Moho topography beneath England, the regional gravity field and speculations on crustal structure.

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Abstract

Thirty-six recent 2.5D gravity model profiles constructed across northern, central and southern England suggest the presence of a significantly varying regional gravity field. The map of this regional field shows that, in northwest and southwest England, gravity values rise to approximately +25mGal. Within southern-central England, the values are considerably lower and drop to approximately -10mGal. A composite depth map to the Mohorovičić discontinuity (Moho) has been constructed based mainly upon published earthquake tomography and deep reflection seismic data. This depth map has been used to create a simple 3D gravity model in an attempt to estimate the gravity effect of the known Moho topography. Gravity anomalies calculated from the 3D model show similarities in position, amplitude and wavelength to the regional field derived from the 2.5D gravity model profiles. This suggests Moho topography to be a significant contributory factor to the observed regional gravity field, with thinner crust beneath northwest and southwest England responsible for the increased regional gravity values. Lower gravity values within southern and central England correlate with thicker crust beneath the Midlands Microcraton. However, secondary effects, unrelated to Moho topography, also appear to be significant and these may relate to changes in average crustal density. The new composite Moho depth map, when compared with magnetic data and coupled with the apparent crustal density changes, provides tentative support to a Fenland, Anglia and Belgium three-block crustal fragment configuration. These blocks are located between the northeast edge of the Midlands Microcraton and the crustal dislocation along the Dowsing-South Hewett Fault Zone. This possible three-block crustal architecture is a topic of current research.

Introduction

In two recent publications, (Pullan & Donato, 2021; Donato & Pullan, 2022), a series of thirty-six 2.5D gravity and magnetic model profiles have been constructed across northern, central and southern England, extending south into the English Channel. The profiles have been constructed using numerous well ties and various published depth structure maps derived from interpretations of reflection seismic data. The 2.5D models have been used to calculate, and strip away, the combined gravity effect of the shallower and better-known geological structure, revealing residual anomalies frequently originating from deeper, less understood features. In this way, anomalies associated with geological features such as sedimentary basins, structural zones and granitic intrusions have been examined and modelled in a simple and approximate way. In order to achieve agreement between observed and calculated anomalies during the construction of the profiles, it was necessary to assume a significant regional gravity field. Care was taken to ensure that this assumed regional variation was consistent across all intersecting profiles. Also, a constant background density of 2.72kg/m^3 was used in all cases. The regional field estimation was extended northeastwards into the offshore area of the Southern North Sea using a series of additional profiles incorporating the work of Donato & Megson (1990) and Donato (1993).

The map of the inferred regional field (Figure 1) shows variations with a large amplitude of approximately 35mGal and long wavelength. It is considered to be of deep origin and is probably related to Moho topography. Regional values rise to above +25mGal in the northwest over Cheshire and northeast Wales, appearing to extend into the Irish Sea. To the southwest, similarly high values occur over Devon and the western English Channel. A broad, flat area of slightly negative regional values occurs over south-central England. The steepest observed gravity gradient of approximately 0.3mGal/km extends from the Bristol Channel to the Isle of Wight with NW-SE trend. Values also rise northeastwards across the Southern North Sea reaching in excess of +25mGal.

Background Regional Gravity Field

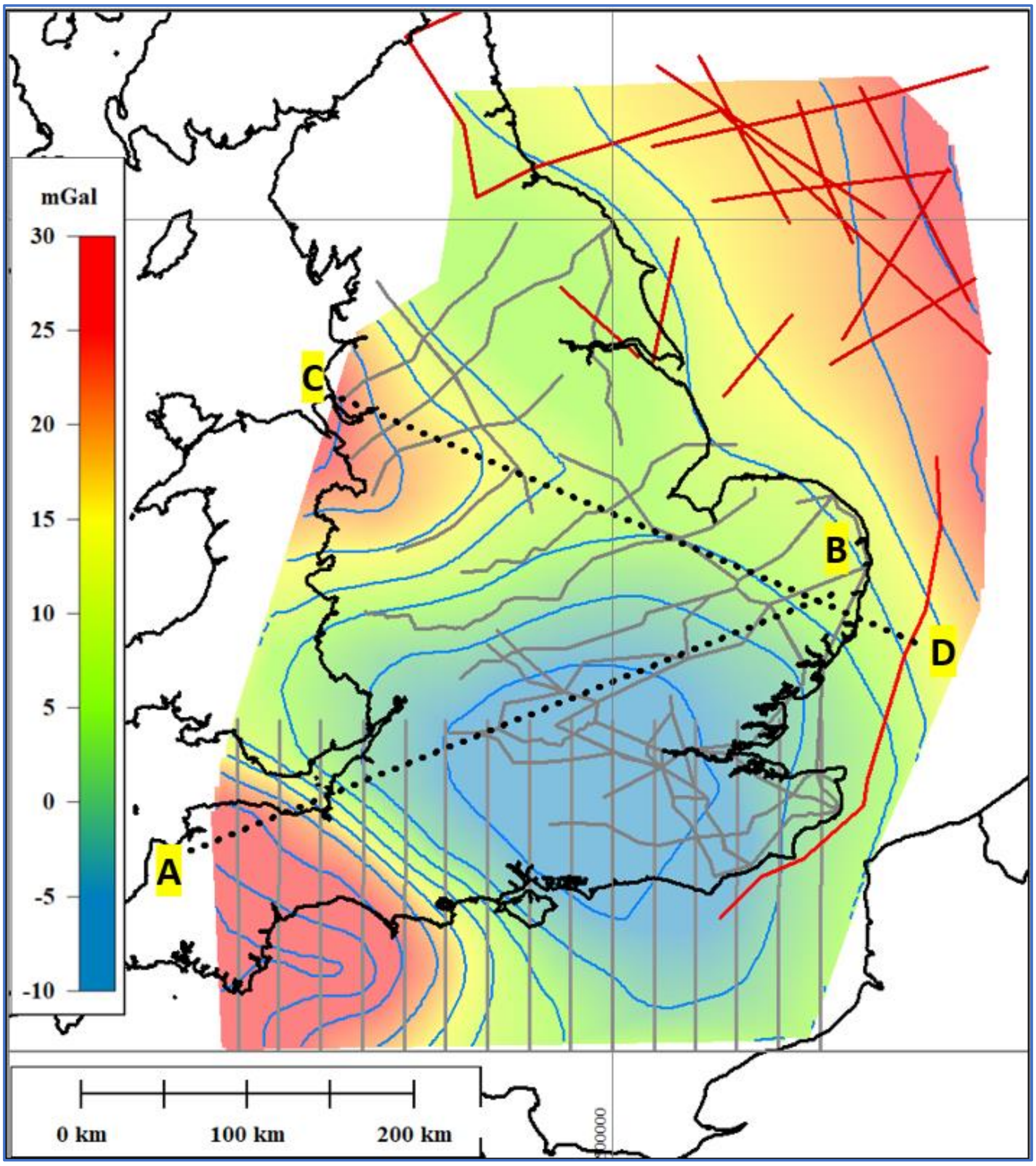


Figure 1 *Inferred regional gravity field (mGal) calculated from the 2.5D gravity profiles of Donato & Pullan (2022). The locations of the thirty-six 2.5D profiles are shown by grey lines. Additional profiles incorporated for the offshore area are shown by red lines. The two black dotted lines, labelled AB and CD, show the locations of the gravity profiles illustrated in **Figure 2**.*

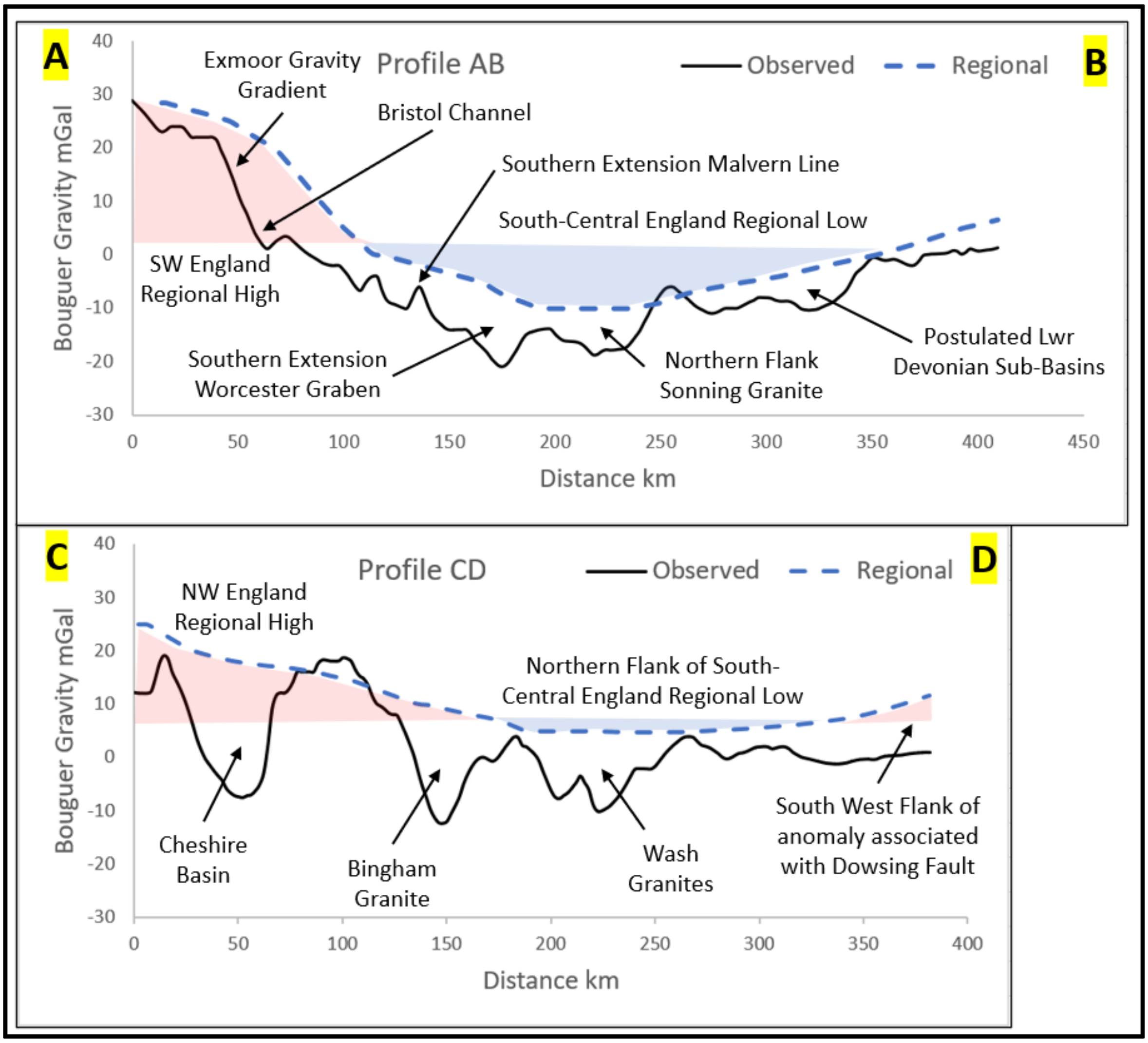


Figure 2 *Gravity profiles AB and CD. For locations see Figure 1. The continuous black curves show the observed gravity profiles (gravity data from Chacksfield and Edwards (2006)) and the blue dashed curves show the regional field determined from the 2.5D profiles (Donato & Pullan, 2022). Selected interpreted anomalies are labelled. Areas of regional high gravity are shaded red with regional low area shaded blue.*

Two gravity profiles, AB and CD (see Figure 1 for locations), are shown in Figure 2. The black continuous curves show the observed gravity profiles with the blue dashed curves showing the regional curves derived from the 2.5D interpreted profiles (Donato & Pullan, 2022),. Selected interpreted anomalies are labelled. Red and blue shading illustrate areas of inferred positive and negative regional gravity field respectively in agreement with our interpretation of the inferred regional field of Figure 1.

