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Groundwater and Land Resources in Tellus Border Coastal Zones

Final Report

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Disclaimer

Tellus Border

Tellus Border is a €5 million cross-border project to map the environment and natural resources in the border region of Ireland and continue the analysis of data in the border counties of Northern Ireland. It is a joint initiative between the Geological Survey of Northern Ireland, the Geological Survey of Ireland, Queen's University, Belfast and Dundalk Institute of Technology.

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1. Report Summary

- The National University of Ireland, Galway was awarded funding as part of the EU INTERREG IVA-funded Tellus Border project to carry out an investigation in to Groundwater and Land Resources in the Tellus Border coastal zones of Dundalk Bay and Carlingford Lough.

- Airborne magnetic, electromagnetic and radiometric geophysical datasets were processed and analysed in conjunction with GIS data gathered from organisations including the Geological Survey of Ireland, the Geological Survey of Northern Ireland, the Environmental Protection Agency, National Parks and Wildlife Service and the Department of the Environment of Northern Ireland among others.

- Detailed analysis of the airborne geophysical data has facilitated the detection and mapping of the following geological and groundwater features:
  - numerous basalt dykes,
  - unmapped faults,
  - soil types,
  - previously unmapped NE-SW Caledonian trending structures within the Silurian bedrock,
  - possible outflow of fresh groundwater to the sea,
  - saline influence into gravel aquifers along the coast.

- The airborne geophysical data provides a new layer of scientific data to assist in examining groundwater movement in the coastal zone.

- The research outcomes from this project present baseline datasets which can assist the development of strategies for coastal zone groundwater monitoring and management.

- Many of the observations made within this research project warrant further detailed investigation including; examining coastal zones across different superficial and bedrock geology types, structural geology settings and aquifer types; assessing the conductivity signature of bedrock lithologies from the electromagnetic data; and examining saline influence in to groundwater bodies.

- This work can also be applied to other areas such as along the Co. Sligo, Co. Donegal and Northern Ireland coastlines.

2. Project Overview

2.1 Project Introduction

The Tellus airborne survey of Northern Ireland was acquired in 2005/2006 and recorded magnetic (AM), radiometric and electromagnetic (AEM) geophysical data (Beamish and Young, 2009). The Tellus Border airborne survey recently acquired similar datasets. Such airborne geophysical surveys can be used for a range of investigations, e.g. delineating bedrock geological trends, mineral exploration and regional scale karst hydrogeology (Gondwe et al., 2012). The main aim of this project is to process the airborne magnetic and electromagnetic data to enhance the detection of the edges of anomalously magnetised or resistive bodies and lineaments associated with bedrock geological trends, fracture zones and basalt dykes (e.g., Blakely (1995)and Beamish (2012b). These features have the potential to identify structurally controlled groundwater pathways in the coastal zone and offshore and may lead to the detection of submarine groundwater discharge (SGD) zones. The delineation and monitoring of SGD is important for the management of fresh water resources in coastal aquifers, and protection against land-based sources of organic and inorganic contaminant plumes which can be transported via preferential groundwater pathways to the sea. Cave and Henry (2011) note that little monitoring of groundwater discharge to the sea is currently carried out in Ireland.

This project focuses on two coastal zone areas (Dundalk Bay and Carlingford Lough) on the east coast of Ireland. Motivation for this project arises from the observation of elevated levels of metals in groundwater in the catchments within this area which have been noted in the environmental impact statement compiled for the completion of the M1 motorway north of Dundalk (RPS, 2002). Geogenic arsenic (As) levels in a number of the sampled wells exceed the limits set in SI 9 (DOEHLG, 2010) and SI 278 (DOEHLG, 2007). An NUI Galway Biogeoscience PhD student is already working on understanding the processes driving these elevated levels and this project makes an ideal study to investigate the potential links between the distribution of metals, structural geology and groundwater pathways using airborne, terrestrial and marine geophysical methods.

The aquifer classification for the low lying, coastal portions of the study area, as defined in the Groundwater Protection Schemes document (DELG et al., 1999), is Lm (Locally Important Aquifer: bedrock which is generally moderately productive) while the remainder of the area (the upland area) is entirely classified as Pl (Poor Aquifer: bedrock which is generally unproductive except for local zones). Pathways for groundwater flow from the upland portion of the study area will likely be limited to areas of high hydraulic conductivity (fault or fracture zones, or weathered zones) and these zones may act to concentrate submarine groundwater discharges to Dundalk Bay and Carlingford Lough. Although terrestrial geophysical methods can be used to monitor groundwater flow regimes, for example, Comte et al. (2012) used electrical resistivity for the catchment scale characterisation of groundwater flow in the metamorphic rocks of Northern Ireland, this project aims to utilise the available airborne geophysical data and couple it with a field campaign to validate significant observed anomalies in the airborne datasets using terrestrial and marine electrical resistivity. Using terrestrial & marine geophysics to complement the airborne data should assist in interpreting and confirming features defined by the airborne data.

In addition to the airborne data, both bays were surveyed as part of the INIS Hydro project, an Ireland, Northern Ireland and Scotland project, funded by a 3 year INTERREG IVA Programme with the

Maritime and Coastguard Agency in the UK as lead partners. Since 2011, the project has generated high-resolution bathymetry using multibeam sonar technology and, importantly for this project, it has acquired sub-bottom seismic reflection profiling data along survey lines. It was proposed that if available, sub-bottom data would be used in this project to understand the sub-surface morphology of any lineaments, identified in the airborne data, that extend offshore. A by-product of this examination would be a preliminary geological assessment of the sub-bottom seismic data for aggregate potential.

2.2 Application of Airborne Geophysics to Groundwater Investigations

The majority of regional airborne surveys have been conducted to stimulate mining exploration activities, such as in Greenland (www.geus.dk), Tanzania (www.gst.go.tz) and Australia (www.geoscience.gov.au). They can also be instrumental in mapping the superficial, bedrock and structural geology of an area, e.g. (Beamish et al., 2010) and (Beamish and White, 2012). In hydrogeological investigations, the conductivities determined from AEM surveys reflect variations in bedrock lithology and in water chemistry. As such, apart from geological mapping, the data can be used in determining aquifer structure, investigating groundwater salinisation and the intrusion of saltwater into coastal aquifers. In Gondwe et al. (2012), frequency domain AEM data has been used to map a karst aquifer structure on the Yucatan Peninsula, Mexico. In addition, AEM has been used to investigate the coastal process of saltwater intrusion in the Isle of Man (Beamish, 2012a). Groundwater contamination can be mapped using AEM, e.g. the current postdoctoral research monitoring groundwater contaminant plumes using Tellus airborne geophysical data at Queen's university Belfast.

Beamish and Farr (2013) have used AEM and airborne radiometrics to identify wetland areas across Anglesey, Wales. Queen's University Belfast and Dundalk Institute of Technology are conducting research using the Tellus Border data investigating wetland ecology and geochemistry with a specific emphasis on the Rockmarshall Wetlands on the Cooley Penninsula.

In the coastal zone, intertidal and submarine groundwater discharge is typically investigated by methods such as utilising seepage meters, piezometers or natural tracers e.g. radium isotopes, or by using hydrograph separation techniques or water balance approaches (Burnett et al., 2006). Terrestrial and marine geophysical techniques have been applied to investigate groundwater interactions in the coastal zone, predominantly using electromagnetic and electrical resistivity techniques e.g. Duque et al. (2008) and Day-Lewis et al. (2006). O'Connell et al. (2011) have used terrestrial and marine electrical methods to delineate groundwater flow paths in the coastal region of southern Galway Bay. O'Connell et al. (2012) have also demonstrated that terrestrial electrical resistivity surveys can be used to map fault controlled groundwater movement in karst.

This project aims to use the airborne magnetic and electromagnetic data and to reference the radiometric data to identify groundwater flowpaths in the coastal zone and offshore into Dundalk Bay and Carlingford Lough and in a multi-disciplinary approach, carry out terrestrial and marine geophysical techniques to confirm the findings of the investigation.

2.3 Project Objectives

The objectives of this project included:

A. **Geological/Structural Mapping:** The main aim of this project was to process AM and AEM data to enhance the detection of the edges of anomalously magnetised or resistive bodies and lineaments associated with bedrock geological trends, fracture zones and basalt dykes, with the possibility of delineating possible targets for future mineral exploration through this process.
B. **Groundwater pathways:** Bedrock geological trends, fracture zones and basalt dykes have the potential to identify structurally controlled groundwater pathways in the coastal zone and offshore into Dundalk Bay and Carlingford Lough. Elevated levels of geogenic metals in groundwater in the catchments within this area have been noted. This was an ideal study to highlight the links between the distribution of metals, structural geology and groundwater pathways using airborne, terrestrial and marine geophysical methods.
C. **Extension of lineaments off-shore:** The sub-bottom data (if available) was to be used primarily to understand the sub-surface morphology of any lineaments, identified in the airborne data, that extend offshore. A by-product of this examination would be a preliminary geological assessment of sub-bottom seismic data for aggregate potential.
D. **Examination of structural features potentially controlling groundwater movement:** a 5-day field campaign would validate significant observed anomalies in the airborne datasets using terrestrial and marine electrical resistivity tomography (ERT). These data would help to establish sub-surface morphology of potential pathways identified by the airborne and shipborne geophysics. If appropriate, these data would be constrained with the sub-bottom seismic reflection datasets.
E. **Delineation of potential submarine groundwater discharge (SGD) locations** initially from AEM data and subsequently from ERT data.
F. **Examination of Saline intrusion in to Rock and Gravel Aquifers** initially from AEM data with confirmation from available groundwater well data and ERT.

2.4 Project Breakdown

In light of the above objectives the project was broken down in to the following tasks:

1. Import Tellus/Tellus Border geophysical data into Oasis montaj (Geosoft, 2013).
2. Process aeromagnetic data for edge detection, lineaments etc in Dundalk/Carlingford area.
3. Process electromagnetic data for lineaments, edge detection etc in Dundalk/Carlingford bays.
4. Assess INFOMAR sub-bottom seismic data in Dundalk/Carlingford bays for fault detection.
5. Preliminary geophysical and geological assessment and identification of field targets.
6. Electrical resistivity data acquisition/modelling to understand sub-surface target structures.
7. Integrated interpretation of all data sets.

With respect to Item 4 the INFOMAR sub-bottom seismic data was not available for examination during this project. Following discussions with Dave Hardy of the GSI it was determined that it was unlikely that the INFOMAR sub-bottom seismic data would play a significant role in the assessment of the airborne geophysical dataset at this stage. Bathymetry data was requested through the INIS Hydro project, however it could not be made available for this project.

3. Overview of Survey Area

The survey area was selected as follows (Figure 3.1):

1. A <u>regional area</u> encompassing Co. Louth and parts of Counties Cavan, Monaghan, Armagh and Down in order to review the broader geological and structural trends. *Irish National Grid limits of: west 247500, east 356500, south 269000 and north 347500.*
2. A <u>coastal area</u> focussing on a coastal corridor across counties Louth and Down. *Irish National Grid limits of: west 295000, east 328000, south 273000 and north 328000.*

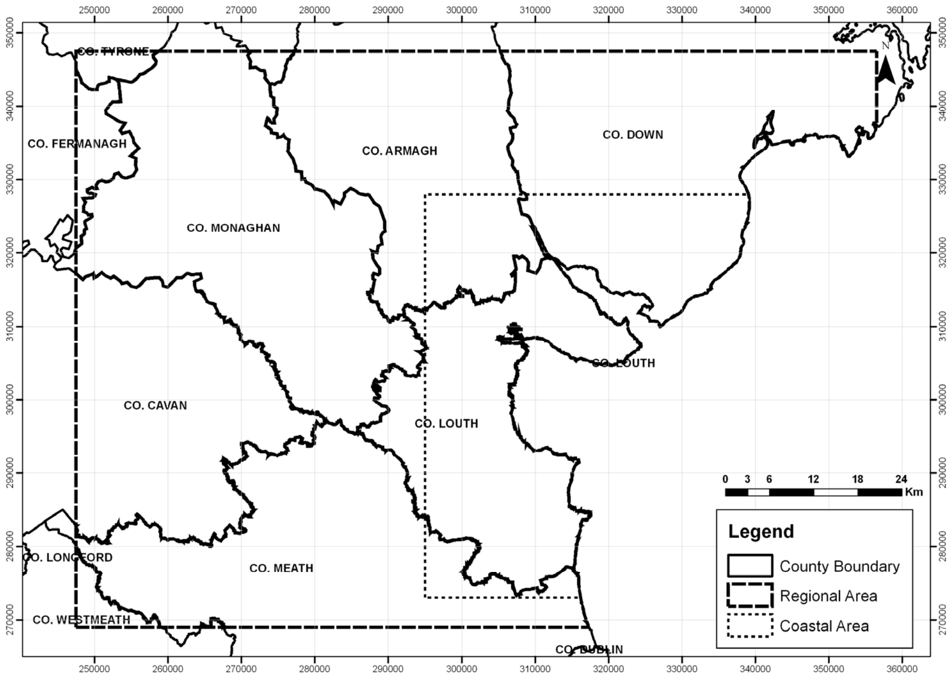


Figure 3.1: Regional area (black outline) & coastal area (shaded).

3.1 Topographic Setting

Topography is generally low-lying across central and southern Co. Louth, with highest elevations associated with the igneous complexes of the Cooley Peninsula and Mourne Mountains (Figure 3.2).

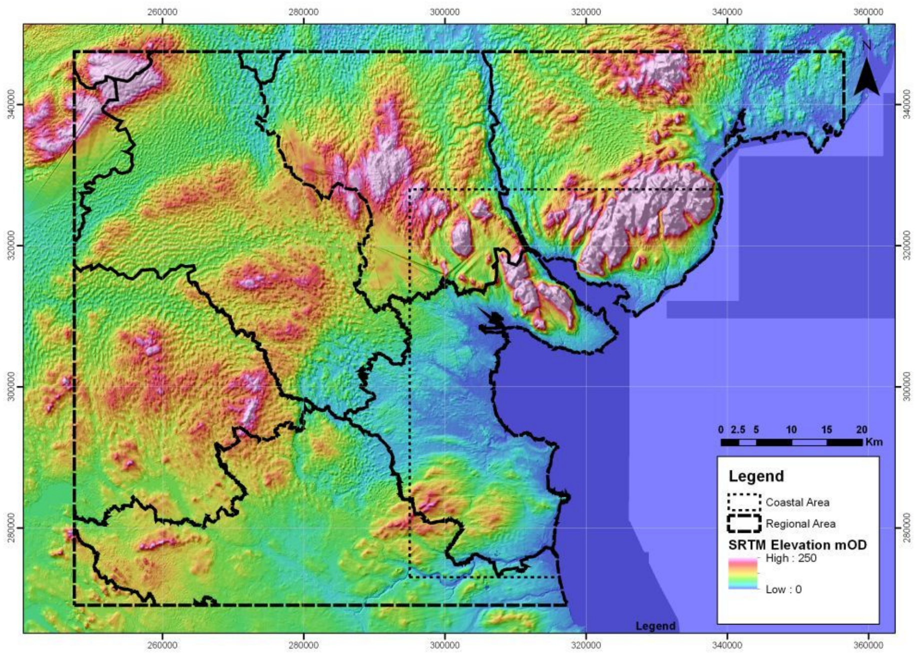


Figure 3.2: Topographic map of SRTM (Shuttle Radar Tomography Mission) data overlying DTM data.

3.2 Geological Setting

The overall survey area lies within a geological complex known as the Longford-Down terrane (Figure 3.3). This complex comprises Lower Palaeozoic Ordovician and Silurian greywacke, mudstone, sandstone and shale lithologies that have a Caledonian trend (Figure 3.4), and are considered to be a continuation of the Southern Uplands in Scotland (Holland, 2009). Younger Carboniferous to Triassic limestones, sandstones and mudstones lie to the northwest and southeast. Faulting is SW-NE trending in the Silurian and Ordovician metasediments, N-S trending in the granites and has varying directions in the Dinantian Limestones. The Tinure Fault, northeast of Slane is interpreted as the surface expression of the Iapetus Suture Zone.

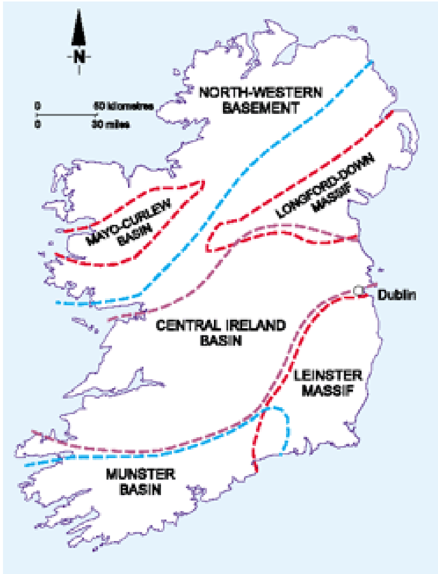


Figure 3.3: Map of main mineral provinces with Longford-Down Terrane in northeast (from www.dcenr.gov.ie).

Igneous intrusions occurred in this area in the Late Palaeozoic. The Newry Granodiorite Igneous Complex comprising the Southwest, Central and Northeast Granodiorite Complexes were intruded in the Lower Devonian c. 400Ma (Meighan and Neeson, 1979). Much later, in the Palaeogene the central complexes of the Mourne Mountains, Slieve Gullion and Carlingford were intruded. The Carlingford Complex has been dated to c. 61 Ma (Mitchell et al., 1999), the Mourne Mountains Complex was intruded c. 56 Ma and the Slieve Gullion Complex was intruded c. 58-56 Ma. (GSNI, 2004).

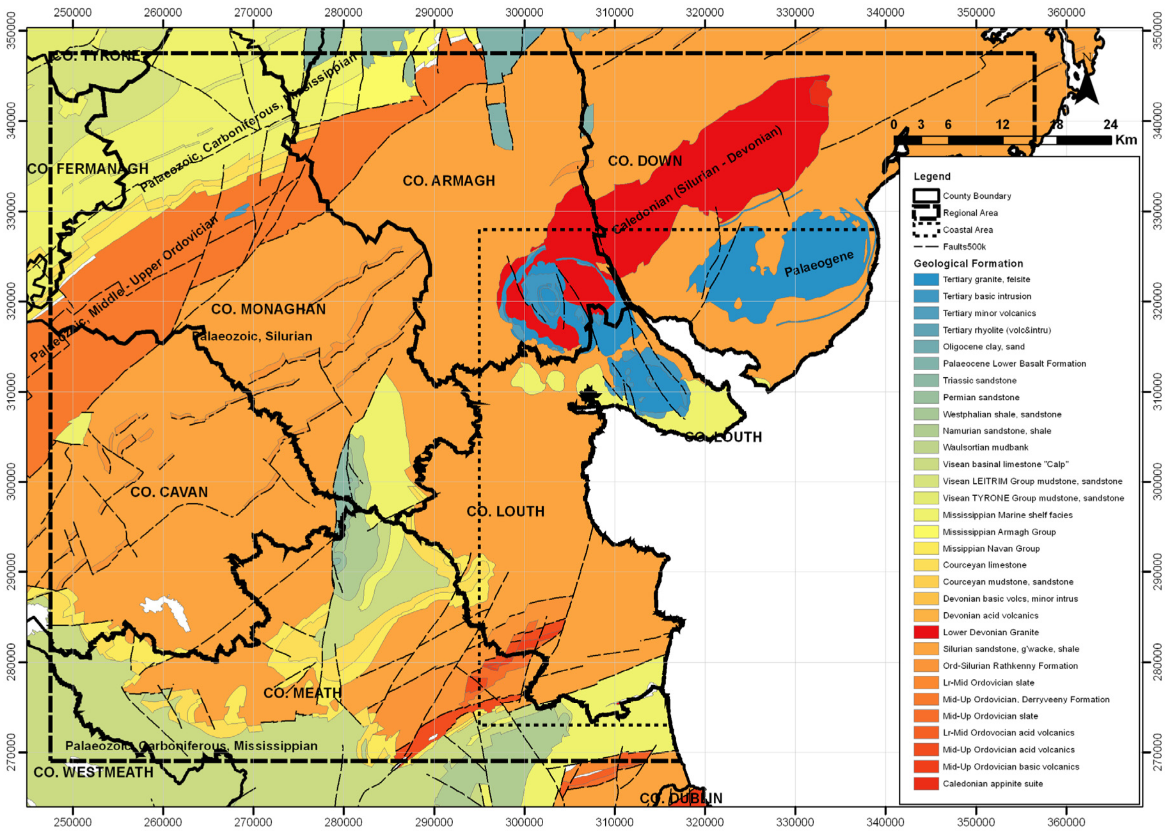


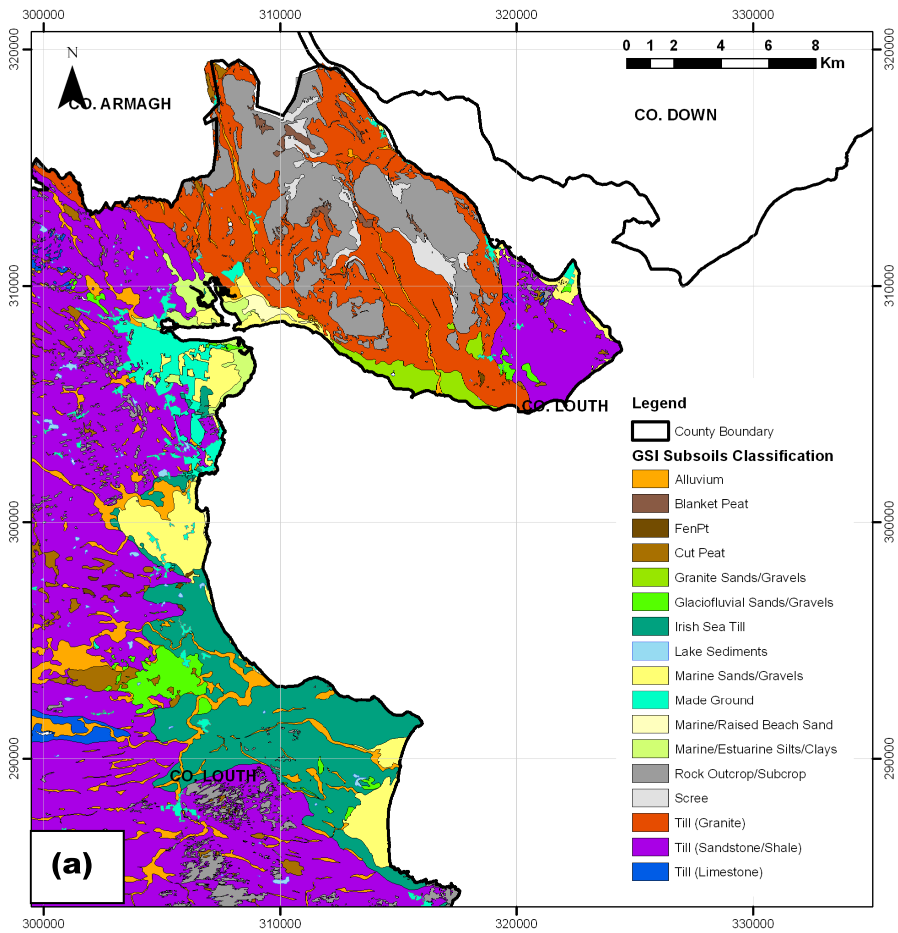
Figure 3.4: Regional geology.

Throughout the early Palaeogene, crustal dilation led to formation fractures. Basaltic magma intruded these crustal fractures, forming linear dyke swarms, which both pre-date and post-date the Palaeogene igneous complexes. Dykes are typically 1 – 5m wide (GSNI, 2004) but mega dykes (10-100m wide) can occur. In general, the dykes transect the structural geology of the area and are only rarely offset by later faulting. The main dyke trend across the north of Ireland is NW-SE while in the Mourne Mountain and Slieve Gullion area, the trend is NNW.

Within the coastal area, the bedrock geology is dominated by six main lithologies. These include Silurian and Ordovician metasediments comprising Clontail Formation calcareous greywacke, Salterstown and Little Harbour Formations calcareous greywacke & banded mudstone, with Lower Carboniferous Dinantian undifferentiated limestone (comprising mixed sandstones, shales and limestones) on the Cooley Peninsula and the Hawick Group on the south coast of Co. Down. The bedrock also includes the granite and igneous rocks of the Slieve Gullion Complex, the Newry Granodiorite Complex, the Mourne Mountains Granite and the Carlingford Complex.

3.3 Superficial Geology Setting

Across Co. Louth, the soils and subsoils are dominated by tills (Figure 3.5a), which have been categorized as predominantly sandstone/shale tills with the exception of granite tills across the Cooley Penninsula (Teagasc, 2006). Areas of subcropping/outcropping rock have been mapped across much of the county. They are generally associated with elevated topography. Large tracts of subcropping/outcropping rock and scree occur across the Carlingford Complex on the Cooley Peninsula. Alluvium deposits are found along river valleys, with many pockets of peat scattered across the county, the largest of which are located in low lying areas of central Co. Louth. The areas of peat can be easily distinguished on the Radiometric data.



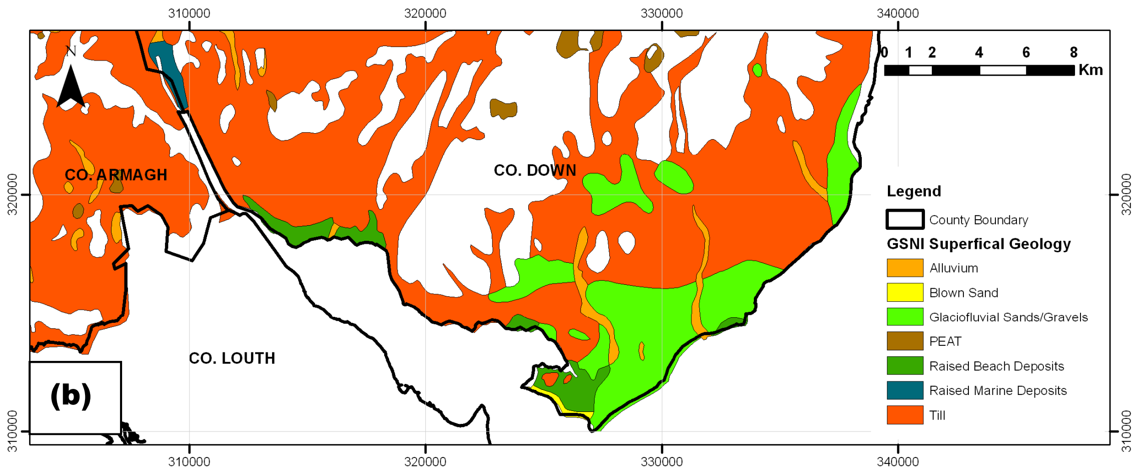


Figure 3.5: Subsoils.map for Co. Louth (a) and superficial geology map for Northern Ireland (b).

The subsoils along the coast of Co. Louth are dominated by marine sands and gravels and Irish Sea till, with marine/estuarine silts/clays around inner Dundalk Bay and deposits of granitic gravels on the south coast of the Cooley Penninsula. Across Co. Down, the superficial geology is dominated by tills and subcropping/outcropping rock, with pockets of peat in places (Figure 3.5b). Along the coast, raised beach deposits of gravel sand and silt, and glaciofluvial sands and gravels dominate.

