The bedrock electrical conductivity structure of Northern Ireland

David Beamish

British Geological Survey, Keyworth, Nottingham, NG12 5GG, UK.

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Corresponding author:

David Beamish (dbe@bgs.ac.uk)

British Geological Survey, Keyworth, Nottingham NG12 5GG, UK

Tel: +44(0) 115 936 3432

Fax: +44(0) 115 936 3437

Email: dbe@bgs.ac.uk

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SUMMARY

An airborne geophysical survey of the whole of Northern Ireland has provided over 4.8 M estimates of the bedrock conductivity over the wide range of geological formations present. This study investigates how such data can be used to provide additional knowledge in relation to existing digital geological map information. A by-product of the analysis is a simplification of the spatially aggregated information obtained in such surveys. The methodology used is a GIS-based attribution of the conductivity estimates using a lithological classification of the bedrock formations. A 1:250k geological classification of the data is performed leading to a 56 unit lithological and geostatistical analysis of the conductivity information. The central moments (medians) of the classified data are used to provide a new digital bedrock conductivity map of Northern Ireland with values ranging from 0.32 to 41.36 mS/m. This baseline map of conductivities displays a strong correspondence with an existing 4 quadrant, chrono-geological description of Northern Ireland. Once defined, the baseline conductivity map allows departures from the norm to be assessed across each specific lithological unit. Bulk electrical conductivity is controlled by a number of petrophysical parameters and it is their variation that is assessed by the procedures employed. The igneous rocks are found to display the largest variability in conductivity values and many of the statistical distributions are multi-modal. A sequence of low value modes in these data are associated with intrusives within volcanic complexes. These and much older Neoproterzoic rocks appear to represent very low porosity formations that may be the product of rapid cooling during emplacement. By way of contrast, extensive flood basalts (the Antrim lavas) record a well-defined and much higher median value (12.24 mS/m) although they display complex spatial behaviour in detail. Sedimentary rocks appear to follow the broad behaviours anticipated by standard theoretical descriptions of rock electrical properties that allow for a term due to grain surface conduction (e.g. the presence of clay). Single lithology sedimentary rocks are represented by an increasing set of conductivities through the sequence sandstone (4.91 mS/m), limestone (8.41 mS/m), mudstone (17.85 mS/m) with argillaceous rocks providing a conductivity of 41.1 mS/m. In the case of both sandstone and limestone, the single lithology conductivities are significantly less than their mixed lithology counterparts. Mudrocks display a bimodal statistical distribution and an extended analysis of these rocks is carried out across a Carboniferous basin. The results clearly indicate that non-shale mudstones are distinctly less conductive than their shale counterparts. Shale formations display rapid and large movements in conductivity and it is suggested that the observed sensitivity may be due to competing surface conduction effects due to clay and organic material. A study of the variation of conductivity with geological period is also performed. Both a decreasing trend with age and a modulation that peaks in the Triassic period are observed.

1 INTRODUCTION

Electrical conductivity is one of the fundamental geophysical properties of rocks (Schon 2004) and rock conductivities, along with density, are often tabulated for a range of sedimentary, igneous and metamorphic rocks in many standard earth-science text books (e.g. Keller & Frishknecht 1966; Telford *et al.* 1991). Over the past decade new high-resolution airborne geophysical coverage of the UK has been provided by a fixed-wing surveying platform (Peart *et al.* 2003; Beamish & Young 2009) flying at 200 m line separations. The electromagnetic measurements have provided near-surface (0 to 100 m) assessments of the conductivity distribution across 5 main areas of the UK (Beamish 2012). The most-extensive survey area (14,160 km^2) was that provided by the Tellus survey of Northern Ireland (NI), as shown in Figure 1a. The airborne system provides magnetic, radiometric and frequency domain electromagnetic survey measurements. The airborne electromagnetic (AEM) data were typically acquired at four frequencies with the depth of investigation increasing with decreasing frequency. The data provide mapping information of apparent (i.e. a uniform and 1D assumption is used) conductivity with increasing depth.

Due to their systematic coverage, the airborne conductivity data provide almost continuous information across each survey area with a typical along flight line sampling of less than 15 m. The Tellus survey of Northern Ireland (NI) conducted in 2005 and 2006 provided over 81,000 line-km of onshore and offshore coverage and examined a wide range of geological formations. Northern Ireland represents one of the most complex and varied areas of geology in the world. The oldest rocks are Neoproterozoic (c. 895Ma) and are succeeded by rocks representing every Phanerozoic system. The study conducted here is an assessment of the central moments and variability of the electrical conductivity of these bedrock formations.

The behaviour of geologically classified values of apparent conductivity has previously been presented for AEM survey data across the Isle of Wight by Beamish & White (2011, 2012). The formations encountered provided the youngest bedrock lithologies encountered during the AEM surveys. The 1:50k map information when attributed with the central moments (a measure of the norm) of the apparent conductivity distributions was referred to as baseline data. The baseline data then allow further assessments/interpretations of data exhibiting departures from the norm. Beamish & White (2011) compared procedures and results obtained for both lithostratigraphic (LEX-RCS) and lithological RCS (Rock characterisation Scheme) attributions at a 1:50k scale. It was noted that the lithological scheme may be considered more appropriate to geophysical attribution in that it represents a more generic description of the rock materials present (e.g. chalk, sandstone, limestone, together with mixed lithologies). The same approach was adopted when examining the conductivity structure of the whole UK at a scale of 1:650k (Beamish 2012) and the same approach is used here.

FIGURE 1

The lithological classification conducted here uses a recent 1:250k digital geological lexicon and over 4.8 million AEM estimates of low frequency (3 kHz) data across onshore NI. There is no fixed depth of investigation but the 3 kHz data can be regarded as providing an assessment of 'near-surface' bedrock electrical conductivity except at locations where thick accumulations of conductive superficial deposits occur. The analysis is geostatistical and both the central moments and dispersion of the conductivities of 56 lithological units are assessed using a GIS-based classification scheme. The analysis allows a new baseline conductivity map of the bedrock of NI to be generated. Although the behaviour of the conductivities of all 56 lithologies are of potential interest, detailed studies of the geostatistical and spatial behaviour of only a subset of the igneous, and sedimentary rock types are performed. The presence of a wide variety of igneous rocks in NI, particularly the widespread Antrim basalts, provides a unique UK geological context.

The study demonstrates how geophysical information can be used to provide additional knowledge of broad lithological descriptions of geological materials. The knowledge provided is necessarily petrophysical and requires interpretation. A by-product of the analysis is a simplification of the spatially aggregated information obtained in such surveys. The techniques employed can be applied to other spatially extensive AEM surveys.

2 BACKGROUND THEORY

AEM measurements, like their ground based counterparts, provide volumetric estimates of total formation conductivity σ_t or its reciprocal, resistivity ρ_t. The use of formation (or bulk) conductivity to investigate the subsurface relies on an ability to understand the factors that control it in a given geological setting. An empirical relationship developed by Archie (1942) indicates that the bulk material conductivity is related to pore fluid conductivity (σ_f), fractional porosity (ϕ) and degree of saturation (S) as the first term of the expression:

$$\sigma_t = a \sigma_f S^n \phi^m + \sigma_s \quad ...(1)$$

where a is an empirically determined constant and S is the fluid-filled fraction of the pore space with an exponent (n) of about 2. The porosity exponent (m) is also an empirically determined parameter that depends on the geometric factor of grain shape and packing. In practice, even the cleanest formations contain small amounts of clay, or argillaceous bands, which can exert a significant influence on σ_t.

The presence of clay implies that the widely used formula of Archie (1942) cannot be used to model the electrical conductivity of the medium. This is due to the increased surface conduction that occurs in media with high specific surface conductance such as clay. A number of models have been developed to take into account the effect of surface conduction (Waxman & Smits 1968; de Lima & Sharma 1990; Pride 1994). A second term (σ_s), due to grain surface conduction, may therefore be introduced into equation (1) to allow for this. The degree of mineral surface coating is determined by pore scale and particle size. In the near-surface, with materials displaying similar porosities and saturations, clay content is often a significant factor in determining the bulk conductivity of mixed lithology formations such as marls and mudstones. Modelling of the electrical conductivity, and transport properties, of pore systems at the nanometer scale continues to be developed for hydrocarbon studies. The use of equation (1) underlies many of the petrophysical investigations carried out. Shabro *et al*. (2011) describe such studies in complex systems with grains coated in clay minerals and in the presence of organic matter. In such gas-shale rocks, conductivity is found to decrease with increasing total organic content.

3 METHODOLOGY

The Tellus airborne geophysical survey of NI (Beamish & Young 2009) was conducted over a two year period (2005 and 2006) and covered the geopolitical landmass of Northern Ireland, an area of 14,160 km^2. Flight lines were extended about 2 km, both over the coast and into the Republic of Ireland. The lines were spaced at intervals of 200 m and orientated at 345°, on the basis of geological trends. The nominal flight height was 56 m, rising to 200 m over populated areas.

The present study uses the EM data obtained with a sampling interval of ~15 m along the flight direction. The EM frequency domain geophysical system employed is described by Leväniemi *et al*. (2009). The project acquired two-frequency EM data (3 and 14 kHz) in 2005 across the western area and four-frequency data (0.9, 3, 12 and 25 kHz) across the eastern area in 2006. The lowest, and deepest penetrating, common frequency is provided by the data acquired at 3 kHz.

3.1 Apparent Conductivity

Electromagnetic (EM) data acquired by airborne frequency domain systems comprise coupling ratios of secondary to primary field ratios at individual frequencies (e.g. Fraser 1978). These data exhibit a sensitive dependence on altitude. The standard method of removing the altitude dependence is to convert the coupling ratios to estimates of apparent, half-space conductivity, at each frequency. The most common procedure employs the Fraser pseudo-layer transform (Fraser 1978). These estimates provide conductivity models with a validity that depends on a vertically uniform, 1D assumption.

The volume (i.e. both laterally and vertically) of the subsurface involved in each measurement is quite complex since it depends on frequency, altitude and the conductivity of the subsurface. Beamish (2004) describes the volumetric footprints (skin-depths) of the airborne system considered here. Each measurement may typically be associated across a principal area of sensitivity of less than 100 x 100 m over the ground surface. At 3 kHz, the dipolar skin-depths (depth at which the induced electric field is reduced to 1/e, 37%, of the surface value) range from ~38 m in a resistive (1 mS/m) environment to ~24 m in a conductive (100 mS/m) environment. Across the survey area, there is no fixed depth of investigation but the 3 kHz data may be regarded as providing an assessment of 'near-surface' (i.e.typically at depths of < 60 m) bedrock electrical conductivity except at locations where thick accumulations of conductive superficial deposits occur. Superficial deposits refer to recent, often unconsolidated, geologic deposits typically of Quaternary age. Such deposits may be spatially discontinuous or absent above bedrock. All pre-Quaternary deposits are referred to as bedrock.

Each specific AEM system has a limited conductivity aperture defined by system parameters and signal/noise. The low conductivity limit of the 3 kHz data set considered here is estimated to be about 0.32 mS/m (i.e. 3125 ohm.m). This means that the precise value of conductivity estimates below 0.3 mS/m is uncertain and the values obtained are regarded as ‘highly resistive’.

The principal analysis conducted here is a geological/geostatistical appraisal of a conditioned set of the 3 kHz conductivity data. The full survey (Fig. 1) provided 5,490,996 onshore and offshore AEM measurements. The conductivity of seawater is far in excess of that arising from geological materials and as such the analysis was restricted to onshore data values only. The survey data were screened for non-geological (i.e. cultural) perturbations as described by Beamish & White (2011a). The procedure includes applying a maximum value of 1000 mS/m to the data and restricting the data to locations where the survey altitude is less than 180 m. The latter condition also has the equivalent effect of restricting the data set to non-urban areas. When sampled onshore, within the area of defined bedrock, the screened data set comprises 4,891 data values.