This paper is split into two parts. The first part describes the production of a map showing Moho topography based upon a synthesis of published data. The second part uses this map to model the likely gravity effect of Moho structure and then to compare these results with the regional field obtained from the network of modelled 2.5D profiles as shown in Figure 1

PART ONE - Published Moho Depth Structure Models

It is generally accepted that a significant density contrast exists at the Moho and that Moho topography influences the long-wavelength regional gravity field. Worldwide average Moho density contrast values have been calculated as approximately 0.3kg/m^3 (Zdenek, 1994) with a global average value calculated as 0.34kg/m^3 (Sjoberg & Abrehdary, 2022). More locally, and beneath the North Sea, estimated values range between 0.3 and 0.5kg/m^3 (Donato & Tully, 1980; Holliger & Klemperer, 1989; Fischler & Hospers, 1990; Nielsen, et al., 2000; Williamson, et al., 2002). In an attempt to understand the structure of the Moho beneath England and to compare this structure with the inferred regional gravity field of Figure 1, ten published crustal studies spanning the area of the UK (Remmelts & Duin, 1990; Chadwick & Pharaoh, 1998; Lefort & Agarwal, 2002; Tomlinson et al., 2006; Kelly et al., 2007; Hardwick, 2008; Grad et al., 2009; Sichien et al., 2012; Artemieva & Thybo, 2013; Yudistira et al., 2017) have been reviewed. The results of seven of these studies are shown in Figures 3 to 9 below.

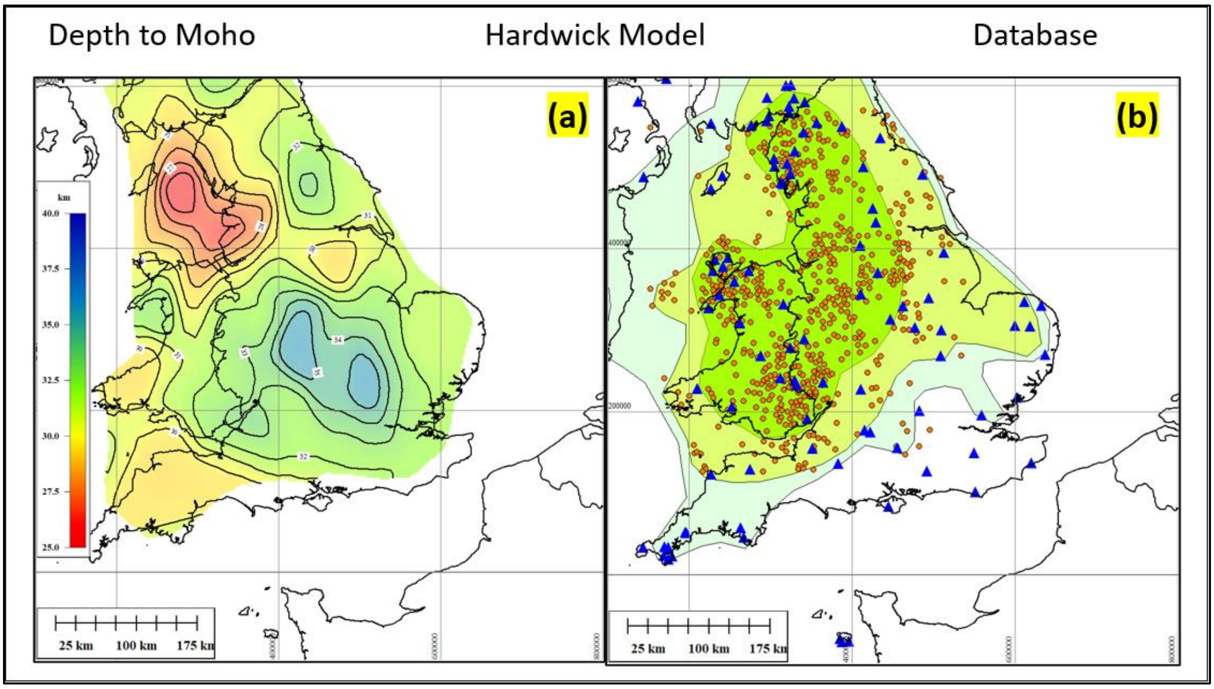


__Figure 3 Hardwick Model (a)__ Summary of the depth to Moho results of Hardwick (2008). Thicker crust is shaded blue with thinner crust shaded red. __(b)__ Database, earthquake epicentres are shown by red dots and recording station by blue triangles. The shading represents ray-path coverage density; central green, outer green and blue represent high, medium and low density coverage respectively.

Hardwick Model Figure 3 shows the database used and the Moho structure calculated by Hardwick (2008). This was an earthquake tomographic analysis of more than 1,000 United Kingdom earthquakes recorded by the British Geological Survey (BGS) seismic monitoring network during a 25-year period. The analysis resulted in 3D images of the crust, including a high-resolution P-wave velocity (Vp) model, enabling an estimate of depth to Moho to be made. The coverage of recorded earthquakes is shown in Figure 3 with earthquake locations shown as red dots and the recording network as blue triangles. Ray-path coverage varies across the area with the densest coverage shown by the central green shading. Lighter green and blue shaded areas represent medium and less dense coverage respectively. The results show thinner crust beneath northwest and southwest England and thicker crust beneath south-central England although the ray-path coverage becomes less dense here. This study probably represents the most comprehensive database available for determining Moho structure across a wide part of onshore England.

Chadwick Model Chadwick & Pharaoh (1998) (Figure 4) based their Moho structure map upon all the deep seismic reflection lines available for the waters surrounding Britain, as well as onshore data, and extends the previous work of Meissner et al. (1986). In the waters around Britain, they interpreted a grid of deep seismic reflection lines acquired by the British Institutions Reflection Profiling Syndicate (BIRPS). Onshore they included short line segments of deep seismic reflection data, acquired by arrangement with the BGS, ranging in length from 2 to 50km (Chadwick et al., 1989). The reflection data were interpreted in two-way-time and depth to Moho calculated using a simple constant-velocity layer-cake depth conversion, including the following layers: Sea, Tertiary, Cretaceous, Jurassic, Permo–Trias, Pre-Permo–Trias, Upper Crust, and Lower Crust. Data from the LISPB (Bamford et al., 1977; Barton, 1992) refraction line were also incorporated.

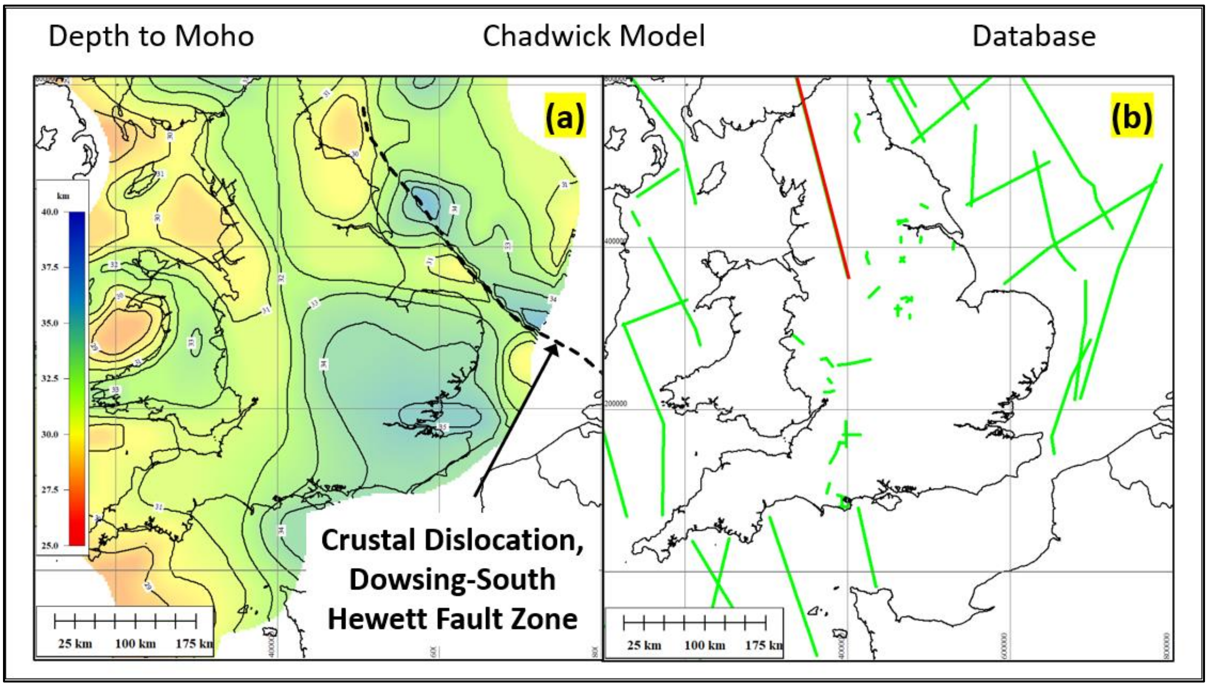


Figure 4 Chadwick Model (a) *Summary of the depth to Moho results of Chadwick & Pharaoh (1998). Areas of thicker crust are shaded blue with thinner crust shaded red. The black dashed line shows the location of an interpreted crustal dislocation following the path of the Dowsing-South Hewett Fault Zone.* ***(b)*** *The offshore database shows the locations of deep seismic reflection lines acquired by the British Institutions Reflection Profiling Syndicate (BIRPS). The red line shows the location of the LISPB refraction line.*

As Figure 4 shows, thinner crust is calculated beneath northwest and southwest England and thicker crust beneath south-central England, in general agreement with Figure 3 based on the tomographic work of Hardwick (2008) and discussed above. Data coverage of south-central England and the eastern part of the English Channel is sparse, however. In addition, Chadwick & Pharaoh (1998) show thinner crust below the Cardigan Bay Basin. They have also interpreted a significant Moho crustal dislocation running approximately along the line of the Dowsing-South Hewett Fault Zone within the Southern North Sea. This dislocation shows thicker crust located on the northeast side. A similar magnitude Dowsing-South Hewett Fault crustal displacement is shown by the gravity and magnetic modelling profile of Williamson et al. (2002).