3.4 Groundwater Setting

The study area lies within the Neagh-Bann River Basin District. There are three main bedrock Groundwater Bodies (GWB) across the study area (Figure 3.6);

- **Louth GWB** dominated by the Silurian Clontail, Salterstown and Little Harbour Formations and the Carlingford Complex granite on the Cooley Peninsula;
- **Dundalk GWB** for which the sole rock group is Dinantian undifferentiated limestone;
- **Newry GWB** which incorporates Gala and Hawick Group Ordovician and Silurian greywackes, part of the Newry Igneous Complex and part of the Mourne Mountains Granite.

The **Louth GWB** encompasses Dundalk Bay and parts of the Carlingford Lough Shore. The GWB description (GSI, 2004b) indicates that transmissivity in the GWB is generally low and most flow is expected to be in the upper parts of the aquifer which comprise an upper <3m of weathered and broken rock over generally <10m of interconnected fissuring, underlain by a <150m zone of isolated poorly connected fissuring. Deep water strikes appear to occur in highly faulted areas. The GWB classification document indicates that no local transmissivity data are available for the Silurian rocks and Granites, however national data generally reflect low (<20 m^2/d) to moderate (20-80 m^2/d) transmissivity values for these rock types. Storativity is also expected to be low and groundwater gradients are expected to be relatively steep due to the low permeability nature of the rocks. Recharge is diffuse via percolation through subsoil and outcropping rock, however as the rocks are low permeability and soil cover can be thick, most of the effective rainfall is unlikely to recharge the aquifer, discharging instead to rivers and streams. Groundwater discharges along short flow paths (30-300m) to rivers and streams in the GWB with some discharge to small springs and seeps at the stream heads and along their course. The overall groundwater flow is expected to be to the east, following the topography.

The **Dundalk GWB** encompasses the southern part of Carlingford Mountain and parts of the Carlingford Shore. The GWB description (GSI, 2004a) indicates that bedrock comprises Dinantian mixed sandstones, shales and limestones which are classified as a locally important aquifer (bedrock which is generally moderately productive). Groundwater flow is expected to be concentrated in the upper parts of the aquifer which comprise an upper <3m of weathered and broken rock over generally <20 - 30 m of interconnected fissuring and in the vicinity of fault zones. Transmissivity has been

categorised as good, especially in the vicinity of faults and storativity is also expected to be good. Groundwater flowpaths are expected to be 100-300m long given that much of the GWB occupies a discharge zone. Recharge is diffuse via percolation through subsoil and outcropping rock and most of the effective rainfall is likely to recharge the aquifer away from the main discharge zones. Groundwater discharges to rivers, streams and lakes in the GWB and to the sea along the coastline. The overall groundwater flow is to the south towards the coast.

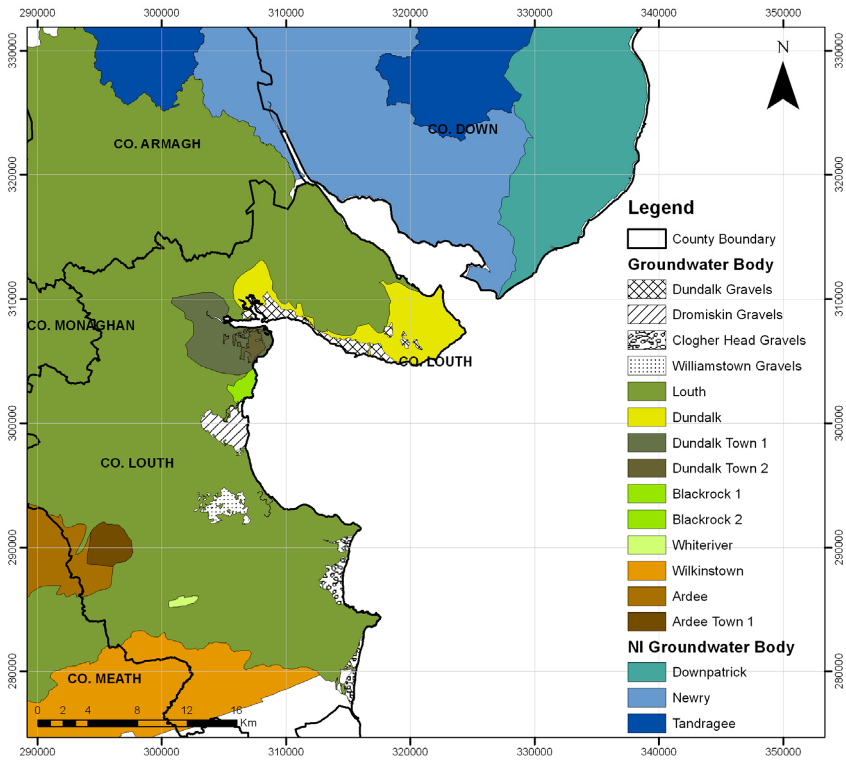


Figure 3.6: Groundwater Bodies.

The **Newry GWB** is defined by catchment areas that drain into Carlingford Lough. The GWB description (NIEA, 2012) indicates that it is a relatively low-lying area apart from the Newry and the Mourne Mountain igneous complexes to the south. Soils across the GWB are predominantly till with glacial sands and gravels in the south. Within the Ordovician and Silurian rocks storativity and permeability is low and groundwater flow is via fractures and the upper weathered rock, mainly within 30m of the ground surface, though some deeper flow may occur via fractures. The igneous rocks are expected to have poorer aquifer potential and flow is expected to be very shallow. Primary bedrock porosity is negligible. Recharge will be direct where rock is at or near the surface. Some recharge may occur through thin tills. Groundwater vulnerability is low to very low with the exception of areas of outcropping rock or permeable soils. Groundwater discharges along short flow paths (10s to 100s metres) mainly to the surface water network and there may be some limited discharge into Carlingford Lough (NIEA, 2012).

There are four gravel aquifer Groundwater Bodies (GWB) across the sudy area;

- **Clogherhead Gravel GWB** (GSI, 2005a)
- **Dromiskin Gravel GWB** (GSI, 2005b)
- **Dundalk Gravel GWB** (GSI, 2005c)
- **Williamstown Gravel GWB** (GSI, 2005d)

The Dundalk, Dromiskin and Clogherhead Gravel GWBs are coastal while the Williamstown Gravel GWB is inland. The GWB descriptions indicate that all four gravel aquifers are categorised as locally important sand and gravel aquifers. The Dundalk Gravel GWB comprises six morphologically similar

sand/gravel deposits, three of which are situated next to the coast. The gravels have high permeability with a typical thickness of 20m, but they can be over 70 m thick. The Dromiskin Gravel GWB is a marine sand and gravel deposit adjacent to the coast north of the town of Dromiskin. The Clogher Head Gravel GWB is another marine sand and gravel deposit with windblown sands. Groundwater in all of these gravel bodies discharges to the sea and to the rivers/streams that flow through and adjacent to the gravel bodies. The Williamstown Gravel GWB comprises glacially deposited sand and gravel up to 50m thick that discharge groundwater outwards to streams flowing from the gravel and to nearby rivers via alluvial deposits.

The marine sands and gravels of the Dundalk Gravel GWB are reported as having high but variable transmissivities which range from 3-1000 m^2/d (NERDO, 1981). Transmissivities in the sand/gravel body along the north shore of Dundalk Bay are likely to be around 1000 m^2/d (GSI, 2005c). The Dromiskin and Clogher Head Gravel GWBs have been characterised as being similar to the Dundalk Gravel GWB in that they are expected to have high but variable permeability and transmissivity (GSI, 2005a, b). Transmissivities for the glacially deposited sand and gravel of the Williamstown Gravel GWB can range from 200 – 1500 m^2/d (GSI, 2005d).

The GWB descriptions do not include values for hydraulic conductivity and their calculation is beyond the scope of this project. However, the potential for saline intrusion could be high in the three coastal gravel aquifers - Dundalk, Dromiskin and Clogher Head Gravel GWBs, given the expected high transmissivities and that they discharge, in part, to the sea.

There are also various Transitional and Coastal water bodies surrounding Dundalk Bay and Carlingford Lough. These include estuaries, lagoons and near shore coastal waters. These are presented in Figure 3.6.

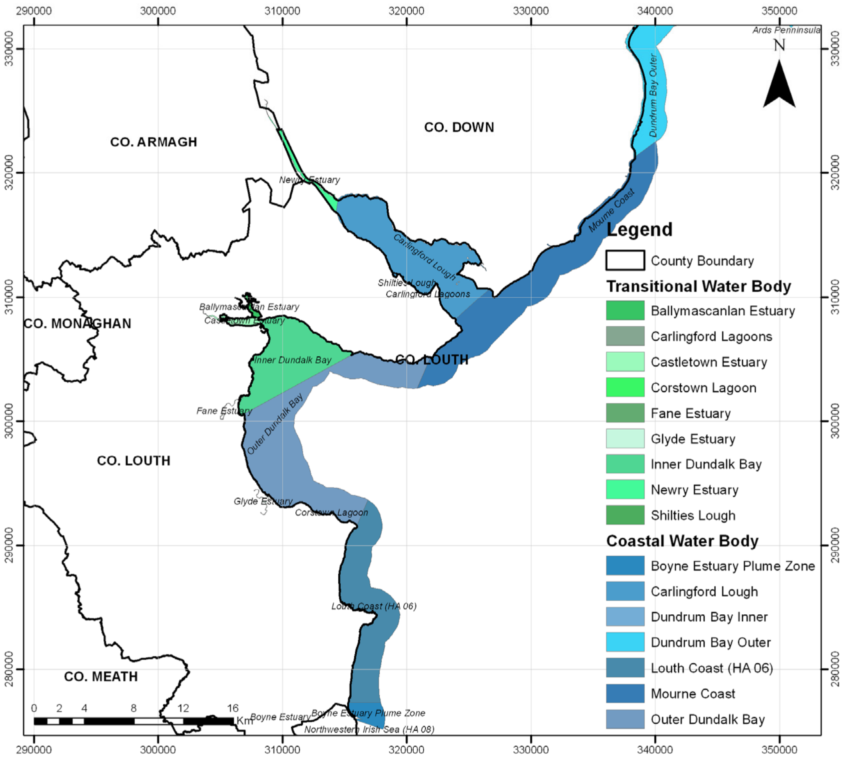


Figure3.7: Transitional & Coastal Water Bodies.

4. Assessment of Airborne Data

4.1 Data Import to Geosoft Oasis montaj

Merged datasets for the AM, AEM (3 kHz and 14 kHz) and Radiometric surveys were provided by the GSI on the 1st May 2013. Clipped datasets for the AEM (900 Hz and 25 kHz) surveys were provided by the GSI on the 5th July 2013 with additional unedited data provided on the 20th August 2013. The datasets were uploaded as databases to Geosoft Oasis montaj.

Prior to data processing, the datasets were reviewed under the following headings:

- Data Processing by GSI & GSNI
    - Tellus Border (TB) Processing
    - Tellus (T) & Cavan (CAV) Processing
    - Merged Datasets
    - FEM Over-water Calibration

- Data Quality
    - Noise
    - Cross-over Error

Resulting from the above review, the following procedures were implemented:

- Flight Line Selections- Only tie-lines for the Tellus Border data were provided within the merged data. Following analysis of the cross-over error, it was decided to remove the tie-lines during processing and gridding of the data in order to improve the smoothness of the dataset.
- Resampling of data - The sampling interval for the magnetics was consistently 0.1sec across all three datasets (T, TB & CAV). As such, the Magnetics database was chosen as the main database and the AEM and Radiometric data were sampled in to this database.
- Screening datasets – Flight altitude has a significant effect on the skin depth of AEM and radiometric surveys. Hodgson and Ture (2013) suggest that T, TB & CAV data in areas where altitude exceeds 180m should be deemed less reliable while Beamish and White (2012) used a cut-off survey height of 100m. A cut-off survey height of 100m was chosen in this project and as such some images will have data gaps. Beamish and White (2012) also chose a conductivity value cut-off of 500 mS/m to eliminate obvious cultural noise. However, as much of the purpose of this project is to investigate the coastal region, which has a very conductive signature due to the salinity, similar high conductivities were not filtered from the AEM data.

A more detailed account of the review process is contained in Appendix I.

In parallel with the airborne data import, GIS information was compiled throughout the course of the project. Acquired GIS information ranges from geology and soils to river courses and groundwater bodies to licenced waste facilities and historic mines. A full list of the GIS data acquired is listed in Appendix II.

4.2 Processing of Magnetic data

To process the AM data the residual magnetic data were reduced to pole and the following procedures and filters were applied:

- Power spectrum analysis
- Upward Continuation
- Downward Continuation
- Analytic Signal

- Vertical Derivative
- Horizontal Derivative
- Tilt Derivative
- Pseudo-gravity
- Horizontal Gradient

The analyses that produced the most significant results for the interpretation of shallow features within the magnetic data were the 1st Vertical Derivative (Figure 4.2), the Analytic Signal and the Tilt Derivative (Figure 4.3) derived from the Reduced to Pole residual magnetic data.

A more detailed account of the AM data processing is contained in Appendix I.

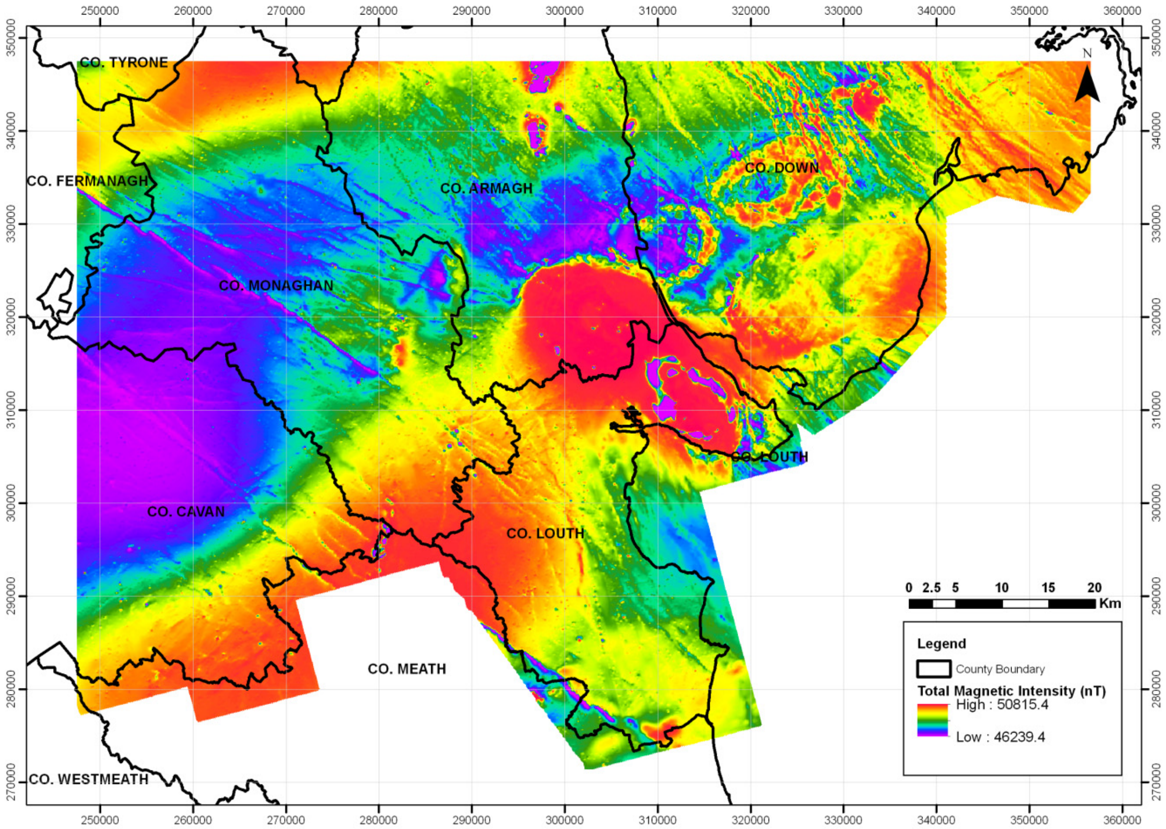


Figure 4.1: Total Magnetic Intensity data prior to processing.

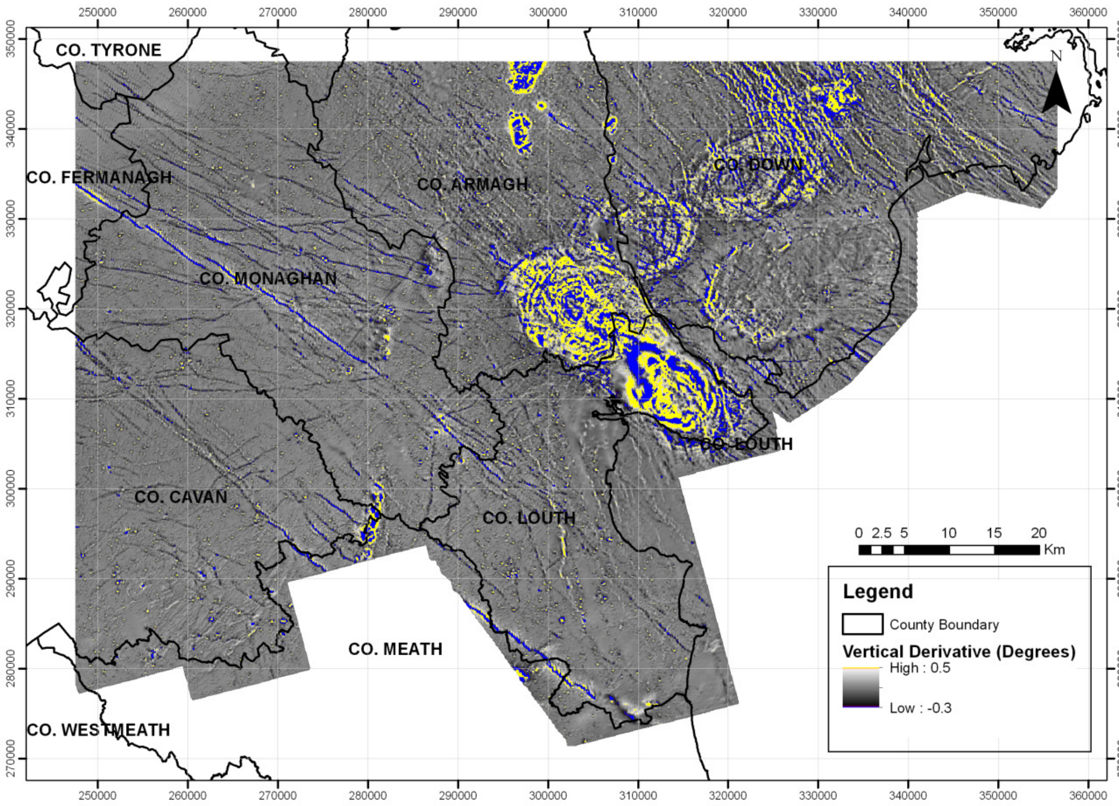


Figure 4.2: 1st Vertical Derivative of Reduced to Pole residual magnetic data.

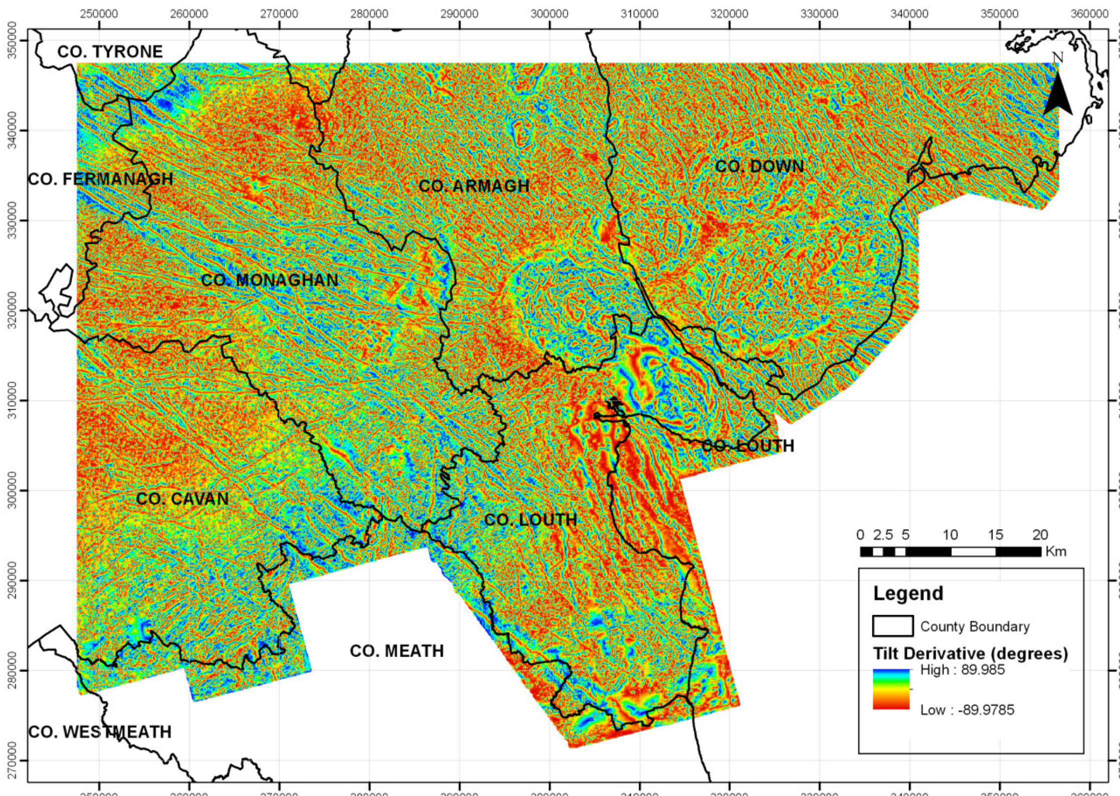


Figure 4.3 : Tilt Derivative of Reduced to Pole residual magnetic data.

4.3 Processing of Electromagnetic data

The AEM data comprises 4 frequencies; 900 Hz, 3kHz, 12/14 kHz and 25 kHz. The depth of investigation of each frequency is very much dependent on the subsurface conductivity. Beamish et al. (2010) in his examination of structural geology of the Longford-Down Terrane calculated that the 3 kHz data is most influenced by conductivity variations in the upper 60 to 100 m. The 900 Hz data provides a greater depth of investigation, while the 25 KHz data looks shallowest. AEM data supplied for this survey included depth calculations for the Co. Louth and Co. Down coastal areas for which the 900 Hz data had a mean depth of 85m, the 3 kHz data had a mean depth of 73m, the 12/14 KHz had a mean depth of 43m while the 25 kHz had the shallowest depth of investigation with a mean depth of 27m.

In addition to a general inspection of the AEM data maps for each of the four frequencies using varying colour bands (Figure 4.4), the analyses of the AEM data also included viewing shaded relief images, analysing horizontal derivatives, as well as the Analytic Signal and Tilt Derivative (Figure 4.5) as demonstrated by (Beamish, 2012b).

A more detailed account of the electromagnetic data processing is contained in Appendix I.

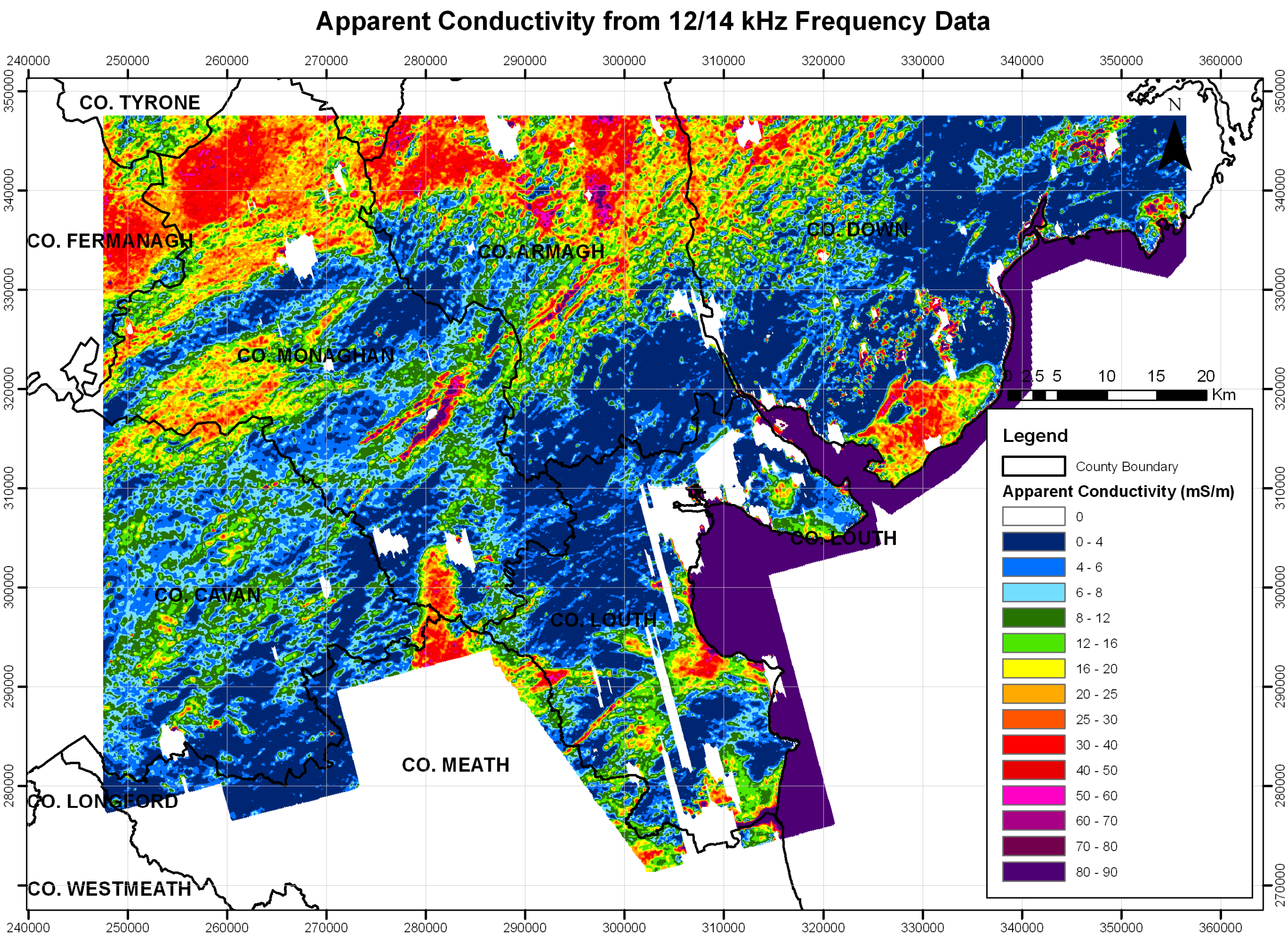


Figure 4.4: 12/14 KHz merged electromagnetic data. High fly zones (>100m flying elevation)in white.