The apparent conductivity estimates used in this study are shown in the continuous colour image of Figure 1b. The image is restricted to the onshore domain and is based on a grid cell size of 50 m. The full data range is from 0.1 to 1000 mS/m however the image is restricted to the interval from 4 to 60 mS/m to preserve dynamic range. Urban conurbations with a population > 1000 are indicated. Electromagnetic radiative sources, such as power lines, tend to give rise to localised high conductivities and a number of the major transmission routes can be observed across the image (e.g. P in Fig. 1b).

A substantial coastal area (labelled M in Fig. 1b) is Magilligan foreland and is Ireland’s largest coastal accumulation feature, comprising marine and wind-blown sand deposits. The high conductivities observed here are likely to due to saline conditions in the thick (> 30 m) superficial deposits. A high conductivity zone extends inland from the deposits for over 6 km. Elsewhere, large areas of more resistive rocks (< 5 mS/m) are observed in the NW and SE quadrants of the image. The large clay and lignite (CLLI, Fig. 1a) unit in the central area associated with Lough Neagh clearly provides a broad zone of enhanced conductivities. The Lough Neagh Group clays contain the youngest Oligocene sediments in western Britain

(Wilkinson *et al.* 1980) and some of the thickest lignite in Europe (Large 2007). Knowledge (including borehole) of their distribution is hampered by the shallow water body of Lough Neagh (the largest area of fresh water in the British Isles). Since the mean water depth is only ~ 9m, the AEM data shown in Figure 1b provide valid estimates of the conductivity of the underlying geology. The data reveal a high degree of spatial complexity that is also observed in the same lithological unit to the north. The data warrant further, more detailed, investigation using borehole stratigraphic control, where possible.

4 ANALYSIS

Spatial lithological classification of the conductivity data was undertaken using ArcGIS ™ software developed by Environmental Systems Research Institute, Inc. (ESRI). Given a spatially continuous GIS classification of information such as that contained in a digital geological database and a discrete set of geophysical observations, a spatial join procedure is undertaken. The spatial join procedure results in the attribution of the spatially-located geophysical data by geological code(s) contained within the geological database. Both superficial and bedrock geological classifications were considered. The attribution of geological information by airborne geophysical data such as electrical conductivity has been referred to as 'geological geophysics' by Beamish (2011, 2012b).

4.1 Geology

The geological diversity of NI provides an opportunity to investigate the electrical conductivities of a wide range of lithologies. According to Mitchell (2004), NI despite being a mere 0.00001% of the land area of Earth, presents an opportunity to study an almost unparalleled variety of geology in such a small area. The major rock types in the UK (by area) are associated with Mudstone and mixed lithology formations such as Sand-Silt-Clay (Beamish 2012a). The bedrock of NI is however characterized by a wide-range of igneous formations in addition to the sedimentary units. The major lithological unit (by area) across NI (23.3% of the total area) is the flood basalts of the Palaeogene Antrim Lava Group. This has an RCS code of BA (see Table 1) and is shown in grey in Figure 1a. The basalt outcrop is a remnant of a much larger area of deposition, now reduced in size and thickness by erosion. Its thickness reaches a maximum of about 800 m towards the northeastern corner of Lough (lake) Neagh (Fig. 1). Lough Neagh (towards the center of NI) is shown in both Figure 1a and 1b by a heavy line. The second major lithology encountered is Sandstone (22% of the total area) which incorporates the extensive Southern-Uplands-Down-Longford terrane, an Ordovician-Silurian accretionary prism (Legget *et al*. 1979; Anderson 2004). Sandstone has an RCS code of SDST (Table 1) and the terrane largely occupies the SE quadrant of NI (Fig. 1a). The third major lithology encountered (8% of the total) is the metamorphic basement (Psammite) associated with pre-Dalradian rocks of the Central Highlands terrane and regarded as the oldest rocks in NI (Cooper & Johnston 2004). Psammite has an RCS code of PSAM (Table 1) and largely occupies the NW area of NI (Fig. 1a).

4.1.1 Superficial deposits

In addition to the bedrock classification for NI discussed below, a superficial (Quaternary) database was examined. The 1:250k geological superficial classification for NI (v 2.18, 2009) provided by the Geological Survey of Northern Ireland (GSNI) provides a 12 unit classification of superficial cover rocks. Glacial sediments (diamicton, or till) dominate the landscape and account for 66% of the total superficial cover. The second two most extensive units in the database are Peat (with 15%) and Alluvium (with 8%).

The potential influence of superficial deposits on bedrock classification was previously noted. The required understanding for bedrock assessments requires knowledge of the conductivity of the superficial deposits together with their thicknesses. Although information on superficial thickness at the UK national scale is available (Lawley & Garcia-Bajo 2009). the information does not cover NI. In the absence of such information the behaviour of a two-layer model comprising superficial overburden above bedrock was studied by forward modelling of the 3 kHz system response at the nominal survey altitude (56 m). Figure 2 shows the behaviour of the estimated bedrock conductivities for resistive (2 mS/m) and conductive (32 mS/m) overburden when their thicknesses range from 0 to 20 m. The bedrock conductivities considered range from 1 to 64 mS/m.

FIGURE 2

It is evident that in the case of resistive overburden, the concealed bedrock conductivities are all well estimated. Conductive overburden produces significant perturbations to the response and in the case of resistive (e.g. <2 mS/m) bedrock, thicker overburden deposits (e.g. > 4 m) may produce significant errors (increases to higher values) in the estimated bedrock conductivities. In the geostatistical and spatial assessment undertaken here, it is acknowledged that zones of persistently thick conductive overburden may provide a bias in the bedrock conductivity distributions obtained. The precise bias will be a complex spatial function of the nature of the superficial/bedrock distributions, their conductivities and their thicknesses.

4.1.2 Bedrock

The bedrock database used here is a recent 1:250k geological bedrock classification for NI (v 2.18, 2009) made available by the GSNI (Cooper *et al.* 1997). The database provides a 151 unit classification of bedrock geology when using the main lithostratigraphic lexicon (RCS-LEX) code descriptions. When a simpler lithological (RCS) classification is used, the number of unit descriptions reduces to 57. A small outcrop (RCS=SDLM) is not sampled by the conditioned survey data set resulting in a 56 unit lithological assessment. The lithological categories considered are described in Table 1 using standard RCS lexicon codes. The geology of NI is fully described by Mitchell (2004); this publication gives a comprehensive account of the rocks and deposits contained within the 1:250k database considered here.

TABLE 1

The 3 major lithologies present (BA, SDST and PSAMM) were noted previously. The 7 lithologies with the smallest outcrop area (and thus poorly sampled i.e. N < 1000) are AGG (N=712), BRSS (244), CONG (655), DLAR (409), LATU (601), PYRR (205) and SEPITE (44).

5 RESULTS

The distributions of the bedrock classified and logarithmically transformed apparent conductivity data are summarised in the box-whisker plot shown in Figure 3. In Figure 3, the central box indicates the first and third quartiles of each distribution with the enclosed horizontal bar denoting the median value. The terminating bars at the end of each vertical line denote the range of the data. A logarithmic scale is used since the data span over 2 orders of magnitude. The interquartile range (the infilled box) provides an indication of the central moments of the bedrock responses. The large ranges of the distributions are, in part, due to the effects of acquiring AEM data across populated areas with a high degree of infrastructure. In most cases, when the range extends to the upper limit of 1000 mS/m, non-geological (i.e. radiative EM) noise within the data set is the cause.

FIGURE 3

The lithologies have been colour-coded to indicate some of the broader rock classifications including igneous (grey), argillaceous (brown), clay (purple), crystalline (red), limestone (green), mudstone (blue) and sandstone (yellow) rocks. Six of the lithologies, with < 1000 samples are shown in black to indicate that the distributions may be unreliable.

The igneous rocks, considered as a group, display the largest variability of central moments. It should be noted that in the case of the laterally compact outcrop patterns of intrusive dykes (e.g. the lamprophyre (LMPY) dykes) the AEM footprint will sample both dyke and host rock across all contact points. The lithologies considered to be most sensitive to this effect are AND, FELS, LMPY, MBAR, MLTU and sampling limitations may be reflected in the large dispersion of central moments observed for FELS and LMPY. A number of the igneous distributions display complex behaviour and these are discussed later.

Within the argillaceous rocks, the single lithology ARGL unit displays the highest conductivity while ARSD, with subordinate sandstone, records the lowest value. The largest observed median conductivity (41.36 mS/m) across all lithologies is observed for CLLI (clay and lignite). The twelve crystalline rock formations (Fig. 3) display persistently low value conductivities with the highest value (6.1 mS/m) observed for MCGB (microgabbro). The lowest conductivity observed across all lithologies is for the granophyric granite (GNGP) with a distribution that is highly skewed towards the low observational limit (0.32 mS/m). The GNGP outcrop is contained with the Slieve Gullion Volcanic Complex and other intrusive lithologies associated with this complex are discussed later (see Fig. 6). The GB median conductivity (1.19 mS/m) is the second lowest value obtained by the analysis. The microgabbro, or diabase, outcrops as a series of both limited and extensive dyke formations (the unit is defined by 741 polygons in the database) and the observed distribution is multimodal and complex. The central moments of the eight sandstone lithologies (yellow) display moderate conductivities with the single lithology SDST unit clearly recording the lowest value.

5.1 Baseline bedrock conductivity map of NI

The lithological classification of the conductivity data provided statistical average behaviours (central moments) which can be used to generate new 1:250k baseline conductivity maps for NI. The median values of the lithologically-derived distributions of the apparent conductivity (Table 1) have been used to generate the baseline conductivity map of NI shown in Figure 4. The map uses a simplified 6 range colour scheme and represents an estimate of the baseline near-surface bedrock conductivities as defined by their central moments. The level of simplification in the classified map can be evaluated by comparing Figures 1b and 4.

FIGURE 4

The map shows broad agreement with the 4 broad chronological divisions of NI geology discussed by Mitchell (2004, Figure 2) :

- The NW quadrant is composed of Dalradian rocks and the early Ordovician Tyrone Igneous Complex. The conductivities are largely in the range 2 to 4 mS/m.
- The SE quadrant is composed of Ordovician and Silurian rocks of the Southern Uplands-Down-Longford Terrane and younger intrusive complexes (identified as more resistive in Figure 4). The older lithologies have conductivities ranging from 4 to 8 mS/m.
- The SW quadrant is largely composed of Carboniferous rocks together with a Devonian component. The quadrant largely provides conductivities in two ranges from 8 to 32 mS/m.
- The NE quadrant has Palaeogene basalt lava across the Antrim Plateau which is underlain by rocks of Permian to Cretaceous age. The lavas provide a well-defined median conductivity of 12 mS/m although a conductive 'halo' is apparent around the margins of Lough Neagh (Fig. 1b).

It should also be noted that conductive elements (16-32 mS/m) in the SE quadrant are associated with MDST that define the carbonaceous Moffat Shale Group (MSG). A detailed analysis of the conductivity variations across this quadrant was undertaken by Beamish *et al*. (2010). The fault traces (tract boundaries) defined by the elevated conductivities were found to cut across those deduced by extrapolation of the limited MSG exposures as illustrated on the current geological map. A potential revision to the existing geological mapping of the tract boundaries was suggested.

Reference has been made above to some of the complex distributions observed in the lithologically attributed conductivity data. Such distributions do not permit simple parametric (e.g. normal or log-normal) assessments of the central modes and variance of the data. This is a common situation when dealing with large scale regional data sets (Reimann & Filzmoser 2000). The non-normal distributions in particular, carry a large amount of information and these are given emphasis in some of the more detailed analyses that follow.

As noted previously, although the behaviour of the conductivities of all 56 lithologies are of potential interest, detailed studies of the geostatistical and spatial behaviour of only a subset of the igneous, and sedimentary rock types are performed. Three selected areas (Fig. 1) are also used to examine the detailed spatial behaviour of particular lithologies. Areas A and B (Fig. 1) provide examples of both recent (Area A) and old (Area B) igneous formations. Area C is used to examine the spatial behaviour of mudstones and shales across a Carbonifereous basin.

