Tellus Border Project

Airborne Geophysical Interpretation Report

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2014
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The Geological Survey of Northern Ireland is part of the Department of Enterprise, Trade and Investment (DETI). GSNI provides geoscience information and services to inform decision making, promote economic development and assist environmental management in Northern Ireland.

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The Tellus Border project

Tellus Border is a geo-environmental mapping project which provides data on soils, waters and rocks across the border region of Ireland and integrates these with existing data in Northern Ireland. This cross-border collaboration between the Geological Survey of Ireland, the Geological Survey of Northern Ireland and research partners supports the assessment of natural resources, sustainable environmental management and improvement of geological mapping on the island of Ireland. For more information on Tellus Border please see www.tellusborder.eu.

Tellus Border is funded by the INTERREG IVA development programme of the European Regional Development Fund, which is managed by the Special EU Programmes Body (SEUPB). The SEUPB is a North/South Implementation Body sponsored by the Department of Finance and Personnel in Northern Ireland and the Department of Finance in Ireland. It is responsible for managing two EU structural funds Programmes PEACE III and INTERREG IV designed to enhance cross-border co-operation, promote reconciliation and create a more peaceful and prosperous society. For more information on the SEUPB please visit www.seupb.eu.

Tellus Border is additionally part funded by the Department of Environment, Community and Local Government in Ireland and the Department of the Environment in Northern Ireland.

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Executive Summary

The Tellus Border Project was a geochemical and airborne geophysical survey of the six northern counties of the Republic of Ireland, funded by the INTERREG IVA programme of the European Regional Development Fund. It was an extension of the successful Tellus project of Northern Ireland (http://www.bgs.ac.uk/gsni/tellus/). Measured data included magnetic field, electrical conductivity and gamma-ray spectrometry. Data were collected using a fixed-wing De Havilland DHC-6 Twin Otter aircraft, over the border counties of Donegal, Leitrim, Sligo, Cavan, Monaghan and Louth within Ireland and the adjacent parts of counties Mayo, Roscommon, Longford, Westmeath and Meath. Data have been fully processed and merged with existing data for Northern Ireland and interpreted to highlight both regional and local scale features.

Geophysical maps have been produced and imported into a GIS allowing detailed analysis of the data and comparisons with existing datasets. Bedrock across the region is highly variable but the geophysical data have allowed continuous mapping to be carried out. Along with confirming existing mapped boundaries, new anomalies and deviations from the known mapped lithologies have been encountered.

This report looks in detail at each of the geophysical data sets (magnetics, electromagnetics and radiometrics) and their subsequent components in respect of their regional geological interpretation, and in particular of the main geological units (Precambrian, Lower Palaeozoic, Carboniferous, Tertiary basalts and intrusions). Local examples and case studies are also shown highlighting the detail of the datasets.

Magnetic and electromagnetic properties of bedrock within the region and the radiometric properties of both bedrock and subsoil categories have been summarised.

The magnetic data have been used to highlight dominant geological structures across the region along with the presence of a number of dyke swarms. The datasets have also been interpreted in conjunction with known mineral locations. The magnetic data allow the depth to basement crystalline rocks to be modeled providing further information on the tectonic history of the region. A number of new anomalies, previously unmapped, have been highlighted.
Electromagnetic data, map variations in the conductivity properties of both bedrock and subsoil deposits. Some of the strongest conductive features correspond to the black Moffat Shales in the southeast of the region that produce narrow linear features. The Antrim Basalts display unusually high conductivity in places, which may indicate an open pore structure or clay-filled amygdales in the lava flows, or possible thicker clay overburden. Precambrian Dalradian rocks in the northwest, such as psammites and pelites, gneisses and schists are generally resistive. However, more conductive graphitic schists or shear zones along thrust faults are also present in the area. Most igneous intrusions such as Slieve Gullion and the Mourne Complex in the southeast, show typically resistive responses, although the EM data provide less significant anomalies when compared to the magnetic data in these areas. Conductive zones are found with shale-rich Carboniferous rocks. The EM data can also be used to create pseudo-cross sections and a number of examples show generally good agreement with borehole data.

Radiometric data highlight variations in the upper soil / subsoil layers and consequently variations in the bedrock from which it was derived. The distribution of total radiometric counts (the combined result of potassium, thorium and uranium elements) shows higher values to the east and north of the region over non-carboniferous limestones chiefly Lower Paleozoic sandstones and greywackes and Proterozoic metasediments. Carboniferous rocks to the south and west with the exception of shale units show lower total count values. The extent of peat deposits are clearly marked by zones where the natural radiation signal is partially or completely impeded. Potassium highs are present over K-feldspar rich meta-sedimentary rocks in the Ox Mountains, Triassic sedimentary rocks, as well as within felsites and granites of the Mourne Mountains Complex, Slieve Gullion Complex, Barnesmore and Tullagh Point. Granite bodies across the region, as expected, exhibit the strongest radiometric signal. Ordovician-Silurian rocks in the south-east and Dalradian rocks to the northwest seem to be relatively enriched in all three elements, while the Antrim Basalts are characterised by very low levels of natural occurring radioactivity. Uranium-rich rocks are present within Carboniferous rock to the southwest of the region and are generally thought to be associated with organic-rich shale deposits.
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1 Introduction

1.1 Overview
The Tellus Border project was a €4.8M EU INTERREG IVA-funded cross border project designed to map the environment and geology of the border region of Ireland. It was an extension of the successful Tellus project of Northern Ireland (http://www.bgs.ac.uk/gsni/tellus/). The project collected geochemistry and airborne geophysics datasets with the aim of merging the new and existing datasets into seamless cross-border baseline data. The airborne part of the project comprised the collection of low altitude magnetic, spectrometry and frequency domain electromagnetic data. The airborne survey was carried out by Sander Geophysics Ltd (SGL, 2012) between October 2011 and July 2012. Geophysical data measures variations in certain physical properties such as magnetic susceptibility, density, conductivity and content of radioactive elements. The data can be interpreted in terms of the distribution of rocks and soils and their structure. By using a combination of methods and in conjunction with other geological information such as existing mapping and drilling, conceptual models of the surface and subsurface can be developed. The new geophysical data allows existing geological maps and ideas to be tested and confirmed as well as highlighting new features and anomalies. This new seamless cross-border data set has allowed a detailed assessment of geological boundaries across the region. The main uses of this merged dataset are;

- To provide high quality data for geological mapping of the 12 northern counties of the island of Ireland, on both regional and local scales, including the mapping of lineaments/faults, tectonic structures and crystalline basement.
- To assist in the mapping of natural resources.
- To provide baseline information for environmental management.
- To contribute to research in the fields of hydrogeology, soil carbon/peat assessment, natural and anthropogenic radioactivity, radon risk, geohazards and the mapping of pollution plumes.

This report provides a general geological interpretation for the geophysical data collected as part of the Tellus and Tellus Border surveys. Chapter 2 briefly outlines the main survey specifications,
however, for more information on the logistics and data processing see Hodgson and Ture (2013 a,b). A brief overview of the geological setting is provided in Chapter 3, while regional geological interpretations and interpretation by the main geological groupings are carried out for each geophysical methodology (magnetics, electromagnetics and radiometrics) in Chapters 4, 5 and 6 respectively. The geophysical properties of different rock types are also discussed in each of the relevant chapters.

1.2 Historical airborne geophysics surveys in Ireland

A number of both large-scale regional and smaller industry related airborne surveys have been carried out within both Northern Ireland and Ireland. In 1959 as part of the aeromagnetic survey covering parts of northern England and Scotland, Canadian Aero Services Ltd acquired data over Northern Ireland. Data was collected on north-south orientated lines at 2km intervals. Data was processed by hand with the results published as a series of contoured anomaly maps (GSNI 1971). These data were later digitised and interpretation maps for both regional aeromagnetic and gravity data produced in a geophysical interpretation atlas of Northern Ireland at 1:250,000 scales. (http://www.bgs.ac.uk/products/geophysics/atlases.html). These results were described by Carruthers et al., (1999) and further reviewed by Reay (2004).

To the south an airborne magnetometer survey of the eastern, central and western parts of Ireland, covering approximately 70% of the country (48,990km$^2$) was flown in three phases during the period August 1979 to September 1981. The objectives of the survey were to outline variations in the crystalline basement and sedimentary cover, to improve knowledge of the regional geological structure and to locate areas of potential mineralisation. This dataset comprised a number of unpublished maps and reports. Survey lines were flown within a number of different blocks using a line spacing of 1 – 2km. Survey altitudes were 200 – 450m (Geological Survey of Ireland, (1981).

Since 1995 numerous airborne geophysical surveys have been carried out within Ireland predominantly within the Irish Midlands/Lower Carboniferous region by mineral companies exploring for base metals. These surveys (59 areas in total) comprised magnetic data usually at 75-
200 m line spacing. Some surveys also included Transient Electromagnetic (TEM) and radiometric data. The data is freely available from the Exploration and Mining Division of the Department of Communications Energy and Natural Resources (EMD) once the 4 year confidentiality period has expired.

The first regional gravity survey of Ireland took place in 1950 by the Dublin Institute for Advanced Studies (DIAS) and this work has continued with new data added to the national survey over the years (Thirlaway 1951, Murphy 1952, 1974, O’Reilly et al., 1996, Readman et al., 1997). There are now more than 23,000 stations across the whole country with an accuracy of 0.2mGal. Gravity surveys of Northern Ireland have been carried out by the British Geological Survey (BGS) over a number of years 1959-60, 1984 and 1990 with a total of approximately 11,000 stations across the country (GSNI 1984). These include 400 measurements taken on the bed of Lough Neagh which used an underwater gravity meter.
2 Geophysical data and survey specifications

2.1 Tellus Border survey area and specifications

The nominal survey area (yellow area) is shown in Figure 1. It comprises counties, Sligo, Leitrim, Cavan, Monaghan and Louth and parts of counties Donegal, Mayo, Roscommon, Longford Westmeath and Meath. The northwest part of Donegal was initially planned to be surveyed but due to financial restrictions only part of Donegal was flown, as shown on Figure 1. The southern boundary was initially planned to be restricted to county boundaries of the border counties however, it was decided to extend the survey into the northern sections of counties Roscommon, Mayo, Longford, Westmeath and Meath. This squaring-off of the southern boundaries was carried out to simplify the planning of possible future surveys. A full account of all survey logistics details is given by Hodgson and Ture (2013a).

The Tellus survey of Northern Ireland (Beamish and Young, 2009) (green area Figure 1) flown in 2005 and 2006 extended into the Ireland for 2 km and therefore no low-flying within Northern Ireland was required as part of the Tellus Border survey (yellow area). A total of 57,681 line km were flown as part of the Tellus Border project. This increased to 58,768 when an additional survey in the SW of the area, funded by industry, is included. The whole merged area for the region (north and south) includes 144,568.4 line km. Table 1 outlines the flight pattern carried out during the survey and is the same as used for previous surveys.
Figure 1: Location map, black lines indicate county boundaries with named counties. Tellus Border survey area in yellow, red area indicates an additional survey carried out by Oriel Selection Trust Ltd as part of an industry survey. Green area refers to the Tellus survey carried out in 2005-2006 while blue shows Cavan-Monaghan survey carried out in 2006.

Table 1: Flight pattern

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tr>
<td>Traverse Line Spacing</td>
<td>200 m</td>
</tr>
<tr>
<td>Tie Line Spacing</td>
<td>2000 m</td>
</tr>
<tr>
<td>Traverse Line Heading</td>
<td>165° - 345°</td>
</tr>
<tr>
<td>Tie-Line Heading</td>
<td>75° - 255°</td>
</tr>
<tr>
<td>Flying Height (rural / urban)</td>
<td>59 / 240 m subject to pilot’s discretion</td>
</tr>
<tr>
<td>Projection / Datum</td>
<td>Irish National Grid / Irish Datum</td>
</tr>
</tbody>
</table>

2.2 Data Processing

Standard data processing was carried out on all magnetics, electromagnetic conductivity and gamma-ray spectrometry datasets. A full account of all calibrations and details of data processing are given in the airborne processing reports (Hodgson and Ture, 2013b and SGL, 2012). Following processing, data along flight lines were gridded using a cell size of 50m x 50m.
The gridded data were contoured or imaged using the industry standard software, Geosoft Oasis Montaj™.

2.3 Data limitations and noise
All geophysical data is subjected to certain limitations due to the accuracy of the instruments, calibration accuracy and cultural interference. Any interpretation should be viewed in respect to the location of potential local sources of noise such as roads and power lines and the survey altitude at which the data was collected.

Magnetic Noise
The standard processing sequence applied to the magnetic data indicates a possible background noise level of better than ~0.1nT based on Figure of Merit calculations (SGL, 2012). Cultural interference is the main source of noise affecting the data, with anthropogenic sources such as houses, farm buildings, roads, power lines etc. creating spikes with the data. A system of deculturing (Lahti et al., 2007) was carried out for Tellus data but was not carried out for Tellus Border and Cavan data due to time constraints.

Gamma-ray Spectrometry Noise
A test line was incorporated into the survey design which allowed direct comparisons of radiometric data at the same locations to be made over the duration of the survey. Measured values varied by a maximum to 6% from the mean (Hodgson & Ture 2013b). Environmental effects in particular rainfall can affect radiometric data. Hodgson & Ture (2013b) show that radiometric data has a negative relationship with rainfall, whereby for every ~1mm increase in rainfall, total count values decrease by about 0.8 %. The reliability of the system reduces with increasing altitude, with measurements taken at survey altitudes greater than 240m deemed to be of low confidence. Urban areas and associated high fly zones often produce radiometric highs and a speckled appearance on the image. Standing water and saturated peat deposits have the biggest affect when assessing radiometric data as they can completely or partially mask the measured signal.
**Electromagnetic Noise**

Frequency domain electromagnetic data is particularly prone to interference from electromagnetic fields from power lines, buildings and electric fences etc., creating sources of noise which cannot easily be resolved. The amplitudes of the measured coupling ratios decrease over areas of high resistivity / low conductivity. Because of this the signal-to-noise ratio is reduced in highly resistive areas making it difficult to distinguish the true signal. In resistive zones levelling of the data also becomes more difficult and can result in small amplitude undulations. This is particularly the case for the lowest frequency surveyed (912 Hz) as this is the most susceptible to highly resistive zones. Survey altitude has a major impact on the electromagnetic signal with increasing altitude attenuating the signal. Increasing altitude also reduces the effective depth penetration of the system. Therefore data collected at survey altitudes exceeding 180m should be disregarded and has been cut from the maps.

