A lithological assessment of the resistivity data acquired during the airborne geophysical survey of Anglesey, North Wales.

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Running head: Lithological signatures in airborne geophysical data

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Abstract

A recent airborne geophysical survey has provided high resolution estimates of the electrical resistivity of the near-surface and deeper (bedrock) formations found across Anglesey and a portion of the coastal area of North Wales. This single small survey provides new geophysical information on both the complex configuration of the Neoproterozoic and Cambrian bedrock units and the shallow near-surface geology and glacial features.

The correlation between the specific rock lithologies (bedrock and sub-glacial) and the derived bulk resistivities are examined. The geological classification of the geophysical data provides an assessment of 16 lithological units and allows baseline resistivity maps at a range of investigation depths to be constructed at 1:250k scale. The study indicates a broad age-dependence with the Palaeozoic (Carboniferous) bedrock units being the most conductive formations. More detailed studies are performed using statistical departures from the norms. The data have been used to identify sub-zones, within the existing lithological classification, that define statistically distinct groupings. The study shows that the Anglesey Blueschists of the Aethwy Complex are dissimilar (displaying higher resistivities and greater dispersion) to the main schistose zones within the survey area.

In the near-surface, the data map surprisingly continuous conductive and resistive zonations. Some of the conductive zones are shown to coincide with the mapped sub-glacial landforms (drumlins) deposited during the Devensian glaciations.

1. Introduction

Throughout the last decade, a series of multi-parameter airborne geophysical surveys have been undertaken in the UK (Peart el at., 2003; Beamish & Young, 2009; Beamish & White, 2011a; White & Beamish, 2011). The surveys acquired electromagnetic, radiometric (gamma-ray spectroscopy) and magnetic data at low altitude, and with a line-spacing of 200 m. These High Resolution Airborne Resource and Environmental (HiRES) surveys have demonstrated the high levels of precision achievable with airborne data. The data offer almost continual coverage over the survey area with sampling in the flight line direction better than every 15 m for airborne electromagnetic (AEM) data.

The present study considers the AEM data acquired during an airborne survey over the Island of Anglesey (Ynys Môn), North Wales. The survey area is a polygon of 1,198 km^2 (see Fig. 1) contained within a rectangle of 44.6 km by 35.25 km that encompasses the whole island and a coastal strip on the Welsh mainland.

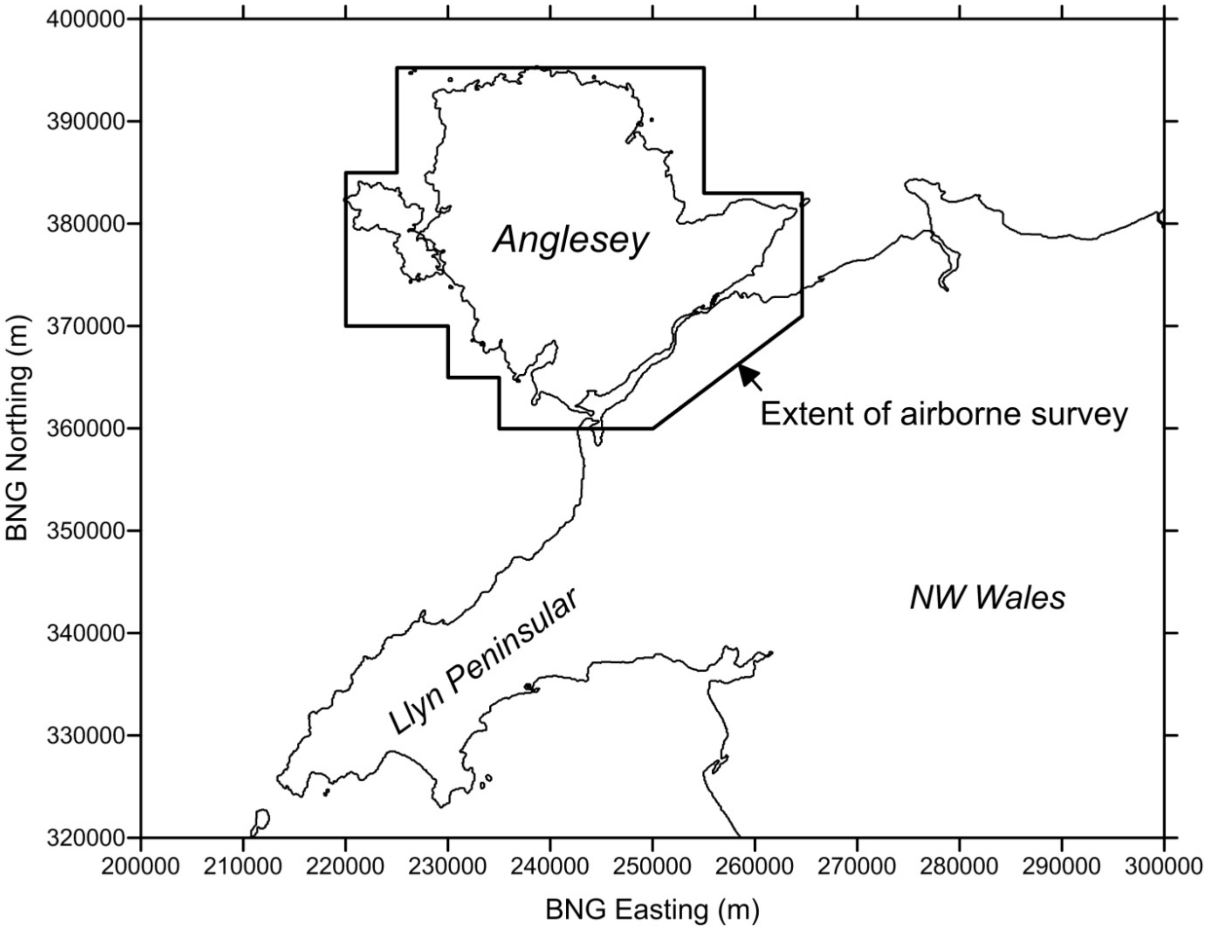

Fig. 1. *Location of the airborne geophysical survey area in relation to NW Wales.*

Our study presents the findings from the electromagnetic component of the survey; then assesses the extent to which these data contain bedrock lithological signatures. Beamish & White (2011b) previously presented the magnetic data acquired during the same survey.

HiRES data have previously been used to investigate the extent to which conductivity data acquired over the relatively young rocks of southern England relate to bedrock characteristics (Beamish & White, 2011c; Beamish & White, 2012). Here, the same procedure is extended to investigate the correlation of lithology with electrical resistivity over the older, hard-rock geology found on the Island of Anglesey. Adopting a generic lithological description of the rocks increases the portability of the technique and is most appropriate for geophysical attribution (Beamish & White, 2012). However, whilst Anglesey is a Precambrian and Cambrian domain overlain by a spatially incomplete Palaeozoic succession, its landscape and near-surface features were reshaped during the last ice age. Distinctive glacial landforms and deposits are widespread and the extent to which their distribution influences the geophysical response is also assessed.

The processed electromagnetic data provide an assessment of the bulk electrical conductivity, or conversely resistivity, of the near surface over four frequencies of investigation. This complete set of electromagnetic data offers an analysis over a range of sub-surface depths. AEM data are commonly utilised for mineral and resource exploration yet HiRES data from the UK have routinely been used as a tool to assess geological structure (Beamish et al., 2010). This study aims to define baseline resistivity values for the distinctive lithological units found on Anglesey. The assessment of the relationship between the geophysical response and the geology is undertaken with a GIS-based scheme. Geostatistical properties are determined as a function of lithology with central moments and measures of dispersion defined. This classification allows baseline apparent resistivity maps of Anglesey to be created. These then allow assessments of the degree to which the data are consistent with, or represent departures from, the norm.

Extending and refining this basic concept enables an analysis of how differing ages and origins can impact on the response from a single broad lithological classification. Particular focus is paid to the various schistose units within the survey area. Additionally, the predictive nature of the scheme is investigated through a comparison of the geophysical response from an equivalent lithology located on both Anglesey and the Welsh mainland.

