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The bedrock electrical conductivity map of the UK

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ABSTRACT

Airborne electromagnetic (AEM) surveys, when regionally extensive, may sample a wide-range of geological formations. The majority of AEM surveys can provide estimates of apparent (half-space) conductivity and such derived data provide a mapping capability. Depth discrimination of the geophysical mapping information is controlled by the bandwidth of each particular system. The objective of this study is to assess the geological information contained in accumulated frequency-domain AEM survey data from the UK where existing geological mapping can be considered well-established. The methodology adopted involves a simple GIS-based, spatial join of AEM and geological databases. A lithology-based classification of bedrock is used to provide an inherent association with the petrophysical rock parameters controlling bulk conductivity. At a scale of 1:625k, the UK digital bedrock geological lexicon comprises just 86 lithological classifications compared with 244 standard lithostratigraphic assignments. The lowest common AEM survey frequency of 3 kHz is found to provide an 87% coverage (by area) of the UK formations. The conductivities of the unsampled classes have been assigned on the basis of inherent lithological associations between formations. The statistical analysis conducted uses over 8 M conductivity estimates and provides a new UK national scale digital map of near-surface bedrock conductivity. The new baseline map, formed from central moments of the statistical distributions, allows assessments/interpretations of data exhibiting departures from the norm. The digital conductivity map developed here is believed to be the first such UK geophysical map compilation for over 75 years. The methodology described can also be applied to many existing AEM data sets.

1. Introduction

Over the past decade, a number of high-resolution airborne geophysical surveys have been conducted across onshore UK (Beamish and Young, 2009; Peart et al., 2003). These High Resolution Airborne Resource and Environmental (HiRES) surveys have typically acquired radiometric (gamma-ray spectroscopy), magnetic and electromagnetic (conductivity) measurements at 200 m line spacings and at low altitude (<60 m). The airborne electromagnetic (AEM) data were typically acquired at four frequencies and the highest frequency provides information on the bulk electrical conductivities of near-surface formations. Progressively deeper information is then provided with decreasing frequency. Due to their systematic coverage, the airborne conductivity data provide almost continuous information across each survey area with a nominal along flight line sampling of less than 15 m.

The HiRES survey areas, flown between 1998 and 2009 are shown in Fig. 1 and summarised in Table 1. The original North Midlands survey of 1998 was largely acquired at lower spatial resolution (400 m line spacing) and at a higher elevation (90 m) than later surveys. The survey did not include active frequency domain EM measurements. AEM data converted to half-space apparent conductivity (e.g. Fraser, 1978) from the remaining 5 surveys are used here. Such data provide a consistent conductivity mapping capability across surveys provided identical/similar frequencies are maintained. Data from most time-domain AEM systems are also capable of transformation to an equivalent estimate of half-space conductivity (Huang and Rudd, 2008).

The term apparent conductivity is used to denote that a vertically uniform, half-space conductivity is assumed. The AEM system used in the UK surveys is described by Leväniemi et al. (2009). Two common EM acquisition frequencies of ~3 kHz and 12–14 kHz were maintained from 1999 onwards. The lower frequency of 3 kHz (3025 Hz prior to 2005 and 3005 Hz thereafter) provides the larger depth of investigation.

The UK surveys necessarily cover a range of UK geological formations. Geological classification is accomplished using a GIS-based scheme and this, in the first instance, defines the range of bedrock formations encountered, together with the AEM data sampling statistics associated with each formation.

The behaviour of geologically classified values of apparent conductivity has previously been presented for the IoW survey by Beamish and White (2011, 2012). The IoW formations provided the youngest bedrock lithologies (Palaeogene and Cretaceous formations) encountered

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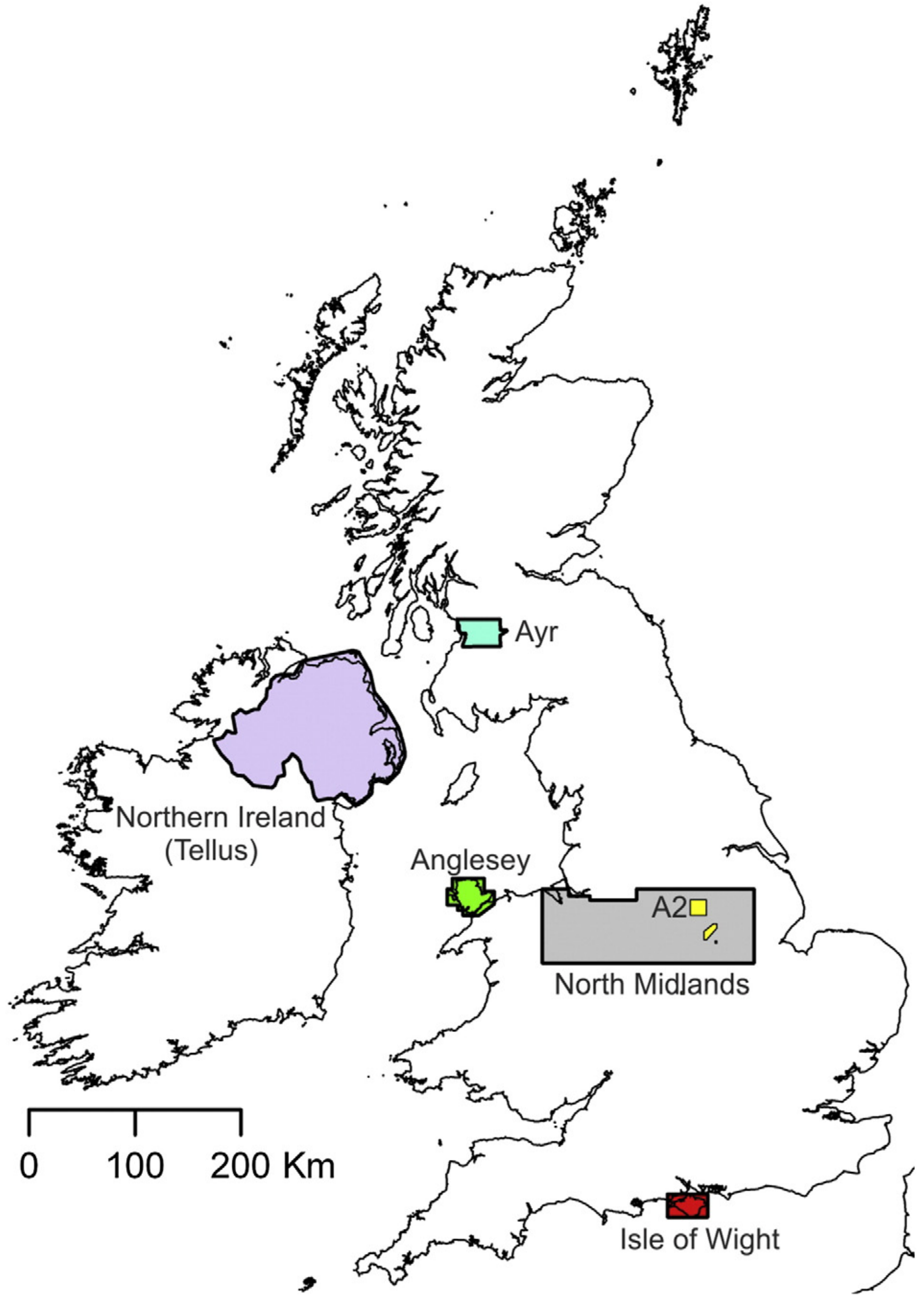

Fig. 1. Six HiRes UK survey areas (1998–2009). The North Midlands survey did not acquire active EM data.

during the HiRES 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. Such baseline data then allow assessments/interpretations of data exhibiting departures from the norm. Beamish and White (2012) compared procedures and results obtained for both LEX-RCS (a lithostratigraphic code description) and RCS (a lithological code description) 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). This observation is based on the dependence of the bulk electrical conductivity on porosity and grain size and packing as embodied in Archie's law (Archie, 1942) together with an additional term to include enhanced conductivity (surface conduction at the pore scale) typically related to the presence of conducting clay/silt materials.