5.2 Igneous rocks

Some of the processes leading to the development of primary porosity in igneous rocks are discussed by Petford (2003). These provide some interpretation guidelines when interpreting the bulk conductivities considered here. It is noted that, in general, primary porosity and permeability will depend on the rate of cooling, the extent of degassing during cooling, and on the viscosity of the magma.

The distributions of 4 of the igneous lithologies (BA=Basalt, FELS=Felsite, GB=Gabbro and GN=Granite) are shown as normalised histograms (logarithmic scale) in Figure 5. The BA distribution displays highly unimodal behaviour with a median value of 12.24 mS/m. Given the scale and nature of the flood basalts, the compact nature of the observed distribution seems remarkable. Between ~62 and ~55 Ma, the NI sector of the North Atlantic Igneous Province, experienced plume-related igneous activity (Geoffroy *et al.* 1996). The present surface of the basalts may be the result of up to 1 km of erosion. An early phase of localised explosive volcanism was followed by widespread eruption of basalt lava flows of the lower basalt formation. According to Mitchell (2004), lava reached the surface from vents and along NNW-aligned fissures.

Despite the apparently simple behaviour of the histogram, the spatial variation of apparent conductivity across the flood basalts is highly complex (Fig. 1b). When examined in detail, the behaviour shows little correlation with established knowledge of the flood basalts such as the distribution of the lower, interbasaltic and upper basalt formations. In order to explain the conductivity behaviour observed, an understanding of the basalt stratigraphy in the upper ~60 m is required. Individual lava flows may be only a few metres in thickness (usually not more than 10 m) and can be commonly divided into three parts (Mitchell 2004). Although the central portions may be massive with columnar jointing, the upper surfaces of the flows are frequently weathered to a palaeosol/lateritic condition. Robins *et al*. (2011) also note kaolinisation associated with upper flow surfaces. The accumulated response of thin-bands of conductive clays, in the upper sequences of the flood basalts may therefore contribute to the observed enhanced conductivities in localised zones across the basalts. Attempts to obtain modern borehole conductivity logs to aid the interpretation have proved unproductive.

In Figures 5b and 5c both the FELS and GB distributions display distinct multi-modal behaviour with localised peaks towards the lowest conductivity that can be observed (~0.32 mS/m). Rocks of the FELS lithology occur in the SE (Fig. 1a) and comprise a number of unnamed intrusive Palaeogene dykes and a smaller number of Late Caledonian dyke. A significant felsitic intrusive is also associated with the Slieve Gullion Complex.

FIGURE 5

The Slieve Gullion Complex (SGC, Fig. 1a) represents the root zone of an eroded volcanic caldera (Richey 1932). A ring dyke (Fig. 6a) marks the outer edge of the intrusive complex. The conductivities associated with the SGC FELS lithology and the associated FELS Palaeogene dykes restricted to a 43.5 x 20 km rectangle are shown in Figure 6a. The sampled data, associated with the FELS lithology have been gridded (direct gridding with no interpolation) using a grid cell size of 200 m and are shown in Figure 6b. It is evident that the conductivities of SGC felsites are consistently low (<1 mS/m) and are responsible for the distribution shown in Figure 5b. Elsewhere, the conductivities of the felsitic dykes generally exceed 2 mS/m and where extensive are observed to display both uniform and spatially progressive changes in conductivity.

FIGURE 6

The granite lithologies outcrop in 4 main areas (Fig. 1a) and here we consider the largest area formed by the Mourne Mountains to the east of the SGC (Fig. 6a). This granite is one of 3 central complexes which provided the focus of Palaeogene igneous activity in the SE area of NI. The Mourne granite was intruded into Silurian greywackes and slates at a high crustal level but did not reach the surface (Gibson *et al.* 1987). The Mourne complex is usually divided into western and eastern centres. The western Mournes centre consists of 2 granites (Gibson 1984) that are distinguishable by petrographic characteristics and texture. The eastern Mournes centre consists of 3 intrusive centres.

The conductivities observed across the granite are shown in Figure 6b, again using a grid cell size of 200 m. Some of the blank data zones are due to high-fly conditions attributable to difficult topographic gradients. The range of conductivity values is from 0.27 to 541 mS/m and there are significant areas which exceed 20 mS/m. The conductivity zonation across the granite has been examined in relation to the detailed (1:50k) petrographic mapping and there is no apparent correlation. The most conductive zones occur along the southern margin (A and B in Fig. 6b); here conductivities persistently exceed 20 mS/m and locally exceed 60 mS/m. The conductivity information has also been examined in relation to detailed topographic information and the highly conductive areas A and B are both associated with topographic lows on the southern margins of the mountains (Area A is a valley). It is possible that both areas contain conductive weathered and transported material (currently unmapped) that is not representative of intact granite. Other, relatively high conductivites in the NE show associations with high elevation topographic peaks.

As noted previously (Figures 3 and 4c) the gabbro unit provides the lowest median conductivity of the main lithologies studied here. Three small areas of gabbro outcrop within the SGC (conductivities range from 0.32 to 1.44 mS/m) however the main outcrop lies to the SE of the Omagh Thrust Fault and to the east of Omagh, within the Tyrone Igneous Complex (area B, Fig. 1a) and is considered part of an early Palaeozoic island arc volcanic complex (Mitchell 2004). The gabbro forms part of the basal unit of the Tyrone Plutonic Group. The GB conductivities observed are shown in Figure 7, across a 20 x 20 km area, again using a grid cell size of 200 m. The relatively small range of values encountered (0.32 to 16 mS/m) reflects the behaviour observed in the histogram of Figure 5c. The most resistive zones would be associated with the lowest porosities typically generated by rapid cooling during emplacement. Despite the preponderance of low value (< 1 mS/m) behaviour, regionally extensive zones of enhanced conductivity (e.g. > 5 mS/m) can be traced along some margins and along a central zone showing an association with one of the bounding faults.

FIGURE 7

5.3 Metamorphic rocks

It is worth noting that metamorphic rocks are not identified *per se* in the 1:250k lexicon. Three of the lithologies with metamorphic attributes are i) Quartzite (QZITE) and the Quartz-Feldspar-Porphyry (QFP), ii) Metabasalt (MBAR) and iii) Psammite (PSAMM, a term applied to metamorphic rocks derived from an arenaceous protolith). All three units have low median conductivities of i) 2.2 (QZITE) & 2.2 (QFP) mS/m, ii) 2.5 mS/m and iii) 2.5 mS/m. The latter result can be compared with a single lithology sandstone median value of 4.9 mS/m (the lowest value of the sandstone lithologies).

The metabasalt median conductivity of 2.2 mS/m compares with a much higher value of 12.2 mS/m for basalt. Thus although the analysis is clearly limited, metamorphic counterparts of the lithologies encountered record lower values of conductivity.

5.4 Sedimentary rocks

The 1:250k lexicon provides three ‘single’ lithology sedimentary rock types (Sandstone:SDST, Limestone:LMST and Mudstone:MDST) together with a single lithology identification of argillaceous rocks (ARGL). According to conventional definitions, the SDST and LMST formations would be entirely clay free while the mudstone would contain clay particles of less than 0.05 mm in size. Potential broad subdivisions of the argillaceous deposits would be a siltstone (comprising less than 25% clay fraction) and claystone (comprising more than 40% clay fraction), (Hawkins & Pinches 1992).

In addition to the single lithologies, the lexicon identifies mixed lithologies associated with each of the main single units, thus in the case of Limestone (LMST), additional units of interbedded LMST and argillaceous rocks (LMAR), interbedded LMST and argillaceous rocks and subordinate sandstone (LMAS) and interbedded LMST and mudstone (LSMD) are defined. In the case of both SDST and LMST, the single lithology median conductivities are always significantly less than their mixed lithology counterparts. The behaviour is interpreted as reflecting the higher grain coating (clay fraction) introduced by the secondary materials.

FIGURE 8

The conductivity distributions observed for the 4 single sedimentary lithologies are shown as normalised histograms (logarithmic scale) in Figure 8. They are arranged in the order of increasing median value noted on each diagram. None of the distributions conform to log-normal behaviour. The very large and spatially extensive nature of the samples (e.g. Fig. 1a) should be noted. The MDST and ARGL distributions are bi-modal (at least). In the case of the MDST distribution we would associate the lower value peak with reduced clay content while the ARGL distribution indicates that there are significant zones with enhanced conductivities (> 100 mS/m) relative to the main central moment.

Since the outcrop of the MDST rocks is spatially extensive, a more compact area of 58 x 50 km, in the Carboniferous basin in the west of the survey area (Fig. 1) is used to illustrate the nature of the bimodal behaviour. The conductivities of the MDST lithology across the area are shown in Figure 9, again using a grid cell size of 200 m. In this area the MDST lithology comprises two main units namely the BLM (Ballinamallard) mudstone (labelled in Fig. 9) and the BBSF (Benbulben) shale (unlabelled in Fig. 9).

It is evident that the extensive BLM mudstone unit is associated with low values of conductivity largely less than 15 mS/m and predominantly less than 10 mS/m. By way of contrast, the BBSF shale conductivities typically exceed 20 mS/m and show a wide dispersion of values across the outcrops of the formation. Localised values exceed 50 mS/m and some strong inter-formation, boundary-like effects are apparent.

FIGURE 9

The behaviour observed across the Carboniferous basin indicates that non-shale mudstones are distinctly less conductive than their shale counterparts. This appears to be the first observation of this type of behaviour at the field-scale. The spatial variations of the shale conductivities are also worthy of note. The range of conductivities encountered across each specific outcrop is far larger than that associated with any of the other formations studied here. It seems clear that the conductivities of shales are particularly sensitive to variations in rock parameters controlling the bulk conductivity (equation 1). The shales in question are known to be organic-rich (Clayton *et al*. 1989).

Shale rocks since they potentially contain organic material have long been studied by the hydrocarbons industry, particularly in the context of well-log analysis. Total organic content (TOC) may be estimated using simple methods (e.g. the ΔLOGR method) based on resistivity logs (Passey *et al.* 1990). The interplay of increasing conductivity due to clay content and decreasing conductivity due to TOC (Shabro *et al*. 2011) may be responsible for the factor of 5 variations in conductivity observed in these shale formations

5.5 Conductivity variation with age

It is evident from the statistical analysis of all 56 units that lithology exerts a strong influence on the central moments of the conductivity distributions. ANOVA (Analysis of Variance) was used to further assess the contribution of lithology to the observed variations of the conductivity data. ANOVA is a statistical model that tests whether or not groups of data have the same or differing means and operates by comparing the amounts of dispersion experienced by each of the groups to the total amount of dispersion in the data. ANOVA tests the hypothesis that the means of two or more populations are equal. The samples are assumed to be close to normally distributed and have similar variances. This is clearly not the case however the analysis was conducted using the logarithms of the classified conductivity data. The analysis indicated that 57.4% of the variations in conductivity are explained by the lithological classification. The value observed is lower than that obtained in similar analyses conducted elsewhere in the UK at a more detailed scale (Beamish & White 2012).

The NI quadrant overview of the conductivity baseline map of NI suggested an apparent broad trend of decreasing conductivity with geological age. To further investigate this behaviour, 3 analyses of lithology subdivided by geological age were conducted. As previously box-whisker plots are used to examine chronological behaviour within a given lithology.

5.5.1 Sandstone-Siltstone-Mudstone (SDSM)

Two geological periods are represented in the mixed lithology SDSM unit. The box-whisker plot in Figure 9 shows the distributions observed in Devonian and Carboniferous groups of rock together with the behaviour across all groups (final box). The groups are defined by their LEX-RCS descriptions. It is evident that the older Permian groups display central moments largely below 10 mS/m. The younger Carboniferous groups display central moments above 10 mS/m with the exception of the TPMS (Topped Mountain Sandstone) formation. This latter group is clearly a low value (resistive) outlier. Since the SDSM lithology is mixed, the behaviour observed would be consistent with an enhanced sandstone component (or reduced siltstone and mudstone) within the latter group. Equally the MG (Millstone Grit) group would then be associated with enhanced siltstone and mudstone contributions.

FIGURE 10

Given the variability that may be introduced by mixed-lithology groups of rock, a single lithology formation in which the influence of clay effects should be minimal is now considered.