2. Geological Setting

Anglesey (Ynys Môn) is a low-lying island located off north-west Wales, UK, and is well-noted as a complex geological setting where a targeted re-mapping program is currently underway (Phillips, 2009). The geology of the island was originally mapped by Greenly (1919) when the warped Precambrian rocks that dominate the island were described in detail (see Fig. 2a). Gibbons and Horak (1990) defined these metamorphosed Neoproterozoic rocks as the Monian Composite Terrane, and highlighted their distinction from the Cambrian rocks present on the mainland. However, subsequent work (Collins and Buchan, 2004; McIlroy and Horak, 2006) has shown that whilst most of the rocks are Neoproterozoic the Monian Supergroup (see Fig. 2a) is of Palaeozoic age in parts.

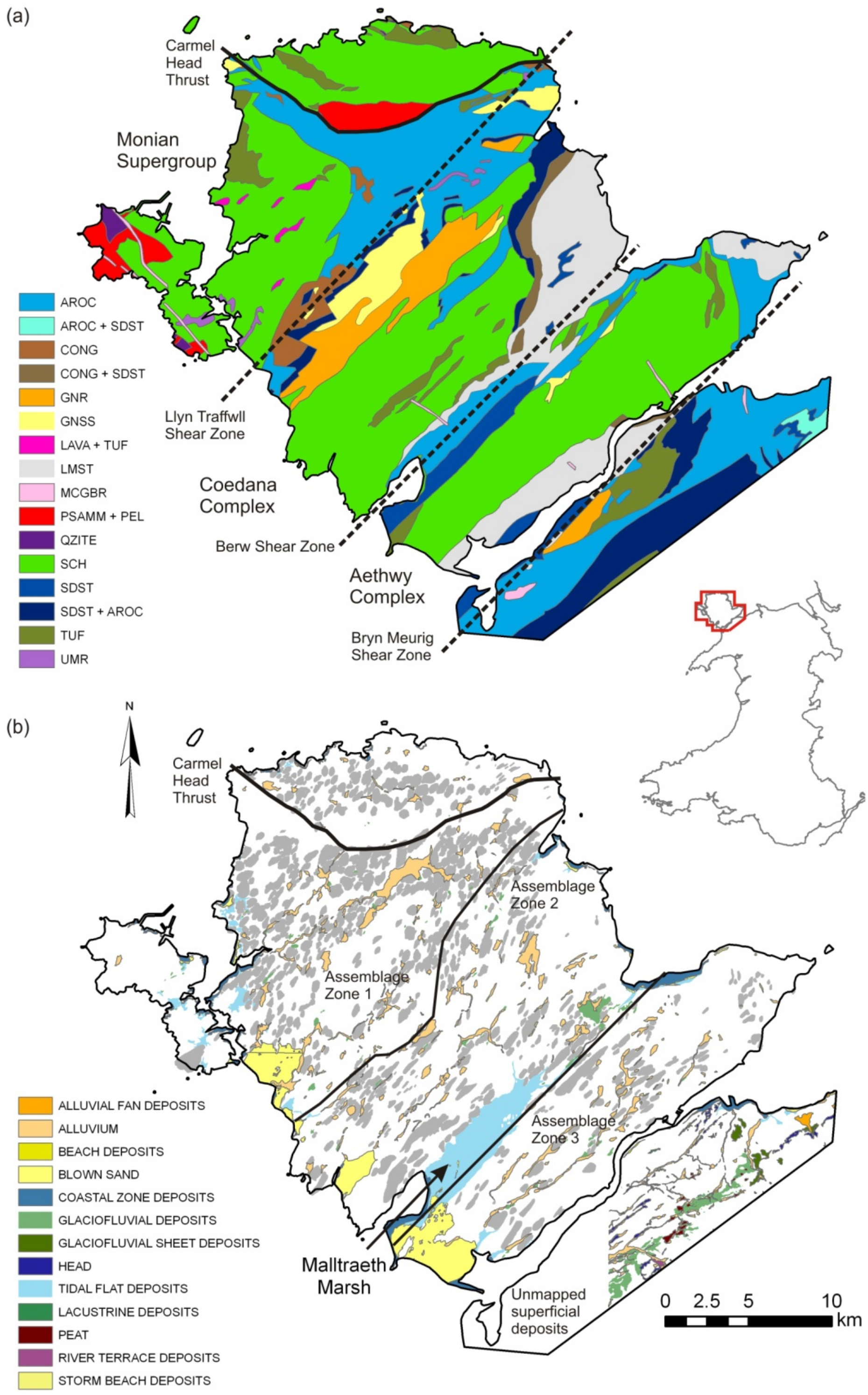

Fig. 2. *Geological maps of Anglesey at 1:250k scale. (a) The distribution of bedrock lithologies within the survey area. Major tectonic boundaries are displayed alongside the components of the Monian Composite Terrane. (b) Superficial deposits alongside the three assemblage zones of Anglesey which differentiate the sub-glacial sediment landform features. The locations of drumlins (Phillips et al., 2010) are overlain in grey.*

The Monian Composite Terrane is commonly broken down into three distinct components roughly separated by regional tectonic boundaries. In the south and east of Anglesey, the Aethwy Complex contains some of the world's oldest blueschists which are believed to have originated from the exhumation of subducted oceanic crust around ~550 Ma (Dallmeyer & Gibbons, 1987). To the north-west of the Aethwy Complex, across the ductile Berw Shear Zone, the exposed outcrop of the Coedana Complex consists of gneisses, schists and granitic rocks. These metamorphic rocks are the upper amphibolite facies found on Anglesey. The brittle Lynn Traffwell Shear Zone to the north-west of the Coedana Complex forms the boundary with the neighbouring Monian Supergroup which reaches a maximum metamorphic grade of greenschist facies. Further complicating the picture, parts of the Monian Supergroup outcrop extensively over Anglesey and are not restricted to this NW region; a consequence of significant rotation about the Carmel Head Thrust in the north of Anglesey. The most important tectonic boundary in the study area is the fault system that coincides with the Menai Straits, separating Anglesey from the Welsh mainland. This zone divides the British Avalonian rocks to the south from the Monian Composite Terrace seen on Anglesey. This separation makes the continuation of any predictive geophysical mapping scheme onto the mainland a challenge.

Overlying the Precambrian and Cambrian are the remains of a Palaeozoic succession comprising: (i) an Ordovician-Silurian sedimentary basin located primarily in a Y-shaped region in central Anglesey; (ii) a Silurian to Devonian red-sandstone fluvial deposit; and (iii) a Carboniferous limestone sequence with sandstone units and coal measures (see Fig. 2a). The classification of bedrock in this study is undertaken using 1:250k scale digital data for bedrock geology (British Geological Survey, 2005; Smith, 2011) based on mapping conducted prior to the current re-surveying program. Locally, a significant number of quasi-linear cross-cutting features (NW – SE trending) are seen in the magnetic data (Beamish & White, 2011b) and represent a largely concealed, near-surface, intrusive Palaeogene dyke swarm originating offshore.

