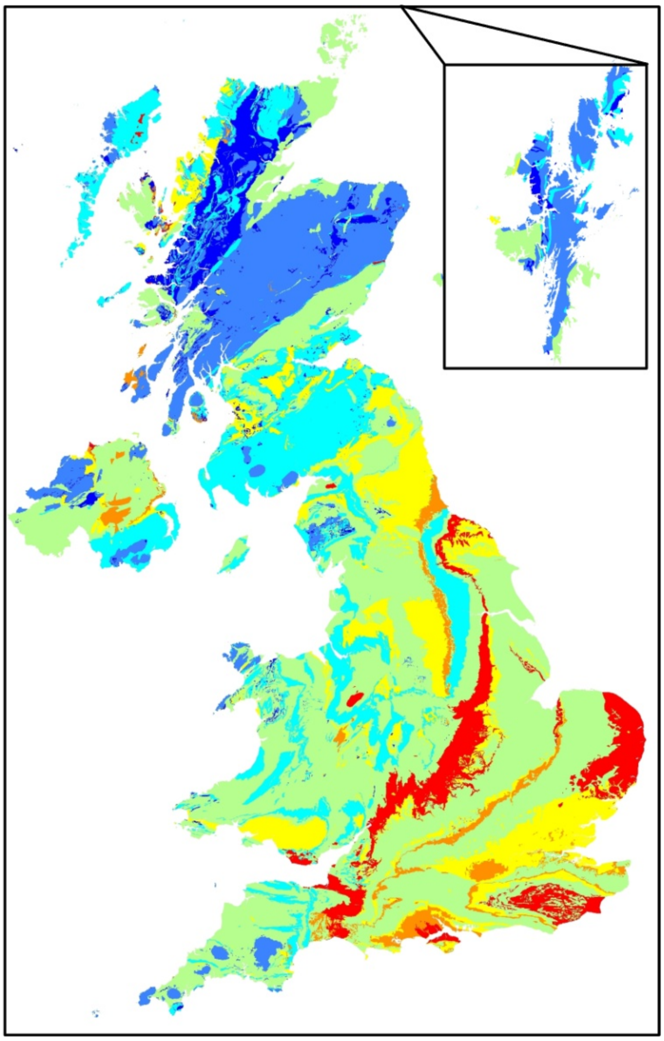
The 1:625k scale near-surface bedrock electrical conductivity map of the UK

Land Use, Planning and Development Programme

British Geological Survey Report OR/12/037



BRITISH GEOLOGICAL SURVEY

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The 1:625k near-surface bedrock electrical conductivity map of the UK

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Front cover

Graphic of the UK conductivity map

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) as part of the Land Use, Planning and Development Programme. The report provides a national-scale assessment and digital model of the electrical conductivity of the UK bedrock. It is believed to be the first such map compilation since that produced in 1935 and presented to the Physical Society (Smith-Rose, 1935; Beamish & White, 2012).

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1 Introduction

Over the past decade, a number of high-resolution airborne geophysical surveys have been conducted across onshore UK (Peart *et al*., 2003; Beamish & Young, 2009). 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 was typically acquired at four frequencies and the highest frequency provides information on the bulk electrical conductivities of near-surface formations. 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.

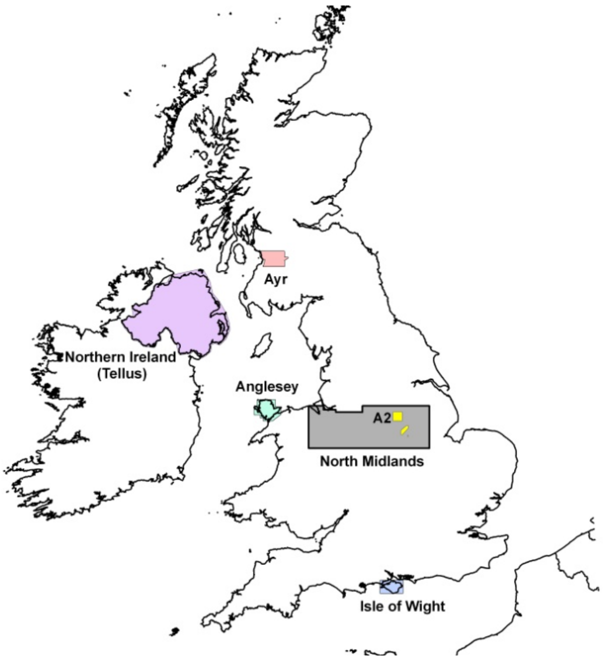

Figure 1. *HiRes UK survey areas (1998-2009). The North Midlands survey did not acquire active EM data.*

The HiRES survey areas, flown between 1998 and 2009 are shown in Figure 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 apparent conductivity from the remaining 5 surveys are used here. The term apparent conductivity is used to denote that a vertically uniform, half-space conductivity is assumed.

