Aeromagnetic data in the UK: a study of the information content of baseline and modern surveys across Anglesey, North Wales

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SUMMARY

A number of modern, multi-parameter, high resolution, airborne geophysical surveys (termed HiRES) have been conducted over the past decade across onshore UK. These were undertaken, in part, as a response to the limited resolution of the existing UK national baseline magnetic survey data set acquired in the late 1950's and early 1960's. Modern magnetic survey data, obtained with higher precision and reduced line spacing and elevation, provide an improved data set; however the distinctions between the two available resources, existing and new, are rarely quantified. In this contribution we demonstrate and quantify the improvements that can be anticipated using the new data. The information content of the data sets is examined using a series of modern processing and modelling procedures that provide a full assessment of their resolution capabilities. The framework for the study involves two components. The first relates to the definition of the shallow magnetic structure in relation to an ongoing 1:10k and 1:50k geological map revision. The second component relates to the performance of the datasets in defining maps of magnetic basement and assisting with larger scale geological and structural interpretation. One of the smaller HiRES survey areas, the island of Anglesey (Ynys Môn), off the coast of NW Wales is used to provide a series of comparative studies. The geological setting here is both complex and debated and cultural interference is prevalent in the low altitude modern survey data. It is demonstrated that successful processing and interpretation can be carried out on data that have not been systematically corrected (de-cultured) for non-geological perturbations. Across the survey area a wide number of near-surface magnetic features are evident and are dominated by a reversely magnetized Palaeogene dyke swarm that extends offshore. The average depth to the upper surfaces of the dykes is found to be 44 m. The existing baseline data are necessarily limited in resolving features < 1 km in scale; however a detailed comparison of the existing and new data reveals the extent to which these quasi-linear features can be resolved and mapped. The precise limitations of the baseline data in terms of detection, location and estimated depth are quantified. The spectral content of both data sets is examined and the longest wavelength information is extracted to estimate the resolution of magnetic basement features in the two data sets. A significant finding is the lack of information in the baseline data set across wavelengths of between 1 and ~10 km. Here the HiRES data provide a detailed mapping of shallow magnetic basement features (1 to 3 km) that display a relevance to current understanding of the fault-bounded terranes that cross the survey area. Equally, the compact scale of the modern survey does not provide deeper (> 3 km to upper surface)

assessments of magnetic basement. This further assessment is successfully provided by the larger scale baseline data which locates and defines a mid-crustal magnetic basement feature, centred beneath the Snowdon Massif, and illustrates that basement of similar characteristic extends beneath much of Anglesey.

1 INTRODUCTION

The existing national-scale onshore magnetic data for the UK was obtained by a series of aeromagnetic surveys flown between 1955 and 1965. A more sporadic series of multi-parameter, higher resolution, airborne surveys have been undertaken, largely for mineral reconnaissance, since that period. These surveys, along with other onshore airborne geophysical surveys which acquired magnetic data through to 1991, are described by Cornwell *et al*. (1995). The main, spatially coherent, onshore UK magnetic database still comprises the 530,648 points of the original and fully processed data set referred to here as the GSGB (Geological Survey Great Britain) magnetic data compilation. This data set formed the basis of the 1:1.5M UK magnetic map compilation published and described by the British Geological Survey (BGS, 1998). The underlying data set forms the baseline magnetic coverage of the UK. Modern geological map revision is typically undertaken at a scale of 1:10k and concealed geology and structure is often assessed using magnetic field information. In order to assist with such revision, the sampling of the available magnetic information must be adequate. By modern standards, the typical 2 to 4 km flight line separation and high elevation (~300 m) of the GSGB surveys provide only a low resolution assessment of onshore UK.

In order to establish a modern UK magnetic baseline data set, the BGS initiated a series of airborne surveys beginning in 1998. The new surveys included magnetic, radiometric and electromagnetic measurements that both individually, and in combination, offered high resolution geophysical assessments of the UK landmass. The set of surveys, referred to as HiRES (High Resolution airborne Resource and Environmental Surveys), were typically flown at low elevation (90 m or less) and ultimately a 'national-scale' line separation of 200 m was adopted. Only the HiRES magnetic data sets are discussed here since they update and potentially supersede existing information. The radiometric and electromagnetic data sets acquired represent new information.

It is self-evident that a modern magnetic survey, obtained with higher precision and reduced line spacing and elevation, will provide an improved data set. However the distinctions between the two available resources, existing and new, has not been fully explored or quantified. An example of some of the perpetual issues and difficulties arising in the near-surface geological interpretation of the existing GSGB data set can be found in Dagley *et al*. (2008). A further useful comparison of modern and legacy airborne magnetic data sets with marine exploration data across the Donegal Basin, Ireland is provided by Allsop *et al*. (2002).In order to understand the differing information content of the vintage and new data sets it is necessary to undertake a case study and subject the data to a series of modern processing and modelling procedures that provide a full assessment of their resolution capabilities.

The present study uses the relatively self-contained geological context area of Anglesey (Ynys Môn), North Wales where existing GSGB and new HiRES magnetic data sets exist. The island of Anglesey lies off the northwest coast of Wales, separated from the mainland by the Menai Strait. Primary geological surveying was published in 1920 and because of the relative antiquity of this data the island is currently undergoing targeted re-mapping by the BGS (Phillips, 2009). The HiRES survey was undertaken in response to this map revision. The geological and tectonic interpretation framework of the region is complex (and often disputed) so the provision of subsurface geophysical information is clearly of some relevance. The location of the Anglesey survey is shown in Figure 1.

The magnetic data obtained across Anglesey are challenging in that the strong response of a near surface dyke swarm potentially masks, and certainly interferes with, the response of deeper basement features. The processing undertaken involves an assessment of both the shallow and deep (basement) information contained in the two data sets.

2 GEOLOGICAL SETTING

The geology of Anglesey was originally described and mapped by Greenly (1919) who first used the term Mona Complex to describe the Neoproterozoic rocks that underlie much of the island. Here we refer to the work of Gibbons & Horák (1990) who described the Neoproterozoic in terms of three main terranes as shown in Figure 2. These fault-bounded blocks are collectively recognised today as the Monian Composite Terrane. This terrane is made up of smaller crustal fragments known as the Monian Supergroup, the Coedana Complex and Aethwy (Blueschist) Complex. These are overlain by a patchy Palaeozoic cover succession including remnants of an Ordovician-Silurian sedimentary marine basin, an Old Red Sandstone fluvial succession, as well as Carboniferous limestone and coal measures.

The Neoproterozoic rocks on Anglesey are discussed by Horák & Gibbons (2000). The Coedana Complex forms a denuded outcrop comprising upper amphibolite rocks (commonly referred to as gneisses), granite and a hornfels carapace. The complex includes the highest grade metamorphic rocks on the island, separating the greenschist facies Monian Supergroup, to the north-west, from the blueschist facies rocks, to the south-east. Because of the contrast in grade and the pressure-temperature conditions of formation, Gibbons and Horák (1990) have argued that these belts must have been generated in separate terranes and subsequently juxtaposed by faults. The north-west boundary of the complex is a post-Arenig brittle fault zone (Llyn Traffwll Shear Zone) whereas the south-east boundary is a wide ductile zone. Although Greenly (1919) concluded that 'the granite intruded and merged with the gneiss' and that they were contemporary, clear relationships are not exposed (Howells, 2007).

The blueschists of the Aethwy Terrane are one of the oldest occurrences of such rocks in the world and can be related to exhumation of a subducted oceanic slab between around 560-550 Ma (Dallmeyer & Gibbons, 1987). The unit is isolated from all other tectonostratigraphical units by ductile shear zones; the Berw Shear Zone in the north-west and the Bryn Meurïg Shear Zone in the south-east. The Berw Fault (see Figure 4) is the most westerly of the Menai Straits Fault System, a terrane boundary that was reactivated into brittle fault displacements throughout Phanerozoic time (Howells, 2007).

The age of the Monian Supergroup has been a subject of controversy over many years. Essentially the sequence is more intensely deformed and metamorphosed than the Cambrian on the mainland but, as discussed by Howells (2007), the elevation of the Monian Supergroup into the Cambrian seems unavoidable. Greenly (1919) discussed the subdivisions of the Monian Supergroup and recognised the Bedded Series, the Gneisses and the Coedana granite and considered that they each reflected successive periods of development. The formations making up the Monian Supergroup are further discussed by Phillips (1991).

The fault systems in the vicinity of the Menai Strait, separating Anglesey from the mainland, have been regarded as a major Precambrian tectonic boundary (Gibbons 1987; Carney *et al.* 2000). The zone separates two distinct Avalonian terranes comprising British type Avalonian rocks to the south and those of the Monian Composite Terrane largely contained within Anglesey. In addition to the terranes discussed above, Figure 2 also shows mapped zones

(1:250k scale) of basic and ultrabasic intrusives. As discussed later, the former constitute part of a largely concealed Palaeogene dyke swarm which adds a degree of complexity to the assessment of magnetic basement. The more localised occurrences of ultrabasic rocks, again partially concealed, possess some of the largest magnetic responses observed by the airborne survey. The observations of Maltman (1975) indicate their consistency with Neoproterozoic ocean-plate subduction provided the model allows for magmatic ascent of the intrusives and their alteration and deformation *in situ*.

3 UK ONSHORE MAGNETIC DATA SETS

Total field Magnetic Intensity (TMI) data is usually provided as a superimposed ‘anomaly’ field related to a model of the International Geomagnetic Reference Field (IGRF) determined at a date appropriate to the acquisition of the data. The GSGB data is referred to IGRF 1990 and the HiRES data is referred to IGRF 2009.

The shape of magnetic anomalies varies as a function of geomagnetic latitude. At northern mid-latitudes, such as the UK, it is useful to transform the data using a filtering operation called ‘reduction-to-the-pole’ or RTP (Blakely, 1995), that generates anomalies that peak over the source location. The transform assumes that the primary source magnetisation is aligned parallel or anti-parallel (within 25°; Bath, 1968) to the local geomagnetic field vector. Some volcanic flows and cultural noise sources may provide anomalies with remnant magnetisation directions that violate the assumption. Structures providing normally and reversely magnetised fields should be adequately represented in terms of their source location.

3.1 The GSGB national baseline compilation

The baseline aeromagnetic data for the UK were acquired between 1955 and 1965, with sections of the survey being flown in different years by Hunting Geology and Geophysics Ltd and Canadian Aeroservices Ltd. The survey was primarily funded by the Department of Scientific and Commercial Research and, in Northern Ireland, by the Department of Commerce. The data for Northern Ireland are held by BGS on behalf of the Department of

Economic Development of Northern Ireland. The data sets underlying the 1:1.5M UK magnetic map compilation are described by BGS (1998).

The bulk of the surveys were flown with a flight line spacing of 2km, with tie-lines usually at 10km. The orientation of the flight lines varied between annual surveys (either N-S or E-W), dependent on the predominant geological strike direction, so as to optimise the resolution of the data. Most of the country was covered with a flight height of 1000 feet (305 m) mean terrain clearance.

The magnetic field was measured by a fluxgate magnetometer, recording onto a continuous paper chart. Positional information was derived from a navigation camera mounted vertically in the aircraft, marking the paper chart at every exposure. Over the sea, Decca navigation was used. Heights were determined by radio altimetry, except in early surveys, when aneroid barometric instruments were used.

After initial reduction, the data were hand-contoured at 10 nT intervals, forming the primary results of the survey. Flight line/contour line intercepts were subsequently digitised from these maps by BGS Regional Geophysics to produce the digital aeromagnetic data set for the UK, comprising 530 648 points. The data have been reprocessed to refer anomalies to a variant of IGRF-90, which makes allowance for the inaccurate prediction of the geomagnetic field model prior to 1971.

The area selected for our study incorporates data from 2 separate zones having principal survey flight lines in the E-W direction (with line separation of 4 km) and in the N-S direction (with line separation of 2 km). The selected rectangle is 110 x 135 km in size with the western edge of the rectangle limited by the GSGB data set. The typical maximum grid resolution (using a quarter-wavelength sampling criterion) that can be achieved using the GSGB data is 500 x 500 m. Obviously in certain undersampled localities, gridding at the maximum resolution may produce artefacts. This is illustrated in Figure 3 which shows the magnetic anomaly information obtained using a minimum curvature gridding interval of 500 x 500 m. The coordinate system used throughout is the British National Grid (BNG). The highly non-uniform sampling provided by the GSGB data set is indicated by the point symbols. Some gaps in the sampled grid have necessarily been interpolated.

The selected data set comprises 9645 points and the gridded data provide anomaly values in the range from -294 to 598 nT. The image uses a linear colour scale with shading from the NE. When using a linear colour scale in this and subsequent images, the upper and lower limits of the colour scale are reduced in relation to the full data range in order to improve the dynamic resolution of the image. The largest amplitude TMI (Total Magnetic Intensity) anomaly values are observed in association with the Snowdon Massif in the SE of the area. Elsewhere, magnetic high values associated with longer wavelengths display a NE-SW orientation. These are features that we would associate with magnetic basement. Even with no processing applied to the data, a series of higher wavenumber linear features can be traced crossing the area with a NW-SE trend. These features are a series of Palaeogene dykes that have been previously discussed, in terms of their geophysical responses, by Kirton & Donato (1985) and by Bevins *et al*. (1996). The dykes form part of a very large scale and extensive set of Irish Sea dyke swarms that appear to connect with Palaeogene centres in Northern Ireland. The rectilinear polygonal area around the coast of Anglesey outlines the HiRES survey area discussed below.

3.2 HiRES data sets

The HiRES data sets acquired across onshore UK are shown in Figure 1. All the surveys were conducted using modern caesium vapour magnetometers with quoted noise levels of 0.1 nT. The first of these surveys (HiRES-1) was obtained in 1998 across the North Midlands. Survey and acquisition parameters are described in detail by Peart *et al*. (2003). The survey was flown at an elevation of 90 m in open areas increasing to 240 m across populated areas. Flight line separation was generally 400 m with a tie line spacing of 1200 m. Flight line and tie line separations were reduced to 200 m and 600 m respectively over 3 infill areas of special interest. The initial HiRES data obtained across densely populated areas allowed assessments of semi-automated cultural noise suppression and removal techniques to be investigated (Peart *et al.* 2003; Cuss 2003). The HiRES-1 survey was followed by four other multi-parameter surveys employing a Twin-Otter platform (see Beamish & Young, 2009). These later surveys were all conducted using a 200 m line separation and at reduced survey elevations of below 60 m. Regulatory control again required increasing the survey elevation to 200 m above populated areas. The Anglesey survey (Fig. 1) was the last survey to be flown (in 2009) and covers 1198 km^2. The data from this survey form the basis of the present study.