Throughout substantial periods of the Devensian Glaciation, the UK and Ireland were covered by the British and Irish Ice Sheet. Several ice streams have been identified as draining the margins of the British and Irish Ice Sheet at this time. Ice streams are corridors of fast flowing ice which work to control the size and movement of ice sheets. Anglesey was coincident with the Irish Sea Ice Stream (ISIS) which served to create the distinctive surface features seen there today. The ISIS had a predominant flow direction from NE to SW and carved ridges into the landscape (highs and channels) that provided the accommodation space for later Holocene deposits. Significant sub-glacial landforms are present on Anglesey as a consequence of the period, shown in grey in Fig 2b. Phillips et al. (2010) describe how bedrock geology influenced the landform distribution beneath the ISIS and highlighted the relationship between the spatial frequency of sub-glacial landforms and the underlying geology. Thomas & Chiverrell (2007) defined three sediment-landform assemblage zones on Anglesey which are approximately coincident with the Monian Supergroup and the unconformable Ordovician sequence overlying it (zone 1), the Coedana Complex (zone 2) and the Aethwy Complex (zone 3); these are highlighted in Fig. 2b. Zone 1 displays major sub-glacial deposition in the form of extensive drumlin fields whilst zone 2 is noted principally for erosional landforms (bedrock ridges). Zone 3 is more complex and contains both erosional and depositional sub-glacial landforms in the form of isolated drumlins and bedrock ridges. Drumlins, elongate in the direction of ice flow, are noticeable for a reduction in their frequency from north to south. The drumlins themselves are defined by a topographic (raised) form but their internal architecture may vary massively with structures ranging from thick till layers to very thin till deposits overlying a bedrock core. The till itself comprises angular bedrock pieces in a sandy to muddy matrix; it is thought to be representative of the underlying geology (Phillips et al., 2010). As such, the electromagnetic response from individual drumlins is expected to vary and relative positive or negative resistivity features may be encountered depending on the specific construction.

An assessment of the extent to which sub-glacial landforms influence the electromagnetic response is undertaken in this study. Anglesey proves to be an excellent location for this analysis for two major reasons: the geology was not significantly modified during ice retreat and since the island is reasonably low-lying the topography only had a minor influence on ice flow. Alongside these significant sub-glacial deposits a pervasive, thin till layer is encountered over much of Anglesey. Due to the limited depth profile of this accumulation, and its bedrock composition, it is expected to provide only a small, common, shift in the resistivity data.

Additional 'non sub-glacial' superficial deposits are spatially limited above the high tide mark (British Geological Survey, 2010), where analysis is undertaken for this study (see Fig. 2b). Over the centre of the island, some alluvium deposits are present at stream and lake locations whilst limited glaciofluvial deposits are also charted. Thin blown sand and coastal zone deposits are also sparsely mapped in some coastal locations. Beamish (2012) considers the effect on the electromagnetic data from the most significant post glacial (Holocene) deposits, a region of salt loaded silty tidal flat deposits now protected by tidal gates. This area, known as the Malltraeth Marsh (see Fig. 2b), contains Holocene sediments over 20 m thick in places.

A geological classification of a geophysical measurement requires an existing categorisation provided by a geological lexicon. The 1:250k scale digital bedrock geology (British Geological Survey, 2005) is used as the basis for the lithological classification on Anglesey. At this scale the geological interpretation is generalised from 1:50k data and provides a guide to the geology on a regional scale applicable to airborne measurements. The mapping provides a unique RCS code defining 16 distinct lithological units, described in Table 1. Due to the broad nature of the lithological description in the geological lexicon some classifications are wide-ranging e.g. Schist describes fine grained foliated rocks with varying degrees of schistosity. However, this generic description of rock lithology is assumed to be the most appropriate scheme for geophysical attribution at medium to large spatial extents (Beamish & White, 2012). At this scale, maps highlighting the statistical nature of the geophysical data can be used to infer the degree to which individual measurements are consistent with, or depart from, the norm. The distribution of these lithological units is shown in Fig. 2a whilst Table 1 identifies the number of data samples taken over each unit. Table 1 reveals that some units are poorly sampled and considering the footprint of an airborne measurement any statistical result derived from these data may not be significant.

***Table 1**. The distinct lithologies found on Anglesey alongside the number of samples (N) acquired over each lithology by the AEM component of the geophysical survey. Lithologies displayed in italics are considered to be poorly sampled and the results of geostatistical analysis should be considered with caution.*

Lithology	RCS	N (AEM)
Siliciclastic argillaceous rock	AROC	53260
Siliciclastic argillaceous rock & sandstone	AROC+SDST	548
Conglomerate	CONG	4117
Conglomerate & sandstone	CONG+SDST	2491
Granitic rock	GNR	11298
Gneiss	GNSS	6964
Lava & tuff	LAVA+TUF	593
Limestone	LMST	27177
Mafite	MCGBR	1232
Psammite & pelite	PSAMM+PEL	5582
Quartzite	QZITE	769
Schist	SCH	111382
Sandstone	SDST	6396
Sandstone & siliciclastic argillaceous rock	SDST+ AROC	16718
Tuff	TUF	12631
Ultramafic rock	UMR	983

3. Geophysical Survey of Anglesey

The HiRES survey of Anglesey was carried out between 12th and 18th of June 2009. Over 6000 line km of data were acquired using a fixed-wing, twin engine DHC-6/300 Twin Otter. Beamish & White (2009) and White & Beamish (2010) describe the acquisition and processing procedures. 223 parallel flight lines were flown, in a N-S direction, in order to cross-cut the dominant geological trends (NE-SW and NW-SE). All the data were acquired and processed in the British National Grid (BNG) coordinate system.

The polygon covered by the airborne survey (Fig. 1) contains a significant extent of seawater. The resistivity of seawater is very low (~0.25 ohm.m) in comparison to geological material so the survey data are cut to the coast, at mean high tide, for the purposes of this study.

3.1 Electromagnetic data

Leväniemi et al. (2009) describe the four frequency (0.9, 3, 12 and 25 kHz) AEM system employed on the survey. The depth of investigation of the system decreases with increasing frequency. For each frequency the recorded data consist of coupling values of secondary to primary field ratios. After application of a non-linear drift correction and standard levelling procedures an estimate of the apparent, half-space resistivity is determined at each frequency through an accurate implementation of the Fraser transform (Fraser, 1978). This step has the added benefit of removing the altitude dependence from the data.

AEM measurements produce an average of the bulk resistivity over a complex volume beneath a surface area typically less than 0.01 km^2 (Beamish, 2004a; Beamish, 2004b). This average resistivity is, in a clean formation, proportional to the resistivity of the pore fluid in place (Archie, 1942). In practice, formations are never perfectly insulating and the presence of clay produces a measurable change in the bulk resistivity of the formation. This change, in materials which display similar porosity and saturations values, can often be used as a direct measure of clay content. It is noted that the apparent resistivity is calculated as the reciprocal of the apparent conductivity.

The complete cut-to-coast data set is subjected to survey-specific conditioning procedures to improve the data quality. Previous studies have indicated that urban environs generate less reliable results due to the concentration of man-made conducting structures. As such, the road network (A and B roads) and power line routes are buffered with a 70 m exclusion zone and all data from a survey altitude of greater than 100 m are excluded; effectively limiting the data to rural areas. The final conditioned AEM data set for Anglesey contains 237,371 measurements. Depths of investigation are complex and a function of the vertical resistivity distribution in the subsurface, in addition to the flight altitude, and the frequency of investigation. However, increasing frequency gives a reduction in investigation depth. Typically in a resistive environment of 500 ohm m the skin-depths (depth at which the incident dipolar field reduces to 1/3 of the surface value) range from 40 m (0.9 kHz) to 32 m (25 kHz) at a survey elevation of 60 m.

The apparent resistivity data are gridded with a natural neighbour algorithm at a cell size of 50 m x 50 m for each frequency. Fig. 3a and Fig. 3b show the electromagnetic data as apparent resistivity grids for the shallowest depth of investigation (25 kHz) and the deepest depth of investigation (0.9 kHz) respectively. The linear colour scale emphasises the variation in electromagnetic response from a number of the highly resistive bedrock formations and spans 3 orders of magnitude. Black lines represent the 1:250k bedrock geology (Fig. 2a). It can be noted that within individual bedrock formations, such as the blueschists of the Aethwy Complex, considerable spatial complexity is observed and the variation is frequency (depth) dependent. Younger (Carboniferous) limestones and sandstones are clearly associated with more conductive behaviour.

In a lithological sense the most persistent low values are observed in association with the sandstone (SDST) unit, a trend distinguishable at all frequencies. High apparent resistivities are seen over a range of lithologies but are especially perceptible for the granitic rocks and the psammites and pelites. The data can be seen to display a high degree of heterogeneity with significant variations observed within individual classifications. Cultural interference is visible and increases with decreasing frequency, a common finding with AEM data. Some significant industrial features generate interference and are labelled in Fig. 3b.