Table 1. Details of the UK HiRES surveys.

Code	Description	Area (km^2)	Year
HiRES-1	Survey across north Midlands	13,408	1998
A2	Surveys in the East Midlands (Area 2, Shirebrook). 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

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 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 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 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 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 encountered during the HiRES surveys The 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 assessments/interpretations of data exhibiting departures from the norm. Beamish & White (2011) compared procedures and results obtained for both LEX-RCS and RCS attributions at a 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) due to the presence of clay/silt materials.

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 1:625k scale in order to predict near-surface bedrock properties across the whole of the UK, at the same scale. 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.

The potential influence of superficial deposits (when sufficiently thick in terms of EM skin-depth) was examined by Beamish & White in relation to the IoW data. When considered at the UK scale, this particular issue relates to the degree to which the control (survey) area data may be influenced by thicker, conductive superficial deposits. Here we make reference to the current superficial thickness map (excluding NI) and note that in the absence of such influences across the *survey* areas, the predicted values at all locations will be associated with near-surface bedrock, irrespective of the presence/absence of overlying superficial material.

2 1:625k UK Lithology

The 5'th edition 1:625,000 (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.htm. The geology is based on two main sources: a) the 1:50,000 scale (50k) vector dataset of digital geology called DiGMapGB-50 (British Geological Survey, 2005) with nearly complete cover of Great Britain; and b) the 1:250,000 scale (250k) geological map of Northern Ireland (Cooper et al., 1997).

Each polygon in the 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, 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, ROCK code, refers to the composition or lithology of the unit in a BGS database then in use. For the final 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 625k digital lexicon contains 244 categories under the LEX-RCS (Rock Characterization Scheme) that would provide the basis for the production of a lithostratigraphic geological map. The 'standard' published map (Smith, 2011) is shown in Figure 2a. The map uses the BGS geological colour scheme (the lexicon is that of the published map) which contains a degree of colour duplication across the 244 categories. The digital product contains 11,244 polygons that form the basis of the geophysical attribution

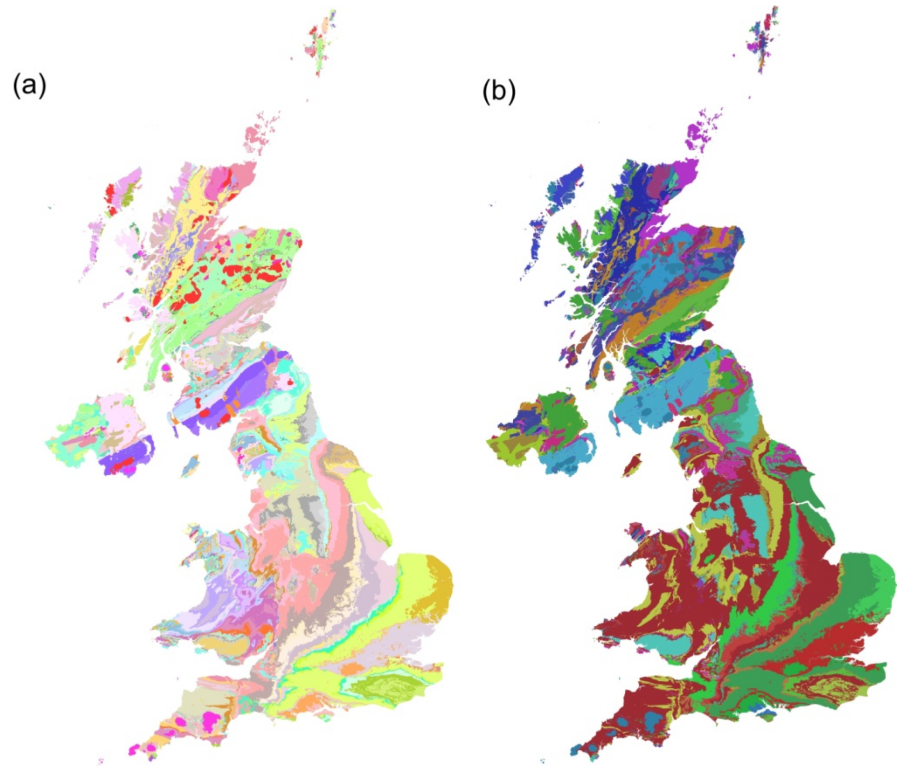

Figure 2. *The BGS 1:625k scale bedrock geological map of the United Kingdom (DiGMapGB-625). (a) Published map using LEX-RCS. (b) Lithological map using RCS, no standard colour scheme is available.*