### 2.4 Geographic projection and image presentation

All geophysical data images have been produced using Geosoft Oasis Montaj™ and exported into ArcGIS Ver10.1. Geophysical grids were calculated using a cell size of 50m (1/4 of line spacing) and a minimum curvature gridding method. Shaded relief has been added to many images to enhance subtle local gradients, therefore creating a topographical surface that is illuminated by a point source of azimuth 45° unless otherwise stated. Most images use a 32 category standard Geosoft rainbow colour scheme. Blues are shown as low values and reds and pinks as highs unless otherwise stated. Colour scales vary due to local minimum and maximum allowing features of interest to be highlighted. All maps are shown in Irish National Grid (TM75) co-ordinates and are orientated to the north. Different scales have been used for maps within this report, therefore, a scale bar is shown on each map. Final data and all map products were referenced to Irish National Grid according to specifications outlined in Table 1.
**Table 2: Irish National Grid geographic projection**

<table>
<thead>
<tr>
<th><strong>IRISH GRID 1975</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference Ellipsoid:</td>
<td>Airy Modified</td>
</tr>
<tr>
<td>Semi Major axis (a):</td>
<td>6 377 340.189</td>
</tr>
<tr>
<td>Eccentricity (e²):</td>
<td>0.006 670 540 15</td>
</tr>
<tr>
<td>Geodetic Datum:</td>
<td>1965</td>
</tr>
<tr>
<td>Vertical Datum:</td>
<td>Malin Head</td>
</tr>
<tr>
<td>Map Projection:</td>
<td>Transverse Mercator (Gauss Conformal)</td>
</tr>
<tr>
<td>True origin:</td>
<td>Latitude 53° 30’ 00” Longitude 08° 00’ 00”</td>
</tr>
<tr>
<td>False origin:</td>
<td>200Km west of true origin / 250 km south of true origin</td>
</tr>
<tr>
<td>Scale factor on Central Meridian:</td>
<td>1.000 035</td>
</tr>
</tbody>
</table>
3 Geological setting

3.1 Regional geology

The geological terranes that form the basement rocks in the northern region of the island of Ireland (Figure 2) began to be assembled in mid-Ordovician time and continued for 80 Ma through the Silurian and finished in the Upper Devonian about 380 Ma ago (Mitchell, 2004).

Closure of the Iapetus Ocean was accompanied by large sinistral strike-slip movement on terrane-bounding faults and along internal faults. The composite continental crust that resulted from these movements formed a basement for subsequent erosion and deposition during the...
remainder of Ireland’s geological history. Three of the seven suspect terranes that together constitute the Caledonian Orogen in Ireland are present within the region. From north to south these are referred to as the Central Highland (Grampian) terrane, Midland Valley terrane and the Southern Uplands/ Longford-Down terrane (Mitchell, 2004) See Figure 2.

The southern margin of the Midland Valley terrane is defined by a strong regional magnetic signal following the Southern Uplands Fault. Magnetic data suggests that the Midland Valley terrane may extend at depth beneath part of the Central Highlands (Grampian) terrane. Magnetic anomalies associated with the Midland Valley itself are for the most part positive. Major faults have been traced by the geophysical data across the region.

Figure 3 shows the bedrock geology of Ireland 1:1,000,000 scale map (GSI 2014).The bedrock of Northern Ireland has been comprehensively discussed by Mitchell (2004), while detailed geological descriptions and map sheets of the geology of Ireland are published by GSI at 1:100,000 scale, in particular. Map sheets 1, 3, 7, 8, 12 and 13 cover the survey area (MacDemott et al., 1996, Geraghty 1997, Long and McConnell 1997, 1999, McConnell et al., 2001 and Morris et al., 2005). Across the 12 counties of the northern part of the island of Ireland the bedrock geology can be broadly grouped into five main categories, (1) Precambrian Dalradian meta-sedimentary rocks primarily located to the northwest and west of the region, (2) Lower Paleozoic Ordovician and Silurian of the Longford-Down terrane incorporating greywacke sandstones and mudstones (shale) to the southeast, (3) Carboniferous and Devonian rocks, primarily limestones and mudstones in the southwest, (4) Palaeogene extrusive volcanic rocks of the Antrim Lava Group in the northeast and (5) numerous igneous intrusions, including large scale granite bodies and smaller dykes and sills of various ages present throughout the region.
Figure 3. 1:1 Million bedrock map (GSI 2014) Tellus Border survey area boundary shown in black.
3.2 **Proterozoic rocks**

These rocks are located towards the northwest and west although a small zone has been mapped to the northeast within County Antrim (Figure 4) (Daly 2009, Cooper & Johnston 2004a). They can be subdivided into two main units; the Slishwood Division and the Dalradian Supergroup meta-sedimentary rocks. The oldest rocks within the region are located close to Lough Derg forming part of the Slishwood Division and are dated between 810-525 Ma (Long & McConnell 1999, Flowerdew & Daly 2005, Daley *et al.*, 2008). These quartzo-feldspathic sedimentary rocks were recrystallized under extreme conditions deep within the crust forming predominantly gneisses and schists (Long & McConnell 1999). All Precambrian rocks in the region show extensive folding and faulting, and in many places are cut by numerous igneous intrusions of a variety of ages.

![Figure 4: Distribution of Proterozoic rocks within region, yellow area corresponds to Dalradian metasedimentary rocks, and the pink rocks from the Slishwood Division, LD = Lough Derg](image-url)
3.3 Lower Palaeozoic rocks
Lower Palaeozoic rocks comprising Ordovician and Silurian units extend from the County Down coastline in the east, south-westward through counties Armagh, Monaghan, Cavan and southern County Leitrim (Figure 5). This extensive belt is referred to as the Longford-Down inlier and can be traced across the Irish Sea to the Southern Uplands in Scotland (Anderson et al., 2004; Graham 2009; Holland 2009). This group of rocks primarily consists of Ordovician to Silurian greywacke sandstones and mudstones of the Moffat Shale Group. The rocks were formed from sediments deposited on the submarine margins of an ancient continent at the edge of the Iapetus Ocean (Geraghty 1997). Ordovician volcanic rocks are present in county Tyrone (Cooper & Mitchell 2004) in the centre of the region as well as in the Charlestown region of County Mayo (Harney et al., 1996). The Longford-Down inlier can be further subdivided into a series of fault-bounded units or tracts. Within individual tracts the strata young predominantly to the north but strike-parallel faults repeatedly throw down younger beds on their southern side (Anderson 2004). Rocks between the Moffat Shale Group are found associated with tract boundaries and form a series of extensive but thin units that extend in a NE-SW orientation across the area.

Figure 5: Lower Palaeozoic rocks based on 1:1 Million bedrock map, TIC = Tyrone Igneous Complex, LD = Longford Down, CI =Charlestown Inlier.
3.4 Upper Paleozoic rocks
Devonian and Carboniferous rocks are widespread in the southwest and centre of region with Carboniferous limestones, sandstone and mudstone. The most prominent (Mitchell 2004a, b; Graham 2009; Sevastopulo & Wyse Jackson 2009; Sevastopulo 2009) Permian rocks are limited within the region to small exposure in County Down (Figure 6) (Mitchell 2004c) and one in County Cavan in the vicinity of Kingscourt (Simms 2009). Much of the Carboniferous is located within the Northwest Carboniferous Basin within the counties of Fermanagh, Tyrone, Cavan, Leitrim, Sligo and south Donegal (Mitchell 2004d; Carruthers et al., 1999). Devonian sandstones and conglomerates crop out in a limited number of places within the southwest of the region. More extensive Devonian units are found with county Tyrone in the centre of the region.

The Belhavel fault cuts through the Carboniferous in a NE-SW orientation to the north of Lough Allen and joins a splay of the Omagh Thrust fault (Figure 6). It may indicate the surface expression of deeper crustal uplift (Sevastopulo 2001).

Figure 6: Carboniferous, Devonian and Permian rocks based on 1:1 Million bedrock map
3.5 Intrusive and extrusive rocks

The main intrusive and extrusive rocks are shown on Figure 7 and can be split into three main categories; (1) Palaeogene: including the Antrim Lava Group and Mournes, Carlingford and Slieve Gullion igneous complexes (Cooper 2004, Cooper & Johnston 2004b), (2) Late Caledonian igneous complexes including Newry, Donegal Batholith, Ox Mountains, Lough Talt and Easkey, and Crossdoney (Cooper & Johnston 2004c; Pitcher & Hutton 2003) (3) Early Caledonian including the Tyrone Igneous Complex and Charlestown Iniler (Cooper & Mitchell 2004; Harney et al., 1996).

![Figure 7: Intrusive and extrusive rocks based on 1:1 Million bedrock map. DG-Donegal Granite batholith, BG – Barnesmore Granite, TIC-Tyrone Igneous Complex, AB-Antrim Lava Group, OX -Ox Mountains granites, LT-Lough Talt, E – Easkey, CG-Crossdoney Granite, SG- Slieve Gullion Complex, NIC – Newry Igneous Complex, C – Carlingford Complex, MM  Mourne Mountains Complex.](image)

Palaeogene

The Antrim Lava Group results from a major period of volcanic activity between 61 and 58 million years ago (Cooper 2004b). The group is split into the Upper and Lower Basalts formations with a maximum known thickness of 800m (Carruthers 1999). These lavas were fed by fissure eruptions.
Post-Palaeocene re-activation of pre-existing NE-SW trending faults such as the Tow Valley Fault bisect the lavas (GSNI 1997).

The Carlingford Complex is the oldest of the intrusives at 61.4 Ma and forms the central part of the Cooley Peninsula. Granite, gabbro and basaltic rocks intrude Carboniferous limestone and Silurian greywacke. Cone sheets and ring dyke structures are present within the complex. The Slieve Gullion Complex (58-56 Ma) is intruded into Silurian rocks, forming three units; an outer ring-dyke, a central doleritic and basaltic ring and a central granite intrusion. The Mourne Mountains Complex (56 Ma) consist of a series of 5 granites intruded into Silurian meta-sediments (Cooper and Johnston 2004b).

Late Caledonian
The Newry Igneous Complex was intruded during the early Devonian (c. 414-407 Ma) (Cooper et al., 2013) and is composed predominantly of three overlapping granodioritic plutons. The Donegal Batholith is composed mainly of granite intruded into Dalradian Supergroup meta-sediments between c. 430 and 400 Ma (Condon 2004). The Ox Mountains are composed mainly of granodiorite dated at 412.3 ± 0.8 Ma (Chew and Schaltegger, 2005), whilst Lough Talt and Easkey plutons are adamellites. The Crossdoney pluton is located in County Cavan and has been dated at c. 417 Ma (Fritschle et al., 2013); it is composed of granodiorite, monzonite and quartz diorite. The Barnesmore Granite is located in southern Donegal and comprises units of leucogranite and adamellite dated by Rb-Sr at 397±7 Ma (O’Connor et al., 1987).

Early Caledonian
The Tyrone Igneous Complex (Cooper et al., 2008, 2011; Hollis et al. 2012, 2013a, b) is located in the centre of the region between Omagh and Cookstown in county Tyrone. The complex is Ordovician in age and is divided into two main parts; the Tyrone Volcanic Group and the Tyrone Plutonic Group (Cooper and Mitchell 2004). The complex is overlain by late Ordovician-Silurian sediments of the Pomeroy Inlier.
3.6 Quaternary geology

The Quaternary Period is the last 2.6 million years of Earth’s geological history. Repeated periods of glaciation have occurred during this time across the region (Bazley, 2004; Coxon & McCarron 2009)) and have resulted in the formation of thick glacial tills, sands and gravels and glaciolacustrine deposits. Glacial till is by far the most significant of these deposits and is present across much of the region as rib moraine and drumlin fields (McCabe & Dunlop 2006). The composition of till has been show to reflect the underlying bedrock geology (Dempster et al., 2013). Extensive peat deposits are found particularly over high ground and can be in the order of 3-12m (Boylan et al., 2008) thick, although can be much thinner in places.
4 Magnetic Data

4.1 Introduction

Magnetic data was collected at 0.1 second intervals along flight lines from two caesium vapour magnetometers; one located in the nose cone and one in the left wing tip. Standard magnetic survey calibrations and corrections were applied to all data by the contractor (SGL, 2012; Hodgson and Ture, 2013b).

The magnetic signature of rocks comprises induced and remnant components, the first being a function of the magnetic susceptibility. Magnetic susceptibility is a measure of the ease with which a body becomes temporarily magnetised by a magnetic field (i.e. the geomagnetic field). Magnetic susceptibility depends primarily upon the amount of ferromagnetic minerals present, of which magnetite (Fe₃O₄) is the most significant because of its common occurrence and high susceptibility values. Magnetic data is therefore highly useful in identifying variations in bedrock as well as geological structures. A summary of the magnetic properties of rocks within the region is given in Section 4.3.

4.1.1 Magnetic data interpretation products

Magnetic data can be processed using sophisticated filtering techniques to produce a series of images which help refine and improve interpretations. All magnetic data was corrected to the International Geomagnetic Reference Field (IGRF) and total magnetic intensity (TMI) data interpolated onto a regular grid of cell size 50 m using the minimum curvature algorithm (Hodgson and Ture 2013b). This grid provided the primary TMI data on which all subsequent (grid) filtering operations (summarised below) were applied in order to extract the optimum level of geological signal from the survey data.

Reduction to the pole

Reduction to the pole is the process of converting the magnetic field from magnetic latitudes where the Earth’s field is inclined (Milligan and Gunn, 1997) to the field at a magnetic pole, where the inducing field is vertical. When the Earth’s field is inclined, magnetic anomalies due to induction have forms that are asymmetrically related to their sources, but when the inducing field
is vertical, the induced anomalies are directly over their sources. Thus, reduction to the pole greatly simplifies the interpretation of magnetic data (Figure 8).

**Upward continuation**

Computation of magnetic fields at higher levels is called upward continuation (Milligan and Gunn, 1997).

\[ L = e^{-2\pi kh} \]

where \( h \) is the distance upward continued relative to the plane of observation and \( k \) is wave number.

This process is utilised to smooth out high-frequency anomalies relative to low-frequency anomalies. Upward continuation is useful for suppressing the effects of shallow anomalies when detail on deeper anomalies is required. An upward continuation filter of 500 m was applied over the Antrim Lava group and 250 m elsewhere to reduce shortwave length anomalies and noise (Figure 8). All subsequent magnetic maps are derived from the upward continued grid. A subset of the data using Antrim Lava Group polygon (Figure 8) was gridded and upward continued by 500m. The remaining data was gridded and upward continued by 250m independently. These two grids were knitted together using suture method and resulted in figure 8. Discontinuity at the boundary of the two grids is observed in the vertical derivative and standard deviation (figures 9 and 10).
**Pseudo gravity**

It is possible to transform magnetic fields into pseudo-gravity fields in which the anomalies due to the magnetic bodies have the character of gravity anomalies (Milligan and Gunn, 1997). This transformation can be useful for relating magnetic and gravity survey data. In practice, however, gravity and magnetic anomalies often arise from different sources, so the application of such a process is limited to specific situations.

**First vertical derivative (FVD)**

The first vertical derivative (Milligan and Gunn, 1997) (or vertical gradient) is the physical equivalent to measuring the magnetic field simultaneously at two points with one point vertically
above the other. By subtracting one from the other and dividing the result by the vertical spatial separation of the measurements, high frequencies relative to low frequencies can be enhanced (Figure 9). This eliminates long-wavelength regional effects and resolves the effects of adjacent anomalies.