The overlapping onshore England databases of Chadwick & Pharaoh (1998) and Hardwick (2008) allow a direct comparison to be made between the crustal depths obtained. This comparison shows an approximate static shift to exist of approximtely 3.5km, with the Chadwick & Pharaoh (1998) depths being the shallower (see Figure 10). Minor variation in the depth conversion parameters employed by Chadwick & Pharaoh (1998), and the use of a slightly different Moho-defining critical velocity used by Hardwick (2008), could probably reduce this shift. However, for the purpose of combining the two datasets into a composite map, the Chadwick & Pharaoh (1998) values have been used as the datum and a shift of -3.5km has been applied to the Hardwick (2008) values. The selection of

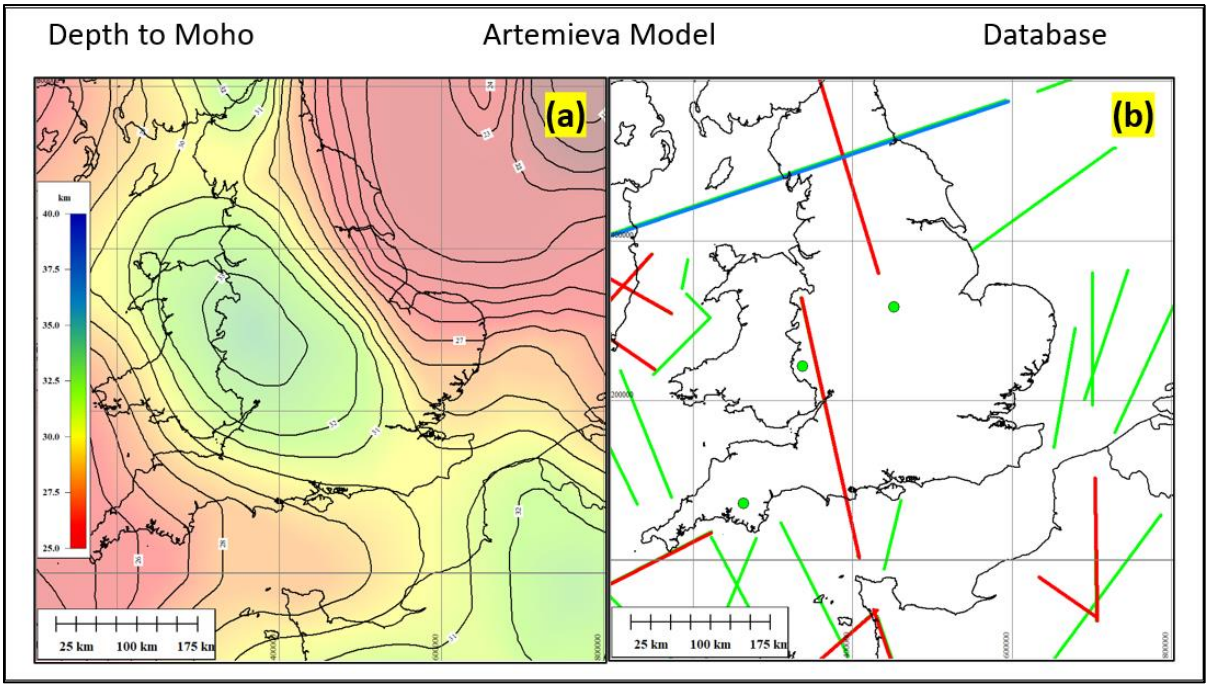


Figure 5 Artemieva Model (a) *Summary of the depth to Moho results of Artemieva & Thybo (2013). Thicker crust is shaded blue and thinner crust red.* ***(b)*** *Green, red and blue lines represent the locations of deep seismic reflection profiles, refraction lines and wide-angle reflection profiles respectively (for details see Artemieva & Thybo (2013)). The figure shown here follows the original figure of Artemieva & Thybo (2013) in which some lines are slightly mispositioned. The green coloured circles show the positions of receiver function studies.*

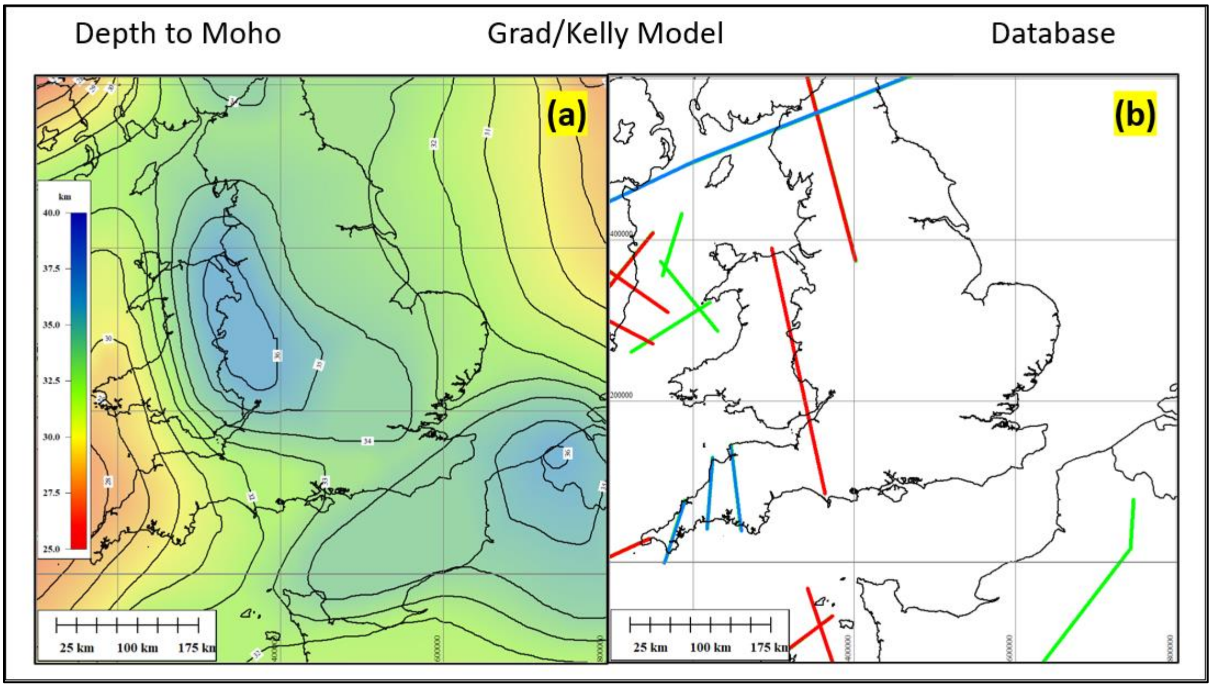


Figure 6 Grad/Kelly Model (a) *Summary of the depth to Moho results of Grad et al. (2009) after Kelly et al. (2007). Note the difference in Moho depths between Figures 5(a) and 6(a) beneath the coast of northeast England, an area with sparse data coverage.* ***(b)*** *Database of the Grad et al. (2009) study. Green, red and blue lines represent the locations of deep seismic reflection profiles, refraction lines and wide-angle reflection profiles respectively (for details see Kelly, et al. (2007).*

the Chadwick and Pharaoh (1998) work as a datum was made because their values are in agreement with the values derived from several of the other studies described below.

Artemieva Model Estimates of Moho topography across the whole European Plate were carried out by Artemieva & Thybo (2013) and Grad et al. (2009). The Artemieva & Thybo (2013) study utilised a wide range of regional publications incorporating many seismic profile and receiver function studies, and provides a comprehensive regional estimate of Moho depth across a wide area. The results and database of Artemieva & Thybo (2013) extending across England are shown within Figure 5.

Grad/Kelly Model For the onshore UK, and for the central and western English Channel, the Moho map produced by Grad et al. (2009) (Figure 6) follows the work of Kelly et al. (2007) who compiled a regional model of P-wave crustal velocity using deep and wide-angle reflection and refraction profiles. Unfortunately, Artemieva & Thybo (2013), Grad et al. (2009) and Kelly et al. (2007) did not fully incorporate the results offered by the grid of BIRPS deep reflection seismic lines surrounding Britain. However, their studies represent comprehensive regional results and allow the more locally-detailed results of Hardwick (2008) and Chadwick & Pharaoh (1998) to be placed in a wider regional context. In common with other studies, the Moho depths of Figures 5(a) and 6(a) show thinner crust beneath southwest England and an area of thicker crust within central England, but the lack of data over eastern, central and southern England explains the differences with the Harwick map.

Tomlinson Model Tomlinson et al. (2006) (Figure 7) investigated crustal and upper mantle velocity variations beneath the British Isles using receiver functions derived from thirty-four three-component seismic stations. (Grad, et al., 2009) continued this work and incorporated data from southern Ireland (Landes, et al., 2006). The contoured grid of Figure 7 shows the work of Grad et al. (2009). Despite the sparce nature of the dataset, resulting in a smoothed Moho topography, the derived structure shows general agreement with other studies.

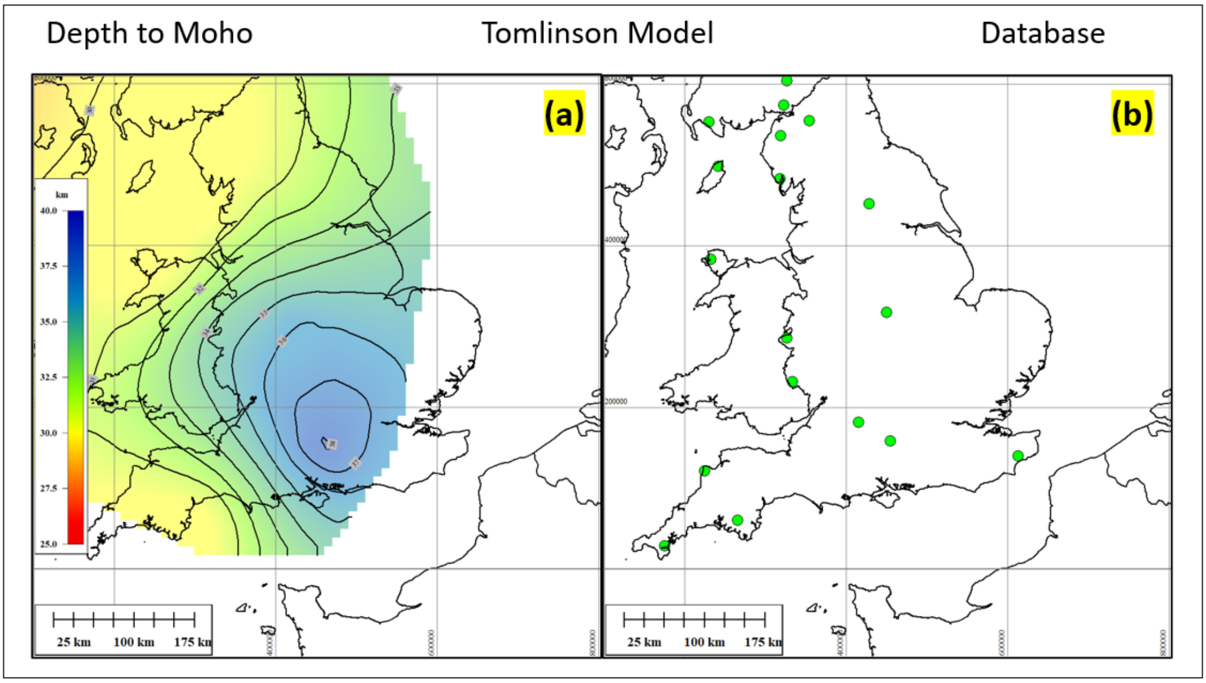


Figure 7 Tomlinson Model (a) *Summary of the depth to Moho results of Tomlinson et al. (2006).* ***(b)*** *The green coloured circles show the locations of the receiver function analyses.*

