Potential field data in NE Scotland and its preliminary interpretation

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Contents

Abstract

In this study we make use of the potential field data made available by the BGS website to make a preliminary interpretation of the geology of Aberdeenshire in Scotland, focusing in particular on the mafic and felsic intrusive suites in the locality. We give a brief overview of the geology in the region and its geological and tectonic history. Then using the acquired data with the application of the oasis montaj software package generate maps of the Bouguer anomaly and total magnetic intensity. Further to this we apply transformations of this data such as derivatives and the analytic signal to enhance interpretation of the geology. The aim is to demonstrate the validity of the application of potential field methods in delineating geological character and structure and to ascertain the usefulness of the data transformations in making geological inferences, which we believe is demonstrated. Using the data and geological constraints we also generate a 2D subsurface model that provides further evidence of the subsurface extent of the Bennachie intrusion. Using our transformed data we would have liked to have seen some evidence for the lineament basement structures proposed by (Fettes 1986) that could have acted as conduits for the basic intrusions, but we don't believe there is evidence for this structure from this particular dataset.

1. Introduction

1.1. Potential fields - The gravitational and magnetic methods

Gravity and magnetic fields are known as potential fields because they are both vector quantities whose magnitudes depend upon the position of measurement in relation to the source. Potential field methods have the advantage of being a fast and relatively cheap source of subsurface investigation despite not producing as high a resolution image as a seismic investigation. Through the development of improved methods of acquisition and increased computing power gravity and magnetics have become powerful tools in making meaningful interpretations of the subsurface geology.

The Rocks that make up the geology of a region can be differentiated by their varying properties that characterise their nature from one another, two of these properties are density and magnetic susceptibility. Gravity measurements are a function of the mass of a rock, which in turn are a function of the rocks constituent minerals and its porosity. In the case of magnetics a rock will generate a magnetic field as a function of its magnetic susceptibility, a property which is largely dependent upon its magnetite concentration, a strongly magnetic mineral.

The different rock types found in Earth's crust have different ranges of density and magnetic susceptibility that we can measure, for example sedimentary rocks generally have a lower density that is largely dependent upon the porosity which can change as the rock becomes compacted with burial. Igneous rocks are crystalline which means that their density is less dependent on porosity and more so on their mineralogy, mafic rocks like gabbro have a density which is greater than acidic rock types rich in silica like granite that have a different mineralogy. The magnetic susceptibility is also largely dependent on the lithology, wherein sedimentary rocks have very low susceptibility due to their low magnetite content and metamorphic rocks are just generally slightly more magnetic than sedimentary rock. Basic Igneous rocks like gabbro have by far the strongest magnetic signature but mafic rocks like granite also have relatively high susceptibilities.

There is some overlap in terms of the ranges of the properties of the rocks but for the most part a rock can be readily identified by its gravitational and magnetic signature. Through the measurement of the gravity and magnetic field strengths which depend on these properties, in addition to further transformations of this data we can make worthwhile interpretations about the geology of interest.

1.2. Aim of study

Our study is focused on the mafic and felsic igneous suites and metasediments of Aberdeenshire in Scotland and the aim is to generate maps not of the susceptibility and density of the rocks but of the gravitational and magnetic anomalies in regard to a reference model for the Earth. The Bouguer anomaly (BA) shows the gravitational anomaly relative to a theoretical reference model at a point on Earth's surface, a negative BA indicates a measure of low gravity relative to this model and as such demonstrates that the rocks are of a low density, a positive anomaly indicates a high density. The same principle applies to the total magnetic intensity (TMI) data wherein the anomaly is measured relative to a theoretical model, high values indicate high magnetic susceptibility and low values indicate low values of magnetic susceptibility. Both are shown on colour shaded maps that represent the anomalies in the results section.

Further transformations of the data are applied that aid in the interpretation process, transformations such as the application of derivatives like the first and second vertical derivatives, the total horizontal derivative (THD) and the total horizontal derivative of the tilt derivative (THDTD) that enhance the edges making finding rock boundaries a simpler task. The total gradient method or analytic signal (AS) as it is otherwise known is applied to the magnetic data which helps in identifying the geometry and depth of a source body. Further we will apply the reduction to pole (RTP) method which corrects for the declination and inclination of Earths ambient magnetic field as if it were in effect directly above the source body. We hope to see what kind of results these transformations can produce for this dataset and get an understanding of their effectiveness in delineating geological features. The transformations are explained in more detail in (*section 2.2*).

In geological terms the goal is to model the upper crust and make an interpretation about how the magnetic and gravity data acquired correlates with our understanding of the geology of Aberdeenshire in Scotland, in particular the relationship of the many known igneous intrusions that are exposed at the surface and the metasediments which surround them. We would also intend to gain an understanding about the subsurface lateral extent of these igneous intrusions and build a 2D subsurface forward model that fit the data constraints. By generating maps of the TMI and the BA in addition to further transformations of this data we can see the variations in density and magnetic susceptibility of the intrusions in Aberdeenshire and observe how this data correlates with our known geological maps and models created in other work. It is also important to consider the geological constraints imposed upon our models and interpretations as well as the geological history and tectonic setting. Further to this we will also be looking for evidence of the Deeside lineament which is a basement structure proposed amongst many to exist within the Dalradian sediments in the crust that does not follow the archetypal NE-SW trend of the Caledonides. The evidence for the existence of the Deeside lineament and other lineament structures is put forward by (Fettes 1986) who further discusses its tectonic significance during the different phases of orogenesis.

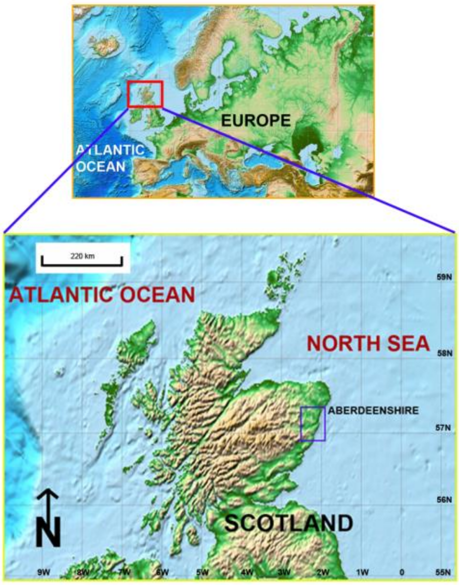
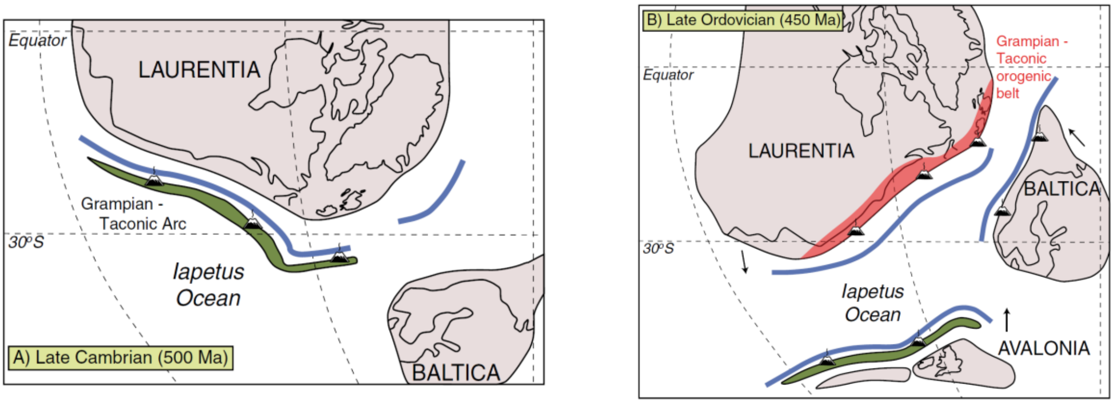


Figure. 1. Location map demonstrating in which region the study was conducted. Extracted and modified from the ETOPO1 global relief model

1.3. Geology and Geological history

Our aim is to focus on the distinct geological interpretation of the magmatic province of Aberdeenshire Scotland. But for anyone to make a good interpretation of what the gravity and magnetic data can show us we must consider what is understood about the geological morphology and history of the area, and to a wider degree the rest of the UK as well. In doing so we may be able to best constrain our models based on our current geological understanding. The following subsection outlines the history of the geology that we see today.