The simpler RCS lithological characterisation, used here, provides 86 categories and is shown in Figure 2b. It may also be noted that the corresponding 1:250k RCS lexicon (Version 4.11, 2005) contains 81 categories. The lexicon codes of the 1:625k RCS characterisation together with their descriptions are provided in Table 2.

Table 2. *The 86 categories of the DIGMapGB lithological RCS lexicon at 1:625,000 scale.*

RCS Code	RCS_DESCRIPTION	AREA km^2
ANO	ANORTHOSITE	8

BCSD	BRECCIA, CONGLOMERATE AND SANDSTONE	42
BRCMBR	BRECCIA AND METABRECCIA	28
CHLK	CHALK	19310
CHSA	CHALK AND SANDSTONE	120
CLLI	CLAY AND LIGNITE	593
CLSISA	CLAY, SILT AND SAND	362
CLSSG	CLAY, SILT, SAND AND GRAVEL	7733
COSD	CONGLOMERATE AND [SUBEQUAL/SUBORDINATE] SANDSTONE, INTERBEDDED	228
CSSM	CONGLOMERATE, SANDSTONE, SILTSTONE AND MUDSTONE	5170
CYCC	SEDIMENTARY ROCK CYCLES, CLACKMANNAN GROUP TYPE	2077
CYCS	SEDIMENTARY ROCK CYCLES, STRATHCLYDE GROUP TYPE	975
DBAT	DOLERITE AND THOLEIITIC BASALT	233
DIAMIT	DIAMICTITE	47
DLDO	DOLOMITISED LIMESTONE AND DOLOMITE	1434
DOLO	DOLOSTONE	94
FELSR	FELSIC-ROCK	8555
FLAVA	FELSIC LAVA	65
FTUFF	FELSIC TUFF	757
GNSMF	MAFIC GNEISS	93
GNSS	GNEISS	3886
GPSP	GNEISSOSE PSAMMITE AND GNEISSOSE SEMIPELITE	957
GSSC	GRAVEL, SAND, SILT AND CLAY	3607
HBSCH	HORNBLENDE SCHIST	62
LATF	FELSIC LAVA AND FELSIC TUFF	292
LATM	MAFIC LAVA AND MAFIC TUFF	9688
LATU	LAVA AND TUFF	25
LMAS	LIMESTONE, ARGILLACEOUS ROCKS AND SUBORDINATE SANDSTONE, INTERBEDDED	1653
LMCM	LIMESTONE, MUDSTONE AND CALCAREOUS MUDSTONE	212
LMCS	LIMESTONE AND CALCAREOUS SANDSTONE	109
LMST	LIMESTONE	229
LSMD	LIMESTONE AND MUDSTONE, INTERBEDDED	64
LSSA	LIMESTONE WITH SUBORDINATE SANDSTONE AND ARGILLACEOUS ROCKS	4925
LSSM	LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTONE	5604
LTVS	LAVA, TUFF, VOLCANICLASTIC ROCK AND SEDIMENTARY ROCK	347
MAFI	MAFITE	10
MDCB	MUDSTONE, CHERT AND SMECTITE-CLAYSTONE	158
MDSC	MUDSTONE, SANDSTONE AND CONGLOMERATE	352
MDSL	MUDSTONE, SANDSTONE AND LIMESTONE	2671