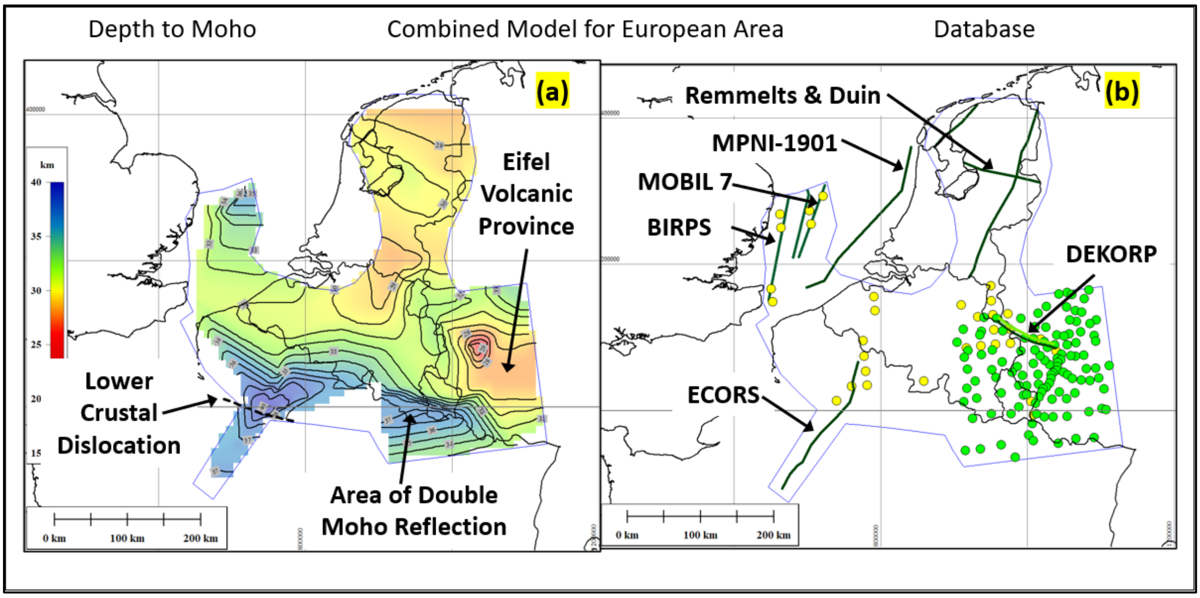


Figure 8 Combined Model for European Area (a) *Summary of the depth to Moho results of Sichien et al. (2012), Budweg et al. (2006), Remmelts & Duin (1990) and Matt & Hirn (1988).* ***(b)*** *Composite database. The yellow circles show the locations of Moho depths calculated by Sichien et al. (2012) supplemented with results derived from selected deep seismic reflection profiles, ECORS, DEKORP, BIRPS and Line MPNI-1901. The green circles show the receiver station locations of the Budweg et al. (2006) study. Moho depths along the ECORS profile have also been incorporated from Matt & Hirn (1988).*

Combined Model for European Area The depth to Moho results of Yudistira, et al., 2017, Sichien et al. (2012), Sichien (2010), Budweg et al. (2006), Remmelts & Duin (1990) and Matt & Hirn (1988) have been integrated within Figure 8. Their combined studies span areas of Belgium and parts of Holland, Germany and France. Three onshore deep reflection seismic lines were acquired over Holland during 1986 and 1987 and an interpretation of the depth to Moho undertaken by Remmelts & Duin (1990). Sichien et al. (2012) evaluated Moho depths beneath Belgium by analyses of Moho reflection arrival times measured from earthquakes and explosions located within Belgium, Germany and the Southern North Sea. Sichien et al. (2012) also integrated results from selected parts of deep regional seismic reflection profiles; ECORS (Matt & Hirn, 1988), DEKORP (DEKORP Research Group, 1991), BIRPS (Klemperer & Hobbs, 1991) and MPNI-1901 (Rijkers & Duin, 1994) (for locations see Figure 8). Receiver function analyses and tomography have been used by Budweg et al. (2006) to investigate deep structure of a possible mantle plume located beneath the Eifel Volcanic Province in western Germany. As part of the Budweg et al. (2006) study, a Moho depth map was produced showing crustal thinning beneath the Eifel Volcanic Province to approximately 28km from a surrounding value of approximately 32km.

Of note within Figure 8 is the thickening crust to the south of the mapped area. This appears to be associated with an east-west trending zone of complex Moho structure. To the west, a lower crustal dislocation is interpreted on the ECORS seismic line by Matt & Hirn (1988). To the east, an area with an apparent double Moho reflection is explained by Giese (1983) as a Variscan-aged, thrusted, mantle wedge inserted into the middle crust. Budweg et al. (2006) interpret an area of slightly thinned crust located beneath the Eifel Volcanic Province corresponding with the interpreted position of a possible Cenozoic mantle plume, an area currently undergoing anomalous uplift (Kreemer, et al., 2020).

Lefort Model Lefort & Agarwal (2002) (Figure 9) undertook an evaluation of primarily French gravity data but with their study extending across the English Channel and slightly into southern England. Their model assumed an average depth to the Moho of 33.5km, derived by frequency spectrum analysis, and a density contrast of 0.4kg/m^3 at the Moho interface. The gravity data were low-pass filtered with a cut-off wavelength of 160 km, and then inverted to provide a modelled estimate of the

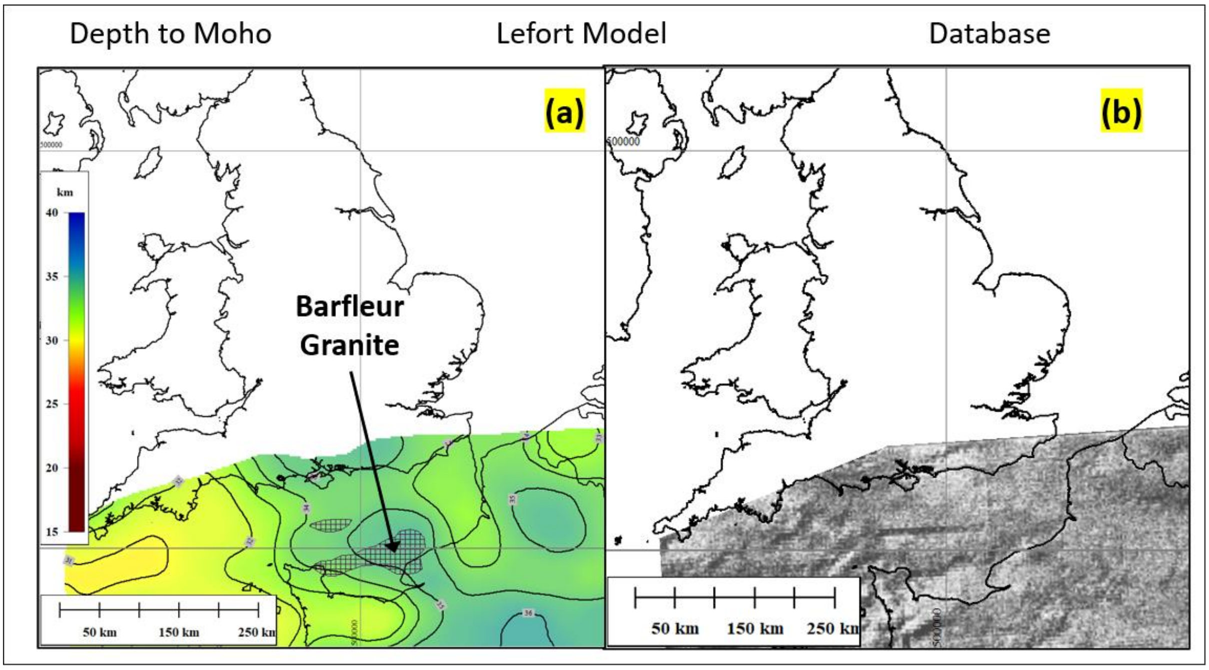


Figure 9 Lefort Model (a) *Summary of the Moho depth results of Lefort & Agarwal (2002). The location of the Barfleur Granite with an additional, smaller granite to the north is shown. The large granite may be interpreted by the Lefort & Agarwal (2002) inversion method as slightly deeper Moho.* ***(b)*** *Database map, the digitally-shaded relief shows the location of the input gravity data.*

depth to Moho. Unfortunately, there are large gravity anomalies present, probably unrelated to Moho depth variations. For example, a large and significant gravity low, associated with the easterly extension of the Barfleur Granite (Baptiste, 2016), is located in offshore northern France. This feature has approximate dimensions of 140km by up to 55km (see Figure 9) and consequently its presence may 'leak through' the low-pass 160km filter to be inverted as a possible Moho depression. Consequently, the Lefort & Agarwal (2002) results should be regarded with caution. However, where their gravity results abut and overlap the Chadwick & Pharaoh (1998) interpretation of the SWAT 11 (South-West Approaches Traverse, (Klemperer & Hobbs, 1991)) deep seismic reflection line, there is a reasonable match. To achieve numerical agreement with the datum of the Chadwick & Pharaoh (1998) results, a static shift of -1km was applied to the Lefort & Agarwal (2002) data.

In addition, the gravity inversion study assumes the filtered long-wavelength gravity anomalies to be solely attributed to Moho depth changes and, as will be discussed later, this is not necessarily the case. Lefort & Agarwal (2002) accept that their map may not show true Moho depths but that it should correctly represent relative Moho undulations. In general agreement with Hardwick (2008) and Chadwick & Pharaoh (1998), the map of Figure 9 shows thinner crust in the area of the western English Channel.

Production of the Composite Moho Depth Map based upon Selected Parts of the Published Models

The presence of thinner crust beneath northwest and southwest England and thicker crust beneath southern-central England is common to the published studies presented here. There are, however, some significant differences between the various analyses. As may be seen from Figures 3 to 9, the distribution of datasets used in the various studies varies considerably and many of the differences in mapped Moho topography may be attributed to the differing concentration and extent of the various datasets utilised. In addition, some differences may be introduced by the contrasting techniques employed. The earthquake tomographic work of Hardwick (2008) offers the densest, and possibly most comprehensive, dataset for onshore England. Offshore, in the near-coastal waters surrounding Britain, Chadwick & Pharaoh (1998) have utilised all available deep reflection seismic data and they would appear to provide the optimum and most detailed interpretation for this offshore area. Over the area of Belgium and parts of Holland, Germany and France, a combination of the studies of Sichien et al. (2012), Sichien (2010), Budweg et al. (2006), Remmelts & Duin (1990) and Matt & Hirn (1988) may offer the most consistent and reliable Moho structure. Extending beyond the onshore and proximal offshore areas, the work of Kelly et al. (2007), Grad et al. (2009) and Artemieva & Thybo (2013) provides a regional and widespread assessment of Moho depths, although there are some significant differences between these three studies. An attempt has been made to combine the benefits of the differing published studies in the composite Moho topographic map of Figure 11(a), produced by combining selected parts of the various published studies, as shown by the database key map of Figure 11(b).