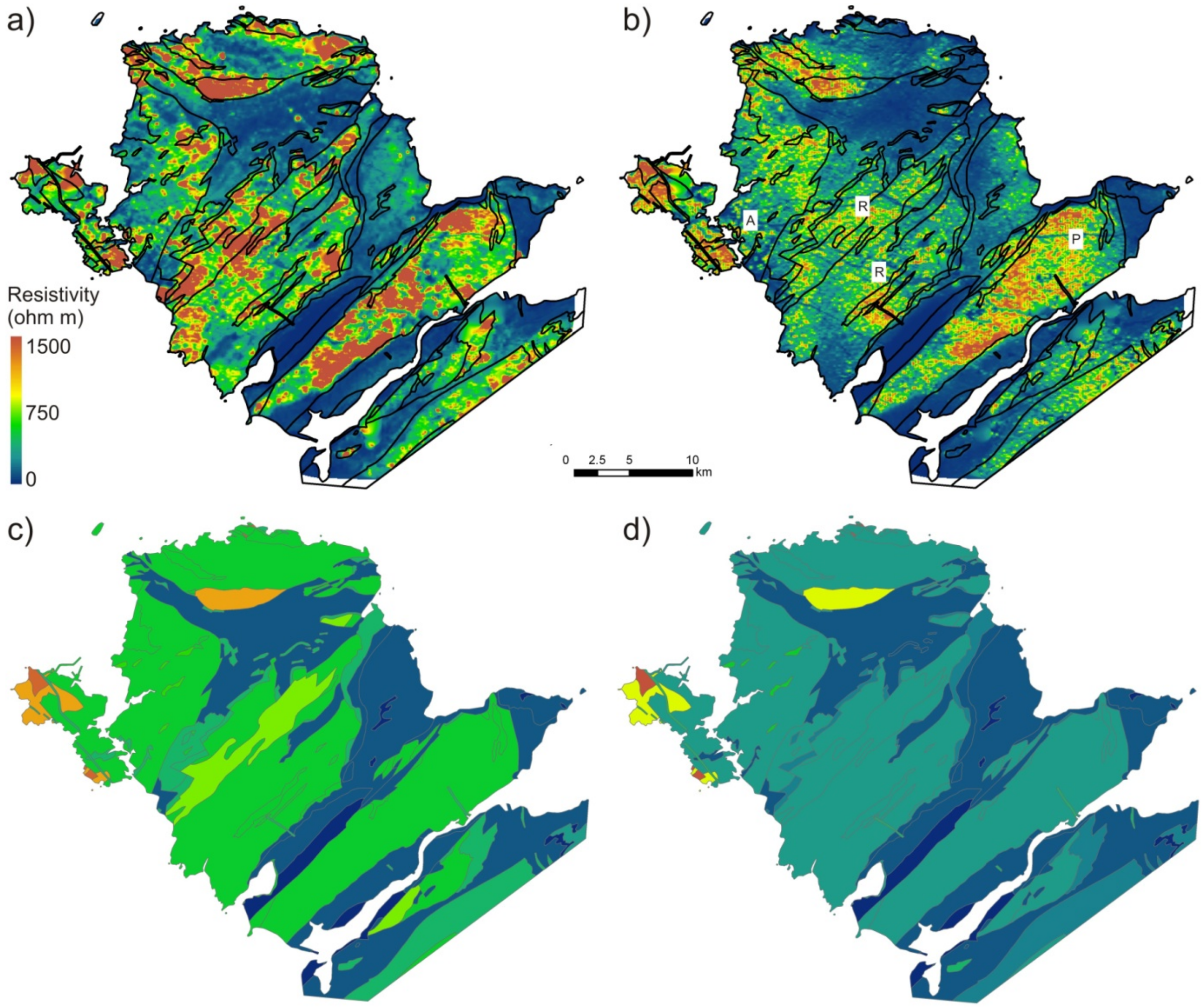

***Fig. 3**. Apparent resistivity data. (a) and (b) show the 25 kHz and 0.9 kHz data, gridded at 50 m x 50 m spacing, with the lithological linework (RCS) overlain. Non-geological features are highlighted in (b): A – aluminium smelting works; P – buried pipeline; and R – road network. (c) and (d) display the median baseline resistivity values based on the simple RCS classification obtained from geostatistical analysis at 25 kHz and 0.9 kHz , respectively.*

Although not apparent in Fig. 3, the lowest onshore resistivity values are found over the Malltraeth Marsh (Fig. 2b) and display resistivities of less than 1 ohm m. Beamish (2012) investigated this region and concluded salt loading of Holocene tidal flat deposits was responsible for the reduced resistivity. It is also noted that the effects of saline intrusion are seen on the east coast of Anglesey and along the northern coast of the mainland; they appear to coincide with regions of superficial coastal zone deposits.

4. Lithological classification

When the apparent resistivity data are examined on the basis of geological classification, they do not behave as a conventional statistical distribution and fail Shapiro-Wilk tests (Shapiro & Wilk, 1965) for both normality and log-normality. This is a common feature of many large geophysical data sets (Beamish & White, 2012). The linear distributions of the lithologically distinct data sets display a long tail (sometimes two) and are highly peaked. However, during statistical tests, the data show a general propensity to better align with a log-normal distribution than any of the alternatives. Fig. 4 displays apparent resistivity distributions of four of the best sampled lithologies (AROC, GNR, LMST and SCH) at 3 kHz and 25 kHz using a logarithm (base 10) of the data. These distributions are representative of all the well-sampled lithologies (Table 1) which cover a substantial proportion of the surface geology of Anglesey. The spatial extent of these four main lithologies is summarised in Fig. 5. The distributions appear unimodal and exhibit a strong central peak. The best fitting normal distributions for the 3 kHz data are shown as solid lines. In the case of the siliciclastic argillaceous rocks (AROC, Fig. 4a) the distributions obtained for 3 kHz and 25 kHz appear equivalent indicating little change with depth. The three remaining distributions all indicate a movement to lower resistivities with increasing depth.

The apparent resistivity data, as a function of lithology, are best summarised by a central moment (e.g. median) and a quantification of the associated dispersion. However it has previously been shown that the superficial deposits (which in the context of this study do not include the sub-glacial till deposits) may have a significant effect on the resistivity data. In order to minimise this potential contribution, analysis is undertaken with a reduced data set after the measurements coinciding with the mapped superficial geology (shown in Fig. 2b) are removed. The procedure results in a data loss of 13.7 % giving 207,251 measurements for consideration in the geostatistical analysis. Table 2 documents the median values for each lithology as a function of frequency.