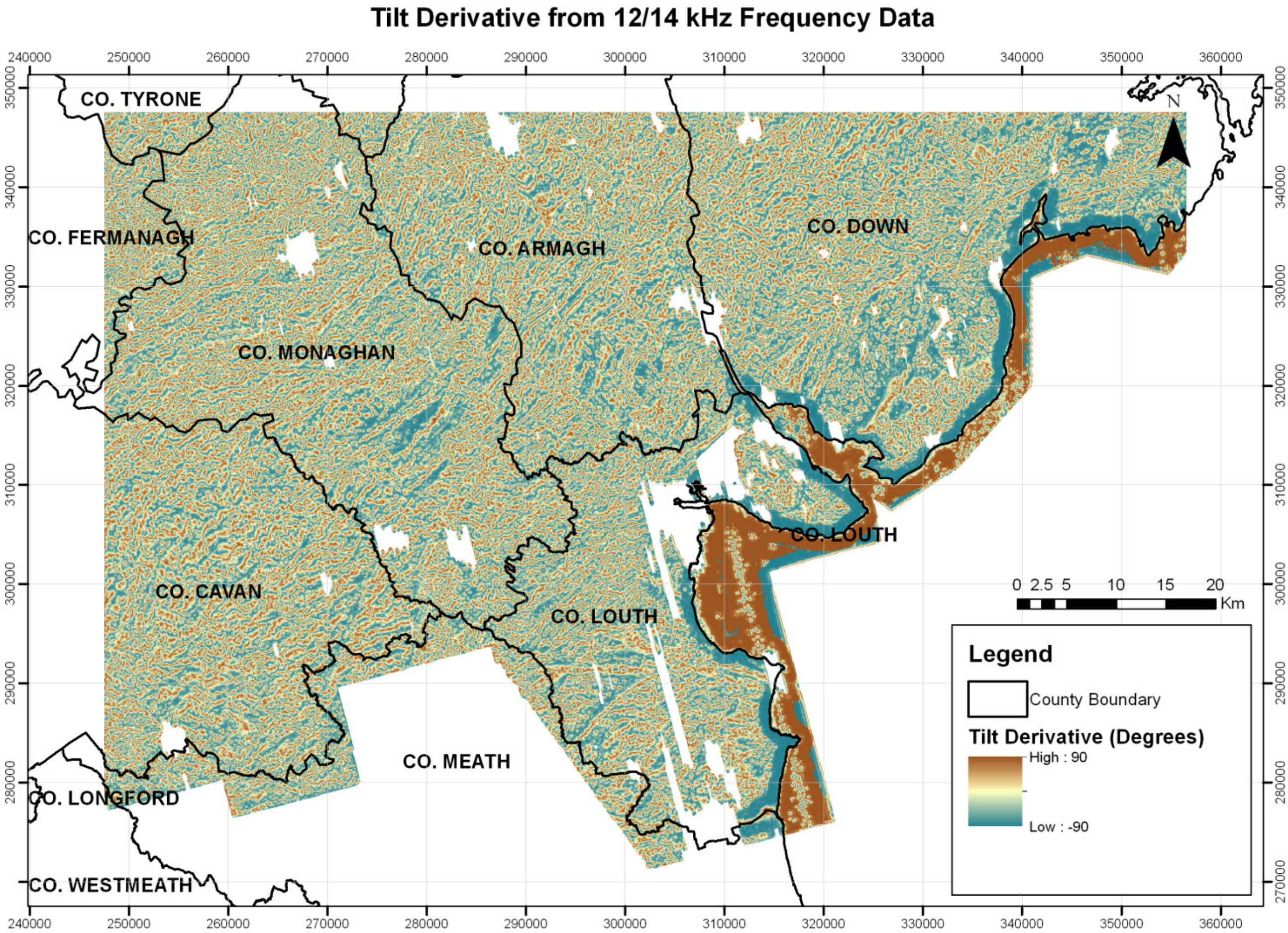


Figure 4.5: Tilt Derivative derived from 12/14 KHz merged electromagnetic data. High fly zones (>100m flying elevation)in white.

4.4 Radiometric Data Processing

For the purposes of this project, the radiometric data was included as an additional layer of information in the integrated interpretation (Figure 4.6). As mentioned in Section 4.1, a cut-off survey height of 100m was applied to the radiometric data resulting in data gaps which are indicated as grey areas in Figure 4.6.

Beamish and Farr (2013) used radiometrics to assist hydrogeological investigations as the radiometric data is attenuated with increased water saturation of the near-surface soils. A ternary plot of the radiometric data was created from the K, Th and U concentrations.

The key features for our observations are that:

- The areas in the plot that are white indicate areas where concentrations of K, Th and U are high.
- The areas in the plot that are black indicate areas where concentrations of K, Th and U are low.
- Near-surface water such as lakes and rivers attenuates the signal (black).
- Peat (due to its saturation) attenuates the signal (black).

The water and peat areas were examined in conjunction with the assessment and interpretation of the AEM data.

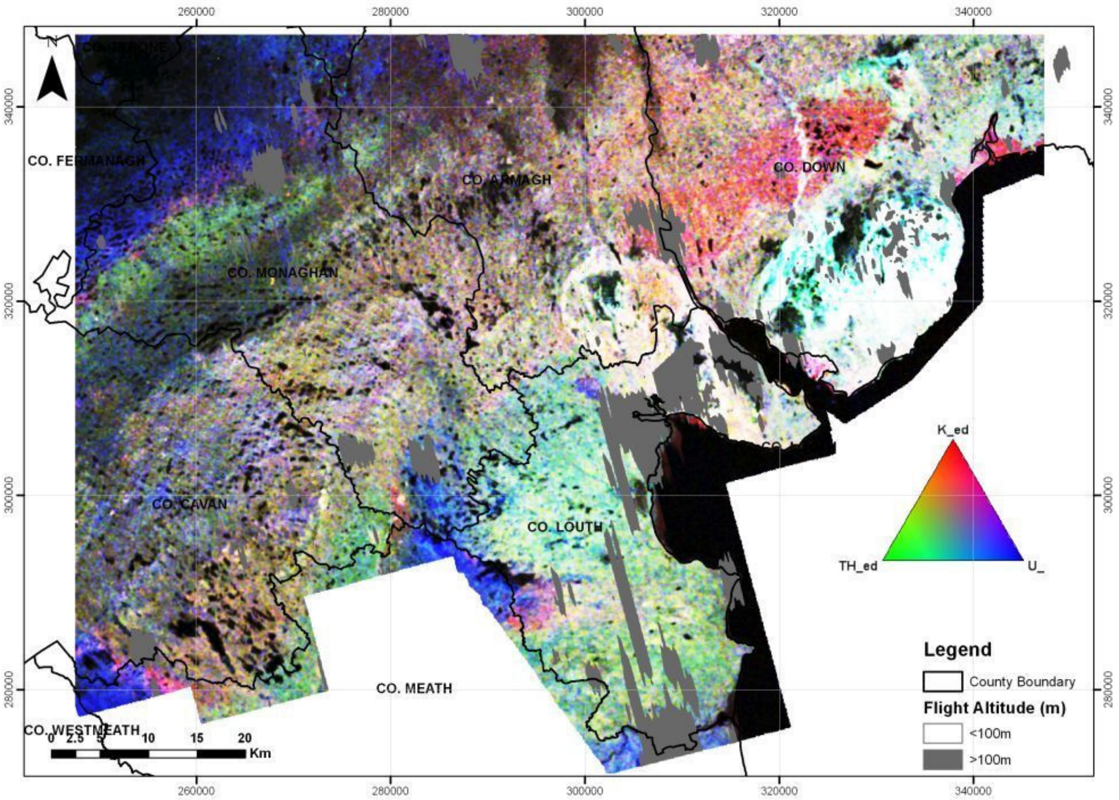


Figure 4.6: Ternary image of the radiometric data indicating concentrations of K, Th and U.

4.5 Data Assessment & Identification of Field Targets

The processed AM and AEM data were analysed against the radiometric and available GIS data using ArcGIS (ESRI, 2010). The main steps in the data assessment were to identify mapped and unmapped faults, geological contacts and lineaments using both the AM and AEM data. The AM and AEM data allow us to investigate features of the geology that are not visible at the surface and have not previously been mapped. Through analysis of the geophysical data with the filters outlined in Sections 4.2 and 4.3, the edges of anomalously magnetised or resistive bodies and lineaments associated with bedrock geological trends, fracture zones and basalt dykes are enhanced.

The AM data allows us to examine the bedrock geology based on variations in the magnetic mineral content and magnetisation of the geology. Within the survey area, rock types such as the granites have distinct magnetic signatures compared to the surrounding mudstones and greywackes. Magnetic lineaments such as dykes become apparent in the contoured data, and can be dated based on elements such as their strike or displacement by faulting.

Variations in conductivity values in the AEM data can be indicative of changes in superficial deposits and bedrock geology. Soils such as peat, silt and clay generally exhibit high conductivity values while dry sands and gravels exhibit low conductivities. Rock types such as mudstones and shales typically exhibit high conductivities while reef limestones would exhibit very low conductivities. Groundwater or saline saturation would result in increased conductivity values. Practical applications of these conductivity variations in AEM data have been used by Beamish and White (2012) to examine bedrock geological classifications and by (Beamish, 2012a) to examine saline intrusion.

The AEM data was then examined to look for increases in conductivity along faults or lineaments that might indicate the presence of groundwater, suggesting a groundwater pathway. Along the shore and offshore, the AEM was examined to look for decreases in conductivity that might indicate the outflow of groundwater to the sea.

GIS data was compiled to assist in the assessment of the geophysical data such that features resulting from cultural noise were not mistaken for geological features and appropriate interpretations of anomalous features could be made.

A number of features considered to have the potential to identify structurally controlled groundwater pathways in the coastal zone and offshore into Dundalk Bay and Carlingford Lough were observed in the data set and these are listed in the table contained in Appendix II. The features were selected based on criteria such as their shape, location, occurrence across a number of electromagnetic frequencies and concurrence between magnetic and electromagnetic anomalies or mapped faults. Key features within these observations were then followed up by terrestrial and marine investigations which are discussed in greater detail in Sections 5 and 6.

The observations from the airborne data were integrated with the terrestrial and marine investigations and the results are presented in Section 6.

5. Fieldwork

5.1 Electrical Resistivity Data Acquisition/Modelling

Fieldwork comprising towed marine Electrical Resistivity Tomography (ERT) in the shallow nearshore, and terrestrial ERT on shore and inland was proposed following the analysis of the airborne data.

A reconnaissance trip was carried out prior to the fieldwork program to determine accessible survey locations. Following this, a program of fieldwork was carried out between the 9th and 13th September. Marine and Terrestrial survey locations were selected based on access, safety, weather, depth of investigation achievable, tidal depths, anomaly strength, etc.. The proposed locations were subject to change throughout the fieldwork period based on results achieved, ground conditions, weather conditions (specifically sailing conditions) at the time of surveying and personnel safety. Some proposed near-shore marine ERT was cancelled and replaced by inshore terrestrial ERT to obtain deeper depths of investigation.

3105m of Terrestrial ERT was recorded at seven inland and coastal locations. Approx. 10200m of Marine ERT was recorded. The electrical resistivity data has been modelled using the RES2DINV inversion software, available in NUI Galway.

The survey locations are indicated in Figure 5.1

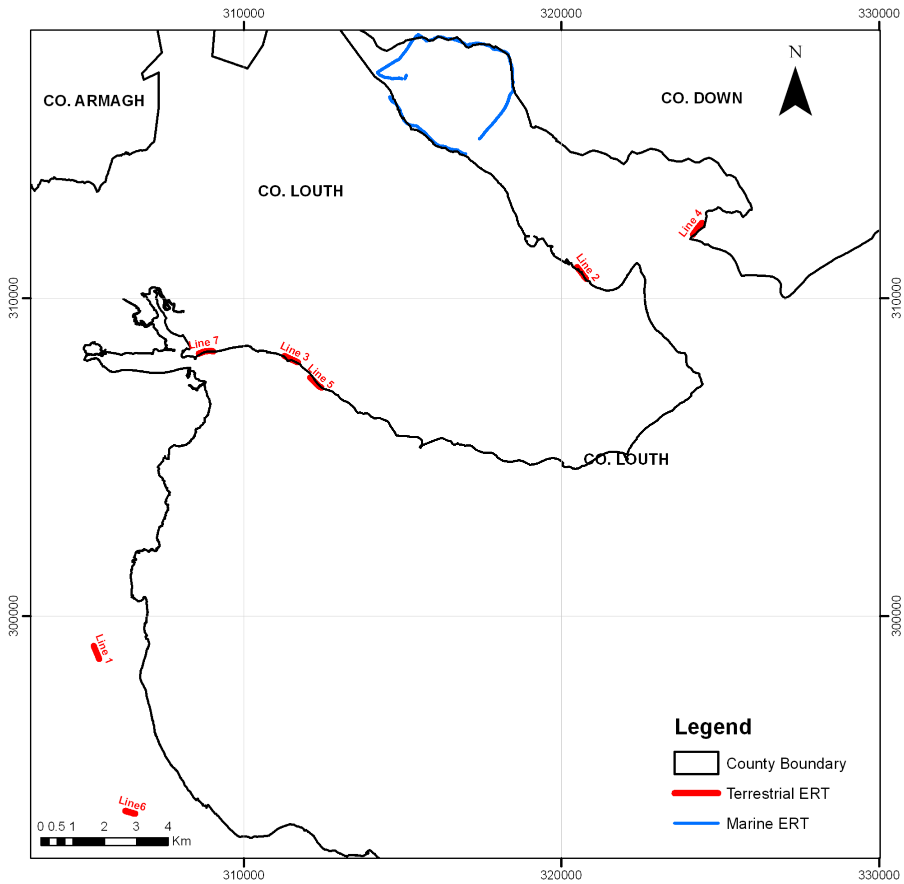


Figure 5.1: Terrestrial and towed Marine ERT survey Locations.

5.2 Terrestrial ERT

Terrestrial surveying of seven ERT profiles was carried out at six sites:

- Line 1 at Dromiskin - *Inland*
- Line 2 at Greenore - *Shoreline*
- Lines 3 and 5 at Rockmarshall - *Inland* (Figure 5.3a) & *Shoreline*
- Line 4 at Greencastle - *Shoreline*
- Line 6 at Kilsaran - *Inland*
- Line 7 at Bellurgan - *Shoreline* (Figure 5.3b)

The data were recorded using an Iris Syscal Pro resistivity meter connected to 4 multicore cables, each with 12 electrode connections (or 'take-outs'). 48 electrodes were used at 7 m to 10 m separations depending on accessibility using the Wenner Schlumberger array type.

In terrestrial ERT surveying, the electrodes are inserted into the ground and connected to the multicore cable at each take-out. Pairs of current and potential electrodes are used along the profile. A current is injected between the current electrodes and the voltage is measured between the potential electrodes. The apparent resistivity of the subsurface can be determined from this measurement when the input current and electrode separation is known. The resistivity meter runs a sequence using different sets of current and potential electrodes. The greater the spacing between electrodes, the greater the depth of investigation. By taking a large number of resistivity readings using different sets of electrodes a 2D profile of the subsurface can be generated.

Terrestrial surveying at Rockmarshall (Lines 3 and 5) and Kilsaran (Line 6), encountered difficulties due to the very low resistivities at depth. Only shallow depths were achievable and the quality of the data was generally poor. The results have not been included in this report.

Figure 5.3: Terrestrial ERT surveying (a) roadside at Rockmarshall, Cooley Penninsula and (b) shoreline at Bellurgan.

5.3 Marine ERT

Towed marine surveying was carried out around the inner area of Carlingford Lough. The towed waterborne ERT data were recorded using a boat mounted Iris Syscal Pro resistivity meter connected to a submersible cable with 13 graphite electrodes (Figure 5.4). The system is coupled to a Garmin GPS for positional accuracy. An echo sounder was attached to the boat and coupled to the resistivity meter, providing water depth along the towed ERT profiles. In addition, a YSI meter recorded water temperature, salinity and conductivity throughout the survey. Some photos of the survey work are presented in Figure 5.5.

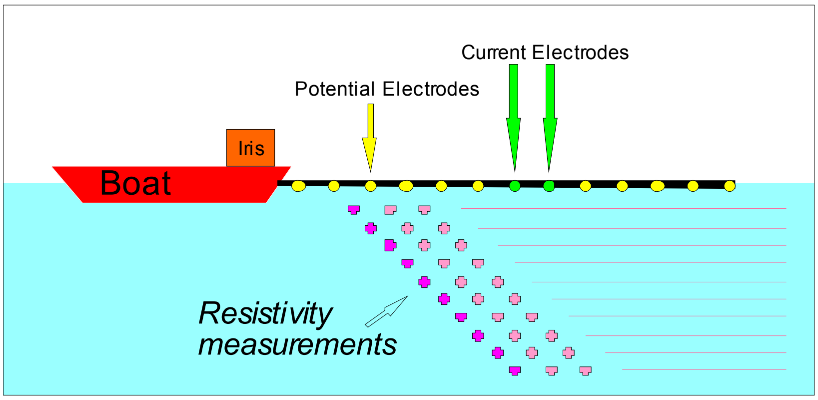


Figure 5.4: Schematic of Marine ERT setup using Wenner-Schlumberger array.

Figure 5.5: Marine ERT surveying (a) launching boat from Omeath slipway and (b) passing southeast of Rostrevor, co. Down.

Approx. 10200m of profiles were recorded with a Wenner-Schlumberger configuration. In the marine ERT configuration, the current electrodes are located in the centre of the cable (Figure 5.4) and use 10 different combinations of potential electrodes to provide a continuous profile of apparent resistivities through the water layer and below the sea bed. The depth of investigation is determined by the electrode spacing and also the thickness of the water column. For this survey, a cable with 10m electrode separations was used. The survey was also carried out as close to the shore as possible to minimise the thickness of the water column.

The YSI temperature, conductivity and salinity data was recorded throughout the towed marine ERT at a depth of 0.5 m from the water surface. This is not necessarily reflective of the entire water column as the surface water may be poorly mixed, possibly with fresh water at the top of the water column due to its lower density. However, averaging the conductivity values along a profile allows us to constrain the first layer in the inversion, stabilising the inversion process. For look at the water conductivity throughought the water column, a separate, more detailed survey would be required.

5.4 ERT Modelling

Both the terrestrial and marine ERT data were modelled using the Res2dinv program (Loke, 2010). This software inverts the recorded apparent resistivities using a non-linear least-squares optimisation technique to produce a 2D resistivity model of the subsurface. For the marine ERT data, the water depth (as recorded by the echo sounder) and the water conductivity (as recorded by the YSI meter) were incorporated into the data inversion, improving the inversion and data resolution. A total of 7 iterations were carried out for all profiles. Examples of the resultant pseudo sections are presented in Section 6.

6. Integrated Interpretation

The observations from the airborne data were the integrated with the terrestrial and marine ERT data and the GIS information to assist with the interpretation. The observations from this research are presented in the Summary Map (Figure 6.1). Key bedrock and soils observations are discussed in detail in Section 6.1 and groundwater observations are discussed in Section 6.2.

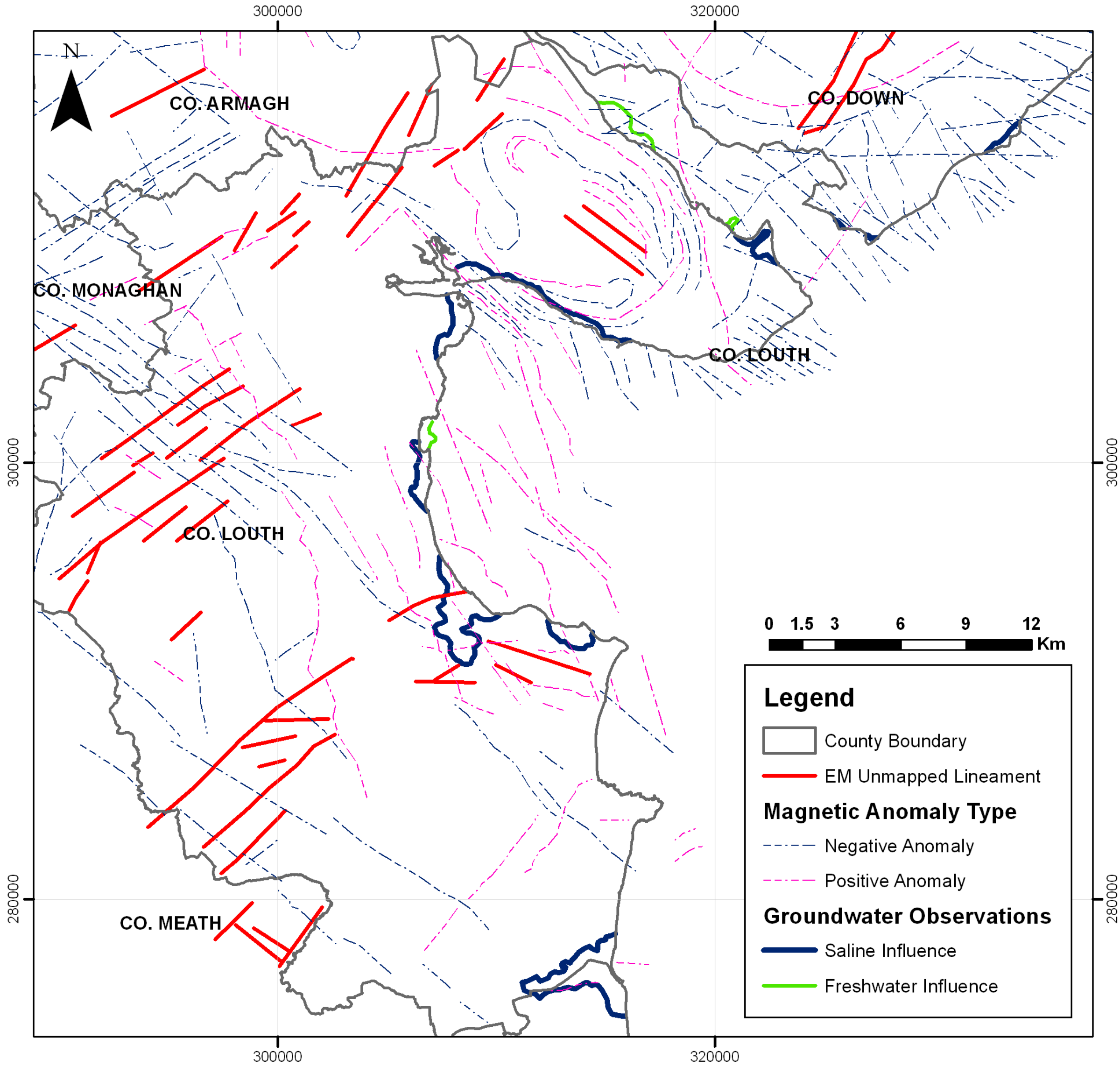


Figure 6.1; Summary Map of features observed within the coastal area.

6.1 Geological Assessment

6.1.1 Magnetic Lineaments

The AM data indicated a large number of previously unmapped lineaments, interpreted as igneous basalt dykes (Figure 6.2). The dykes exhibit a number of general strike trends; NW-SE and WNW-ESE with some approximate W-E strikes. The dykes can be positively or negatively magnetised, with negative dykes being dominant across the survey area. A cluster of NW-SE trending positive dykes are located in the northeast of the survey area.

Dyke dimensions for this area are typically 1-5m wide and mega-dykes (10-100m wide) can occur across Northern Ireland (GSNI, 2004). One such possible mega-dyke is presented in Figure 6.3 and runs in a NW-SE direction, south of Ardee towards Drogheda. A second possible mega-dyke is presented in Figure 6.4 and runs in a NW-SE direction through Co. Monaghan.

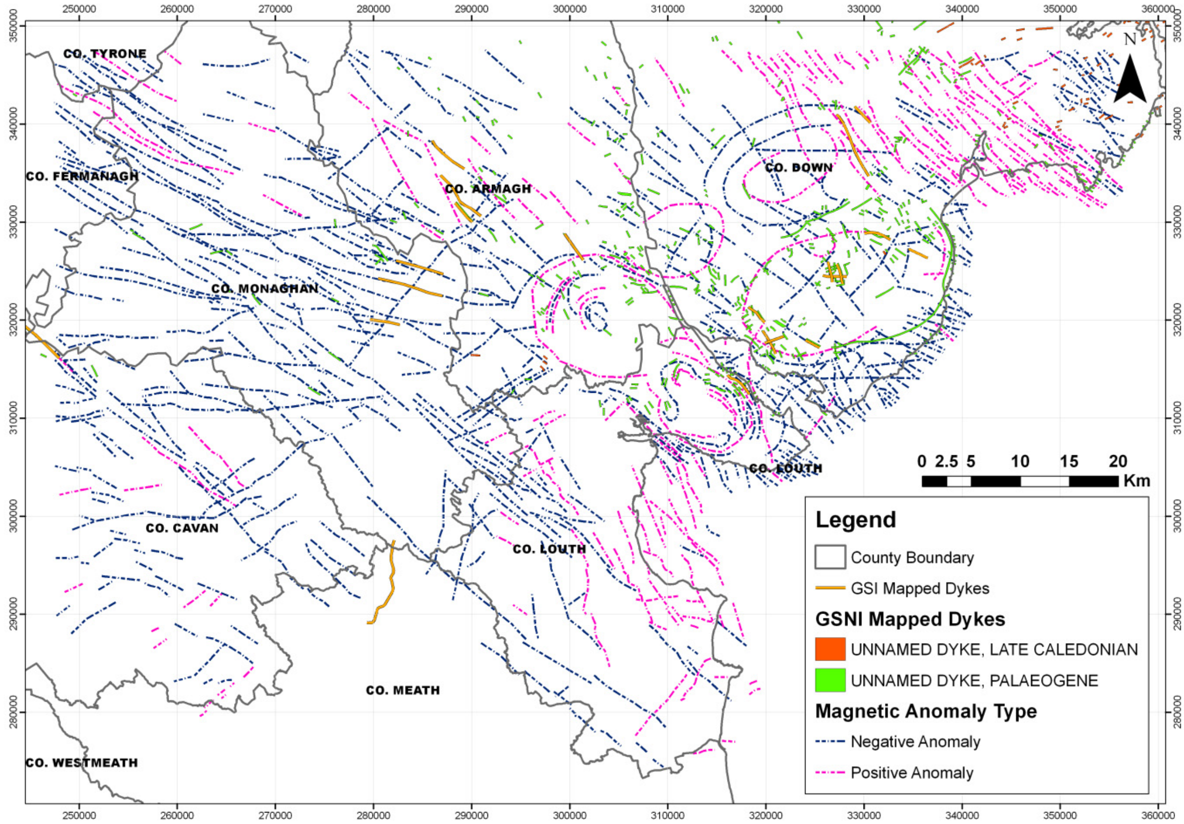


Figure 6.2: Magnetic Lineaments

Following the Tellus Border Conference in October 2013, interest was expressed by Dr. Norman Moles of the BGS research team for the critical metal potential of the Mourne Mountains project to obtain the above lineament map to investigate if there is any correlation between incidences of critical metals and magnetic lineaments.

6.1.2 Unmapped Faults

In addition to dykes, low and high magnetic values and trends relating to variations in the bedrock lithologies and faulting were also examined. The strong magnetic signature of the dykes masks variations in bedrock lithology that would be characterised by lower magnetic variations. Due to the frequency of dykes across the entire survey area, and the varying dyke directions, directional filtering was not a feasible option for removing the influence of the dykes within the data.

The mapped dykes can however be used to locate unmapped faults. The structural geology has been overlain in Figure 6.3 and it is clear that the dyke was intruded prior to the faulting that cuts through the Ordovician and Silurian bedrock in that area. An unmapped faulted offset in the dyke is indicated by the yellow arrows. In Figure 6.4 additional unmapped faults are also indicated by offsets in the dykes and are indicated by yellow arrows. These results can assist in the updating of the GSI geological maps.