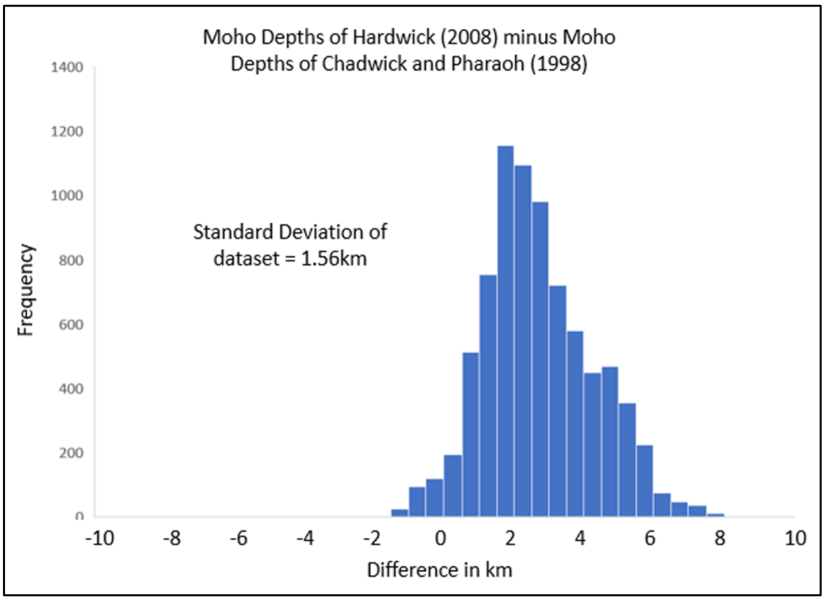


__Figure 10__ Histogram showing the difference between the grids derived from the Hardwick (2008) and Chadwick and Pharaoh (1998) Moho depth maps prior to the application of a -3.5 km shift applied to the Hardwick (2008) values.

In the composite map, the results of Chadwick & Pharaoh (1998) were taken as the datum and static shifts of -3.5km (see Figure 10) and -1km were applied to the Hardwick (2008) and the Lefort & Agarwal (2002) maps respectively. No static shifts were necessary for the contours from the other sources integrated. All contours were digitised from the original published maps, hand-smoothed across segment boundaries and then re-digitised. The resulting contour-set was gridded to produce the final composite Moho map of Figure 11(a). Consequently, the compilation attempts to include those parts of individual studies based upon more detailed and reliable datasets. It is important to be aware that the composite map is an amalgamation of different datasets derived from diverse geophysical techniques and with a highly variable data density. As such, the map must be regarded as tentative, with reliability varying across the map. Nevertheless, it is possible to make some general comments regarding the observed crustal thickness changes, and the map has been used to estimate the gravity effect of the mapped varying Moho topography.

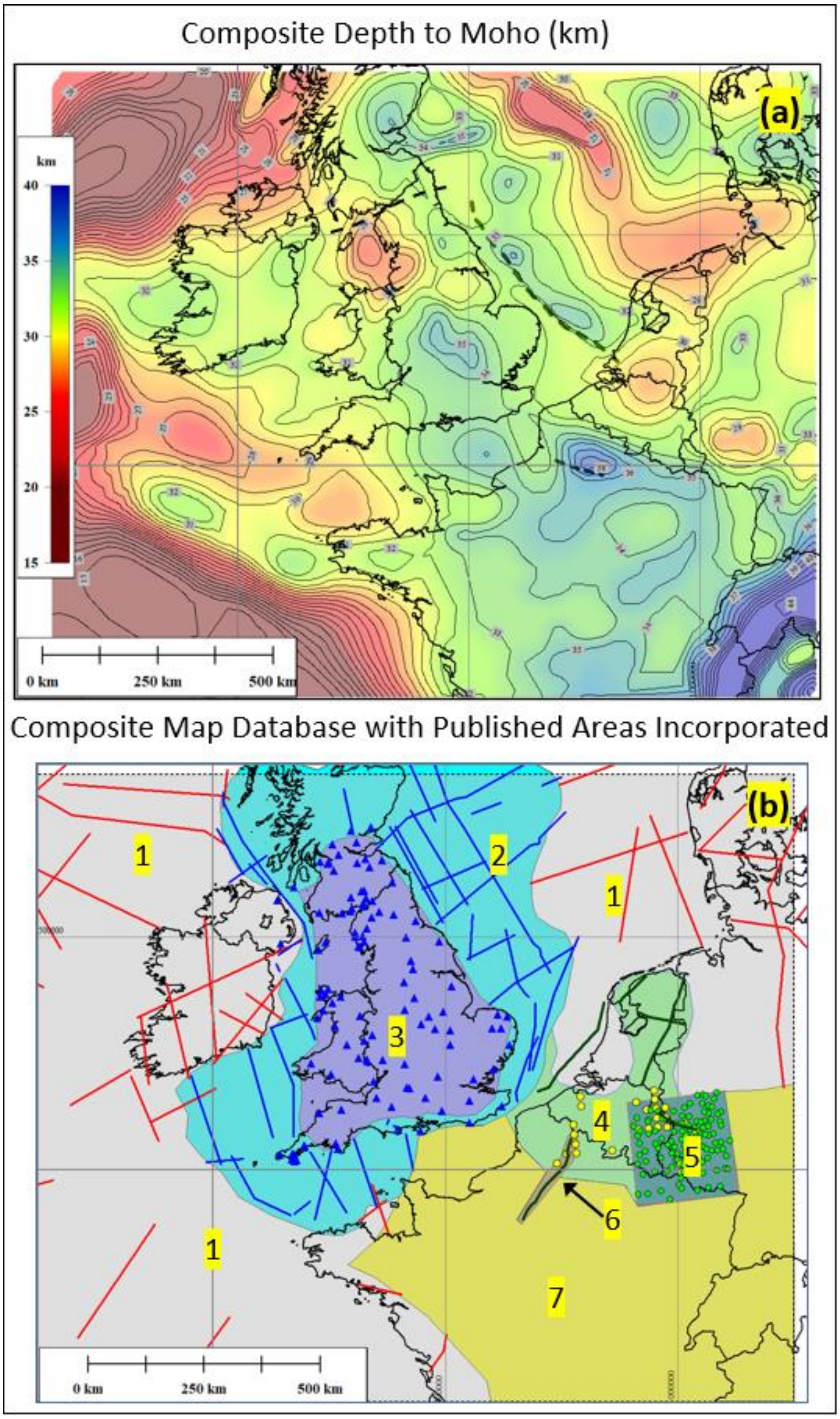


Figure 11 (a) *Composite depth to Moho with contour interval of 1km. Shallower Moho is shown by red shading, deeper Moho by blue/green shading. Three areas of possible lower crustal/upper mantle dislocation are shown by the black dashed lines. The line within the Southern North Sea is taken from Chadwick & Pharaoh (1998), the line within northern France shows the location of a dislocation mapped by Matt & Hirn (1988) on the ECORS deep seismic profile, and the line of the Iapetus Suture across northern England is taken from Evans et al. (2002).* ***(b)*** *Database map showing the parts of the various published Moho maps incorporated and their associated databases; 1- Grad et al. (2009) and Kelly et al. (2007), 2- Chadwick & Pharaoh (1998), 3- Hardwick (2008), 4- Sichien et al. (2012) and Rijkers & Duin (1994), 5- Budweg et al. (2006), 6- Matt & Hirn (1988) and 7- Lefort & Agarwal (2002).*

PART TWO - 3D Moho Gravity Model and Comparison with the Observed Background Gravity Field

The Moho surface of Figure 11(a) was gridded at a 20km grid interval and was used as the input structure to a Moho 3D gravity model. Two cases were run, assuming density contrasts at the Moho of +0.3kg/m^3 and +0.4kg/m^3. The models calculate the gravity effect of the Moho topography and the results for the +0.3kg/m^3 case are shown in Figure 12(b) (Model Map). As an example of the relationship between Moho depth and related gravity anomaly, a widespread crustal thinning of 1km would produce a positive gravity anomaly of 12.5mGal (for the +0.3kg/m^3 density contrast case) or 16.8mGal (for the +0.4kg/m^3 case).

Figures 12(a) and 12(b) allow a comparison to be made between the Model Map (3D gravity model results, +0.3kg/m^3 case) and the inferred regional gravity field, as defined by the Profile Map (derived from 2.5D modelled profiles). When comparing the two maps, there is general agreement in the location and amplitude of the main anomalies. Both maps display gravity high areas over northwest and southwest England with a broad area of low values located over south-central England. Values rise northeastwards across the Southern North Sea. The general agreement between the two maps strongly suggests, as may be expected, Moho topography to be an important factor in producing the observed background regional gravity field.

There are, however, some notable variations and Figure 13 displays the Difference Map where the difference between Profile Map (the inferred regional field) and the Model Map (the Moho model calculated gravity values, +0.3kg/m^3 case) is shown. Figure 13 therefore, shows the residual gravity field remaining after removal of the calculated Moho effect. Four notable areas, Anomalies A, B, C and D, are recognised on the Difference Map, three with anomaly amplitudes of the order of +15 to +20mGal (A, B and D) and one with an anomaly of -20mGal (C). Anomaly, A, is located over the central and northern parts of the Midlands Microcraton. The southern anomaly, B, lies over the English Channel, with highest amplitude to the southwest of the gravity lineament described by (Pullan & Donato, 2021) and here called the Southwest England Lineament. To the east of the Isle of Wight, the anomaly is weaker and is controlled by the possibly less reliable gravity inversion study. Anomaly C lies over the onshore area adjacent to the Irish Sea and possibly extends eastwards. Anomaly D lies within the Southern North Sea, to the northeast of the Dowsing-South Hewett Fault Zone.

The four anomalies, A, B, C and D, indicate the presence of features independent of Moho topography. Possible origins include slight changes in crustal density or the presence of extensive deep bodies not included in the modelled profiles. On all of the 2.5D profiles, the regional field has been defined on the basis of a constant background density of 2.72kg/m^3. Any variation in this value will appear as an anomaly in Figure 13. For example, a variation of +15mGal, as seen for Anomaly A, could be produced by an average crustal density increase of approximately +0.02kg/m^3. Conversly, Anomaly C might suggest an average density decrease of an approximately similar magnitude.