MDSS	MUDSTONE, SILTSTONE AND SANDSTONE	54902
MFIR	MAFIC IGNEOUS-ROCK	2596
MFLAVA	MAFIC LAVA	453
MFTUF	MAFIC TUFF	179
MIGM	MIGMATITIC ROCK	1208
MLMST	METALIMESTONE	691
MSCI	MUDSTONE, SILTSTONE, SANDSTONE, COAL, IRONSTONE AND FERRICRETE	10609
MSDR	METASEDIMENTARY ROCK	440
MSLS	MUDSTONE, SILTSTONE, LIMESTONE AND SANDSTONE	8778
MSSP	GNEISSOSE SEMIPELITE AND GNEISSOSE PSAMMITE	50
MVIVS	METAVOLCANICLASTIC IGNEOUS-ROCK AND METAVOLCANICLASTIC SEDIMENTARY-ROCK	19
MYCFB	MYLONITIC-ROCK AND FAULT-BRECCIA	557
PEL	PELITE	1200
PGCP	GRAPHITIC PELITE, CALCAREOUS PELITE, CALCSILICATE-ROCK AND PSAMMITE	1531
PPSPC	PSAMMITE, PELITE, SEMIPELITE AND CALCSILICATE-ROCK	25
PSAMM	PSAMMITE	6627
PSP	PSAMMITE, SEMIPELITE AND PELITE	5864
PSPE	PSAMMITE AND PELITE	6462
PSSP	PSAMMITE AND SEMIPELITE	4215
PYRR	PYROCLASTIC-ROCK	90
QAREN	QUARTZ-ARENITE	390
QZITE	QUARTZITE	1669
SARL	SANDSTONE WITH SUBORDINATE ARGILLACEOUS ROCKS AND LIMESTONE	691
SCAR	SANDSTONE, CONGLOMERATE AND [SUBORDINATE] ARGILLACEOUS ROCKS	164
SCGS	SANDSTONE WITH SUBORDINATE CONGLOMERATE AND SILTSTONE	24
SCH	SCHIST	39
SCHM	MICA SCHIST	33
SCON	SANDSTONE AND CONGLOMERATE, INTERBEDDED	16514
SCSM	SANDSTONE WITH SUBORDINATE CONGLOMERATE, SILTSTONE AND MUDSTONE	3397
SDAR	SANDSTONE AND [SUBEQUAL/SUBORDINATE] ARGILLACEOUS ROCKS, INTERBEDDED	65
SDBC	SANDSTONE, BRECCIA AND CONGLOMERATE	684
SDBR	SANDSTONE AND SUBORDINATE BRECCIA	16
SDLM	SANDSTONE AND [SUBEQUAL/SUBORDINATE] LIMESTONE, INTERBEDDED	20
SDSL	SANDSTONE AND SILTSTONE, INTERBEDDED	2111
SDSM	SANDSTONE, SILTSTONE AND MUDSTONE	3399

SEDS2	LIMESTONE, MUDSTONE, SANDSTONE AND SILTSTONE, WITH SUBORDINATE CHERT, COAL AND CONGLOMERATE	2070
SEMPEL	SEMIPELITE	335
SISDM	SILTSTONE AND SANDSTONE WITH SUBORDINATE MUDSTONE	1139
SLAR	SANDSTONE, LIMESTONE AND ARGILLACEOUS ROCKS	3716
SMLP	SERPENTINITE, METABASALT, METALIMESTONE AND PSAMMITE	30
SMSC	SANDSTONE, MUDSTONE, SILTSTONE AND CONGLOMERATE	1401
SPPE	SEMIPELITE AND PELITE	484
SSCL	SAND, SILT AND CLAY	2234
STMD	SANDSTONE AND MUDSTONE	3316
SYR	SYENITIC-ROCK	73
UMFT	ULTRAMAFITITE	219
WACKE	WACKE	11355

The total UK area covered is 244,871 km^2. 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.

3 Lithological classification

The standard method of geological attribution by airborne geophysical measurements (half-space apparent conductivity at a particular frequency) follows the procedures given in Beamish & White (2011) and Beamish & White (2012). Here we make use of 5 separate HiRES survey data sets (AYR, NI, ANG, IoW and A2_Thoresby) shown in Figure 1. A single frequency of ~3 kHz (precisely 3125 prior to 2006 and 3005 Hz thereafter) 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.

Following screening/conditioning, each data set was used to attribute the 1:625k lithological 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 (Scotland/England) rocks where no airborne data exist. The NI 1:250k bedrock geology database (version 2.18, 2009) 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 625k scale, but which can be attributed using the extensive sampling of the NI survey and the NI 250k geological database. The results of the lithological attribution procedure are recorded in Table 3. The second column (625k analysis) records the survey data which were sampled by the attribution of the 625k database. Where multiple survey data exist, the largest sampling survey (typically NI) was used. Cases in which the same RCS code is available from an RCS classification at a different scale are also recorded by identifying the survey and the lithological database scale used (third column of Table 3). This first-pass procedure resulted in the attribution of 54 of the 86 lithological units as defined by the 625k lexicon. The number of samples obtained (N, Table 2) ranges from 198 (RCS=PEL) to 1,196,650 (RCS=LATM).