![Figure 9: First vertical derivative of region using pole reduced and upwardly continued magnetic grid, white polygon is Tyrone Igneous complex, (SC) Scrabo sill, (S) Seeconnell Complex, (CD) Crossdoney granite](image)

**Analytic Signal**

The concept of the analytic signal of magnetic anomalies was developed by Nabighian (1972, 1974). The analytic signal is calculated by taking the square root of the sum of the squares of each of the three directional first derivatives of the magnetic field as follows:

\[
    AS(x, y) = \left( \left( \frac{dT}{dx} \right)^2 + \left( \frac{dT}{dy} \right)^2 + \left( \frac{dT}{dz} \right)^2 \right)^{0.5}
\]
The resulting shape of the analytic signal is independent of the orientation of the magnetisation of the source and is centred over the structure giving rise to the anomaly. Thus the effect is one of transforming the shape of the magnetic anomaly from any magnetic inclination to a single positive anomaly (or peak).

**Standard Deviation (CET - Textural Analysis)**

Lineaments along ridges and edges of geologic structures can be detected using the Centre for Exploration Targeting (CET) Grid Analysis extension for Oasis Montaj. The system uses a standard deviation to provide estimates of the local variation in the data. At each location in the grid, it calculates the standard deviation of the data values within the local neighbourhood. Features of significance often exhibit high variability with respect to the background signal.

For a window containing $N$ cells, whose mean value is $\mu$, the standard deviation $\sigma$ of the cell values $x_i$ is given by:

$$
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \mu)^2}
$$

The standard deviation was calculated using 5x5 cells. Since the true grid cell size of magnetic grid was 50m, the window size used to calculate standard deviation corresponds to 250m x 250m.

Figure 10 shows textural analysis carried out for upwardly continued magnetic data across the whole of the region.
Figure 10: Magnetic Texture Map (Standard deviation) obtained from upward continued grid; white polygon is Tyrone Igneous Complex, (SC) Scrabo sill, (S) Seeconnell Complex, (CD) Crossdoney granite.

Regional / residual filter

All regional-residual field separation methods are based on the fact that the regional field is smooth and its spectrum is dominated by relatively low frequencies. Digital filtering in frequency domain or in spatial domain separates the low-frequency regional anomalies from the higher frequencies that correspond to the residual field.

Magnetic data observed in geophysical surveys are the sum of magnetic fields produced by all underground sources. The targets for specific surveys are often small-scale structures buried at shallow depths. The magnetic responses of these targets are embedded in a regional field that arises from magnetic sources that are often deeper than the targets. Correct estimation and
removal of the regional field from initial field observations yields the residual field produced by the target sources (Jiakang et al., 2005).

**Werner deconvolution**

Werner deconvolution is a profile-based interactive technique used to analyse the depth to and horizontal position of magnetic source bodies, and the related parameters of dip and magnetic susceptibility (Ku and Sharp, 1983). It is a rigorous, iterative, two-dimensional inversion technique that takes into account interference from adjoining anomalies. Analysis of the total magnetic intensity data yields these parameters for thin, sheet-like bodies such as dikes, sills, intruded fault zones, and basement plates of minor relief compared to the source-sensor separation distance. Applied to horizontal gradient data, Werner deconvolution yields similar parameters for geologic interface features such as dipping contacts, edges of prismatic bodies, major faults, and slope changes of the basement surface. The apparent depth to a magnetic source is derived from Euler’s homogeneity equation (Reid et al., 1990) as discussed above.

The above products have all been used and assessed in the geological interpretation of the magnetic data. However, typically TMI, textural and derivative maps provide the most useful information in simple geological mapping. Shaded relief is also applied to many of the map images to highlight strong gradients in the data.

### 4.2 Regional interpretation

#### 4.2.1 Overview

Previous comprehensive regional geophysical interpretations for Northern Ireland have been discussed in Carruthers et al., (1999) and Reay (2004). The most recent account was produced as a result of the Tellus Project airborne geophysics (Young & Donald 2013).

The airborne magnetic data (Tellus and Tellus Border projects) have provided a wealth of new information about the geology, regional structure and mineral potential of the 12 northern counties of the island of Ireland. Numerous filtered and derivative maps were produced providing huge amounts of geological detail (Figure 8 - Figure 10). The rocks that make up the region show a
considerable variation in their magnetic properties. Many of the identified features in Northern Ireland have previously been described in Chacksfield (2007), van Dam (2007) and Young and Donald (2013). The main features in the magnetic data for the region can be summarised as follows.

- **The Antrim Lava Group.** The strong magnetic signature of the Antrim Lava Group basalts, allows their surface extent to be mapped accurately in areas of poor exposure. Within the basalt outcrop, lineaments associated with bounding faults of sedimentary basins have also been identified.

- **The Tyrone Igneous Complex.** The margins of the Tyrone Igneous Complex and its internal structure are revealed in detail with many new faults and structures identified (Hollis et al., 2012, 2013a, b).

- **The Dalradian Supergroup.** The Dalradian rocks in the northwest are mapped by high to intermediate magnetic signatures. Within the Dalradian rocks linear magnetic anomalies related to fold structures and several important magnetic marker horizons have been revealed.

- **Dyke swarms.** Interpretation of Tellus Project airborne geophysics revealed at least 4 prominent dyke swarms across Northern Ireland (Cooper et al., 2012). Tellus Border has revealed an additional dyke swarm in the vicinity of Killala in County Sligo.

- **Major intrusive centres.** The margins and internal structures of the major intrusive centres of the Newry Igneous Complex, Mourne Mountains, Slieve Gullion, Barnesmore, Ox Mountains and the Carlingford Complexes are delineated by the magnetic data in great detail.

- **Magnetic gradients.** Strong magnetic gradients indicating possible changes in lithology are observed over the Ox Mountains and the Newry, Slieve Gullion and Carlingford complexes. Other areas of strong magnetic relief are observed in the southeast, over Silurian greywacke (possibly due to uplifted of mafic basement controlled by regional faulting) and over granitic intrusions. Slishwood Division rocks of the Lough Derg Inlier have a strongly
negative magnetic anomaly which may be due to the dominantly quartzo-feldspahic nature of these rocks (Daly 2009).

- **Ring intrusions.** Prominent circular or elliptical anomalies are associated with Palaeogene extrusive and intrusive rocks (Antrim Lava Group, Mourne Mountains, and Slieve Gullion and Carlingford complexes) and the Late Caledonian Newry Igneous Complex. Structures and textures within these anomalies (visible at a large scale) characterise different periods of intrusion or later cross-cutting relationships.

- **Shear/fault zones.** Prominent areas of faulting and associated shearing are found associated with upper Dalradian rocks of the Sperrin Mountains, north of the Omagh Thrust Fault, within Ordovician rocks of the Tyrone Igneous Complex, south of the Omagh thrust Dalradian rocks of Co. Donegal and in Ordovician Charlestown Inlier rocks in Co. Monaghan.

- **Basement terrane boundaries.** Two principal groups of geological structures relating to basement rocks derived from P-Depth calculation from the magnetic data are observed orientated NE-SW and NW-SE at depth (Figure 30). These structures can be interpreted as controlling lithological boundaries and are consistent with the regional (NE-SW) terrane boundary faults mapped at the surface. The presence of such orientations at 3.5 km depths may indicate the presence of Caledonian structures within basement rocks. The NW-SE trending structures are generally detached and displace the NE-SW orientated structures/lithologies (Figure 32). A strong magnetic signal is seen over the Belhavel Fault which runs through Carboniferous rocks in the southwest and may be due to uplifted basement rocks at depth.

### 4.3 Magnetic properties
The presence and quantity of magnetite within rocks dominates susceptibility values particularly within igneous and metamorphic rocks with values typically more than 1 x 10^{-3} SI, (Telford et al., 1990). Pyrrhotite is the second most significant ferromagnetic mineral component with greigite
and maghaemite of lesser importance. Hematite is an important carrier of natural remnant magnetisation (NRM) in sedimentary rocks but has relatively low susceptibilities. Lower susceptibilities (<1 x 10^{-3} SI) are largely a function of the content of paramagnetic minerals, such as biotite and amphibole in igneous rocks, or clay minerals. Diamagnetic minerals such as quartz and halite effectively have zero susceptibility.

Large magnetic anomalies, i.e. with amplitudes of more than 100 nT, require susceptibility contrasts of about 10-30 x 10^{-3} SI. This is equivalent to a magnetite content of about 1%, a typical value for ‘magnetic’ igneous rocks (but not necessarily all igneous rocks). For anomalies with amplitudes of about 1nT, the required susceptibility contrast of 0.1 x 10^{-3} SI can be achieved by rocks bearing paramagnetic minerals only, or alternatively, by as little as 0.003% magnetite. Susceptibility data for igneous rocks (both intrusive and extrusive) indicate that for basic and ultra-basic igneous material, magnetisations are high and dominated by the remnant component. In contrast, susceptibility values for sedimentary rocks tend to be low (< 0.1 x 10^{-3} SI) for sandstones, carbonates and evaporates and higher (0.20-0.30 x 10^{-3} SI) for argillaceous rocks. This is considered to be due to the dominating paramagnetic component, with clay minerals being responsible for the higher values. Sedimentary rocks associated with volcanic activity generally have higher susceptibilities.

Fully comprehensive information of the NRM of sedimentary rocks is rare in the literature but the evidence suggests that remnant magnetism does not generally contribute sufficiently to dominate total magnetisations. Unusually high susceptibility for sedimentary rocks (i.e. > 0.4 x 10-3 SI), with an upper limit of 5 x 10-3 SI are generally due to either ferruginous beds, where the main source is probably paramagnetic minerals, or to sediments containing material of volcanic origin, including magnetite. A record of the magnetic susceptibilities of different rock units within Northern Ireland is outlined in Table 3. These values are based on in-situ measurements taken during the Tellus project using a hand held susceptibility metre. The numbers shown in the table are averages from five measurements for each rock type. The result of physical property measurements was reported in (Entwisle et al., 2007). The values indicated in the table can be applied for the whole region. As can be seen from Table 3 the average susceptibilities of basalts and Diorites are much higher than those for sedimentary and Dalradian groups.
Table 3: Magnetic susceptibility of rocks samples from Northern Ireland data source, Tellus project and Entwisle et al., (2007)

<table>
<thead>
<tr>
<th>Name / Lithology Code</th>
<th>Group/Complex</th>
<th>Formation</th>
<th>Rock type</th>
<th>min</th>
<th>max</th>
<th>Average</th>
<th>Geometric mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>TPG-GABB</td>
<td>Antrim Lava Group</td>
<td>Upper Basalt Formation</td>
<td>Basalt</td>
<td>0.3</td>
<td>28.5</td>
<td>7.0</td>
<td>2.4</td>
</tr>
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<td>UBF-BASA</td>
<td>Antrim Lava Group</td>
<td>Upper Basalt Formation</td>
<td>Basalt</td>
<td>0.5</td>
<td>58.0</td>
<td>11.8</td>
<td>4.6</td>
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<tr>
<td>LBF-BASA</td>
<td>Antrim Lava Group</td>
<td>Lower Basalt Formation</td>
<td>Basalt</td>
<td>0.7</td>
<td>41.5</td>
<td>8.7</td>
<td>3.7</td>
</tr>
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<td>MNG3-GRAN</td>
<td>Mourne Mountains</td>
<td>G3</td>
<td>Granite</td>
<td>0.5</td>
<td>1.7</td>
<td>1.3</td>
<td>1.2</td>
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<td>HGUW-CKSD</td>
<td>Ulster White Limestone Formation</td>
<td>Chalk</td>
<td>Chalk</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>WAMU-ARLM</td>
<td>Waterloo Mudstone Formation</td>
<td>Limestone</td>
<td>Limestone</td>
<td>0.4</td>
<td>3.1</td>
<td>1.3</td>
<td>0.9</td>
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<tr>
<td>MER-MDST</td>
<td>Mercia Mudstone Group</td>
<td>Mudstone</td>
<td>Mudstone</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>MMS-SDAR</td>
<td>Tyrone Group</td>
<td>Mullaghmore Sandstone Formation</td>
<td>Sandstone</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>NEG-DIOR</td>
<td>Newry Igneous Complex</td>
<td>Diorite</td>
<td>Diorite</td>
<td>2.4</td>
<td>27.2</td>
<td>11.0</td>
<td>8.2</td>
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<td>NEG-GRAD</td>
<td>Newry Igneous Complex</td>
<td>Granodiorite</td>
<td>Granodiorite</td>
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<td>1.5</td>
<td>1.4</td>
<td>1.4</td>
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<tr>
<td>UIEC-TONA</td>
<td>Unnamed igneous intrusion</td>
<td>Tonalite</td>
<td>Tonalite</td>
<td>0.2</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>SHAN-SDSM</td>
<td>Fintona Group</td>
<td>Shanmullagh Sandstone Formation</td>
<td>Sandstone</td>
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<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
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<td>HWK-SDST</td>
<td>Hawick Group</td>
<td>Greywacke</td>
<td>Greywacke</td>
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<td>0.2</td>
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<td>GALA-SDST</td>
<td>Gala Group</td>
<td>Sandstone</td>
<td>Sandstone</td>
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<td>0.3</td>
<td>0.3</td>
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<td>GILN-SDST</td>
<td>Gilnahirk Group</td>
<td>Greywacke</td>
<td>Greywacke</td>
<td>0.1</td>
<td>0.7</td>
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<td>0.2</td>
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<td>BAL-LMST</td>
<td>Tyrone Group</td>
<td>Ballyshannon Limestone Formation</td>
<td>Limestone</td>
<td>0.0</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>BUNS-MDLM</td>
<td>Tyrone group</td>
<td>Bundoran Shale Formation</td>
<td>Mudstone/limestone</td>
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<td>0.2</td>
<td>0.1</td>
<td>0.0</td>
</tr>
<tr>
<td>CPLF-BASA</td>
<td>Tyrone Volcanic Group</td>
<td>Copeny Pillow Lava</td>
<td>Basalt</td>
<td>20.1</td>
<td>61.8</td>
<td>41.6</td>
<td>38.4</td>
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<td>CPLF-BASA</td>
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<td>Copeny Pillow Lava</td>
<td>Basalt</td>
<td>0.4</td>
<td>0.8</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>MCA-PSSP</td>
<td>Southern Highland Group</td>
<td>Mullaghcarn Formation</td>
<td>Psammitte/semipelite</td>
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<td>3.0</td>
<td>0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>TVG-LAVA</td>
<td>Tyrone Volcanic Group</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
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<td>67.9</td>
<td>11.1</td>
<td>1.0</td>
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<td>Tyrone Volcanic Group</td>
<td>Rhyolite</td>
<td>Rhyolite</td>
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<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>GLLY-PSSP</td>
<td>Southern Highland Group</td>
<td>Glendun Formation</td>
<td>Psammitte &amp; semipelite</td>
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<td>0.4</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>DART-PSSP</td>
<td>Southern Highland Group</td>
<td>Dart Formation</td>
<td>Psammitte &amp; semipelite</td>
<td>0.1</td>
<td>2.3</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>DCCF-LMST</td>
<td>Southern Highland Group</td>
<td>Claudy Formation</td>
<td>Limestone</td>
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<td>0.1</td>
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<tr>
<td>DCCF-PSSP</td>
<td>Southern Highland Group</td>
<td>Claudy Formation</td>
<td>Psammitte &amp; semipelite</td>
<td>0.1</td>
<td>0.8</td>
<td>0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

4.4 Qualitative interpretation by dominant geological group

4.4.1 Proterozoic Rocks (Dalradian Supergroup)
Apart from an inlier in the northeast of Co. Antrim, most of Dalradian Supergroup rocks are located in the northwest of the region. These rock units show high and low magnetic signatures.
and exhibit strong gradients between (Figure 11 and Figure 12). The northern part of the group (A4) shows NE–SW trending structures, whilst the central part (around Co. Londonderry) is characterised by relatively uniform, intermediate to low magnetic values. Magnetic values increase towards the south, with a relatively high magnetic zone oriented NE–SW northwest of the Omagh Thrust (A1). This zone is separated from another magnetic high between Gortin and Sperrin by a low magnetic zone observed around Plumbridge.