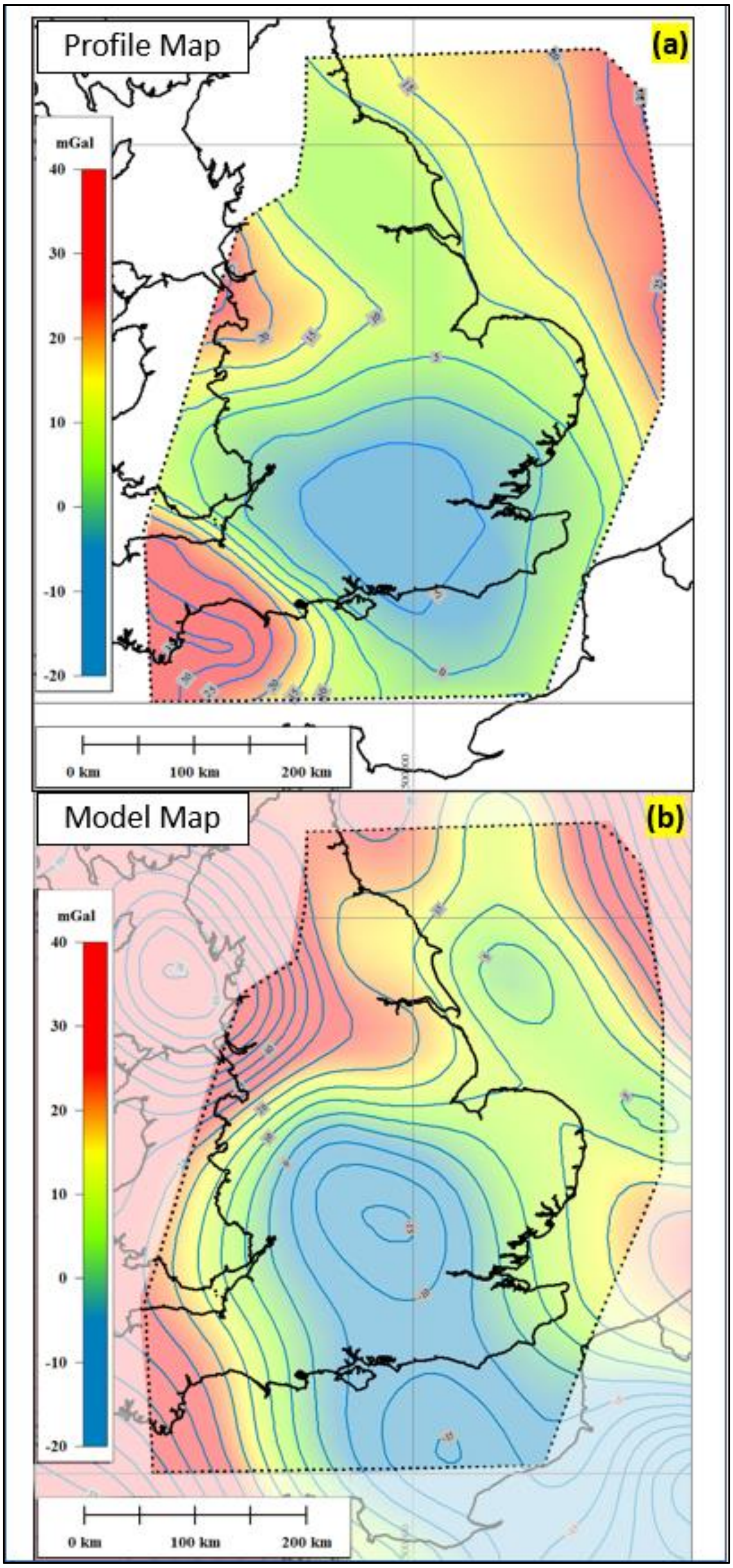


Figure 12 ***(a) Profile Map*** *The regional gravity field as inferred from the 2.5D modelled profiles****. (b) Model Map****. The calculated gravity values from the 3D Moho Model assuming a density contrast at the Moho of +0.3kg/m*^{3}*. In both cases the contour interval is 5mGal and high gravity areas are shaded red with low areas shaded blue.*

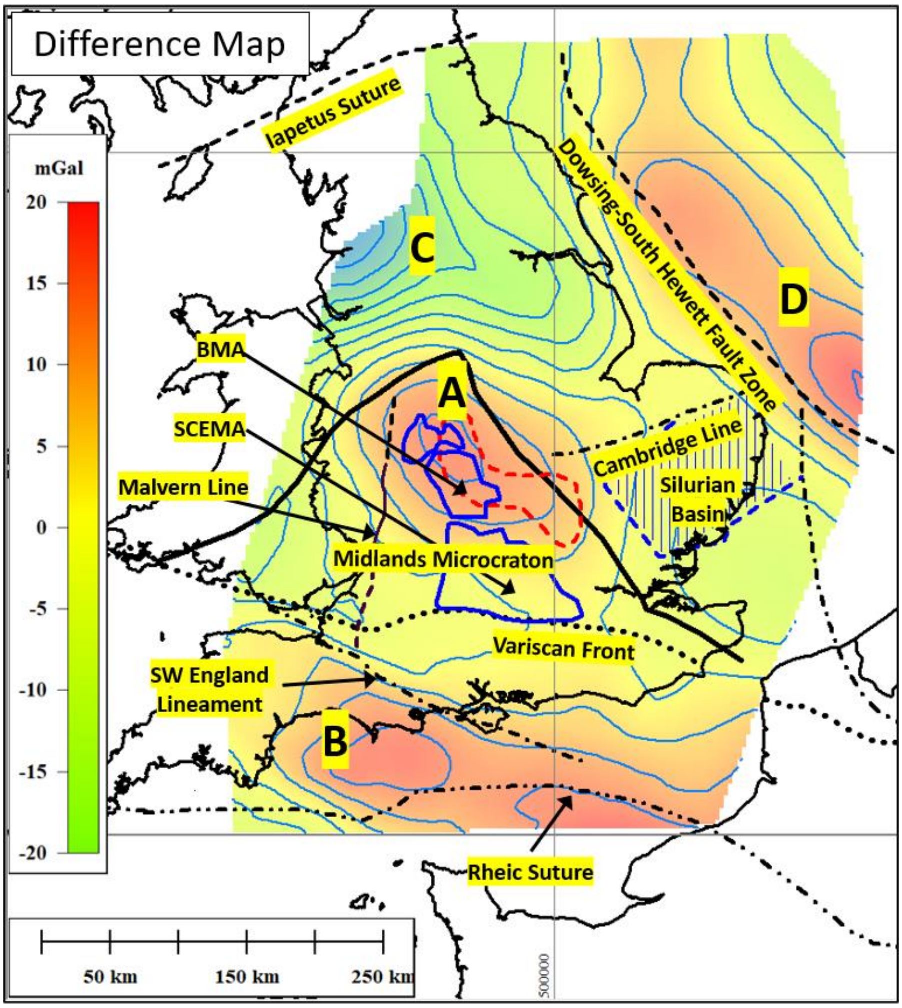


Figure 13 Difference Map *The difference between the regional field defined by the 2.5D profiles and the calculated gravity values from the 3D Moho model i.e. Map 12(a) minus Map 12(b). Positive numbers are shaded red and negative numbers blue. There are four significant features; a positive anomaly located over the northern Midlands Microcraton (A), a similar amplitude positive anomaly located over the western English Channel (B), a negative anomaly over northwest England (C) and a positive anomaly to the northeast of the Dowsing-South Hewett Fault Zone (D). Locations of Midlands Microcraton and Malvern Line from Butler (2018), Variscan Front from Pharaoh (2018) and the SW England Lineament from Pullan & Donato (2021). The line of the Rheic Suture is taken, with slight modification, from Baptiste (2016) and Schulmann et al. (2022) The red dashed line shows the 35km Moho contour encircling the area of thickest crust taken from Figure 11(a). The blue polygons show the areas of the Birmingham (*BMA*) and South-Central England Magnetic Anomalies (SCEMA). The vertical hatch shows the approximate area of the Silurian Basin* (Woodcock & Pharaoh, 1993)

In summary, therefore, two independent effects are suggested to explain the observed regional gravity field. The first is the gravity effect of the known variations in crustal thickness associated with Moho topography. These are the anomalies shown on the Model Map (Figure 12(b)). The second is a possible variation in average crustal density as shown by the anomalies on the Difference Map (Figure 13). The combination of these two suggested contributions will, by definition, produce agreement with the observed background gravity field.

Discussion

Figure 14 shows part of the composite Moho depth structure map together with selected published tectonic lineaments. The locations of Midlands Microcraton and Malvern Line are taken from Butler (2018), the Variscan Front across England from Pharaoh (2018), and the SW England Lineament from Pullan & Donato (2021). The line of the Rheic Suture is taken, with slight modification, from Baptiste (2016) and Schulmann et al. (2022). The Dowsing-South Hewett Fault Zone follows Chadwick & Pharaoh (1998). The Variscan Front across northern France and Belgium is taken from Laurent et al. (2021) and the Brabant Crustal Boundary from Mansy et al. (1999). The Cambridge Line is extracted with slight modification from Woodcock & Pharaoh (1993). The edge of the Luneberg North Sea Microcraton follows Doornenbal & Stevenson (2010) and the Variscan Crustal Dislocation is extracted from from Matt & Hirn (1988). A discussion of the primary features of the Moho depth map follows.

Midlands Microcraton:- The Midlands Microcraton appears to demonstrate two zones with differing crustal characteristics. An area, approximately 100km wide and 200km long, runs down the northeastern side of the Microcraton. This zone demonstrates slightly thicker crust with values reaching in excess of 35km. The crust here also appears to have slightly higher average density as shown by the presence of Anomaly A (Figure13). A core of high magnetic susceptibility rocks is located within this zone of thicker, denser crust as witnessed by the Birmingham and South-Central England Magnetic Anomalies (Beamish, et al., 2016; Donato & Pullan, 2022). Elsewhere on the Microcraton, crustal thickness values are slightly thinner at approximately 33-34km with the crust appearing to have slightly lower density and with no large areas of increased magnetic susceptibility. The separation between the two zones is poorly defined due to the low resolution of the gravity study but appears to run with NW-SE trend across the Microcraton. Note that the Malvern Line does not appear to align with any significant crustal features.

A geological explanation for the zone of thickened, denser crust associated with a band of high susceptibility rocks is clearly required and these aspects are the subject of continuing studies.

Dowsing-South Hewett Fault Zone:- The Dowsing-South Hewett Fault Zone appears as a crustal dislocation with thicker crust of up to 35km located immediately to the northeast of the fault. Along the fault line, Chadwick & Pharaoh (1998) (Dowsing Reflector) and Blundell (1993) ('X' Reflector) interpret a southwesterly-dipping lower crustal/mantle seismic reflector intersecting and offsetting the Moho. The line of dislocation is considered to be a major tectonic feature and is interpreted by Doornenbal & Stevenson (2010) to represent the southwestern edge of the North Sea–Luneberg Terrane and by Pharaoh (2018) to suggest the presence of a southwesterly-dipping relic subduction zone of Ordovician age. Anomaly D of Figure 13 would support the presence of a major crustal discontinuity along the line of the Dowsing-South Hewett Fault Zone with thicker crust and an increase in average crustal density both located to the northeast. This agrees with the interpretations of Kearey & Rabae (1996) for the offshore MOBIL 7 seismic line.

Area between the Midlands Microcraton and the Dowsing-South Hewett Fault Zone and extending southwestwards into Belgium:- Within this area, the crust may be divided into three coherent segments. It is of interest to compare these possible segments with the Total Intensity Magnetic Anomaly Map shown in Figure 15 (Chacksfield, et al., 2006).