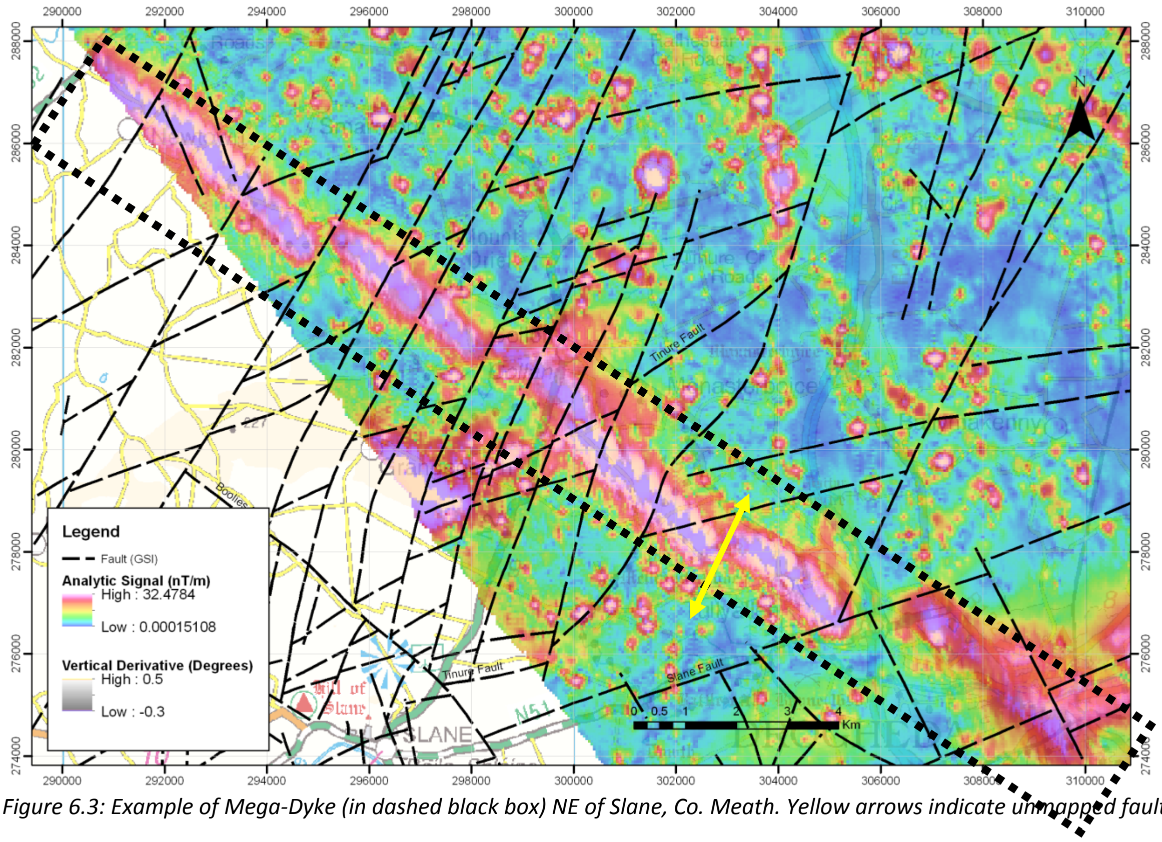


Figure 6.3: Example of Mega-Dyke (in dashed black box) NE of Slane, Co. Meath. Yellow arrows indicate unmapped fault.

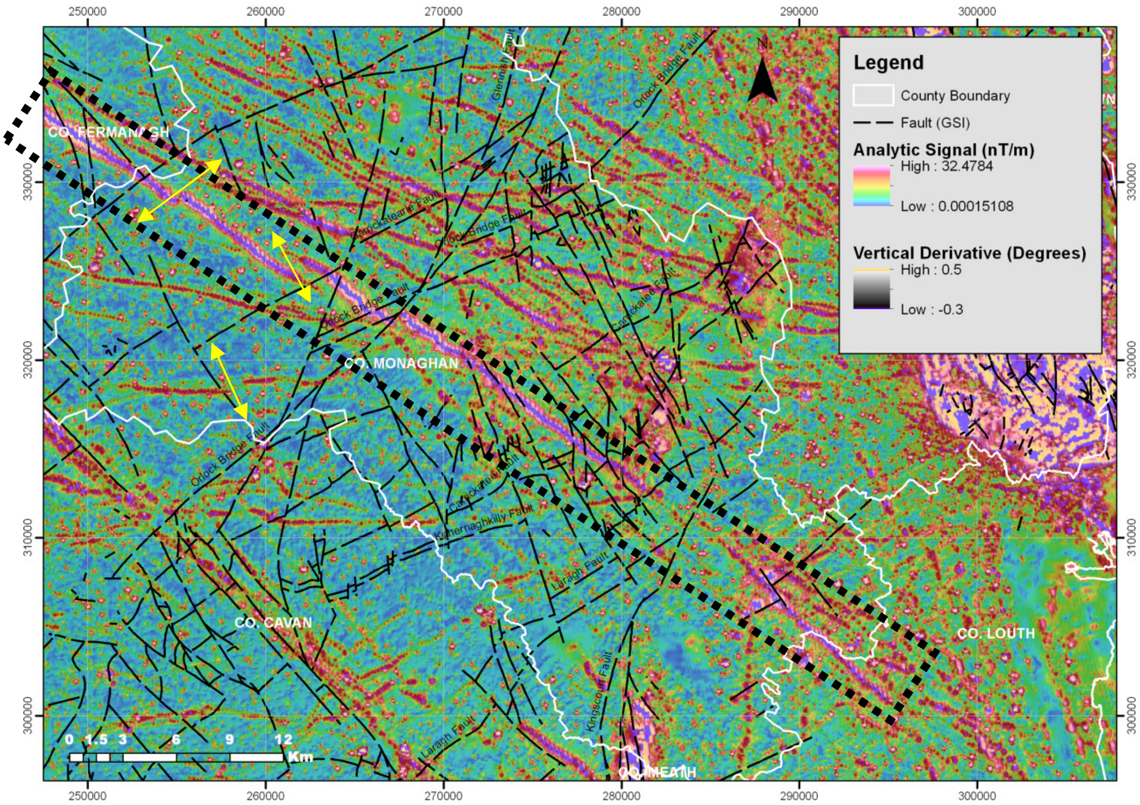


Figure 6.4: Example of Mega-Dyke (in dashed black box) cross-cutting Co. Monaghan. Yellow arrows indicate unmapped faults.

6.1.3 Bedrock Mapping

The ability to map changes in lithology across geological units using the AEM data is determined by the existence of conductivity contrasts between the lithological units. Beamish and White (2011) have examined AEM data to carry out a GIS based assessment of the subsurface geology across the Isle of Wight where there were strong apparent conductivity contrasts for the various lithological units. Some of the main bedrock lithologies and soil types across Counties Louth and Down have been examined to assess their conductivity signatures within the four frequencies (3 kHz, 14 kHz and 25 kHz) of AEM data. Estimates of the apparent conductivity ranges for each lithology, based on visual inspection of the data, is presented below:

Geological Formation	Period	Description	App. Conductivity (mS/m)
Rathkenny	Ord-Sil	Mudstone, Siltstone & Greywacke	0-30
Glaspistol	Silurian	Mudstone & Greywacke	1-5
Little Harbour		Greywacke & Mudstone	1-5
Red Mans Cove		Mudstone	1-5
Clogherhead		Greywacke	0-30
Salterstown		Greywacke & Mudstone	2-20
Clontail		Greywacke	0-5
Inniskeen		Turbidite & Shale	0-5
Hawick Group		Sandstone	0-10
Newry	Lwr Devonian	Granodiorite	0-10
Dinantian Limestones	Carboniferous (Mississippian)	Limestone	2-8
Milverton Group		Grainstone/Packestone	0-25
Navan Beds		Limestone, Mudstone & Sandstone	2-15
Cruicetown Group		Argillaceous Limestone	5-20
Fingal Group		Limestone, Shale & Micrite	5-30
Ardagh Shale	Carboniferous (Namurian)	Shale	15-75
Carrickleck		Sandstone & Shale	15-75
Clontrain		Sandstone & Shale	15-75
Corratober		Sandstone & Shale	15-75
Cabra		Sandstone & Shale	15-75
Westphalian	Westphalian	Shale, Siltstone & Sandstone	20-70
Kingscourt Gypsum	Permian	Gypsum	15-75
Kingscourt Sandstone	Triassic	Sandstone	5-20
Carlingford Complex	Tertiary	Microgranite	0-30
		Gabbro	0-3
Mourne Mountains		Granite	0-15
Slieve Gullion		Microgranite & Dolerite	2-25

Most of the Ordovician, Silurian, Devonian and Carboniferous rocks are within the range 0-20 mS/m, occasionally up to 30 mS/m such that conductivity contrasts are low across lithological boundaries. The Carboniferous Namurian and Westphalian sandstones and shales exhibit a much higher range of values (15-75 mS/m). The earliest sedimentary rocks of the Kingscourt Sandstone are again low (5-20 mS/m). Notably, the Tertiary ignesous rocks of the Carlingford complex, Mourne Mountains and the Slieve Gullion granites have low apparent conductivities (<30 mS/m) and are generally poorly distinguished from the surround country rocks of the Hawick Group (0-10 mS/m), the Clontail Formation (0-5 mS/m) and the Dinantian Limestones (2-8 mS/m).

However, even with such low conductivity contrasts, the AEM data can provide information on bedrock structure. For example, some previously unmapped NE-SW Caledonian trending structures are visible within the Silurian bedrock. Their locations are indicated on the Summary Map in Figure 6.1 and a detailed look at some of the features overlying the 3 kHz EM data is presented in Figure 6.5. They are generally evident as linear features exhibiting small increases in apparent conductivities and may be indicative of thicker mudstone or shale bands in the rock, or possibly may indicate fault zones.

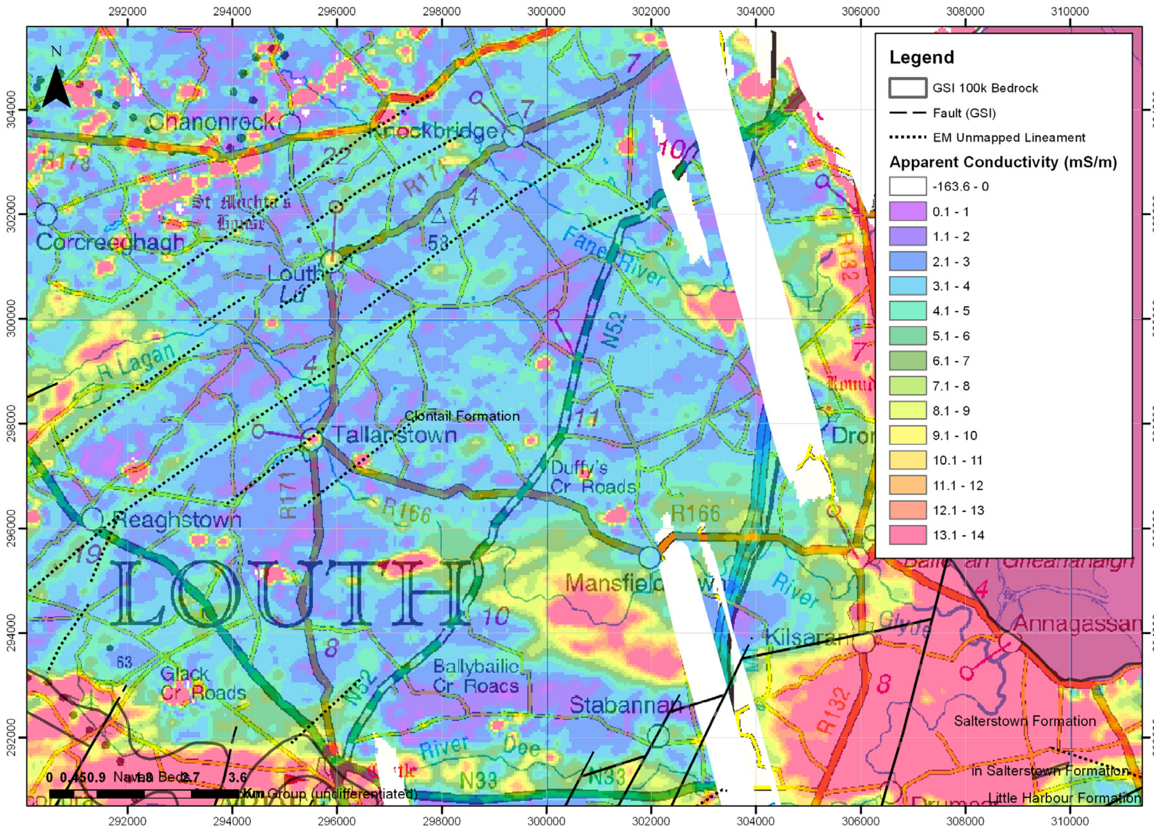


Figure 6.5: 3 kHz conductivity data showing unmapped lineaments. Other conductive linear features reflect cultural interference from power lines and roads or conductive soil deposits such as alluvium or marine deposits.

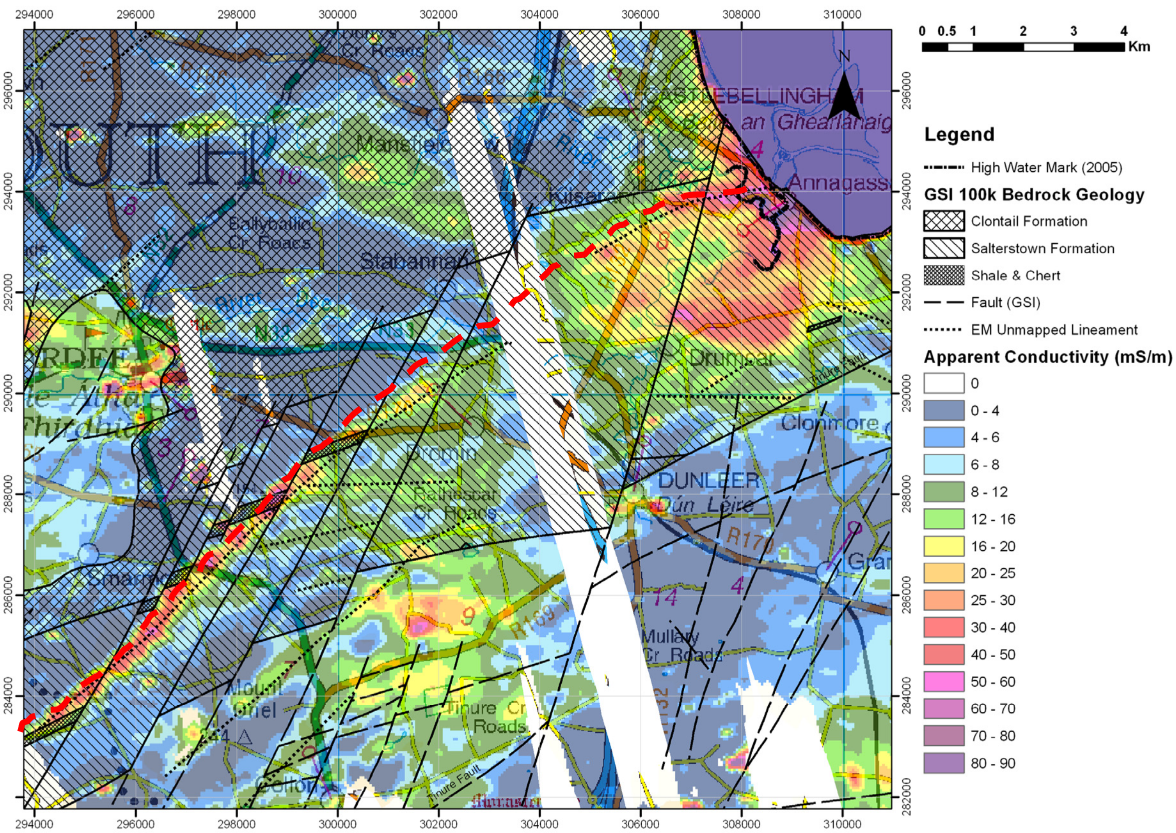


Figure 6.6: EM apparent conductivity from 3 kHz frequency showing conductive linear feature (dashed red line) southwest of Ardee to Annagassan, Co. Louth.

One of the most apparent unmapped geological structures in the AEM data is a NE-SW trending linear feature (approx. 15km long) and is present on all frequencies of apparent conductivity data, southeast of Ardee, Co. Louth (Figure 6.6). It has very high apparent conductivites (up to 100 mS/m). It lies within the Salterstown Formation, just south of its faulted contact with the Clontail Formation and approximate to a band of black shale and chert. It appears to continue to the coast at Annagassan, where it is only visible on 3 kHz and 900 Hz frequencies. The high conductivities may indicate that the shale is quite graphitic.

It is apparent that the AEM data plays a key role in providing information on bedrock structure. Other projects currently utilising the AEM data for bedrock mapping include an examination of the Moffatt Shale Group by Dr. Mark Cooper of the GSNI.

6.1.4 Soil Mapping

Various soils and subsoils as mapped by Teagasc/EPA/GSI (Teagasc, 2006) are clearly evident within all frequencies of the AEM data. Soils that have a high clay, silt, peat, water and/or saline content exhibit elevated conductivity values. As such, within the survey area, alluvium, peat, Irish Sea Tills, lacustrine sediments, marine/estuarine silts and clays and saline influenced marine gravels can be observed as having elevated apparent conductivity values. Made ground also generally exhibits elevated conductivity values. To demonstrate this, Figure 6.7 shows a small part of the entire survey area where various subsoil types have been plotted overlying the 12 kHz apparent conductivity data. The saline influence on soils is discussed in more detail in Section 6.2.3.

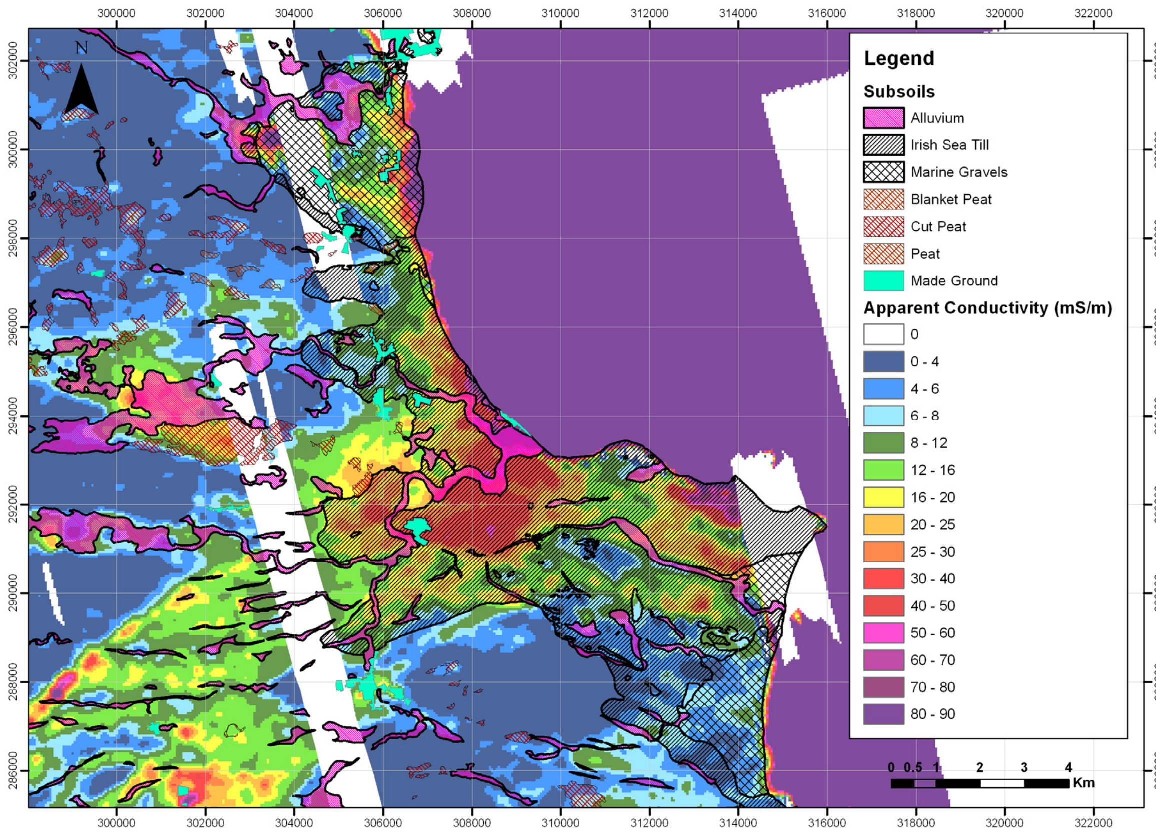


Figure 6.7: 12 kHz Apparent Conductivity Data with overlying conductive subsoil types.

The majority of the survey area is overlain by limestone or granite till which is likely to be quite thin as there is much subcropping or outcropping of bedrock. The AEM apparent conductivities are generally more reflective of the bedrock in these areas.

6.2 Groundwater Assessment

The groundwater observations from this research are numbered in Figure 6.8 (No. 1 to 14) and are discussed in more detail in this Sections 6.2.1 to 6.2.5.

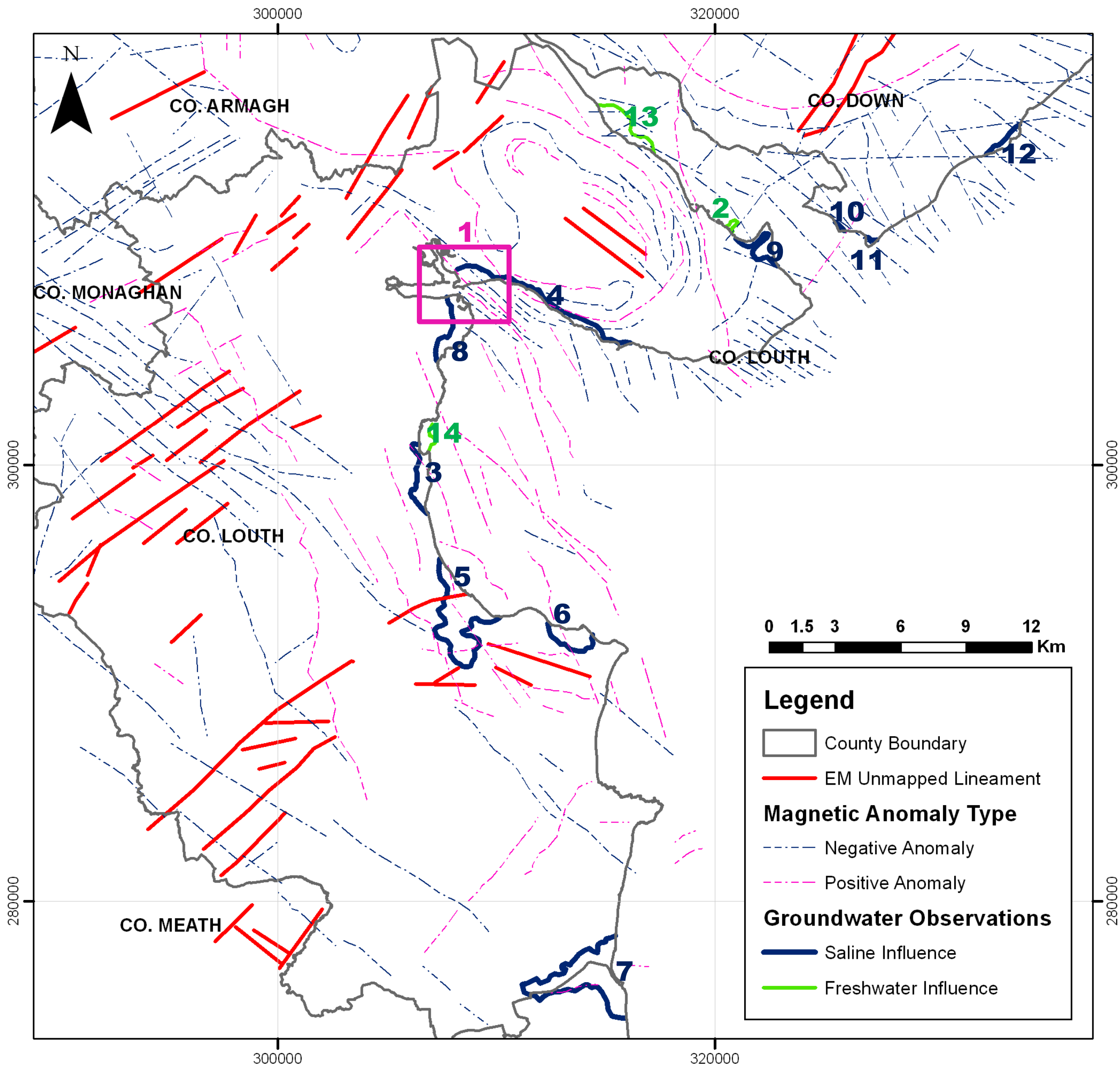


Figure 6.8; Summary Map of features observed within the coastal area.

6.2.1 Offshore Conductivity Features

Many dykes traverse the coastal zone clearly indicating bedrock structure in the nearshore. Along the coast of the Cooley Penninsula and the south coast of Co. Down these generally trend NW-SE and NNW-SSE. The dykes are less visible entering Dundalk Bay. Nevertheless, a number of magnetic lineaments have been mapped, particularly with a NW-SE strike in the inner bay area (Feature No.1 on Figures 6.8 and Figure 6.9). This information will assist in updating offshore geological maps.

The AEM data for the area also indicates linear trends that run approximately parallel to these magnetic lineaments. Linear features are visible extending approx. 1.5 km offshore from the High Water Mark surrounding inner Dundalk Bay. The features occur as slightly lower conductivities (on frequencies 25 kHz, 3 kHz and 900 Hz) within the highly conductive saline coastal zone (Figure 6.9). These features do not have any obvious correlation with mapped structural geology, bedrock geology, soil and subsoil distributions and cultural noise. They may indicate preferential flow paths for

groundwater.

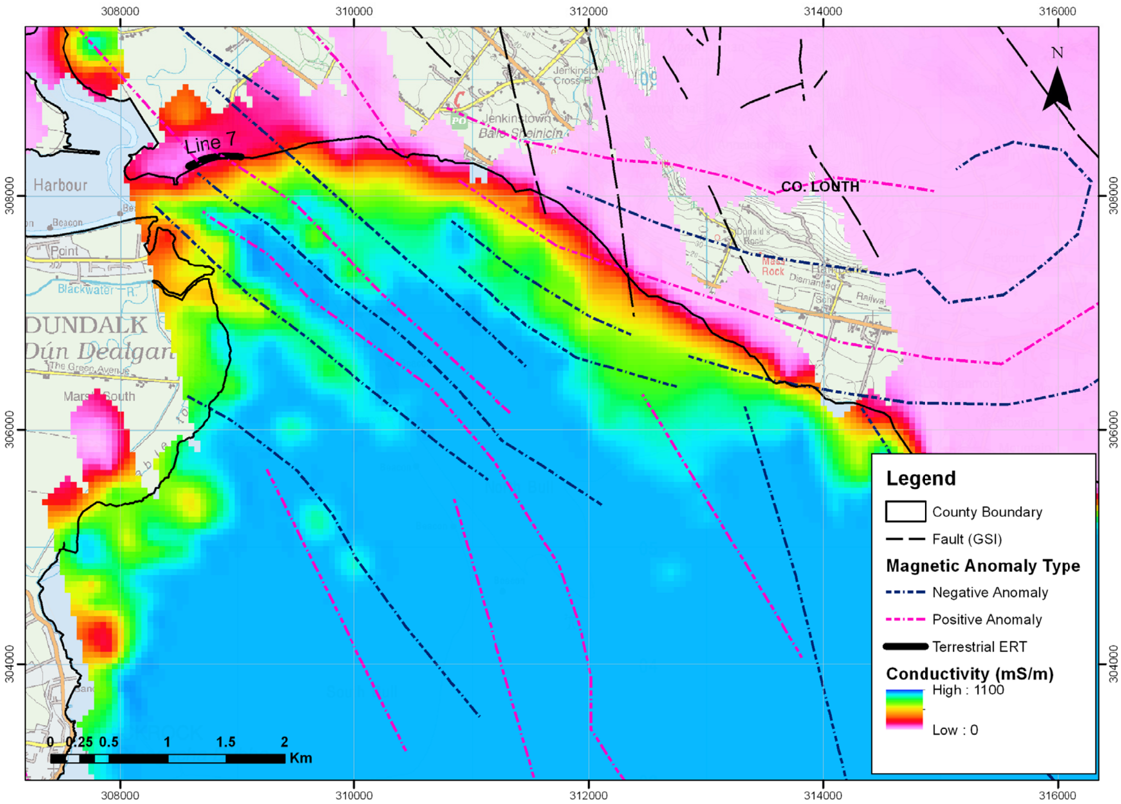


Figure 6.9: EM 3 kHz frequency showing lower conductivities along or parallel to magnetic lineaments in Dundalk Bay (refer to feature No.1 on Figure 6.8).

