within the Tweed Basin, north of the Cheviot Granite, with thickness up to 120m. The Cottonshope Lavas lie on the England/Scotland border and comprise three lava flows with a combined thickness of 24 m. The Cockermouth Volcanic Formation lies to the south of the Solway Basin, just north of the Lake District, and contains four to six lavas. Kimbell et al (1989) have suggested that the lavas may be laterally extensive and could be represented by strong amplitude seismic reflection events close to the base of the Mississippian sequence. Leeder (1974) however suggests that the lavas are more local in nature and are not widespread. The short wavelength and complex pattern on the magnetic data of Figures 3 and 5 suggest that the Kelso (i) and Birrenswark (k) Lavas may extend beyond the present-day outcrop. There are also numerous small volcanic necks present and these range from Visean to Tournaisian in age. Taken as a whole, these various Dinantian volcanic rocks define a linear NE-SW trend.

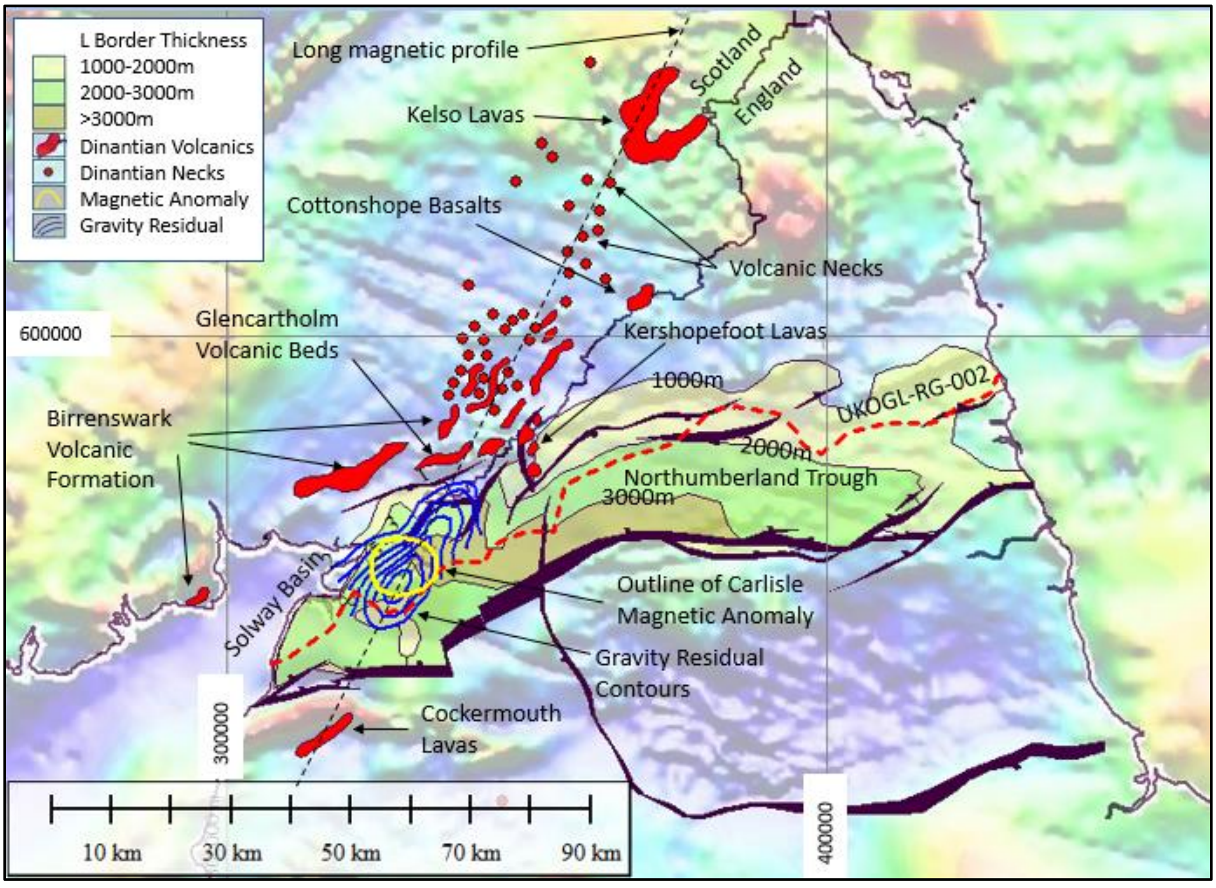

Figure 5 Map showing the thickness of the Lower Border Group interval beneath the Top Lynebank Beds (redrawn from Chadwick et al, 1995) and the distribution of Dinantian volcanic outcrops (redrawn from Stevenson et al, 2003). The location of the Carlisle Magnetic Anomaly is shown by the yellow circle and the shape of the 3D gravity residual (Kimbell, 2006) by the blue contours.

Similar trends are observed within the Midland Valley and are thought to represent deep-seated Caledonian basement orientations (Cameron et al, 1998). Associated with the Dinantian volcanic exposures of Figure 5 is a prominent NE-SW fault trend (see Figures 1 and 5) extending into the main defining faults of the Solway Basin (Chadwick et al, 1995), slightly oblique to the more ENE trend of the Northumberland Trough. Interestingly, the proposed mafic intrusion beneath the Solway Basin lies directly along these NE-SW faulting and volcanic trends. Also, there