3.3 HiRES Anglesey survey

The acquisition parameters and processing procedures applied to the Anglesey survey data are described by Beamish & White (2009) and White & Beamish (2010). Flight line direction was N-S in order to intersect geological features having two predominant directions (NW-SE and NE-SW). The Anglesey HiRES TMI anomaly map is shown in Figure 4. HiRES data collected at 200 m line separations are routinely gridded at 50 m intervals, although along-line sampling of the field is about 5 m. In this study we use minimum-curvature gridding with Akima spline functions since more advanced procedures, for example making use of cross-line gradients, tend to smear the response of localised noise sources. The TMI image uses a linear colour scale with shading from the NE. The magnetic measurements comprise 1.04 million data points and the gridded data set has maximum and minimum values of 1439 and -2645 nT, respectively. If the GSGB data set is also restricted to the HiRES survey polygon it contains 1440 data points with a range of values from -236 to 301 nT. The lower flying height and increased flight line sampling of the HiRES surveys inevitably leads to an improved registration of the actual field distribution. Figure 4 also shows geological line work of the 1:250k mapping of fault lines. Two particular faults, with particular relevance to the magnetic data, are labelled CH and BF. Both CH (Carmel Head) and BF (Berw) faults are major shear zones with the Carmel Head Fault representing a thrust with its hanging wall to the north.

If an initial comparison is made of the TMI anomaly data across Anglesey, it is evident that the longer wavelength features trending NE-SW are reproduced in both data sets. At shorter wavelengths, it is also apparent that the majority of magnetic features observed in Figure 4 are poorly defined and suffer from extensive aliasing in the GSGB data set. The HiRES data provide significant detail in the mapping of the sequence of quasi-linear, NW-SE trending negative anomalies that we associate with the largely concealed Palaeogene dykes. The largest negative anomaly is associated with the dyke labelled 1 in Figures 3 and 4. Other expressions of weaker negative features are also observed to the NE of the main swarm axis. Although there are many new magnetic structures resolved and thus revealed when the HiRES data are further processed, three high amplitude features are worth noting. The first feature is labelled 2 in Figure 4 and corresponds to a series of ultrabasic (serpentinite) bodies that provide anomaly values in excess of 800 nT. The new data set provides considerable detail in relation to the subsurface continuity of the body. The second feature, labelled 3 in Figure 4 is only revealed by its geophysical response since it exists offshore (and is modelled at subsea depths). The structure comprises a central positive core surrounded by a crescent-shaped zone of positive anomalies. The feature, having an average diameter of about 3.5 km, is located centrally between two of the Palaeogene dykes. The third set of features are found in the hanging wall of the Carmel Head Thrust in the north. They appear as a series of quasi-linear magnetic highs that splay into, and terminate at, the fault location. The structures appear to have a finite spatial extent (i.e. offshore, to the north) and possess considerable internal structure when examined in detail.

3.4 Initial comparison of the data sets

3.4.1 Cultural interference

A feature of the HiRES magnetic data sets acquired across onshore UK is the degree of cultural interference that exists, largely as high-wavenumber and isolated perturbations to the data. The enhanced cultural interference is a result of the low survey height (required by the additional geophysical measurements) in combination with the 200 m flight line separation and the fact that the UK has a high population density across most of our survey areas.

The degree of cultural interference can be examined by applying the analytic signal transform (Roest *et al*. 1992) to the data sets. The analytic signal (AS) applied to gridded observations of the total magnetic field (T) is defined as:

$$AS = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad \text{...(1)}$$

where T is the magnetic field. The AS, or total gradient, is defined by derivatives in all 3 dimensions and is sensitive to high-order wavenumber gradients in the data. The analytic signal obtained for the two data sets within the HiRES survey polygon are shown as shaded-relief images in Figures 5a (GSGB) and 5b (HiRES). Identical procedures have been applied to both data sets and shading is from the NE. The total gradient content of the two datasets is quite distinct with the lower resolution GSGB data displaying some gridding artefacts at the 500 m interval used. Although NW-SE dyke features are highlighted by the shading angle, the HiRES data set is seen to contain a plethora of isolated and clustered gradients that are likely to be associated with cultural interference.

Magnetic deculturing techniques that combine manual and semi-automatic procedures have been examined and applied to some of the HiRES data sets (Cuss 2003; Lahti *et al*. 2007). Here we use data that has had no deculturing applied apart from the removal and resampling of a large amplitude response from an extensive (industrial units extending over 1 km) aluminium smelting works, shown as an infilled diamond shape in Figure 5b. Modern high resolution airborne magnetic surveys are typically synonymous with accuracy; however when acquired in the UK the accuracy (of the geological signal) may be compromised by cultural artefacts. Due to these limitations, unless carefully controlled and lengthy deculturing is attempted, the use of high order derivatives in the processing of these data is typically avoided.

Three other features are also labelled in Figure 5 and are worthy of note. North of the inner fault line of the Carmel Head Thrust (CH), the magnetic gradients observed in the HiRES data (Fig. 5b) are largely absent in the GSGB data set (Fig. 5a). This is a direct result of the inadequate sampling across the area as is evident from Figure 3. In the area of superimposed ultrabasic and dyke anomalies (Feature 2) the gradient content of the GSGB data set (Fig. 5a) is particularly poor. The square symbol in Figure 5b notes a strong response from the direct overflight of a marine vessel. This forms an instance of a single isolated cultural perturbation. These, and similar instances of cultural interference, can be routinely identified in modern surveys with the assistance of a downward-looking video that provides detailed and continuous images of the flight path linked to the survey database (Lahti *et al*. 2007; Leväniemi *et al*. 2009).

3.4.2 Spectral content

The consideration of the information contained in the analytic signal provides an assessment of the high wavenumber gradient content of the data sets. The existing GSGB airborne data set was limited to a rectangle of 110 x 135 km and a data grid constructed at a uniform interval of 500 m. The Anglesey HiRES survey data is contained within an area of 44.6 x 35.25 km and was gridded at a uniform interval of 50 m. Since a number of magnetic processing procedures take place in the spectral wavenumber domain, it is natural to first summarise the two data sets in this framework. Figure 6a shows the radially/azimuthally-averaged (2D) power spectra of the two data sets discussed above. The lowest wavenumber is determined by the number of cells within the grid while the highest wavenumber represents the Nyquist sampling interval (e.g. 100 m and 1 km for the HiRES and the GSGB data sets, respectively).

The higher energy content of the HiRES data is evident across the whole spectrum. When magnetic spectra are examined from a framework of spectral shape, Spector & Grant (1970) showed that a statistical population of magnetic sources at depth h would generate a straight line slope of $-4\pi h$, on a plot of the natural logarithm of energy against wavenumber. From this perspective, the energy spectra shown in Figure 6a indicate that only 2 to 3 such lines are required by simpler regional data while the HiRES spectrum requires at least 4. The comparison is indicative of the greater information content of the HiRES data set even though a much smaller area is sampled.

The spectral slopes observed can be used to provide first-order estimates of source depth h. These continuous estimates, derived from a 5-point averaging of the spectral slopes are shown in Figure 6b. The low wavenumber content of the regional GSGB data indicates potential sources at 17 and 12 km while for the equivalent HiRES data the estimated source depths are reduced to significantly shallower levels of 5.8 and 3 km. Between wavelengths of 10 km and 1 km the GSGB depth estimates display a high degree of variance, indicating a significant noise level.

3.4.3 Comparison along profile A-A'

The TMI anomaly data resolved along the profile A-A' (Figures 3 and 4) are shown in Figure 7a. The vertical offset between the two data sets is due to the different IGRF reference fields used. Along the 28 km profile, the GSGB data display a range of 212 nT that results from the regional trend observed. In contrast, the HiRES data display a range of 350 nT that results from the higher wavenumber variations across the profile. The first 4 negative anomalies are associated with linear features mapped in Figure 4 and interpreted as Palaeogene dykes. The third and largest negative anomaly is that labelled 1 in Figures 3 and 4.

The profile A-A' is approximately normal to the strike of the magnetic variations. The form of the dyke anomalies when allowance is made for the regional trend is consistent. The offshore magnetic dykes to the NW of Anglesey have been discussed by Wright *et al*. (1971) and by Kirton & Donato (1985). Kirton & Donato (1985) undertook an extensive modelling of the magnetic responses of Palaeogene dykes across the UK. Two of the dykes off Anglesey were modelled using marine magnetic profiles. Although the trial-and-error modelling was necessarily non-unique, depths of ~50 m and ~200 m to the upper surfaces of the structures were obtained. In addition, the total magnetisation vectors required to fit the observed responses were within 20° of the vertical (i.e. within 20° of the totally reversed magnetisation direction). This is significant since some of the processing and interpretation procedures discussed below relate to the detection and definition of isolated magnetic anomalies for which the total magnetisation vectors are assumed to be normal (i.e. +90° in the magnetic RTP response) or reversed (-90° in the magnetic RTP response).

4 PROCESSING TECHNIQUES

It is evident from the data presented that shallow and deeper magnetic sources are directionally distinct and are close to being orthogonal. One of the significant features of the Palaeogene dyke swarm is the NW-SE regional scale persistence in direction. They can be traced across the Irish Sea and into and through Northern Ireland (Beamish & Schofield, 2010). The NE-SW directional trends observed in the magnetic data at longer wavelengths are consistent with the tectonic and geological framework summarised in Figure 2. This directional dependence is exploited in the structural assessments considered below. Azimuthal (directional) filters have been applied in the wavenumber domain to selectively remove signal and noise along specified directions. To avoid introducing artefacts, we use a smooth cosine function of degree 2 having a gain of unity at the chosen azimuth and a gain of zero in the orthogonal direction.

Spatial derivatives have a well-established role in the interpretation of potential field data from both ground-based and airborne surveys. There exists a range of processing procedures and filters, largely relating to vertical and horizontal derivatives and their combinations that perform as enhanced mapping functions when applied to the basic data sets (Blakely, 1995; Cooper & Cowan, 2006). The methods are all based on the use of the spatial derivatives of the data. The source parameters that may be estimated include the lateral and the upper vertical boundaries of the source region (Blakely & Simpson, 1986; Cooper & Cowan, 2008). Other methods such as Euler deconvolution (Thompson 1982; Reid *et al*. 1990) also exist for the estimation of the location and depth of the source. All the methods entail a number of simplying assumptions since the magnetic bodies (e.g. contacts, dykes, pipes) comprise idealised geometries.

4.1 The Tilt Derivative (TDR)

Structural information in the data sets is first examined here using the Tilt Derivative (TDR) as described by Miller & Singh (1994). The tilt derivative or tilt angle is defined as the arctangent of the ratio of a vertical to a combined (total) horizontal derivative:

$$TDR = \tan^{-1}\left[\frac{\partial T/\partial z}{\sqrt{(\partial T/\partial x)^2 + (\partial T/\partial y)^2}}\right] \qquad (2)$$

where T is the magnetic or gravity field.

The amplitude range of the dimensionless ratio is restricted to the range π/2 to - π/2 (or 90° to -90°) by virtue of the arctan function. The TDR acts as an Automatic Gain Control (AGC) filter when applied to the field observations. The TDR thus responds equally to both shallow and deep sources. Summaries of the behaviour of tilt derivatives in the case of magnetic field data are provided by Fairhead *et al*. (2004) and Cooper & Cowan (2006). The function typically allows a normalisation of both shallow and deep sources in broadband TMI anomaly data but here we also apply it to anomaly data that have been subjected to matched spectral filtering (see below).

Existing modelling of the TDR response to isolated magnetic bodies (e.g. Fairhead *et al.* 2004; Verduzco *et al.* 2004; Cooper & Cowan 2006; Salem *et al.* 2008) indicate that the TDR is positive when over the source, it passes through zero when over (or near) the edge of the source, where the vertical derivative is zero and the horizontal derivative is a maximum, and is negative outside the source region. It should be noted however that the modelling of magnetisation vectors is typically confined to azimuths of between 0° and +90° so that the sources considered (e.g. step basement, blocks and dykes) are effectively normally magnetised. In addition to the edge detection functionality, Verduzco *et al.* (2004) and Salem *et al.* (2008) note an approximate depth mapping functionality of the TDR in relation to the top of an isolated source region. Using the TDR mapping interval between 45° and -45°, with the zero defining the edge location, these authors indicate that the source depth is roughly equivalent to half the distance between the 45° and -45° contours.

It is possible, as in our study, to encounter both positively and negatively magnetised structural features. To confirm the anticipated behaviour of the TDR response in this case, a modelling study was undertaken using two concealed dyke features, one with normal magnetic polarity and one with reversed polarity. The data sampling interval along a profile perpendicular to the strike is 25 m. The magnetic anomaly across the two features is shown in Figure 8a.

Each dyke structure has a width of 75 m with an upper surface at a depth of 30 m. The depth extent of each feature is effectively infinite. The centre of the positively magnetised dyke (+90°) is located at 662.5 m along profile while the negatively magnetised dyke (-90°) is at 4337.5 m. The magnetic susceptibility of each body is 0.05 SI and the background has zero magnetic susceptibility. As anticipated, the magnetic anomalies due to the two features are inverted. A similar inversion is generated when the TDR of this data set is considered (Fig. 7b). The half-width of the TDR response between +45° and -45° is 35 m in both cases. If however a mapping of the TDR response is conducted, it is clear that the interpretation of the primary mapping intervals of the TDR response (e.g. the interval from +45° to +90° shown in red in Fig. 7b) must take into account the relative polarity information that is omitted from the TDR response. This additional relative amplitude information is contained in, for example, the magnetic intensity field and must be consulted in the interpretation of the TDR response.

4.2 Matched band-pass spectral filters

In order to compare the information on magnetic basement contained in the GSGB and HiRES data sets it has been necessary to perform spectral filtering. The starting point for this procedure is the spectral content previously summarised in Figure 6. In order to examine the longer wavelength components in the data we use a technique referred to as matched band-pass spectral filtering that extends the original procedures described by Spector & Grant (1970) and Syberg (1972). Here we follow the procedures described by Phillips (2001). In the simple case, it may be assumed that the observed field is the sum of the regional (basement) field, a residual (shallow) field and a noise component. The more general model takes into account the shape of the observed spectrum and allows for a general multi-layer case and considers the effects of sources at a number of distinct levels. The physical significance of the number of layers and their thicknesses always remains questionable given the equivalence inherent in such a modelling procedure (Pedersen, 1991).

Using a graphical procedure, the plot of the logarithm of energy against wavenumber is used to establish a number of straight-line segments (a matched filter model) whose slopes are then optimised to minimise the residual spectrum between that observed and that calculated from the model layers. The layered model generally terminates in a magnetic half-space that provides a linear spectrum at all wavenumbers. Here we assume that that this half-space forms an estimate of magnetic basement and compare the results obtained using the two data sets.

The depths obtained by the analysis are treated as approximate and the procedure is essentially used to obtain the distribution of magnetic source bodies responsible for the longest wavelengths. The source locations and depths of the sources are then investigated using the TDR response, as described above, and Euler deconvolution as described below.