ERT Line 7 was recorded from west to east along the shoreline at Bellurgan during low tide conditions (Figure 6.9). The ERT data (Figure 6.10) indicates up to three parallel, resistive zones to the east of the profile, between depths of -10mOD and -20mOD. Mohammednur Dessisa from the GSNI suggested (pers. comm) that these features may indicate remnants of weathered granitic bodies which look like a sill detached by faulting, while the underlying conductive rock is due to intrusion of saline water through fractures. These weathered zones in the rock could act as preferential groundwater flow paths. An alternative interpretation could be that these features may indicate shallow, parallel dykes intruded in to the bedrock. This could be confirmed with follow up magnetometry work. These observations highlight the potential in the AEM data in examining geological features in the nearshore.

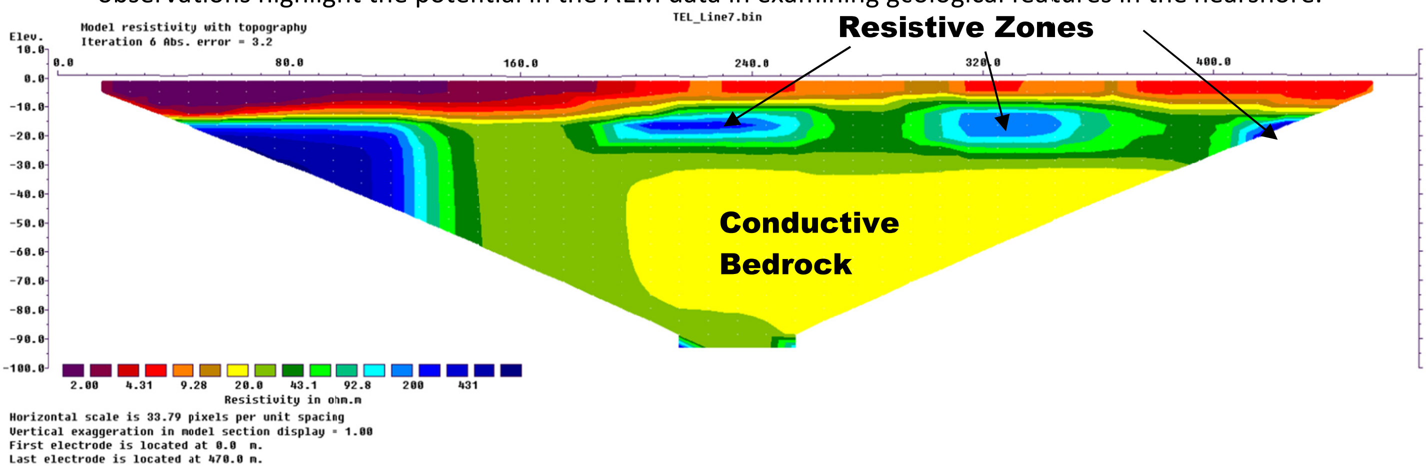


Figure 6.10: ERT Line 7.

6.2.2 Coastal Flow Paths

The conductivity data along the shoreline was examined to investigate for possible groundwater outflow features. Figure 6.11 shows the 25 kHz and 12 kHz AEM data on the northern coast of the Cooley Penninsula between Carlingford Point and Greenore. A linear magnetic feature has been mapped with a NE-SW strike. The conductivity data indicate linear features (a & b) extending approx. 500m offshore from the High Water Mark evident as slightly lower conductivities on all frequencies within the highly conductive saline coastal zone(indicated as Feature No. 2 on Figure 6.8). This trend does not have any obvious correlation with mapped structural geology, though is trending along geological strike. Though a stream outflows to the north of feature (b), there are four other stream outflow points within a 1.5 km radius with no associated low conductivity features emanating from the shore.

ERT Line 2 was recorded from northwest to southeast crossing feature (b) during low tide conditions. The ERT data indicates a possible channel in the bedrock, or a highly weathered band of rock to -30mOD, with possible preferential fresh/brackish water flow along it, as indicated by the lower conductivities within the coastal sediments (Fig.6.12). This information again confirms the potential in the AEM data in examining geological features in the nearshore.

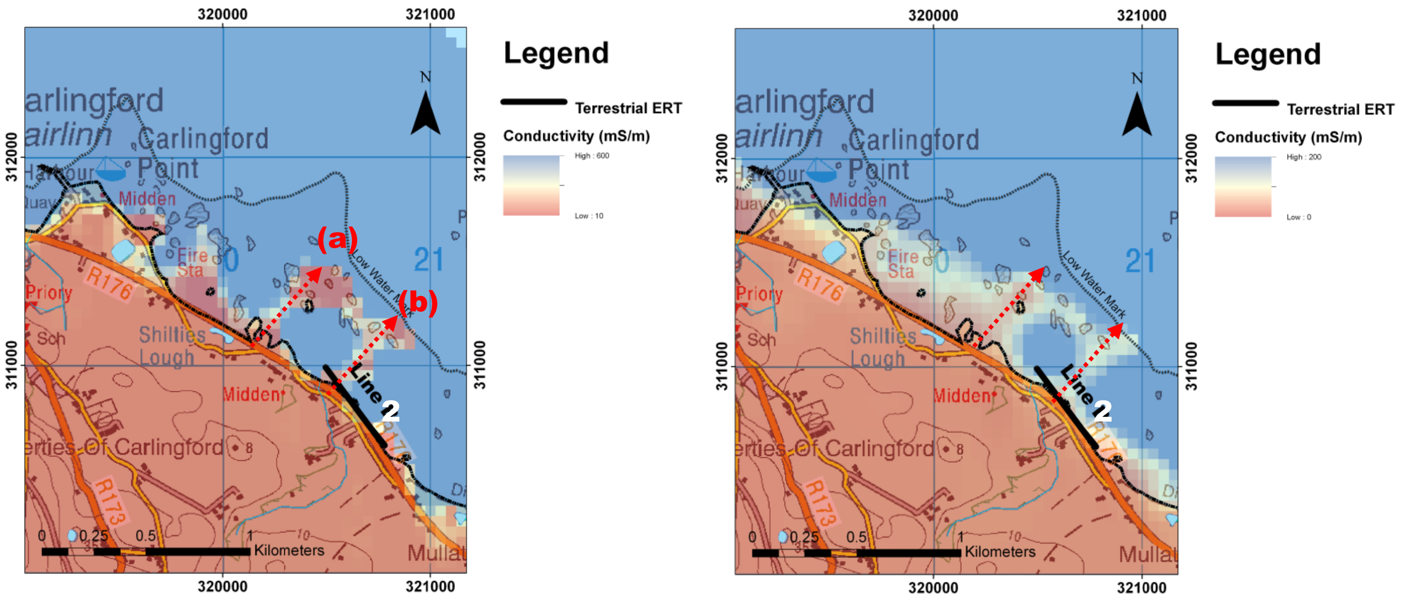


Figure 6.11: EM 25 kHz (left) and 12 kHz (right) frequency apparent conductivity data possible outflow paths (refer to feature No.2 on Figure 6.8).

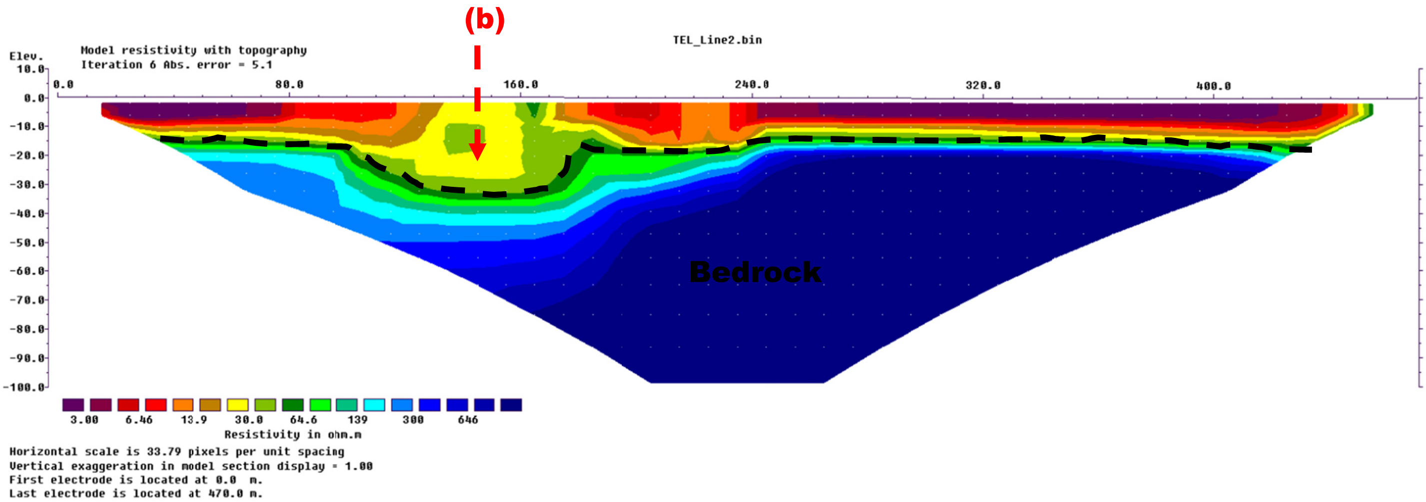


Figure 6.12: ERT Line 2.

6.2.3 Onshore Saline Influence

Beamish (2012a) has used AEM data to examine saline intrusion in to Holocene sediments across an inter-tidal zone in the southwest of Anglesey. Viezzoli et al. (2011) conclude that AEM appears as a promising and powerful additional tool for the hydrogeological characterization of large fresh-salt transitional environments such as wetlands, lagoons and deltas.

Within our survey area, high to very high apparent conductivity values (25 to >500 mS/m) have been observed in places along the coast, within the four AEM frequency datasets. These high values reflect saline influence in the sediments and possibly the bedrock. Most significantly, the saline influence can be seen in the Dromiskin and Dundalk gravel aquifer GWBs (No.s 3 & 4 respectively on Figure 6.8). The likely saline influence in to the marine gravels of the Dromiskin GWB is presented in Figure 6.13, possibly extending for approx. 750m inland as indicated by the dashed black lines.

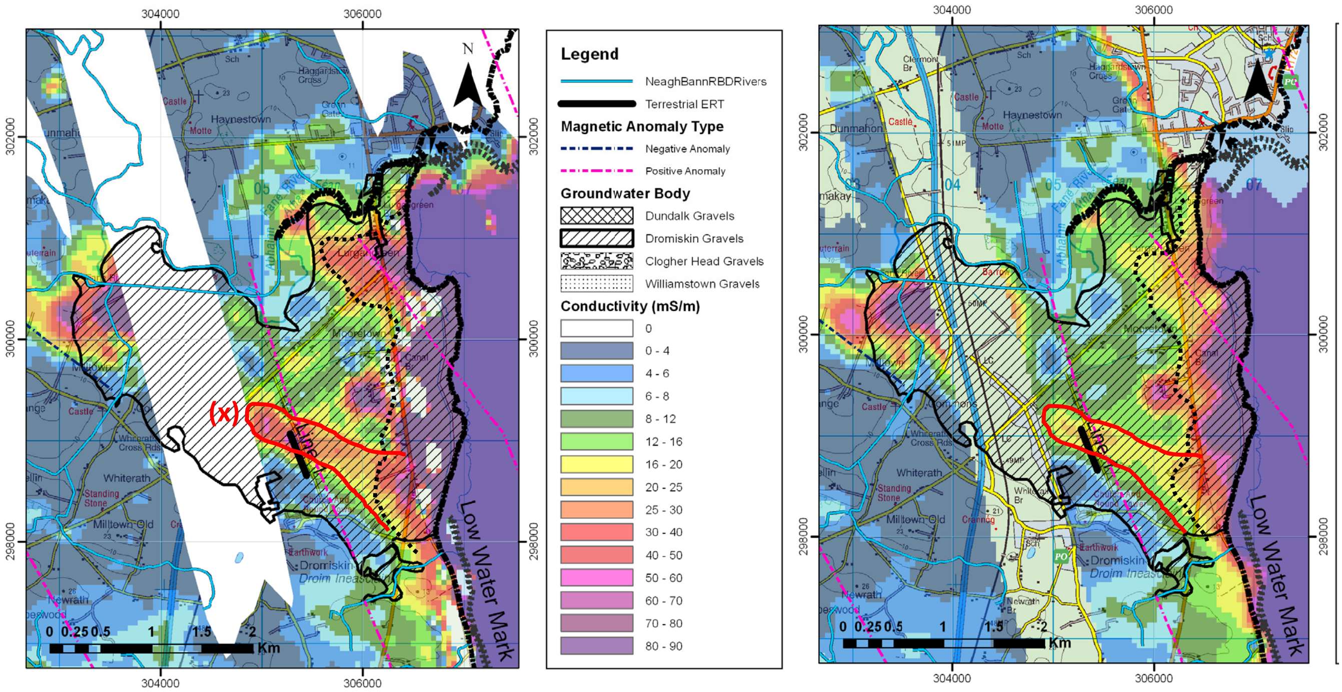


Figure 6.13: EM apparent conductivity from 25 kHz frequency (a) and 12 kHz (b) showing saline influence into the Dromiskin Gravel GWB plus a linear feature extending inland. Extent of saline influence indicated by dashed black line (refer to feature No.3 on Figure 6.8).

Also within the Dromiskin Gravel GWB, a conductive linear feature (x) is visible extending 2km inland from coast, unrelated to cultural noise and strongly visible on AEM frequency 25kHz, decreasing in strength on the 12kHz and 3kHz data, and absent on the 900Hz. Ground survey ERT Line 1 (Figure 6.14) was recorded to cross the feature from north to south.

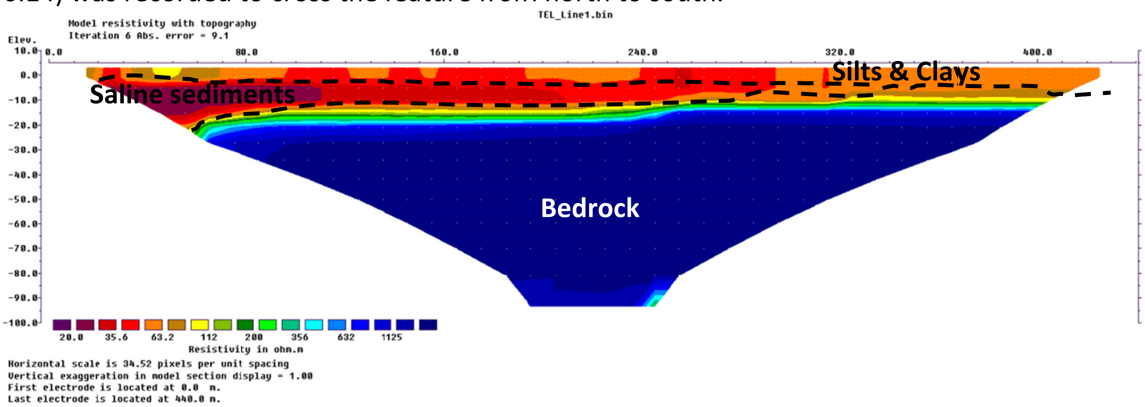


Figure 6.14: ERT Line 1

The ERT data indicates low resistivity (20-40 Ohm-m), conductive, probable saline influenced, soils to depths of approx. -20mOD along the northern half of the line, in agreement with the AEM data. This area is now cultivated for crops and habitation but the data appears to indicate that it was a coastal inlet prior to either reclamation or a drop in sea level.

The apparent conductivity data across the Dundalk Gravel GWB, north of inner Dundalk Bay, also suggest possible saline influence in to the gravels (Figure 6.15).

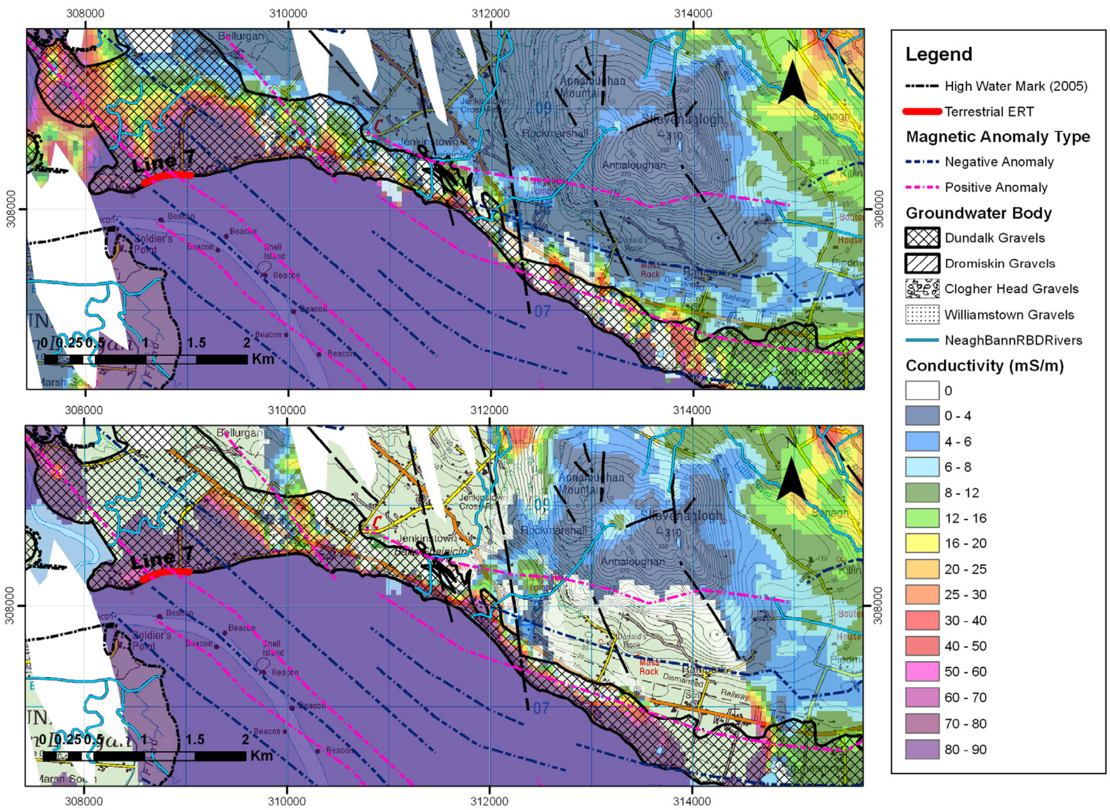


Figure 6.15: EM apparent conductivity from 25 kHz frequency (a) and 12 kHz (b) showing coastal saline influence into the Dundalk Gravel GWB (refer to feature No.4 on Figure 6.8).

In contrast, conductivity data across the Clogher Head Gravel GWB, south of Dundalk Bay, do not indicate any significant saline influence in to these gravels (Figure 6.16). The GWB descriptions indicate that the sand and gravel types for Dromiskin and Clogher Head are the same and at similar elevations but there are no thickness data available for either deposit. There is however, a change in bedrock lithology. The absence of saline influence in the Clogher Head GWB may be due to shallower bedrock and thinner gravel deposits.

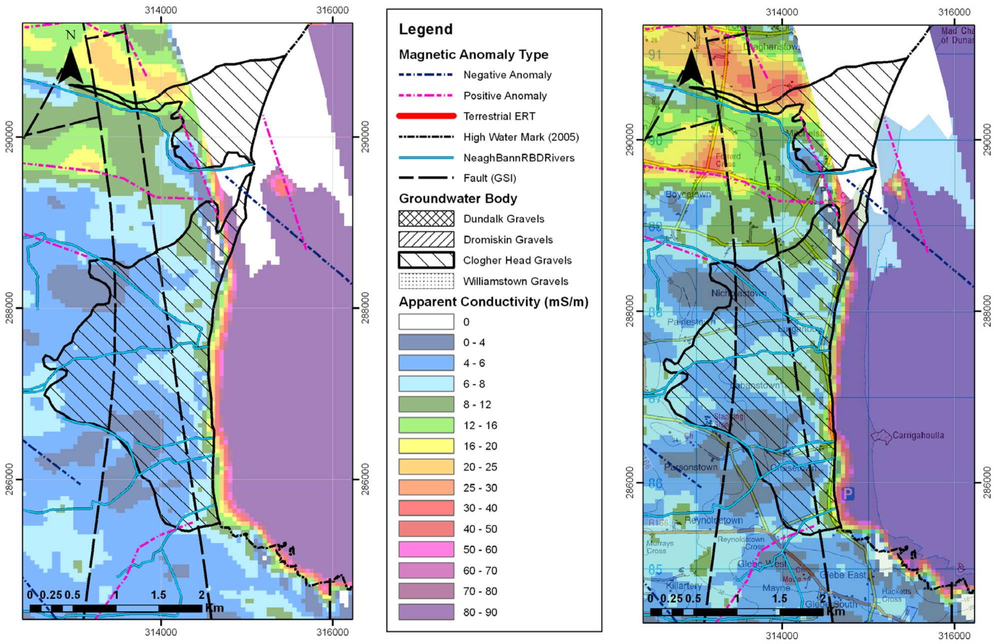


Figure 6.16: EM apparent conductivity from 3 kHz frequency (a) and 12 kHz (b) showing little or no saline influence into the Clogher Head Gravel GWB.

Two high conductivity zones are located along the coastline between Castellbellingham and Dunany Point in south Co. Louth (No.s 5 & 6 in Figure 6.8 and Figure 6.17). These zones are located within Irish Sea Tills, which are known to be conductive, however there may be potential for saline intrusion in to the bedrock, particularly near Dunany Point where there is known faulting in the bedrock.

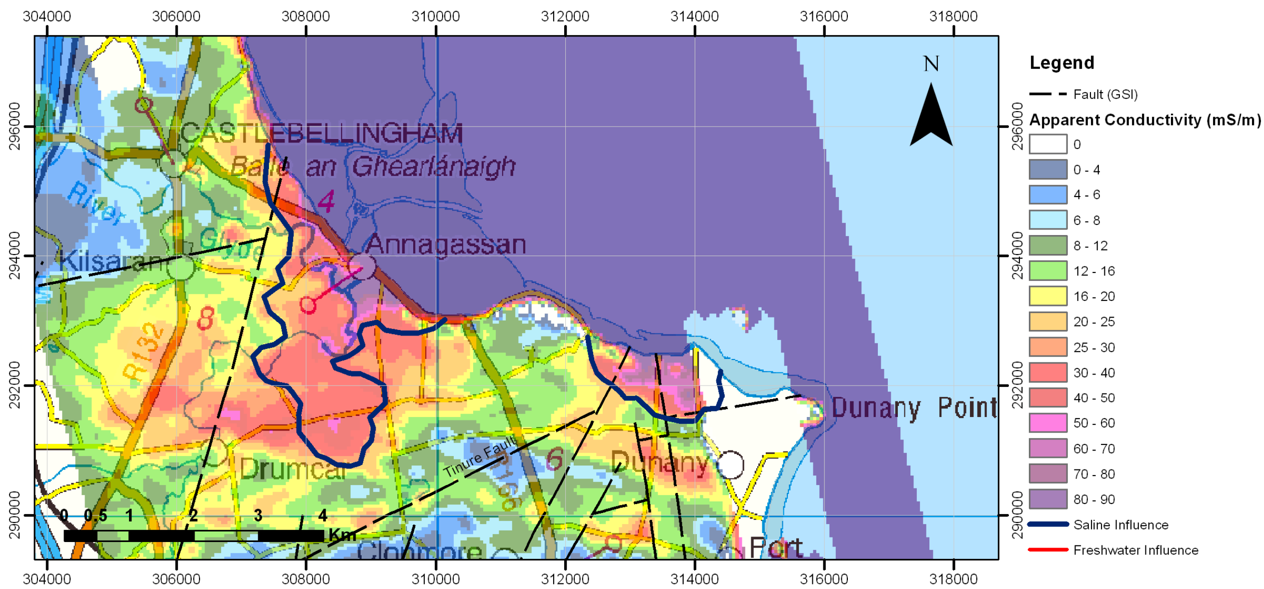


Figure 6.17: EM apparent conductivity from 12 kHz frequency showing possible saline influence near Annagassan and Dunany Point (refer to feature No.s 5 & 6 on Figure 6.8).

All frequencies of the AEM data across the Boyne Estuary east of Drogheda, Co. Louth, recorded very high (>90 mS/m) conductivity values indicating potential saline influence. The location is indicated as feature No. 7 in Figure 6.8 and in detail in Figure 6.18. Subsoils in this zone include glaciofluvial sands and gravels, estuarine silts and clays, Irish Sea till, windblown sands and some made ground. A well for industrial use within glaciofluvial sands and gravels, in the eastern end of this zone (BH NERDO 8b, from NERDO (1981)) drilled to 22m in unconsolidated material without encountering bedrock and

noted 2000 mg/l of NaCl (Figure 6.18). Other nearby wells encountered salty water and water unsuitable for drinking.