is a marked NE-SW orientation to the contours of the residual anomaly produced by 3D gravity stripping (Kimbell et al, 2006) (see blue contours of Figure 5). This suggests a linked relationship between the outcropping Dinantian volcanics and the buried intrusion. The intrusion would then also be of Tournaisian age and would have been in place prior to the deposition of the Lower Border and Cementstone Groups.

Analogies may be drawn between magnetic anomalies of the Solway Basin and those of the Midland Valley. Figure 6 plots two long regional profiles, one from each area. The upper profile (blue) runs along the strike of the Midland Valley passing over the pronounced magnetic and gravity anomalies of the Bathgate area, west of Edinburgh, and also over an outcrop of Clyde Plateau Lavas of Mississippian (Chadian to Asbian) age. The Bathgate anomalies have been variously modelled (McLean et al, 1966, Powell, 1970, Gunn, 1975 and Davidson et al, 1984) and more recently (Rollin in Cameron et al, 1998). The consensus being that the anomalies are produced by a combination of shallow lavas, of an equivalent age to the Clyde Plateau Lavas and up to 1 km thick, above a deep, mafic intrusion. Cameron et al (1998) have suggested a Mississippian age for the intrusion with their modelling showing approximately 1km of Visean to Namurian lavas at shallow depth above a deeper mass, of suggested diorite or gabbro composition, extending to 8km. The lower profile (orange) crosses the Solway Basin magnetic anomaly and also shows irregular anomaly patterns likely to be associated with the Kelso and Birrenswark Lavas of Tournaisian age. The Solway profile magnetic anomaly amplitudes are smaller than those in the Midland Valley, but this may be explained by generally thinner lava sequences and, as proposed, a currently deeper mafic intrusion. The analogy would suggest an early Mississippian, possibly Tournaisian, age for the deep intrusion beneath the Solway Basin.