Table 1
HiRES AEM surveys conducted in the UK from 1998 to 2009.

Code	Description	Area (km^2)	Year
HiRES-1	Survey across North Midlands	13,408	1998
A2-Thorseby	Surveys in the East Midlands (Area A2, Thorseby). 4 trial areas surveyed.	329	1999
AYR	Survey across west Ayrshire	977	2004
NI	Tellus survey of Northern Ireland	16,089	2005–06
IoW	Survey of Isle of Wight	836	2008
ANG	Survey of Anglesey	1198	2009

The lithological classification of all the 3 kHz apparent conductivity data across the 5 HiRES survey areas indentified above is considered here. The classification is largely undertaken at a 1:625k scale in order to predict near-surface bedrock properties across the whole of the UK. The potential influence of superficial deposits (when sufficiently thick in terms of EM skin-depth) was examined by Beamish and White

(2012) using the IoW data. When considered at the UK scale, this particular issue relates to the degree to which the survey data, across specific bedrock formations, may be influenced by thicker, conductive superficial deposits. Here we make reference to the current superficial thickness map of the UK (excluding NI) but have to acknowledge that the conductivities of such formations are not broadly defined. As a consequence, there is no 'fixed' AEM depth of investigation but the 3 kHz data should be regarded as providing an assessment of 'near-surface' bedrock electrical conductivity except at locations where thick accumulations of conductive superficial deposits occur.

The study is a first attempt to assemble this information using observed high-resolution geophysical data. It is anticipated that the initial baseline model developed here can be further refined. In addition, the techniques employed here can be applied to many existing spatially extensive AEM data sets.

2. AEM survey data

Frequency domain AEM data is acquired using either fixed wing (wing-tip sensors) or helicopter (towed bird HEM) systems. The data comprise in-phase and in-quadrature components (coupling ratios in ppm) at each operational frequency.

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 AEM system considered here. Each measurement may typically be associated with a principal area of sensitivity of less than 100×100 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. Depths of investigation exceed the skin-depth values in all cases.

Each specific AEM system has a limited conductivity aperture defined by the 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 (a resistivity value of 3125 $\Omega \cdot$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 data used in the study comprise 2- and 4-frequency AEM coupling ratios which may be used to provide conductivity models using formal 1D inversion methods (Beamish, 2002). The limited vertical resolution of the available bandwidth has to be accommodated in any specific inversion and interpretation procedure (Beamish and Klinck, 2006). Leväniemi et al. (2009) demonstrate and compare the type of vertical resolution that may be achieved using the 2- and 4-frequency systems considered here. In both systems, the two highest frequencies control the resolution of the near-surface conductivity distribution. Depending on any conductivity contrasts encountered, the resolution of the upper 10 to 15 m is generally poor. Given the extensive nature of the data sets considered, attempts to provide consistent and reliable inversion models of superficial–bedrock relationships has proved problematic. The half-space apparent conductivity, used here, provides a conservative and consistent, estimate of broad spatial variations in conductivity suitable for the data sets and procedures used here.

3. 1:625k UK Lithology

The fifth edition 1:625,000 (1:625k) scale bedrock geological map of the United Kingdom was released as DiGMapGB-625 in 2008 (BGS, 2008). The data are described by Smith (2011) and further details can found at http://www.bgs.ac.uk/products/digitalmaps/digmapgb_625.html.

The geology is based on two main sources: i) the 1:50k scale vector dataset of digital geology called DiGMapGB-50 (BGS, 2005) with nearly complete coverage of Great Britain; and ii) the 1:250k scale geological map of Northern Ireland (NI) (Cooper et al., 1997).

Each polygon in the 1:50k data was at that time identified by a two-part 'LEX-ROCK' code such as MMG-MDST (Mercia Mudstone Group-Mudstone). The first part, the Lexicon code, refers to the name of the unit, as listed in the BGS Lexicon of Named Rock Units and accessible on the BGS website at http://www.bgs.ac.uk/lexicon/home.cfm. The second part, the ROCK code, refers to the composition or lithology of the unit in a BGS database then in use. For the final 1:625k data release the LEX-ROCK codes were replaced with LEX-RCS, using lithology codes derived from the hierarchical BGS Rock Classification Scheme (RCS).

The 1:625k digital lexicon contains 244 categories under the LEX-RCS classification that would provide the basis of a standard lithostratigraphic geological map (Smith, 2011). The simpler RCS lithological characterisation, used here, provides 86 categories. The digital product contains 11,244 polygons that form the basis of the geophysical attribution. The lexicon codes of the 1:625k RCS characterisation together with their descriptions are provided in Table 2.

The line-work of the 1:625k product is shown in Fig. 2. The total UK area considered is 244,871 km^2 and the total number of samples is 8,146,855 (Table 1). It is also worth noting that use is also made of partially corresponding RCS lexicons at 1:250k and 1:50k scales from the BGS DIGMapGB products. Single sedimentary lithologies such as MDST (MUDSTONE) and SDST (SANDSTONE) do not appear at the 1:625k scale but can be obtained using the RCS lexicon at the 1:250k scale.

4. Lithological classification

The standard method of geological attribution of airborne geophysical measurements (half-space apparent conductivity at a particular frequency) follows the procedures given in Beamish and White (2011, 2012). Spatial lithological classification was undertaken using ArcGIS ™ software developed by Environmental Systems Research Institute, Inc. (ESRI). Here we make use of the 5 separate HiRES survey data sets (AYR, NI, ANG, IoW and A2) shown in Fig. 1. A single frequency of ~3 kHz has been analysed. Each of the 5 data sets has had various degrees of conditioning (data screening to remove outliers) applied. The procedures include applying a maximum value of 500 to 1000 mS/m to the data and restricting the data to locations where the survey altitude is less than 120 to 180 m. This second condition also has the equivalent effect of restricting the data set to non-urban areas. The use of the upper maximum thresholds relates, in part, to the fact that many of the surveys contain coastal and offshore data. Although, in this study, assessments are only undertaken onshore, the coastal zone often contains a number of data that are influenced by seawater intrusion and are therefore geologically unrepresentative.