4.3 Euler Deconvolution

Li (2003) provides a useful summary of the many different methods used for estimating magnetic depth. The review also summarises the potential strengths and weakness of each procedure. Here we use located 3D Euler deconvolution which is based on Euler's homogeneity equation (Thompson 1982; Reid *et al.* 1990):

$$(x-x_0)\frac{\partial T}{\partial x}+(y-y_0)\frac{\partial T}{\partial y}+(z-z_0)\frac{\partial T}{\partial z}=-\eta T \qquad (3)$$

where η is a measure of the fall-off rate of the magnetic anomaly field (T). The relationship is used to generate a series of linear equations that can be solved using a least-squares approach. As defined by equation (3), the procedure is based on first-order vertical and horizontal derivatives.

The technique uses the anomaly field, measured at (x, y, z) and determines a source position (x_0, y_0, z_0), for a single source of given type. The source type is expressed in the form of a structural index (η) which is a gauge of the rate of change of the field with distance. The system holds not only for the TMI anomaly field but also for its derivatives, and can be extended to handle more complex derived grids such as the Analytical Signal (Li, 2003) or the Tilt Derivative, where the structural index is determined along with an estimate of the source position (Salem *et al.* 2008). However, the use of higher order derivatives means these methods are susceptible to any noise in the data and only first-order derivatives are used here.

The magnetic data is studied using a located Euler scheme which avoids excessive numbers of solutions. Instead initial locations (x, y, z) are determined independently from a suitable first derivative property which defines inflections (e.g. peaks or troughs) in the data. Data at these initial locations, together with the calculated window sizes, are then used in the standard Euler deconvolution procedure. In our case, in order to trace depth solutions of the reversely magnetised dykes, troughs in the first vertical derivative of the anomaly data were used to provide the initial locations. In the case of magnetic basement, peaks in the magnitude of the total horizontal gradient provided the initial locations. Our Euler deconvolution analysis is thus restricted to defining reversely magnetised dykes at shallow depths and positively magnetised magnetic basement. In both cases the data is conditioned using combinations of azimuthal and/or matched band pass filters with fixed structural indices (η) of 1 (for dykes) and 2 (for contacts) applied.

4.4 Terracing operator

The terracing operator was originally described by Cordell & McCafferty (1989). The terracing operator is applied to potential field data to produce regions of constant field amplitude that are separated by sharp boundaries. The method involves a filtering operation that gradually increases the slopes of the first horizontal derivatives while simultaneously levelling the field between gradients (e.g. Cooper & Cowan, 2009). The procedure is generally considered to be an aid to geological interpretation (Cordell & McCafferty, 1989). Here the procedure is intended to provide a geologically-orientated map of shallow basement magnetisation as discussed later.

5 APPLICATION TO SURVEY DATA (SHALLOW DYKE STRUCTURE)

5.1 The GSGB data

The TDR response of the vintage GSGB TMI RTP data (Figure 3) is shown in Figure 9a. The TDR response has been contoured in 45° intervals with red and blue colours representing positive and negative responses, respectively. The negative interval from -45° to -90° is shown in white following the discussion above. The linear negative features with a NW-SE trend that we would associate with the Palaeogene dyke swarm are superimposed on longer wavelength (deeper) positive responses that appear to trend NE-SW, orthogonal to the dyke direction.

The magnetic data in the spatial domain (e.g. Fig. 9a) were subjected to a directional (azimuthal) cosine filter to pass the magnetic components in a direction 135 degrees (i.e. the NW-SE direction). The TDR response was then obtained using the filtered data set. A contour plot of the resulting TDR response is shown in Figure 9b with only the negative response between values of -45° and -90° outlined. This TDR response region outlines the maximum negative excursions (i.e. the responses that would, potentially, be associated with the centres of reversely magnetised anomalies). Obviously features with intermediate, or no, strike directions will be distorted by the directional filtering applied so the mapping provided in Figure 9b must be interpreted alongside the information already presented. In practice a suite of TMI derivative maps (not shown here) are also used to arrive at a greater understanding of the data characteristics. It can be seen that the directional filtering has suppressed all the gradients (edges) with a NE-SE (45°) component observed in Figure 9a. The main Palaeogene dyke swarm is observed to the SW of a central NW-SE axis through the HiRES survey area shown. Individual dykes are identified through partial linear continuity since gaps may exist due to data sampling limitations and/or along strike changes in depth and/or magnetisation strength. The larger area zones of negative response are associated with low gradient areas and are interpreted as distorted noise levels given the azimuthal filtering that has been applied. The limitations of the gridding can also be observed since these effects are amplified in the TDR response.

5.2 The HiRES data

Since there is significant interference from cultural features, the HiRES TMI RTP data were first upward continued to a height of 100 m to attenuate the highest wavenumbers. This has only a marginal effect (a slight increase) on the width of the features in the TDR response. The TDR response of the unrotated data is shown in Figure 10. The TDR response has again been contoured in 45° intervals with red and blue colours representing positive and negative responses, respectively. As previously, the negative interval from -45° to -90° is shown in white. Previously, some of the positively magnetised large amplitude features were discussed in relation to the TMI data shown in Figure 4. They can now be re-examined in relation to the mapping of the +45° to -45° TDR interval providing approximate depth estimates for vertical and isolated contacts. The zone of ultrabasic serpentinite (feature 2 in Fig 4) is partially mapped (i.e. at outcrop) at its western end. TDR depth estimates are in the range -20 (i.e. above ground due to inherent inaccuracies) to 20 m below ground level corresponding to a shallow, partially concealed body. Offshore, the central positive anomaly (feature 3 in Fig. 4) has an estimated depth of about 100 m below sea level. The major positively magnetised bodies in the hanging wall of the Carmel Head shear zone (CH in Figure 4) are unidentified on geological maps and the TDR depth estimates again suggest near-surface bodies.

A contour plot of the directionally (135°) filtered HiRES TDR response is shown in Figure 11 with only the negative response between values of -45° and -90° outlined in blue. These are overlaid on the equivalent rotated TDR response of the GSGB data (from Figure 9b) in the immediate vicinity of the HiRES survey. The latter response is outlined in grey to allow comparisons to be made. In a broad sense the good correspondence between the two data sets in mapping the main set of dykes to the SW of a central NW-SE axis is evident. The HiRES data inevitably provide both a greater continuity and better resolved location of the features (e.g. Feature 1). Dyke displacements, particularly across the Berw fault (see BF, Figure 4) are evident as discussed by Bevins *et al.* (1996) but the detail of these, and other, displacement features are now well defined and circled in Figure 11. Two other, more subtle, displacements across one dyke indentified by the HiRES data are outlined with squares. The observations have a significance since the interpretation of the previously known dyke offsets in terms of Cenozoic fault movement is disputed (Maddock *et al.* 1997).

To the NE of the central NW-SE axis, the HiRES data indicate a variety of parallel NW-SE striking zones that have the potential to be interpreted as concealed Palaeogene dykes. These additional features are closer to the limits of detection than those discussed above and their definition is more susceptible to cultural interference. Many of the NW-SE trending features extend over many kilometres and possess the same character as that of the established (i.e. easier to detect) dykes. The most obvious example is labelled TB in Figure 11. This feature is probably the Traeth Bychan dyke and can be detected entering the vicinity of the former copper mine of Parys Mountain at its northwestern limit. The current mapping of identified and outcropping Palaeogene dykes at a scale of 1:50k is shown in red for comparison. In terms of the existing outcrop mapping of dykes (i.e. red zones in Figure 11), there is only one isolated occurrence that is not identified in the processed HiRES magnetic data.

The variations in the unrotated TDR response along profile A-A' for both GSGB (sampled at 500 m) and HiRES (sampled at 50 m) data are shown in Figure 7b. Negative responses associated with the HiRES data are shown with infill. At profile distances less than ~20,000 m, we are concerned with the behaviour of the negative variations in the TDR response. Here the GSGB data indicate three minima in the TDR response while the HiRES data indicate seven minima that may be associated with dykes. The location of the centre of the strongest response (Feature 1) differs by ~ 1 km in the two estimates. The results also indicate that while the GSGB data may be used to partially map a number of high-wavenumber structures, particularly those possessing linear continuity, the HiRES data provide well-constrained locations of the dykes.

5.3 Euler deconvolution of shallow structure

Given the behaviour of the GSGB data and their spatial derivatives, the Euler deconvolution of shallow structure is restricted to the HiRES azimuthally filtered data set. The located Euler solution results for these data are plotted in Figure 12. As noted previously a structural index (η) of unity, appropriate to dyke structure, was used. The solutions shown are selected based on their estimated uncertainties in depth and position (x, y). These restricted solutions have an error (standard deviation) of less than 10% in each of these error estimates. Depths are referenced to the level of the ground surface assuming a constant flying elevation of 56 m. Also shown in Figure 12 are the TDR results between the intervals from -45° to -90° from the HiRES data shown previously. It can be seen that the TDR and Euler location estimates display a high degree of correspondence along the quasi-linear features we would associate with reversely magnetised dykes. Continuous zones where both processing methods provide collocated results reinforces the interpretation of some of the more marginal features. As noted previously the results obtained to the north of the Carmel Head fault (CH) should be disregarded in the assessment of the dyke swarm.

The Euler estimated depth to magnetic source along the Palaeogene dyke swarm displays a significant degree of variation along individual lineaments. The scatter in depth estimates is typical of Euler solutions. Figure 12 shows the 8221 solutions obtained by the Euler analysis, after winnowing based on accuracy. If we select only the solutions along the quasi-linear trends of negatively magnetised features, we can reduce the solutions to a subset of 1285. This subset has a median depth of 44 m with first and third quartiles at depths of 26 and 66 m, respectively. Some correlation with outcropping dykes is observed and the scattering is possibly a consequence of both significant lateral variation in depth and considerable weathering effects on the volcanic intrusives. It is also worth highlighting the offset between the negative peaks in the TDR results and the Euler solutions in the north of the survey area where positively magnetised intrusions are responsible for the anomalies.

6 APPLICATION TO SURVEY DATA (MAGNETIC BASEMENT)

It is evident that in both the GSGB and HiRES data sets, the near-surface anomalies discussed in Section 4 possess significant amplitudes and thus potentially interfere with the longer wavelength, deeper features in the data sets. After utilising the approximate orthogonality in the data between the shallow and deep features the magnetic basement characteristics in both data sets are examined using matched spectral filtering. The basement features associated with the HiRES data, being relatively shallow, retain an influence from the shallow dykes even after azimuthal processing to minimise their influence has been performed.

6.1 The GSGB data

As noted previously the regional data spectrum can be adequately modelled using 2 magnetic layers above a half-space. A matched filter analysis of the data indicated the first 2 layer depths were 540 m (below the observational height of ~300 m) and 1920 m. The magnetic basement was estimated to be at a depth of about 13 km. The information content of the first 2 layers appears noise-like and not structurally significant. Removal of the spectral components of the first two layers provided the TMI magnetic anomaly basement map shown as a colour image in Figure 13. A high amplitude positive centre is defined below the Snowdon massif to the SE of the survey area. In order to define the source location and depth, the TDR response of the data are shown as contour lines with an interval of 45°. The zero contour would again outline body edges subject to the usual assumptions. The trend of the main anomaly edge SSW and parallel to the coast is significant given the occurrence of similar tectono-metamorphic terranes on Anglesey and on the Llyn Peninsula that is located in the southern-most centre of the area (Gibbons & Horák, 1990). Offshore a NE-SW trending, lower amplitude feature is observed that may be associated with the Mid-Irish Sea

Uplift (Jackson *et al.* 1995). Depths to the top of the main body estimated from the TDR interval from -45° to +45° range from about 10.5 to 12 km below the observational height.

3D Euler solutions were investigated using the magnetic basement features shown in Figure 13. Located Euler deconvolution was again performed on the data in an effort to locate magnetic contacts. In the case of basement features, the initial locations were derived from peaks in the total horizontal gradient of the anomaly field. The solutions, determined with a structural index of zero (i.e. a contact) are also shown in Figure 13 using 4 depth ranges between 6 and 14 km. The results are a subset of the total solutions obtained. The results shown provided an error estimate of <10% in the Euler x,y,z solution locations. Depths are referenced to the level of the ground surface assuming a constant flying elevation of 300 m.

The solutions display a high degree of spatial correspondence with the zero value of the TDR response and serve to reinforce confidence in the edge location of the deep magnetic feature. The third Euler depth range between 10 and 12 km corresponds to the TDR contact depth estimate noted previously. The depth solutions also display some significant trends; the solutions along the western edge exhibit shallower depths (e.g. 8 to 10 km) than the northernmost boundary depth estimates which exceed 10 km. The boundary feature is deepest at the convergence point of the two trends.

6.2 The HiRES data

The estimation of magnetic basement features in the HiRES data is more challenging. The spectral content of the HiRES data (e.g. Fig. 6) indicates a reduced depth to basement compared to that of the GSGB baseline data. In the HiRES data, both the amplitudes and number of the Palaeogene dykes interfere with the resolution of the longer wavelength, basement features. In these circumstances, it has been necessary to process the data using combined azimuthal and matched-filtering procedures. It has already been noted that geological, fault and long wavelength magnetic features across Anglesey display a predominant trend direction of +45° from North. This direction is orthogonal to the NW-SE strike direction of the dykes. It is therefore possible to minimise the contribution of the dykes by applying a directional filter. The magnetic data in the space domain (shown in Figure 4) were subjected to a directional cosine filter to pass the magnetic components in a direction of +45°. It is recognised that a number of non-dyke features, particularly those at intermediate wavelengths, in the data set (Figure 4) will be distorted by the filtering; however only the regionally continuous large scale features i.e. those associated with basement, are the subject of this analysis.

The azimuthally filtered data were analysed using a matched band spectral filtering procedure as previously discussed. The matched filter analysis indicated the data spectrum could be modelled using 3 magnetic layers above a half space. The layer depths obtained by the analysis were 83, 173, 646 and 2708 m below the observational height of 56 m. Removal of the spectral components of the first 3 layers thus provided a TMI magnetic basement estimate at a depth below surface of 2652 m. This depth is clearly considerably less than that obtained from the regional data and, as previously noted, relates to the high information content of the HiRES data at relatively shallow depths.

The TMI basement features are shown in Figure 14a with the 1:650k mapping of fault lines for reference. The basement anomaly response can be compared with the full spectrum anomaly response shown in Figure 4. Two areas of potentially distorted localised magnetic basement features are circled; these relate to features 2 and 3 identified in Figure 4. Two main regional basement magnetic highs are identified with the zone to the SE of the Berw Fault being the most prominent. This feature probably extends beyond both edges of the survey area. The additional central magnetic high zone shows a close association with the Coedana Complex granite and gneiss. The geophysical information of the first, more highly magnetised body to the SE of the Berw Fault, is of relevance since the significance of the shear zone, interpreted as a terrane boundary by Gibbons (1990) and Gibbons & Horák (1990) is disputed (Strachan *et al.* 2007).