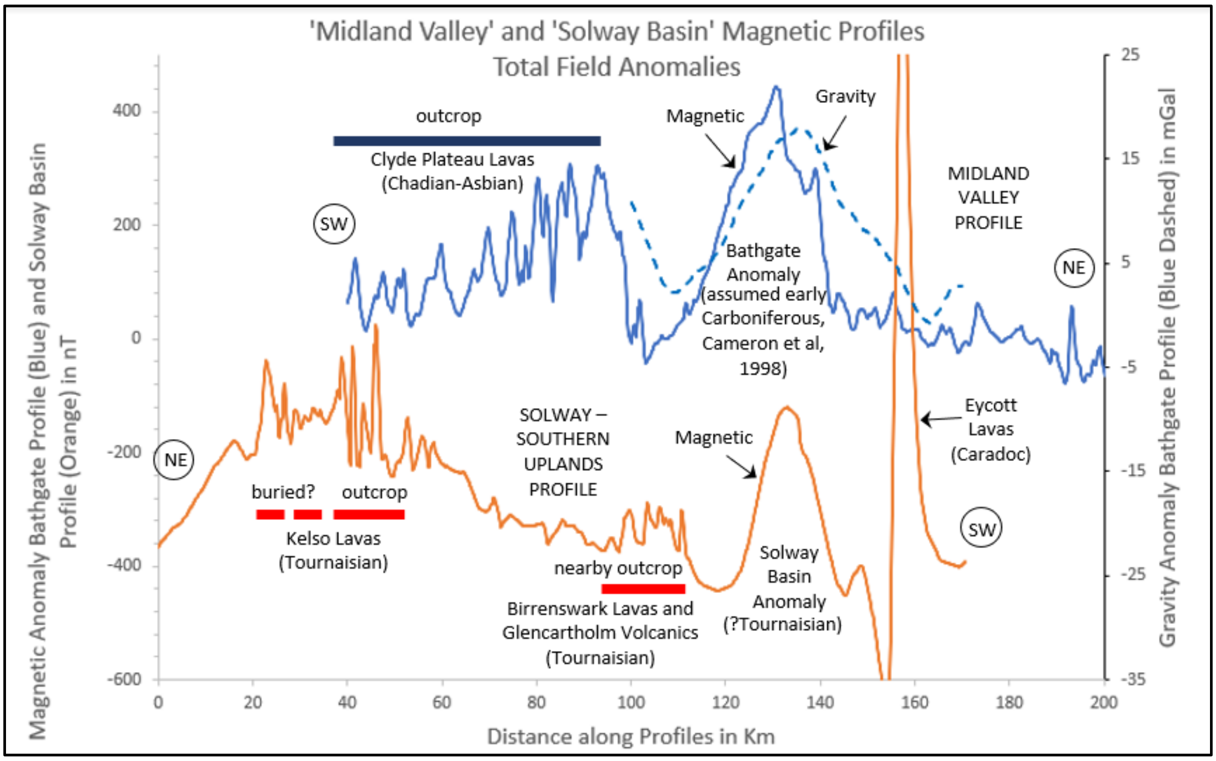

Figure 6 Comparison between magnetic (total field) profiles across the Solway Basin (blue curve) and Southern Uplands (orange curve, for location see Figure 5) and across the Midland Valley of Scotland

(blue curve). Note that to allow analogies to be drawn, the profiles are plotted with different orientations. Also, the magnetic values for the Solway Basin and Southern Uplands profile have been scaled up by a factor of 3 and a constant shift of -150 nanoTesla (nT) applied.

Clearly however, there are other possibilities for the age of the Solway intrusion. The Lake District, with extensive Ordovician volcanics, lies immediately to the south. A strong, arcuate, positive magnetic anomaly is located on the northern edge of the Lake District and is related to the outcrop of the Ordovician Eycott Group Lavas. Magnetic modelling of this anomaly by Kimbell et al (2006) results in a remnant vector not too dissimilar to one described here for the buried Solway Basin intrusion. In addition, Gunn (1975) has proposed that the Bathgate anomalies, rather than being of Mississippian age, may be compared to the potential field anomalies of the Distinkhorn Plutonic Complex, central Ayrshire, with magnetic and gravity anomalies of approximately 250 nT and 10mGal (Busby et al, 2009) and could therefore be of a similar Caledonian age.