Following screening/conditioning, each data set was used in the attribution of the 1:625k lithological database. The spatial join procedure employed results in the attribution of the spatially-located geophysical data by geological code(s) contained within the geological database. As expected the procedure resulted in a variable number of conductivity samples per lithological unit. Some intricacies of nomenclature across the 1:625k, 1:250k and 1:50k RCS lexicon codes were discovered. For example the RCS code SARL at 1:625k only identifies a suite of Border Group (i.e. Scotland/England) rocks where no airborne data exist. The NI 1:250k bedrock geology database (version 2.18, 2009), however, allows an estimate of RCS = SARL conductivity to be made. A similar set of circumstances applies to other RCS codes (e.g. LMST), omitted at 1:625k scale, but which can be attributed

Table 2
The 86 categories of the DIGMapGB lithological RCS lexicon at 1:625k scale. The area of each formation is given in km^2. N refers to the number of AEM samples used in the classification.

RCS code	RCS_DESCRIPTION	AREA km^2	N
ANO	ANORTHOSITE	8	32,346
BCSD	BRECCIA, CONGLOMERATE AND SANDSTONE	42	224
BRCMBR	BRECCIA AND METABRECCIA	28	224
CHLK	CHALK	19,310	14,011
CHSA	CHALK AND SANDSTONE	120	37,804
CLLI	CLAY AND LIGNITE	593	198,574
CLSISA	CLAY, SILT AND SAND	362	57,551
CLSSG	CLAY, SILT, SAND AND GRAVEL	7733	5599
COSD	CONGLOMERATE AND [SUBEQUAL/SUBORDINATE] SANDSTONE, INTERBEDDED	228	4147
CSSM	CONGLOMERATE, SANDSTONE, SILTSTONE AND MUDSTONE	5170	4147
CYCC	SEDIMENTARY ROCK CYCLES, CLACKMANNAN GROUP TYPE	2077	30,863
CYCS	SEDIMENTARY ROCK CYCLES, STRATHCLYDE GROUP TYPE	975	9946
DBAT	DOLERITE AND THOLEIITIC BASALT	233	38,926
DIAMIT	DIAMICTITE	47	655
DLDO	DOLOMITISED LIMESTONE AND DOLOMITE	1434	9563
DOLO	DOLOSTONE	94	9563
FELSR	FELSIC-ROCK	8555	201,299
FLAVA	FELSIC LAVA	65	12,543
FTUFF	FELSIC TUFF	757	7192
GNSMF	MAFIC GNEISS	93	61,393
GNSS	GNEISS	3886	61,393
GPSP	GNEISSOSE PSAMMITE AND GNEISSOSE SEMIPELITE	957	13,774
GSSC	GRAVEL, SAND, SILT AND CLAY	3607	57,511
HBSCH	HORNBLENDE SCHIST	62	8229
LATF	FELSIC LAVA AND FELSIC TUFF	292	9298
LATM	MAFIC LAVA AND MAFIC TUFF	9688	1,196,650
LATU	LAVA AND TUFF	25	580
LMAS	LIMESTONE, ARGILLACEOUS ROCKS AND SUBORDINATE SANDSTONE, INTERBEDDED	1653	49,266
LMCM	LIMESTONE, MUDSTONE AND CALCAREOUS MUDSTONE	212	87,476
LMCS	LIMESTONE AND CALCAREOUS SANDSTONE	109	31,902
LMST	LIMESTONE	229	251,552
LSMD	LIMESTONE AND MUDSTONE, INTERBEDDED	64	26,951
LSSA	LIMESTONE WITH SUBORDINATE SANDSTONE AND ARGILLACEOUS ROCKS	4925	28,825
LSSM	LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTONE	5604	134,842
LTVS	LAVA, TUFF, VOLCANICLASTIC ROCK AND SEDIMENTARY ROCK	347	2667
MAFI	MAFITE	10	1225
MDCB	MUDSTONE, CHERT AND SMECTITE-CLAYSTONE	158	17,459
MDSC	MUDSTONE, SANDSTONE AND CONGLOMERATE	352	39,282
MDSL	MUDSTONE, SANDSTONE AND LIMESTONE	2671	39,282
MDSS	MUDSTONE, SILTSTONE AND SANDSTONE	54,902	8791
MFIR	MAFIC IGNEOUS-ROCK	2596	63,681
MFLAVA	MAFIC LAVA	453	4544
MFTUF	MAFIC TUFF	179	12,224
MIGM	MIGMATITIC ROCK	1208	61,393
MLMST	METALIMESTONE	691	51,930
MSCI	MUDSTONE, SILTSTONE, SANDSTONE, COAL, IRONSTONE AND FERRICRETE	10,609	472
MSDR	METASEDIMENTARY ROCK	440	80,137
MSLS	MUDSTONE, SILTSTONE, LIMESTONE AND SANDSTONE	8778	13,690
MSSP	GNEISSOSE SEMIPELITE AND GNEISSOSE PSAMMITE	50	61,393
MVIVS	METAVOLCANICLASTIC IGNEOUS-ROCK AND METAVOLCANICLASTIC SEDIMENTARY-ROCK	19	6107
MYCFB	MYLONITIC-ROCK AND FAULT-BRECCIA	557	Estimated
PEL	PELITE	1200	198
PGCP	GRAPHITIC PELITE, CALCAREOUS PELITE, CALCSILICATE-ROCK AND PSAMMITE	1531	132,925
PPSPC	PSAMMITE, PELITE, SEMIPELITE AND CALCSILICATE-ROCK	25	132,925
PSAMM	PSAMMITE	6627	18,270
PSP	PSAMMITE, SEMIPELITE AND PELITE	5864	400,786
PSPE	PSAMMITE AND PELITE	6462	132,925
PSSP	PSAMMITE AND SEMIPELITE	4215	117,106

Table 2 (*continued*)

RCS code	RCS_DESCRIPTION	AREA km^2	N
PYRR	PYROCLASTIC-ROCK	90	816
QAREN	QUARTZ-ARENITE	390	18,449
QZITE	QUARTZITE	1669	18,449
SARL	SANDSTONE WITH SUBORDINATE ARGILLACEOUS ROCKS AND LIMESTONE	691	58,277
SCAR	SANDSTONE, CONGLOMERATE AND [SUBORDINATE] ARGILLACEOUS ROCKS	164	52,701
SCGS	SANDSTONE WITH SUBORDINATE CONGLOMERATE AND SILTSTONE	24	201
SCH	SCHIST	39	36,623
SCHM	MICA SCHIST	33	26,854
SCON	SANDSTONE AND CONGLOMERATE, INTERBEDDED	16,514	6820
SCSM	SANDSTONE WITH SUBORDINATE CONGLOMERATE, SILTSTONE AND MUDSTONE	3397	423,972
SDAR	SANDSTONE AND [SUBEQUAL/SUBORDINATE] ARGILLACEOUS ROCKS, INTERBEDDED	65	22,106
SDBC	SANDSTONE, BRECCIA AND CONGLOMERATE	684	14,711
SDBR	SANDSTONE AND SUBORDINATE BRECCIA	16	2584
SDLM	SANDSTONE AND [SUBEQUAL/SUBORDINATE] LIMESTONE, INTERBEDDED	20	3421
SDSL	SANDSTONE AND SILTSTONE, INTERBEDDED	2111	201
SDSM	SANDSTONE, SILTSTONE AND MUDSTONE	3399	134,842
SEDS2	LIMESTONE, MUDSTONE, SANDSTONE AND SILTSTONE, WITH SUBORDINATE CHERT, COAL AND CONGLOMERATE	2070	705,648
SEMPEL	SEMIPELITE	335	400,786
SISDM	SILTSTONE AND SANDSTONE WITH SUBORDINATE MUDSTONE	1139	423,972
SLAR	SANDSTONE, LIMESTONE AND ARGILLACEOUS ROCKS	3716	2006
SMLP	SERPENTINITE, METABASALT, METALIMESTONE AND PSAMMITE	30	44
SMSC	SANDSTONE, MUDSTONE, SILTSTONE AND CONGLOMERATE	1401	423,972
SPPE	SEMIPELITE AND PELITE	484	400,786
SSCL	SAND, SILT AND CLAY	2234	6434
STMD	SANDSTONE AND MUDSTONE	3316	29,866
SYR	SYENITIC-ROCK	73	1709
UMFT	ULTRAMAFITITE	219	758
WACKE	WACKE	11,355	835,616

using the extensive sampling of the NI survey and the NI 1:250k geological database. Further details are given in Beamish (2012).