(i) **Fenland Block** - Northwest of the Wash and to the northwest of the Cambridge Line (location shown in Figure 14 modified slightly from Woodcock & Pharaoh (1993)), the crust thins to approximately 30km. In this area, the magnetic data show a complex anomaly character. These magnetic anomalies are thought to be associated with a shallow to moderate depth magnetic basement (2-4km) and/or intrusions including non-magnetic granitic bodies. Within the complex magnetic signature, two positive magnetic trends occur with NW-SE orientation. These are the Burnley to Stamford and the Furness to Norfolk Magnetic Anomalies (Donato & Pullan, 2022) (for locations see Figure 15). Differing possible origins for these anomalies have been suggested involving Precambrian basement (Wills, 1978; Cornwell & Walker, 1989), Ordovician intrusive rocks (Allsop, 1987; Pharaoh et al., 1993) or early Paleozoic metasediments (Lee, et al., 1993). Donato & Pullan (2022) prefer an interpretation involving magnetic sedimentary sequences in the Ordovician (Wilson & Cornwell, 1982) supplemented by Upper Ordovician igneous activity. A marked magnetic character change occurs at the position of the Cambridge Line. This is clearly defined in the spectral decomposition studies carried out by Beamish et al. (2016). Granites are identifiable as gravity lows, often with flanking positive magnetic anomalies, and are shown on Figure 15 as green coloured features (Bott et al., 1978; Chroston et al., 1987; Allsop, 1987; Allsop et al., 1987; Donato & Megson, 1990; Chacksfield et al., 1993; Rabae & Kearey, 1997; Donato, 2019 and Donato & Pullan, 2022).

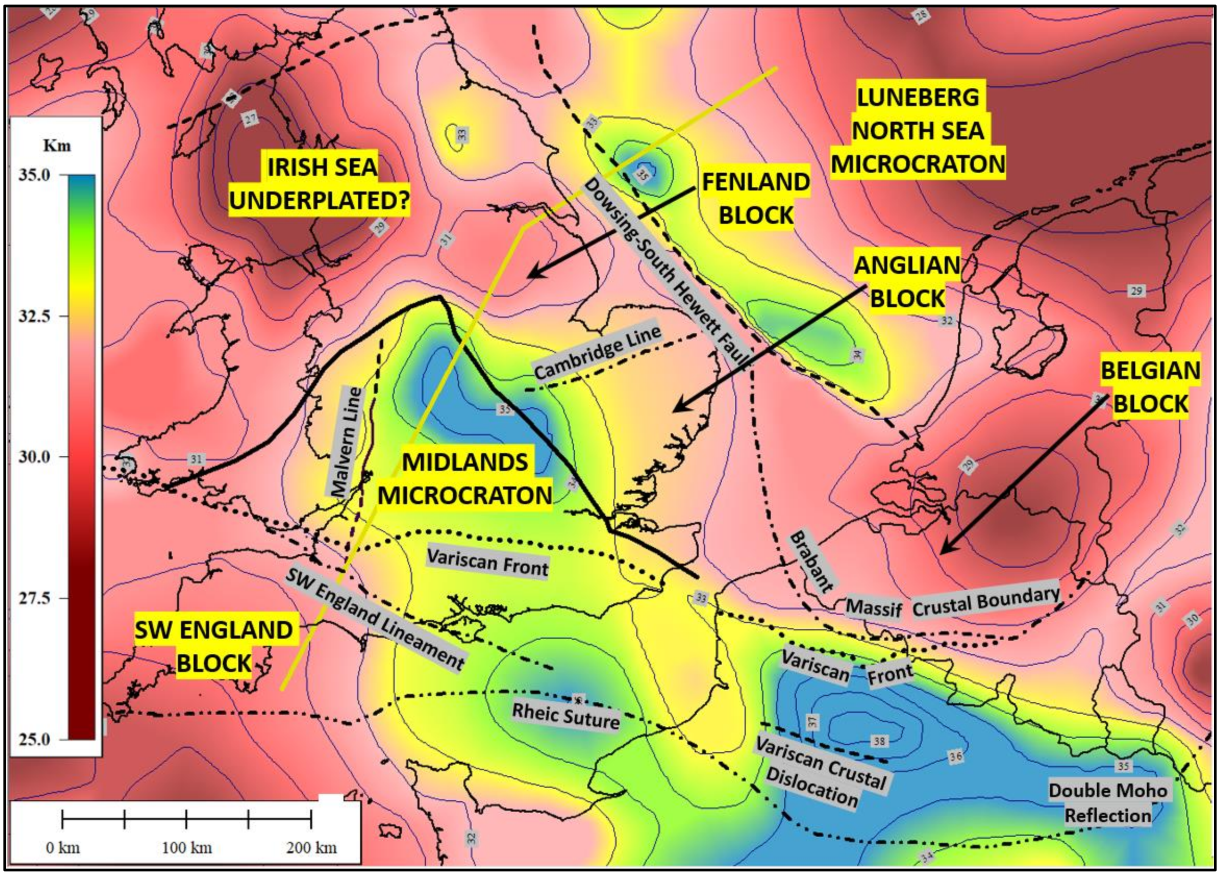


__Figure 14__ Part of the composite map constructed showing the depth to Moho. Shallow Moho areas are shaded red with deep areas shaded blue. The grid shading differs from Figure 11(a). The sources of the superimposed and labelled tectonic lineaments are as Figure 13 with the following additions:- Dowsing-South Hewett Fault Zone from Chadwick & Pharaoh (1998), Variscan Front across northern France and Belgium from Laurent et al. (2021) and Brabant Crustal Boundary from Mansy et al. (1999), Cambridge Line with slight modification from Woodcock & Pharaoh (1993), Luneberg North Sea Microcraton from Doornenbal & Stevenson (2010) and Variscan Crustal Dislocation from Matt & Hirn (1988). The line of the cross-section of Figure 16 is shown by the yellow line.

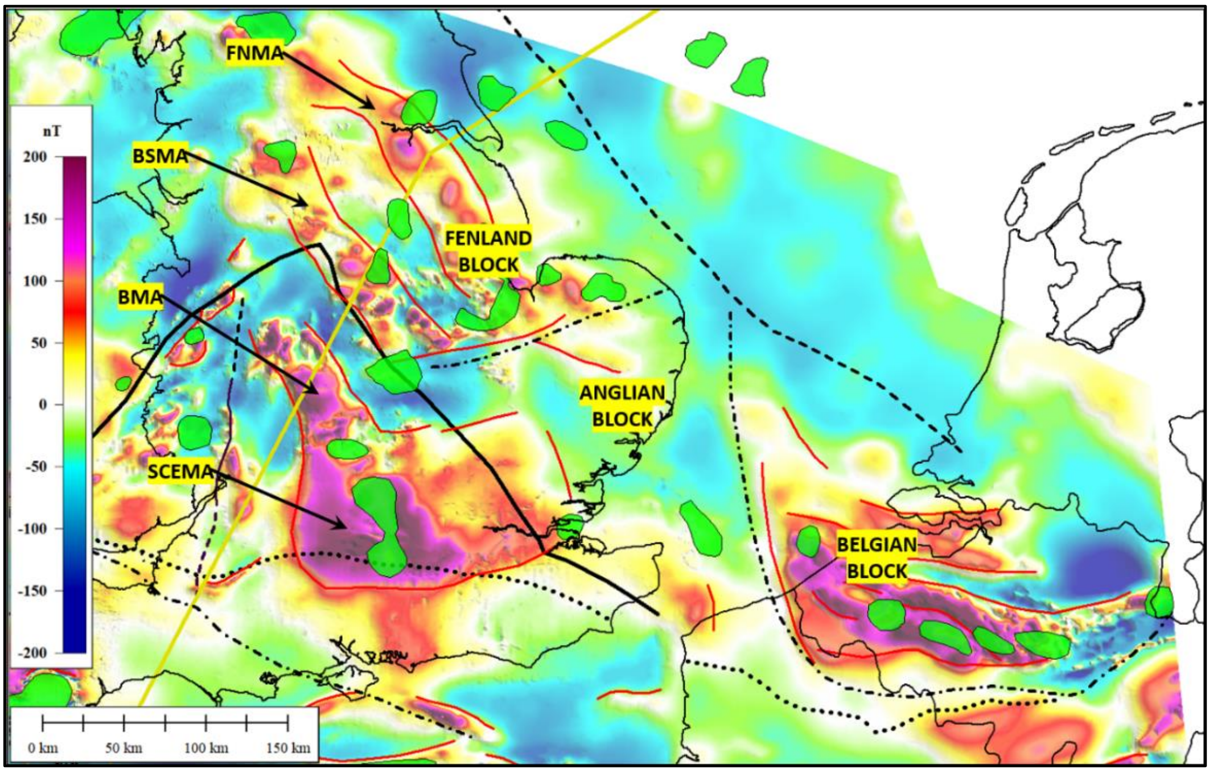


__Figure 15__ Total magnetic field (Chacksfield, et al., 2006) with tectonic lines superimposed from Figure 14. The three proposed crustal blocks are labelled and show markedly different magnetic characteristics. Locations of postulated granitic intrusions are shown by green shaded features (see text for details). Significant magnetic (red) lineaments have also been added and the magnetic anomalies (MA) labelled as follows: SCEMA-South Central England, BMA-Birmingham, BSMA-Burnley to Stamford and FNMA-Furness to Norfolk.

(ii) **Belgium Block** - To the southeast, a similar slight crustal thinning occurs with Moho depths of up to 28km located beneath Belgium and southern Holland and extending into the offshore area. Associated with this zone, the magnetic data again show a strong anomaly character, interpreted by Chacksfield et al. (1993) to be associated mainly with magnetic sediments of Cambrian (Tubize Group) age. The magnetic data show an abrupt and major change to the west and south along the line of the Brabant Crustal Boundary (Mansy, et al., 1999). Again, granitic intrusions are present (Everaerts et al., 1996; Mansy et al., 1999) as demonstrated by the presence of circular low-gravity features.

(iii) **Anglian Block** - Between these two areas of thinner crust and their associated strong magnetic character, the crust thickens slightly to approximately 33km beneath the Silurian Basin of East Anglia (Woodcock & Pharaoh, 1993) (see Figure 14) and extends eastwards into the offshore area. A quiescent magnetic pattern exists here, suggesting an absence of igneous intrusions with a deep magnetic basement present beneath thick non-magnetic Silurian, and possibly older, sediments. Lee et al. (1993) have modelled the magnetic anomalies present along the nearby offshore BIRPS line (MOBIL 7, for location see Figure 8(b)) and interpret the weak magnetic anomalies to originate from sources below 10km.

Southern and Southwest England, the English Channel and Northern France - Variscan movements are likely to have exerted a strong influence on crustal structure to the south. Within northern France, the crust thickens to 38km between the possible deep crustal dislocation seen on the ECORS seismic line (Matt & Hirn, 1988) and the surface location of the Variscan thrust front (Laurent, et al., 2021). West of this area and offshore, the crust shows minor changes in thickness, varying between 33 and 35km, until a significant thinning occurs beneath SW England and the western English Channel. South of Cornwall, the crust thins to approximately 28km. Anomaly B of Figure 13 shows that, in addition to the westward crustal thinning, there is a possible increase in background density located beneath the English Channel and southwest England. Anomaly B may best be considered in two parts:-

(i) To the west of the Isle of Wight, Moho structure is defined by the interpretation of Chadwick and Pharaoh (1998) using the SWAT deep reflection seismic lines. The northern edge of Anomaly B aligns with the WNW-ESE trending SW England Lineament, corresponding with the northeasterly edge of the large residual positive gravity anomaly of Pullan and Donato (2021). It is suggested (Pullan & Donato, 2021) that this line is a major crustal discontinuity along which a large dextral translation of a southwest England crustal block took place (Holder & Leveridge, 1986; Woodcock et al., 2007).