Table 3. *Lithological classification procedure for the 86 RCS formations at 625k scale. The 625 k analysis notes the survey data used in the initial attribution. The Further analysis column notes the RCS code and survey and scale used to attribute the main RCS table. The Notes column refers to a note in Appendix 1. N is the number of AEM data used in the final classification. Median σ is the final median conductivity resulting from the analysis.*

RCS	625k analysis	Further analysis	Notes	N	Median σ (mS/m)
ANO		GB NI_250k	2	32346	1.19
BCSD		BRSS NI 250k	3	224	2.59
BRCMBR		BRSS NI 250k	4	224	2.59
CHLK	IoW			14011	10.37
CHSA	NI			37804	19.27
CLLI	NI			198574	41.25
CLSISA	IoW			57551	126.27
CLSSG	IoW			5599	27.14
COSD	NI			4147	12.11
CSSM		COSD NI_625k	11	4147	12.11
CYCC	AYR			30863	7.46
CYCS	AYR			9946	5.60
DBAT		MCGB NI_250k	14	38926	6.11
DIAMIT		CONG_NI_250k	15	655	37.27
DLDO	A2			9563	38.67
DOLO		DLDO A2_625k	17	9563	38.67
FELSR	NI, AYR, ANG			201299	2.72
FLAVA		FELS NI_250k		12543	1.02
FTUFF	ANG			7192	4.77
GNSMF		GN NI_250k	21	61393	4.35
GNSS		GN NI_250k	22	61393	4.35
GPSP	NI			13774	2.54
GSSC		CLISSA IoW_625k	24	57511	126.26
HBSCH	ANG			8229	4.51
LATF	NI, ANG			9298	16.74
LATM	NI, AYR			1196650	11.92
LATU	NI_250k			580	19.81
LMAS	NI			49266	15.13
LMCM		MDLM NI_250k	30	87476	18.03
LMCS		LMAS NI_250k	31	31902	16.47
LMST	NI_250k			251552	8.41
LSMD		LSMD NI_250k	33	26951	18.93
LSSA	ANG			28825	11.50

LSSM		LSMD NI_250k	35	134842	23.90
LTVS	NI			2667	2.53
MAFI		MCGBR ANG_250k	37	1225	6.63
MDCB	NI			17459	5.61
MDSC		MDSL NI_625k	39	39282	40.73
MDSL	NI, IoW			39282	40.73
MDSS	NI, AYR, IoW, ANG			8791	9.50
MFIR	NI, AYR, ANG			63681	1.78
MFLAVA	ANG			4544	3.20
MFTUF		TUF ANG_250k	44	12224	4.34
MIGM		GN NI_250k	45	61393	4.35
MLMST	NI, ANG			51930	3.01
MSCI	NI, AYR, AYR			472	19.08
MSDR	ANG			80137	3.82
MSLS	NI			13690	74.95
MSSP		GN NI_250k	50	61393	4.35
MVIVS	NI			6107	2.21
MYCFB		FAULT ZONE	52	Estimated	145.00
PEL	ANG_50k			198	4.40
PGCP		PSPE NI_625k	54	132925	3.32
PPSPC		PSPE NI_625k	55	132925	3.32
PSAMM	NI			18270	0.69
PSP	NI			400786	2.70
PSPE	NI			132925	3.32
PSSP		PSPE NI 250k	59	117106	3.81
PYRR	NI, AYR			816	0.32
QAREN		QZITE NI_625k	61	18449	2.61
QZITE	NI			18449	2.61
SARL	NI 250k			58277	17.72
SCAR	NI			52701	19.04
SCGS		SDSL IoW_625k	65	201	129.37
SCH	SCH ANG_50k		66	36623	3.51
SCHM	SCHM ANG_50k		67	26854	3.26
SCON	NI, AYR, ANG			6820	5.98
SCSM		SMSC NI_625k	69	423972	8.94
SDAR	NI			22106	11.21
SDBC	AYR			14711	6.98
SDBR	NI			2584	15.13
SDLM	NI			3421	17.78
SDSL	IoW			201	129.36

SDSM	NI, AYR			134842	23.90
SEDS2	NI			705648	14.20
SEMPEL		PSP NI_625k	77	400786	2.70
SISDM		SMSC NI_625k	78	423972	8.94
SLAR	ANG			2006	8.66
SMLP		SEPTITE NI_250k	80	44	2.17
SMSC	NI			423972	8.94
SPPE		PSP NI_625k	82	400786	2.70
SSCL	IoW			6434	58.08
STMD	IoW			29866	26.85
SYR		IGRU ANG_50k	85	1709	2.66
UMFT	ANG			758	4.25
WACKE	NI, AYR			835616	4.04