5.5.2 Limestone (LMST)

Two periods are represented in the single lithology LMST unit. The box-whisker plot in Figure 11 shows the distributions observed in Neoproterozoic (Dalradian Supergroup, late-Cambrian to early Ordovician) and Carboniferous groups of rock together with the behaviour across all groups (final box). This is clearly a large time span.

FIGURE 11

The median conductivities for the Neoproterzoic rocks range from 2.80 to 3.60 mS/m while the two largest units sampled in the Carboniferous provide median values of 10.96 and 11.90 mS/m. The analysis is therefore indicative of an age-related component.

5.5.3 Geological period

The digital geological lexicon also provides rock classifications of geological chronologies. The attribution of the conductivity data with minimum and maximum geological period was used to provide a data classification for the nine geological periods shown in Table 2. The total number of samples used in the classification was 4,102,708. The very limited areal extent and hence poor data sampling of the oldest (Cambrian-Ordovician) period should be noted.

TABLE 2

Individual periods can encompass a wide range of lithologies as indicated in Table 2. The box-whisker plot in Figure 12 summarises the conductivity distributions observed across all 9 geological periods. The geostatistical assessment shown is largely a reworking of the lithological assessments considered previously and so the number of lithologies and the main lithologies encountered within each period are identified in Table 2.

Taken at face value the age dependence identified in Figure 12 moves from the oldest and most resistive formations of the Cambrian-Ordovician through to most conductive in the Triassic. The Triassic period is however dominated by argillaceous rocks (ARGL) with a median conductivity value of 41.1 mS/m (Table 1) and so the lithological dependence of this behaviour should be acknowledged. One of the largest movements takes place between the Devonian and Carboniferous. The movement may be partially controlled by the lithologies encountered. The clearest example of age dependence is observed between the SDST dominated Silurian (3.94 mS/m) and the SDST dominated Permo-Triassic rocks (26.17 mS/m). Paleogene formations contain 13 litholgies but are dominated by the large area of the Antrim flood basalts. The median Palaeogene conductivity observed (20.23 mS/m) is however significantly higher than that observed for Basalt (12.2 mS/m, Table 1).

FIGURE 12

The age dependence of conductivity observed here partially mirrors the behaviour of the resistivities of sedimentary rocks measured in the United States and reported by Keller and Frishknecht (1966, Fig. 24). All the resistivity values reported in that study were less than 1000 ohm.m (> 1 mS/m) and are similar to the equivalent median conductivities reported here . The oldest (Precambrian) rocks were observed to be the most resistive (about 2 mS/m). Low resistivity peaks (about 20 mS/m) were evident during the Mesozoic (Triassic to Cretaceous). Miocene and Pliocene (post-Palaeogene) rocks then recorded low conductivity values before increasing in the Quaternary (not studied here).

From the observations and analyses conducted here it is evident that there is an apparent broad dependence with age in the conductivity data. It should also be noted that since each geological period contains a range of lithologies; it is the petrophysical attributes of each lithology, as described by equation (1), that govern the bulk conductivity observed.

6 CONCLUSIONS

The study has provided an assessment of the central moments and dispersion characteristics of the conductivity of 56 lithological units across NI. The formations sampled have been further assessed in terms of other broad sub-categories including igneous, crystalline, argillaceous, clay, limestone, mudstone and sandstone rocks. The analysis results are summarised as a box-whisker plot and the central moment medians were used to provide a new 1:250k digital bedrock conductivity map of NI. The median conductivity values range is from 0.32 mS/m (a low value measurement limit) to 41.36 mS/m in the clay and lignite formation. The baseline conductivity map shows a broad level of agreement with an existing 4 quadrant chronological division of NI. Superimposed on the broad quadrant divisions is a large area of high conductivity associated with the clay-lignite (CLLI) formation. The detailed response across this formation is highly complex (Fig. 1b) and it is likely that rapid variations in the thickness of the glacial (diamicton) cover (e.g. Wilkinson *et al.* 1980) contribute to the spatial complexity, particularly under Lough Neagh. It has been noted that the data warrant further investigation with borehole stratigraphic control, where possible.

The twelve crystalline formations display persistently low value conductivities with coarse-grained gabbro (GB) recording the second lowest value (1.19 mS/m). The igneous rocks display the largest variability and the distributions tend to display strong multimodal behaviour. One of main features of NI rock lithologies are the Antrim flood basalts. These are found to be relatively conductive (12.24 mS/m) with respect to the other igneous lithologies encountered. The distribution obtained for the 1.1 M samples appears close to log-normal and this is despite quite complex localised behaviour across the formation (Fig. 1). It is likely that the conductivity behaviour observed will remain enigmatic until control is provided by modern geophysical logs in the upper sections of the lava flows. Although metamorphic rocks are not well-represented in the 1:250k lithological lexicon, the limited analysis indicates the low values observed (2.2 to 2.5 mS/m) are lower than the non-metamorphic counterparts.

Single lithology sedimentary rocks are represented by an increasing set of conductivities through the sequence SDST (4.91 mS/m), LMST (8.41 mS/m), MDST (17.85 mS/m) with argillaceous rocks (ARG) providing a median conductivity of 41.1 mS/m, close to that of the clay-lignite formation. The general behaviour accords with the increasing dominance of surface conduction (e.g. clay content) in the second term of equation (1). In the case of both SDST and LMST, the single lithology median conductivities are always significantly less than their mixed lithology counterparts. The behaviour is again interpreted as reflecting the higher clay fraction introduced by the secondary materials.

The strong spatial variations observed in the conductivities of the Carboniferous and Devonian rocks of the SE quadrant (Fig. 1) were previously noted by Beamish & Young (2009). Since the conductivity distribution for the MDST is distinctly bimodal, the MDST lithology was sub-categorised using the RCS-LEX descriptions that allow for mudstone and shale discrimination. The results across the Carboniferous basin in the SE clearly indicate that non-shale mudstones are distinctly less conductive (predominantly < 10 mS/m) than their shale counterparts. The large outcrop of the Benbulben shale displays rapid and large-scale movements in conductivity, locally varying from < 5 mS/m to over 40 mS/m. Other shale formations across the basin display similar behaviour (Beamish 2012b). It would appear that the response of the shale group rocks is particularly sensitive to rapid changes in the second term of equation (1). It is noted that the potential interplay of increasing conductivity due to clay content and decreasing conductivity due to the presence of pore-scale hydrocarbons, in these shale rocks, deserves further research.

An assessment of the variation of conductivity with age (geological period) was also undertaken for some individual lithologies and then for all the lithologies present. In the individual studies it is apparent that there is a trend of decreasing conductivity with age. When all lithologies and chronologies are considered, a modulation of the trend is apparent with peak values recorded in the Triassic period. The modulation follows a similar pattern to that observed in the USA. Underlying this trend and modulation, it is worth noting that since each geological period contains a range of lithologies; it is the combined petrophysical attributes of all lithologies within a given period, that actually govern the bulk conductivity.

This broad study of the characteristics of bedrock electrical conductivity is not common in the literature. The study has demonstrated how such data can be used to provide additional knowledge in relation to existing digital geological map information. One of its additional aims has been to simplify the spatially aggregated information obtained from a high-resolution AEM survey using geological classification techniques. The techniques employed can be applied to other spatially extensive AEM surveys.

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TABLES (2)

Table 1. The 56 categories of the NI lithological RCS lexicon at 1:250,000 scale. N refers to the number of AEM conductivity estimates associated with each lithology. The areas of each lithology are given in km^2 and as a percentage (%) of the total area (14,757 km^2). AC refers to the median value of the apparent conductivity resulting from the classification procedure.

RCS	LITHOLOGY	N	Area km^2	Area %	AC (mS/m)
AGG	AGGLOMERATE	712	1.9	0.01	0.3
AND	ANDESITE	6965	20.4	0.14	8.6
ARGL	ARGILLACEOUS ROCK	47184	190.3	1.29	41.1
ARLMST	ARGILLACEOUS, MUDDY LIMESTONE/CEMENTSTONE/CALCILUTITE	67595	195.3	1.32	13.9
AROCLS	INTERBEDDED ARGILLACEOUS ROCK AND [SUBEQUAL/SUBORDINATE] LIMESTONE	177436	522.6	3.54	16.8
ARSD	INTERBEDDED ARGILLACEOUS ROCKS AND [SUBEQUAL/SUBORDINATE] SANDSTONE	1446	4.0	0.03	5.0
ARSE	ARGILLACEOUS ROCKS WITH SUBORDINATE SANDSTONE AND EVAPORITIC ROCKS	2842	17.7	0.12	17.5
BA	BASALT	1139326	3414.0	23.13	12.2
BRSS	BRECCIA AND SANDSTONE, INTERBEDDED	224	0.6	0.00	2.6
BUXCLY	BAUXITE-CLAY	13177	39.2	0.27	17.7
CHSA	CHALK AND SANDSTONE	29033	88.7	0.60	21.0
CLLI	CLAY AND LIGNITE	197522	589.0	3.99	41.4
CONG	CONGLOMERATE	655	2.0	0.01	37.3
COSD	CONGLOMERATE AND [SUBEQUAL/SUBORDINATE] SANDSTONE, INTERBEDDED	98772	293.1	1.99	6.4
DI	DIORITE	2061	6.3	0.04	2.2
DLAR	DOLOMITIC LIMESTONE AND ARGILLACEOUS	409	1.2	0.01	25.5

	ROCKS				
FELS	FELSITE	12543	37.5	0.25	1.0
GB	GABBRO	32346	94.6	0.64	1.2
GD	GRANODIORITE	105397	336.8	2.28	2.5
GN	GRANITE	61393	191.8	1.30	4.4
GNGP	GRANOPHYRIC GRANITE	11157	34.6	0.23	0.3
LATU	LAVA AND TUFF	601	1.9	0.01	20.6
LAVA	LAVA	42908	127.9	0.87	2.6
LMAR	INTERBEDDED LIMESTONE AND [SUBEQUAL/SUBORDINATE] ARGILLACEOUS ROCKS	35956	108.8	0.74	15.5
LMAS	INTERBEDDED LIMESTONE, ARGILLACEOUS ROCKS AND SUBORDINATE SANDSTONE	31902	98.3	0.67	16.5
LMMD	MUDMOUND LIMESTONE	26953	77.8	0.53	8.9
LMPY	LAMPROPHYRES	4943	14.6	0.10	3.5
LMST	LIMESTONE	215552	631.4	4.28	8.4
LSMD	INTERBEDDED LIMESTONE AND MUDSTONE	26951	77.8	0.53	18.9
MBAR	METABASALTIC-ROCK	15430	45.0	0.30	2.5
MCGB	MICROGABBRO	38926	117.9	0.80	6.1
MDCO	MUDSTONE AND [SUBEQUAL/SUBORDINATE] CONGLOMERATE	1879	5.7	0.04	36.3
MDLM	MUDSTONE AND LIMESTONE, INTERBEDDED	87476	252.4	1.71	18.0
MDSA	INTERBEDDED MUDSTONE AND SANDSTONE	1186	3.2	0.02	11.8
MDST	MUDSTONE	143726	421.4	2.86	17.8
MLTU	METALAVA AND METATUFF	6391	19.4	0.13	2.3
PSAMM	PSAMMITE	83698	249.9	1.69	2.5
PSEP	EPIDOTIC PSAMMITE	22314	66.8	0.45	2.6
PSPE	PSAMMITE AND PELITE	117106	373.5	2.53	3.8
PSSP	PSAMMITE AND SEMIPELITE	425277	1273.0	8.63	2.7
PYRR	PYROCLASTIC-ROCK	205	0.6	0.00	34.8
QFP	QUARTZ-FELDSPAR-PORPHYRY	4849	14.2	0.10	2.2

QZITE	QUARTZITE	5613	16.8	0.11	2.2
RY	RHYOLITE	10824	32.5	0.22	14.1
SARL	SANDSTONE WITH SUBORDINATE ARGILLACEOUS ROCKS AND LIMESTONE	58277	171.3	1.16	17.7
SCAR	SANDSTONE, CONGLOMERATE AND [SUBORDINATE] ARGILLACEOUS ROCKS	52518	162.1	1.10	18.9
SCON	INTERBEDDED SANDSTONE AND CONGLOMERATE	43137	127.6	0.86	8.4
SDAR	INTERBEDDED SANDSTONE AND [SUBEQUAL/SUBORDINATE] ARGILLACEOUS ROCKS	108653	320.2	2.17	13.6
SDBR	SANDSTONE AND SUBORDINATE BRECCIA	2011	11.6	0.08	15.7
SDSM	SANDSTONE, SILTSTONE AND MUDSTONE	171154	501.6	3.40	8.5
SDST	SANDSTONE	1064656	3253.8	22.05	4.9
SEPITE	SERPENTINITE	44	0.1	0.00	2.2
SLMDST	SILTY MUDSTONE	2337	6.9	0.05	11.4
STMD	SANDSTONE AND MUDSTONE	19616	57.8	0.39	19.4
TO	TONALITE	9284	27.2	0.18	2.5
TULA	TUFF AND LAVA	1359	4.1	0.03	19.7

Table 2. Analysis of the NI apparent conductivity data by geological period. Nsamp refers to the number of AEM conductivity estimates associated with each period. The areas sampled are given in km^2. The number of lithologies (Nlith) and the major litholgies present are also noted. AC refers to the median value of the apparent conductivity resulting from the classification procedure.