The more central, and less pronounced, basement high appears confined within the survey area and displays a correspondence with the outcrop of the Coedana Complex granite and gneisses. The basement anomaly features shown in Figure 14a have been analysed using the terracing operator of Cordell & McCafferty (1989) and discussed previously in the section on processing techniques. The procedure used here is described by Phillips (1992). The result of applying the terracing operator is shown in Figure 14b with only the high amplitude values above 20 nT displayed using a 6 colour scheme. The transformation of the original magnetic variation data shown in Figure 14a to sharp boundary contacts is evident. Also shown in Figure 14b are stippled zones that denote the outcrop of the Coedana (and other) granites. It is clear that the central zone of higher magnetisation is closely associated with this complex, currently interpreted as a volcanic-arc granite generated in the late Precambrian Avalonian subduction system (Gibbons & Horák, 1996). The northerly trending fault (labelled A in Figure 14b) appears to have controlled the development of the magnetic basement structure. It is worth noting that this interpretation is only achieved by the application of the terracing operator to the data in Figure 14a (compare Figures 14a and 14b).

6.3 Tilt Derivative and Euler deconvolution of shallow basement structure

In order to estimate shallow basement source depths, TDR response estimation together with located Euler deconvolution were applied to the shallow basement magnetic response of Figure 14a. The same procedures and parameters that were used in the deep basement study of the GSGB data were applied again. The results of the study are summarised in Figure 15 with the TDR response shown as contour lines at 45° intervals and the Euler depth estimates as colour symbols in 5 ranges extending to a depth of 3 km. Depths, in this case, are referenced to ground surface assuming a constant flying elevation of 56 m. The outline of the contours > 20 nT obtained by the terracing procedure (Figure 14b) is shown in grey, for reference.

Using the zero contour of the TDR response as a reference for source edge location, the two basement magnetic highs, discussed above, are outlined. An additional source boundary, trending NE-SW across the NW area of the survey is also defined; this feature (labelled A in Figure 15) is only partially resolved in the previous maps (Figures 14a,b) that used only the magnetic field data. The TDR zero response of this feature is highly linear as confirmed by the Euler solutions; the body edge becomes progressively deeper to the NE where it terminates in the hanging wall of the Carmel Head thrust. The Euler solutions can be seen to track the trace of the TDR zero contour thus providing reinforcement to the geophysical interpretation. This is illustrated in detail in the associated behaviour of both TDR and Euler depths in the vicinity of the northern edge of the central magnetic high associated with the granite. A relatively narrow zone is defined by the TDR contours in the interval from -45° to +45° and the associated estimated depth to contact is ~1000 m. The corresponding Euler depth estimates range from 500 to 1500 m with a central mean close to the TDR estimate. Further to the NE, the TDR edge location contours display an expansion to a wider zone with an associated depth estimate of about 2200 m and here the Euler solutions consistently provide depth estimates of over 2000 m.

7 CONCLUSIONS

The study has considered airborne magnetic data sets of relevance to the geophysical assessment of UK geology and its application to mapping and interpretation. The study uses existing national scale, baseline UK magnetic data across Anglesey in relation to one of a number of modern high resolution data sets. The analysis conducted has focussed on the information content of both data sets in relation to both shallow and deep magnetic structure. The geological setting of the case study area is both complex and controversial and a geological remapping project of the area is currently underway.

The analysis procedures applied to both data sets have used and compared the Tilt Derivative and 3D Located Euler Deconvolution to identify both location and depth (to upper surfaces) of isolated magnetic bodies. Since both techniques are subject to assumptions and errors, we have found that the dual assessment provides a reinforced and more robust interpretation of the data. We have also noted the potential pitfall in the isolated use of the Tilt Derivative when, as here, both normally and reversely magnetised bodies are present.

Cultural perturbations, so prevalent in the modern HiRES data sets are rare in the GSGB data due to much higher survey elevation. The cultural artefact content of the HiRES low altitude surveys has been briefly outlined. Modern high resolution airborne magnetic surveys are synonymous with accuracy; when acquired over onshore UK however, the accuracy (of the geological signal) is routinely compromised by cultural perturbations. The two largest HiRES data sets (North Midlands and Northern Ireland, Figure 1) have been decultured by semi-automatic procedures. Typically about 9% of the data is rejected or flagged and interpolation procedures are applied through data gaps (Lahti *et al.* 2007). The analysis conducted here has used a largely non-decultured data set. The analysis demonstrates that successful processing and interpretation can be carried out on data that have not been systematically corrected for the non-geological perturbations.

Inevitably the baseline data is limited in resolving features < 1 km in scale. However the comparisons reveal that a broad assessment of linear shallow features (e.g. dykes largely confined to the upper 200m) can be achieved. The precise limitations of the baseline data are revealed when the HiRES data are used in a joint assessment. Both the locations, widths and presence of lower amplitude features, including offsets, may be either misrepresented or omitted by the vintage data. The highest wavenumber noise content of the GSGB data set is associated with the intrinsic variable sampling (e.g. Figure 3) and subsequent aliasing of features when data are gridded and spatial derivatives are calculated (e.g. Figure 5a). Spatial sampling limitations will vary with selected location across the UK (e.g. BGS, 1998). In the worst case, potentially resolvable features will be omitted due to sampling variations. A particular instance where the limited and variable sampling of the GSGB data set fails to register significant magnetic variations can be seen across the Carmel Head Thrust zone (Figures 3, 4 and 5).

The high precision of the HiRES data in relation to defining the locations of concealed dykes and their approximate depths has been noted. The precise determination of dyke offsets is illustrated in Figure 11. The southern-most displacements are those discussed by Bevins *et al.* (1996) and by Maddock *et al.* (1997) and are associated with locations along the Berw Fault zone (circled in Figure 11). Much of the discussion on the evidence, or otherwise, for Cenozoic sinstral fault movement concerns paleomagnetic dating evidence. We do not wish to comment on that here and simply note that the HiRES data have also resolved dyke offsets, in the opposing sense, along one of the main dyke structures (square symbols in Figure 11). There are no known faults at the two locations.

The resolution capabilities regarding magnetic basement features of the two data sets are related to their differing spectral content. Perhaps the most significant finding is the lack of coherent magnetic information in the GSGB data set across wavelengths of between ~2 and 10 km. As demonstrated by the HiRES data set, shallow magnetic basement features exist and are of fundamental significance to a geological assessment of the Precambrian terrane assemblages across the study area. According to the analysis conducted, a broad level of shallow magnetic basement exists at a depth around 2700 m. Three localised magnetic basement highs are identified across the survey area all with a strong NE-SW trend (Figures 14 and 15). The most northerly of these features is only resolved by its southernmost edge. The central body appears to be confined to the landmass although the limited spatial extent of the survey should be recognised. The outline of the source body shows a high degree of spatial correspondence with the outcrop of the Coedana granite and gneisses. The body displays a distinct deep (2000 to 3000 m) edge along its northwestern margin approximating to the major cataclastic zone (Llyn Traffwill Fault Zone) identified by Gibbons & Horák (1990) . The third and most magnetic body extends offshore to the NE and SW. Magnetic anomaly values are variable along strike and become most intense in a localised zone in the SW (in the vicinity of the village of Dwyran). The edge of the body shows associations with the Berw Fault to the NW and the zone of blueschists (Figure 2) but extends, in a continuous fashion, beneath other formations to the NE. The magnetic information confirms the significance of the Berw Fault as a steep lithological boundary with depths to the upper surface of the body varying between 500 and 1500 m (Figure 15), becoming deepest in the south-west.

The above assessments cannot be achieved using the GSGB baseline data. Equally the HiRES survey data are limited in any deeper (> 3 km) assessments of magnetic basement structure. It has been demonstrated that the main structural application potential of the baseline data are associated with the assessment of deep (e.g. > 5 km) magnetic basement features that, in this case study, cannot be achieved by the new data. Using the spectral content of the GSGB data, the depth of the deep magnetic basement is estimated to be about 13 km. A combined analysis using the Tilt Derivative and 3D Euler analysis has refined the location and depth of the main structure across NW Wales. If the features are considered as a single zone of magnetic basement then the centre is clearly located in the vicinity of the Snowdon Massif (Figure 13). This regional high is consistent with the presence of a large deep body of mafic material that supported the genesis of the Ordovician volcanic eruptive sequences. The NW edge of the feature appears well located at depths of between 10 and 12 km and displays a linear strike across onshore Anglesey. The deep magnetic information suggests that the NW part of Anglesey, predominantly the Monian Supergroup, is underlain by weekly magnetic mid-crustal basement. This then appears consistent with the suggestion of van Staal *et al*. (1998) that the mid-crustal basement forms part of a genuinely separate terrain while the rest of Anglesey and North Wales is underlain by magnetic basement characteristic of Eastern Avalonia.

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Figure Captions

Figure 1. Airborne geophysical survey location map showing UK areas covered by HiRES surveys since 1998 (areas with shade). The Anglesey survey discussed here is shown in red.

Figure 2. A summary of the geology of Anglesey taken from current 1:250 k mapping. Palaeozoic features are largely shown in grey. Following Gibbons & Horák (1990) and Kawai *et al*. (2006) the three subdivisions (terranes) of the Monian Supergroup across Anglesey are labelled.

Figure 3. The GSGB TMI anomaly data shown as a shaded-relief image with a linear colour scale. The area has dimensions of 110 x 135 km and shading is from the NE. The area of the HiRES survey of Anglesey is shown as a rectilinear polygon together with a profile (A-A’) discussed in the text. A strong, regional scale, magnetic feature with a negative response (a dyke) is labelled 1. The data sampling is shown with dots. The coordinate system used is British National Grid.

Figure 4. The HiRES TMI anomaly data shown as a shaded-relief image with linear colour scale. Shading is from the NE. Data across the profile A-A’ is discussed in the text. Thinner black lines show mapped faults (1:250k) with two faults CH (Carmel Head Thrust) and BF

(Berw Fault) noted. Feature 1 is the same dyke noted in Figure 3 and features labelled 2 and 3 are discussed in the text.

Figure 5. The Analytic Signal (AS) of the TMI data across the HiRES survey area shown as a shaded relief image with shading from the NE. CH denotes the Carmel Head fault. (a) GSGB data. (b) HiRES data. Feature 2 is discussed in the text. The area outlined with a square shows the magnetic response of a marine vessel.. The diamond denotes an area of interpolated data.

Figure 6. Radially-averaged (2D) spectral analysis of the TMI data sets. (a) The power spectra of the data sets. (b) First-order estimates of magnetic source depths determined from the spectra.

Figure 7. Comparison of data resolved along Profile A-A'. (a) TMI anomaly. (b) Tilt Derivative (TDR). The data values in (a) are obtained from the gridded TMI anomalies. The data values in (b) are obtained from the gridded TDR data sets. Feature 1 is the main dyke anomaly referred to in other figures and the text.

Figure 8. Results of magnetic modelling of two magnetic dykes, left feature with positive vertical polarity (+90°) and right feature with negative vertical polarity (-90°). (a) TMI anomaly. (b) Tilt Derivative (TDR) calculated from data in (a). Infill in (b) relates to positive and negative 45° to 90° intervals of the TDR response.

Figure 9. Tilt Derivative (TDR) response of the GSGB data shown using a contour interval of 45°. (a) Unrotated data with the interval from -45° to -90° shown in white. (b) Directionally filtered (135°) data with only the interval -45° to -90° shown in black. HiRES survey polygon outline shown in red.

Figure 10. Tilt Derivative (TDR) response of the HiRES data shown using a contour interval of 45°. Unrotated data with the interval from -45° to -90° shown in white.

Figure 11. Tilt Derivative (TDR) response of the directionally filtered (135°) HiRES data. Only the interval from -45° to -90° is shown in blue. The equivalent TDR response obtained from the GSGB data is shown in grey, for comparison. Features identified by open circles and squares denote dyke offsets discussed in the text. CH indicates the Carmel Head fault. TB indicates the Traeth Bychan dyke. The diamond denotes an area of interpolated data. Red symbols denote features mapped (1:50k) as outcropping basic intrusions.

Figure 12. Comparison of TDR response estimates and 3D Euler solutions obtained from the directionally filtered (135°) HiRES data. The grey areas denote the TDR interval from -45° to -90°. The located Euler depth solutions are shown using 5 depth intervals. CH denotes the Carmel Head fault. The diamond denotes an area of interpolated data.

Figure 13. Comparison of TDR response estimates and 3D Euler solutions obtained from the band-pass spectral estimate of magnetic basement for the GSGB data. The depth of the magnetic basement half-space is 13 km. The basement magnetic values are shown as a colour image. TDR response estimates are shown as white contours at 45° intervals. The located Euler depth solutions are shown using four depth intervals. The area of the HiRES survey is shown as a rectilinear polygon. The cross denotes the location of the summit of Snowdon. LP: Llyn Peninsula.

Figure 14. Magnetic basement estimated from the band-pass spectral processing of the rotated (45°) HiRES data. The depth of the magnetic basement half-space is 2652 m below surface. The black lines show mapped faults (1:250k). (a) Basement magnetic values are shown as a colour image. (b) Terraced values of magnetic basement showing values > 20 nT. Hatching shows the Mona Gneiss suite and Coedana Granite. Circles are referred to in the text. The fault labelled A is referred to in the text.

Figure 15. Comparison of TDR response estimates and 3D Euler solutions obtained from the band-pass spectral estimate of magnetic basement of the rotated (45°) HiRES data. TDR response estimates are shown as contours at 45° intervals. The located Euler depth solutions are shown using 5 depth intervals. The Euler feature labelled ‘A’ is referred to in the text. The grey areas denote terraced values of magnetic basement > 20 nT (from Figure 14).