This first-pass procedure resulted in the attribution of 54 of the 86 lithological units as defined by the 1: 625k lexicon. This corresponds to a 84.6% coverage of the UK landmass. The number of samples obtained (N, Table 2) ranges from 198 (RCS = PEL) to 1,196,665 (RCS = LATM). In order to obtain complete coverage of the UK lithologies, it has been necessary to obtain estimates using the lithological associations of the remaining 32 RCS classifications. The unsampled lithological units cover an area of only 33,267 km^2 (13.6% of the total UK area). It is worth noting some simple points about the procedure adopted. In a number of cases the remaining lithologies represent very small, localised occurrences of particular units (e.g. RCS = ANO, 8 km^2 and RCS = MAFI, 11 km^2, Table 2). Fourteen of the 32 units have spatial areas of less than 100 km^2. The distribution of the main unsampled lithologies is summarised in Fig. 2 which shows the 9 most significant units having areas of > 1000 km^2. It can be noted that a significant proportion of the lithologies are confined to Scotland. Many of the unsampled units comprise multi-lithological components and natural associations with sampled lithologies exist. The reassignment of the attribution of the unsampled lithologies is described in detail by Beamish (2012).

5. Analysis

5.1. Superficial thickness

The potential influence of superficial deposits on bedrock classification was previously noted. The required understanding requires knowledge of the conductivity of the superficial deposits together with their thicknesses. Information on superficial thickness at the national scale (but excluding NI) is available through the National Superficial Deposit Thickness Model (Lawley and Garcia-Bajo, 2009). The thickness map, at the national scale, with the HiRES surveys areas superimposed is shown in Fig. 3.

In general terms, the 3 survey areas of A2, IoW and ANG contain only thin superficial deposits. The AYR survey contains thicker deposits however it is also necessary to consider the precise spatial areas covered by the lithological zones used in the attribution. In the case of the AYR survey these are just 2 lithologies (CYCC and CYCS, Table 2). If the conductivities of these superficial deposits were known, it might be useful to further exclude zones with larger superficial conductivity-thickness products and thus refine the bedrock analysis of the CYCC and CYSS formations. Since the superficial thickness is not currently available for NI, the present study does not include any assessment of the influence of superficial deposits. The bedrock model produced is, however, capable of further refinement.

Forward modelling of the ‘bias’ introduced into the estimate of the 3 kHz apparent conductivity by variations in the overburden conductivity and thickness is described by Beamish (2013). 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 3 kHz apparent bedrock conductivities. In the geostatistical and spatial assessment *over large areas* undertaken here, it is acknowledged that zones of persistently thick conductive overburden may provide a bias in the bedrock conductivity distributions obtained. The analysis conducted is statistical and central moments of classified conductivity distributions are used. It is therefore anticipated that the procedure may be

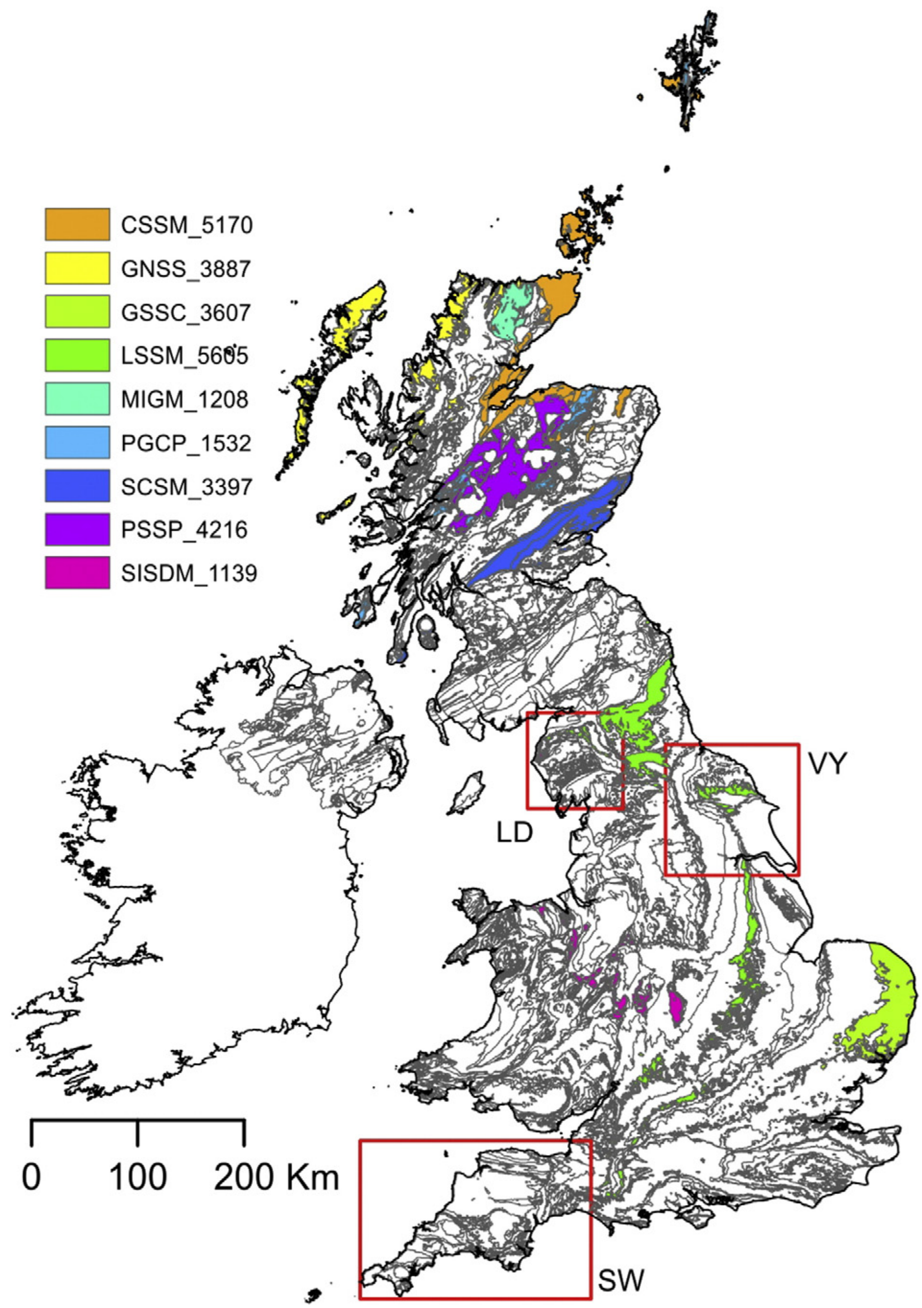

Fig. 2. The line-work (in grey) of the 1:625k digital geological map. The nine main lithologies (see Table 2) omitted from the attribution are identified in the legend along with their areas (km^2). Three rectangles identify areas discussed in the text (LD = Lake District, VY = Vale of York, SW = South West England).