It is now generally accepted that the mass deficit associated with large granite masses can influence basin development, with tectonic stability and isostatic buoyancy forces active especially during times of extensional faulting. In the area considered here, this effect was originally proposed for the Weardale and Wensleydale Granites by Bott (1987) and more recently by Howell et al (2019). The opposite effect has also been widely considered in numerous cases (notably McKenzie, 1978) with a large scale, lower crustal mass excess associated with crustal thinning, resulting in widespread basin subsidence. The influence on subsidence of more local dense bodies, such as the proposed Solway Basin intrusion, seems to have escaped general consideration.

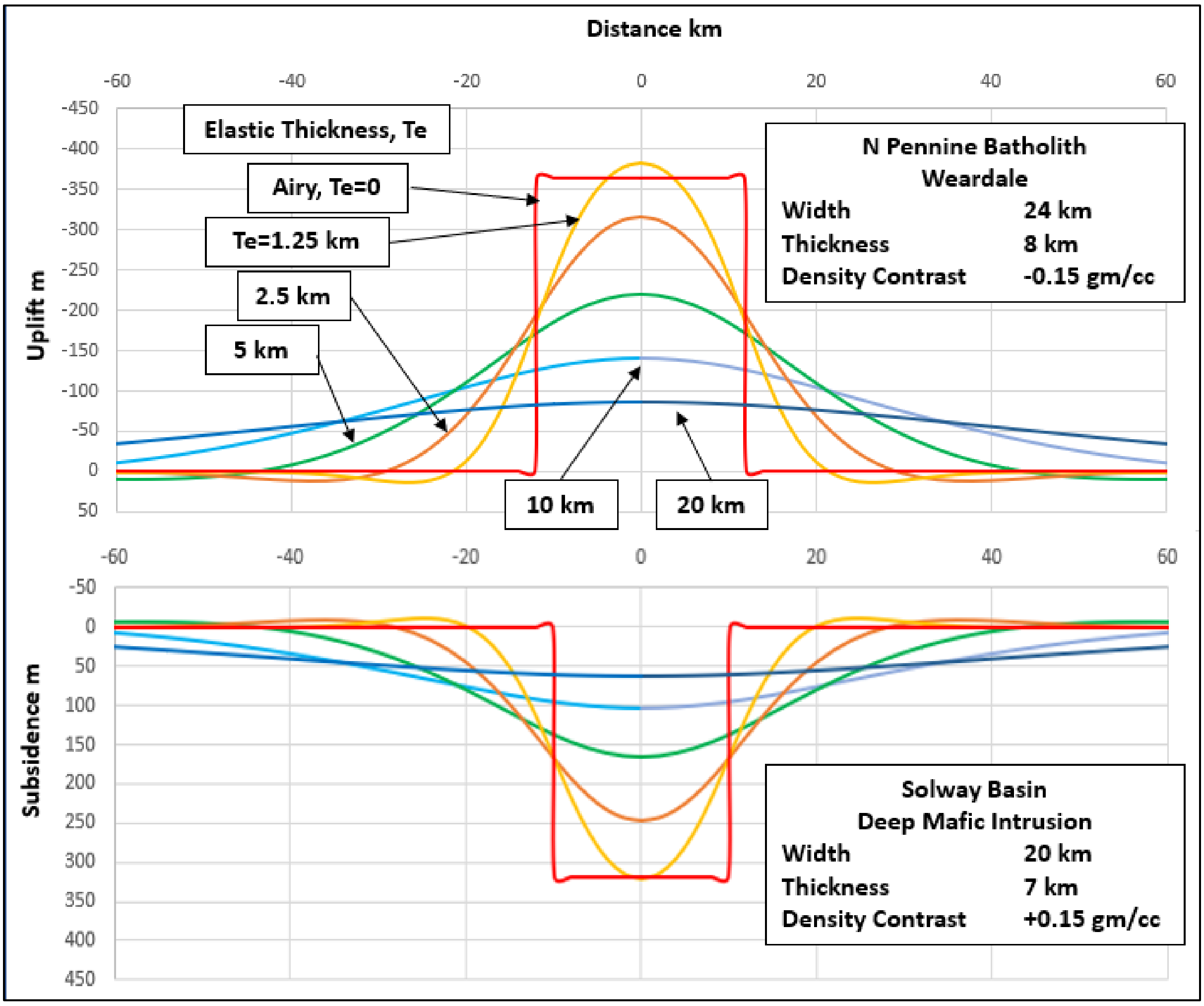

Figure 7 Comparison of the uplift and subsidence 'isostatic potential' of the Weardale Granite (upper graph) and the Solway Basin mafic Intrusion (lower graph). The two graphs are plotted at identical horizontal and vertical scales. A range of possible elastic thicknesses (Te) have been modelled.

Figure 7 is a simplistic 2D modelled attempt to estimate the potential isostatic uplift and subsidence effects of the Weardale Granite and the proposed Solway Basin intrusion. Flexural uplift and subsidence have been estimated for a range of crustal elastic thicknesses (Te). Tiley et al (2003), using an analysis of free-air gravity data and topographic relief over the whole of the British Isles, have calculated an appropriate elastic thickness (Te) value as 5±2 km. The upper graph shows the estimated uplift for a model of the Weardale Granite. This is very similar to the model described by Howell et al (2019). For a granite with width 24 km, thickness 8 km and density contrast -0.15 Mg m^{-3}, an uplift of up to 350 m is calculated. At a Te value of 5 km, the model shows flexure to be able to contribute approximately half of this uplift, with the remainder potentially produced by peripheral extensional faulting, allowing the body to achieve an equilibrium state close to local Airy isostacy (Howell et al, 2019). The lower graph shows a similar case for the proposed dense Solway Basin intrusion. Here, model values for the intrusion are based upon the results of the profile of Figure 4. A maximum subsidence of between 300 m and 350 m is predicted, similar in magnitude to the calculated granite uplift. The intrusion model assumes no fill within any subsidence created. If sedimentary fill is assumed, the calculated subsidence will be significantly increased. In summary, therefore, it would seem that the Solway Basin intrusion has at least an equivalent potential for subsidence as the Weardale Granite has for uplift.