In order to obtain complete coverage of the UK lithologies it has been necessary to obtain estimates from within the information available for the remaining 32 RCS classifications. The unsampled lithological units cover an area of only 33,267 km^2 (13.6% of the total). It is worth recording 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 1). Fourteen of the 32 units have spatial areas of less than 100 km^2. The distribution of the unsampled lithologies is summarised in Figure 3. The diagram shows all the polygons of 32 unsampled units using colour infill. Due to scale limitations, all the units with areas of less than 1000 km^2 use black infill. The more significant 9 units having areas of > 1000 km^2 are shown in colour. 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 below.

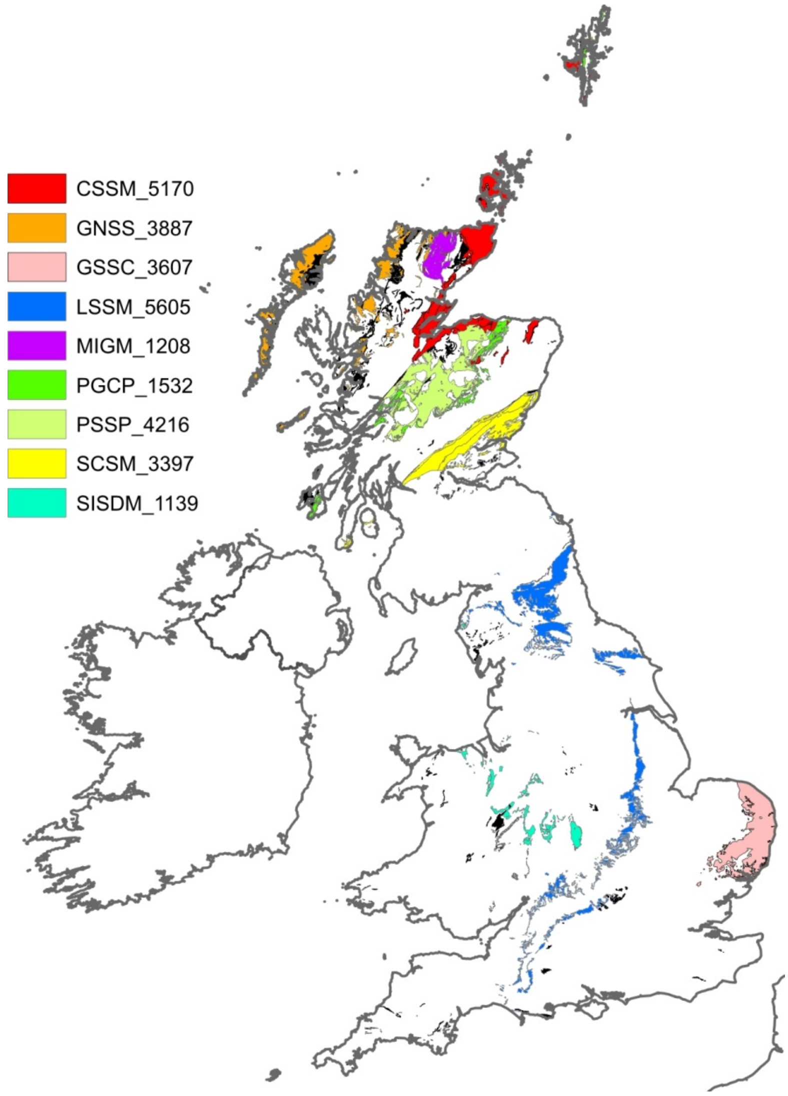

Figure 3. *The distribution of the 32 unsampled lithologies (625k scale). The 9 lithologies having total areas > 1000 km^2 are shown in colour, with the areas (km^2) identified in the legend.*

3.1 ASSIGNMENT STRATEGY

The conductivity assignment strategy for the 9 main unassigned lithologies is described below. The complete strategy is described in Appendix 1.

1) CSSM refers to CONGLOMERATE, SANDSTONE, SILTSTONE AND MUDSTONE. This was reassigned using COSD (CONGLOMERATE AND [SUBEQUAL/SUBORDINATE] SANDSTONE, INTERBEDDED), see Table 2.