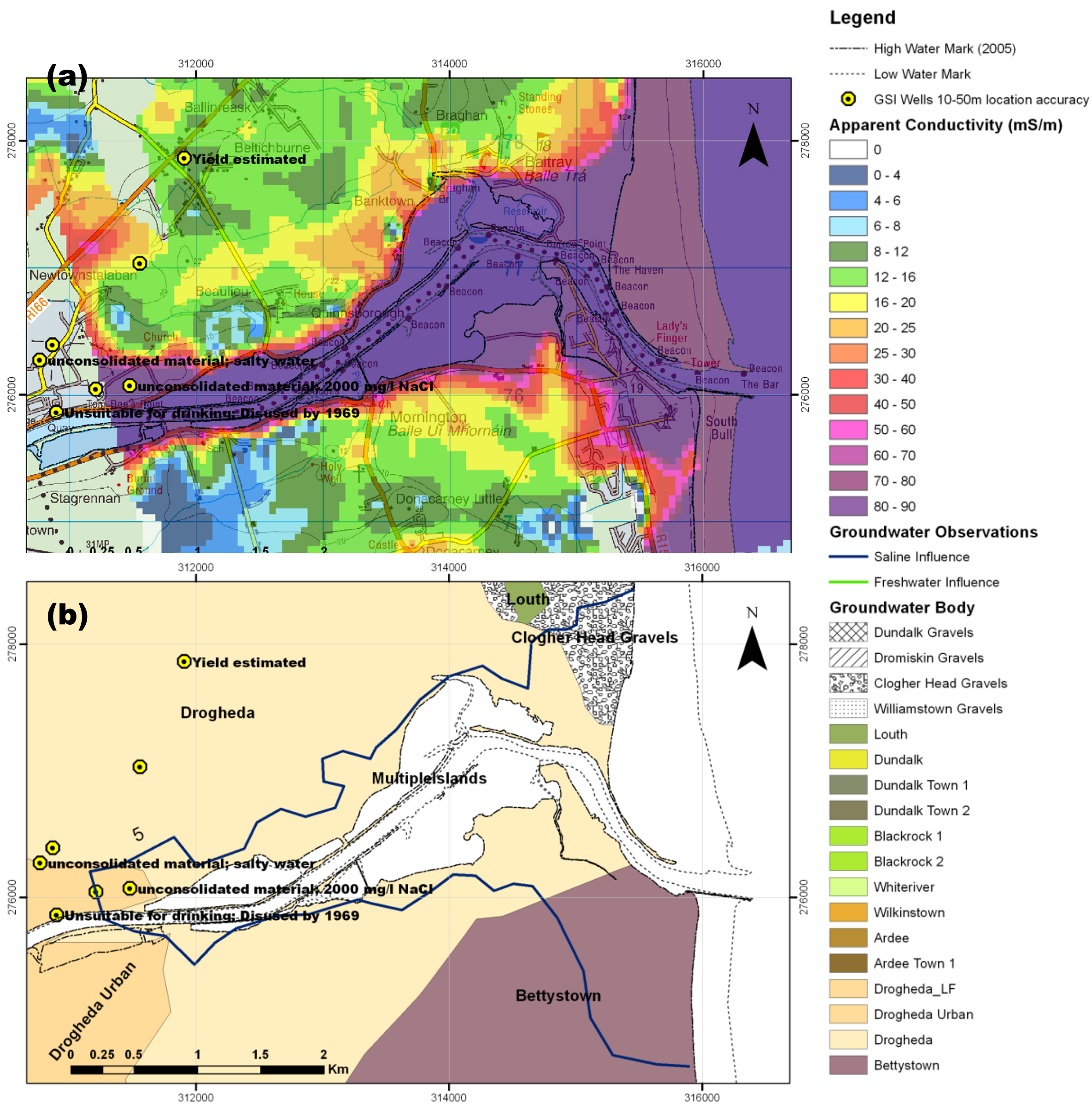


Figure 6.18: Boyne Estuary groundwater wells from the GSI well database labelled with comments as per the database notes overlying (a) EM apparent conductivity from 12 kHz frequency AEM data and (b)the GWBs (refer to feature No.7 on Figure 6.8).

A number of other areas exhibiting very high conductivities typical of saline influence are presented on the Summary Map in Figure 6.8 and include the marshland area at Blackrock in Co. Louth (No.8), the marine gravels at Greenore (No.9), and within sands and gravels at three locations along the south Co. Down Coastline (No.s 10, 11 & 12).

The AEM data has been shown to have a clear potential to investigate saline influences in the coastal zone, and the observations presented within this report can serve as a baseline study into fluctuations in saline influences that may arise as a result of changes in sea levels in the future.

6.2.4 Freshwater Saturated Offshore Sediments

Along the conductive saline coastline, the AEM data indicates some lower conductivities at a number of locations in the nearshore that may be related to storage of fresh/brackish water within sediments in the vicinity of some freshwater outflow points (e.g. Feature No.s 13 & 14, Figure 6.8). For example, Figure 6.19 indicates lower conductivities (black arrowed line) at the shoreline south of Omeath on the western shoreline of Carlingford Lough, where rivers/streams enter bay. Note that the large data gaps are due to survey flight height.

Various authors have examined freshwater-saturated sediments in saline environments (Belaval, 2003; Day-Lewis et al., 2006; Manheim et al., 2004) using towed marine ERT. A towed ERT profile (Marine ERT Line 5) was recorded across this feature and part of it is presented in Figure 6.20. It runs from southeast to northwest and indicates zones of slightly higher resistivities (0.5 – 1.5 Ohm-m) within the sub-seabed sediments. These are very subtle increases but possibly indicate a higher degree of freshwater saturation within the saline saturated sediments. Similar zones of higher resistivities within the sub-seabed sediments are visible in the towed ERT in areas of river/stream run-off. These are indicated by black circles in Figure 6.19.

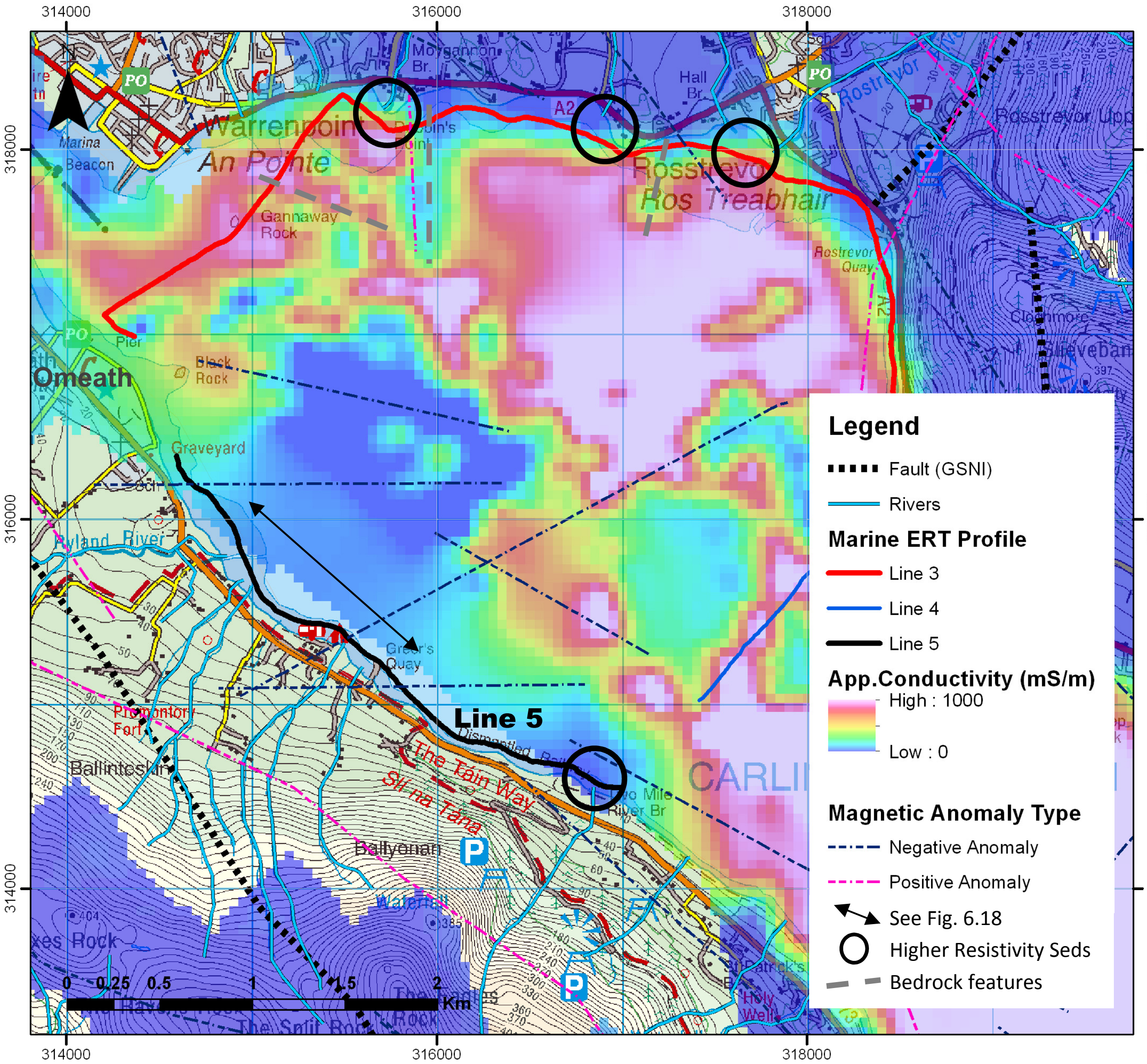


Figure 6.19: 12kHz apparent conductivity in Carlingford Lough. Low AEM conductivities south of Omeath indicated by black arrowed line (refer to feature No.13 on Figure 6.8). Dashed grey lines indicating linear low conductivity bedrock features.

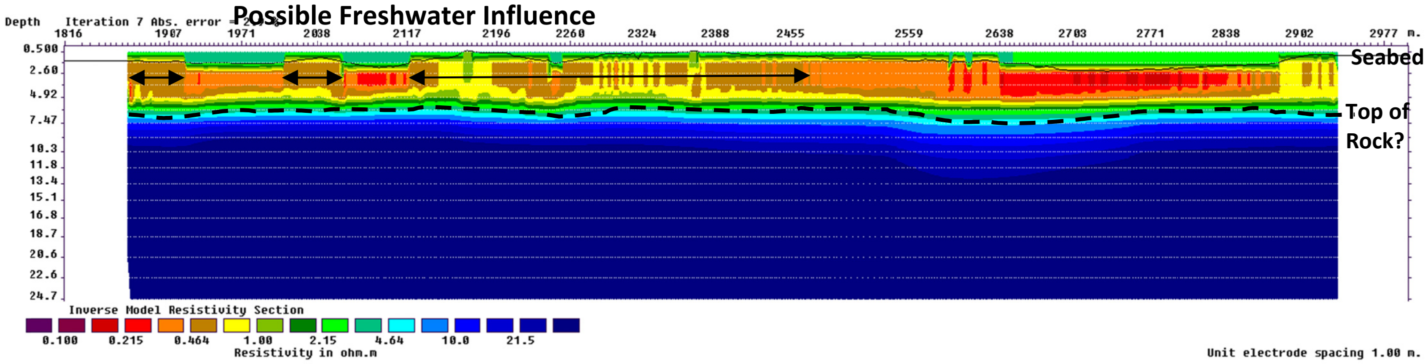


Figure 6.20: Marine ERT Line 5 along western shoreline of Carlingford Lough. Higher resistivity sediments indicated by black arrows. Dashed line indicates probable top of rock.

6.2.5 Other Offshore features in Data

A fault zone running offshore at Rostrevor, Co. Down was investigated as there appeared to be a zone of lower conductivity off shore, in line with the fault. ERT Line C (Figure 6.22) runs from northwest to southeast and indicates that the main fault or fault zone is located slightly further to the northwest of the mapped fault zone location (as indicated by the orange dashed line in Figure 6.21).

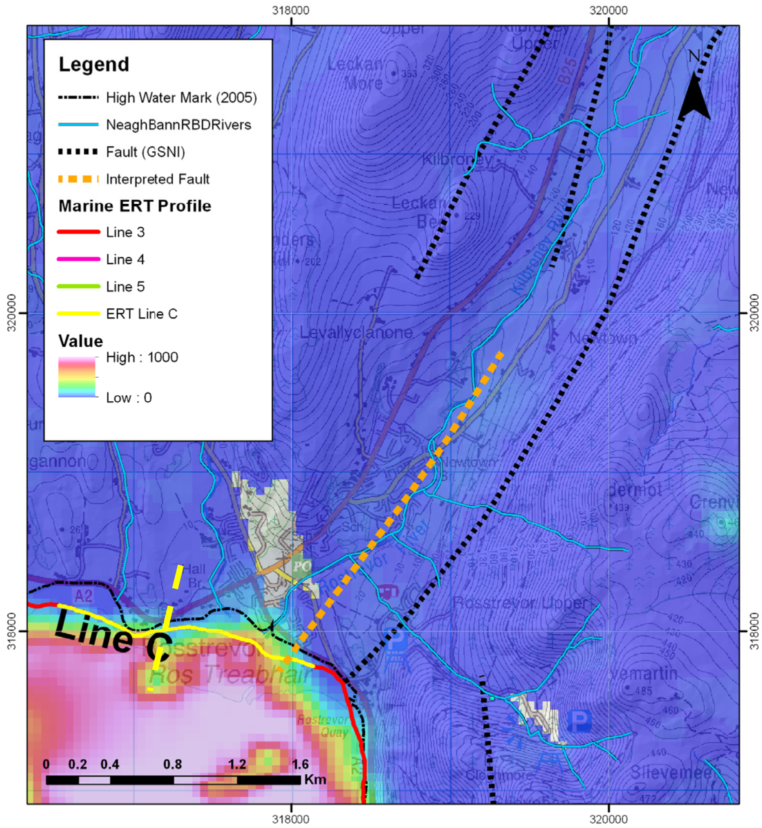


Figure 6.21: EM 12 kHz frequency showing fault locations and marine ERT survey Line C.

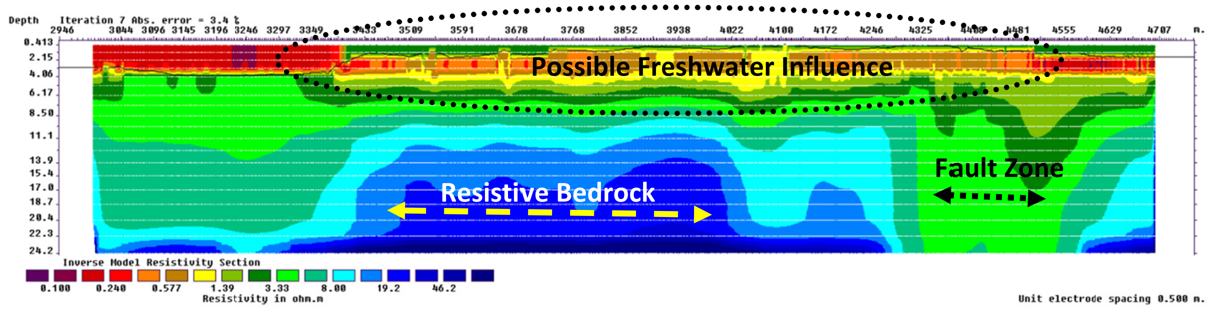


Figure 6.22: ERT Line C along shoreline of Carlingford Lough.

A number of other features extending offshore within Carlingford Lough are evident across the 12 kHz frequency AEM data as slightly lower conductivities within the very highly conductive seawater and sediments (Figure 6.19). Features highlighted as grey dashed lines in Figure 6.19 were examined in the towed ERT data and appear to be indicative of occurrences of higher resistivity bedrock such as on ERT Line C in Figure 6.22.

7. Discussion

The key objective of this project was to use the AM and AEM data to enhance the detection of the edges of anomalously magnetised or resistive bodies and lineaments associated with bedrock geological trends, fracture zones and basalt dykes that have the potential to identify structurally controlled groundwater pathways within the coastal zones of Dundalk Bay and Carlingford Lough.

Other objectives included analysis of the data to detect lineaments extending off-shore, potential submarine groundwater discharge locations, potential sites of saline intrusion with the possibility of delineating targets for future mineral exploration through this process.

7.1 Specific Project Outcomes

The specific outcomes of this project are summarised below:

- Interpreted airborne magnetic and EM filtered maps and interpreted terrestrial and marine electrical resistivity profiles have been compiled.

- A large number of previously unmapped magnetic lineaments have been identified. These exhibit a number of general strike trends; predominantly NW-SE and NNW-SSE with some approximate W-E and NE-SW strikes. Many dykes traverse the coastal zone clearly indicating bedrock structure in the nearshore. The mapped dykes also indicate a number of unmapped faults. This information can be used to assist in the updating of GSI geological maps.

- Though no specific mineral targets have been detected, the magnetic lineaments map has been forwarded to Dr. Norman Moles of the BGS research team for the critical metal potential of the Mourne Mountains project to investigate if there is any correlation between incidences of critical metals and magnetic lineaments.

- Various conductive soils and subsoils (e.g. alluvium, peat and Irish Sea Tills) have been identified within all frequencies of the AEM data, providing an extensive dataset to assist in soil mapping.

- Estimates of the apparent conductivity ranges for bedrock lithologies in the coastal area have been made based on visual inspection of the AEM data. In addition, some previously unmapped NE-SW Caledonian trending structures have been identified within the Silurian bedrock. This information confirms the role that the AEM data plays in providing information on bedrock lithology and structure.

- Offshore, along the conductive saline coastline, the AEM data indicates low conductivities possibly related to the outflow of fresh groundwater to the sea and to storage of fresh/brackish water within sediments in the vicinity of some freshwater outflow points.

- Onshore, high to very high apparent conductivity values (25 to >500 mS/m) have been observed along the coast, reflecting saline influence into sediments and possibly bedrock. Most significantly there appears to be a strong saline influence in both the Dundalk and Dromiskin Gravel GWBs. The observed saline influences presented within this report can serve as a baseline study into fluctuations that may arise as a result of future sea level rise.

7.2 Impacts

The key impacts of this project include:

- The airborne geophysical data provides a new layer of scientific data to assist in examining groundwater movement in the coastal zone. The research outcomes from this project present baseline datasets to assist the state with its obligations under (1) Water Framework Directive (2000/60/EC) and Groundwater Directive 2006/118/EC http://ec.europa.eu/environment/water/water-framework/index_en.html, (2) MSFD 2008/56/EC) http://ec.europa.eu/environment/water/marine/directive_en.htm , (3) the proposed Soil Framework Directive (http://ec.europa.eu/environment/soil/index_en.htm) and (4) the Nitrates Directive (http://ec.europa.eu/environment/water/water-nitrates/index_en.html), (5) EU Environmental Objectives (Groundwater) regulation 2010 (S.I No 9 of 2010), all of which will require baseline studies on groundwater flow and will feed into the management of existing Special Areas of Conservation (SAC), Special Protection Areas (SPA) and proposed National Heritage Area pNHA classifications in Dundalk Bay and Carlingford Lough.

- The AEM data has potential to act as a reconnaissance tool for future ground based environmental sensor technology to examine water fluxes and water quality in real time.

- The results of this project are presented in an attractive visual manner (within a GIS framework) for the facilitation of above mentioned environmental monitoring obligations.

- This project has allowed NUIG to gain expertise in processing and interpreting airborne geophysical data with the specific training of one researcher.

- The current SFI research centres call includes themes for Earth and Ocean Observation and Geoscience. It is envisaged that these centres are to be constructed from a hub and spoke model. Within the current Geoscience bid the results of this project fits nicely within two potential research spokes Marine Geosciences and Environment and Groundwater.

- Over the next year the results of this project will be presented as part of general outreach activities in the Ryan Institute at NUI Galway (which showcased environmental, marine and energy research activities to > 50,000 members of the general public in 2012). The upcoming Galway Science and Technology festival on Nov 24th could be an ideal opportunity to bring Tellus to the west, which last year attracted 25,000 + members of the public.

- Currently staff in Earth and Ocean Science in NUIG, are discussing the options for a second field trip to the Antrim basalts. We plan to include the Tellus and Tellus Border data with its online data viewer to introduce students to geological mapping and GIS data layers. The result of this project will contribute directly to two undergraduate modules from Jan 2014.

7.3 Future Work

Many of the observations in this report could warrant further investigation. Some recommendations for future work beyond the scope of this project include:

- Interrogation of the Tellus & Tellus Border data could be carried out across other coastal areas to investigate the occurrences of groundwater pathways across different superficial and bedrock geology types, structural geology settings and aquifer types.

- To categorise the bedrock lithology and unmapped geological features, a detailed assessment of the conductivity signature of bedrock lithologies from the Tellus & Tellus Border AEM data could be carried out in a similar approach to Beamish (2013).

- Drinking water sources in Co. Louth include public schemes and small private supplies. Many are close to the coastline and are groundwater sourced e.g. the Cooley public water supply scheme serving a population of 2,450 and a private well at Fitzpatricks Restaurant at Rockmarshall serving 200 people (EPA, 2013). Additional ground-truthing, integrating geophysical surveying with well, discharge and hydrochemical investigations could be carried out where drinking water supplies are located within zones that exhibit saline influences e.g. the Dundalk and Dromiskin Gravel GWBs. Ground investigations in tidal zones should be coupled with tide time data.

- Analysis of the Tellus & Tellus Border AEM data should be carried out over a wider area to investigate potential saline intrusion in to GWBs along the Co. Sligo, Co. Donegal and Northern Ireland coastlines in order to assess the potential risks to drinking water supplies and to provide a baseline study for future reference.

- The Tellus & Tellus Border AEM data would also be a useful component in integrated catchment management, providing information to assist in the characterisation of catchments.

- The shallow focus of the high frequency (25 kHz) AEM data could be combined with high resolution spectral imagery, e.g. the future European Space Agency Sentinel Program, in monitoring the critical zone.

- From an oceanography and marine biology perspective, the higher frequency AEM data could be examined with the potential for habitat mapping of sand dwelling marine organisms which rely on saline incursion along the sandy beaches of the Sligo and Donegal coastlines.

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Appendix I: Data Processing

Merged datasets for the Magnetic, Frequency Domain Electromagnetic (3 kHz and 14 kHz) and Radiometric surveys were provided by the GSI on the 1st May 2013. Clipped datasets for the Airborne Electromagnetic (900 Hz and 25 kHz) surveys were provided by the GSI on the 5th July 2013 with additional unedited data provided on the 20th August 2013.

The datasets include data from three different surveys as indicated in Figure 1.1: **CAV** the Cavan pilot study (2006); **TEL** the Tellus survey (2005 and 2006); and **TB** the Tellus Border survey (2011 to 2012). All have undergone data processing by Dr. Jim Hodgson of the GSI and Mohammednur Desissa Ture of the GSNI (Hodgson and Ture, 2013).

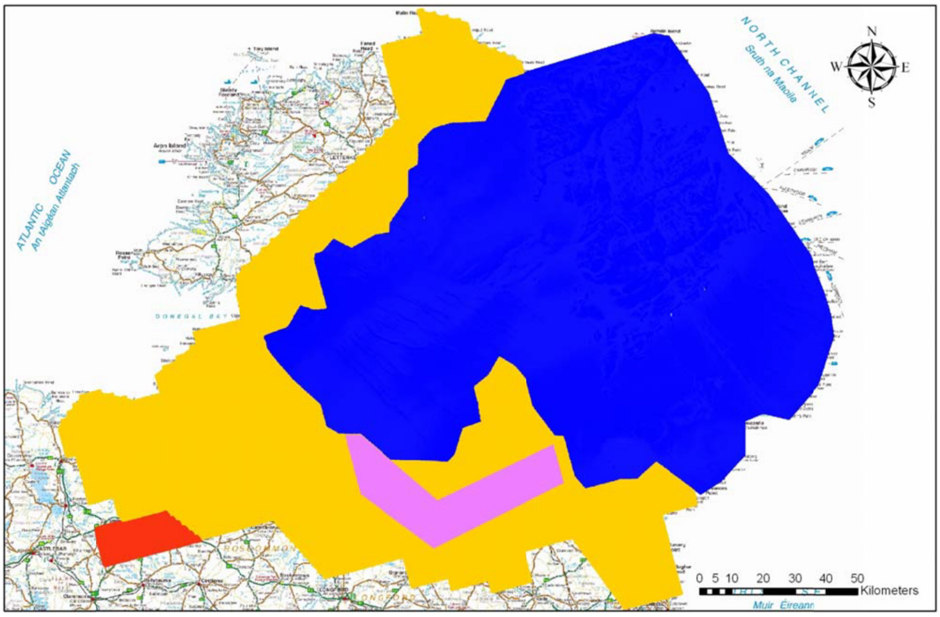

Fig.1.1. Taken from Hodgson and Ture, 2013. Survey locations, blue = Tellus, yellow = Tellus Border, pink = Cavan. The red block is an additional area called the Charlestown block surveyed in 2012.

The Cavan survey comprised 5,110 line km, the Tellus survey 80,458 line km and the Tellus Border survey 57,681 line km. The survey specifications included:

	Tellus & Cavan	**Tellus Border**
Line spacing	200m	200m
Line direction	345 degrees	345 degrees
Tie line spacing	2000m	2000m
Tie line direction	75 degrees	75 degrees
Min. survey altitude (rural)	56m	**59m**
Min. survey altitude (other)	244m	**240m**
Typical survey speed	70m/s	**60m/s**
Magnetic Sampling	0.1 sec	0.1 sec
Electromagnetic Sampling	0.25 sec	**0.1 sec**
Radiometric Sampling	1.0 sec	1.0 sec
GSP Positional Sampling	1.0 sec	1.0 sec
Magnetic/GPS base station Sampling	1.0 sec	1.0 sec
Radiometric total energy range	0.396 – 2.808 MeV	0.396 – 2.808 MeV
Electromagnetic Frequencies	**Phase 1 - 3.125 & 14.368 kHz**	0.912, 3.005, 11.962 & 24.510 kHz
	Phase 2 - 0.912, 3.005, 11.962 & 24.510 kHz	

Magnetic Data

The Tellus Border datasets were collected with a Scintrex CS-2 and a Geometrics G-822A.

Tellus Border Magnetic Data Processing

Data from the wing mounted magnetometer was used. The contract applied standard magnetic survey calibrations & corrections to the data. The contractor also carried out:

- height adjustment,
- tie line levelling and
- micro-levelling.

Diurnal corrections were applied to the data. The data was IGRF corrected using the survey date, the 2010 IGRF model and elevations above the GRS-80 ellipsoid.

Tellus & Cavan Magnetic Data Processing

The contract applied standard magnetic survey calibrations & corrections to the data. The contractor also carried out:

- tie line levelling and
- micro-levelling.

Diurnal corrections were applied to the data.
The Phase 1 data was IGRF corrected using the base station set-up date of 01/06/2005 based on the 2005 IGRF model and GPS_H heights above geoid GRS-80 ellipsoid at lat/long locations. The Cavan data was corrected using IGRF data calculated for 06/06/2006 and GPS_H heights above geoid GRS-80 ellipsoid at lat/long locations.

Merged Datasets

Levelled and IGRF corrected data for all three blocks were compared to assess offsets. Hodgson and Ture (2013)indicate that consistent offsets were found between the datasets. The three datasets were independently gridded using the minimum curvature algorithm and a 50m cell size (¼ of the flight line spacing).

Grid knitting was then carried out using the suture stitching method (Geosoft, 2013) with an output grid cell size of 50m. The suture stitching method defines a suture line at which to join the two grids. This line lies within the overlapping area of the two grids. The overlapping data either side of the line are removed from the final grid. This technique uses a multi-frequency approach whereby corrections are spread over the adjacent grids in proportion to the wavelength of the mismatch found along the suture line. This produces a smoother transition between grids irrespective of the amplitude and the wavelength of the features that the suture line traverses. Two stages of grid knitting were carried out as the Tellus and Cavan data do not overlap. De-trending was set to none for both grids. The merged grid was re-sampled into a 'Master' database.

The coordinates provided were Lat/Long and Airy modified 1965 Irish National grid.

Noise

The main source of noise within the data is cultural. Deculturing involving automatic and manual processes was carried out on the Tellus dataset. No deculturing was carried out on the Tellus Border & Cavan datasets. However all interpretations of the data take account of the cultural noise.

Pre-Processing

The merged Magnetic, Frequency Domain Electromagnetic, and Radiometric datasets were imported as Geosoft databases.

A rectangular polygon (BLOCK.ply) was constructed with Irish National Grid limits of: west 247500, east 356500, south 269000 and north 347500. The extent of the polygon is indicated in Figure 1.2. A smaller coastal area was constructed for more detailed analysis with Irish National Grid limits of: west 295000, east 328000, south 273000 and north 328000. The extent of the polygon is indicated by the shaded area in Figure 1.2.