It is expected that any granite-related uplift or intrusion-related subsidence would occur at least partly during periods of extensional faulting tectonics. In this area, crustal extension, beginning in late Devonian times, became prevalent during the Tournaisian and early Visean (Fraser and Gawthorpe, 1990). The main faults, particularly along the southern margin of the Northumberland Trough, became active at this time and may have been linked to reactivation of the underlying Iapetus Suture (Chadwick et al, 1995). The synsedimentary normal fault movements resulted in thick sediments of Tournaisian and early Visean age (Middle and Lower Border) being deposited and confined mainly to the hanging wall, fault-bounded areas of the main faults. Later sediments became more laterally widespread as extensional faulting reduced and thermal relaxation prevailed (Fraser and Gawthorpe, 1990). Figure 5 shows the thickness of the Lower Border Group beneath the Top Lynebank Beds (Chadwick et al, 1995). Such an interval might be expected to show the influence on subsidence of the buried, dense intrusion. Along the central and eastern parts of the Northumberland Trough, the thickest parts of this interval are confined to the immediately-downthrown parts of the main fault system. To the west, however, the thicker section moves away from the fault and migrates northward towards the vicinity of the buried intrusion. It is clear that faulting is the primary controlling factor on the distribution of early Mississippian sediments. It is possible, however, that the excess mass associated with the dense, mafic intrusion may have been a secondary factor perturbing the subsidence geometry and possibly playing a part in the location and structural trend of the early development of the Solway Basin.

Ackowledgements

Digital potential field data used was downloaded from the BGS website. The BGS also generously provided access to their GravMag Interactive 2.5D interpretation software on which all modelling was undertaken.

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