2) GNSS refers to GNEISS. This was reassigned using GN (GNEISS) i.e. a different code but the same named lithology.

3) GSSC refers to GRAVEL, SAND, SILT, CLAY covering the Neogene to Quaternary across the eastern area of East Anglia. This was reassigned using the CLISSA (CLAY, SILT, SAND), Eocene lithology.

4) LSSM which refers to LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTONE) and is the Carboniferous Oolite formation. This was reassigned using the Carboniferous SDSM (SANDSTONE, SILTSTONE AND MUDSTONE) lithology.

5) MIGM refers to MIGMATIC ROCK which is an interface lithology between igneous and metamorphic rock formations. It forms part of the Neoproterozoic Moine Supergroup rocks (Fig.3) This was reassigned using GN (GRANITE) since MIGM grades into granite.

6) PGCP refers to GRAPHITIC PELITE, CALCAREOUS PELITE, CALCSILICATE-ROCK AND PSAMMITE. This was reassigned using PSPE (PSAMMITE and PELITE).

7) PSSP refers to PSAMMITE, PELITE, SEMIPELITE AND CALCSILICATE-ROCK. This was reassigned using PSPE (PSAMMITE and PELITE).

8) SCSM refers to SANDSTONE WITH SUBORDINATE CONGLOMERATE, SILTSTONE AND MUDSTONE. This was reassigned using SMSC (SANDSTONE, MUDSTONE, SILTSTONE AND CONGLOMERATE).

9) SISDM refers to SILTSTONE AND SANDSTONE WITH SUBORDINATE MUDSTONE. This was reassigned using SANDSTONE, MUDSTONE, SILTSTONE AND CONGLOMERATE

The reassignments of all 32 unsampled lithologies are summarised in Appendix 1. Table 3 also records the reassignments applied. The only unit not reassigned was MYCFB which refers to the Mylonitic and Breccia fault zone rocks found in Scotland. The major extent is found on Lewis and elsewhere compact zones exist in association with faults. The electrical conductivity of fault zone rocks (including mylonitic rocks) has largely been studied in relation to deep tectonic and earthquake studies (e.g. Becken & Ritter, 2011). Their properties are known to be highly anisotropic and the electrical conductivity is typically high in the presence of fault zone fluids. Conductivities of near-surface (e.g. depths of < 50 m) are not established. Here the RCS=MYCFB rocks are assumed conductive and a value of 145 mS/m has been assigned. This value represents the highest lithological conductivity assignment (~130 mS/m) + 10%.

4 Analysis

4.1 SUPERFICIAL THICKNESS

The potential influence of superficial deposits on bedrock classification was previously noted. The required understanding requires a 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 & Garcia-Bajo, 2009). The thickness map, at the national scale, with the HiRES surveys areas superimposed is shown in Figure 4.