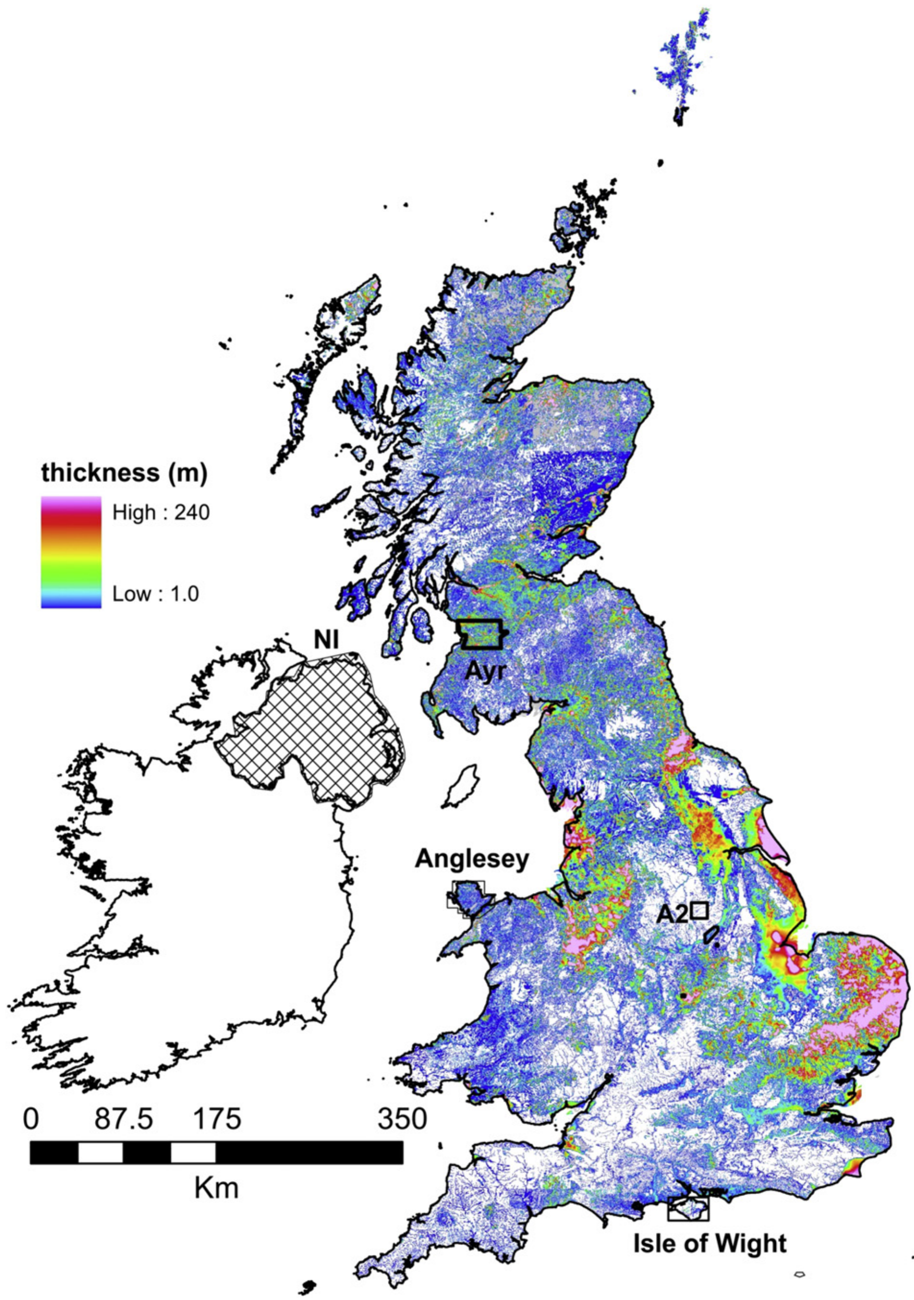

Fig. 3. The superficial deposit thickness map of the UK (excluding Northern Ireland) with 5 HiRES survey areas identified.

reasonably robust to non-spatially persistent outliers that then appear in the tails of the distributions (e.g. Figs. 4 and 5).

5.2. Statistical conductivity distributions

Beamish and White (2012) noted that the apparent conductivity distributions obtained across selected geological areas are distinct from conventional statistical distributions. They are typically highly peaked, with one or two long tails. Conventional statistical tests (e.g. the Shapiro–Wilk test; Shapiro and Wilk, 1965) for normality or log-normality typically indicate that the classified distributions conform to neither. This is a common situation when dealing with large-scale regional datasets (Reimann and Filzmoser, 2000). Although the data distributions are, in a strict sense, non-parametric, there is a general tendency for the distributions to be closer to log-normally distributed when standard statistical tests are applied. Here a logarithmic (base 10) transform is applied to all the data sets.

When extracting central moments of the conductivity distributions it is important to understand their detailed behaviour (e.g. Beamish and White, 2012). Here only a limited set of examples is considered. Fig. 4 shows 4 lithologically attributed conductivity distributions obtained from the 1:625k analysis. The lithological units considered are:

1) LATM (MAFIC LAVA AND MAFIC TUFF). The largest lithology sampled in this study (the Antrim basalts). N = 1, 1,119,665.
2) COSD (CONGLOMERATE AND [SUBEQUAL/SUBORDINATE] SANDSTONE, INTERBEDDED). A 2-way mixed lithology sedimentary rock. N = 4147.
3) SCAR (SANDSTONE, CONGLOMERATE AND [SUBORDINATE] ARGILLACEOUS ROCKS). A 3-way mixed lithology sedimentary rock. N = 52,701.
4) MSLS (MUDSTONE, SILTSTONE, LIMESTONE AND SANDSTONE). A 4-way mixed lithology sedimentary rock. N = 13,690.