The Iapetus ocean that separated the supercontinents of Laurentia to the north and Gondwana plus Baltica to the south began rifting along the Laurentian and Amazonia continental margin during the late Neoproterozoic precisely 613-614 Ma according to (O'Brien & van der Pluijm 2012) and reached its maximum extent by the beginning of the Ordovician, being possibly as wide as 5000 km (D. Stephenson 2000). It was during the Neoproterozoic approximately between 800 Ma and 520 Ma that the dalradian sediments were deposited in an evolving basin on the margins of Laurentia before they were metamorphosed during the upheaval of the Caledonian orogeny (MacDonald & Fettes 2007). The plates began to converge with one another during the early Ordovician, the direct motions of which are still being debated to this day. There is strong geological evidence that Scotland originated as part of the Laurentian supercontinent whilst the rest of Britain existed on the fringes of Gondwana as part of a minor continent known as Avalonia. It is understood that by the mid Silurian that the last remnants of the Iapetus seabed were subducted under the Laurentian continental crust which brought what we know of today as Scotland and England together and further resulted in the generation of a new supercontinent known as Laurussia around 435-425 Ma (Dewey and Strachan 2005).



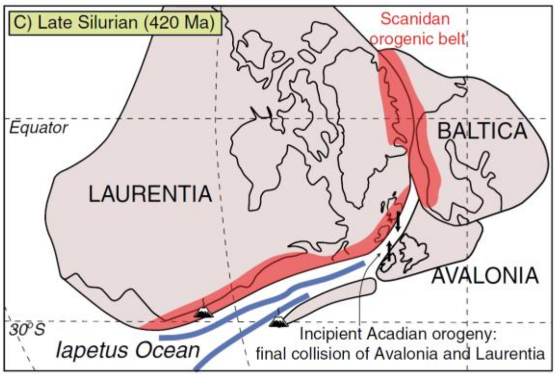
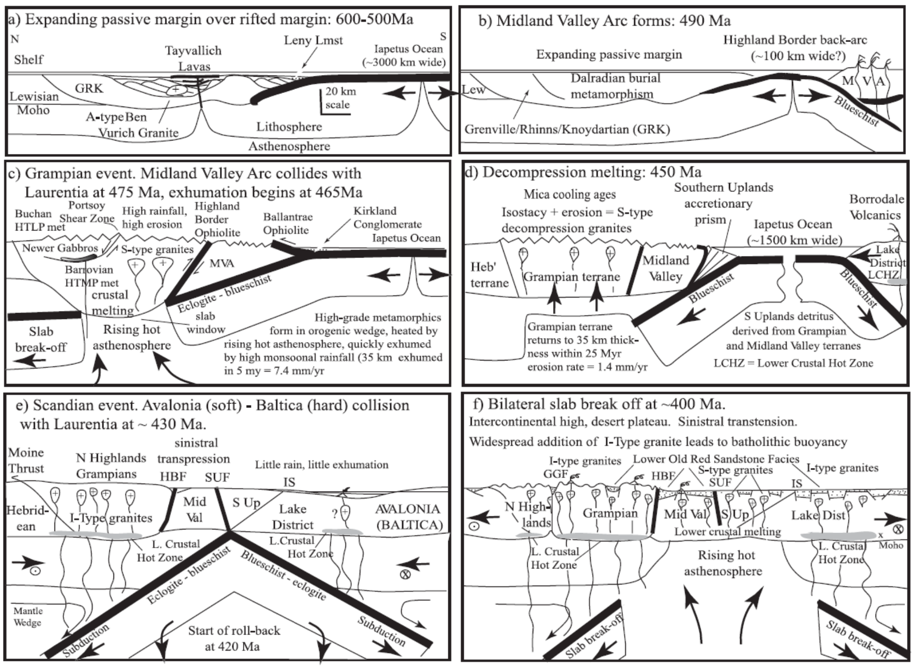


Figure. 2 a) *top left.* The Iapetus ocean including Baltica and Laurentia, Late Cambrian approximately 500 Ma **2 b)** *top right.* The beginning of the closure of the Iapetus ocean and Grampian orogeny, Late Ordovician approximately 450 Ma **2 c)** *Bottom left*. Initiation of the Scandian event where Baltica and Avalonia collided with Laurentia approximately 420 Ma, Late Silurian. from (Chew 2009)

Figure. 3) *Below* An overview of the tectonic sequence of events during the Caledonian orogeny from (Oliver 2008)

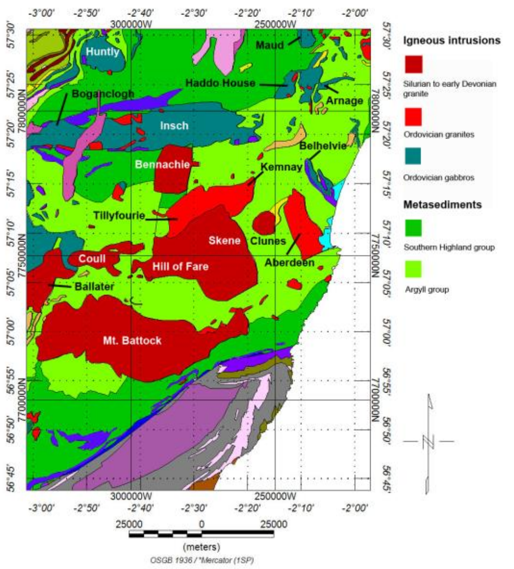


The closure of the Iapetus ocean is part of a much larger event known as the Caledonian orogeny which took place over a large timescale that includes the Cambrian, Ordovician, Silurian and Devonian periods, a time scale of around 200 Ma (McKerrow 2000). This orogenic event and time period can be associated with vast mountain building and crustal deformation in addition to the generation of most of the igneous intrusions of interest to us in Aberdeenshire. More specifically the Grampian event which occurred before the closure of the Iapetus suture between 480 and 465 Ma when Scotland was 20° S of the equator. This event may be attributed to a series of arc continental collisions with Laurentia during the Arenig (Dewey and Shackleton, 1984) which resulted in the injection of mafic intrusions such as the Insch gabbro 470 Ma and the Portsoy gabbro 474 Ma (Oliver *et al* 2008) which are thought to be the roots of the volcanic arc. S-type granitic intrusions are also associated with this time period, namely the Aberdeen granite 470 Ma, the Tillyfourie granite 471 Ma and Strichen granite at 473 Ma (*See figure 4 for intrusion location*). Whilst the Grampian event was occurring eastern Avalonia began to rift from Gondwana creating what is known as the Rheic ocean, which simultaneously reduced the width of the Iapetus ocean to approximately 2000 km. After the Grampian event the Iapetus continued to close and there was a period of 12 Ma where no igneous activity took place. That is until subduction begins to occur and decompression melting takes place allowing for the further initiation of igneous activity. There is then a further gap of another 17 Ma before initiation of the Scandian event ~430 Ma which is when Avalonia and Baltica collided with Laurentia, most of the igneous intrusions associated with this event and time period such as the Aldearn granite, Comrie diorite and Rubha Mor appinite but do not pertain to our area of interest. The genesis of most of the Aberdeenshire Caledonian Granites such as The Hill of fare granite 403 Ma, Skene granite 396 Ma and Bennachie granite 408 Ma formed in the lower parts of the crust as the subducting slab broke off, the intrusion of these granites lowered the density of the crust resulting in the effect of batholitic buoyancy that raised the Grampian Terrane by as much as 2.6 km (Oliver *et al* 2008).