From Figure 11 it would appear that zones of high magnetic anomaly are associated particularly with Argyll Group formations that have volcanic origin, or that contain volcanic detritus, for example in north Donegal (A4) and southeast Sperrin Mountains (A1). Figure 12 defines these high magnetic anomalies as linear features associated with specific parts of the stratigraphy. For example, the pronounced linear magnetic high contained within the Mullaghcarn Formation just north of the Omagh Thrust and A1, correlates with a unit of volcanic origin referred to as an amphibolitic green bed (GSNI 1995). In north Donegal on the Inishowen Peninsula, linear magnetic highs are seen associated with rocks of the Argyll Group, Fahan Slates and Termon pelite formations, whilst in the Southern Highland Group, highs correspond to the Cloghan and Greencastle green beds (see Long & McConnell 1997). It is proposed that these lithologies contain relatively high concentrations of magnetite compared to other parts of the stratigraphy. Such variations in the magnetic signature, associated with lithology and magnetite content, has recently been demonstrated in the Lack Inlier (A6) by McFarlane et al., (2009).

In recent decades, there has been some debate regarding the stratigraphic position of the Dalradian formations adjacent to the Omagh Thrust, particularly the Mullaghcarn, Glengawna and Glenelly formations. The 1:250,000 scale bedrock map of Northern Ireland (GSNI 1997) shows these to be Southern Highland Group, however, studies by Alsop & Hutton (1993) and McFarlane et al., (2009) now show these to be Argyll Group in age.
Strong linear magnetic anomalies run within the outcrop of the Glengawna Formation. These magnetic highs reflect graphitic pelite horizons within the Glengawna that are also associated with thrust faulting parallel to the Omagh Thrust. Magnetic lows in all parts of the Dalradian outcrop are associated with either low magnetite content or in some instances demagnetisation, for example by removal of magnetite due to silicification, by palaeo-fluid flow of mineralised fluids (McFarlane et al., 2009).

The south western part of the Dalradian around Stranorlar cross roads and Castlefinn (A3) is mapped by high magnetic amplitudes, which may indicate the presence of more volcanic rocks in this area. NE-SW trending high magnetic anomalies are observed parallel to the Ox mountains from east of Foxford to Cloonacool (A5) and may reveal structurally controlled high magnetic zones. It can be concluded that magnetic data can help differentiate both lithological and magnetite variations within Dalradian and can help identify areas that have undergone demagnetisation.
4.4.2 Lower Palaeozoic (Ordovician – Silurian)

Lower Paleozoic rocks are predominantly located in the southeast of the region (Figure 5) and form part of the Longford-Down Terrane. They are generally magnetically homogeneous although regional trends are seen throughout (Figure 13). Typically the Lower Paleozoic greywacke and mudstone sequences are of low susceptibility. Magnetic rocks of the Marchburn Formation derived from an ophiolitic source within a thrust slice to the south of the Southern Uplands Fault in Scotland (Oliver et al., 2002) do not appear to be present here. There is no obvious magnetic response to the numerous Caledonian faults that cross the area. There is a broad subtle regional increase in the magnetic anomaly towards the extreme southeast over greywacke and red shale members of the Hawick Group. This magnetic high may indicate uplifted/shallow basement parallel to Southern Uplands – Longford-Down Terrane. The Lower Paleozoic rocks of the southeast of the region are extensively intersected by Palaeogene dolerite dykes.
4.4.3 Tyrone Igneous Complex

The Tyrone Igneous Complex lies south of the Dalradian Supergroup within the Midland Valley Terrane. It is a plutonic and volcanic complex deposited in an oceanic-island arc setting in the early to middle Ordovician (Cooper et al., 2008, 2011; Hollis et al., 2012, 2013a, b). The core of the complex is the fault-bounded Central Inlier or Corvanaghan Formation (Cooper & Johnston 2004a) which consists of silliminite grade, gneissose psammites considered originally to be part of the Grampian Terrane. Recent work has demonstrated that the Central Inlier is most likely to be a piece of Dalradian Supergroup that has been metamorphosed to a much higher grade (Chew et al., 2008) The Tyrone Igneous Complex itself is divided into the Tyrone Plutonic and Volcanic groups. The Tyrone Plutonic Group is composed of isotropic and layered gabbro, sheeted dykes and rare
pillow lavas (Hutton et al., 1985; Cooper & Johnston 2004a), and represents the upper portion of an obducted ophiolite (Hollis 2012, 2013b). The Tyrone Volcanic Group is made up of predominantly basic tuffs and pillow lavas, but also contains more acidic rock such as rhyolite (Hollis 2012, 2013a).
Figure 14 a & b: a) Geological context of the Tyrone Igneous Complex. Magnetic features overlying GSNI 1:250 000 solid geology. Tyrone Igneous Complex is shown by thin dashed black line (a) and by number 2 on Figure 8 and dashed line on Figure 9. 3a is an area with low magnetic anomaly in Fig.11, 3b is an area of with high magnetic anomaly, magnetic value (A1) in fig.11. while 2 is the Tyrone Central Inlier. (b) Standard deviation (texture) of magnetic data within Tyrone Igneous complex (heavy dashed black polygon).
The faulted margins of the Tyrone Igneous Complex and the internal structure are revealed in stunning detail on the 1st vertical derivative and CET Standard deviation map (Figures 9 & 10).

The magnetic gradients associated with the Tyrone Igneous Complex form a complex pattern of cross cutting anomalies that represent faulting and shearing. The main magnetic features are shown superimposed over known geology on Figure 14.

The northern margin of the Tyrone Plutonic Group (Figure 14b) is defined in some places by sinuous curved gradients that represent thrust faults. Other margins are linear, for example where it is bounded by the Caledonian Tempo–Sixmilecross Fault. Both linear bounding faults have pronounced gravity gradients associated with them and are probably related to deep basement faults.

Within the Tyrone Igneous Complex a set of strong east-northeast lineaments related to faulting and/or shear zones run parallel to the bounding faults. A second set of lineaments trend sub-parallel to the bounding faults. One of these, running through the centre of the complex, is the Beleevnamore Fault (GSNI 1995) which locally disrupts the magnetic anomalies. A third structural magnetic trend is also evident characterised by a series of short acute lineaments. However, it is not clear if these represent an earlier structural fabric.

4.4.4 Carboniferous
Carboniferous rocks dominate the southwest of the region but extend towards the centre with further outcrops located to the north on the western edge of the Antrim Lava Group, in parts of Southern Donegal as well as towards the south east in counties Louth and Cavan. Figure 15 shows the TMI of Carboniferous rocks throughout the region. Strong SW-NE Caledonian trends are apparent with magnetic lows either side of a central high. This probably reflects magnetic basement at depth relating to the regional geological terrain as shown in Figure 2 rather than Carboniferous rocks themselves. The dominant feature is a strong positive linear anomaly which aligns with the Belhavel fault and probably corresponds with basement uplift.
Broad circular high magnetic anomalies (concentrated at two centres) are observed to the south of Lower Lough Erne and north of Lough Allen (number 8 on Figure 15). These circular anomalies are present within dark and calcareous shale units and may indicate high occurrences of sulphide/iron oxides within black shales. These anomalies are also associated with relatively high conductivity values due to shale and/or sulphide mineralisation. These two magnetic anomalies are separated by the regional faults of Clogher Valley and Tempo-Sixmilecross. Alternatively these features may correspond to deeper intrusions or basement uplift. The TMI map (Figure 15) and magnetic textural map (Figure 16) show a number of localised anomalies within mapped Carboniferous units. These magnetic anomalies (number 1-8) are interpreted as the response of buried intrusive bodies beneath Carboniferous sediments.
4.4.5 Palaeogene Antrim Lava Group

The Antrim basalts are located in the northeastern corner of Northern Ireland (Figure 7) and the magnetic anomalies associated with them dominate the TMI map. Their strong magnetic signature allows the surface extent of the Antrim basalts to be mapped accurately in areas of poor exposure. Short wavelength, high amplitude magnetic anomalies were smoothed out by upward continuation by 500m (Figure 17). The strong negative anomalies (coloured blue) partly result from a strong natural remnant magnetisation component that was acquired when the lavas cooled in the opposite direction to the Earth’s present day magnetic field and are partly due to sub-basalt basin fills. Paleomagnetic studies have shown that the stable bulk magnetisation of the basalt lava has a declination of about $190^0$ and an inclination of $-60^0$ (Wilson, 1970; Gibson et al., 2009). The current values of declination and inclination for the induced magnetic field are about $-6^\circ$ and $69^\circ$ respectively.
The margins of the basalt show characteristic strong positive linear anomalies on the reduced to pole and upward continued by 500m map (Figure 17) which are enhanced on the texture map (Figure 18). The margins of distinct magnetic units within the basalt outcrop are bound by positive anomalies. These show a general alignment believed to represent the margins of structural blocks separated by faulting.

Mainly negative magnetic anomalies occur in the north of Co. Antrim accompanied by a few poorly defined areas of local positive anomalies. This may suggest variation in the magnetic properties of the lavas which in the main are reversely magnetised. The negative anomalies in this area are terminated by the Tow Valley Fault which has a strong magnetic gradient associated with
it. Figure 18 shows NE-SW, NNW-SSE trending structures as well as structures oblique to both directions. Few dykes are observed towards the east of the area. It is difficult to differentiate the response of dykes from the main basaltic units. Moreover, the high magnetic values are seen to follow certain directions which may suggest that the Antrim lava evolved by fissure filling eruption from nearby sources.

The thickness and orientation of basalt formation might be related to subsidence rates, basement topography and the degree of erosion. Present thickness variation reflects both the depositional variations and differential erosion prior to emplacement of Antrim lava group (Simms, 2000). Paleo-surfaces (low and/or high reliefs) as well as foot wall uplift are suggested as the main factors effecting thickness of the Antrim lava (Simms, 2000).

Magnetic anomalies beneath Lough Neagh are locally displaced by at least two northeast linear gradients marked by positive anomalies on the TMI (Figure 17). These are accompanied by pronounced gravity gradients which probably represent the continuation of two large faults mapped in the Crumlin area displacing the Lough Neagh Group and basalt outcrop. There is no obvious magnetic expression of the Sixmilewater Fault beneath Lough Neagh. Low magnetic values observed within the Tow Valley Fault are observed to extend towards Ballybogy, Ballyrashane and Blagh (BS) on Figure 17. This low magnetic zone is associated with high conductivity values (Figure 35-Figure 37), which suggests the extension of the Oligocene clay, sand and lignite formation towards these localities.
A magnetic structural map of the Antrim basalts (Figure 18) helps reveal lithological boundaries, faults, volcanic centres/intrusions and dykes, which are critical to understand the geology of the area. Circular and semi-circular features oriented in NNW-SSE direction are observed on this image. Some are associated with rhyolite outcrops for example Tardree, Templepatrick, Quarrytown and Broughshane. Carnmoney is a dolerite plug and Knocklayd is a circular outlier of chalk and basalt on Dalradian basement (GSNI 1997). These circular features are numbered from 1 to 6 on Figures 17 and 18 and are summarised in Table 4.
Table 4: Summary list of identified volcanic centres

<table>
<thead>
<tr>
<th></th>
<th>Name/locality</th>
<th>Centre location</th>
<th>Shape</th>
<th>Approximate diameter</th>
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<td></td>
<td></td>
<td>East North</td>
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<td></td>
<td></td>
</tr>
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<td>1</td>
<td>Templepatrick Plug</td>
<td>326900 383800</td>
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<td>Rhyolite plug</td>
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<td>Broughshane</td>
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<td>?Rhyolite plug</td>
</tr>
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<td>Quarrytown</td>
<td>313000 408600</td>
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<tr>
<td>6</td>
<td>Knocklayd</td>
<td>311800 436200</td>
<td>circular</td>
<td>2.5km</td>
<td>Basalt outlier</td>
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</tbody>
</table>

Figure 19 a & b: Detail examples of circular features shown in Figure 19 and (locations in Table 4), black line is geological boundary of Tardree rhyolite (b).

4.4.6 Intrusions

Slieve Gullion & Carlingford Complexes

Large magnetic highs are observed over both the Slieve Gullion and Carlingford complexes (Figure 20). These anomalies most likely represent basic rock that extends at depth beneath both centres. The joined body is elliptical and orientated NW-SE. The combined anomalies of the Slieve Gullion and Carlingford complexes extend to the west and southwest of their mapped surface area, suggesting that the complexes continue at depth in this direction.
The standard deviation or textural map (Figure 21) provides information on the shape of igneous complexes and their relationship with dyke swarms. The Mourne Mountains Complex exhibits a circular magnetic high which surrounds a lower magnetic anomaly, and it is thought that the magnetic high may represent high susceptibility basic rocks within the Glasdrumman cone sheet. Linear magnetic highs and lows that are truncated by the Mourne Mountains anomalies have been interpreted to represent the Donegal-Kingscourt and St. John’s Point-Lisburndyke swarms (Cooper et al., 2012)
Figure 21: Textural map of intrusion within the southeast of the region overlying 1:1M bedrock geology. White lines are geologic boundaries, (SG) Slieve Gullion, (CF) Carlingford, (MM) Mourne Mountains, (S) Seeconnell Complex, (SC) Scrabo sill, (CD) Crossdony granite, (DD) Dolerite dyke, (B) Antrim basalt, (NIC) Newry Igneous Complex.

Figure 22 & Figure 23 show detailed images over the Slieve Gullion and Carlingford complexes. A number of circular features indicative of intrusive bodies or volcanic centres can be observed. The central inner zone of these features show consecutive circular centres along the main orientation in NW-SE direction. Thin and elongated features are seen to follow the general direction of the circular centres forming oval shapes elongated in a NW-SE direction. The whole feature shows complicated structural architecture and complex inter relationships between intrusive bodies and dykes.
Figure 22: CET standard deviation (a) map over Slieve Gullion (SG) and Carlingford (CF) complexes.

Figure 23: CET standard deviation map (b) over Newry Igneous Complex (NIC).
The Late Caledonian Newry Igneous Complex comprises three granodiorite plutons, previously termed the Northeast, Central and Southwest (Meighan & Neeson 1979), which we rename here the Rathfriland, Newry and Cloghoge respectively. Recent U-Pb dating (Cooper et al. 2013) show that the plutons were intruded oldest to youngest from NE to SW in agreement with known field relationships. Interpretation of TMI, first vertical derivative and CET images (Figures 8, 9 & 22) reveal significant zonation of the complex including the presence of striking concentric positive and negative aeromagnetic anomalies in the Rathfriland and Newry plutons which may reflect reversals in the earth’s magnetic field Cooper et al. (under review). In addition to the granodiorite plutons the Seeconnell intermediate-ultramafic complex is clearly visible (S on Figure 20 & Figure 21). This intrusion is oriented NNW-SSE and shows a “T” shaped feature at its northern end. The width of this body on magnetic map reaches 3.8 km in NS direction 4.3 km in EW direction.