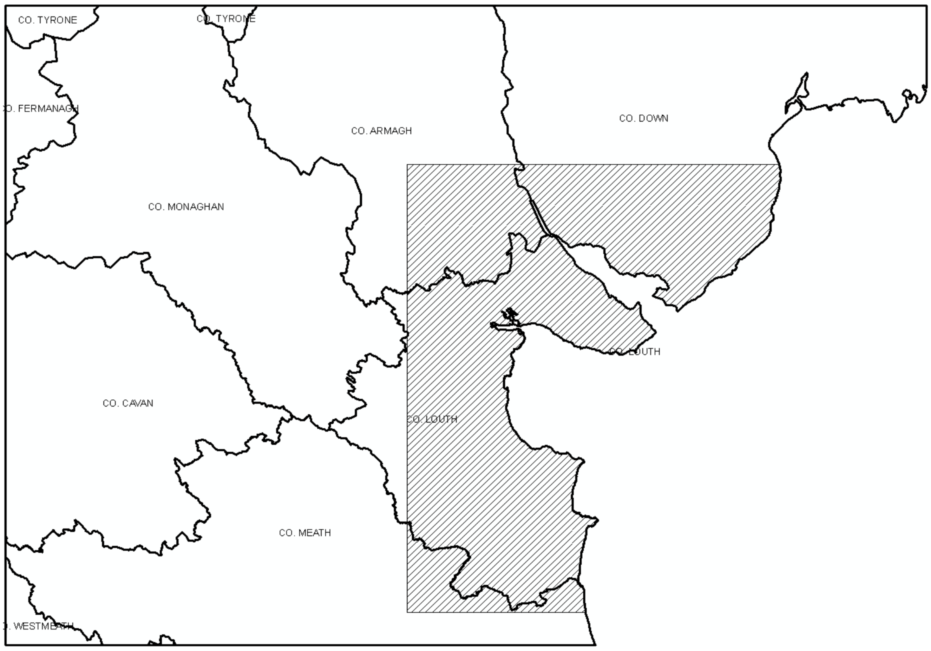

Fig.1.2. Block extents showing county boundaries.

The Magnetic, Frequency Domain Electromagnetic, and Radiometric databases were clipped to the polygon extents. The flight lines that cover this area are indicated in Figure 1.3.

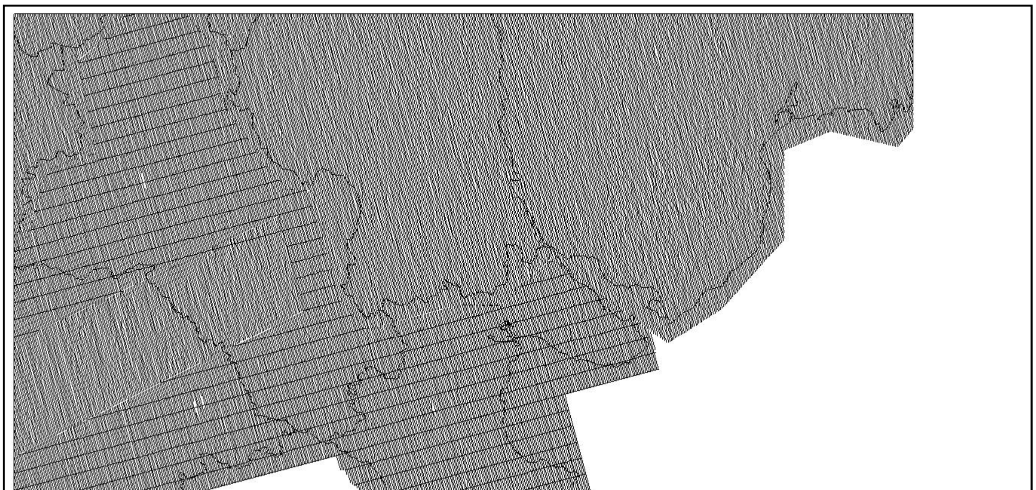

Fig.1.3. Flight Lines within the selected block. Tie line data is only provided for the Tellus Border region.

The clipped Magnetic database was taken as the main database. The Low and High Frequency Electromagnetic channels and the TH, K and U Radiometric channels were resampled to the Magnetic database locations.

Gridding was carried out using minimum curvature with a grid cell size of 50m (¼ of the flight line spacing).

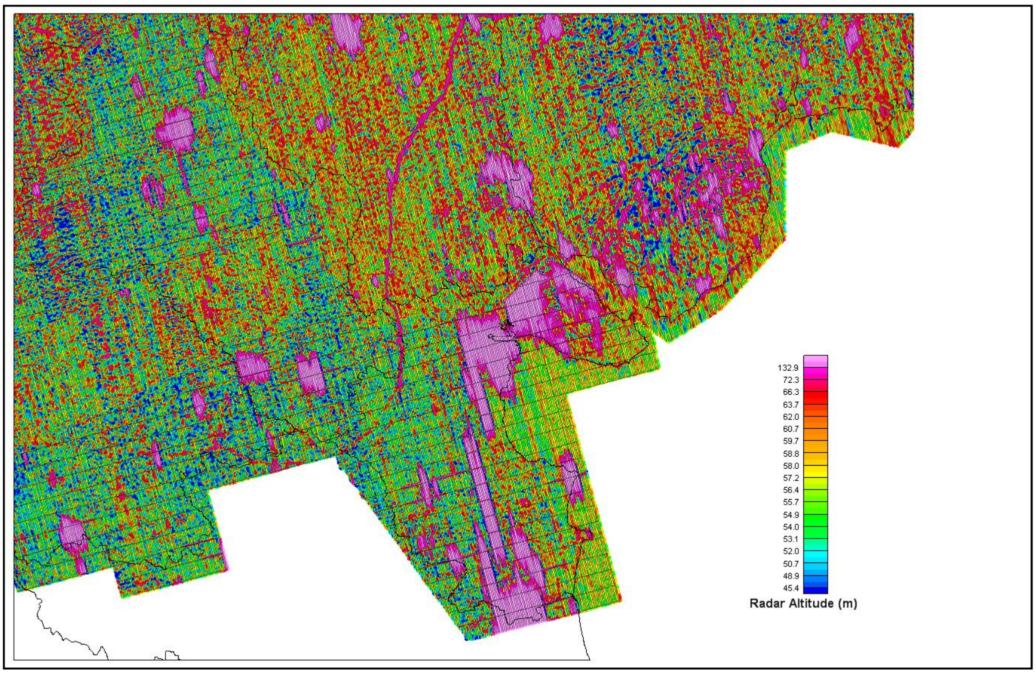

Fig.1.4. Gridded Radar Altitude data. High values indicate greater height above ground level which results in reduced resolution of non-potential field EM and Radiometric data.

Data Quality

Cross-over Error

Using the INTERSCT extension in Oasis montaj (Geosoft, 2013) the intersections between regular survey lines and tie lines of the merged datasets were assessed. For the TMI, EM_LF and EM_HF datasets, individual tables in the form of databases were constructed indicating the ground location of the intersection point, the tie line and survey line numbers, the recorded TMI/LF/HF value on each line, and the horizontal gradient of the data at that location. The intersection tolerance was set at 0 such that only points where lines actually intersect were assessed.

Statistical analysis of the difference in values at the intersection points are presented in tabular format below:

Statistical Analysis of Cross-over Errors			
	TMI (nT)	**EM_HF (mS/m)**	**EM_LF (mS/m)**
Number of items	13767	13767	13767
Minimum Value	-65.4	-7.2	-5.8
Maximum Value	65.4	7.2	5.8
Mean Value	0.0	0.0	0.0
Standard Deviation	1.671	0.2294	0.1612

The cross-over differences for the various datasets have been plotted if Figures 1.5, 1.6 and 1.7.

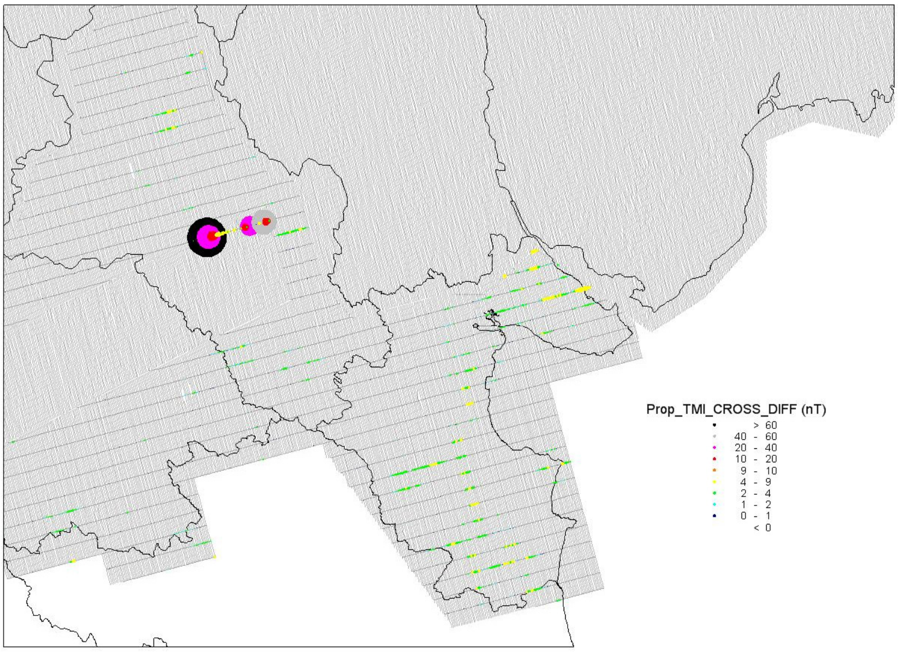

Fig.1.5. Plot of TMI cross-over error. The symbol colour and size reflect the magnitude of the error.

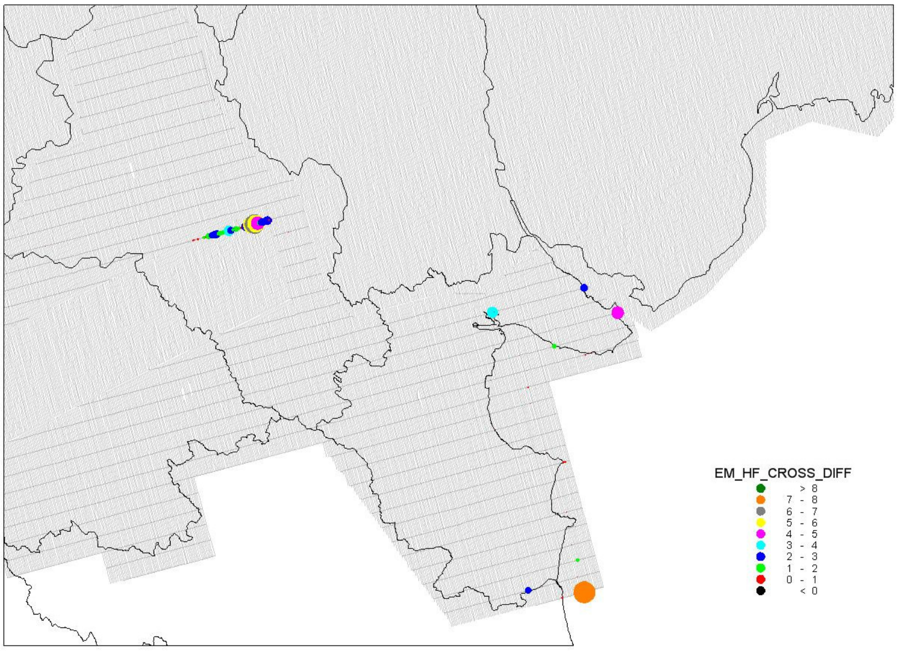

Fig.1.6. Plot of EM_HF cross-over error. The symbol colour and size reflect the magnitude of the error.

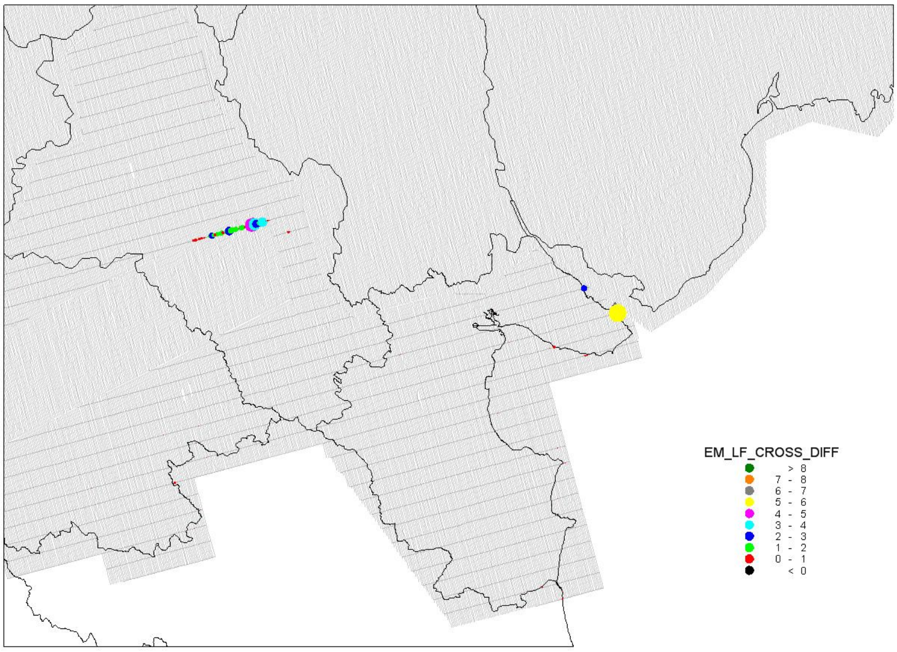

Fig.1.7. Plot of EM_LF cross-over error. The symbol colour and size reflect the magnitude of the error.

The TMI cross-over errors encountered in Co. Louth, in the southeast, are generally coincident with high-fly zones and variations in flight altitude between regular survey lines and tie lines (Figure 1.8). The values in the 2.5 to 5nT range are mainly over towns and motorways. Slightly higher values in the 5 to 10 nT range are predominantly located in the high-fly zones over the Mourne complex.

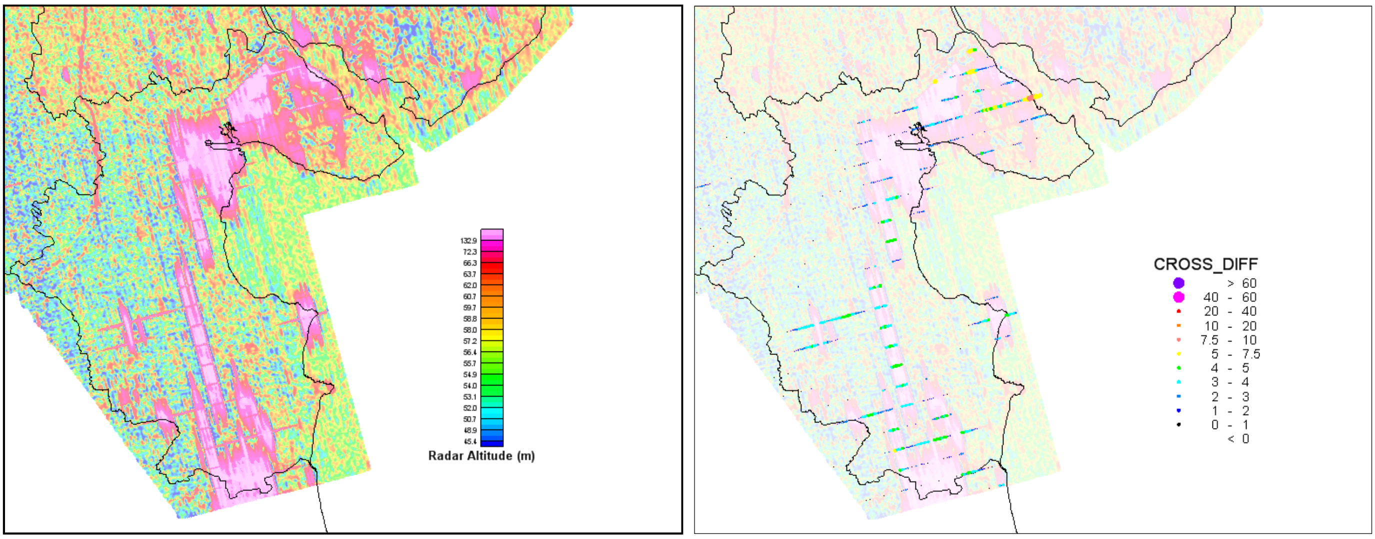

Fig.1.8. Plot of (a) RALT and (b) TMI cross-over error overlying RALT.

The highest cross-over errors occur on the 2011/2012 Tellus Border tie line T128 which transects the 2006 Cavan survey lines and also on T127 which is within the Tellus Border regular survey lines and which is not associated with a high fly zone (Figure 1.9).

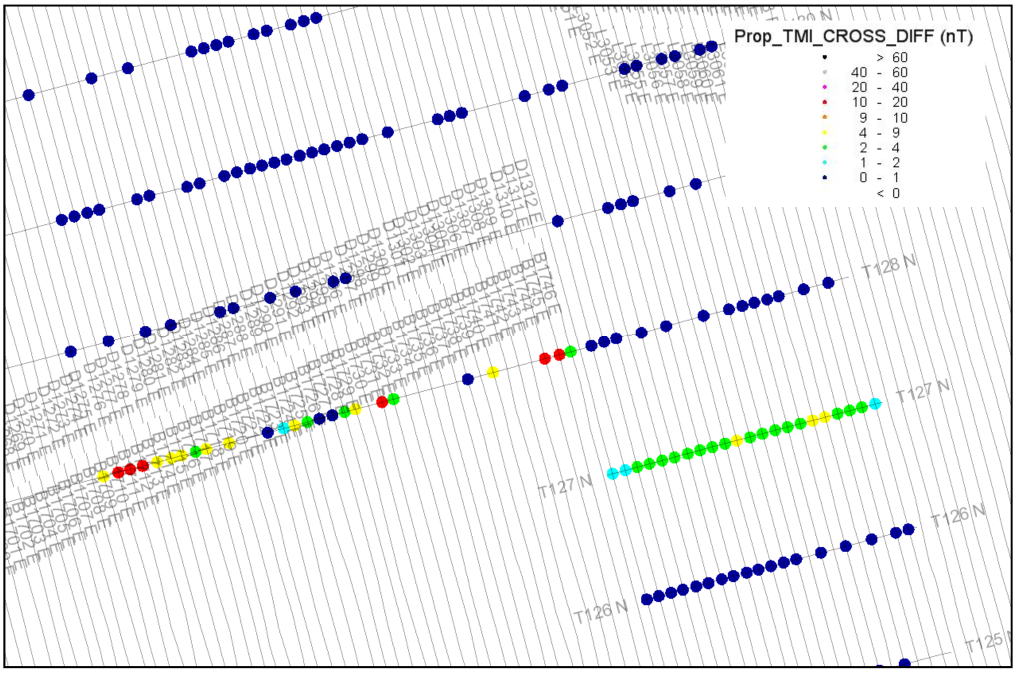

Fig.1.9. Plot of TMI cross-over error on tie lines T127 and T128.

Flight Line Selections

We can see in Fig.1.5 that only tie-lines for the Tellus Border data were provided. We have also seen that the cross-over error was limited to high-fly zones and tie-lines T127 and T128. In total there are 42 parallel tie-lines in the Tellus Border data of this block. To improve the smoothness of the dataset, it was decided to remove the tie-lines during processing and gridding of data.

Resampling of data

To process the data, the Magnetics database was chosen as the main database and the gridded EM and Radiometric data were sampled in to this database. The sampling interval for the magnetics was consistently 0.1sec across all three datasets (T, TB & Cavan) while the sampling interval for the EM varied from 0.1sec to 0.25sec and the Radiometrics was 1sec.

The resampled data was then compared to the original gridded data. As an example the EM_HF data is presented below. Fig.1.10 shows the original data gridded on the left and the resampled data gridded on the right.

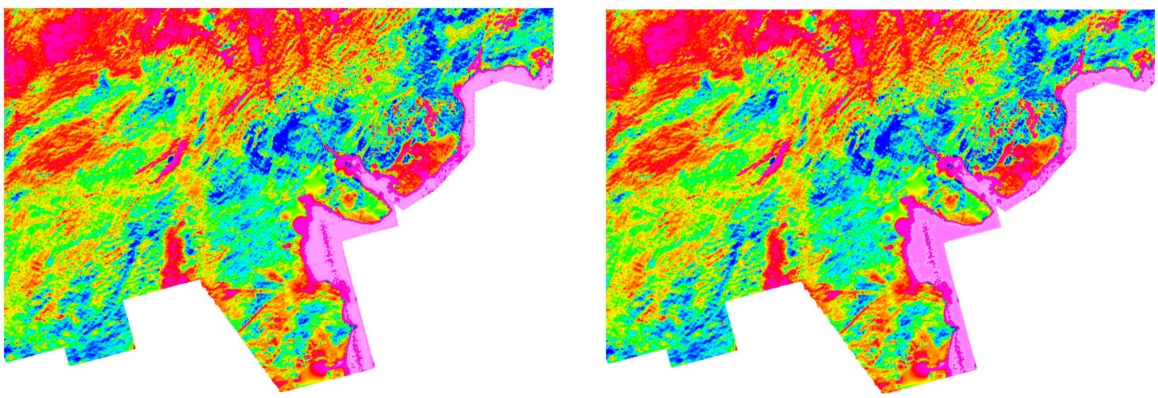

Fig.1.10. EM_HF original data gridded on the left and resampled data gridded on the right.

Figure 1.11 shows the difference between the two grids, calculated using the Geosoft 'Grid Math' function. While the gridded data have a range of values from -163.63 to 1196.71 mS/m, while the gridded differences are of the order of -1.2 to 0.6 mS/m, which are negligible. The mean value in the gridded difference data is 0.001 with a **standard deviation of 3.06**.The gridded EM_LF differences are of the order of -1.1 to 0.5 mS/m, which again are negligible. The mean value in the gridded difference data is 0.002 with a **standard deviation of 1.97**.

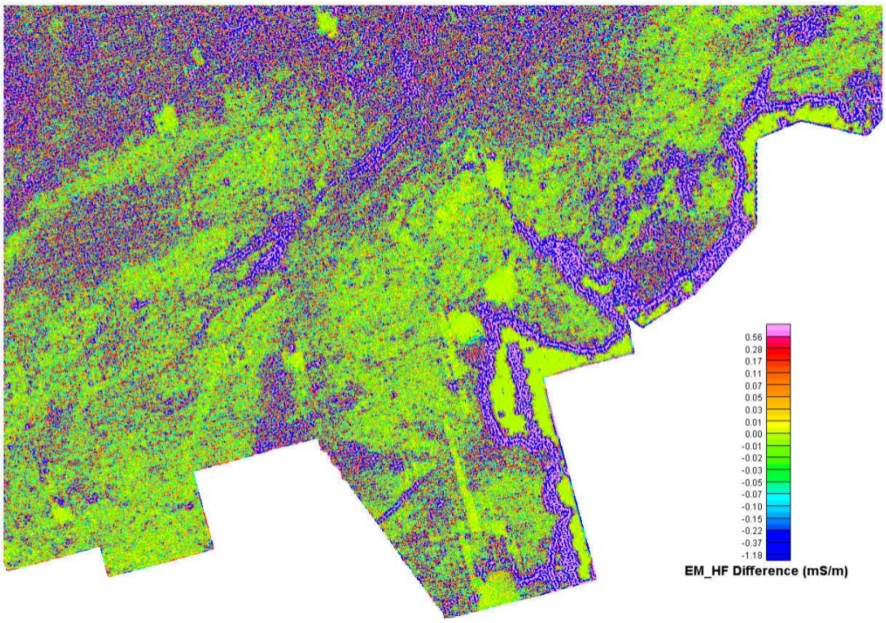

Fig.1.11. EM_HF difference between the two grids.

For the Radiometrics, the ranges are slightly different. As the sampling interval is greater, there is likely to be a higher degree of variation in the resampled data. The Total Count has been resampled and the difference is presented in Fig. 1.12. The range of values in the gridded original data is -327 to 7584. The mean value in the gridded difference data is 0.01 with a **standard deviation of 14.2**.

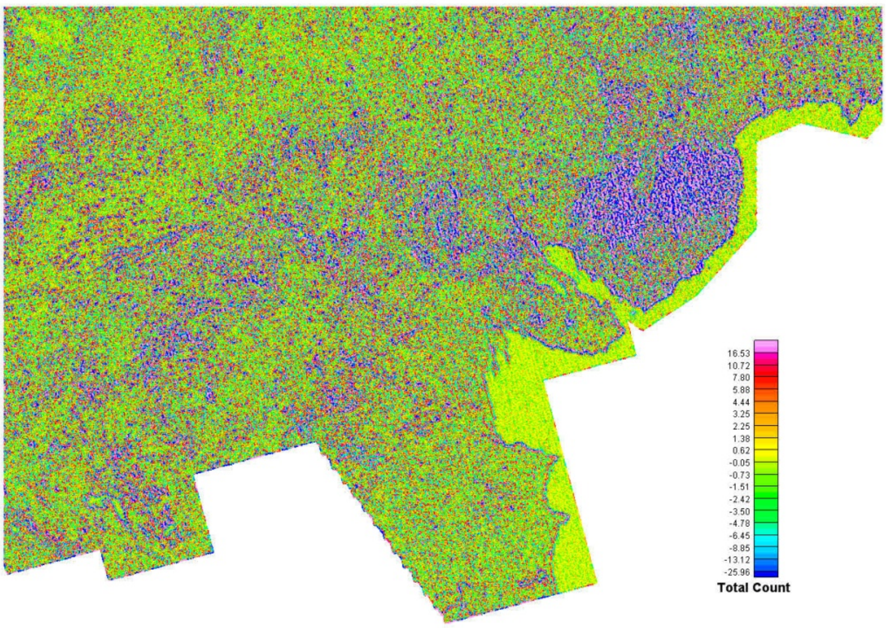

Fig.1.12. Radiometrics Total Count difference.

Screening datasets

Altitude has a significant effect on the skin depth of airborne EM and radiometric surveys (Beamish, 2004) and (Lee et al., 2001). As such it is important to clip the dataset to eliminate data recorded above an excessive altitude. Beamish and White (2012) describe the data screening of airborne EM data recorded across the Isle of Wight in which flight altitudes varied from a nominal altitude of 56m to 240m over urban area. Beamish chose a cut-off of 100m altitude. For this project I have also chosen to clip all radiometric, LF and HF EM values recorded above a survey height of 100m. The number of values in the EM datasets was 3,654,305. The number of values in the EM dataset with a 100m cut-off was 3,356,232. This amounts to an 8% decrease.

Beamish and White (2012) also chose a conductivity value cut-off of 500 mS/m to eliminate obvious cultural noise. The EM dataset with 100m cut-off ranges in value from -15 to 1088 mS/m. Taking 500mS/m as a cut-off, the number of data values is 3,124,440 which amounts to an additional 6.5% decrease. However, as much of the purpose of this project is to investigate the coastal region, which has a very conductive signature due to the salinity, the higher conductivities have not be filtered from the EM data used in this research.

Fast Fourier Transform (FFT)

A FFT was applied to the Residual Total Magnetic Intensity data**.** Following transformation into the wavenumber domain using the FFT, a number of filters were applied to analyse the data. These include:

For Potential Field Data:

- Reduction of magnetic data to the magnetic pole or equator.
- First/second/nth vertical derivatives.
- Upward/downward continuations to any horizontal surface.
- Tilt Derivatives.
- Analytic Signal.
- Conversion between different directional components of the field

The first step of the FFT involves gridding the basic data. The second step involved preparing the grid for FFT using *MAGMAP – Step-by-step Filtering – Prepare Grid* (Geosoft, 2013). The default settings were used during this process. A 1st order (linear trend) was removed. MAGMAP then used an algorithm to apply a 10% square expansion to fill the grid, creating dummy values, in preparation for the Fourier transform. The third step involved using *MAGMAP – Step-by-step Filtering – Forward FFT* which creates a grid file in which the expanded and filled grid is transformed to the Fourier domain which now allows for the application of various filters. Filters were defined using the *Step-by-step Filtering* function in *MAGMAP* (Geosoft, 2013).