The geology of Scotland today can be subdivided into five distinct terranes with differing geological characteristics that are separated by three major strike-slip faults that strike south-west to north-east in direction, in the north west of Scotland there exists the moine thrust zone which is the fourth boundary between these terranes. The five terranes of Scotland are the Hebridean terrane, the Northern Highland terrane, the Grampian Highland terrane (GHT), the Midland valley terrane and the Southern Upland terrane. The Aberdeenshire intrusions are situated in the GHT which is bounded by the Great Glen fault (GGF) to the north and the Highland boundary fault (HBF) to the south. The geology of the GHT consists of high grade polydeformed (Fettes 1970) metasedimentary rock that is primarily precambrian in age, the metasediments are part of what is known as the Dalradian supergroup. The Dalradian supergroup itself consists of more minor groups known as, in chronological order from oldest to youngest the Grampian, Appin, Argyll and Southern Highland groups. Of these groups only the metasediments of the Argyll and Southern Highland groups lie exposed at the surface within our study location. The metasediments have a lithology that consists of psammite, semipelite and pelite when at around 15-20 km there is a transition to what is thought to be a granulite facies.

The distribution of the igneous bodies is strongly correlated to linear features in the basement structure of the crust that do not meet the normal SW-NE Caledonian trend correlated within the Dalradian belt there are two distinct styles of metamorphism that have also been identified, known as Buchan and Barrovian. Each is characterised by a distinct facies and associated mineral type that correspond to distinct pressure and temperature conditions. The

Buchan facies series which lies around the Portsoy region is defined by high temperature and low pressure conditions whereas the Barrovian facies which is found by the HBF is characterised by high pressure high temperature conditions.



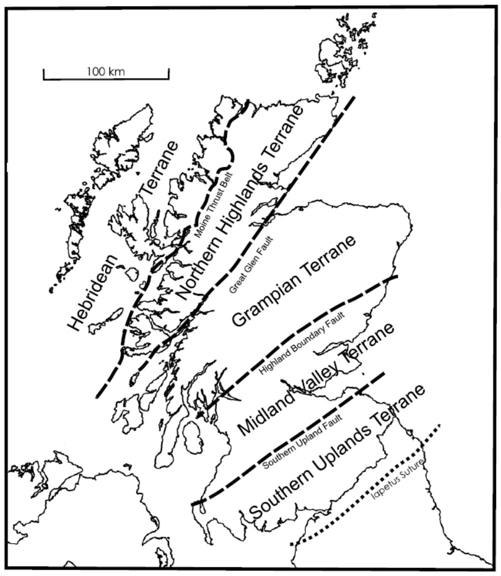


Figure. 4. *Left* Geological map of the study location with named intrusions. Reproduced with the permission of the British Geological Survey ©NERC. All rights Reserved. **Figure. 5.** The geological terranes of Scotland from (MacDonald & Fettes 2007)

2. Data and methodology

2.1. Data and Acquisition

Field data acquisition was unfortunately not possible due to the time constraints of the project so gravity and magnetic data were downloaded from the British Geological Survey website (BGS 1980's) which has data for the whole of the British Isles. As we are only concerned with the data within a given geological locality the results were filtered for the data range of latitude between -3.01° and -1.95° W in addition to 56.73° and 57.50° N for longitude. Within these co-ordinates there are 22842 magnetic data entries and 2678 gravity data entries.

Information on the acquisition of the data is quite poor but according to the BGS site an aeromagnetic survey was conducted between 1955 and 1965 with a flying height of 305m and a line spacing of 2km with a tie line occurring every 10km. The trend of the acquisition was in an N–S and E–W direction. The data has also been pre-processed with regard to the IGRF-90 magnetic reference model such that it gives the value of the TMI for the region. Unfortunately there is no information on what equipment was used to record the data for the survey. The aeromagnetic survey can be defined as a reconnaissance survey as it covers the whole of the UK, this resulted in a large flight line spacing of 2 km and as a consequence low resolution of data, not ideal for the small area in which we are interested. A regional survey over the area of interest with a much smaller flight line spacing and lower flying height would have been preferable as it would have produced a higher resolution of data, which in turn would aid interpretation and our ability to build a model.

There is no data on the gravity acquisition other than that an observation was carried out for roughly every 1.6 km^2 over the UK. Corrections were applied to the data which gives the resulting Bouguer anomaly for all observations. The reference models used are GRS67, IGSN71 and NGRN73 although it is not explicitly stated which reference models were used where and for which bits of data. The datum used in both datasets is the OSGB36 datum which is localised for the British Isles.

2.2 Transformation of data

2.2.1 Gridding methods

To plot the gravity and magnetic data correctly on the map for interpretation requires the use of a gridding algorithm. The Oasis software package has seven algorithms available for displaying data that are suited for different purposes. The gravity and magnetic data was gridded using the minimum curvature method which produces "a minimum curvature surface, which is the smoothest possible surface that will fit the given data values" as outlined in (Geosoft 2012) (Briggs 1974). The algorithm generates an interpolated surface that repeats an equation for a certain number of iterations until a given tolerance value is met, the method does not give an exact solution but is a good approximation of interpolated data. In theory the grid spacing should not be less than half the data point spacing (Geosoft 2012), but in our case this did not produce good results which is probably down to the very low resolution of the data. This resulted in using a grid spacing of 50m which is not in accordance with theory but gave us the best result as transformation had far less artefacts evident in the resulting grids.

2.2.2 Gravitational and magnetic gradients

The first spatial derivative of the horizontal or vertical potential field tells us how quickly the BA or TMI is changing. Vertical derivatives are effectively a form of high pass filter which supress the signature of deeper structures make them useful for sharpening near surface anomalies, unfortunately it also gives them the property of enhancing noise (Cooper & Cowan 2004). The first and second vertical derivatives are applied to both the BA and RTP-TMI grids.

$$1VD = \frac{\partial A}{\partial z} \tag{1}$$

$$2VD = \frac{\partial^2 A}{\partial^2 z} \tag{2}$$

A more commonly used method is the total horizontal derivative (THD) method which is an edge detecting filter that gives the best response for shallow bodies that produce short wavelength high amplitude anomalies. The THD calculates the square of the derivative of the potential field in the x and y directions and takes the square root of the result. Since the THD is only a first order derivative it has the advantage of not being especially sensitive to noise in the same way second order derivatives are and is useful in determining the edges of both shallow and deep source bodies. The THD has also proven to be useful in for identifying structures such as faults contacts and dykes. the magnetic and gravity data of the THD can be found in (Cooper & Cowan 2004)

$$THD = \sqrt{(\frac{\partial A}{\partial x})^2 + (\frac{\partial A}{\partial y})^2} \tag{3}$$

We can also apply second order special derivatives to our potential field data, unless the first derivative which shows us how quickly the result is changing in a particular direction these derivatives give us the location where the maximum rate of change of the BA occurs but it does not give us much information about what is going on at depth. It is much more complex trying to calculate the vertical derivative because we do not have measurements of the BA at depth from which to calculate the derivative. This is why we employ the Laplace equation

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} + \frac{\partial^2 A}{\partial z^2} = 0 \tag{4}$$

Gravitational and magnetic fields are both potential fields because the measurement is a function of the position relative to the source of the ambient field. Potential fields are subject to the Laplace equation which is a second order partial differential equation, where the second order partial derivative of the field A with regard to the spatial dimensions is equal to 0, this equation can be rearranged to solve for the depth component z.