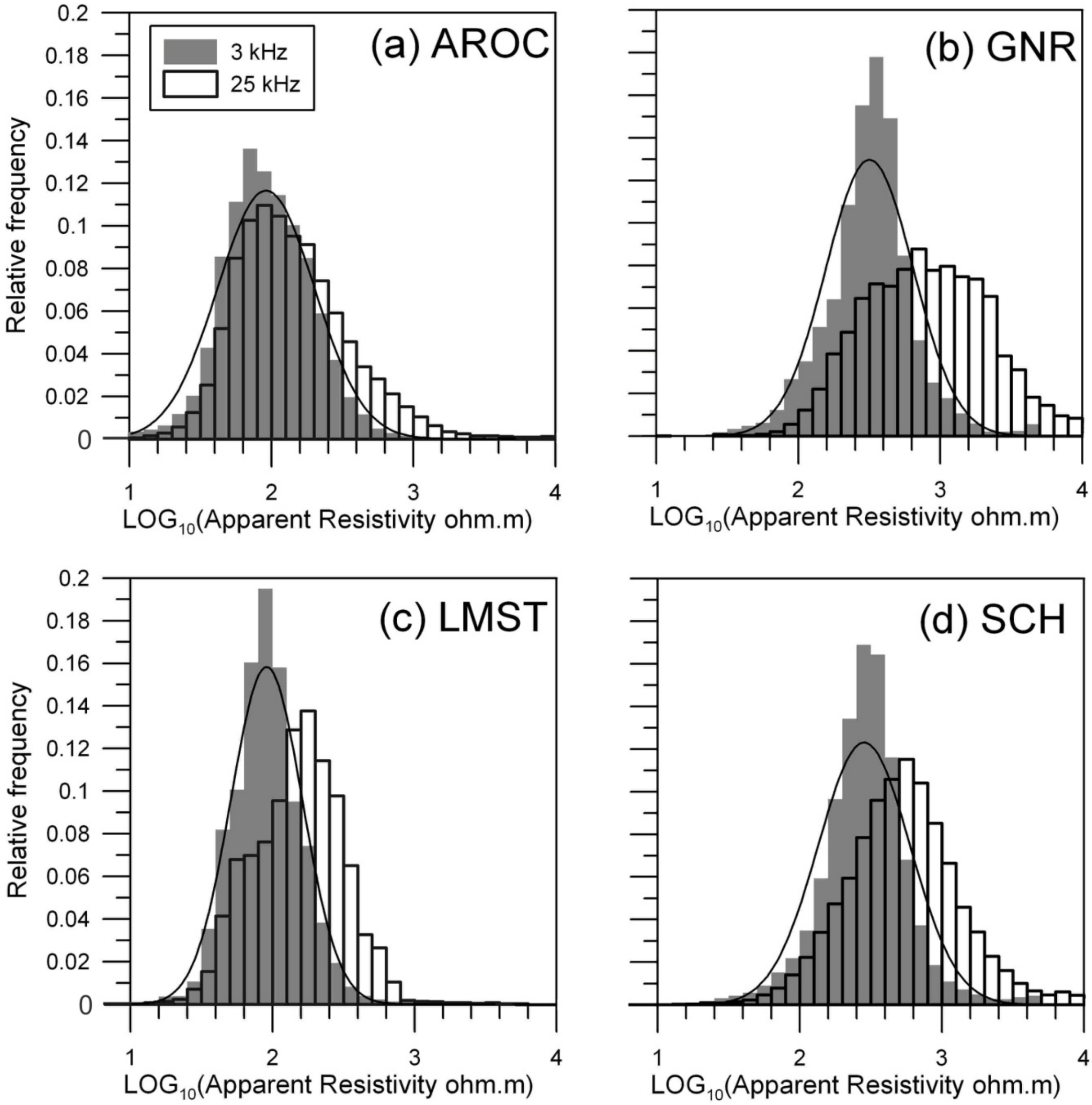

***Fig. 4**. Histograms showing the distribution of apparent resistivity values for distinct lithologies at 25 kHz and 3 kHz. (a) AROC, Siliciclastic argillaceous rock; (b) GNR, Granitic rock; (c) LMST, Limestone; and (d) SCH, Schist.*

Table 2. *Median values of apparent resistivity observed across the bedrock lithologies of Anglesey and a swathe of the North Wales coast. Measurements coinciding with superficial deposits have been omitted.*

RCS	Median apparent resistivity (Ohm m)			
	0.9 kHz	3 kHz	12 kHz	25 kHz
AROC	107.66	89.27	109.41	124.43
AROC+SDST	285.04	88.10	428.67	345.30
CONG	359.10	263.73	378.28	434.30
CONG+SDST	130.72	122.37	116.91	110.44
GNR	380.19	329.21	694.39	782.97
GNSS	337.12	280.96	493.42	573.19
LAVA+TUF	506.17	339.29	632.21	643.39
LMST	134.51	89.11	130.75	156.19
MCGBR	400.67	142.24	479.14	467.18
PSAMM+PEL	850.57	218.52	795.77	1102.35
QZITE	1459.35	125.28	1554.12	1376.63
SCH	357.97	289.57	528.02	573.06
SDST	76.15	57.20	76.15	93.48
SDST+ AROC	263.44	172.56	372.04	443.44
TUF	319.62	250.20	502.22	549.34
UMR	168.60	167.06	333.94	411.45

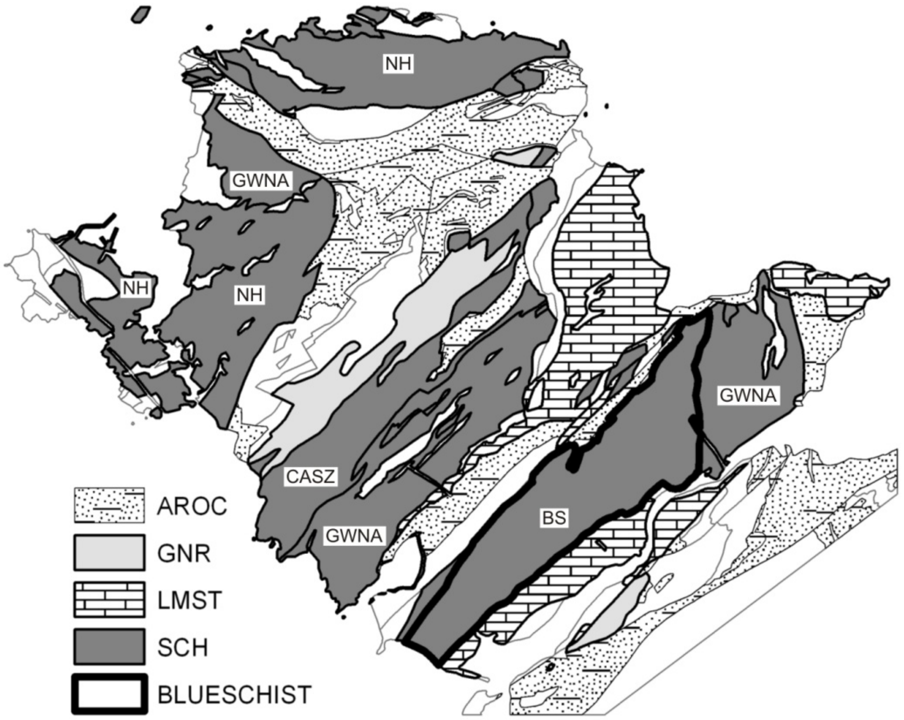

Fig. 5*.* *Location of the four best sampled lithologies across the survey area. AROC, Siliciclastic argillaceous rock; GNR, Granitic rock; LMST, Limestone; SCH, Schist. The different schistose rocks located on Anglesey are highlighted (NH – New Harbour Group; GWNA – Gwna group; CASZ – Central Anglesey Shear Zone of the Coedana Complex; and BS – the Anglesey Blueschists of the Aethwy Complex.*

Fig. 6 summarises the 16 unit lithologically classified data dispersion characteristics through a series of box and whisker plots. The two frequencies correspond to shallow depths (Fig. 6a, 25 kHz) and deeper (bedrock) depths (Fig. 6b, 3 kHz). The five poorly sampled units are displayed to the right of the more robust distributions. The central in-filled box signifies the inter-quartile range, with the enclosed horizontal line denoting the median value. The terminating bars highlight the range of the data whilst the outliers are omitted. The box and whisker plots demonstrate the variation in resistivity data as a function of lithology and demonstrate the differences in bedrock resistivity over the different lithological units.