Ayr
Northern Ireland
(Tellus)
Anglesey
North Midlands
Isle of Wight

Figure 1

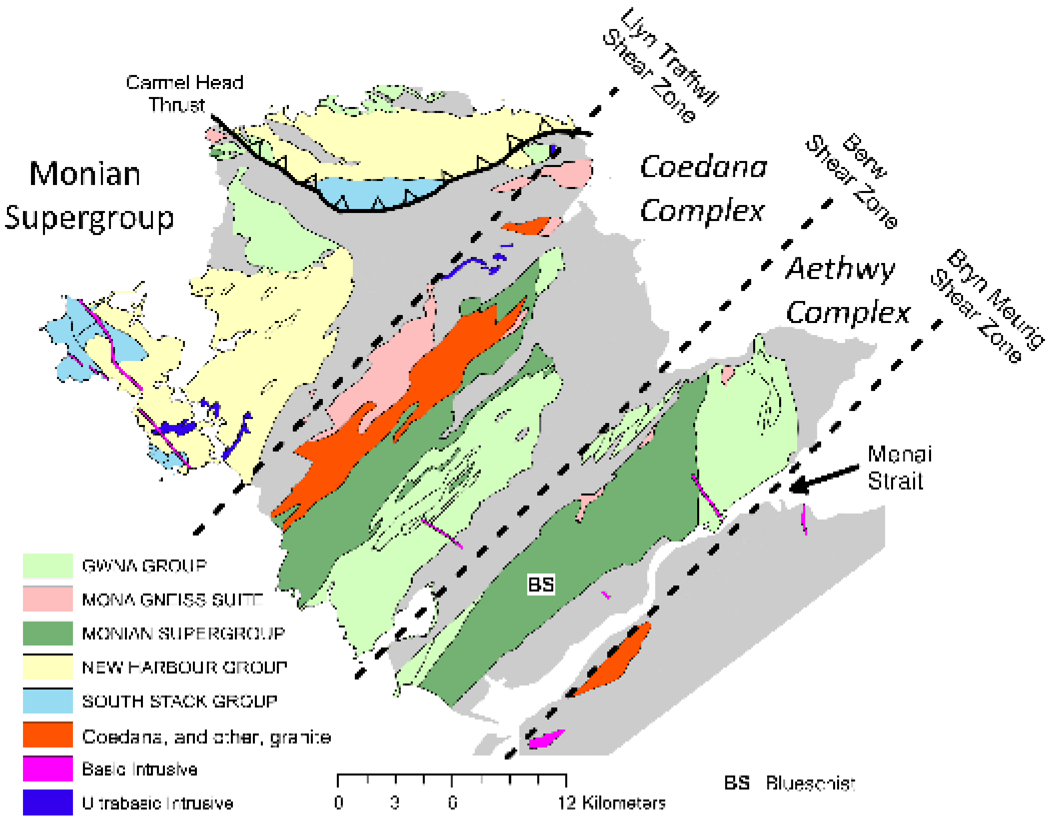

Llyn Traffwll Shear Zone
Carmel Head Thrust
Monian Supergroup
Coedana Complex
Berw Shear Zone
Aethwy Complex
Bryn Meurig Shear Zone
Menai Strait
BS
GWNA GROUP
MONA GNEISS SUITE
MONIAN SUPERGROUP
NEW HARBOUR GROUP
SOUTH STACK GROUP
Coedana, and other, granite
Basic Intrusive
Ultrabasic Intrusive
0 3 6 12 Kilometers
BS Blueschist

Figure 2

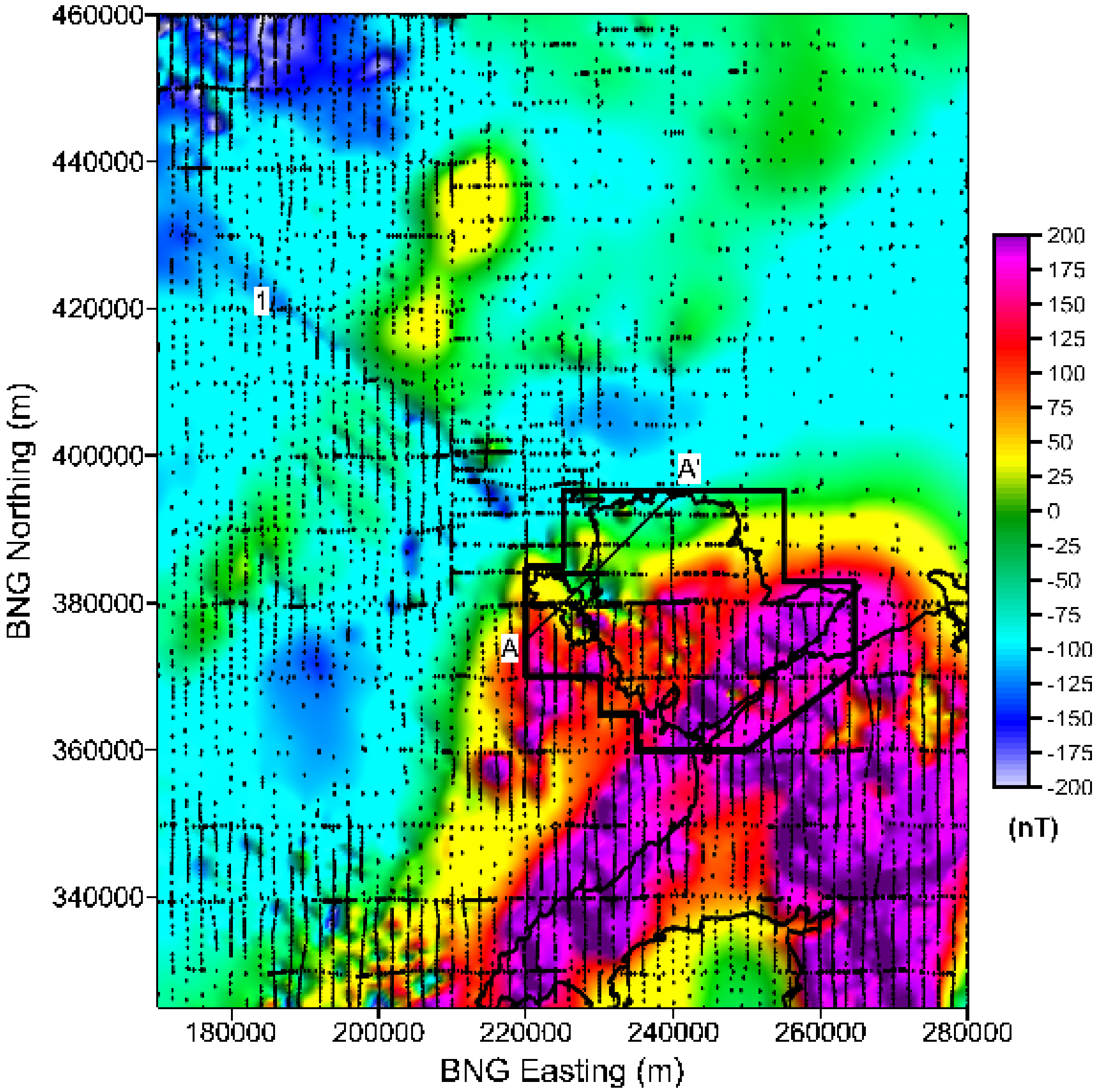

460000
440000
420000
400000
380000
360000
340000
BNG Northing (m)
180000
200000
220000
240000
260000
280000
BNG Easting (m)
1
A
A'
200
175
150
125
100
75
50
25
0
-25
-50
-75
-100
-125
-150
-175
-200
(nT)

Figure 3

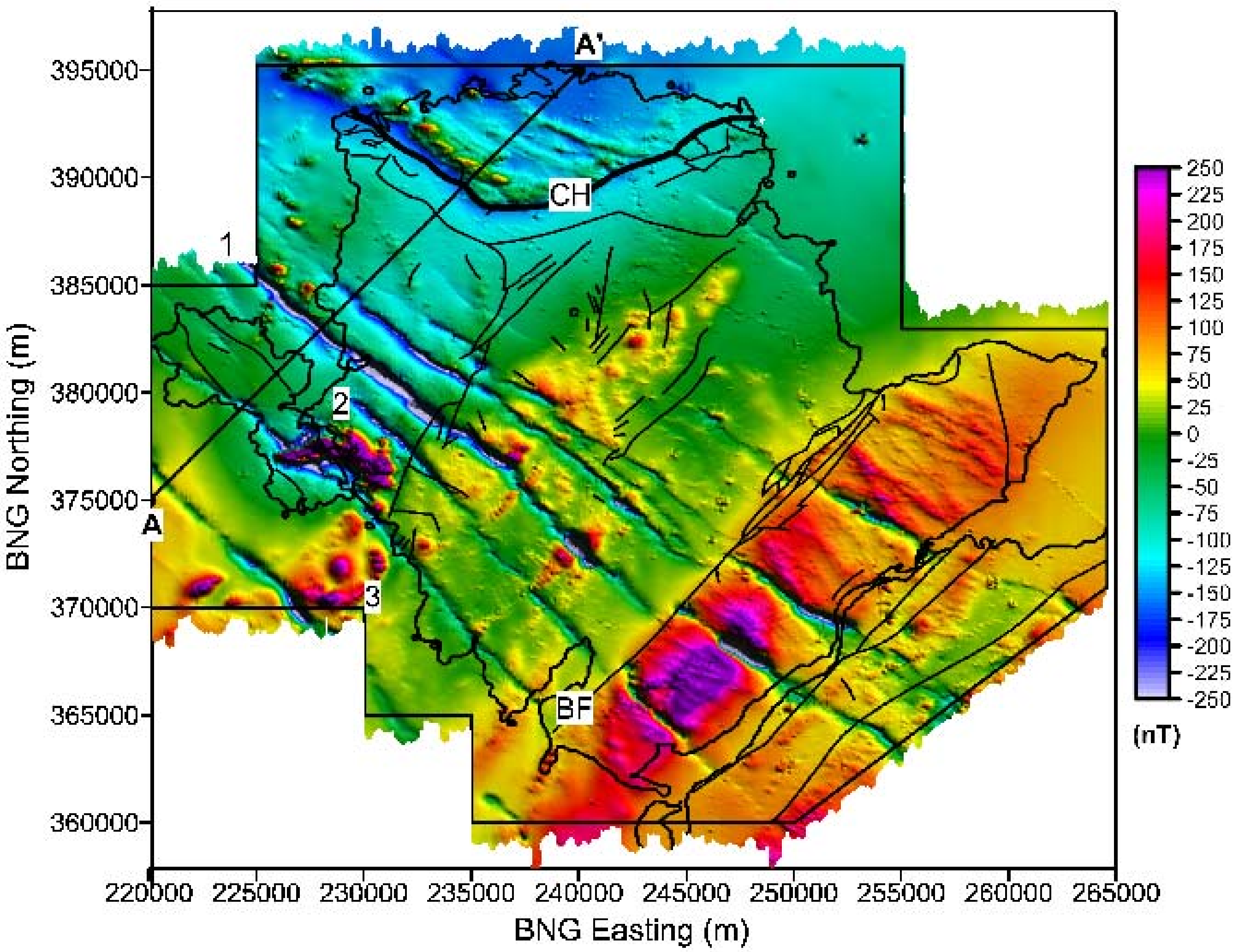

A'
CH
1
2
A
3
BF
395000
390000
385000
380000
375000
370000
365000
360000
BNG Northing (m)
220000
225000
230000
235000
240000
245000
250000
255000
260000
265000
BNG Easting (m)
250
225
200
175
150
125
100
75
50
25
0
-25
-50
-75
-100
-125
-150
-175
-200
-225
-250
(nT)