2.2.3 Reduction to pole

In achieving a true representation of the total magnetic intensity at the Earth's surface the magnetic data must undergo some processing. Reduction to pole corrects for the declination and inclination of the Earths ambient magnetic field in addition to the inclined magnetic field of the source. Without accounting for these anomalies we would not be able to get a true representation of the source location as any deviation in the inclination of the magnetic source gives a lower value for the magnitude of the anomaly and in the northern hemisphere moves the peak of the anomaly to the south, thus making interpretation more difficult. The reduction to pole filter essentially corrects for the magnetic vector of the remanent magnetisation of the source such that it is aligned with the ambient field. Applying RTP involved choosing six equally distributed positions across the map area and inputting the chosen co-ordinates into a magnetic field calculator that would output data for the magnetic inclination and declination values for the given location. I then took the average value of these results to produce my RTP map in the Oasis montaj software package.

Latitude	Longitude	Magnetic inclination	Magnetic declination	Total field nT
57° 25’	-02° 50’	71.0845°	-10.8078°	48,689.2
57° 25’	-02° 30’	71.0769°	-10.6916°	48,686.1
57° 25’	-02° 10’	71.0695°	-10.5756°	48,683.2
56° 50’	-02° 50’	70.6039°	-10.6429°	48,517.8
56° 50’	-02° 30’	70.5962°	-10.5288°	48,514.8
56° 50’	-02° 10’	70.5886°	-10.4149°	48,511.9
	Average	**70.8366°**	**-10.6103°**	**48,600.5**

Table 1. RTP calculated values from (NOAA 2015)

2.2.4 Analytic signal (total gradient method)

The analytic signal is another processing tool that can help in determining the geometry and depth of the source body. One of the advantages of the analytic signal is that it has no regard towards the direction of the ambient magnetic field in addition to the field of the source meaning that it can be applied to data without the application of RTP. The amplitude of the three dimensional analytic signal at a location at the surface is given by

$$|A(x,y)| = \sqrt{(\frac{\partial T}{\partial x})^2 + (\frac{\partial T}{\partial y})^2 + (\frac{\partial T}{\partial z})^2} \tag{5}$$

T is the total magnetic intensity, x, y and z represent the co-ordinates of three dimensional space. (Roest *et al* 1992)

The equation calculates the derivatives of the total magnetic field at a location in both horizontal directions and also in the vertical direction, or in other words the total gradient of the magnetic field, the addition of these derivatives gives the absolute value of the analytic signal at a position (x,y) on the surface . The maxima of the analytic signal occurs at the boundary of the source body where the magnetic properties vary, it is in this regard that the analytic signal is useful in helping to determine the location and geometry of the source of the anomaly.

2.2.5. Total horizontal derivative of the tilt derivative

The tilt derivative of the total horizontal derivative is a transformation that can be applied to magnetic data that is useful in shape and edge detection. The tilt derivative is the arctan of the first vertical derivative divided by the total horizontal derivative of the TMI. Because of the trigonometric nature of the tilt derivative the amplitude must range between + π/2 and –π/2 radians (Verdusco 2004). The THDTD is invariant to geomagnetic inclination which is useful as the magnetic field generated by a rock can have two vector components consisting of a remanent and induced part, this can affect the result of derivatives if you are to only assume that the rock produces an induced component of magnetisation. The TDTHD is given by the square root of the sum of the squares of the tilt derivative in the x and y directions.

$$THDTD = \sqrt{(\frac{\partial TD}{\partial x})^2 + (\frac{\partial TD}{\partial y})^2} \qquad (6)$$

2.3. Forward modelling of a subsurface 2-D Profile

The Oasis Montaj software program has an inbuilt feature called GM-SYS which allows you to build 2D subsurface models for gravity and magnetic data. Using this software we have selected a profile across our region (*see figure. 18*) the profile covers the Huntly Insch, Mt. Battock intrusions as well as part of the Skene complex and the metasediments. The profile also crosses the HBF covering a small section of the Midland valley terrane. The concept is to build a model such that it minimises the misfit of the gravity and magnetic profile data, to do this we must also make use of the measured geological data for the density and magnetic susceptibilities of the rock, these values are outlines in *table 2*.

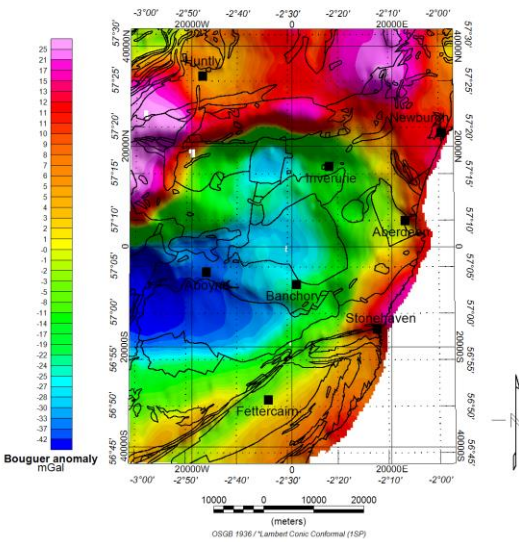
The 2-D model will be a simplified version of the geology that will only account for the igneous intrusions, and will only consider the exposed Argyll and Southern uplands groups as one amalgamated group of Dalradian metasediments. The constrained density data for the Dalradian metasediments as well as the intrusions will come from (McGregor & Wilson 1967). There does not appear to be any good data on the magnetic susceptibilities of the intrusions, so we intend to apply average values from (Clark and Emerson 1991) for the gabbro and granitic bodies. The magnetic susceptibilities of the sediments is negligible, other parameters not well constrained are adjusted accordingly to minimise the misfit in the resulting model. (Sallomy & Piper 1973) Made measurements of the remanent component of magnetisation of the younger gabbros, and these values were initially added to the model but the resulting misfit was only increased reducing the value of the magnetic data to the resulting model. (Carmichael & Storetvedt 1981) Further surmise that the Huntly and Insh intrusions have complex multicomponent magnetisation.

Table. 2. *Density and magnetic susceptibilities*

Lithology	**Density (Mg m^{-3})**	**Magnetic susceptibility SI units**
Huntly (basic intrusion)	2.920	0.045
Insch (basic intrusion)	2.910	0.045
Hill of Fare (acidic intrusion)	2.630	0.025
Mt. Battock (acidic intrusion)	2.590	0.025
Dalradian	2.740	-
Midland Valley	2.600	-
Granulite basement	2.630	0.015

3. Results

The following section includes maps of the unmodified BA, TMI and transformed maps of the data generated in the Oasis Montaj software package. We also include a diagram of the profile section selected for our finalised 2D forward model and the final model itself. The model diagram also includes the measured BA and TMI anomalies along the profile, the calculated fields generated by the model and the residual between the measured and observed values.