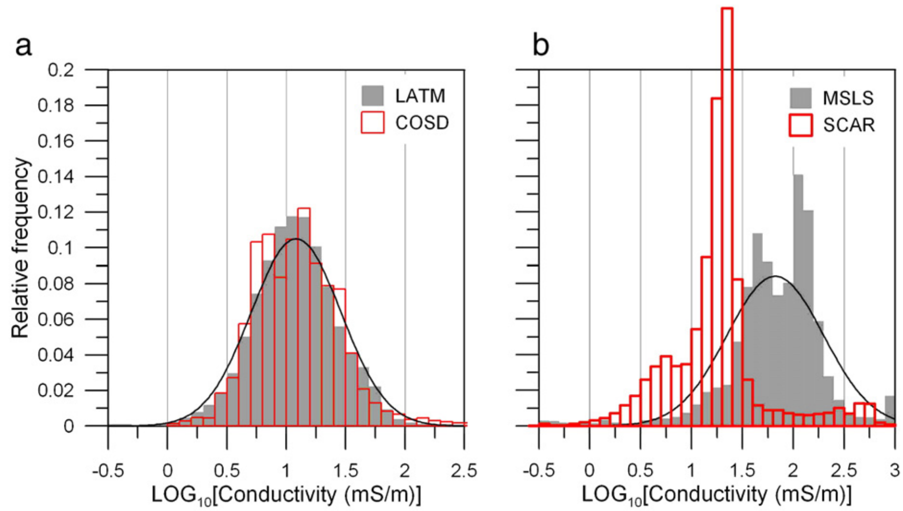

Fig. 4. Histograms of conductivities (LOG transformed) of 4 lithologies (see Table 2) discussed in the text. (a) LATM with best-fitting normal distribution and COSD. (b) MSLS with best fitting normal distribution and SCAR.

Despite the large sampling area (9688 km^2), the LATM distribution appears unimodal and close to log-normal (the best-fitting log-normal is displayed in Fig. 4a). The distribution is compared with that of COSD which has a similar form but a 2-peak distribution is observed in the central moment area. Despite this, an assessment of central moments using quartile/decile statistics would provide an adequate summary of the behaviour of both sets of data. The far more complex distributions obtained in the case of the MSLS and SCAR lithologies are shown in Fig. 4b. Highly peaked and skewed multimodal behaviour together with significantly long tails, is observed in both cases. The best fitting log-normal distribution is shown for the MSLS distribution. Although specific central moments (e.g. the median) can be obtained for all the data, the detailed complex behaviour of a number of the data distributions should be acknowledged.

The classification procedure undertaken allows for a wide range of studies of the conductivity behaviour of the sedimentary, metamorphic and igneous rocks contained in each lexicon (e.g. Beamish, 2013). Here we provide an example of the distributions and central moments of the conductivities of mixed lithology sandstone units. The 1:625k lexicon (Table 2) contains a wide range of these formations but does not include a single lithology formation. Fig. 5 uses a box–whisker plot to summarise the distributions of 10 sandstone formations from the NI, AYR and ANG survey data. In Fig. 5, the central box indicates the limits of 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.

The first distribution shown (SCAR) is the box–whisker summary of the rather extreme distribution noted in Fig. 4b. A significant difference between the median and mean (in the centre of the box) central moments is apparent. Other distributions display behaviour that is closer to log-normal. Across the ensemble, distinct differences occur in the central moments that are attributable to the behaviour expected from Archie's (1942) expression extended to account for clay/silt contributions. The highest median conductivity (23.9 mS/m) is observed for SDSM (SANDSTONE, SILTSTONE AND MUDSTONE). The second highest conductivity (19.4 mS/m) is then observed for STMD (SANDSTONE AND MUDSTONE). The lowest median conductivity (5.6 mS/m) is obtained for SCON (SANDSTONE AND CONGLOMERATE, INTERBEDDED) with the next lowest value (7.0 mS/m) observed for SDBC (SANDSTONE, BRECCIA AND CONGLOMERATE). Further examples of the distribution behaviours of geologically classified AEM conductivity data can be found in Beamish (2013).

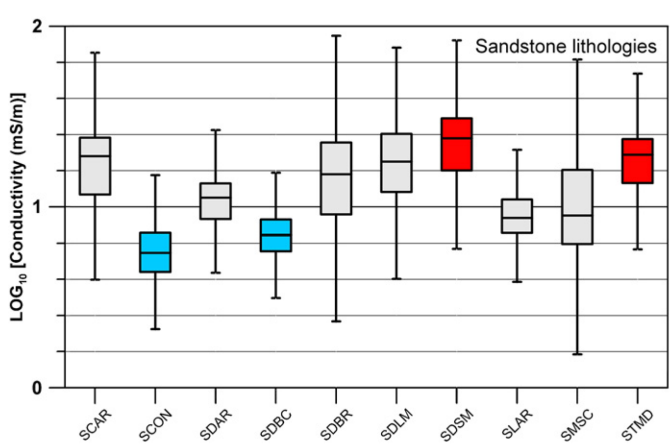

Fig. 5. Box–whisker plot (outliers not shown) of distributions of conductivities (LOG transformed) of 10 sandstone lithologies identified by their RCS lithological codes (see Table 2).

6. Results

The central moments of the conductivity distributions obtained from the RCS lithological analysis (Table 2) are obtained using the logarithmically transformed data, as discussed previously. Here the central moment used is the median value associated with each distribution. The median value is then transformed into linear conductivity and used to provide the lithologically-classified conductivity map of the UK. The two most conductive lithologies are obtained for MYCFB (145 mS/m, an assumed value for fault zone rocks), and CLISA (126 mS/m, a value for Clay, Silt, Sand). A third high value for SDSL (129 mS/m, a value for Sandstone/Siltstone) was obtained by the analysis but only 201 values were available and so the result may be considered unreliable. The three most resistive lithologies are obtained for PYRR (0.32 mS/m, Pyroclastic rock), PSAMM (0.69 mS/m, Psammite, a metamorphic/metasedimentary rock) and FLAVA (1.02 mS/m, Felsic Lava, a fine grained volcanic rock). The conductivity map obtained is shown using a 7 range, non-linear colour scale in Fig. 6.

The conductivity attributed polygons necessarily follow the behaviour of the 1:625k lithological map. At the scale shown, there is an evident association between the larger scale terranes found in northern