Figure 4

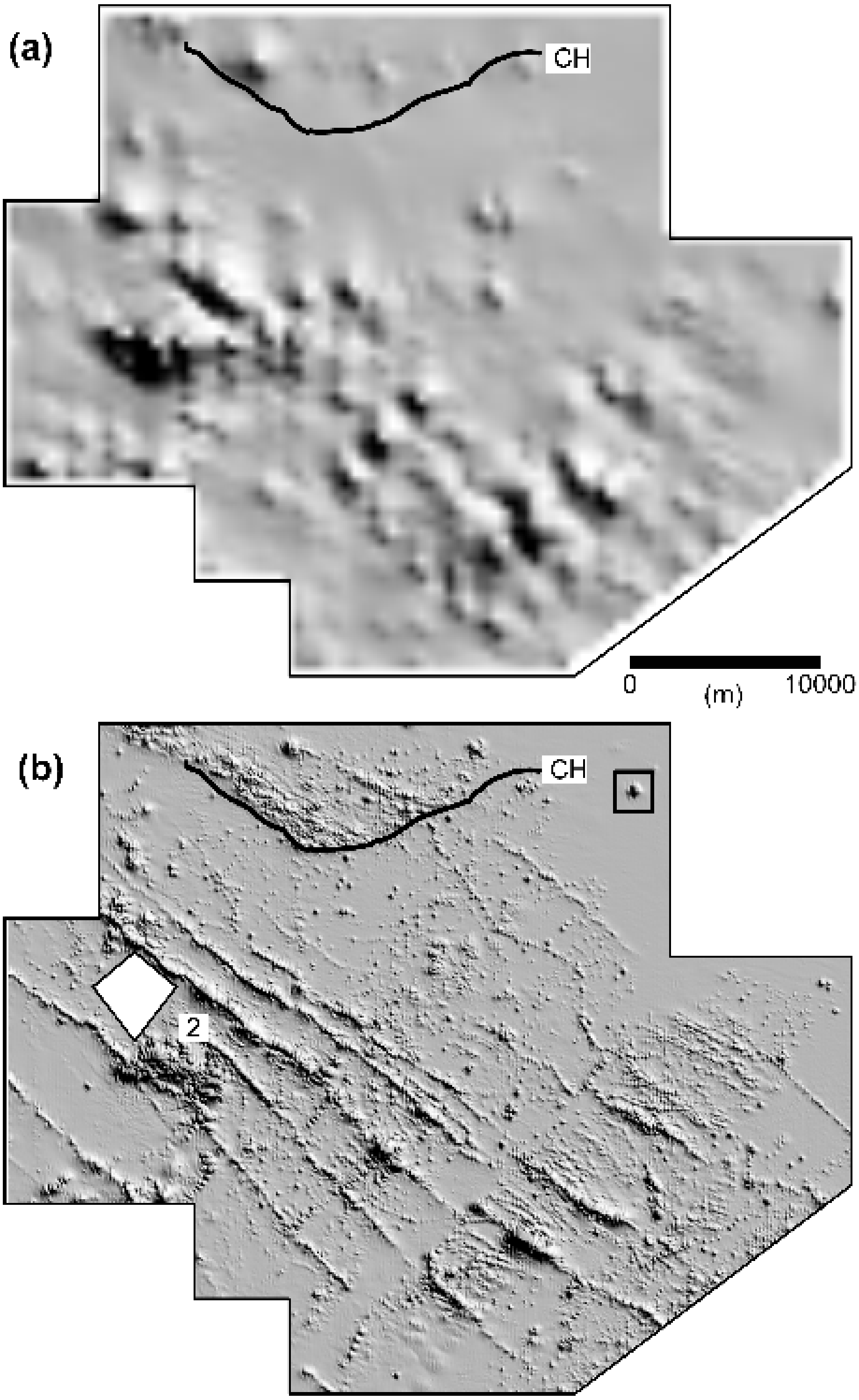


Figure 5

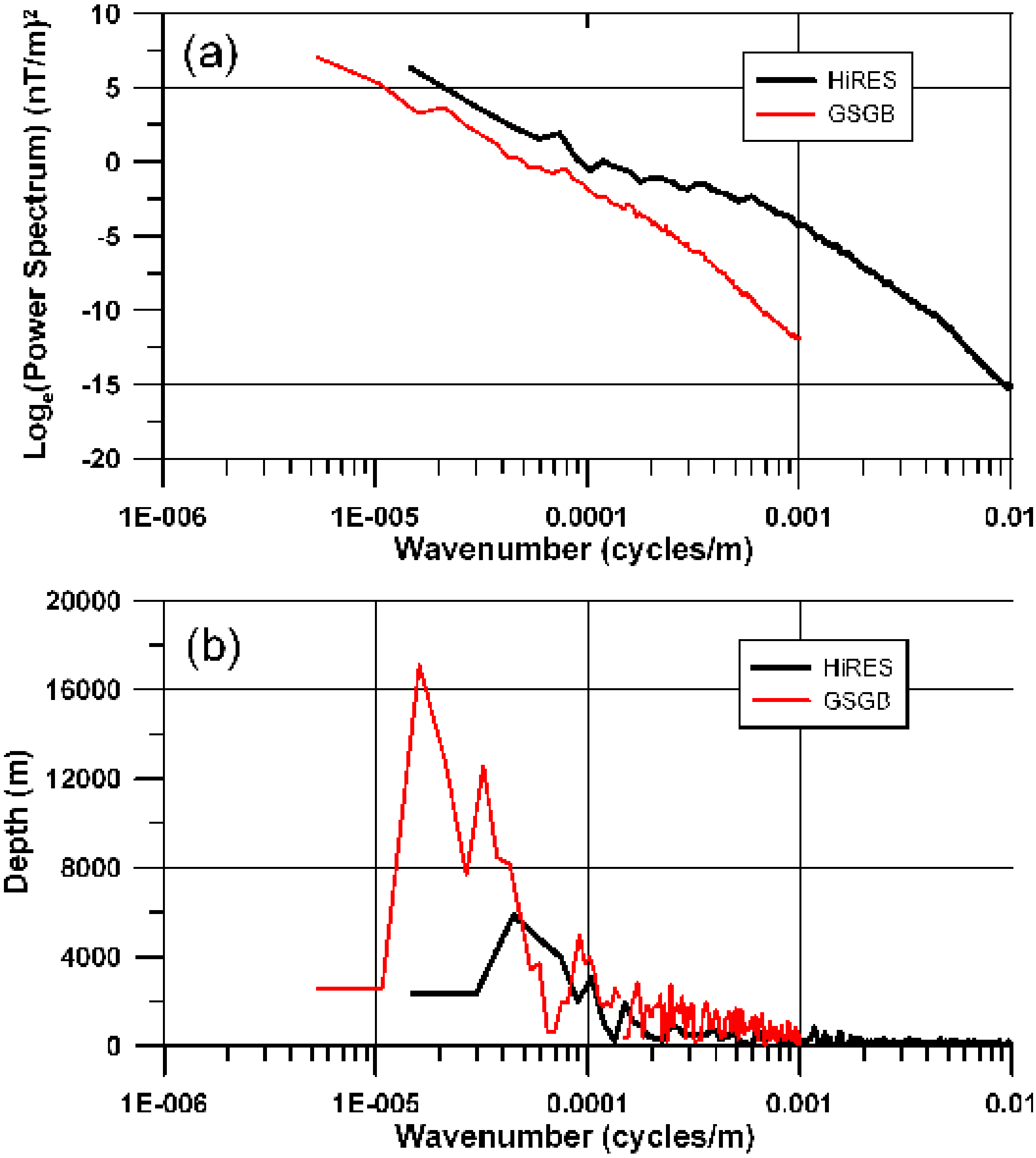
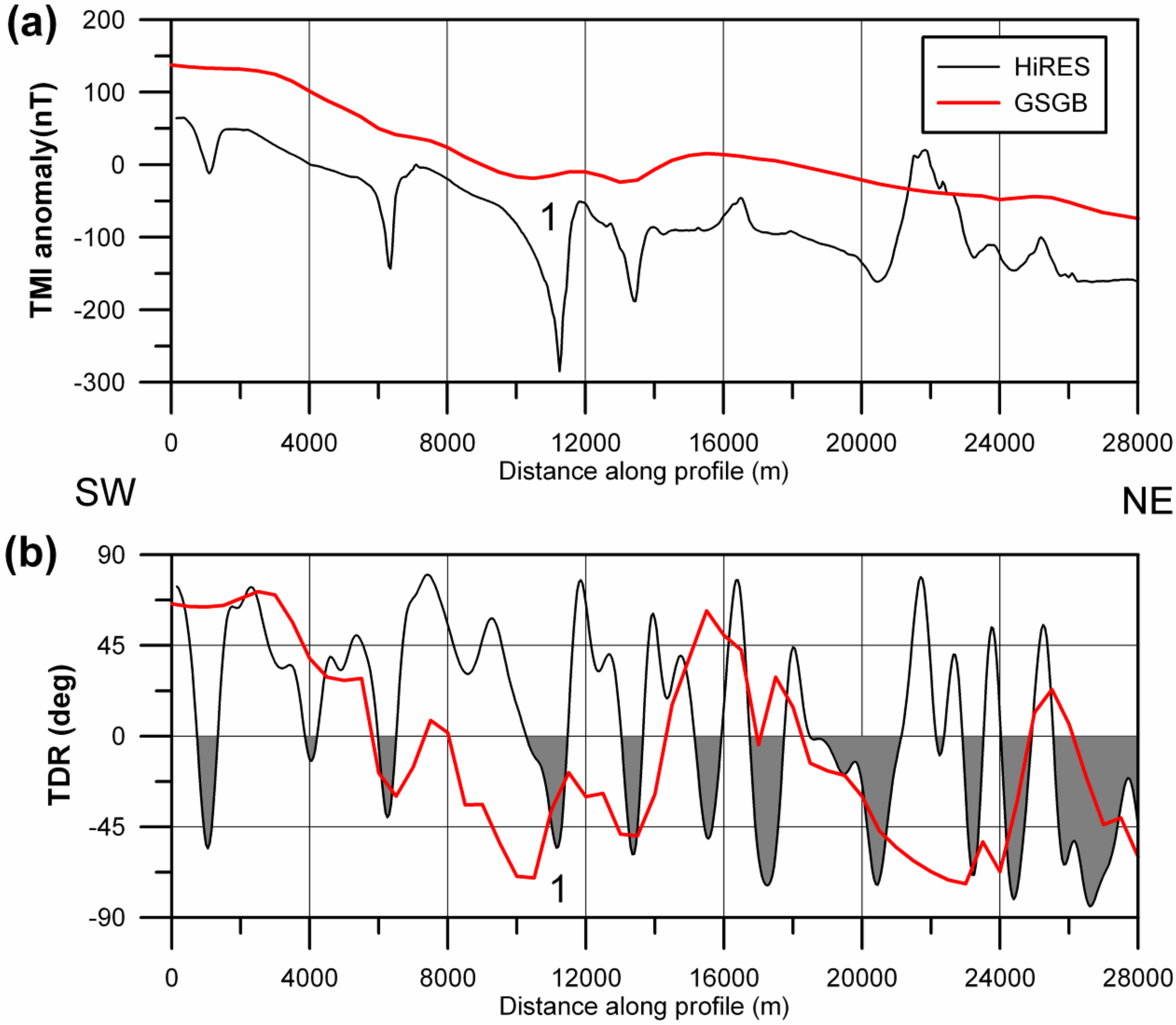

(a)
HiRES
GSGB
10
5
0
-5
-10
-15
-20
Log$_e$(Power Spectrum) (nT/m)^2
1E-006
1E-005
0.0001
0.001
0.01
Wavenumber (cycles/m)
(b)
HiRES
GSGB
20000
16000
12000
8000
4000
0
Depth (m)
1E-006
1E-005
0.0001
0.001
0.01
Wavenumber (cycles/m)

Figure 6



(a)
TMI anomaly(nT)
200
100
0
-100
-200
-300
HiRES
GSGB
1
0
4000
8000
12000
16000
20000
24000
28000
Distance along profile (m)
SW
NE
(b)
TDR (deg)
90
45
0
-45
-90
1
0
4000
8000
12000
16000
20000
24000
28000
Distance along profile (m)

Figure 7

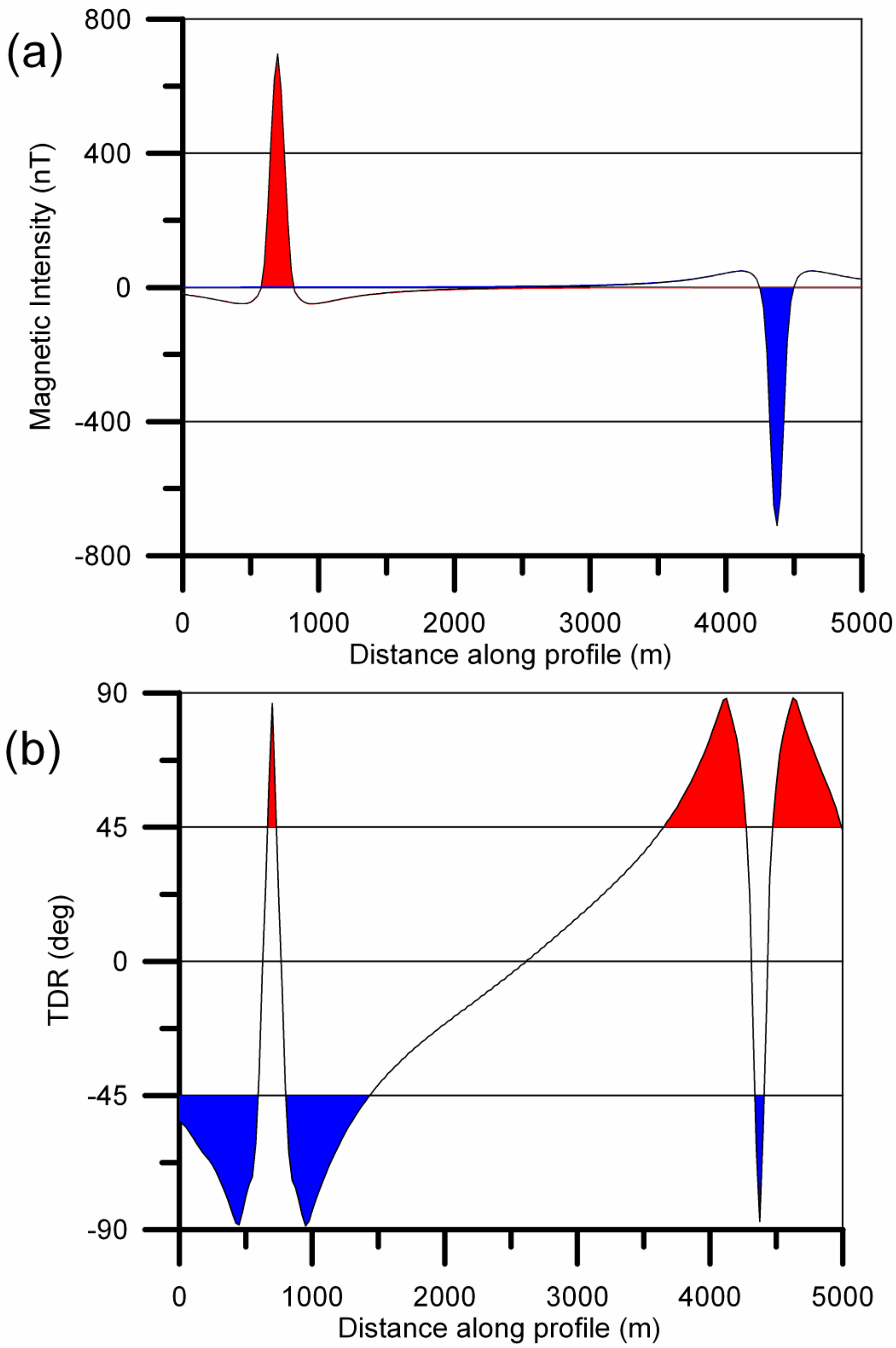
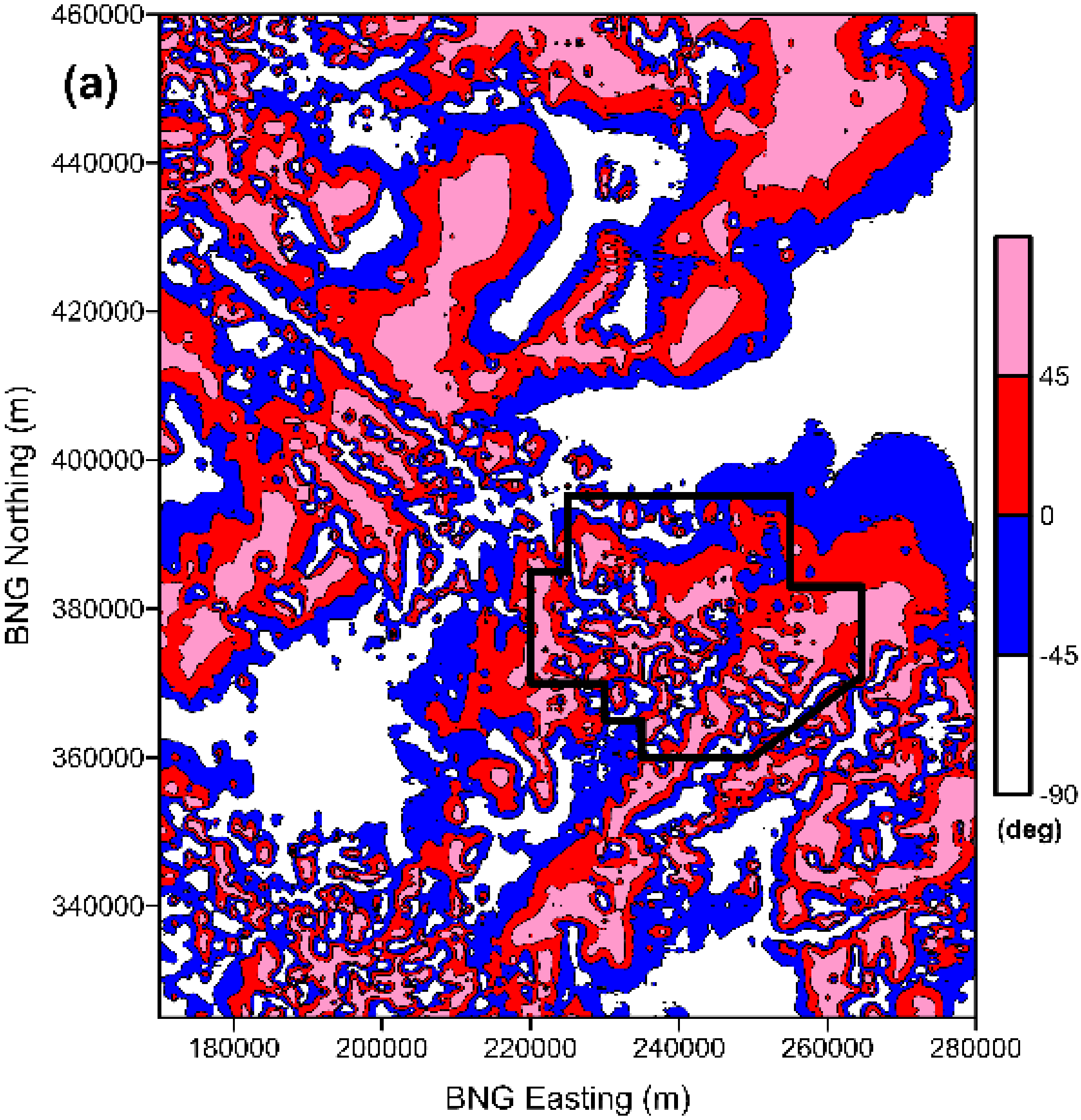