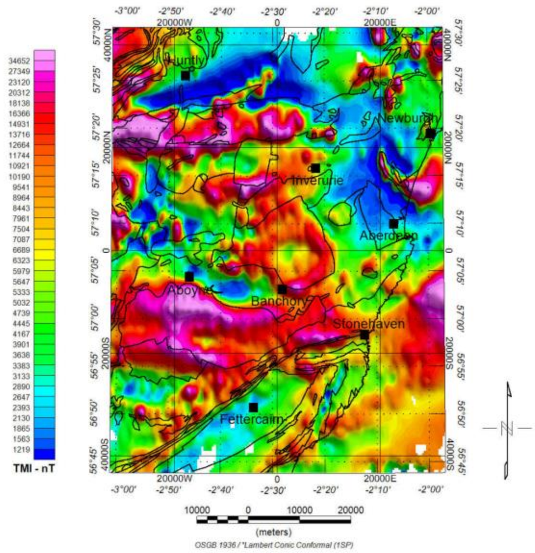
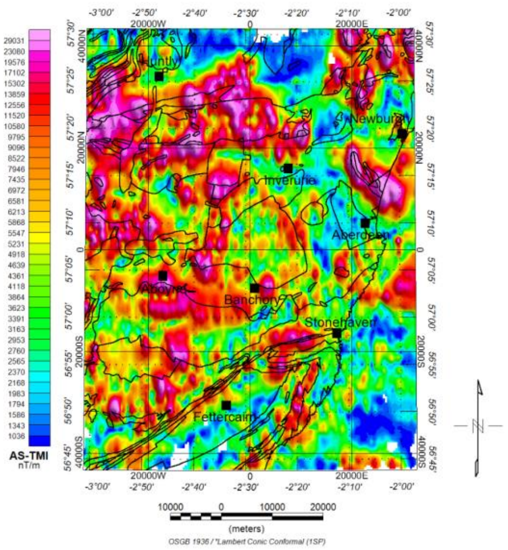


Figure. 6. *Left.* Bouguer anomaly map. **Figure. 7.** *Right* Total magnetic intensity map - Reproduced with the permission of the British Geological Survey ©NERC



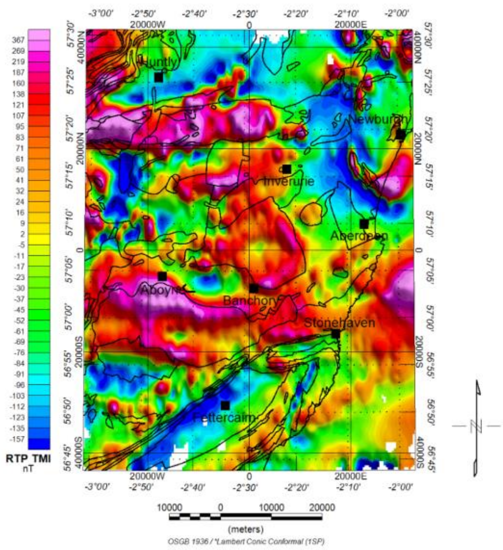
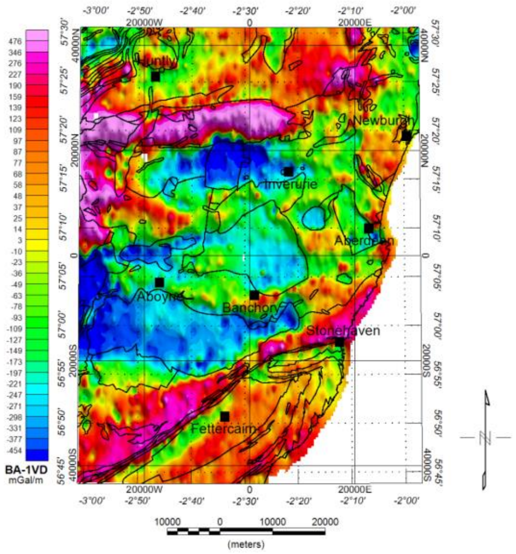


Figure. 8. *Left.* Analytic signal of total magnetic intensity map. **Figure. 9.** *Right.* Reduced to pole total magnetic intensity map - Reproduced with the permission of the British Geological Survey ©NERC



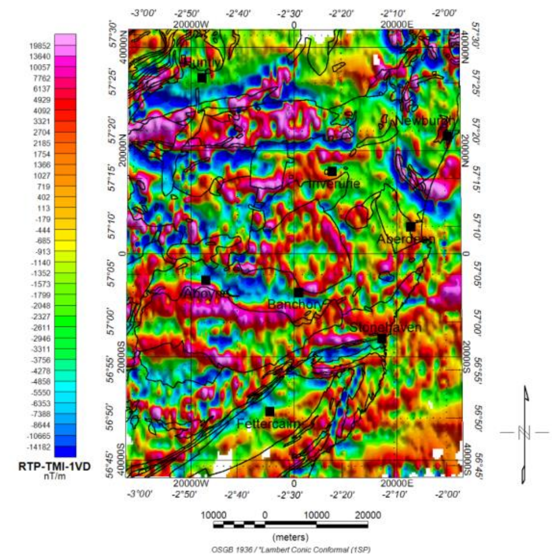
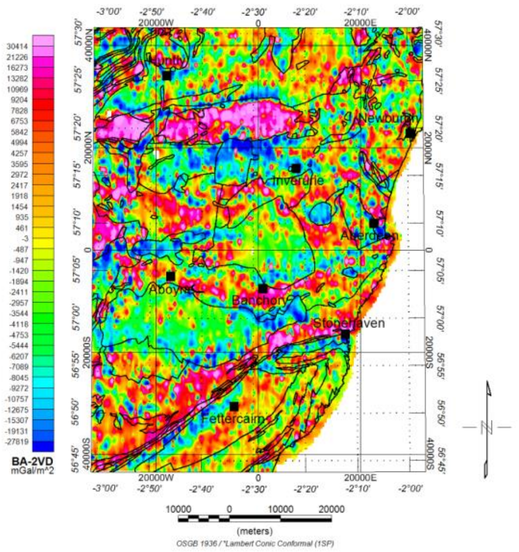


Figure. 10. *Left.* First vertical derivative of the Bouguer anomaly map. **Figure. 11.** *Right.* First vertical derivative of the reduced to pole total magnetic intensity map - Reproduced with the permission of the British Geological Survey ©NERC