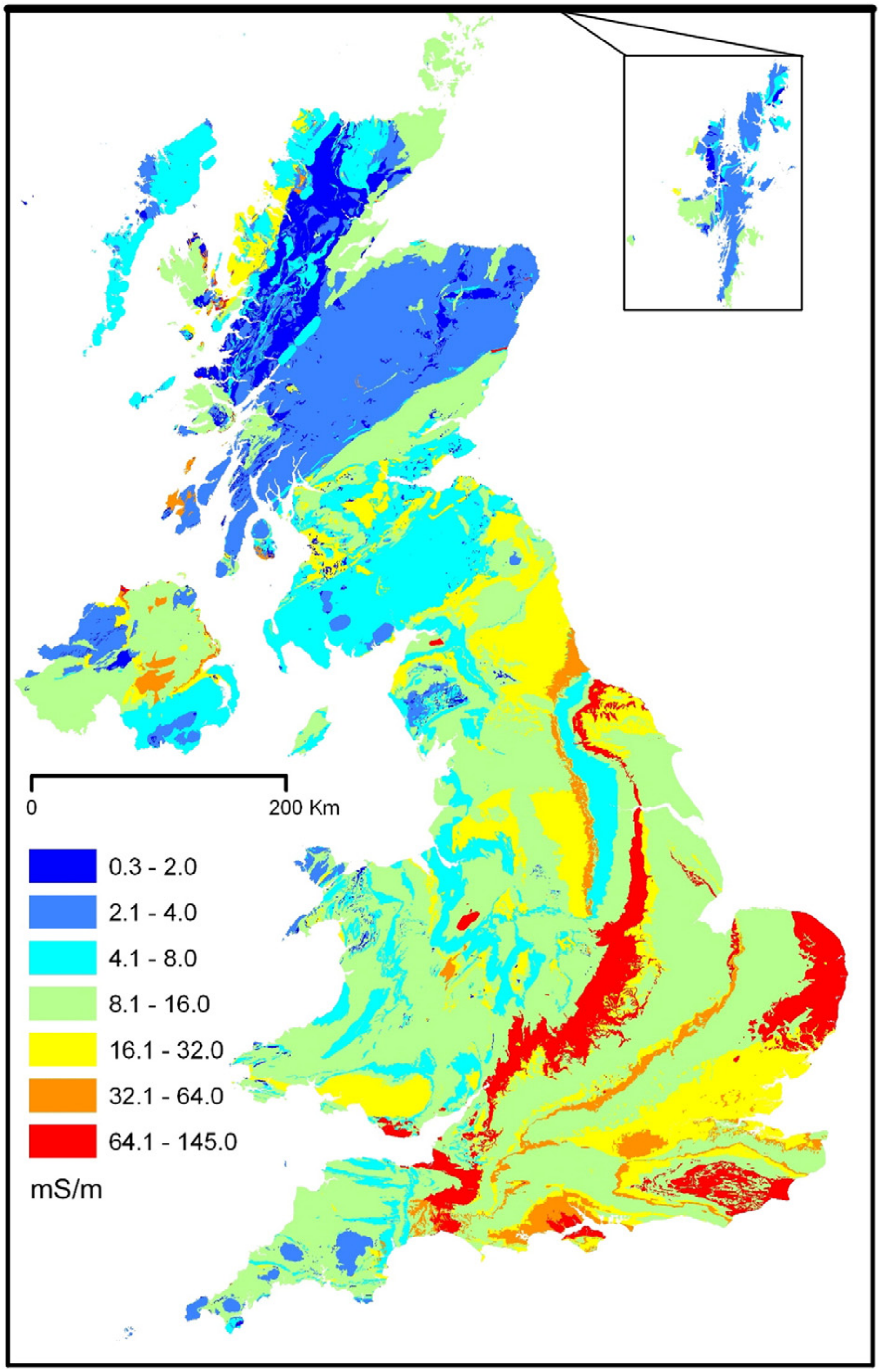

Fig. 6. The 1:625k near-surface bedrock conductivity distribution produced by lithological classification. Inset shows Shetland Islands (not to same scale).

Scotland (omitting the Midland Valley), the Southern-Uplands–Down-Longford terrane, the Lake District (see below), NW Wales (particularly Anglesey) and the south west England granitic terrane (see below) which are all associated with the lowest conductivities (<5 mS/m). The general areas of eastern and southern England, largely represented by sedimentary formations, are generally associated with the highest conductivities.

The 1:625k conductivity map is digital and capable of further manipulation. In order to demonstrate some of the detail available within the map, 3 areas identified in Fig. 2 were selected. The conductivity data for each area is then displayed using a 5 range colour scheme with natural breaks based on the conductivity distribution across each area.

6.1. Lake District

The conductivity map across this 90 $\times$ 90 km area is shown in Fig. 7. The highest conductivity range is from 15.2 to 75 mS/m and thus this large area is predominantly resistive (i.e. <15 mS/m). The large central area is dominated by the Lake District volcanics (Late Ordovician lavas

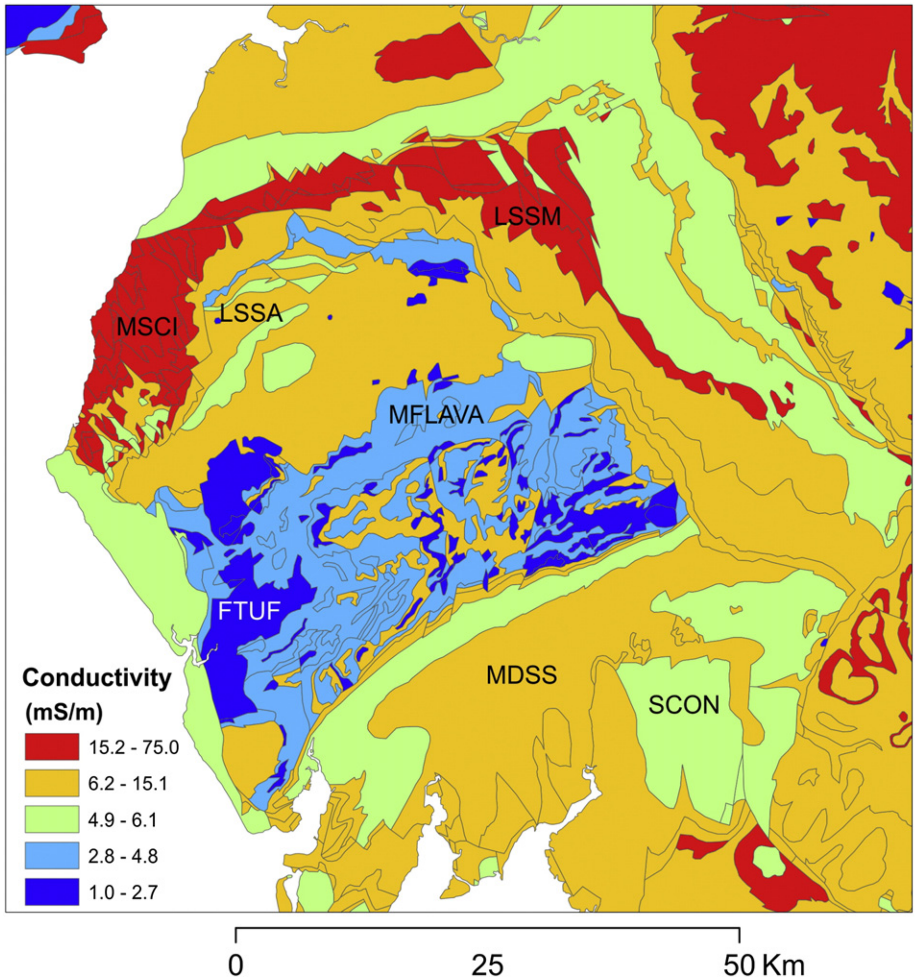

Fig. 7. Conductivity distribution across a 90 × 90 km area centred on the Lake District (LD). A five band colour scheme, using natural breaks across the data subset, is used.

and tuffs) across which conductivities are <4.8 mS/m. The highest conductivities derive from a combination of Limestone–Sandstone–Siltstone–Mudstone (LSSM) and Mudstone–Siltstone–Sandstone–Coal–Ironstone (MSCI) lithologies.

6.2. Vale of York

The conductivities obtained across an area of 120 × 123 km centred on the Vale of York and extending from the Tees estuary in the north to the Humber estuary in the south are shown in Fig. 8. Bedrock across a large area of the eastern coast is dominated by the Chalk formation. The lowest conductivities (6 mS/m) are found in association with the Sandstone and Conglomerate (SCON) formation. This N–S trending resistive zone is separated by the Chalk from the more conducting Dolomitised Limestone (DLDO) to the west and the highly conducting Mudstone–Siltstone–Sandstone (MSLS) formation to the east.