Geological Period	Nsamp	Area (km^2)	Nlith	Major Lithology	AC (mS/m)
Cambrian-Ordovician	277	0.8	1	GN	2.92
Ordovician	170,096	528.7	11	SDST, LAVA, GB	2.97
Silurian	824,545	2465.1	6	SDST	3.94
Devonian	308,713	930.4	7	GD, SDSM, COSD	5.91
Carboniferous	1,168,210	3441.8	22	AROCLS, LMST, MDST	14.10
Permian-Triasic	125,080	451.1	7	SDST	26.17
Triassic	45,163	188.8	3	ARGL	42.66
Cretaceous	28,789	88.7	1	CHSA	20.72
Palaeogene	1,431,835	4306.6	13	BA	20.23

FIGURE CAPTIONS (12)

Figure 1. Geological and geophysical data sets and survey location (lower right). (a) 1:250k lithological map of Northern Ireland with 3 areas (A, B and C) studied in detail. Legend colours have been simplified into similar groups. Heavy black line towards centre of map is Lough (lake) Neagh. Outer line is full extent of survey. SGC=Slieve Gullion Complex, MG=Mourne Granite. (b) Apparent conductivity (3 kHz). Towns are shown as dark grey zones. M=Magilligan foreland. P=example power grid response.

Figure 2. Apparent conductivity modelling results for a 2-layer (superficial above bedrock) sequence for overburden thicknesses to 20 m. (a) Resistive (2 mS/m) above bedrock (1 to 64 mS/m). (b) Conductive (32 mS/m) overburden above bedrock (1 to 64 mS/m).

Figure 3. Box and whisker plot summarising the statistical behaviour of the apparent conductivity data (logarithmic scale) classified according to lithology. Lithological codes are described in Table 1. The lithologies are colour-coded as igneous (grey), argillaceous (brown), clay (purple), crystalline (red), limestone (green), mudstone (blue) and sandstone (yellow). Six of the lithologies, with < 1000 samples are shown in black to indicate that the distributions may be unreliable.

Figure 4. The 1:250k bedrock conductivity map of Northern Ireland obtained by lithological classification.

Figure 5. Normalised distributions of the conductivity data (logarithmic transform) for 4 igneous rock types. (a) Basalt (BA), (b) Felsite (FELS), (c) Gabbro (GB) and (d) Granite (GN). The best-fitting log-normal distributions and median values (dash red lines) and median values are indicated.

Figure 6. Study of 43.5 x 20 km area (A) in Fig. 1. (a) 1:250k lithological map with the FELS formation highlighted in red and the GN formation (Mourne granite) identified in white. GNGP is granophyric granite. (b) Conductivity estimates across the FELS and GN formations. Cross-hatch areas are towns and dash lines are faults. The outer blue line is the survey extent.

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Figure 10. Box and whisker plot summarising the statistical behaviour of the apparent conductivity data (logarithmic scale) of SDSM formations in the Devonian and Carboniferous. RSF=Raveagh, SHAN=Shanmullagh, TEDD=Tedd, OMSG=Omagh, ANNA=Annaclare, CRSF=Carrickaness, TPMS=Topped Mountain and MG=Millstone Grit formation.

Figure 11. Box and whisker plot summarising the statistical behaviour of the apparent conductivity data (logarithmic scale) of LMST formations in the Neoproterozoic and Carboniferous. DBAF=Aghyaran, DBTR=Torr Head, DCBF=Ballykelly, DCCF=Claudy, DUNN=Dungiven, BAL=Ballyshannon, CDML=Carlingford, DARL=Darty formation.

Figure 12. Box and whisker plot summarising the statistical behaviour of the apparent conductivity data (logarithmic scale) with geological period.

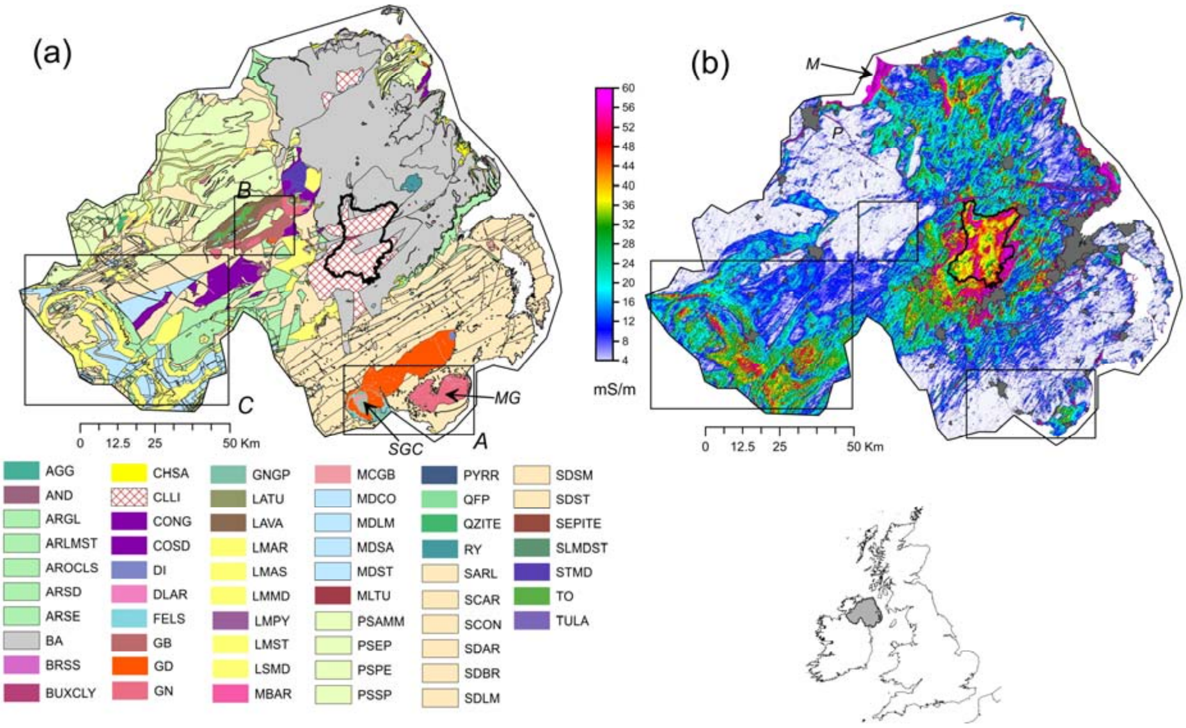


Figure 1

Figure 1. Geological and geophysical data sets and survey location (lower right). (a) 1:250k lithological map of Northern Ireland with 3 areas (A, B and C) studied in detail. Legend colours have been simplified into similar groups. Heavy black line towards centre of map is Lough (lake) Neagh. Outer line is full extent of survey. SGC=Slieve Gullion Complex, MG=Mourne Granite. (b) Apparent conductivity (3 kHz). Towns are shown as dark grey zones. M=Magilligan foreland. P=example power grid response.

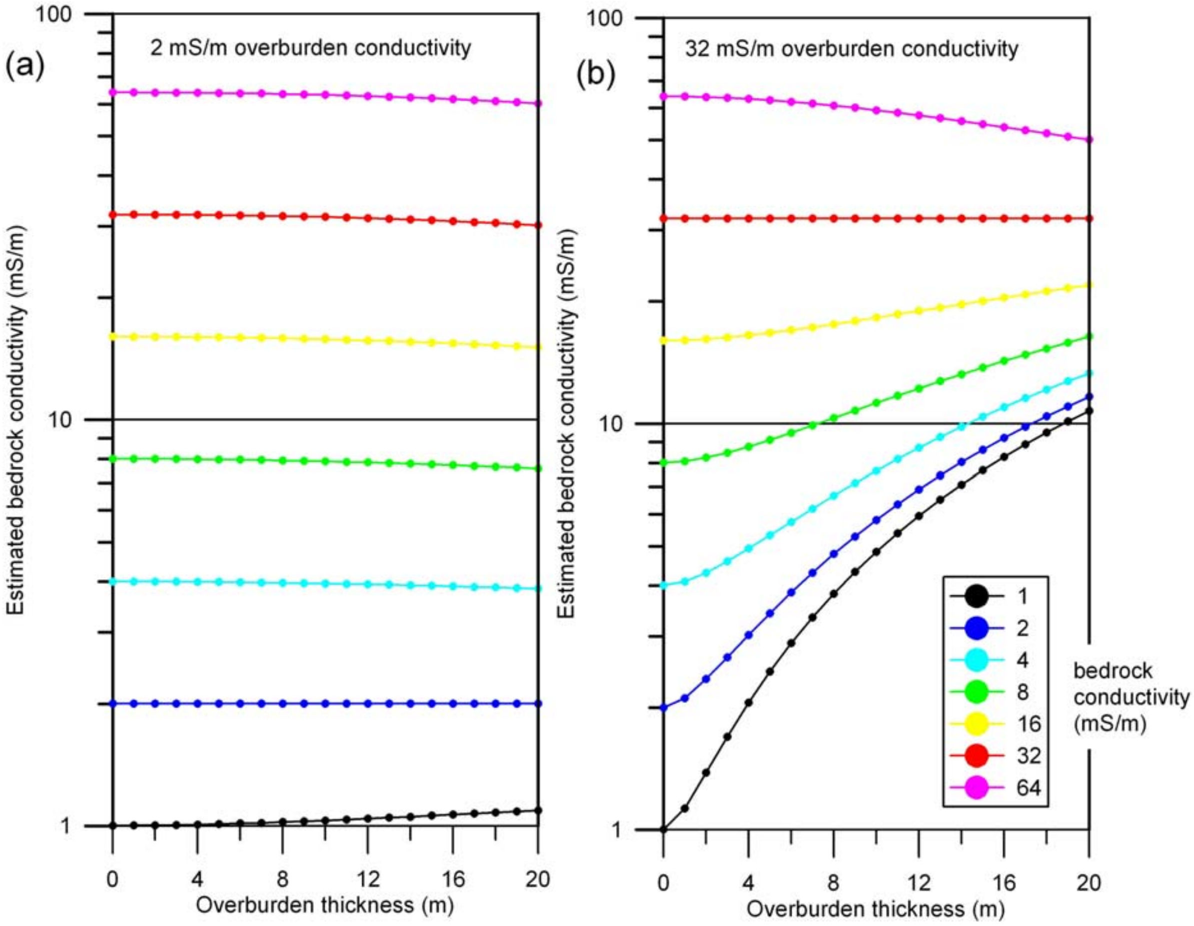
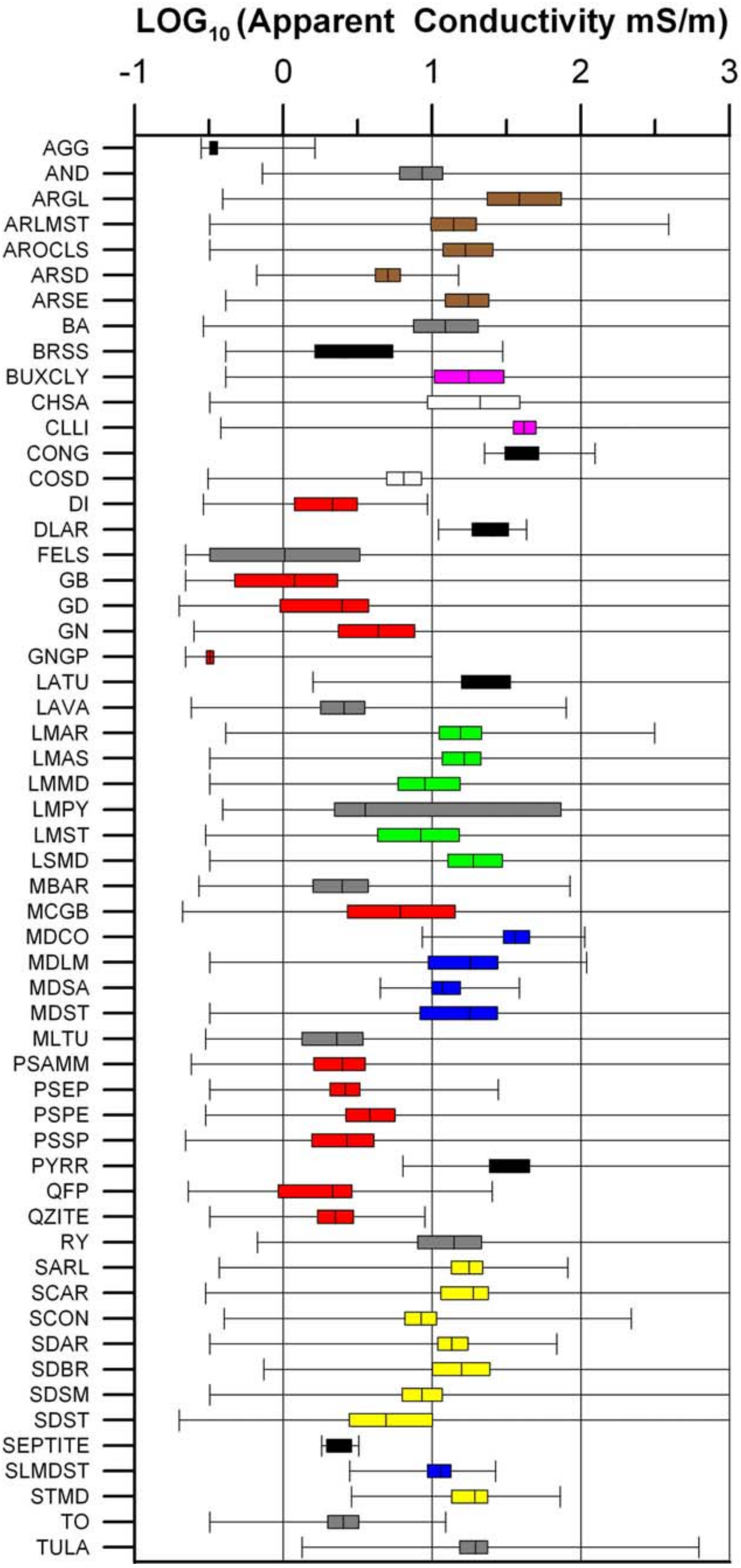