Other intrusive bodies
First vertical derivative and standard deviation maps of the magnetic data across the region (Figure 9 and 10) highlight a number of other intrusive bodies identified by their shape and strong gradients. These include;

- Scrabo sill near Newtownards (SC on Figure 20 & Figure 21) is an olivine dolerite and gabbro (Cooper and Johnston 2004b) and is mapped with a negative magnetic response. It shows a crescent shaped feature oriented NE-SW which may relate to a saucer shaped intrusion.

- The Crossdoney Granite in Co. Cavan (CD on Figure 9 and Figure 21) shows a complex pattern of circular magnetic gradients and agrees well with the mapped geology.

4.4.7 Dykes
The magnetic data have revealed numerous basic dykes extending across the region (Cooper et al., 2012). Gibson and Lyle (1993) traced many of these from earlier airborne magnetic imagery. These dykes are aligned in a number of different orientations. The magnetic signature of these dykes show widths varying from 400 m to 1000 m, however, ground observations show that the majority of dykes mapped are much narrower, typically 2-30 m. In essence, due to flight height and survey line spacing, the airborne magnetic survey is unable to resolve individual dykes. Instead, the
magnetic data often maps the anomalies of groups of dykes which appear as coalesced features, giving the (false) impression of a single linear feature or structure. The dykes are of major importance in unravelling the igneous history of the region and can be used to measure recent displacements along faults of up to 2.5 km (Cooper et al., 2012). They are also important in determining the regional stress fields at the time of emplacement.

Based on their orientation, relative age, density of distribution and remnant magnetic polarity, five distinct dyke swarms have been identified. Four swarms were originally identified from Tellus data across Northern Ireland (Cooper et al., 2012) and a fifth was recognised in County Sligo from Tellus Border (Figure 24) these are;

1. Erne, generally low density, positively polarised with an average strike of 111° (Green).
2. Donegal-Kingscourt, high density, negatively polarised with an average strike of 128° (Blue).
3. Ardglass-Ballycastle, high density, negatively polarised with an average strike of 130° (Cyan).
4. St. John’s Point-Lisburn, high density, positively polarised with an average strike of 137° (red).
5. Killala, low density negatively polarised, with an average strike of 103° (Light blue).

Relationships observed between the various dyke swarms, Antrim Lava Group, central complexes and major regional scale faults allow a relative chronological sequence of intrusion to be established (Cooper et al., 2012). In the west of Northern Ireland, the oldest dyke swarm (Erne) is offset by as much as 2.5km across the Tempo-Sixmillecross Fault, whereas the next youngest is only offset by 1.5 km and is unconformably overlain by the Antrim Lava Group. In the east the next youngest swarm (Arglass-Ballycastle) intrudes the Lower Basalt Formation but not the Upper Basalt Formation. The youngest swarm observed from Tellus (St. John’s Point – Lisburn) appears to cut both the Lower and Upper basalt formations. The relationships seen between dyke swarms and faults suggest an interaction between pulses of plume related uplift and far field Alpine compression.

A series of SW-NE to WSW-ENE orientated dykes, shown as orange on Figure 24, are interpreted to be Late Caledonian lamprophyric bodies and as such are not part of any of the above.

4.5 Mineralisation structures in magnetic data
The association of mineral occurrences with NE-SW and N-S lineaments and shear zones is shown on Figure 25. In particular, the area in and around the Tyrone Igneous Complex is associated with regional magnetic anomalies, electromagnetic conductors and regional gravity features which suggest possible mineral targets. These targets largely fall within the area that covers the Dalradian rocks of the Sperrin Mountains, the Omagh Thrust Fault and the sheared rocks of the Tyrone Igneous Complex. The northern and south-western ends of the Dalradian Supergroup show similar NE-SW shearing and are candidates for metaliferous mineral potential.
Figure 25: Relationship between structures and metallic mineral occurrences. Lines are structures inferred from magnetic data. The lines were mapped from: CET standard deviation automatic lineament detection, horizontal gradient of magnetic anomaly and first vertical derivative of Total magnetic intensity.

Within Dalradian rocks south of the Sperrin Mountains, gold has been reported in localities that align along an outer semi arcuate zone that is tentatively coincident with a linear local magnetic high. The total magnetic intensity map (Figure 26) highlights many localities within a belt of low magnetic intensity shown by pale blue colours. These anomalies lie at the contact between the Dart and Glenelly Formations. To the south of this line mainly gold but also lead anomalies are mapped over four prominent acute magnetic linear highs within outcrops of the Mullaghcarn Formation. Other sporadic gold occurrences are also coincident with local magnetic gradients adjacent to the Omagh Thrust Fault. Two of these magnetic zones are separated by a conductivity anomaly that occurs at the top of or locally within the Glengawna Formation. Few gold deposits are recorded south of the Omagh Thrust except for one significant occurrence that lies over a small local magnetic lineament.
A band of copper and lead deposits occurs between the Omagh Thrust Fault and the linear magnetic gradient marking the margin of the magnetic part of the Tyrone Igneous Complex. Two copper occurrences lie on the pronounced linear magnetic gradient over the Omagh Thrust Fault. There is also a cluster of copper anomalies over the thrust coincident with a local magnetic high over the northeast margin of the non-magnetic part of the Tyrone Igneous Complex.

Copper, lead and zinc deposits are found in the non-magnetic Tyrone Volcanic Group and appear aligned with the magnetic gradient along the margin of the Tyrone Igneous Complex. Most localities are along the north-western margin of the Laght Hill Tonalite. The copper and lead belt here lies within a broad magnetic low on the reduced to pole map but there is a subtle lineament within this zone where most of the deposits are clustered.

Overall mineralisation is generally concentrated in areas of shearing and faulting which increase within the Dalradian rocks towards the Omagh Thrust and the Tyrone Igneous Complex (Figure 26). Magnetic lineaments and EM conductors suggest a series of deep thrusts and shear zones which have the potential to provide conduits for mineralisation.

Some gold locations in the Dalradian rocks north of the Sperrin Mountains appear to align along an ENE trend concordant with the main Dalradian strike, other locations lie on the margins of Standard deviation and first vertical derivative features as well as pseudo-gravity horizontal gradient highs, however any relationships with magnetic anomalies are less clear.
4.6 Crystalline basement derived from magnetic data

Magnetic data can be successfully used to help determine the depth to the top of magnetic sources associated with crystalline basement. For hydrocarbon exploration, this is usually equivalent to determining the thickness of the sedimentary section. For mineral exploration, depth estimates are often used to determine the depth of ore bodies which contain magnetic minerals.

A basement signature is obtained by using local and regional interactive Gaussian filters of the aeromagnetic data using a filter wave-number length of 0.78 (Figure 27). By comparing the basement signature at known geological areas, it is possible to extrapolate these results to other areas with similar signatures where basement rocks are overlain by thick sediments. For example, low magnetic responses in the area to the north of the Clew Bay – Fair Head line (Central Highland Terrane, Figure 2), may indicate siliceous and feldspathic units known to exist to the southwest in the Lough Derg Inlier. Pseudogravity (Figure 28) and magnetic data has helped delineated prominent basement terrane boundaries. The pseudo-gravity field helps define the Midland Valley Terrane as a broad positive magnetic high bounded to the northwest by the Tow Valley Fault and
to the southeast along the margin of the low magnetic anomaly where magnetic basement is absent.

Figure 27: Basement component of total magnetic intensity grid. NE trending lines are major terrane boundaries, the lines drawn at northern and southern ends are additions from regional magnetic response. The oblique lines are structures inferred from regional magnetic response.
4.6.1 Depth to basement using profile depth method

The profile depth to the basement, (P-depth) is an automated method for determining the distance, depth, dip (orientation) and intensity (i.e. susceptibility) of magnetic source bodies along each profile. The profile depth (P-Depth) module of Oasis Montaj provides three different depth to basement techniques; Werner deconvolution, analytic signal and extended Euler deconvolution depth solutions. The algorithm of P-Depth is based on a USGS derived program (Geosoft Technical Note for profile Depth to Basement). Depth calculations are based on structural indices. Solutions are written to separate output databases, those derived from the total field profile are designated as Z-dikes while those derived from horizontal gradients are designated as Z-contacts. All solutions are derived relative to the flight altitudes. In addition to the calculated solutions, input channels (elevation, TMI) as well as horizontal and vertical derivatives are also sampled in the output database. A number of approaches and different algorithms were used to generate depth
solutions. Analytic signal solutions with minimum and maximum window size of 500 and 1000m with maximum depth of 10km were used to generate depth solutions. The depth solution that best correlated with borehole data was the one obtained from TMI Z-dikes (dyke model). The result is shown in Figure 29.

Figure 29: Depth to top of basement from P-Depth relative to survey altitude and basement structures. Black lines indicate inferred basement structures.

The highly magnetic Antrim Lava Group can have a considerable effect on the depth calculation, as the depth transformation algorithm assumes that such responses are caused by basement. This effect is seen to be proportional to their thickness. To reduce this effect an upward continuation of 1000m and 2000m was applied to the data. This was then compared with available borehole data. The best correlation between borehole data and depth to the top of basement is achieved when magnetic data at the Antrim Plateau is upward continued by 2000m. Shallow basement topography is observed at the western side over the Tyrone Igneous Complex, parts of county Monaghan, south-eastern part of County Down, over Dalradian rocks in the northwest and below the Ox Mountains.
Deeper basement morphology is delineated to the northeast close to the Tow Valley Fault, between the Sixmilewater Fault and Southern Uplands Fault (Figure 2), south of Lough Erne and around the area covered by Lough Allen.

One of the unexpected results of the depth to the top of basement is the signature under Lough Neagh, which indicates shallow basement in comparison with other deep sedimentary basins. Depth to basement below the Lough is about 2km while below the surrounding area it is about 3km. To the northeast and south of the Lough depth to crystalline basement are modelled at 4.3km depth. A number of basement structures running under the Lough might be due to up-thrown basement blocks or thrust faults. The depth solutions and depth contours in Figure 29 are in agreement with depths calculated in Reay (2004).

4.6.2 Basement structures observed from magnetic data

The depth of an “ensemble” of sources can be determined by measuring the slopes of the energy (power) spectrum. The typical energy spectrum of the Tellus/Tellus Border aeromagnetic data exhibits three components: deep, intermediate and shallow source components (Figure 30). The black curve at the top panel indicates the radially averaged power spectrum while the coloured curves show separate slopes related to respective source bodies. The depth of magnetic source bodies can be sliced according to a given slope to enhance information of interest. The greatest depth reached is about 10km while the shallowest is about 500-800m. The average depth to magnetic source is 2km on the bottom panel (red lines). The deepest depth (between two pink vertical lines) reaches 12-14km.

Figure 31 was created using the susceptibility values obtained from P-depth solution using a depth slice between 3.0 and 3.5km. Two main geological structures related to basement rocks are clearly shown. These structures are orientated NE-SW and NW-SE. A few, N-S structures are also mapped. The NE-SW trending structures are correlated with the regional basement terrane. Susceptibility slicing at different depths confirms the presence of these two regional structures.
Figure 30: Radially averaged 2D power spectrum and depth estimation of magnetic data. Figure 31 (bottom panel) helps to estimate maximum depth in estimating solutions.
The NE-SW trending faults and shear zones are typical expressions of gross sinistral transgressional deformation during periods of plutonism (425-400Ma) (Jaques and Reavy 1994; Watson, 1984). Some of these features, such as the Great Glen Fault in Scotland, of which the Leannan fault is a splay in Co. Donegal, have been shown to extend through the Moho into the uppermost mantle by seismic data (Watson, 1984). These NE-SW structures are believed to have strong tectonic controls and their presence at 3.5 km depths indicate the presence of Caledonian structures within basement rocks (Watson, 1984).

NW-SE trending structures generally look detached and displace by NE-SW structures. These structures may indicate reactivated pre-Caledonian structures at depth. These deep and older structures are rejuvenated at shallower depths over younger units, such as the reactivation of the NE-SW Tow Valley Fault and Southern Uplands Faults. The Hebridean craton is traversed by
several pre-Caledonian NW-SE lineaments which originated as shear zones in the Lewisian basement (Watson, 1984). The distribution of sites of magmatic activity may be controlled by the combined influences of transgressional Caledonian (NE-SW), and reactivated transverse pre-Caledonian lineaments (NW-SE), faults and shear zones (Jaques and Reavy, 1994).
5 Electromagnetic (EM) Data

5.1 Introduction
The merged Tellus, Tellus Border and Cavan airborne electromagnetic (AEM) data provided valuable information on the surface geology and structure of the 12 northern counties of the island of Ireland. The rocks that make up the survey area show considerable variation in their electrical conductivity properties, helping to map different geological formations and their distributions both laterally and vertically.

The AEM systems used in the Tellus/Tellus Border surveys acquired data utilising two and four frequency systems with vertical coplanar coils. The coil pairs (vertical transmitter coils at one wingtip and vertical receiver coils at the other) for the dual frequency systems are mounted on the wingtips; the coil spacing being 21.36 m for the Twin Otter system (Suppala et al., 2005). The high frequencies used in this report are 11,962 Hz and 14,368 Hz, while the low frequencies are 3,005 Hz and 3,125 Hz. The data were collected along lines 200 m apart, at a nominal flight height of 56 m and 59 m (except for the lines flown over populated areas, manmade barriers or restricted areas). A data sampling interval of 0.25 seconds was used for the Tellus and Cavan surveys (every ~17 m along survey line) and 0.1s (every 6-7 m) for the Tellus Border data set. The total line km covered by the merged EM data is 139,531 km, which included 14.76 million data points.

Four different frequencies were employed for the whole Tellus Border and eastern part of Tellus surveys. These four frequencies are: 912, 3005, 11962 and 24510 Hz (Figure 32). The western part of Northern Ireland was surveyed in 2005 using two frequencies, 3125 and 14368Hz, (Figure 32) which are used to merge with 3005 and 11962 Hz. These two frequencies are the closest to those employed in 2005 (3125 and 14368 Hz) and therefore were used to interpolate an EM response for the whole region.
The primary EM, in-phase and quadrature components were transformed to apparent resistivity and apparent depth using a half-space model (Beamish et al., 2007a; Beamish, 2013a). The method returns apparent resistivity and apparent depth at each measured frequency. The model program employs minimum limits on the real and imaginary coupling ratios to identify the noise level in the coupling ratios.

Two merged datasets were used for interpretation of the whole region (Tellus, Cavan and Tellus Border survey areas). These were a combined high frequency (HF) (11962 & 14368 Hz) and low frequency (LF) (3125 & 3005 Hz) datasets. The main interpretations across the region are based on these two merged datasets.

5.1.1 EM data processing
Data processing of the merged EM datasets are described by Beamish (2013a). The apparent conductivity for Tellus Border for HF and LF data had been fully processed and merged with existing Tellus and Cavan data sets resulting in seamless integrated data for the northern 12
counties of the island of Ireland. A nominal flight altitude of 56 m (Tellus and Cavan) and 59 m (Tellus Border), line spacing of 200 m, and line orientation of 345° were employed for the whole data.