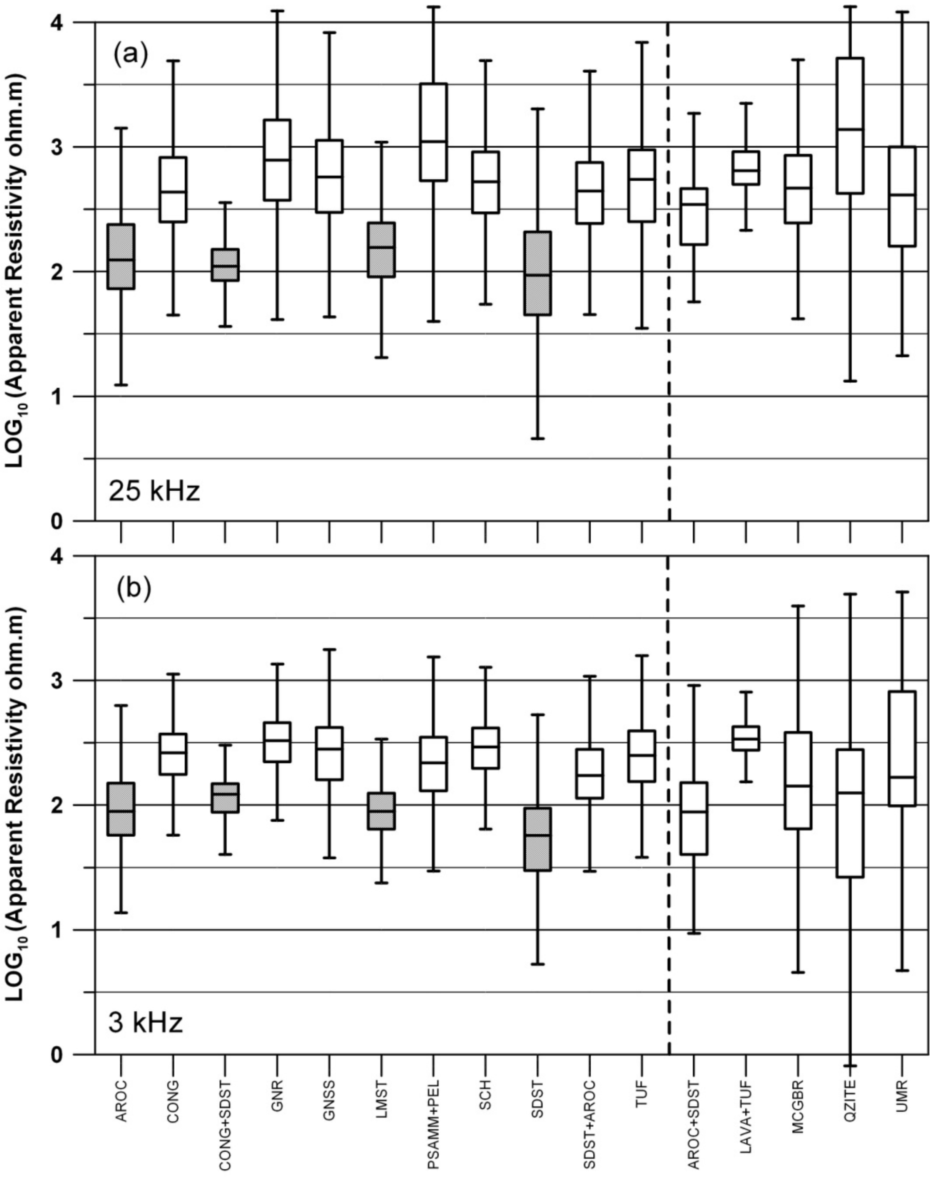

Fig. 6. *Box-and-whisker plots summarising the statistical behaviour of the apparent resistivity data based on the RCS lithological classification at 2 frequencies. The 4 lowest central moments are shown with infill and the dashed line differentiates the poorly sampled units. (a) 25 kHz, shallow depth and (b) 3 kHz.*

Although the central moments of the classification display common behaviour across the frequency range, it is apparent that the distributions at the highest frequency show the greatest degree of cross-lithological variation. These data have the greatest potential to be influenced by shallow (non-bedrock) materials. In contrast the behaviour observed at the lower frequency (Fig. 6b) provides a more compact response set with the majority of central moments confined to the interval with log values between 2 and 3; equivalent to a linear range of 100 to 316 ohm m.

The lowest resistivity values, from well-sampled lithologies, are seen in the sandstones (SDST), limestones (LMST), conglomerate and sandstones (CONG+SDST) and siliciclastic argillaceous rocks (AROC). These units appear distinct from other lithologies and are shown with infill in Fig. 6. These sets of lithologies represent the youngest rocks under investigation, principally deposited in the Carboniferous, and the results point to an increase in resistivity with geological age. A similar conclusion was drawn from the younger Palaeogene and Cretaceous rocks on the Isle of Wight (Beamish & White, 2012). The most resistive lithology, at the highest frequency, is associated with the poorly sampled quartzite (QZITE). This is largely located on Holy Island forming part of the South Stack group of rocks. The persistent high values (>1000 ohm.m) indicate a low porosity, highly sealed material. The data also contain a significant number of outliers across all frequencies and lithologies; a consequence of airborne surveying across populated areas with associated infrastructure.

The generation of baseline resistivity images for the survey area provide a summary of the analysis conducted. Here the previously unsampled regions (gaps due to data conditioning) are populated based upon their underlying bedrock lithology. Fig. 3c shows the response of the shallowest depths of investigation (at 25 kHz) whilst Fig. 3d shows the results for the deepest investigation depths (at 0.9 kHz) allowing an assessment of change in electrical properties with depth to be made. The siliciclastic argillaceous rocks (AROC) display little change in resistivity with depth yet some classifications, e.g. gneisses (GNSS), granitic rocks (GNR) and psammite and pelites (PSAMM+PEL), show significant increases. However, the overall appearance of the two images is not drastically different noting the fact that the 0.9 kHz data broadly indicate a less resistive bedrock.

In order to quantitatively assess the degree to which geology contributes to the observed variation; an analysis of variance (ANOVA) is undertaken. ANOVA is a statistical tool to determine whether or not groups of data have equivalent means. The analysis relies upon the determination of the dispersion in both the total data set and in specific subsets of the data (our lithologically distinct groups) then comparing the two. This partitioning of variance allows the percentage of variation explained by the groups to be calculated. The groups are required to display similar variances and be approximately normally distributed. Using the logarithm (base 10) of the apparent resistivity data, after removal of the lower and upper deciles, gives a percentage due to lithological classification of 58% (25 kHz), 62%

(12 kHz), 59% (3 kHz) and 61% (0.9 kHz). Thus a significant proportion (~60%) of the apparent resistivity variability can be explained by the bedrock lithologies.

5. Classified Data Analysis

Four focussed topics of investigation have been undertaken using the classified data. The first two utilise the baseline data and assess the local variance from the median, initially across the entire survey and then over a reduced extent, focussing on the mapped sub-glacial deposits. Next an assessment of the suitability of the broad RCS classification is carried out by dividing the most sampled lithology (SCH) into 4 separate units of differing origins and examining the dispersion in each of the sub-groups. Finally, the portability of the technique is considered by comparing the central moment and variance of a single lithology well-sampled on both Anglesey and the mainland.

All further analysis and interpretation in this study is undertaken with the logarithm (base 10) of the resistivity data.

5.1 Analysing the variation from the median

Having established baseline resistivities for each of the lithologies (e.g. Fig. 3c,d), assessments of the degree to which the data are consistent with, or represent departures from, the norm are now considered. The local variance from the median is determined, once again utilising the logarithm (base 10) of the data, across the entire survey area. Fig. 7 shows the departure from the norm across all the lithologies, at high frequency (a) and low frequency (b). The superficial deposit locations are overlain in grey to highlight regions where the analysis was not undertaken. Only the more significant departures (values greater than ±0.3 from the median value) are displayed with red indicating a more resistive feature and blue a less resistive one, within each lithology. The median values are used instead of the means since highly resistive outliers can skew the mean to an unrealistically large value.

The data in Fig. 7 are plotted as point (posted) values and the spatial grouping of positive and negative anomalies (departures from the norm) defines a series of ‘natural clusters’. Intriguingly some of these features persist across the range of frequencies whilst others disappear or switch polarity with frequency/depth signifying a subtle depth dependence in the resistivity structure. The spatially persistent zones at high frequency (Fig.7a) imply a considerable change in the near surface electrical properties. Whilst further detailed interpretation of these differences would be required, they generally point to a change in mineralogy and a variation in clay content.