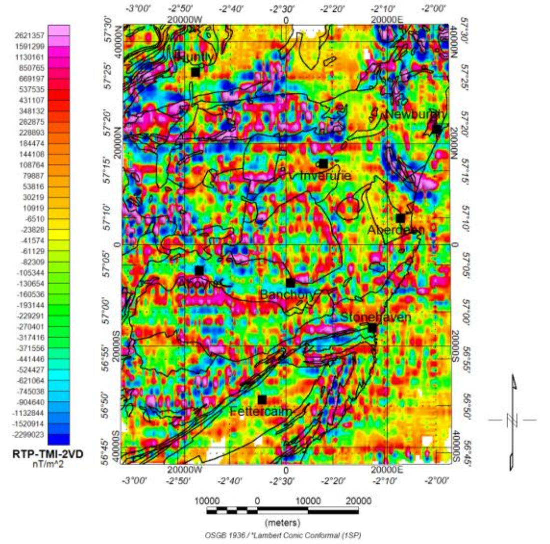
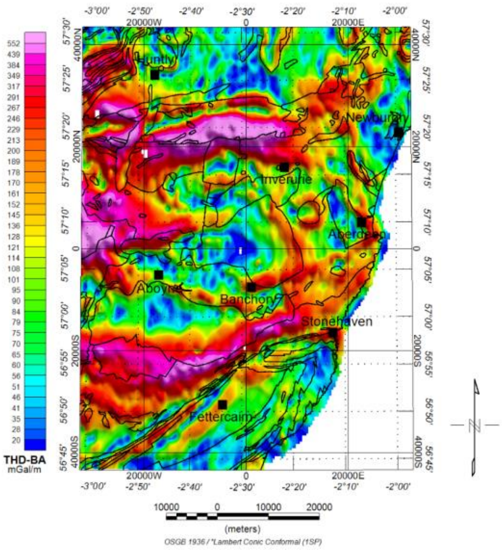


Figure. 12. *Left.* Second vertical derivative of the Bouguer anomaly map. **Figure. 13.** *Right.* Second vertical derivative of the reduced to pole total magnetic intensity map - Reproduced with the permission of the British Geological Survey ©NERC



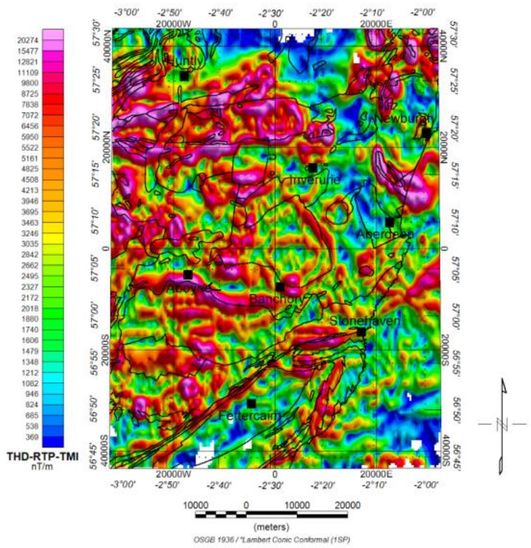
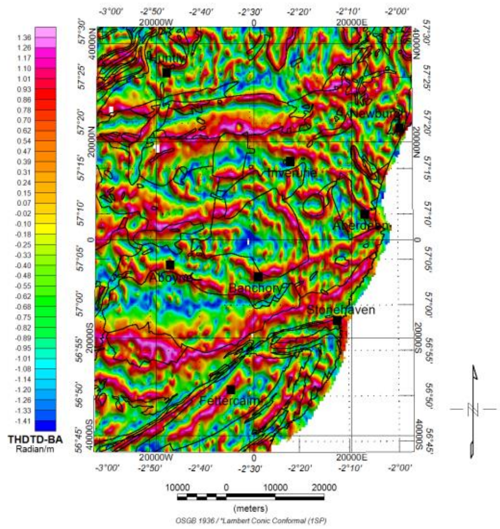


Figure. 14. *Left.* Total horizontal derivative of the Bouguer anomaly map. **Figure. 15.** *Right.* Total horizontal derivative of the reduced to pole total magnetic intensity map - Reproduced with the permission of the British Geological Survey ©NERC



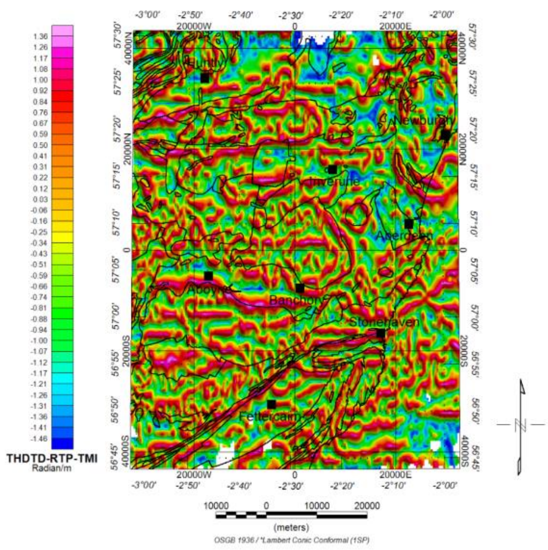
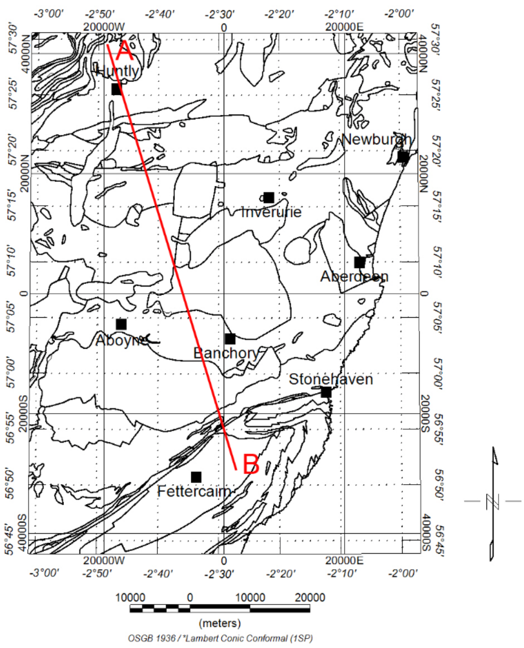


Figure. 16. *Left.* Total horizontal derivative of the tilt derivative of the Bouguer anomaly map. **Figure. 17.** *Right. R*educed to pole, total horizontal derivative of the tilt derivative total magnetic intensity map - Reproduced with the permission of the British Geological Survey ©NERC