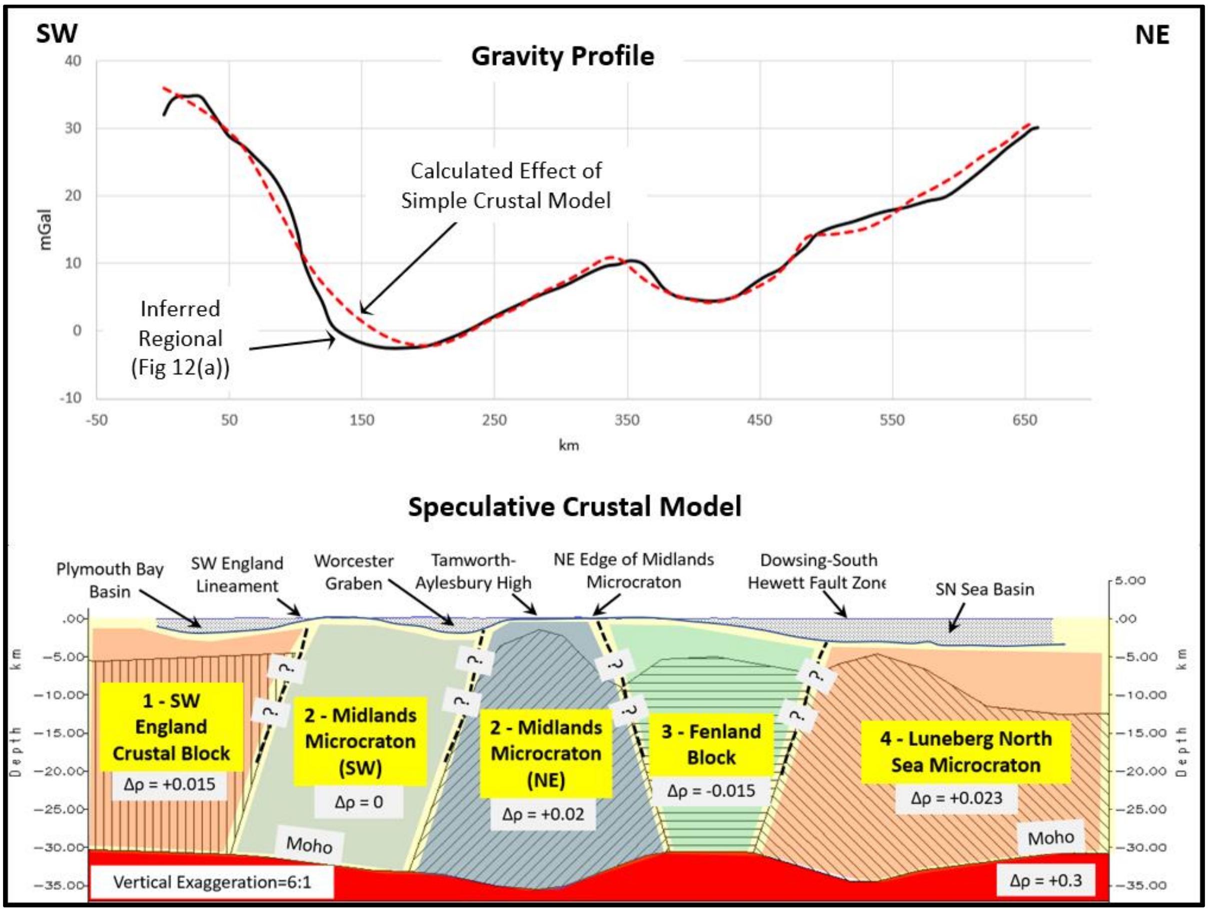
(ii) To the east of the Isle of Wight, Moho mapping relies upon the gravity inversion study of Lefort & Agarwal (2002) but, as discussed earlier, this study may have limitations. Anomaly B appears to extend weakly beneath the central and eastern English Channel with its northern boundary running, with ESE trend, approximately along, or south of, the English south coast. Further to the southeast, the anomaly merges with the location of the Rheic Suture (Baptiste, 2016; Schulmann et al., 2022).

Interestingly, no significant crustal density changes appear associated with the Variscan Front, commonly drawn further to the North, despite this line being coincident with a change in basement depth at the southern boundary of the South-Central England Magnetic Anomaly (Donato & Pullan, 2022). This finding is in agreement with the results of the profile work, where Southern England appears to be an extension of the Midlands Microcraton during the Lower Paleozoic but that the boundary between the two areas was tectonically reactivated during the Variscan movements. The Moho structure across southern England and the eastern English Channel is, however, poorly defined due to inadequate deep data coverage.

***Irish Sea and Northwest England* -** In the northwest corner of the map, crustal thickness reduces to approximately 27km beneath the Irish Sea and extends into northwest England. Data coverage is however sparse, particularly for the area between the Isle of Man and Cumbria. The assumed thinner crust may contribute to the positive regional gravity values rising to +27mGal. Anomaly C of Figure 13, however, suggests that, in addition to the positive gravity effect related to the crustal thinning, there may be a reduction in average crustal density or the presence of a deep, low-density body. Over the area of the Irish Sea and extending into northwest England, Arrowsmith et al. (2005) have identified a P-wave, low-velocity anomaly extending from the base of the crust to over 100km depth. This is interpreted in terms of 'a hot, low-density upwelling in the uppermost mantle' being possibly related to crustal underplating (Brodie & White, 1994; Al-Kindi, et al., 2003; Shaw Champion, et al., 2006; Maguire, et al., 2011; Davis, et al., 2012; Luszczak, et al., 2018) along an arm extending laterally southwards from the Iceland Plume into the UK. Consequently, the lower crustal structure of the Irish Sea and the adjacent onshore area may be anomalous, with Anomaly C signifying the presence of the suggested deep, low-density feature.

Speculative Crustal Model

It is suggested that the changes in geophysical character noted above, when combined with the locations of published tectonic lineaments, allow the area to be divided into of a series of adjacent crustal units. These include the Fenland, Anglian, Belgian and Southwest England Blocks, the Midlands Microcraton and the Luneberg North Sea Terrane. By way of simple illustration, a proposed crustal geometry is shown by the speculative summary map and 2D profile of Figure 13. The profile crosses four of the proposed crustal features and the model incorporates two separate gravity effects. These are: (i) the effect of the crustal thickness changes (as defined by the composite Moho map of Figure 14) and (ii) the effect of small average density changes assumed for the notional crustal blocks (as related to Anomalies A, B and D). When these two separate gravity effects are summed, it becomes possible to explain the inferred regional gravity field.



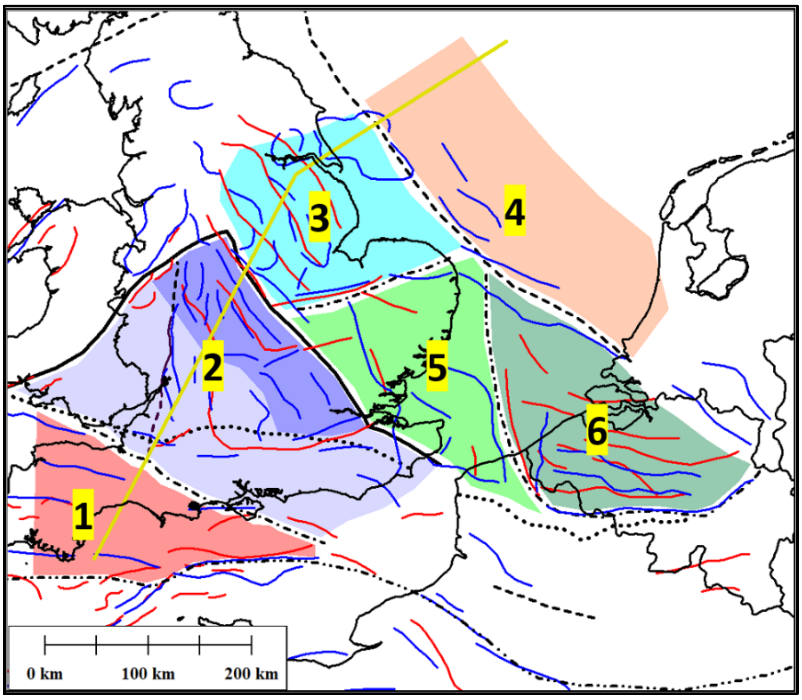


Figure 16 Speculative and simplistic SW-NE 2D crustal cross-section with calculated gravity anomaly. The location of the profile is shown by the yellow line (also shown in Figures 14 and 15). The profile illustrates that the combination of the assumed average crustal density changes when coupled with the calculated effect of the Moho topography are able to explain the inferred regional gravity field. The lower map shows the speculative crustal blocks coloured as for the cross-section and labelled as follows:- 1-SW England, 2-Midlands Microcraton (with possible crustal density difference shown by colour shading change), 3-Fenland, 4-Luneberg North Sea Microcraton, 5-Anglian and 6-Belgium. Blue and red lines show significant gravity and magnetic lineaments respectively.

It is interesting to note that crustal blocks with apparently lower average crustal density lie above areas of slightly elevated Moho. Also, Blocks with higher average density lie above depressed Moho. A simple Airy-type calculation using the excess mass associated with the +0.02kg/m^3 density increase of the northeastern Midlands Microcraton Block and assuming a density contrast at the Moho of

0.3kg/m^3, results in a depression of the Moho of approximately 2km beneath the Microcraton. In a similar way, the mass deficit associated with Fenland Block density decrease of -0.015kg/m^3 produces a calculated Moho uplift of approximately 1.5km. Deflections of this magnitude are broadly similar to those shown in the 2D model. Consequently, the suggestion, albeit very speculative at this early stage of analysis, is that the crustal blocks may currently be close to isostatic equilibrium.

The gravity model shown is not intended to represent crustal structure in detail, merely to illustrate, in a semi-quantitative way, that small density changes extending over a significant part of the crust, when coupled with the likely gravity effect of the Moho topography, are able to explain the inferred regional gravity field. No polygon attempting to simulate the lower crust has been included. As such, a full and integrated crustal profile model has not been attempted and lies outside the scope of this paper.

Conclusion

A series of 2.5D gravity profiles has been used to define the significant regional gravity field covering England and part of the Southern North Sea. Two contributions are thought to comprise this regional field. The first contribution is produced by the gravity effect of the known Moho topography. The second contribution is thought to be caused mainly by changes in average crustal density. The addition of these two separate contributions enables the inferred regional gravity field to be explained. This explanation leads to the speculative proposal for a series of adjacent, crustal units including the Fenland, Anglian, Belgian and Southwest England Blocks, the Midlands Microcraton and the Luneberg North Sea Terrane.

No attempt has been made to attribute ages to the proposed blocks nor to explain a geological evolution involving their genesis. They are simply defined on the basis of observed geophysical characteristics in conjunction with published tectonic boundary lineaments. The tentative suggestions presented here clearly require further, more detailed consideration, involving the integration of the differing geological evolutions of the proposed individual crustal blocks or fragments and their historical interaction with each other. It is hoped to produce further publications that try to answer some of these outstanding and important questions.

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