(a)
800
400
0
-400
-800
Magnetic Intensity (nT)
0
1000
2000
3000
4000
5000
Distance along profile (m)
(b)
90
45
0
-45
-90
TDR (deg)
0
1000
2000
3000
4000
5000
Distance along profile (m)

Figure 8


(a)
460000
440000
420000
400000
380000
360000
340000
BNG Northing (m)
180000
200000
220000
240000
260000
280000
BNG Easting (m)
45
0
-45
-90
(deg)

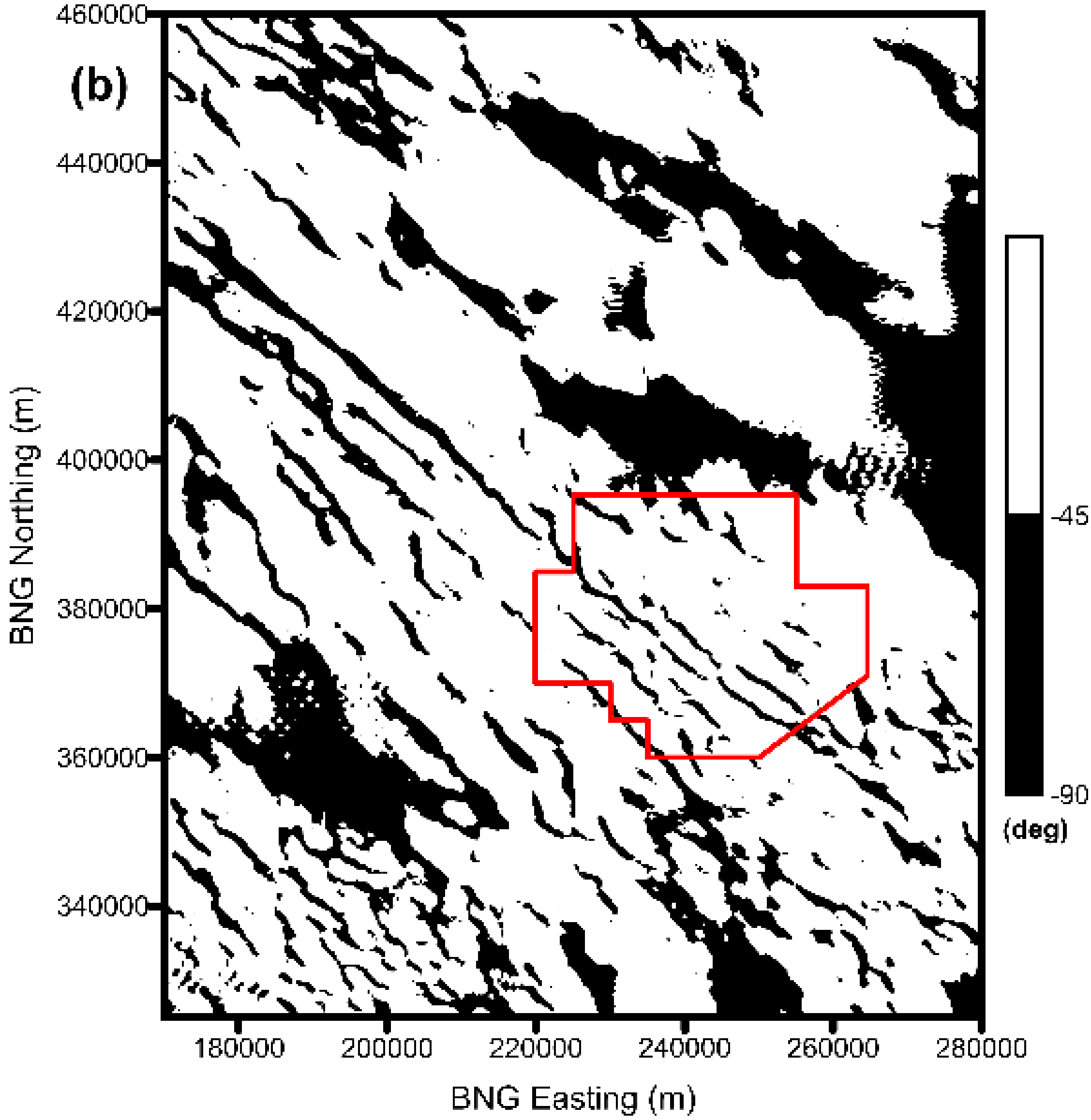

(b)
460000
440000
420000
400000
380000
360000
340000
BNG Northing (m)
180000
200000
220000
240000
260000
280000
BNG Easting (m)
-45
-90
(deg)

Figure 9

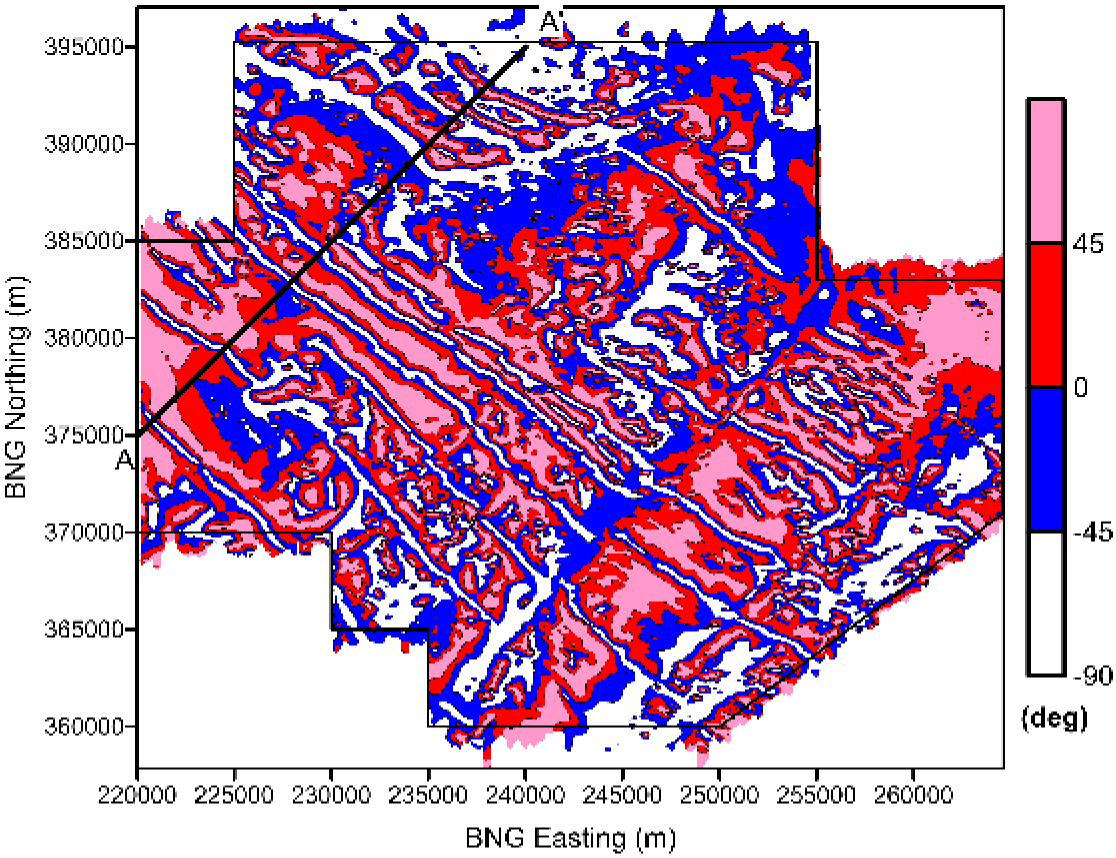
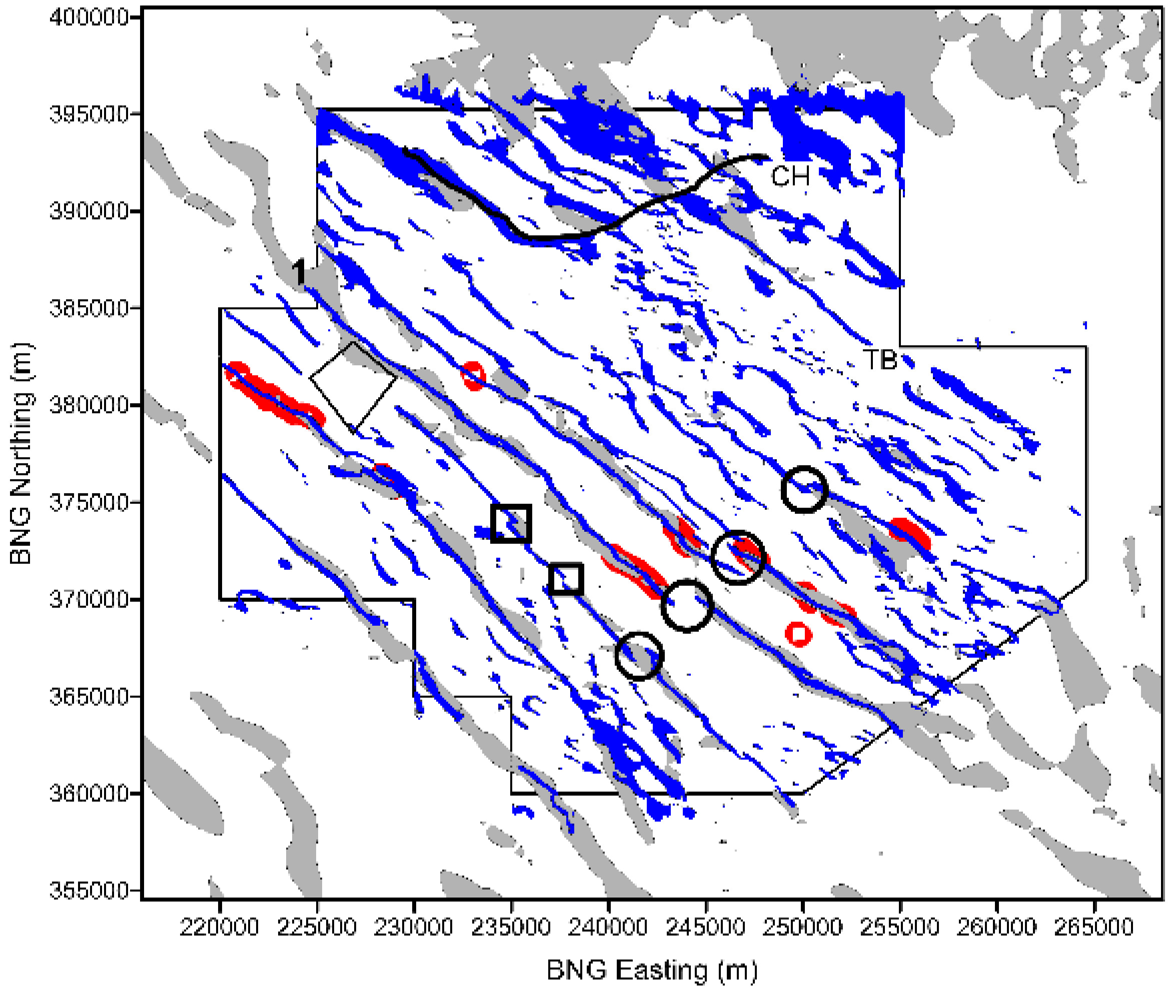

395000
390000
385000
380000
375000
370000
365000
360000
BNG Northing (m)
A
A'
220000
225000
230000
235000
240000
245000
250000
255000
260000
BNG Easting (m)
45
0
-45
-90
(deg)

Figure 10


400000
395000
390000
385000
380000
375000
370000
365000
360000
355000
BNG Northing (m)
220000
225000
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240000
245000
250000
255000
260000
265000
BNG Easting (m)
CH
TB
1