The apparent conductivity, or resistivity, data supplied by the contractors are generated by a simple transform procedure that uses the in-phase (IP) and quadrature (Q) data at each frequency but not the altitude (Beamish, 2013b). In order to provide a valid estimate of apparent conductivity, each IP and Q measurement must be greater than zero and also greater than the noise level with a threshold value of 20 and 30 ppm set for IP and Q readings for low- and high-frequency data respectively. These data were also clipped to only include points with an altitude less than 180 m (altitudes greater than 180 m were dummied). The merged AEM data were loaded into Geosoft databases which provided the base datasets for subsequent processing and analysis. All data processing (gridding, filtering and image preparation) was performed using Geosoft Oasis Montaj software (Version 8.1).

A number of filtering techniques were tested on the airborne EM data during attempts to minimise cultural (non-geological) ‘noise’ (including the effect of power lines, motorways, etc.). The most effective and acceptable results were achieved through bi-directional micro levelling with a non-linear, low pass filter 1000 m in length (5 times the survey line spacing). It is acknowledged that non-linear filtering may distort the data and damage the geological signal. This operation was applied to the AEM data, gridded using a cell size of 50 m. The process was applied to both the high-frequency (HF) and low-frequency (LF) data sets. The main aim of this processing stage was to minimize/eliminate visible levelling errors which were not addressed during routine pre-processing prior to data delivery. Figure 33 and Figure 34 show an example of ‘before’ and ‘after’ filtering of AEM data over anomalies associated with cultural noise i.e. effects of electrical power lines, railway routes and motorways. The filtered data (bottom) show that these features have been removed or minimized, without damaging the ‘geological’ signal inherent in the data. However, the filtered data may mask the strength of minor and local anomalies. Therefore, different processing methods were tried to help identify geological features associated with structures and localized anomalies. One of the techniques utilized here is Gaussian regional/local separation using interactive Magmap module in Geosoft using interactive filter of length 0.2 (similar to fractional vertical derivative of 0.5). Though the module has been developed for
potential field methods, magnetics and gravity, it is seen that reasonable results were obtained and show good correlation with the mapped geological structures. The EM maps are presented overlying ordnance survey base maps, so as to compare with features associated with cultural noise.

Figure 33: Example of unfiltered LF conductivity data. Note strong linear conductivity anomalies associated with power lines.
5.2 Regional Interpretation

5.2.1 Overview
The airborne electromagnetic system maps variations in electrical conductivity (the reciprocal of resistivity). These changes relate to porosity, saturation, pore-water salinity, sulphide and clay content of rocks.

The apparent conductivity maps (Figure 35 and Figure 36) show the general distribution of the major rock units and linear features/faults. Where the rocks are overlain by a significant cover of conductive drift deposits the response from the geological units is suppressed. Figure 37 is obtained using interactive Gaussian regional/local separation and helps delineate NE–SW and N–S trending structures. Some levelling errors are apparent when the data is displayed with a gradient with a NNW grain throughout many images. The linear trends on this map correspond closely with geological structures and boundaries at regional and local scales. It can be concluded that the EM
data shows mapped geological structures as well as new ones and may act as an invaluable tool for improving the existing geological maps.

The Dalradian Supergroup in the northwest and northeast parts are mapped by relatively low conductivity. Distinct and isolated high conductive areas are observed in places within Dalradian rocks associated with water bodies and linear units and structures. Relatively high conductivity is seen in association with linear graphitic intervals that occur within the Glengawna Formation and in faults close to and including the Omagh Thrust.

Figure 35: Filtered merged apparent conductivity data from high frequency (HF) AEM data for whole region.
Across the region thin lineaments, associated with some of the main geological terrane bounding faults, are clearly mapped. Numerous linear conductors are also associated with the mineralisation observed in Co. Tyrone. Carboniferous shales, sandstones and evaporites in Co. Leitrim, Co. Fermanagh and north Co. Cavan are also generally conductive. Ordovician greywackes of the Longford–Down terrane are generally resistive, but bands of Moffat Shale Group mudstones are mapped running in NE-SW orientations through this area are highlighted as strong linear conductors. Relatively broader NE-SW tending, highly conductive EM anomalies extending through counties Sligo and Leitrim parallel with the Ox Mountains may indicate black shale horizons, with possible occurrence of graphite or possible hydrothermal alteration and basement uplift as indicated in magnetic data (section 4.1.1).
To the east of the region the Slieve Gullion and Carlingford complexes are resistive, while part of the Mourne Mountains is conductive, which could indicate deep weathering, saline water intrusion through fractures or thick clay (glacial till) overburden.

The basalts of the Antrim Lava Group display high conductivity, particularly to the west, which may reflect an open pore structure or clay-filled amygdales in the lava flows, but may also, indicate a covering of conductive peat or clay. This could also be due to higher degree of weathering in the western side. The eastern side is relatively resistive, indicating thinner clay cover or less weathering. High conductivity is also observed over Oligocene clay, sand and lignites of the Lough Neagh Group. Seawater and tidal inlets show extremely highly conductive values and are generally masked from the grid so as to reduce the extreme conductivity values.

The difference in conductivity over different lakes indicates the degree of salinity and interaction of sea water or the thickness of associated sediments, for example Lough Neagh is more conductive than Lough Erne. This may suggest that Lough Neagh may have relatively more dissolved salts or that the unconsolidated sedimentation under Lough Neagh is thicker. A number of borehole records around Lough Neagh show maximum sediment thickness of 489m with an average of 150m.

Anthropogenic responses, such as major and minor power lines and roads, are apparent within the data, particularly when unfiltered. They are more visible in the low frequency, rather than the high frequency data. No major industrial pollution plumes are recognised at the regional scale, but local anomalies in the proximity of landfills and industrial sites are mapped at a finer scale. Significant cultural noise is also apparent within the data and should be considered with all interpretations.
5.3 EM data properties

The bedrock electrical conductivity structure of Northern Ireland was described and geo-statistically analysed by Beamish (2013). This provides a comprehensive analysis of the conductivity estimates using a lithological classification of the bedrock formations based on the Tellus airborne EM data for the region. These results will be similar for lithologies within the border region.

Geotechnical and petrophysical geophysical laboratory analysis of rock samples from Northern Ireland (Entwisle et al., 2007) provided information on density, porosity, resistivity, sonic velocity and uniaxial compressive strength parameters. These analyses are summarised in Table 6 and in
Figure 38 and show Devonian and Carboniferous sandstones, Jurassic limestones and Triassic mudstones with high conductivity, high porosity, low density and relatively low P-wave velocity.

Table 5: Measured physical parameters of different lithologies within Northern Ireland, the resistivity value are obtained using 3.5g/l salinity. The numbers represent average values

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<th>P-wave velocity</th>
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5.4 Qualitative interpretation by dominant geological group

5.4.1 Proterozoic Rocks
Apart from a zone in the northeast of Co. Antrim, most of the Proterozoic rocks are located in the northwest of the region (Figure 4 & Figure 39). These rock units show both high and low conductivity signatures, with more conductive values to the northwest and resistive values to the south and east. Little difference is seen between the HF and LF maps (Figure 39 & Figure 40). The high conductivity observed to the north western part of the central area of Dalradian rocks may be due to a high degree of weathering or possibly thicker deposits of clay overburden. The southern part of the map includes Proterozoic schist and gneiss (PSG) and the south-east includes the Tyrone Igneous complex (TIC). The most prominent anomaly is observed along the River Foyle associated with saline intrusion. The Dalradian and TIC structures are highlighted in the fractional derivative (first vertical derivative obtained using power of 0.5) map (Figure 41) with strong NE–SW trending structures. The middle of the Tyrone Igneous Complex displays very low conductivity, due to resistive Ordovician volcanic rocks and its northern and southern margins are marked by
NE–SW trending lineaments which indicate possible shearing. Dalradian rocks in the northeast (Co. Antrim) show relatively high conductivity values at the northern end, which could be due to thick clay or intrusion of sea water.

Figure 39: HF filtered apparent conductivity data over Dalradian rocks. TIC = Tyrone Igneous Complex, PSG = Proterozoic schists and gneiss.
Figure 40: LF filtered apparent conductivity data over Dalradian rocks. TIC = Tyrone Igneous Complex, PSG = Proterozoic schists and gneiss.

Figure 41: Fractional derivative (first vertical derivative obtained using power of 0.5) map of conductivity data over Dalradian rocks. TIC = Tyrone Igneous Complex, PSG = Proterozoic schists and gneiss.

5.4.2 Lower Paleozoic (Ordovician–Silurian)
Lower Palaeozoic rocks within the Longford-Down terrane are located in the southeast of the region (Figure 5, Figure 42 and Figure 43) and generally show intermediate to low conductivity.
values except for areas immediately south of Lough Neagh, which are of relatively high conductivity, with Ordovician–Silurian greywackes generally resistive. Limestone and calcareous shales in the southwest of the region are mapped by relatively high conductivity values. The NE–SW oriented Moffat Shale horizons are mapped by very high conductivities. These shale units are generally black in colour and contain varying concentrations of graphite, which is highly conductive (greater than 30 mS/m), helping to map these thin shale horizons. These Moffat Shale Group bound packages of rocks are host to gold mineralisation and have been further investigated by Cooper et al., (2013). Single, linear conductive anomalies from the AEM data (Figure 45) have been shown to comprise a series of these shale units often only a few to tens of metres thick.

Figure 42: High frequency filtered apparent conductivity map over Lower Palaeozoic rocks. Black lines indicate geological boundaries.
Figure 43: Low frequency filtered apparent conductivity data over Lower Palaeozoic rocks.
Figure 44: Fractional derivative of EM data of Lower Palaeozoic rocks in SE of region.
5.4.3 Carboniferous

Carboniferous rocks are extensive in the southwest of the region, with Viséan aged sandstones, mudstones, evaporates, limestones and calcareous shales, plus Namurian aged shales, sandstones, siltstones and coals all exhibiting conductive anomalies (Figure 46 and Figure 47). The SW–NE conductivity anomaly within Viséan sandstones, mudstones and evaporites could be due to black shales with graphitic horizons. This feature is coincident with the Belhavel Fault (Figure 6 and Figure 15).
Figure 46: High frequency filtered apparent conductivity data for Carboniferous rock

Figure 47: Fractional derivative of apparent conductivity data for Carboniferous rocks
5.4.4 Tertiary Basalts

The Antrim Lava Group outcrops in the northeastern quadrant of Northern Ireland (Figure 48-50) and shows a variety of conductivity signals with dominantly high but also intermediate and low conductivity values. Very high conductivity anomalies are seen following the River Bann in the north, which could be due to infiltration of seawater into the river. The conductivity values towards the south are diminished due to reduced salinity of the river.

The basalts display relatively high conductivity values to the west which is unusual for such formations. This may be due to an open pore structure or clay-filled amygdales in the lava flows, but may also indicate a covering of conductive peat or clay or high degree of weathering. The eastern side is generally resistive as expected over less weathered rock.

A significant conductivity anomaly is observed to the NE of Lough Neagh associated with the Glenwhirry River. Oligocene clay, sand and lignite show relatively high conductivity.
Figure 48: High frequency filtered apparent conductivity data over Antrim Basalts, (RB) River Bann, and (GWR) Glenwhirry River.
5.4.5 Intrusions

As shown in the maps above particularly for the southeast of the region (Figure 42) the Slieve Gullion Complex is highly resistive while the Carlingford Complex is mapped by moderate conductivities. The Newry Igneous Complex and the Mourne Mountains Complex show a dominantly low conductivity, except the southern part of Mournes, which is either due to seawater intrusion or thick clay cover. Other granitic intrusions (i.e. Crossdoney and Barnesmore) show few distinctive conductivity signatures, often indistinguishable from the surrounding country rock. These granitic intrusions are typically low to moderately conductive. The dolerite dykes that are clearly evident across much of the region in the magnetic data provide little conductivity contrast with the country rock and are poorly defined by the EM data.
5.5 Depth transformation
The depth of investigation of an AEM system is defined as the maximum depth at which a buried target can be detected (Vozoff, 1972). The response of the target should be sufficiently large compared to the noise of the AEM system and to the primary field. Estimation of the depth of investigation is crucial for design and interpretation of EM sounding. Though the depth of penetration is mainly controlled by resistivity/conductivity and frequencies of investigation, transmitter moment, noise-level and flight height in AEM surveys also affect depth of investigation.

An electromagnetic wave is attenuated when travelling through a medium other than free space, depending on the frequency and electrical characteristics of the medium (σ, μ, ε, ω), (Simpson and Bahr, 2005), where ε is electric permittivity [F/m], μ is magnetic permeability [H/m], and σ is conductivity of the medium [S/m] and ω angular frequency. The permeability of free space is; \( \mu_0 = 4\pi 10^{-7} \) H/m.

The electromagnetic skin depth (P) is the depth at which the field strengths have fallen off to \( \frac{1}{e} \) of their values at the surface, given by;

\[
P = 0.5 \sqrt{\frac{1}{\sigma f}} = 0.5 \sqrt{\frac{\rho}{f}} km = 503.5 \sqrt{\frac{\rho}{f}} m
\]  

(1).

Where, \( \rho \) is resistivity and \( f \) is frequency.

Algorithms developed for resistivity and depth estimate for Magnetotelluric data (equations 2 to 4) could be applied for the data acquired by frequency domain AEM systems with specific consideration of flight height in AEM systems. As can be seen from equation (1), depth penetration has direct and inverse relations to the square roots of apparent resistivity and frequency. Most approximate 1D interpretation schemes (Tikhonov, 1950; Bostick, 1977; Niblett and Sayn, 1960) are based on a direct transformation of the data to resistivity-depth section. The works of Tikhonov (1950) and (Bostick 1977) provide a reasonable first approximation of the true conductivity-depth distribution beneath the recording location. Both the Bostick transformation and Niblett approximation give a resistivity-depth distribution, \( \rho_B (h) \) and \( \rho_N (h) \),
where \( h \) is a penetration depth in half space medium of resistivity equal to the apparent resistivity at that particular frequency defined by

\[
h = \sqrt{\frac{\rho_a(f)}{2\pi f \mu_0}} = \frac{P}{2}
\]  

(2)

Where \( P \) is skin depth in (1). Note that this penetration depth implies an attenuation factor of approximately \( \frac{1}{2} \) instead of more usual skin depth attenuation of \( \frac{1}{e} \) (Niblett and Sayn, 1960).

Equation (2) is referred to as Bostick-Niblett, (BN) transform in this report. Depth transformation of the TEL and TB AEM data sets was based on equation (2), and applied to the data that was micro levelled using a non-linear low pass filter with filter length of 1000m (5 times line spacing). A number of researchers have indicated depth transformation that includes apparent depth; the difference between the calculated and measured sensor height \( (d_a = D_a - h) \), where \( D_a \) is calculated and \( h \) is measured sensor height.

\[
C_d = d_a + \frac{P}{2}
\]  

(3)

Centroid depth \( C_d \) is often used in AEM data, which adds apparent depth \( d_a \) to equation (7) (Siemon, 2001). For a homogeneous earth model calculated sensor height \( D_a \) equals the measured sensor height \( h \) and (3) becomes (2), (Siemon, 2001).