6.3. SW England

The conductivities across a large area (217 × 149 km) of SW England encompassing the Cornubian granite batholith are shown in Fig. 9. The majority of the SW area is resistive with the outcropping felsic granites providing conductivities <3.3 mS/m. Within the resistive terrane there are small areas of highly conductive Gravel–Sand–Silt–Clay lithologies (GSSC, arrowed in Fig. 9). In the NE of the area, large areas of conductive Mudstone–Siltstone–Limestone–sandstone (MSLS) lithologies occur in association with Lias group rocks.

7. Summary and conclusions

A classification of the current 1:625k DiGMapGB bedrock lithological map of the UK has been conducted using estimates of apparent electrical conductivity obtained from high-resolution AEM surveys conducted between 1999 and 2009. The conductivity estimates are based on the central moments of the conductivity distributions obtained. Only the median values are reported here. The map, based on central norms, forms an initial UK baseline map of the conductivity distribution of near-surface bedrock. Across the UK surveys, there is no fixed depth of investigation but the 3 kHz data should be regarded as providing an assessment of 'near-surface' bedrock electrical conductivity except at locations where thick accumulations of conductive superficial deposits occur.

The conductivities obtained by the classification analysis range from 0.3 to ~145 mS/m. The lower limit is influenced by the signal/noise limits (low conductivity aperture at 3 kHz) of the AEM system. There is an evident association between the terranes of northern Scotland, the Southern-Uplands–Down-Longford terrane, the Lake District, NW Wales and the SW granitic terrane which are all associated with the lowest conductivities (<5 mS/m). The general areas of eastern and southern England, associated with younger sedimentary formations, are generally associated with the highest conductivities.

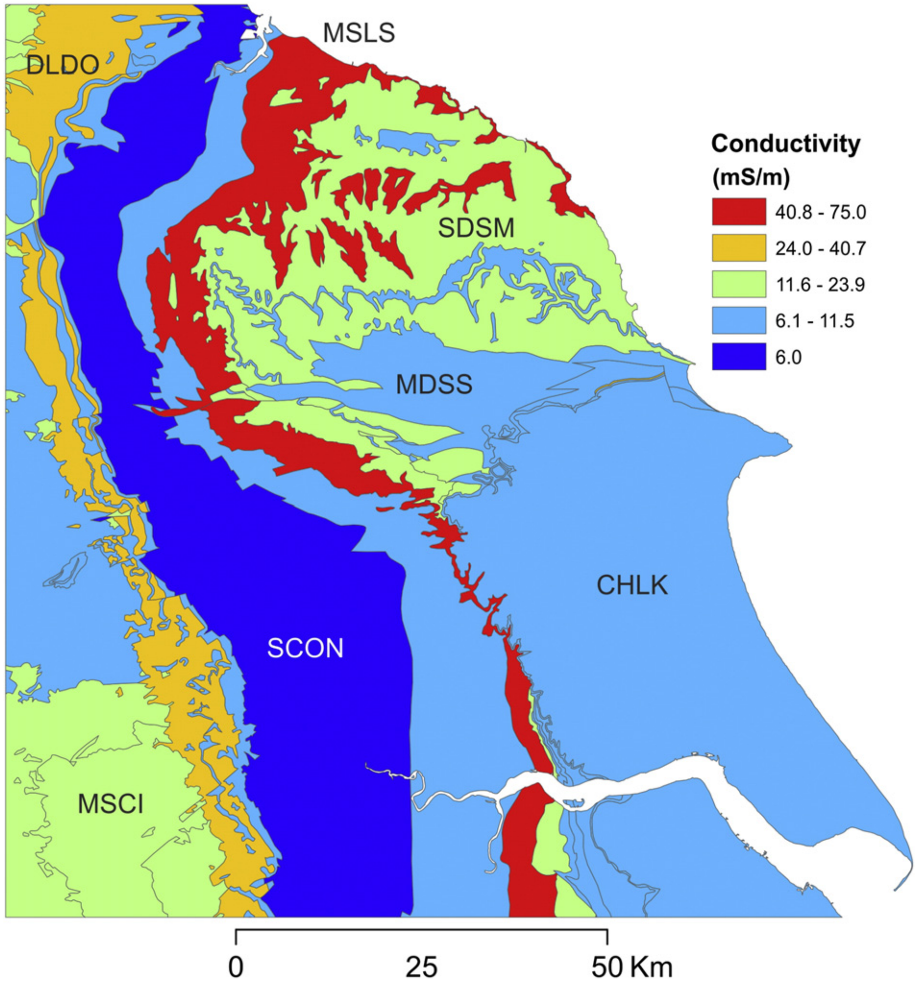

Fig. 8. Conductivity distribution across a 120 × 123 km area centred on the Vale of York (VY). A five band colour scheme, based on the natural breaks across the data subset, is used.

The study carried out is a first attempt to assemble this information using observed high-resolution geophysical data. It is anticipated that the initial baseline model developed here can be further refined on the basis of additional information on the conductivity/thickness products of superficial deposits and/or additional new information on the estimated conductivities of the unsampled lithologies. The

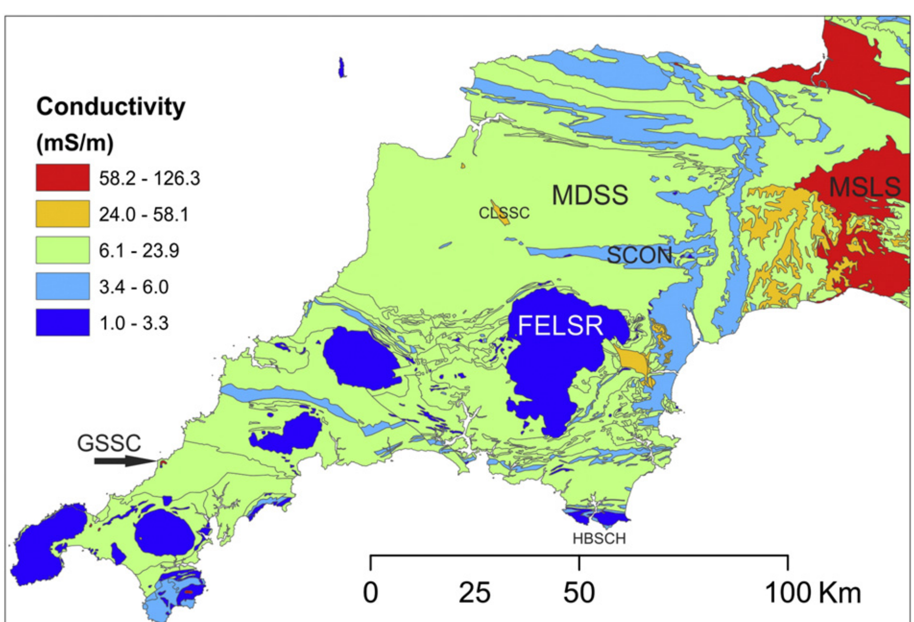

Fig. 9. Conductivity distribution across a 217 × 149 km area of SW England. A five band colour scheme, based on the natural breaks across the data subset, is used.

bedrock conductivity map developed here is believed to be the first such UK map compilation since that presented to the Physical Society in 1935 (Griffiths and Pilling, 2004; Smith-Rose, 1935; Tagg, 1964). The techniques employed here can be applied to many existing spatially extensive AEM data sets.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.jappgeo.2013.06.001. These data include Google maps of the most important areas described in this article.

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