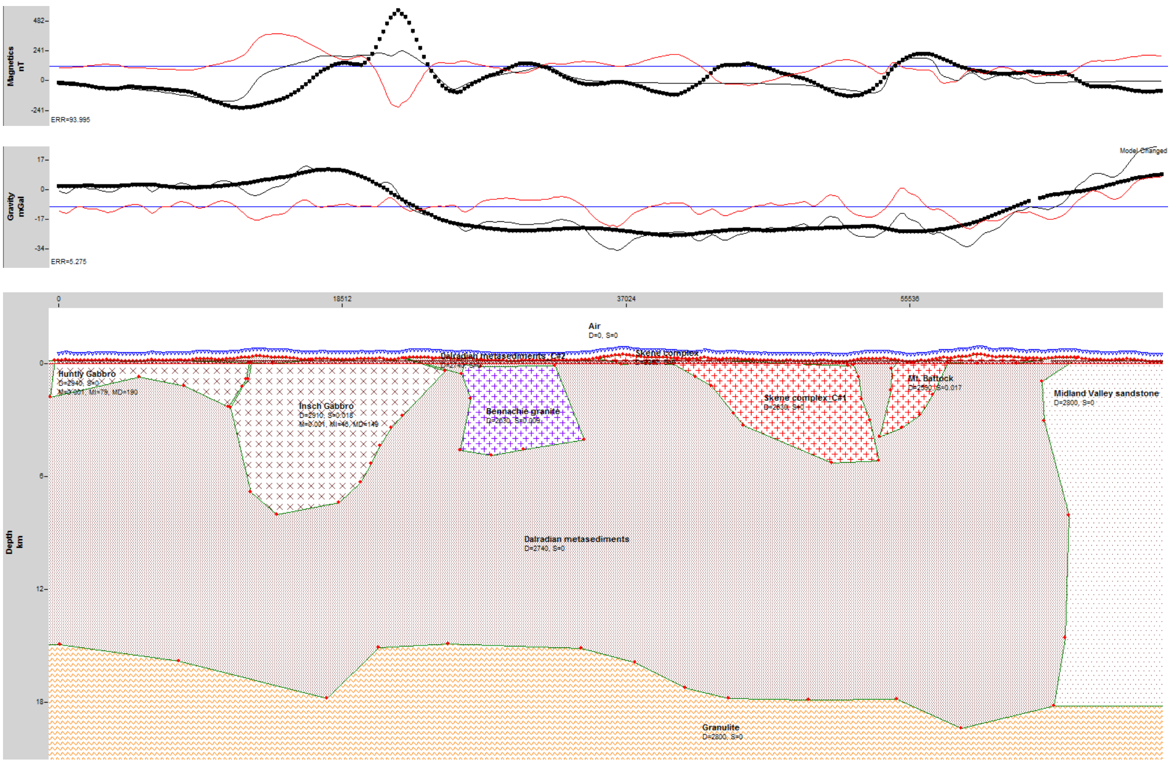


Figure. 18. *Top.* Map demonstrating the chosen profile line over Aberdeenshire, distance is about 75 km from A to B. **Figure. 19.** *Below.* The 2D forward model. The dotted black lines represent the observed anomalies, the black line represents the calculated anomaly and the red line is the error for both gravity and magnetic data.

4. Interpretation and discussion

4.1. The Bouguer anomaly and total magnetic intensity maps

The qualitative interpretation involves making a description of the resulting maps, data and their association with the wider geological features of the locality without the application of transformations or filters (Anudu *et al* 2012). Where the results do not match expectations from our current geological interpretation. It cannot be stated clearly enough that the resolution of the data is very poor and that for a more comprehensive interpretation a higher quality of data is required.

The BA map (*see figure. 6*) shows the reduced gravity data. The gravitational anomaly on the map ranges from highs of up to 25 mGal and lows of -42 mGal across the region. Areas of highest gravity occur where we find basic igneous intrusive bodies such as Haddo House and Boganclogh which is as expected since gabbro has the highest density of the lithologies we have in the area. The lowest values of the BA are associated with the granitic intrusions which have the lowest densities, such as the Bennachie and Skene complex intrusions. This makes intuitive sense as we would expect to see the most negative anomalies associated with these intrusions. The lowest value of the anomaly recorded lies to the south west region of the map on the fringes of the Mt. Battock intrusion which had the lowest recorded density measurement by (McGregor & Wilson 1967), moving towards the east along the intrusion sees a reduction in the negative anomaly which may be in part due to a shallowing of the mafic body. Along the south west margin of the HBF there is a clear association with a slightly positive anomaly of up to 5 or 6 mGals that lies mostly just to the north of the boundary and which ends just west of Fettercairn, this anomaly can probably be attributed to the Barrovian metamorphic facies sequence in the area. The whole of the northern region of the locality from around 57°20’ shows a strongly positive anomaly including above the metasediments, which may be due to the basic igneous sheet that (Mcgregor & Wilson 1967) propose.

The TMI (*see figure. 7*) shows the reduced magnetic data. In accordance with theory we would expect to see high values for basic igneous intrusions, slightly lower values for the acidic intrusions and the lowest values for the metasediments. The lowest recorded value observed is 1219 nT which lies just north of the Insch intrusion where there is a small outcrop of pelite, this difference in lithology is the probable explanation for low value of TMI. The highest values of TMI are associated with the Boganclogh and Mt. Battock mafic intrusions with a TMI of about 35,000 nT. The boundary of the Boganclogh intrusion correlates very strongly with the high TMI values which may indicate that there is very little heterogeneity within the intrusion. This is in contrast to the Insch intrusion where there is a strong heterogeneity of TMI within its structure, (Ashcroft & Munro 1978) describe this heterogeneity as being due to shearing zones that trend ENE caused by an extensive period of deformation. The Skene complex shows a distinct ring structure around its boundary of magnetic highs with a max TMI of ~ 18,000 nT, near the centre of the structure is a low of ~ 5,000 nT which is a very strong contrast of ~ 13,000 nT. We know that the Skene complex is complicated and consists of many intrusions, further analysis is required. The Coull and Bennachie granites show relatively low TMI signatures that are not especially distinctive whereas the Aberdeen granite has an anomalously low TMI of < 2000 nT.

In contrast to the gravity data the magnetic data shows a greater number of short wavelength anomalies that tend to be associated with the igneous bodies, this is probably due to the much higher concentration of data for the magnetic survey

4.2. The transformed maps

The quantitative interpretation involves the applications of the transformations and derivatives of the gravity and magnetic data for the region. These transformations were applied with the use of the oasis montaj software package to aid in the interpretation of the geology by helping to define their edges, the lateral extent of the lithology in addition to the trends encountered.

The RTP TMI map (*see figure. 9*) shows some differences in its result from the TMI map which are most notably, the low magnetic anomaly that arises just to the west of Fettercairn and just south of the HBF. South of the HBF is the midland valley terrane which consists of sediments rather than the metasediments you find in the GHT. The low RTP TMI signal is associated with part of the Strathmore group which consists of sandstone with the addition of some conglomerate, siltstone and mudstone which have a low magnetic signature. The anomalously low magnetic signal is probably associated with a change in the lithology within this group. The RTP TMI map doesn't offer us too much more insight in terms of the igneous intrusions of Aberdeenshire alone as the result does not differ greatly from the unmodified TMI map.

The AS-TMI map (*see figure. 8*) is useful in highlighting the source and depth of the magnetic material as it produces a maxima directly above a source bodies edges. The result seems to highlight some structures within the Insch intrusion and somewhat manages to delineate the eastern boundary of the Skene complex although the strongest signal seems to lie on the western side of the intrusive complex. The RTP-TMI map combined with the AS-TMI map appears to show that the south easterly margin of the Mt. Battock intrusion has a much weaker magnetic signal than the rest of the body, if the surface lithology is well constrained then it may indicate that there is a sharp change in lithology at depth.

Like the AS-TMI map the THD maps (*see figures 14 and 15*) for both the magnetic and gravity data aid in the detection of boundaries for different geological structures. The magnetic map offers a higher resolution than the gravity map due to the higher number of data points but both maps nicely highlight the eastern boundary of the Skene complex. The internal structure of the Skene complex is complicated and consists of more than one igneous intrusion, the circular ring structure found in the THD of RTP-TMI map seems to indicate the boundary of an internal intrusion as part of the complex. The boundary for the Clunes granite is also nicely illustrated in these maps and seems to match amiably with the known surface boundary. As well as marking the boundary for intrusions the THD method is also useful at finding fault boundaries with the HBF marked agreeably on the magnetic map, and although less clear on the gravity map it can still be seen. It would be a stretch to suggest that there is any evidence of the Deeside lineament structure in the magnetic map but the THD-BA map definitely highlights some sort of linear structure just north of the Mt. Battock intrusion where the Deeside lineament supposedly cuts across. The THD-RTP-TMI map in conjunction with some of the other maps seems to highlight the edge of a structure that exists on the easterly margin of the Insch intrusion. It is also interesting that just North of the Insch intrusion both

THD maps including the AS-TMI map show some sort of structure that reaches towards the sandstone group in the North.