Figure 2

Figure 2. Apparent conductivity modelling results for a 2-layer (superficial above bedrock) sequence for overburden thicknesses to 20 m. (a) Resistive (2 mS/m) above bedrock (1 to 64 mS/m). (b) Conductive (32 mS/m) overburden above bedrock (1 to 64 mS/m).


LOG10 (Apparent Conductivity mS/m)
-1
0
1
2
3
AGG
AND
ARGL
ARLMST
AROCLS
ARSD
ARSE
BA
BRSS
BUXCLY
CHSA
CLLI
CONG
COSD
DI
DLAR
FELS
GB
GD
GN
GNGP
LATU
LAVA
LMAR
LMAS
LMMD
LMPY
LMST
LSMD
MBAR
MCGB
MDCO
MDLM
MDSA
MDST
MLTU
PSAMM
PSEP
PSPE
PSSP
PYRR
QFP
QZITE
RY
SARL
SCAR
SCON
SDAR
SDBR
SDSM
SDST
SEPTITE
SLMDST
STMD
TO
TULA

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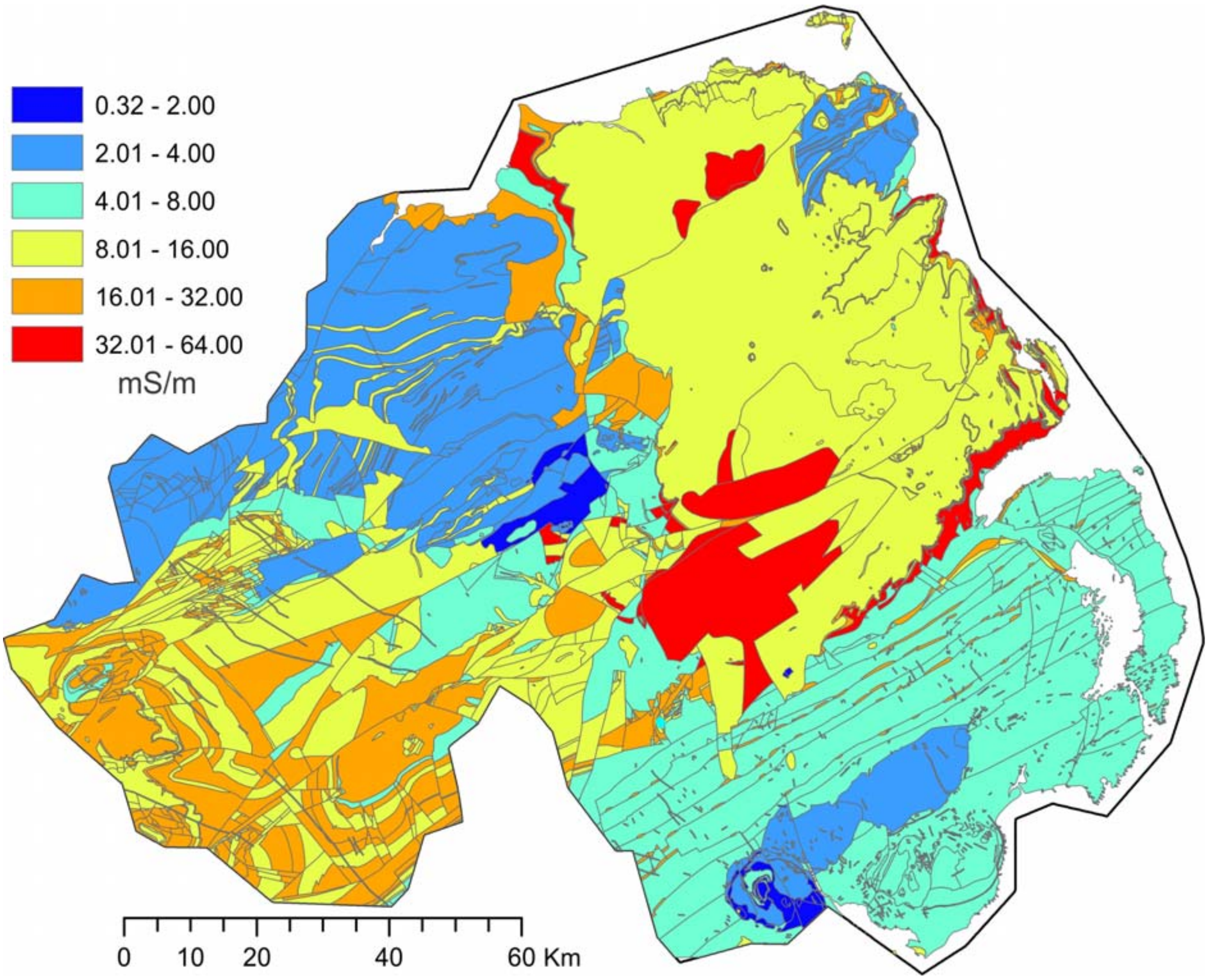

Figure 3

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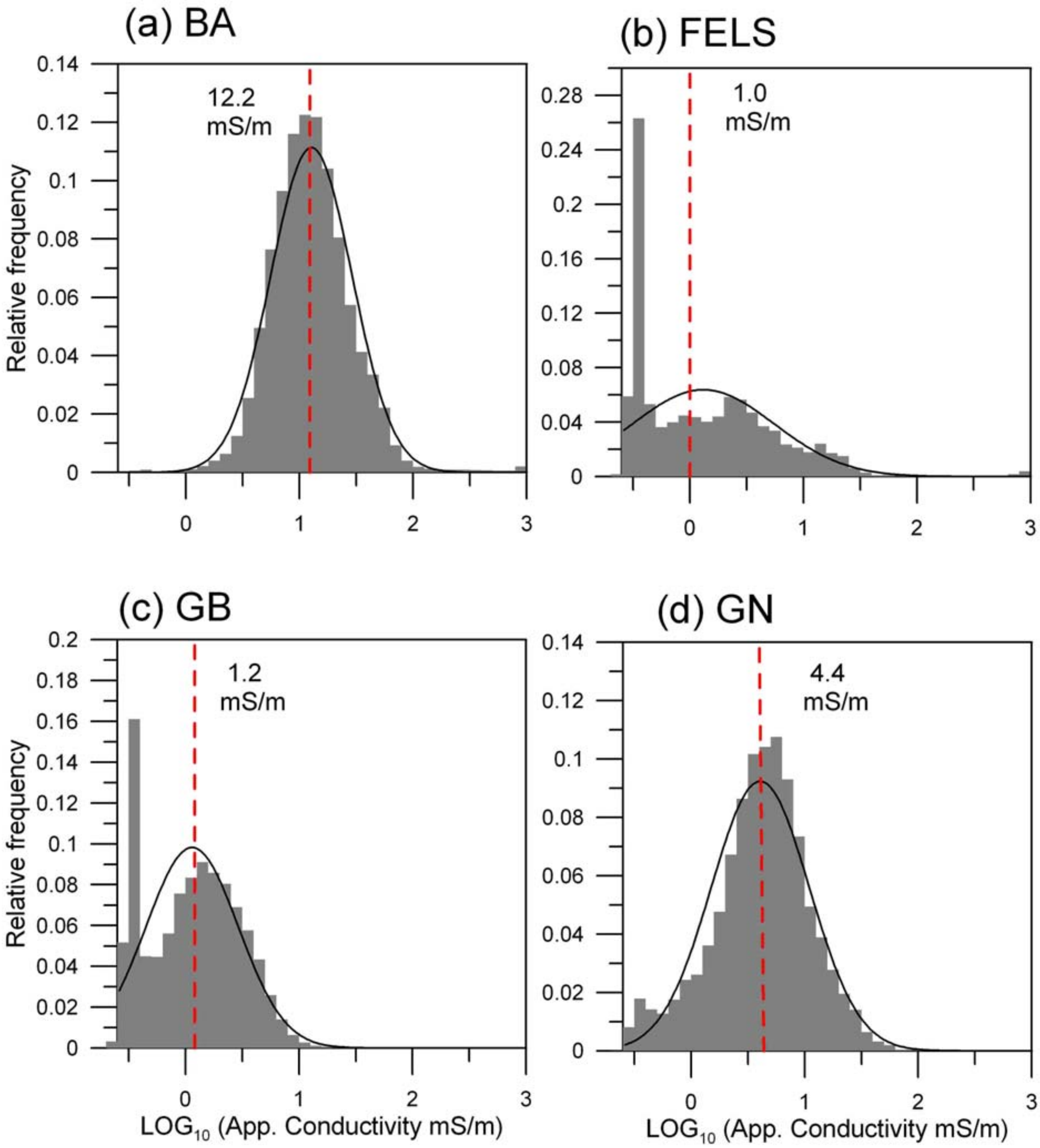