The merged Tellus/Tellus Border AEM data suffers from errors contributed by high fly zones, in particular, the data collected in 2006 and 2012. Moreover, cultural noises of different sources (power lines, rail routes, pipe lines, moving conductive objects etc.) contaminated the data. Hence, filtering and removing short wavelength noises is crucial before depth transformation.

Based on the above discussions and formulas, depth transformation for low frequency data for the whole survey area is presented in Figure 50. This provides the filtered resistivity and depth contour map for low frequency data. In addition to this, resistivity-depth sections are presented along 5 lines from Tellus and 3 lines from Tellus Border data sets. The aim of presenting these example lines is to:
• Compare and contrast depth-resistivity cross-sections obtained from the EM data with the borehole record, where borehole data exists along or very close to the example lines so as to use the EM data to map bedrock variation.

• Delineating resistivity variation over the known structures/faults. Lines 1246E and 1263E show inverted data across the Tow Valley Fault (Figure 50 & Figure 51). These depth sections delineated subsurface resistivity distribution and clearly mapped the architecture of the TVF.

• To observe and compare cross-sectional data where no borehole record is available. Resistivity, conductivity and phase cross-sections were compared and all show reasonably good correlation.

5.5.1 **EM depth penetration obtained from low frequency data**

Figure 50 shows depth penetration of the low frequency of TEL-TB AEM data. The maximum depth reached is about 90 m over resistive rocks, while very shallow depths (less than 5 m) are observed at boundaries with the sea. Devonian to Carboniferous rocks in the southwest are delineated by depth ranges of 10 m (over shaley units) to 40 metres towards south. The depth penetration over Dalradian rocks in the northwest and northeast is deeper in the range of 50 to 70 m. The south eastern margins, which comprise the Slieve Gullion and Carlingford complexes, Newry Igneous Complex, Mourne Mountains granites and the greywackes, are mapped by a depth range of 50 to 90 m.

AEM depth penetration over the Antrim plateau is variable. The maximum depth penetration of the low frequency data reaches 50 m in places (eastern side). While, around Lough Neagh it is 7 to 15 m. Note that depth penetration indicates how deep EM signals penetrated but not the depth to the top or bottom of the units.
5.5.2 Comparison of EM depth pseudo-sections with borehole data

The resistivity-depth cross sections, discussed below are oriented along the flight lines at 345°. The western and the eastern ends of the sections are NW and SE respectively (beginning and end of flight lines). The locations of the lines are presented on Figure 50. The lines run from the NW to the SE.
Figure 51 (a, b) represents resistivity depth sections along two lines at the northern part of the grid crossing the TVF. These sections show very low values at the NW margin, due to conductive seawater. The high resistivity values observed at western and eastern sides of TVF indicate the presence of both Upper and Lower Basalt formations. The eastern high resistivity zone (a) shows relatively low values as compared to the western zone, which may be due to high degree of weathering and fracturing at this locality. It can be seen that this line follows a NNW trending structure. Fractured and porous rocks give low resistivity (Figure 38 and Table 5 since resistivity is related to porosity by Archie’s equation.

\[ \rho = \rho_0 \phi^{-m} S^{-n} \]  

(4)

Where \( \rho_0 \) is resistivity of water filling the pores, \( \phi \) is porosity (volume fraction of pores), \( S \) is fraction of pore space filled by water and \( m \) and \( n \) are certain parameters.
The low resistivity zone in the middle of the profile is caused by the TVF and associated fracture zone. High resistivity gradients on both sides of the TVF show V-shaped features possibly indicating step faulting. The effect of the fault zone extends more than 15 km along the line, which generally agrees well with a low magnetic zone across the fault. Moreover, the borehole data are reasonably correlated with resistivity-depth sections. Low values of resistivity (0-30 ohm-m) are associated with upper superficial deposits, while values in the range of 30-50 ohm-m show the response of sedimentary rocks (sandstone and mudstone). High resistivity values greater than 60 ohm-m are indicative of basaltic rocks.
Figure 52: Resistivity depth sections across SW part of Antrim plateau

Figure 52 represents the SW area of the Antrim plateau. High resistivity values are associated with basaltic rocks of Antrim plateau. The variation of resistivity values on (a) indicate degree of
compactness/hardness of the units. The boundary between superficial and sedimentary rocks is generally well defined on (b). The thickness of superficial deposits obtained by EM data shows a reasonable agreement with borehole data although it can be quite variable. There are two vertical/sub-vertical low resistivity zones within the Lough Neagh basin indicative of faults that are not observed at the surface (Figure 52c). The western and the eastern high resistivity values are caused by the Antrim Lava Group. The relatively high resistivity values within Lough Neagh indicate concealed basaltic rocks. This area of Lough Neagh has been interpreted as an area of basement uplift from the magnetic data (see section 4.4.5 of this report). The undulating conductive surface underlain by relatively resistive sandstone is also observed (Figure 52a, b). The resistivity responses of superficial deposits range between 10 and 25 Ohm-m. The sediment response is between 30-50 Ohm-m, while, the response of basalt is greater than 70 Ohm-m.

As shown by Figure 51 & Figure 52 EM conductivity data can not only help map the lateral extent of geological boundaries but by using different frequency data can help construct cross-sections to highlight vertical variations of geological features. Inverted data shown on the cross-sections are highly smoothed and provides information on general trends, detailed features are often difficult to resolve.
6 Radiometric Data

6.1 Introduction
The radiometric data recorded gamma radiation on 256 spectral channels and the total count potassium (K), thorium (eTh) and uranium (eU) at 1 second intervals along flight lines. Standard radiometric survey calibrations and corrections were applied to all data by the contractor (SGL, 2012; Hodgson and Ture, 2013). Typically most terrestrial gamma radiation stems from the distribution of potassium, thorium and uranium concentrations within the upper 30-40cm of soil and rock. Variations in these three radionuclides help in mapping lithological differences as well as characterising soil types and textures. The content of water in particular in peat deposits results in the attenuation of the radiometric signal and reduced count rates.

Potassium-40 occurs in a fixed proportion to total potassium so gamma-radiation from this radioisotope directly represents the amount of total potassium and is therefore expressed as a percentage. The uranium and thorium radioisotopes arise from the decay chain associated with bismuth and thallium respectively and therefore are recorded as equivalent uranium and thorium concentrations (expressed in parts per million, ppm). Total counts are a summation of all of the gamma-radiation and is expressed in counts per second, with increasing numbers of counts relating to increased levels of radioactivity.

Equivalent values of uranium, thorium and potassium are based on calibration of the detectors over concrete pads dosed with radioisotopes. Radiometric counts measured by the aircraft on survey are converted to ppm based on this calibration. However, disequilibrium in the uranium and thorium decay series within the rocks can result in these concentrations being underestimated by the airborne survey. This effect was described after the Tellus survey by Appleton et al., (2011).
6.2 Regional interpretation

6.2.1 Overview

Radiometric data allows lithological distributions to be resolved and surface processes to be investigated. Interpretation of the data is based on the assessment of all radiometric elements in particular the ratios between them and builds on previous interpretations carried out for the Tellus survey such as Jones and Scheib (2007). Figure 53 shows a ternary map of radiometric data (where potassium (K), thorium (eTh) and uranium (eU) channels are assigned to primary colours red, green and blue; and where high occurrences of all three are shown in white, and low occurrences shown in black). Figure 54 shows the distribution of total counts across the region while Figure 55-Figure 57 shows potassium, thorium and uranium concentrations respectively. A generalised geological map is shown in Figure 3 for reference. Some of the main features highlighted by the radiometric data across the region can be summarised as;

Figure 53: Ternary map of radiometric data, potassium (red), thorium (green), uranium (blue), low values are shown by dark colours and highs by whites, overlying digital terrain model.
• Peat deposits and saturated ground are extensive across the region particularly in uplands area and the west of the region, as well as surrounding drumlin features. These areas are easily mapped as they significantly attenuate the radiometric signal resulting in low or minimal radiometric signals.

• Permian to Triassic sediments particularly on the western edge of the Antrim Basalts and within the Lagan Valley appear to be relatively enriched with potassium. Potassium highs are also seen over K-feldspar rich meta-sediments in the Ox Mountains as well as within felsites / granitites of the Mourne Mountains, Slieve Gullion, Barnesmore and Tullagh Point granites (see Figure 7 for locations).

• Ordovician to Silurian rocks in the south-east of the region are relatively enriched in all three elements.

• Uranium rich rocks are present within Carboniferous rock to the southwest of the region.

• High concentrations of uranium are found along the northern Sligo coastline and may be related to marine-derived sediments.

• Dalradian rocks to the northwest generally exhibit high concentrations of the radioactive elements.

• The Antrim Basalts to the northeast of the region are characterised by very low levels of natural occurring radioactivity.

• Data over urban areas is probably more related to building and construction material used than to the underlying rock. Data over urban areas is also noisy due to the greater survey height.

• Internal zonation within the Barnesmore granite is apparent using ratios of uranium and potassium concentrations.
Figure 54: Total radiometric count measured in counts per second across the region, overlying digital terrain model.

Figure 55: Airborne potassium measured in per cent, overlying digital terrain model.
Figure 56: Airborne equivalent thorium measured in parts per million, overlying digital terrain model.

Figure 57: Airborne equivalent uranium measured in parts per million overlying digital terrain model.
6.2.2 Bedrock Geology

The broad scale relationships between the radiometric data and regional solid geology (1:1 million bedrock map) are clearly apparent (Figure 53-55). The Lower Palaeozoic rocks in the southeast of the region form a zone with higher values for total count and all three radioelements. The highest concentrations are found over the acid intrusives of the Newry, Mourne Mountains, Carlingford, Slieve Gullion and Barnsemore complexes. The lowest concentrations apart from peat deposits and water bodies are found over the Antrim Basalts, with low concentrations in all 3 radioisotopes. Along the western margin of the basalts relatively high levels of potassium are measured corresponding to the Triassic Sherwood Sandstone Group and parts of the overlying Mercia Mudstone Group. Potassium highs are also associated with meta-sedimentary rocks of the Ox Mountains and K-feldspar found within the main acidic intrusions.

Along with acidic intrusions, uranium highs Figure 57 are also measured within black shale units within the Carboniferous rocks of counties Sligo and Leitrim with a prominent uranium anomaly along the northern Sligo coastline, which could be related to marine sediments.

The more heterogeneous geology of the north western part of the region is reflected in the radiometric data with juxtaposed areas of relatively high and low radioelement content. However increased deposits of peat particularly on high ground to the west within this area may explain some of this variation.

6.2.3 Superficial geology

Radiometric data reflect variations in potassium, thorium and uranium in the overlying superficial deposits. These variations in soil chemistry generally relate to the rock below from which the soil derived, however, erosion and transport of sediment predominantly through fluvial and glacial processes can create increased complexities within the data.

River valleys form distinctive features and can be clearly discerned, with compositional difference between alluvial deposits and the surrounding terrain also providing marked contrasts. The deposits related to the NNW-SSE-oriented drainage pattern of the River Bann to the north of
Lough Neagh are readily apparent. This is particularly apparent within the potassium distribution but similar features are also present within the uranium and thorium data. The river Boyne in south Co. Louth/Co. Meath shows radiometric lows as it flows eastward into the Irish Sea. The Yellow River to the northwest of Ballinamore in Co. Leitrim drains from high ground around Lough Allen and shows up clearly within the ternary image Figure 58 with an elevated uranium signal. This would suggest that water draining the Lough Allen uplands is enriched in uranium due to the presence of black shale. Elevated uranium values are also found in the Ballinamore canal just to the south of the town suggesting a common source for both the river and canal.

Figure 58: Radiometric ternary map showing uranium highs (blues) associated with local river network near Ballinamore Co. Leitrim.

Peat deposits provide an attenuating effect on the airborne radiometric data allowing the extent of peat deposits to be mapped from low radiometric signals. Significant peat deposits are visible across the whole region but are particularly prominent on the high grounds in the west of the region. Blanket peat as opposed to cut and fen peat has a greater tendency to suppress the radiometric signal. Peat is also sufficiently low in potassium, uranium and thorium (close to zero) to be readily apparent overlying basalts, which are the least radioactive of the major rock types.
As previously stated the overburden geology generally reflects the rocks that they sit on however, glacial influences are seen at a number of examples, in particular a zone of higher K, U and Th immediately northwest of the Tardree Rhyolite Complex is seen to extend from the complex for approximately 4km Figure 59. This is probably due to material derived from the complex being deposited to the northwest as the ice retreated and is consistent with the later phases of ice movement from the Lough Neagh axis northwards (Bazley, 2004). Drumlín fields produce distinctive patterns in the radiometric images, especially in the southwest of the region in particular Cos. Sligo, Leitrim, Fermanagh and Cavan, highlighting low concentrations in areas of saturated soils.