Vertical derivatives (*see figures. 10 and 11)* show how the potential field changes with depth and effectively act as a high pass filter that allow short wavelength anomalies. This effectively means they enhance the near surface but unfortunately also enhance noise (Cooper & Cowan 2004). The highest positive rate of change in the field is associated with the basic igneous intrusions and the lowest associated with the acidic intrusions for both 1st vertical derivative maps. The 1VD-BA map highlights the Insch intrusion and gives an interesting perspective on its relationship to the Bennachie intrusion, the map suggests that the Bennachie intrusion imposes itself somewhat upon the Insch intrusion to the north, it also appears to show that Bennachie may extend further laterally to the east and west of its marked position on the surface. The HBF is also demonstrated nicely in this map due to the high positive values just north of the fault line, this information may be useful in inferring the slope and direction of the fault in the subsurface. Further to this there is also a dotted structure that provides evidence of the fault that lies just south of Aberdeen. The 1VD magnetic data map is far less homogeneous than the 1VD gravity map which may be in part due to lower resolution of the data in the gravity map, or it could perhaps suggest that the density structure of the intrusions is more homogeneous than the magnetic susceptibility.

The 2VD gravity and magnetic maps (*see figures. 12 and 13*) obviously display a lot more noise, particularly the 2VD magnetic map but theoretically are better at showing the boundaries of a body. Despite some noise both maps are still useful in displaying the nature of some of the structures. Like the 1VD maps the highest positive rate of change in the potential fields is associated with basic igneous bodies and the highest negative rate of change associated with the acidic intrusions. There is not a lot the 2VD magnetic tells you that the 1VD map does not, whereas there is a stronger difference between the 1VD and 2VD gravity maps. The boundary of the Skene complex, Aberdeen and Clunes intrusions are more clearly marked amongst the metasediments that surround them.

Like the AS-TMI map the THDTD maps (*see figures. 16 and 17*) produce a maxima above source bodies and is good for determining the edges of structures. The THDTD-BA map shows the boundary between the Southern highland group and the Argyll group of the metasediments south of Aberdeen, it is the only map amongst all of them that manages to clearly demonstrate this boundary. In addition the THDTD-BA map also shows the major fault that lies just south of Aberdeen. The southern boundary of the Insch intrusion is quite broad, which could be more evidence in favour of the structure dipping towards the north in conjuction with the Bennachie intrusion. The THDTD-RTP-TMI is equally effective at highlighting the boundaries in structures but of course does so in relation to the magnetic field, the map nicely highlights boundaries of intrusions but also illustrates some of the structures that lie within the intrusions. It is clear from this map particularly that within the Skene complex there are different components of igneous bodies that show varying magnetic characteristics.

4.3. 2D Forward model of the TMI and BA data

The profile line used for this 2D model (*see figure. 18*) covers a distance of about 75km across the GHT and a small section of the MVT, this particular profile was chosen because it covers a broad stretch of the geology in the area and lies almost perpendicular to the HBF at the surface. It covers the Huntly, Insch, Skene complex and Mt. Battock intrusions in addition to the Dalradian metasediments. It also crosses the HBF into the MVT sediments. It is of course important to consider that there are an almost infinite number of solutions to these sorts of models but with some applied geological conditions we have to create a model can best constrain the geometry of the intrusions.

The resulting model (*see figure. 19*) covers the upper crustal structure to a depth of just over 15km and shows the interpretation of the Igneous intrusions which appear to average at a depth of around 6km given the constrained density values. The model is clearly very simplified as it only considers the bulk density of the dalradian metasediments which are quite variable across the region. Furthermore the model does not take into account the increase in density of the lithology due to the increase in pressure with depth. The densities of the bodies were measured by (McGregor & Wilson 1967) but the magnetic susceptibilities as well as their remanent component were not so well constrained. This led to initially taking the median value of magnetic susceptibilities for the igneous bodies listed by (Clark & Emerson 1991) and modifying them to try and minimise the misfit. The resulting error on the gravity model is 5.275 mGals and for the magnetic component it is 93.995 nT.

4.4. Comparison with McGregor and Wilsons findings

The (Mcgregor & Wilson 1967) paper postulates the existence of a “basic sheet” in the subsurface to account for the strongly positive Bouguer anomalies in the region where a number of basic intrusions are exposed at the surface. The author further supposes that the sheet varies in thickness between 1-2 km at Huntly to 7km at Cabrach (not in our study location) and builds a model of the relationship between the Insch “mass” and the Bennachie granite. Their model suggests a thickness of around 3-4 km for the Insch mass that dips towards the north at its juncture with the Bennachie granite. Our model also considers the Insch intrusion but on a more westerly margin where the Bennachie granite is not exposed at the surface. We are in agreement with (McGregor & Wilson 1967) in regard to the dip of the southern margin of the Insch intrusion lying towards the north. The depth of the Insch intrusion is closer to 7 or 8 km deep according to our model as opposed to 3-4 km depth in the authors’ locality further to the east. This could be feasible as the western margin of the Insch intrusion lies closer to the Portsoy lineament which acted as a conduit for the magma through the crust for the basic intrusions (Fettes 1986).

In our model the Huntly intrusion has a thickness of about 2km and quite closely matches the observed gravitational anomaly in this locality, this is similar to the ideas of the author who has suggested a thickness of 1-2 km for the Huntly mass due to the anomalously low BA measured at its surface exposure relative to its surroundings. The author offers a possible explanation which is that “there may be acid intrusions beneath the southern area of the Huntly basic mass”, this is possible but seems farfetched in the sense that the anomaly appears only around the Huntly intrusion and that the mass is surrounded by intrusions of a basic composition. An area of agreement between the author and this study is that the Bennachie intrusion extends some distance in the subsurface to both the east and the west of its marked surface boundary, our profile does not cross the Bennachie intrusion but we have included it in our model because we have shown that it can account for the sharp drop in the BA as you move south from the Insch intrusion. We didn't have any density data for Bennachie so we used the density value found by the author for the Skene complex and found that the error in the model was greatly reduced.

5. Conclusion

1) A high resolution data set is imperative to the final quality of work that can be produced. No amount of processing to data of a poor quality will give you the kind of detail required for an intensive study. A higher resolution of data would have allowed for a more detailed 2D subsurface model.

2) The TMI and BA grids demonstrate the feasibility of using potential fields to identify areas of high and low density and magnetic susceptibility. This information can be further utilised to infer information about lithology and its regional extent.

3) The application of derivatives to the dataset was worthwhile and added insight into defining the boundaries of different geological structures. The THDTD grids were particularly useful in defining the edges of structures and the AS-TMI is an effective tool in locating the source of the strongest magnetic signals.

4) Our 2D model which is largely constrained only by the gravity and surface boundary exposure data provides evidence of the existence of subsurface lateral extent of the Bennachie intrusion west of its marked surface boundary.

5) The poor quality of the magnetic constraints and its remanent component lead to it having little impact on our 2D model.

6) We saw no strong evidence of the Deeside lineament structure in any of our transformed data maps. There is a linear like trend in the northern region of the magnetic signal of the Mt. Battock intrusion but there is no evidence of the continuation of this trend out with the intrusion itself.

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