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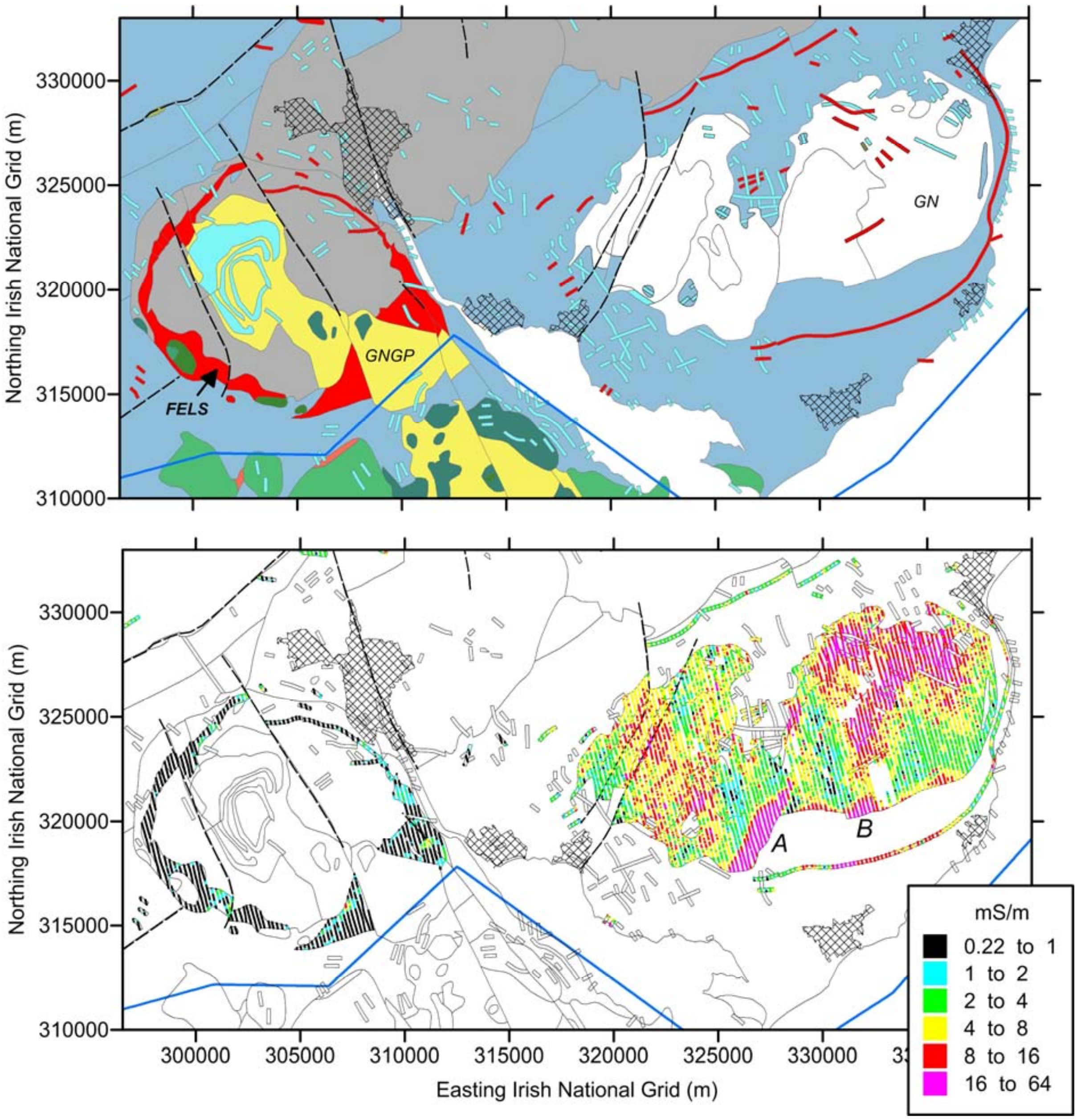

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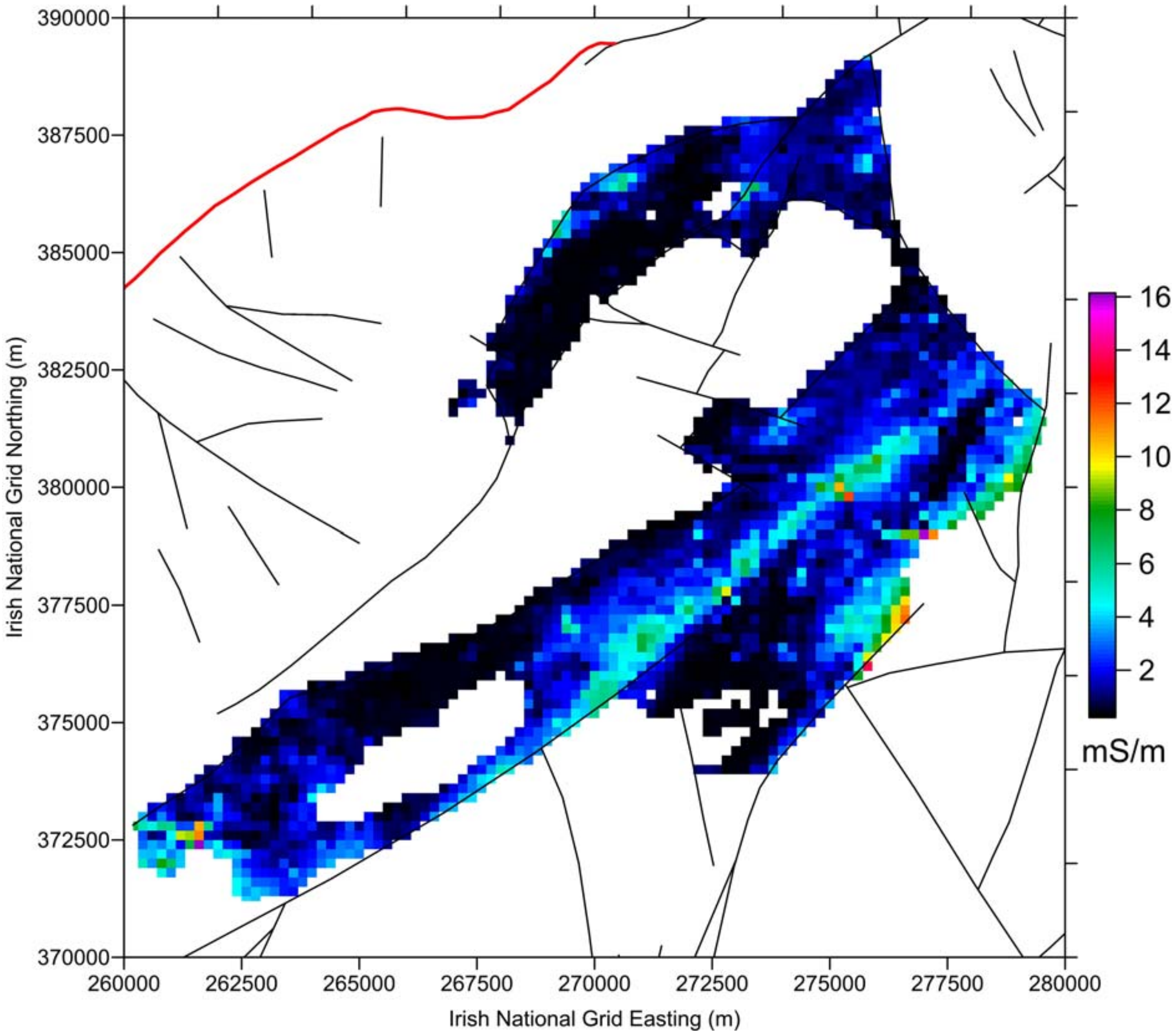

Figure 6

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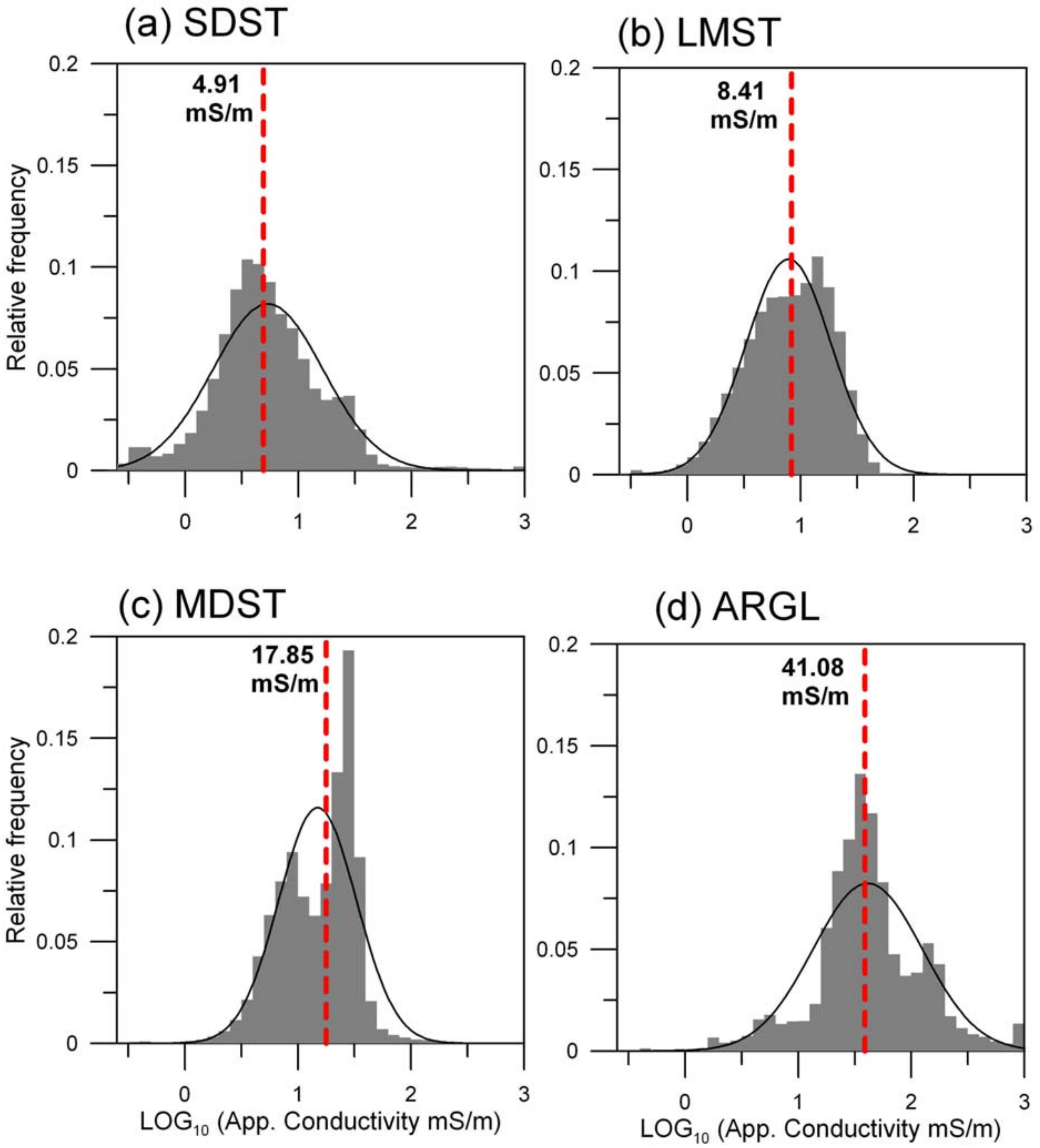