Magnetic Data Enhancement

Reduction to Pole (RTP)

When assessing magnetic anomalies, if the magnetisation and ambient field are not vertical, the magnetic anomaly will be skewed (Blakely, 1995). Using the RTP technique, we can transform the measured total field anomaly into the vertical component of the field (Figure 1.13). Effectively RTP shifts anomalies laterally to be located over their sources and adjusts the anomaly shape such that symmetrical sources produce symmetrical anomalies.

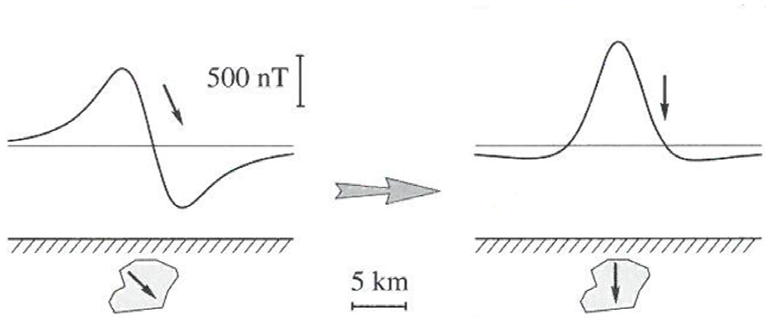

Fig. 1.13:.A magnetic anomaly before and after being reduced to the pole from Blakely (1995)

Reduction to pole requires input of the magnetic inclination and declination. The extension IGRF (Geosoft, 2013) was used to calculate the magnetic inclination and declination across the block.

The analysis is presented in tabular format below:

	Declination (degrees)	Inclination (degrees)
Number of items	5160535	5160535
Minimum Value	-5.883	68.060
Maximum Value	-4.117	68.641
Mean Value	-4.920	68.397
Standard Deviation σ	0.516	0.154

For the RTP analysis, a Reduction to Magnetic Pole filter was designed using the mean declination and inclination values of -4.920° and 68.397° respectively. The filter was applied to the fast Fourier transformed data.

Power spectrum analysis

The Fourier transform of the potential magnetic field consists of real and imaginary amplitude values as a function of wavenumber in cycles per ground distance unit. We can analyse the power spectrum of the transformed potential field, which when plotted logarithmically (Figure 1.14), can indicate 'ensembles' of anomalies manifested a straight-line segments on the log curves. These straight-line segments can be used to design filters that separate anomalies from differing depths. The relationship is defined by Spector and Grant (1970):

$$\log E(\kappa) = 4\pi h \kappa$$

where h is the depth in ground units and κ is the wavenumber in cycles/ground unit. The depth of an 'ensemble' of sources can be determined by measuring the slope of the power spectrum and dividing by 4π.

The Geosoft extension MAGMAP allows the automated calculation and display of the power spectrum.

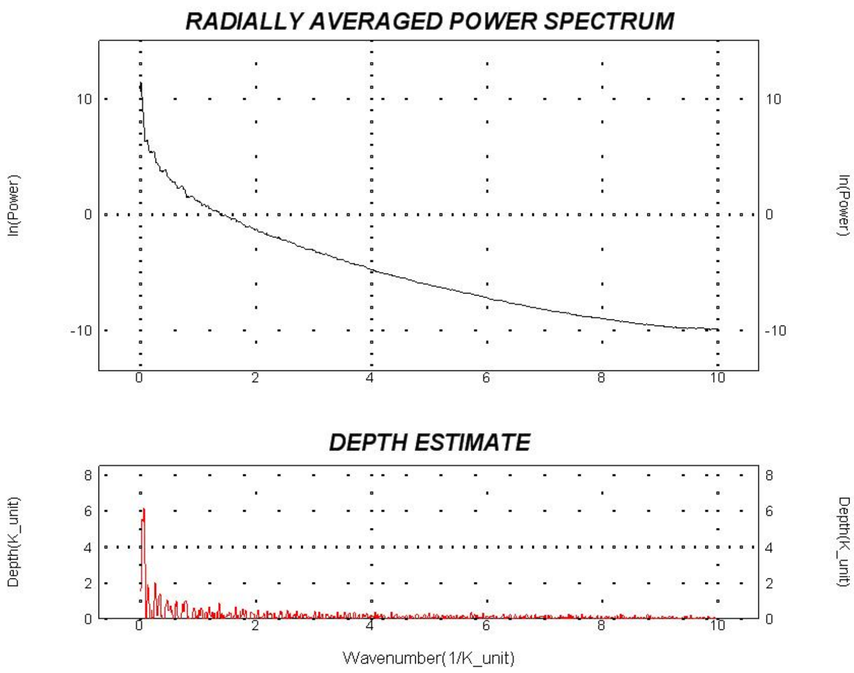

Fig. 1.14:.Calculated Power Spectrum

Typically, a power spectrum will have slopes associated with deep sources in the lower wavenumber range, shallow sources in the higher wavenumber range and noise which is at the highest range of wavenumbers. The calculated spectrum was analysed such that the following filters were applied:

Upward Continuation

Upward continuation can be used as a smoothing procedure for potential field data. It does not produce mathematical artefacts that might require additional filters to correct. It enhances the lower wavenumber content of the data and minimises the higher wavenumber noise.

The RTP data was upwardly continued to the levels 200 m, 250m, 500 m, 1000 m and 2000 m in order to examine the changes in the presence of high wavenumber data.

Downward Continuation

Downward continuation can be used to enhance higher wavenumber content. To apply the downward continuation, a low pass Butterworth filter was applied coupled with a downward continuation. Statistically, the mean radar altitude was 66.74 m. In order to examine the changes in the data, downward continuation levels of 10 m, 50 m and 68 m were used. The most effective downward continuation used the mean flight altitude 57m coupled with a 250 wavelength cutoff.

Analytic Signal

The analytic signal is a useful mapping tool for detecting edges of remanently magnetised bodies. It is derived through a combination of the horizontal and vertical derivatives which can be expressed as follows:

$$AS = \sqrt{(dz.dz + dx.dx)}$$

where *dz* is the vertical derivative and *dx* is the horizontal derivative. Using the MAGMAP extension (Geosoft, 2013), *dz* is calculated using the FFT process and the *dx* is calculated by applying a convolution filter in the space domain. The analytic signal is independent of the direction of magnetisation of the causative body (Blakely, 1995).

Vertical Derivative

The vertical derivative is used to enhance the higher wavenumber content of the data, highlighting shallow geologic sources in the data. The first and second vertical derivatives are used as general mapping procedures since they accentuate and help to resolve the edges of short wavelength sources.

Horizontal Derivative

The horizontal derivative enhances the higher wavenumber content of the data and is used in the identification of geologic boundaries in profile data.

Tilt Derivative

The tilt derivative is useful in edge detection and is formed by combinations of vertical and horizontal derivatives. It operates as an AGC filter, emphasising both weak and strong gradients in the geophysical datasets. The extension TILTDRV (Geosoft, 2013) is used and requires an input grid and produces a tilt derivative grid (TDR) and a horizontal derivative of the TDR. The vertical derivative *dz* is calculated using either the FFT or convolution process. Grids were produced in radians and subsequently converted to degrees where **1 degree = π/180 = 0.0174532925 radians**. The tilt derivative values range from -90° to +90°. The zero contours can be used to identify source edges e.g. faults and lithological boundaries.

As in (Beamish and Young, 2009) the magnetic data has been reduced to pole and upwardly continued to varying levels (200m, 500m, 1000m, 2000m, 5000m) prior to calculating the tilt derivative.

Electromagnetic Data Enhancement

The data were recorded in volts. The system used has a 40 Hz sampling rate which was later decimated to 10 Hz during processing. Four frequencies were recorded:

- 0.9 kHz (912 Hz)
- 3Khz (3005 Hz)
- 12 kHz (11962 Hz)
- 25 kHz (24510 Hz)

Each frequency has two components:

- levelled P (real or in-phase) in ppm
- levelled Q (imaginary or in-quadrature) in ppm

Both components are secondary to primary field coupling ratios (ppm units).

$P = Re = H_z/H_0$

$Q = Im = H_z/H_0$

Where H_z is the vertical anomalous field and H_0 is the horizontal primary field.

FEM Over-water Calibration

The frequency domain electromagnetic system was calibrated using a test site over Donegal Bay, in an area where water conductivity and temperature were measured several times over the years, at every meter from surface to sea floor, by the Irish Marine Institute. A detailed discussion on this calibration can be found in the SGL Technical Report Republic of Ireland 2011 – 2012 (SGL, 2012). Water depths were >60m. Analysis of the conductivity data from two different stations taken at three different years allowed the creation of a single layer model (half-space), which was employed to calculate the EM response for each component of each frequency, for the range of altitudes covered during the calibration flight using Airbeo software.

The results (Figure 1.15) indicate how sensitive the EM response is with respect to separation distance between the system and the water.

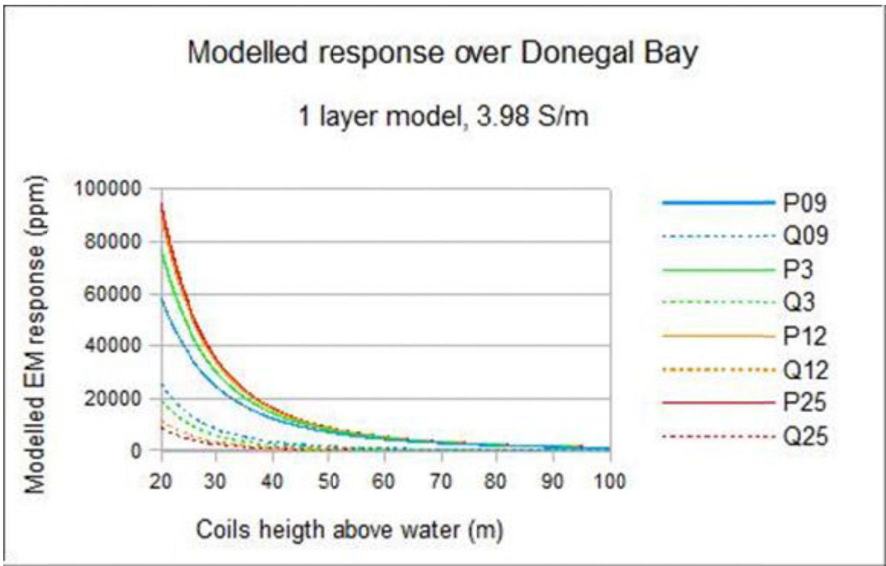

Figure 1.15: Modelled EM Response over Donegal Bay

Calculating Apparent Resistivity

Similar to the Tellus survey processing procedure, the in-phase and quadrature components of the EM survey were transformed to apparent resistivity and apparent depth for each frequency using a half-space model (Beamish et al., 2006). This transformation process used a program based on a GTK version of TRANSAEM.

Apparent resistivity was calculated using a look-up procedure which employs the in-phase and quadrature data components at each frequency (Hodgson and Ture, 2013). The process used was the same as in the Airbeo program (http://www.electromag.com.au/csiro.php). The ground was modelled as a single layer half-space assuming a constant lithology.

Hodgson and Ture (2013)indicate that heights of the lookup table were modelled from 16 meters to 240 meters below the surface at 2 meter intervals, while the resistivity sampling was from 0.001 ohm.m to 79,432 ohm.m using a uniform logarithmic sampling interval of 20 points per decade .

The apparent resistivity values were converted to an apparent conductivity using the reciprocal equation $\boldsymbol{\rho_a = 1/\sigma_a}$ where ρ_a is the apparent resistivity and σ_a is the apparent conductivity.

A number of filters and image enhancement procedures were applied to analyse the data. These included:

Horizontal Derivative

Horizontal derivatives are a measure of the rate of change in the two horizontal directions and can be meaningfully applied to non-potential data. The first and second horizontal derivatives were applied to AEM data.

EM Tilt Derivative

The tilt derivative (TDR) is typically applied to magnetic datasets but has recently been applied to electromagnetic data (Beamish, 2012b; Beamish et al., 2010). In Beamish et al. (2010) a tilt derivative was performed on EM data. Beamish writes that when the tilt derivative is applied to the airborne EM

data, it allows the identification of the centre and the width of conductive zones. However, the process may result in equal amplifications of the geology and cultural noise.

Beamish (2012b) states that:

> *'In the magnetic case, the depth scale of detection may only be limited by survey scale (and inherent signal/noise characteristics). In the electromagnetic case the depth scale of detection is largely related to frequency with the lowest frequency providing the largest depth of investigation. Deeper features tend to provide the lowest signal/noise gradients within a geophysical data set and it is the ability of the TDR response to define such features that potentially provides an enhanced mapping capability. Although the magnetic tilt derivative may be used to estimate depth to source, the more complex field interactions involved in the electromagnetic case preclude this option.'*

The TDR procedure was carried out on the 900Hz, 3kHz, 12kHz and 25kHz data. The tilt derivative values range from -90° to +90°. Beamish and Young (2009) indicate that the contours from 45° to 90° facilitate a representation of shallow and deep conductive zones.

Horizontal Derivative

The horizontal derivative enhances the higher wavenumber content of the data and is used in the identification of geologic boundaries in profile data (Geosoft, 2013).

Linear Filtering

Both Low Pass and High Pass linear filters were applied to the EM data to enhance the lower and higher wavenumber content.

Shaded Relief

Shaded relief can be used to apply emphasis to features that have a particular orientation eg, dykes and geological contacts. Using the GRIDSHAD extension (Geosoft, 2013) the illumination inclination (vertical) and declination (horizontal) angles must be specified, coupled with a vertical exaggeration scale factor. For this survey, the orthogonal declinations of 45° and 135° coupled with an inclination of 45° have been selected, as used by Beamish and Farr (2013).

Additional filters e.g. 3x3 Hanning and Laplace Convolution were also applied to the AEM data during data processing.

CET Grid Analysis

A free trial period of the CET Grid Analysis extension was utilised following data analysis. This is an extension for Oasis montaj created by Geosoft partners to assist in the detection of linear features. This process is ideally used to analyse magnetic data, however can be used on any geophysical dataset that may be representative of the geological structure.

Two analysis options are available –

Texture Ridges: where texture analysis is applied to identify areas of textural complexity in the data which are then assessed for axes of symmetry.

Edges: where edge detection is applied.

Edge analysis was applied to various data grids including e.g. Reduced to pole AM data, Analytic Signal AM data, Tilt Derivative AM data and EM data grids.

Texture Ridge analysis was applied to various data grids including e.g. Reduced to pole AM data, Analytic Signal AM data and EM data grids.

The analysis was useful in confirming strong trends within datasets however it was found that visual inspection of the filtered data using various combinations of overlying grids in ArcGIS provided greater amounts of information.

Dynamic Range Compression is an additional filter which is used to reveal subtle features within a dataset with a high dynamic range. It operates by applying a highpass filter, calculating the 2D analytic signal to determine the local phase and amplitude at each point, attenuating the amplitude by taking its logarithm with the final step being the reconstruction of the signal using the original phase values. Dynamic Range Compression was carried out on various AM and AEM gridded data.

Appendix II: GIS Data

The GIS compiled to date includes the following:

From the Geological Survey of Ireland –

- 10m DTM
- 500k Bedrock Geology
- 100k Bedrock Geology
- Bedrock Aquifers & Aquifer Classification
- Gravel Aquifers
- Karst Features
- Groundwater Vulnerability
- Borehole & Geotechnical Boreholes
- Wells
- Quarry Locations
- Mining Locations & Historic Mine Locations
- EMD Geophysics locations
- OS Maps – 600K, 450k, 210k and 50k
- 1:10560 Maps
- 2000 and 2004 Orthophotos

From the Geological Survey of Northern Ireland –

- 250k Bedrock Geology
- 250k Superficial Geology
- Aquifer Classification
- Gravel Aquifers
- Groundwater Vulnerability
- Mineral Occurrence
- Quarry Locations
- Shaft and Adit Locations

From the Environmental Protection Agency –

- Soils
- Subsoils
- River Basin Districts
- River SubBasins
- Hydrometric Areas
- Groundwater bodies
- Coastal Water Bodies
- Transitional Water Bodies
- Licenced Waste and IPPC Facilities
- UWWT Plant Locations
- Dumping at Sea Locations
- Land Usage

From the Department of the Environment of Northern Ireland –

- Areas of Natural Beauty (AONB)
- Area of Special Scientific Interest (ASSI)
- Groundwater bodies
- Lakewater bodies

Coastal Water Bodies
Transitional Water Bodies
Landscape Character Areas (LCAs)
Marine Nature Reserves (MNRs)
National Nature Reserves(NNRs)
Ramsar dites
SPAs
SACs

From National Parks & Wildlife –
SPAs
SACs
Natural Heritage Areas
Proposed Natural Heritage Areas

90m topographic data from the Shuttle Radar Topography Mission (SRTM).

Appendix III: Data Interpretation

Anomalous features selected following the preliminary assessment of the data are listed in the table below:

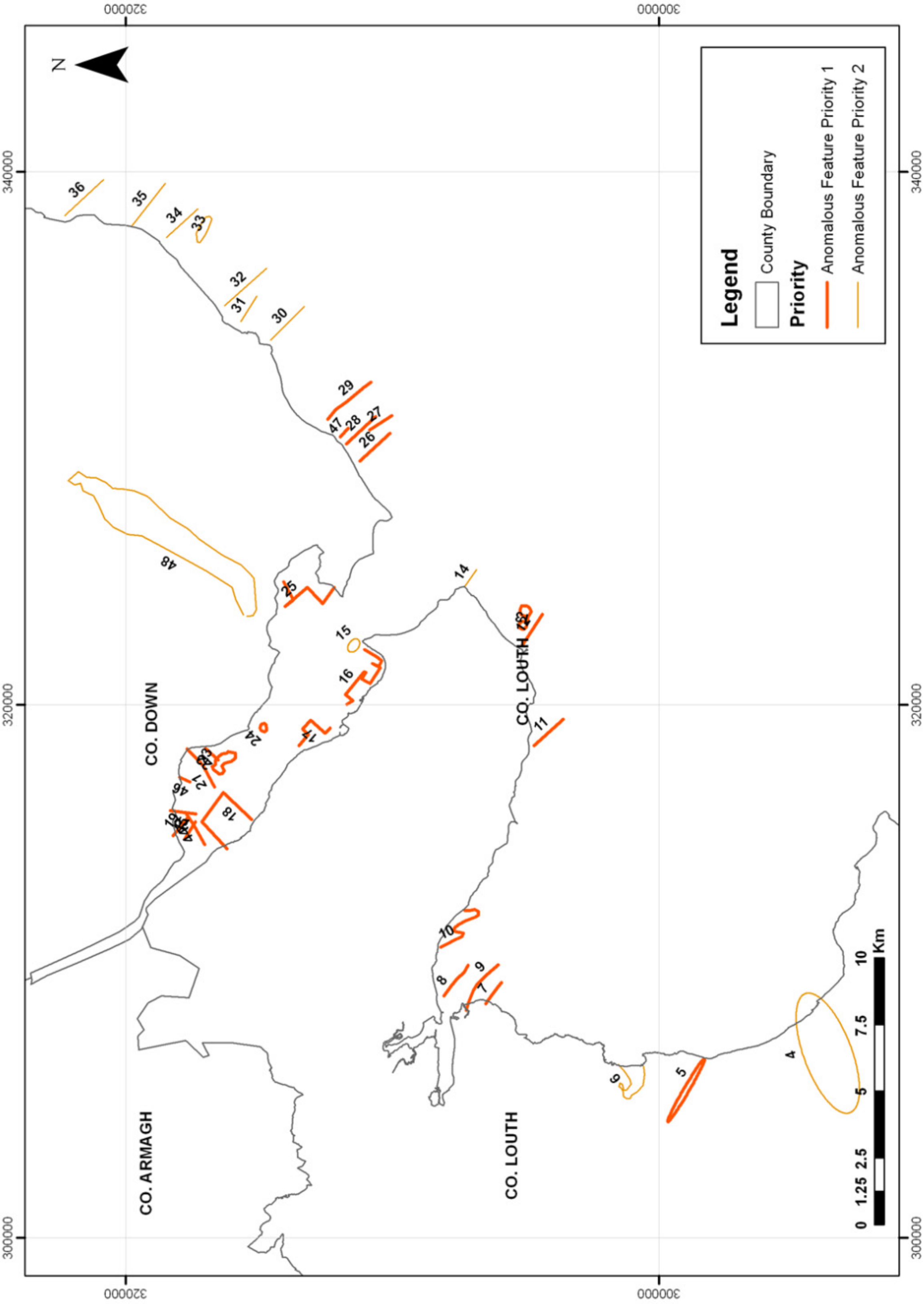

Figure 3.1 Location diagram of anomalous features identified following the preliminary analysis of the data.

Id	Object	Priority	AEM Frequency	Soils	Lgeology	Comment_4	Observation 1	Observation 2	Well_Info
4	Very High Conductivity	2	03/09	GLPSsS & IrSTLPSsS	Salterstown		Faults & High conductivities (saline) on low freq	Possible Saline Investigation	Well in zone poor yield (estimated 10.9m3d - but 32.7m3d in gravels @24.4m). Rock at 48.8m
5	High Conductivity	1	25/14/3	MGs	Clontail		Possible incursion of Saline - or FAULT		NW of zone Geotech BH to 17.5m - no rock.
6	High Conductivity	2	25/14/3	MGS & A	Clontail		Possible saline incursion - River nearby		No well info. Nearest to N. Poor yield (17.28m3d). Rock at 3m
7	Lower Conductivity	1	3/25	Mesc & MGs	Clontail or Dinantian		along -ve mag lineament		No well info. Nearest onshore poor 3.3m3d. no bedrock to 5.2m
8	Lower Conductivity	1	3 Mainly/25	Mesc & MGs	Clontail or Dinantian		along -ve mag lineament		No well info. Nearest onshore poor 3.3m3d. no bedrock to 5.2m
9	Lower Conductivity	1	3 Mainly/also 14/25	Mes c	Clontail	see Tilt & vert	along -ve mag lineament		No well info. Nearest onshore poor 3.3m3d. no bedrock to 5.2m
10	Lower Conductivity	1	25/14/3	Mbs	Dinantian		two faults - is it associated discharge	possible gravel aquifer near wetlands	No well info. Nearest onshore no bedrock to 8m. No yields
11	Lower Cond in Marine	1	25	GGr	Dinantian	Limestone	number of similar features around.	possible shallow groundwater_in line with mag	No well info. Nearest onshore EXCELLENT 550m3d. no bedrock to 36.6m
12	Lower Cond in Marine	1	25	TLPSsS	Dinantian	Limestone	number of similar features around.	in line with mag	No well info. SPRING onshore (intermediate spring yield) 1360m3d.
13	Lower Cond in Marine	1	25	TLPSsS	Dinantian	Limestone	local features?		No well info. SPRING onshore (intermediate spring yield) 1360m3d.
14	Lower Cond in Marine	2	25	TLPSsS	Dinantian	Limestone	number of similar features around.		No well info
15	Lower Cond in Marine	1	25	MGs	Dinantian	Limestone	local low	Strong on FEM_4Freq_25. Not on EMAP_F25	No well info
16	Lower Conductivity	1	14/3/25	MGs & Rck	Inniskeen & Dinantian		Possible fault or dyke alon mag lineament		No well info. Nearest onshore poor 9.8m3d. Bedrock at 4.6m, BH to 73.2m
17	Lower Cond in Marine	1	25	TGR/RckNCa	Iniskeen			potential mag link	No well info. Nearest onshore poor 6.5m3d. Bedrock at 6.7m, BH to 85.3m
18	Lower Cond in Marine	1	14/poss 25_slightly 3	TGR/Rck	Inskeen	Turbidite/shale	5 Rivers entering Lough	Traversing ERT May show freshwater in beach sands	No well info. Nearest onshore MODERATE 87m3d. Bedrock at 4.6m, BH to 109.7m
19	Lower Cond in Marine	1	14/no 25	Till	Hawick Group		Not on 3Hz-not linked to river	May be dyke related	GSNI_no well info
20	Lower Cond in Marine	1	14	Gravel/Sand/Silt_RBD	Hawick Group	Sandstone	Not on 3Hz-not linked to river		GSNI_no well info
21	Lower Cond in Marine	1	14/poss 25	Till	Hawick	Sandstone	Possible fault extension in to lough	No river entry	GSNI_no well info
22	Lower Cond in Marine	1	14/25	Till	Hawick	Sandstone	Possible fault extension in to lough	No river entry	GSNI_no well info
23	Lower Cond in Marine	1	14/25	RBDU/Till	Hawick	Sandstone	Large area of low values	No river entry	GSNI_no well info
24	Lower Cond in Marine	1	14	Till	Hawick Group	ERT	Shellfish Beds located here	Not on 25	GSNI_no well info
25	Lower Cond in Marine	1	14/3/25	RBDU/GSG	Hawick Group	Sandstone	EM tends to follow Mag lines_many rivers	sweep ERT_Beach gravels may show freshwater	GSNI_no well info
26	Lower Cond in Marine	1	25				parallel to dykes		GSNI_no well info
27	Lower Cond in Marine	1	14/3/slightly 25	GSG	Hawick	Sandstone	on 2 freqs and poss mag	Between Mag 251 and 252	GSNI_no well info
28	Lower Cond in Marine	1	25				parallel to dykes		GSNI_no well info
29	Lower Cond in Marine	1	14/3	GSG	Hawick	Sandstone	on 2 freqs and poss mag	Beside mag 53	GSNI_no well info
30	Lower Cond in Marine	2	14/3/25	GSG	Hawick	Sandstone			GSNI_no well info
31	Lower Cond in Marine	2	14/3/slightly 25	GSG	Hawick	Sandstone	on 2 freqs and poss mag	Along Mag 56	GSNI_no well info
32	Lower Cond in Marine	2	25						GSNI_no well info
33	Lower Cond in Marine	2	14/25	Till	Hawick	Sandstone	vissible slightly on 3		GSNI_no well info
34	Lower Cond in Marine	2	14/poss25	Till/GSG	Hawick	Sandstone	vissible slightly on 3	May be part of gravel aquifer	GSNI_no well info
35	Lower Cond in Marine	2	14/3/25	GSG	Hawick	Sandstone	parallel to dykes	PARALLEL TO MAG 328	GSNI_no well info
36	Lower Cond in Marine	2	14/3/25	GSG	Hawick	Sandstone	parallel to dykes		GSNI_no well info
44	Lower Cond in Marine	1	14	Gravel/Sand/Silt_RBD	Hawick Group		Not on 3Hz-not linked to river		No well info. Nearest onshore MODERATE 54.5d. Bedrock at 9.1m, BH to 54.9m
45	Lower Cond in Marine	1	14	Gravel/Sand/Silt_RBD	Hawick Group		Not on 3Hz-not linked to river	May be dyke related	GSNI_no well info
46	Lower Cond in Marine	1	14	RBDU	Hawick	Sandstone		No river entry	GSNI_no well info
47	Lower Cond in Marine	1	14	GSG	Hawick	Sandstone	poss mag connection		GSNI_no well info
48	High Conductivity	2	25/14/3/09	Till/GSG	Hawick/MNG4		25-100mS/m_valley_	Very high cond in this valley_broad	GSNI_no well info