Figure 11

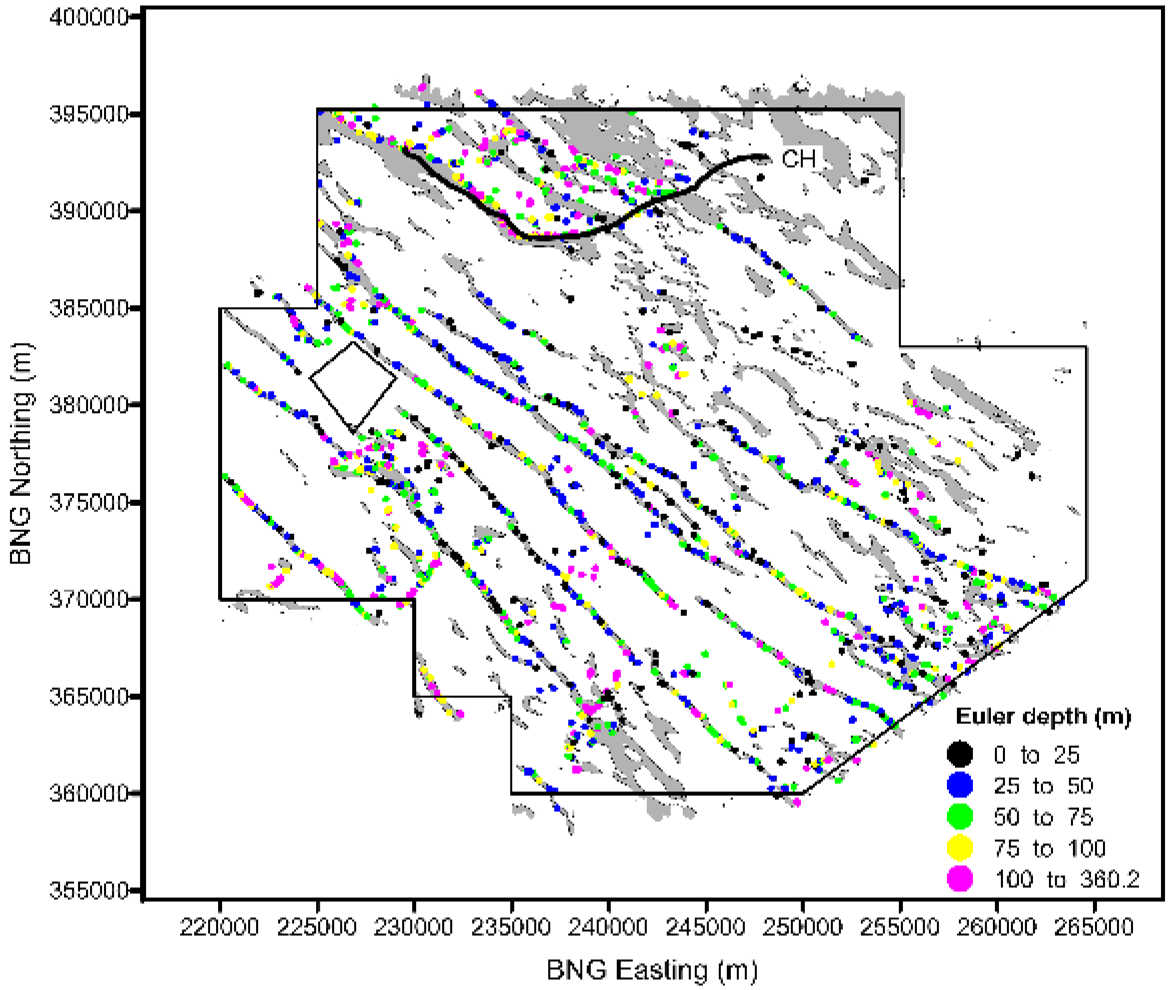
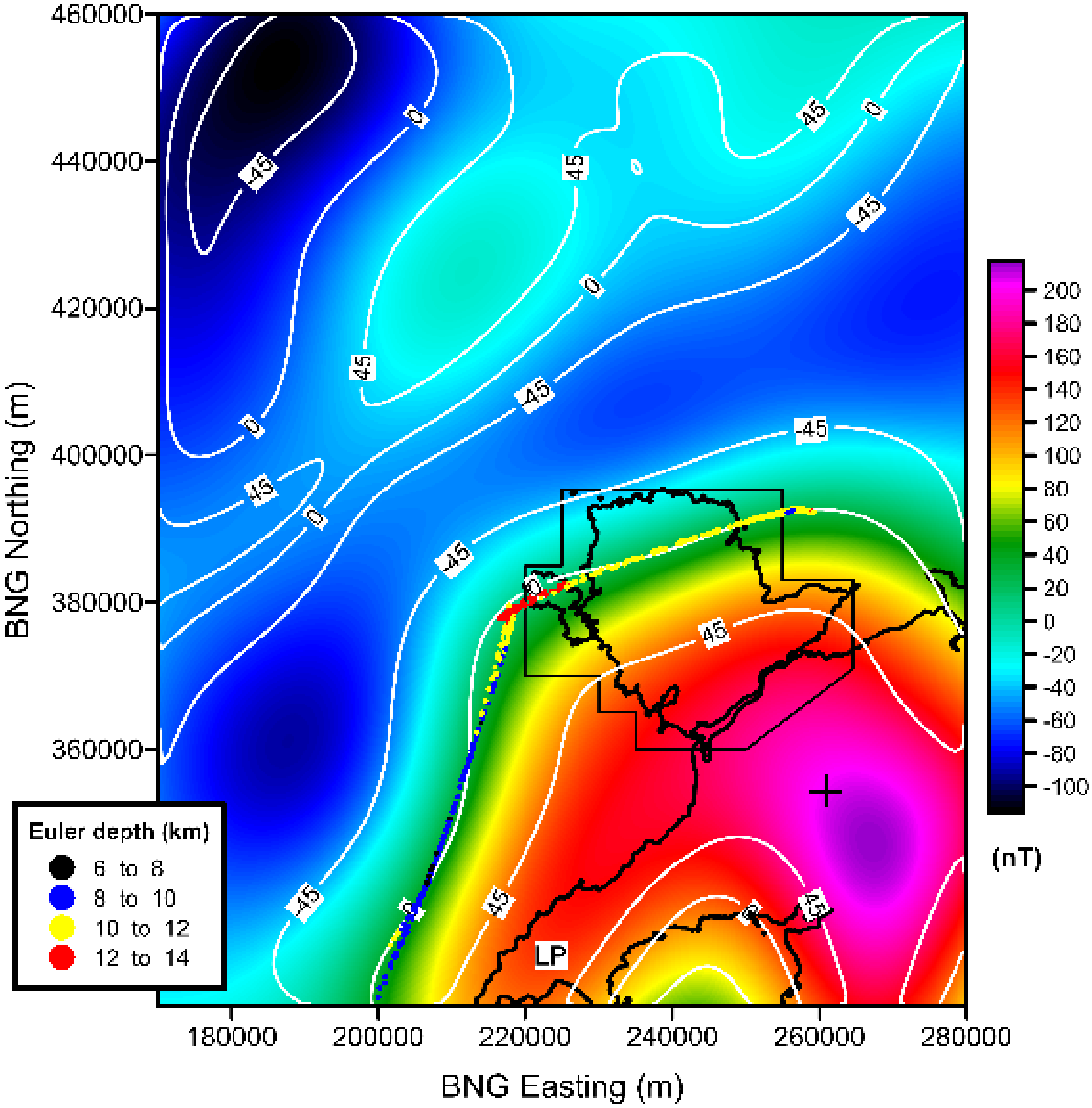
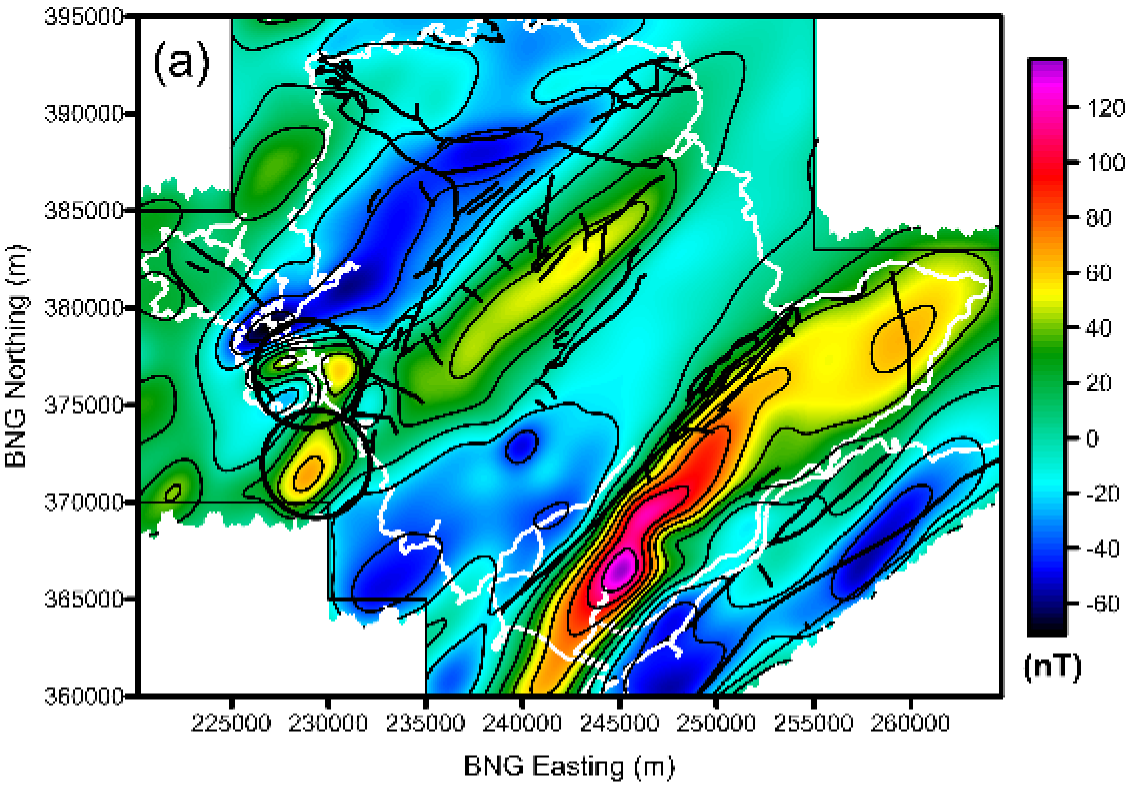

400000
395000
390000
385000
380000
375000
370000
365000
360000
355000
BNG Northing (m)
220000
225000
230000
235000
240000
245000
250000
255000
260000
265000
BNG Easting (m)
CH
Euler depth (m)
0 to 25
25 to 50
50 to 75
75 to 100
100 to 360.2

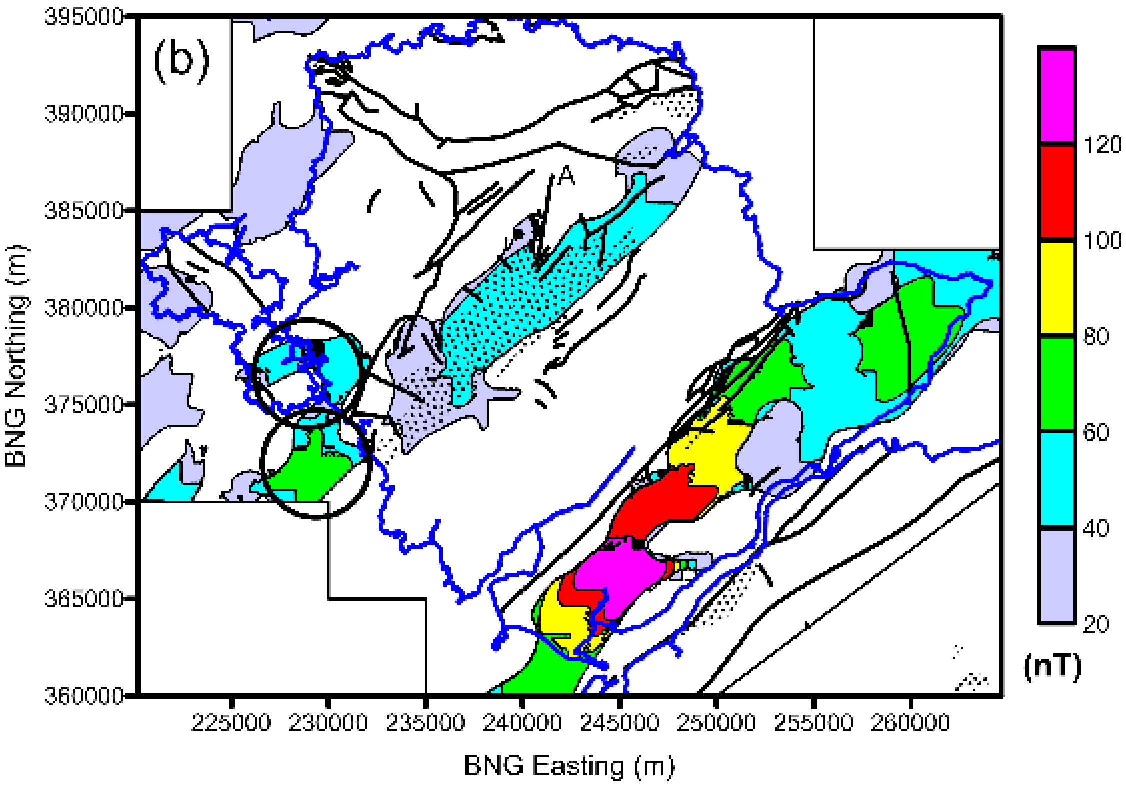
Figure 12



460000
440000
420000
400000
380000
360000
BNG Northing (m)
180000
200000
220000
240000
260000
280000
BNG Easting (m)
Euler depth (km)
6 to 8
8 to 10
10 to 12
12 to 14
LP
200
180
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
(nT)

Figure 13


(a)
395000
390000
385000
380000
375000
370000
365000
360000
BNG Northing (m)
225000
230000
235000
240000
245000
250000
255000
260000
BNG Easting (m)
120
100
80
60
40
20
0
-20
-40
-60
(nT)



(b)
A
395000
390000
385000
380000
375000
370000
365000
360000
BNG Northing (m)
225000
230000
235000
240000
245000
250000
255000
260000
BNG Easting (m)
120
100
80
60
40
20
(nT)

Figure 14

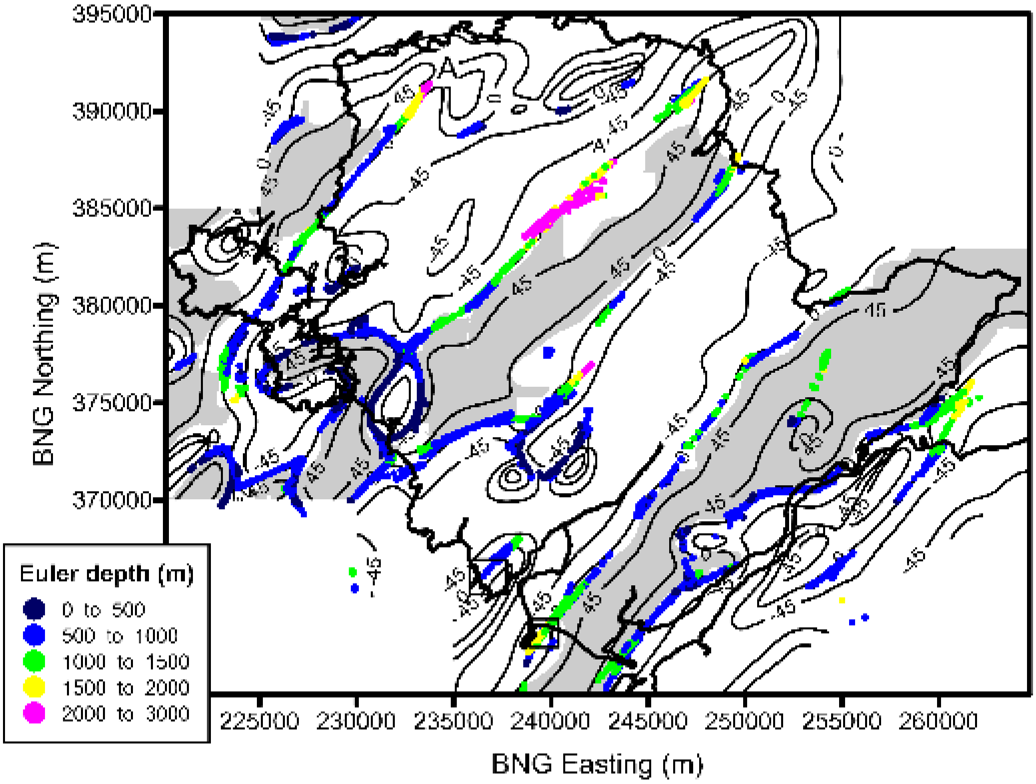

Euler depth (m)
0 to 500
500 to 1000
1000 to 1500
1500 to 2000
2000 to 3000
BNG Northing (m)
BNG Easting (m)
395000
390000
385000
380000
375000
370000
225000
230000
235000
240000
245000
250000
255000
260000

Figure 15