Figure 7

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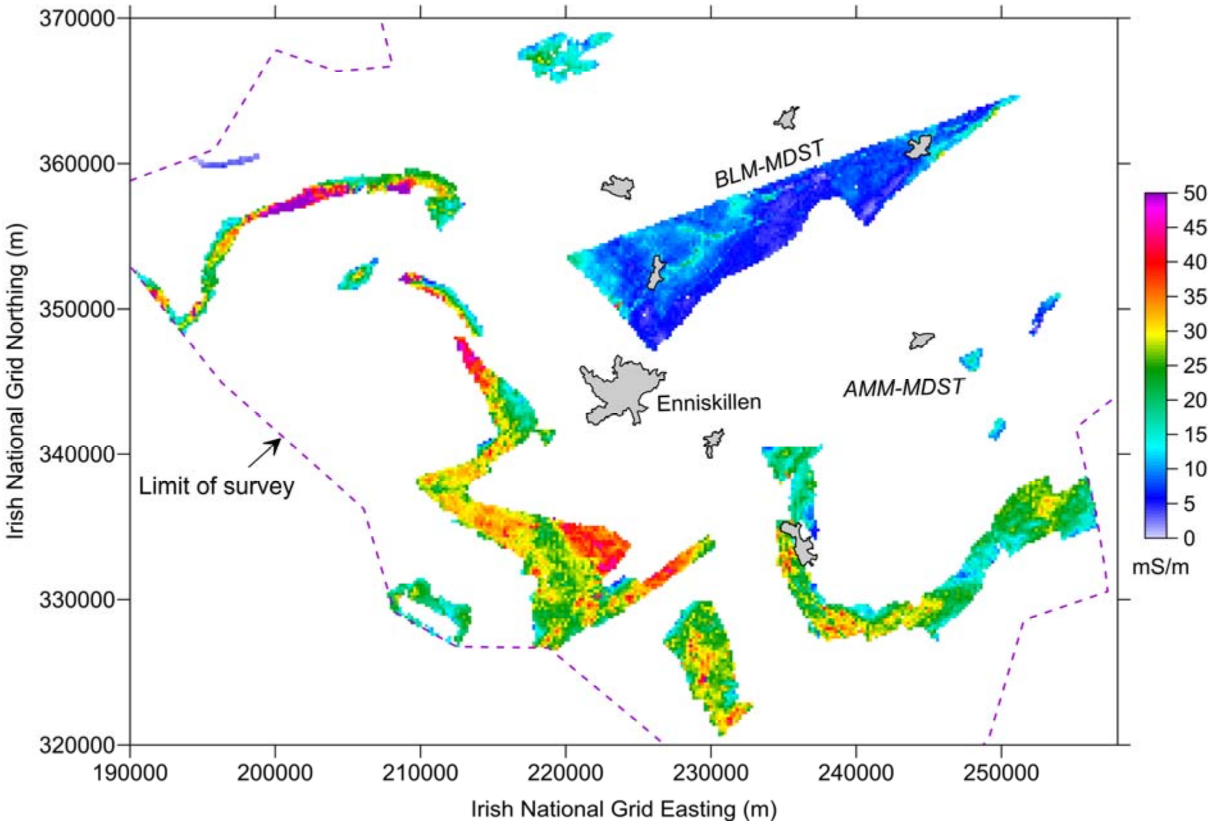

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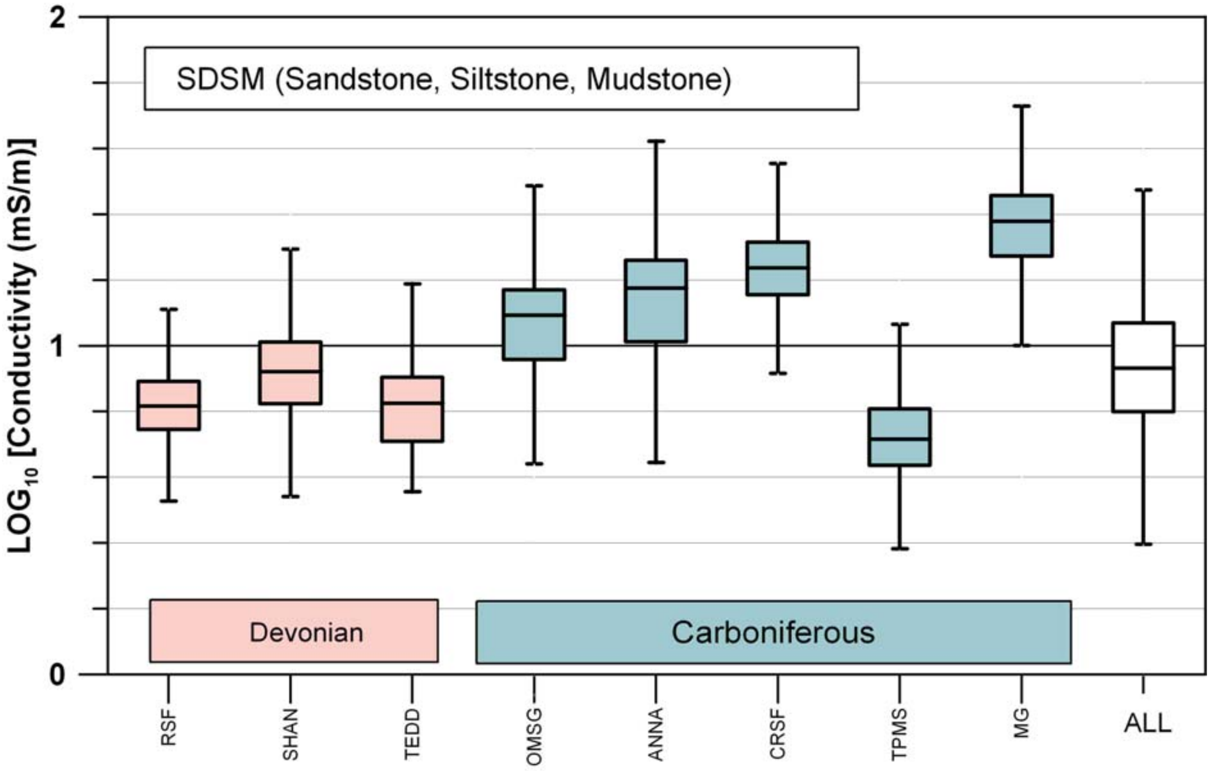

Figure 9

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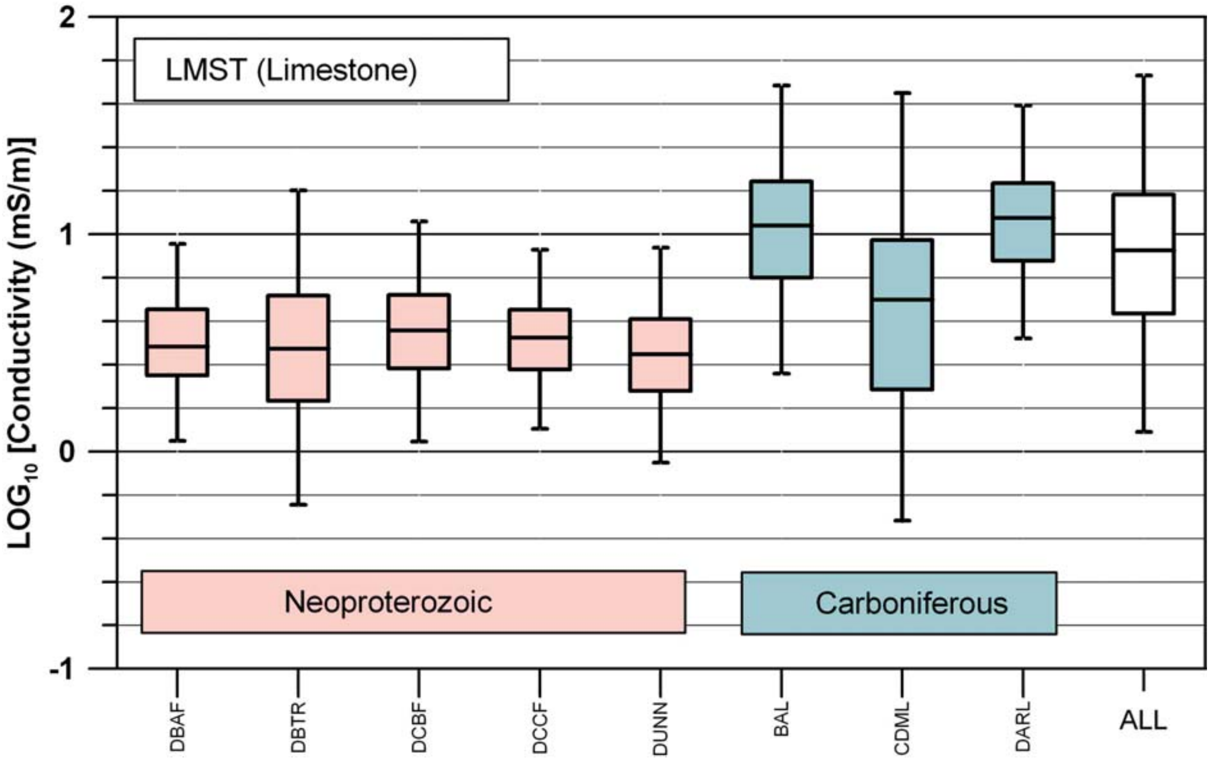

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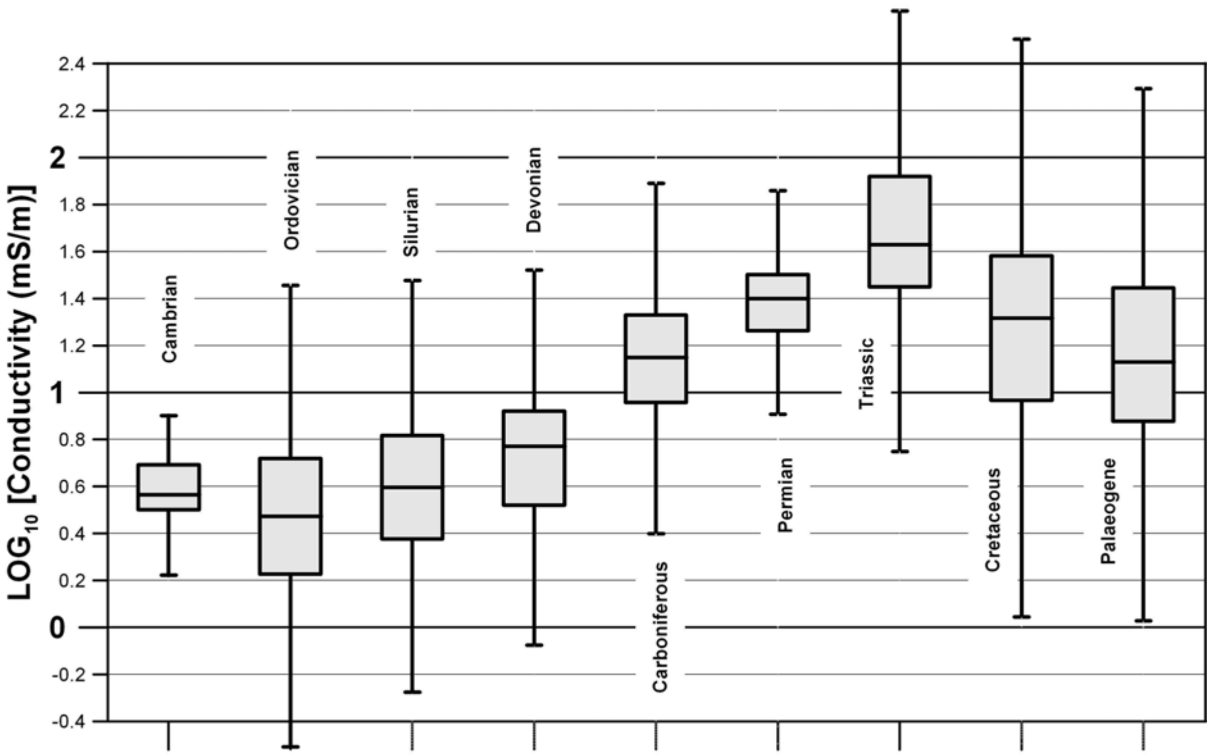

Figure 11

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