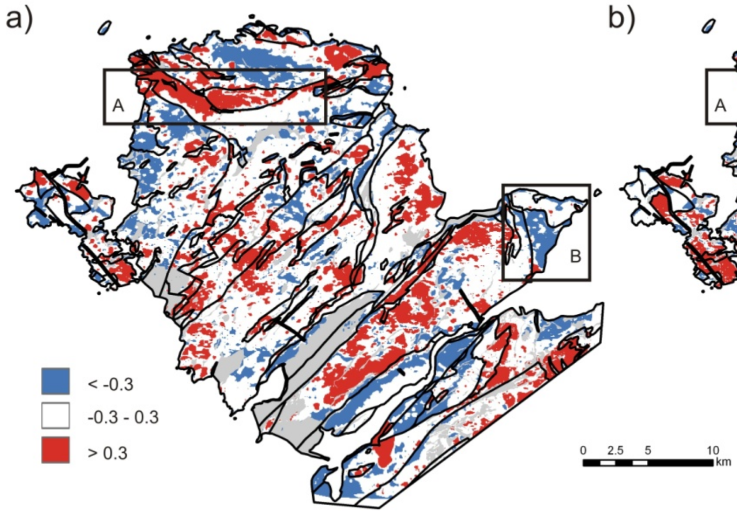

Fig. 7. *Departures from the baseline median value of apparent resistivity (base 10 logarithmic scale) following the RCS lithological classification of bedrock at (a) 25 kHz and (b) 0.9 kHz. Red indicates a more resistive feature and blue a less resistive one. (Grey areas contain superficial deposits and were not analysed.) Regions marked A and B are subject to discussion in the text.*

Two specific areas are considered and are labelled A and B in Fig. 7. Area A surrounds the northerly dipping Carmel Head Thrust, a brittle zone responsible for the rotation of the Monian Supergroup in the north of Anglesey. A resistive region which crosses the Carmel Head Thrust is seen at higher frequencies (Fig. 7a) and persists over the siliciclastic argillaceous rocks (AROC) and the psammites and pelites (PSAMM+PEL), two highly distinct lithologies. It is noteworthy that the anomaly is evident at all frequencies over AROC but diminishes then disappears over PSAMM+PEL for the deeper depths of investigation (Fig 7b). This entire region is noted for the absence of significant sub-glacial landforms (see drumlin locations overlain on Fig. 2b) and the higher frequency/near surface response cannot be explained by sub-glacial deposition or superficial deposits.

Area B contains a region of reduced resistivity which neatly maps the AROC deposit on the east of Anglesey. The Ordovician siliciclastic argillaceous (AROC) lithologies are found across the whole of Anglesey (Fig. 2a) and are part of the Ogwen group. The AROC zone within Area B, displays low resistivity values at all frequencies but becomes less continuous with decreasing frequency (increasing depth). The 25 kHz data could, potentially, be used to map the extent of the deposit. This shift to a less resistive value, points to a change of mineralogy, an increase in clay content or the effects of salt loading at the surface.

The schists of the Aethwy Complex (known as the Anglesey Blueschists and considered in greater detail later) display the opposite effect; an elevated resistivity across all the frequencies. This, and the previous, examples indicate that a broad lithological classification may not be appropriate in all cases, yet it serves to highlight how the technique can be used to infer variations in the material properties of the geology under investigation. One further comment regards the coastal zone surrounding the Menai Straits separating Anglesey from the Welsh mainland. This region is noticeable for a reduced resistivity and is an obvious candidate for saline intrusion or loading.

5.2 Assessing the effect of Devensian sub-glacial landforms on resistivity data

The emplacement of substantial sub-glacial drumlin deposits serves as a reminder of the Devensian Glaciation of the UK and Ireland over Anglesey. This period has given the island its dominant surface topography and these landforms have recently been the subject of a remapping program (Phillips, 2010). Drumlins offer a tool to assess the primary direction of ice stream movement since they are elongate in the flow direction. Anglesey drumlins have an average length and width of approximately 1 km by 0.25 km. Fig. 2b highlights their locations and emphasizes the three assemblage zones where sub-glacial action had a different dominant effect. In the north, depositional features were dominant and sizeable drumlin fields are present. It is expected that this area would, potentially, provide the greatest influence on the electromagnetic response assuming these features display a consistently different resistivity compared to their underlying bedrock. Devensian sub-glacial landforms are a near-surface feature, with a typical thickness of approximately 35 m meaning they would be most evident on the 25 kHz data. It is acknowledged that the internal structure of drumlins is often conjectural and may vary between limits of ‘mainly bedrock’ to ‘mainly till’ with many intermediate forms possible (Stokes et al., 2011). In the former case, no large departure from the bedrock resistivity is expected while in the latter case, a movement to a decreasing resistivity may be anticipated.

In order to examine the effect of drumlin landforms on the resistivity data, the local variance from median data set, presented in Fig. 7 is used again. The variational data set at 25 kHz (Fig. 7a) was analysed at the locations of the drumlins mapped in Fig. 2b. A reduction in the variational threshold, to +/- 0.25 from the median resistivity (logarithmic scale), was employed. Fig. 8 shows the clipped variational data with locations defined in grey considered as normal bedrock responses (i.e. within +/- 0.25). It can be seen that a variety of resistive (red) and conductive (blue) responses are observed across the three assemblage zones on Anglesey. It is evident that a persistent shift to lower resistivities is observed in the northern-most drumlin field of assemblage zone 1. Taken at face value, the type of analysis conducted here may offer a means of assessing the gross characteristics of the internal resistivity structure of drumlins however to control the interpretation much more detailed assessments would be required. This is an area of ongoing research yet it can be determined that an average linear reduction in resistivity of 77 ohm m, compared to the median baseline resistivity, is observed at mapped drumlin locations in the 25 kHz data. However, Phillips et al (2010) highlighted how the local tectonic framework and the bedrock geology play a significant role in the accumulation of sub-glacial features and the assumption of a spatial random deposition is flawed. Table 3 shows the logarithm of the mean shift from the median over the 11 well-sampled lithologies. A shift to less resistive values is seen in all cases except for the Carboniferous conglomerate and sandstone lithology (CONG_SDST) which has only a limited number of measurements. The largest changes are seen in the more resistive older rocks where the contrast in resistivity would be largest. Notwithstanding that the sub-glacial landforms primarily consist of broken bedrock pieces, it is assumed that the increased accommodation space for fluid, and a clay component in the till matrix, would produce a sizeable reduction is resistivity in the drumlins.

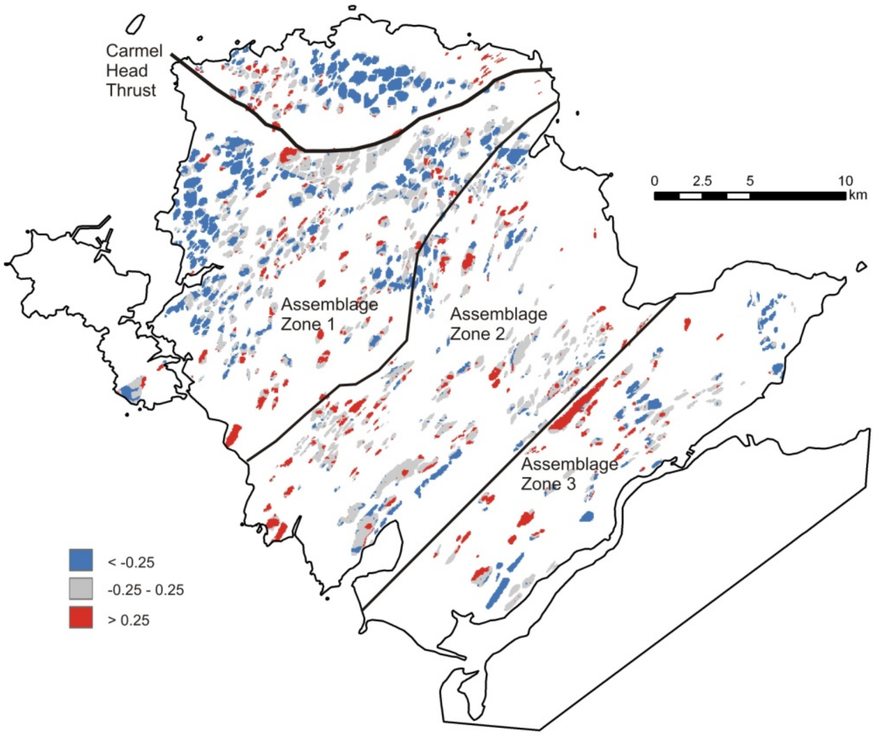

Fig. 8. *Local departures from median value of apparent resistivity (base 10 logarithmic scale) at 25 kHz; clipped to the location of mapped sub-glacial drumlins. Red indicates a more resistive feature and blue a less resistive one. Drumlin responses in grey denote 'normal' behaviour.*