Figure 59: Left image shows bedrock geology based on 1:500,000 geological map centred on the Tardree rhyolite complex in county Antrim. Right image shows the mapped potassium over the same area. The potassium signature extends towards the northwest suggesting a glacial influence.
6.3 Radiometric properties

6.3.1 Bedrock
Figure 60 - Figure 62 show how radioisotope values vary for different bedrock units using Tukey box plots which mark the median by a line within the box with the upper and lower bounds of the box indicating the third and first quartile. The data was grouped based on the 1:1 Million national bedrock map (Figure 3) which shows the simplified geology across the Tellus Border region. Box plots are only produced where airborne data has been measured. The same colours used within the box plots (Figure 60 - Figure 62) correspond with the colours from the bedrock map.
Figure 60: Potassium values by bedrock (based on 1:1 Million National bedrock map)

Tukey Boxplot by Geology:

K (%)

Devonian volcanics
n = 165
Ontonian Longford - Down
n = 16700
Mid-Up Ontonian
n = 6821
Namurian shales
n = 27168
Dalradian meta-sed.
n = 14747
Neoproterozoic schists/gneisses
n = 19666
Ordovician granites
n = 421
Ordovician volcanics
n = 1254
ORZ
n = 5202
Paleogene basic intrusions
n = 2015
Paleogene granites
n = 2357
Permian Sandstone
n = 561
Paleozoic Sedi-melange
n = 115
Silurian greynacles
n = 263
Sil-Dev Gravels
n = 9620
Tournaisian Limestones
n = 16271
Tournaisian Sandstones
n = 24062
Triassic sandstones
n = 1110
Viscian Limestone shale
n = 24955
Viscian Sandstone/mudstone
n = 51574
Westphalian shale/mudstone
n = 342
Figure 61: Thorium values by bedrock (based on 1:1 Million national bedrock map)

Tukey Boxplot by Geology:

- Devonian volcanics (n = 165)
- Ordovician Longford-Down (n = 67560)
- Mid-Low Ordovician (n = 8214)
- Namurian shale (n = 27185)
- Dalradian meta-seds (n = 147175)
- Neoproterozoic schists/gneisses (n = 19665)
- Ordovician granites (n = 421)
- Ordovician volcanics (n = 1294)
- ORS (n = 5302)
- Palaeogene basic infusions (n = 2015)
- Palaeogene granites (n = 2857)
- Permian Sandstone (n = 581)
- Palaeozoic Sed-molten (n = 115)
- Silurian greywacke (n = 263)
- Silur-Dev Granites (n = 9820)
- Tournaisian Limestones (n = 16271)
- Tournaisian Sandstones (n = 24062)
- Triassic sandstones (n = 1110)
- Visean Limestone/shale (n = 24695)
- Visean Sandstone/mudstone (n = 51574)
- Westphalian shale/sandstone (n = 342)
Figure 62: Uranium values by bedrock (based on 1:1 Million national bedrock map)

Tukey Boxplot by Geology:

- Devonian volcanics: n = 165
- Ordovician Lungford: Down: n = 167308
- Mid-Up Ordovician: n = 65214
- Namurian shale: n = 27185
- Dalradian mélange: n = 147475
- Neoproterozoic schists/gneiss: n = 19965
- Ordovician granites: n = 421
- Ordovician volcanics: n = 1294
- OPS: n = 5302
- Palaeogene basic intrusions: n = 2015
- Palaeogene granites: n = 2357
- Permian Sandstone: n = 561
- Palaeozoic Sédiments: n = 115
- Silurian greywacke: n = 283
- Silur-Dev Granites: n = 9820
- Tourmaisian Limestones: n = 18271
- Tourmaisian Sandstones: n = 24602
- Triassic sandstones: n = 1110
- Visean Limestone/shale: n = 249951
- Visean Sandstone/mudstone: n = 51574
- Westphalian shale/sandstone: n = 342
As expected granite bodies record high values of thorium and uranium and particularly potassium. The more recent Paleogene granites show significantly higher values than those for Silurian and Devonian granites which probably relates to differences in the source of the granites. Namurian shales record low values of potassium and thorium but high uranium concentrations. Ordovician Longford-Down sediments primarily greywackes and sandstones show generally high concentrations in all radioisotopes consistent with high total count readings in the southeast of the region. However, Silurian greywacke rocks show generally low concentrations in comparison to greywackes within the Longford-Down group. The radiometric data shows good correlation with comparable geochemical topsoil data across different bedrock units in particular for uranium and thorium concentrations. Greater variability between potassium concentrations particularly from granite derived sources is found and may reflect differences in the determination of concentrations from the two datasets.

6.3.2 Subsoils

There are noticeable variations of radiometric values by differing subsoil unit (based on EPA/Teagasc Subsoil Map of Ireland, 2006) and displayed in Figures 63-65. As would be expected granite derived till and gravels record the highest values for all three elements consistent with bedrock distributions. Lower Palaeozoic tills and gravels also record high values for all radiometric elements. The lowest measured values correspond with peat deposits for potassium and peat and pure sand deposits for thorium and uranium concentrations.

Generally potassium and thorium show very similar trends for the different subsoil units. However, uranium shows strong concentrations associated with Carboniferous limestone and shale derived till and gravel which are not reflected in potassium and thorium values. Table 7 summaries the variations of potassium, thorium and uranium shown in Figure 63-65.
Figure 63: Potassium distribution by subsoil unit (Teagasc 2006), subsoil codes explained in Table 7.
Figure 64: Equivalent Thorium distribution by subsoil unit (Teagasc 2006), subsoil codes explained in Table 7
Figure 65: Equivalent uranium distribution by subsoil unit (Teagasc 2006), subsoil codes explained in Table 7.
<table>
<thead>
<tr>
<th>Subsoil code</th>
<th>Subsoil name</th>
<th>K median (%)</th>
<th>Th median (ppm)</th>
<th>U median (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Alluvium</td>
<td>0.80</td>
<td>4.26</td>
<td>1.09</td>
</tr>
<tr>
<td>Ac</td>
<td>Acidic Alluvium</td>
<td>0.91</td>
<td>4.72</td>
<td>1.03</td>
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<td>AcEsk</td>
<td>Acidic esker sands and gravels</td>
<td>0.81</td>
<td>3.47</td>
<td>0.76</td>
</tr>
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<td>Ag</td>
<td>Sandy Alluvium</td>
<td>0.20</td>
<td>2.83</td>
<td>0.72</td>
</tr>
<tr>
<td>Asi</td>
<td>Clayey Alluvium</td>
<td>0.995</td>
<td>5.175</td>
<td>1.19</td>
</tr>
<tr>
<td>BasEsk</td>
<td>Basic esker sands and gravels</td>
<td>0.80</td>
<td>2.555</td>
<td>0.93</td>
</tr>
<tr>
<td>BktPt</td>
<td>Blanket peat</td>
<td>0.14</td>
<td>0.84</td>
<td>0.1</td>
</tr>
<tr>
<td>Cut</td>
<td>Cutover peat</td>
<td>0.31</td>
<td>1.74</td>
<td>0.48</td>
</tr>
<tr>
<td>FenPt</td>
<td>Fen peat</td>
<td>0.22</td>
<td>1.99</td>
<td>0.59</td>
</tr>
<tr>
<td>GDCSs</td>
<td>Sandstone sands and gravels (Devonian/Carboniferous)</td>
<td>0.81</td>
<td>3.1</td>
<td>0.8</td>
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<tr>
<td>GDSs</td>
<td>Sandstone sands and gravels (Devonian)</td>
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<td>2.75</td>
<td>0.94</td>
</tr>
<tr>
<td>GGr</td>
<td>Granite sands and gravels</td>
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<td>8.58</td>
<td>1.585</td>
</tr>
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<td>GLPSsS</td>
<td>Sandstone and shale sands and gravels (Lower Palaeozoic)</td>
<td>1.245</td>
<td>6.01</td>
<td>1.075</td>
</tr>
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<td>GLs</td>
<td>Limestone sands and gravels (Carboniferous)</td>
<td>0.95</td>
<td>2.97</td>
<td>1.06</td>
</tr>
<tr>
<td>GMP</td>
<td>Metamorphic sands and gravels</td>
<td>1.00</td>
<td>4.25</td>
<td>0.78</td>
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<td>GNSSs</td>
<td>Shales and sandstones sands and gravels (Namurian)</td>
<td>0.28</td>
<td>2.37</td>
<td>0.93</td>
</tr>
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<td>IrSTLPSsS</td>
<td>Sandstone and shale till (Lower Palaeozoic) with matrix of Irish Sea Basin origin</td>
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<td>6.79</td>
<td>1.27</td>
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<tr>
<td>L</td>
<td>Lake sediments undifferentiated</td>
<td>0.59</td>
<td>3.0</td>
<td>0.93</td>
</tr>
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<td>3.565</td>
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<td>1.68</td>
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<td>Blown sand in dunes</td>
<td>0.73</td>
<td>1.15</td>
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6.4 Qualitative interpretation by dominant geological group

6.4.1 Proterozoic Rocks

Dalradian meta-sedimentary rocks dominate the northwestern portion of the region and typically correspond with high concentrations in all elements. However, the patterns of highs and lows do not always fit closely with the mapped solid boundaries. This is predominantly a result of the influence of the overlying superficial deposits (mainly peat). Certain features do reflect the regional solid geology, with higher K, eU and eTh concentrations found on the upper Dalradian psammites and semipelites (Cooper and Johnston, 2004a) of the Southern Highland Group (Londonderry, Ballykelly and Claudy formations (Mitchell, 2004b). The Dalradian, Dart, Glenelly and Mullaghcarn formations, of the Sperrin Mountains (Cooper and Johnston, 2004a), tend to have generally low values for K, eU and eTh. While the Slishwood Division in southern Donegal and Co. Sligo generally shows a relatively high potassium signal although strong zonation is apparent within the Ox Mountain units.

6.4.2 Lower Paleozoic (Ordovician – Silurian)

The total count map and ternary map indicate generally high concentrations across the southeastern zone corresponding to greywacke and sandstone units forming part of the Longford-Down-Southern Uplands terrane. The ratio of potassium concentrations to thorium are seen increasing towards the northeast and decreasing towards the south below Dundalk in county Louth. This decrease in potassium may be explained by a reduction in sandstone units and more dominant greywacke rocks. It is noticeable from the box-plot diagrams that Silurian greywackes have average lower concentrations in all elements than those for Ordovician sandstone, greywacke and shale units.

5.4.4 Carboniferous

Carboniferous rocks are relatively enriched in uranium, particularly in areas of county Sligo and Leitrim although levels of thorium are seen to increase moving towards the east (Figure 66). These uranium enriched carbonate rocks probably indicate the presence of organic matter through black shales as well as the presence of phosphates. Increasing quantities of evaporate units may also
increase the thorium signal to the east, in the southeast region of county Fermanagh and south county Tyrone.

Figure 66: Ratio of uranium to thorium for Carboniferous rocks. Red-pink colours indicate high uranium concentration with respect to thorium and green colours high thorium concentrations with respect to uranium. Blue colours generally correspond with low values due to peat deposits or surface water.

To the south of Lower Lough Erne, acute patterns are seen in the radiometric data, particularly for eU and eTh concentrations. These mirror the outcrop patterns as they parallel the western side of the Lough. The strongest response is from the lower Carboniferous Ballyshannon Limestone and Bundoran Shale formations which are closest to the Lough shore (Mitchell, 2004b), and the Benbulben Shale Formation to the south west. These two shale formations have similar characteristics to the east of Upper Lough Erne.

5.4.5 Tertiary Basalts
Radiometric data is low over the Antrim basalts, however, re-plotting the data for the basalts only (Figure 66) enhances the contrast appreciably and can help provide additional detail. The vast
The majority of features relate to the superficial deposits rather than the bedrock geology; extreme lows correspond with known peat deposits, while variations relating to the NNW-SSE-oriented drainage pattern of the River Bann to the north of Lough Neagh are readily apparent. Little contrast within the radiometric data is seen between the upper and lower basalt formations.

6.4.3 Intrusions

Radiometric data of the Newry Granites show increased potassium levels in the central areas with thorium elevated towards the eastern edge. Elevated levels of all elements but in particular uranium are seen along the River Bann draining from the Mourne Mountains, which cuts through the granite (Figure 68). Some internal zoning is apparent from the data with potassium rich feldspars dominate in the centre and west of the granite, while more thorium rich elements are found to the northeast. This increase in thorium concentrations to the northeast does not appear to be related to superficial deposits, unlike the higher values associated with the River Bann draining north from the Mourne Mountains. Rather it may indicate a marginal zone within the granite. This appears to contradict the mapped zonation at the NE end of the granodiorite, which is described as being more basic at the margins of the intrusion (Cooper and Johnston, 2004c).
However, it does match well with an area of bedrock, free of superficial deposits, but this does not explain why the drift-covered western portion is distinguishable from the country rocks, which are themselves blanketed by the same superficial deposits. The Mourne Mountains Complex stands out on the ternary and uranium images (Figure 53, Figure 69) from the other intrusives, with a mix of white areas, where all three radioelements are high.

Slieve Gullion Complex appears to have a different composition than the Newry Granite. K:Th and U:K ratios show significant differences between the two, with the Newry Granite revealing higher potassium concentration, although some potassium zoning is also apparent over the Slieve Gullion Complex. The felsitic ring dykes and the granophyritic inner part of the Paleogene complex appear to have similar compositions in terms of potassium, uranium and thorium. The more basic rocks within the intrusions generally correspond to low concentrations in all three radioelements and therefore are mapped by black or brown colours in the ternary maps. The central granophyre core to the Slieve Gullion Complex is mapped with low radiometric concentrations, however, this appears, from the soil map, to be the result of peat covering the bedrock.
Figure 68: Geology at 1:500,000 for the Newry and Mourne Mountain complexes in South east Northern Ireland.
The Barnesmore Granite in southern Donegal (Figure 7) also exhibits a strong signal in all three radioisotopes and is clearly highlighted in white on the Ternary map (Figure 53). Internal zonation is also apparent within the Barnesmore granite with lower concentrations in the main adamellite unit (rocks with equal proportion of plagioclase and alkali feldspar) and higher concentrations within the central leucogranite units (light coloured granite rocks with no dark minerals). Uranium values are more dominant towards the east while thorium becomes more apparent to the west. A high U:K ratio (Figure 70) corresponds with the leucogranite in comparison with the adamellite, probably due to reduced potassium values associated with decreased abundance of biotite minerals within the leucogranite. The Barnesmore Granite provides a good example to investigate the radiometric signal in respect of magma differentiation as the area has little peat or till cover masking the signal, with rock at or close to the surface and therefore the radiometric data can be used to further refine the local geological map without interference from overburden deposits.
Figure 70: The internal zoning within the Barnesmore Granite, a) mapped 100,000 bedrock geology, b) uranium/potassium ratios.

Dolerite dykes, which extend across the region typically in a NW-SE orientation and are clearly resolved by magnetic data, are not seen within the radiometric data. This may be due to the fact that most of these dykes are typically 1-10 m wide while radiometric data points are on average 60 m apart. There would also be a smaller radiometric contrast between the dykes and the country rock than for the magnetic data.
7 Conclusions

The Tellus Border airborne geophysical data has been merged with existing datasets from the Tellus survey of Northern Ireland and the Cavan survey to produce seamless cross-border data sets of magnetic, electromagnetic and radiometric data of the 12 northern counties of the island of Ireland. The merged data has been used to help confirm existing geological features, help redefine known boundaries and structures and reveal buried or previously unknown geological structures. The magnetic, conductive and radioactive properties of rock and soil in the survey region have been investigated and summarised.

Magnetic data is particularly useful in helping to identify geological structure. Numerous dyke swarms have been mapped and their offsets across faults, has been used to map unknown faulted. Information on faults plus resolution of the magnetic crystalline basement assists the understanding of the tectonic history of the region and associated stresses. This structural information is also important in the interpretation of existing and potential mineral locations.

The highly conductive black Moffat shales in the southeast of the region produce a series of narrow linear features. However, some mapped shale units display less distinct conductivity contrasts to similar units and often terminate at fault boundaries. This information is being used to help further understand these differences between units.

The Antrim Basalts display unusually high conductivity in places which may indicate an open pore structure or clay-filled amygdales in the lava flows, or possible thicker clay overburden. Dalradian rocks such as psammites, pelites, gneisses and schists are generally resistive as are most igneous intrusions such as Slieve Gullion and the Mourne Complex.

The electromagnetic data has also been inverted to produce pseudo cross-sections allow structures to be resolved in 2D and 3D.

Peat deposits are easily resolved by the radiometric data, and internal variations of till deposits reflect changes in their derived material. Potassium highs are present over K-feldspar rich meta-sediments in the Ox Mountains, Triassic sediments as well as within felsites and granites across
the region. In fact all granitic bodies across the region produce radiometric highs within all elements as do to a lesser extent, Ordovician-Silurian rocks in the south-east and Dalradian, rocks to the northwest. The Antrim Basalts on the other hand exhibit low levels of natural occurring radioactivity. Organic-rich shale deposits within Carboniferous rocks show elevated uranium levels. Internal zonation representing different magmas within the Barnesmore Granite can be resolved by mapping the ratio between uranium and potassium concentrations

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Tutorial and user guide. Montaj Grav / Mag Interpretation, processing, Analysis and Visualization system for 3D Inversion of potential Field data for Oasis montaj v7.1.