Table 3. *Shift in the local variance from median of the resistivity data (logarithmic scale) based on the simple RCS classification at locations coincident with the mapped drumlins.*

RCS	No. of samples	Mean shift from median
SCH	25245	-0.13
AROC	11412	-0.02
LMST	2633	-0.05
GNR	1889	-0.10
TUF	1763	-0.11
GNSS	1266	-0.10
SDST+AROC	983	-0.18
CONG	592	-0.04
CONG+SDST	567	0.01
SDST	336	-0.01
PSAMM+PEL	171	-0.16

Fig. 8 also contains some regions of sub-glacial deposition which display a higher than expected resistivity. It is postulated that a more resistive drumlin would be significantly uncompacted, may contain large amounts of bedrock derived from a more resistive neighbouring lithology or may simply be drier and better drained.

5.3 Assessing the effect of origin and age

A criticism of a simple lithological classification is the absence of discrimination of both origin and age of deposition. As previously shown through the box and whisker plots (Fig. 6) the younger lithologies on Anglesey display the lowest resistivity. In order to assess the effect of bedrock origin the most sampled lithology, the schist units (SCH), are subdivided into their four terrane groups as indicated in Table 4 and shown in Fig. 5. These highly variable metamorphosed rocks would be an obvious candidate where lithological classification might fail on the basis of differing predominant mineral compositions. Schists are present within each of the terranes of the Monian Composite Terrace: the Monian Supergroup contains schistic metamudstones of the New Harbour Group (NH) and the olistostromic schists of the Gwna Group (GWNA); the Coedana Complex contains a band of schistose rocks commonly referred to as the Central Anglesey Shear Zone (CASZ); and the Aethwy Complex includes the highly schistose metasedimentary Anglesey Blueshcists (BS). This broad classification of the schistose lithology, from the dense foliated metabasites of the blueschists to the less dense mica schists, highlights the variability in metamorphic grading at 1:250k regional mapping. Fig. 5 indicates the locations of each grouping in the survey area.

***Table 4**. Schistose rocks present within survey area as a function of terrane. Each group is sampled by a large number of measurements (N).*

Code	Terrane	Group	N (No. of Samples)
NH	Monian Supergroup	New Harbour	26624
GWNA	Monian Supergroup	Gwna	28672
CASZ	Coedana Complex	Central Anglesey Shear Zone	11919
BS	Aethwy Complex	Anglesey Blueschist	16969

Table 5 summaries the central moments and the inter-quartile range (a measure of dispersion) of the data in the 4 categories at each frequency. The data from the different zones display excellent correlation, with the exception of the Anglesey Blueschists. This correlation is supported by the equivalence of their central moments across the electromagnetic frequency range and by the similarity in their inter-quartile ranges. The significantly more resistive Anglesey Blueschists, with their glaucophane mineralogy, provide a note of caution regarding a simplified classification of geology where differing mineral composition occurs. However, this analysis emphasizes the advantage of adopting a lithological classification of geology when attempting to differentiate statistically distinct regions within broad groupings.

Table 5. *Statistics of the logarithm (base 10) apparent resistivity distributions (medians and inter-quartile rage) observed across the different schists at each frequency of investigation.*

Frequency (k Hz)	Median resistivity (log ohm m)				Inter-quartile Range (log ohm m)			
	GWNA	NH	BS	CASZ	GWNA	NH	BS	CASZ
0.9	2.52	2.51	2.87	2.49	0.64	0.68	0.64	0.41
3	2.47	2.42	2.50	2.48	0.34	0.33	0.43	0.29
12	2.70	2.63	2.90	2.74	0.41	0.49	0.55	0.40
25	2.74	2.67	2.93	2.82	0.42	0.52	0.68	0.45

5.4 Assessing the predictive nature of lithological mapping

An approach to test the predictive use of lithologically classified resistivity data acquired over a small spatial extent is now considered. The respective statistical variance seen in a single lithology present on both Anglesey and the Welsh mainland is analysed. The Ordovician siliciclastic argillaceous rocks, AROC, are the only lithological classification that provides a significant number of measurements over both the Monian Composite Terrace of Anglesey and the British Avalonian rocks of North Wales. The extensive distribution of the AROC formation is shown in Fig. 5. The histograms of the complete apparent resistivity data set for this lithology were shown in Fig. 4a and it was noted that the central moments appeared largely independent of frequency (depth). The AROC classified data were divided into two sub-groups defined as on-Anglesey and on-mainland. Table 6 summarises the central moments (median values) and provides a measure of the dispersion at each frequency for these two sub-groups.

Table 6. *Statistics of the log (base 10) apparent resistivity distributions observed across the AROC deposits on Anglesey and the mainland at each frequency of investigation.*

Frequency (k Hz)	Median (log ohm m)		Inter-quartile Range (log ohm m)	
	Anglesey	Mainland	Anglesey	Mainland
0.9	2.04	1.98	0.49	0.54
3	1.99	1.79	0.38	0.43
12	2.06	1.97	0.45	0.53
25	2.11	2.03	0.50	0.55

The median values and inter-quartile ranges are well matched with the mainland deposits showing a slightly less resistive response, with greater dispersion, at all frequencies. However there is a general persistence in the equivalence between the two spatially isolated deposits. The reduction in resistivity in the on-mainland data may be partially explained by saline intrusion; this is evident on the north Welsh coast, in Fig. 3a,b and would serve to reduce the median values.

6. Conclusions

This study has presented an assessment of near-surface electrical resistivity data acquired during the HiRES airborne geophysical survey of Anglesey. This survey has generated a valuable data set since the rocks under investigation are the oldest formations sampled in the UK by HiRES surveys and offer an insight into the electrical properties of Neoproterozoic rocks in the UK.

The data show a resistive response in all locations where significant Holocene deposits are absent. The data, presented as apparent resistivity distributions due to the increased range of analysis this offers in comparison to apparent conductivity, show a substantial degree of heterogeneity across the survey area.

The lithological classification of geology adopted in this study highlights how geophysical data contains a strong lithological signature. An analysis of variance determined that a high percentage of the variation seen in the total data set (at all frequencies of investigation) could be explained by a lithological categorization.

This study has presented baseline resistivity images, derived from the median values for each lithology. These provide a useful visual tool to simplify the results onto a single plot. They also serve to illustrate the similarity of the data with frequency, suggesting that the bedrock is sampled across a broad frequency range. The sandstones (SDST), limestones (LMST), siliciclastic argillaceous rocks (AROC) and the conglomerates and sandstones (CONG+SDST) are shown to be the least resistive rocks pointing to an age dependence in the response since these deposits are all Carboniferous.

The spatial variation from the median value has been mapped and surprisingly continuous conductive and resistive zones have been defined. Some of these conductive zones, in the highest frequency data, have been shown to coincide with the mapped sub-glacial landforms deposited during the Devensian glaciation; further work to model the AEM response over such deposits is currently underway.

Additionally, the data has been used to identify sub-zones, within a lithological classification that define a statistically distinct grouping. This study has shown that the Anglesey Blueschists of the Aethwy Complex are dissimilar to the other schists in the survey area in an AEM sense, displaying higher resistivities and greater dispersion. The variations observed demonstrate how the mineralogical content of distinct formations can have a significant effect on the bulk conductivities obtained from AEM data.

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