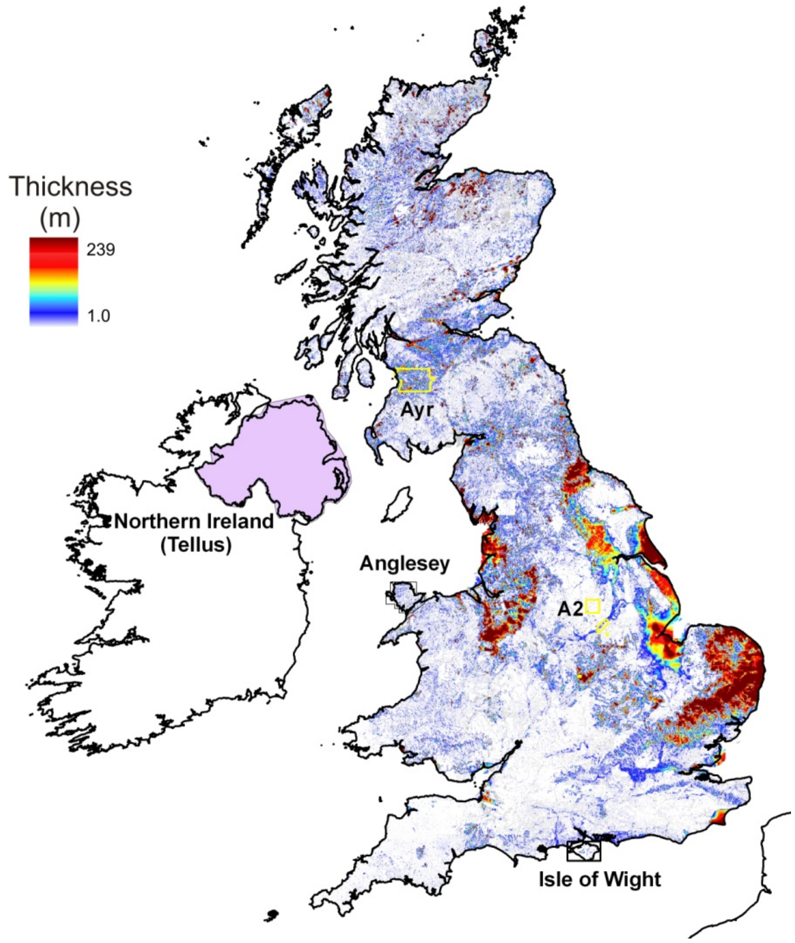

Figure 4. *The superficial deposit thickness map of the UK (excluding NI) with HiRES survey areas identified.*

In general terms, the 3 survey areas of A2, IoW and ANG contain only thin superficial deposits (see also Beamish & White (2012). The AYR survey contains thicker deposits as shown in Figure 5.

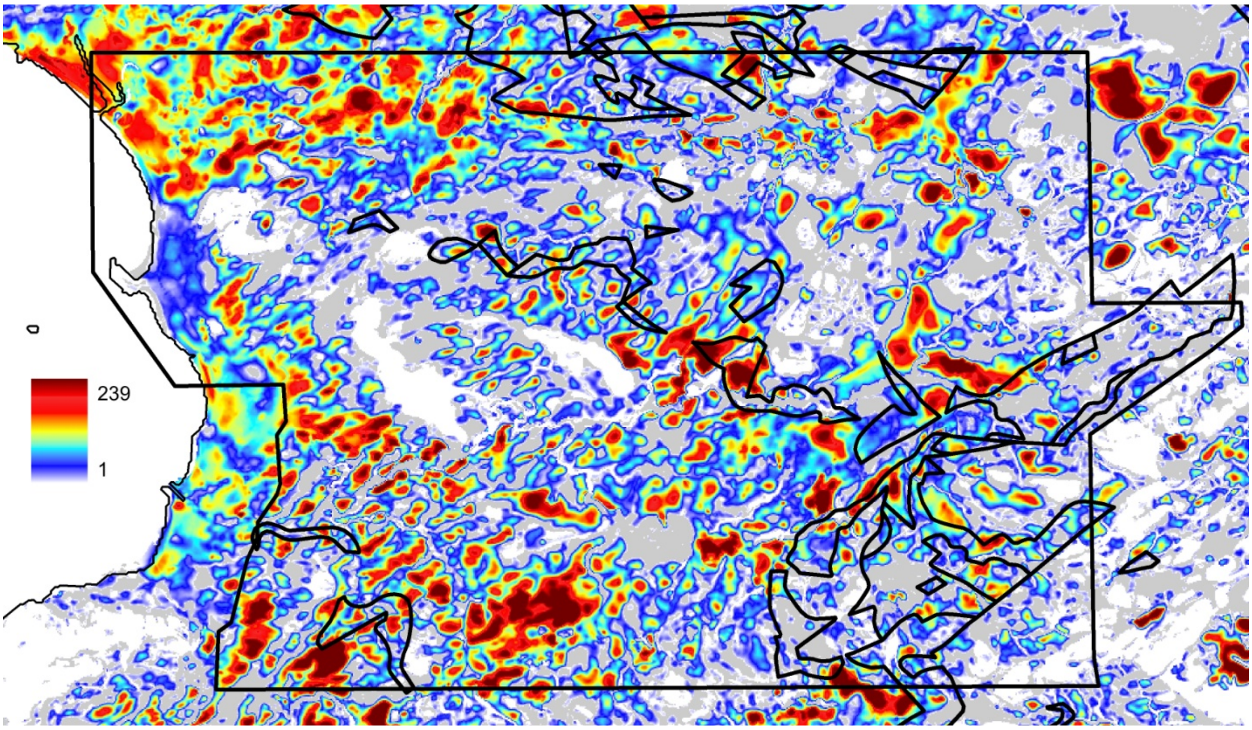

Figure 5. *Detail from the superficial deposit thickness map of the UK (previous Figure) with the outline of the AYR survey and extent of 2 lithologies (CYCC and CYCS) used in the RCS conductivity classification.*

Figure 5 also shows the 2 lithologies CYCC and CYCS (Table 2) used in the 625k attribution from the AYR survey data. 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 lithological formations. In addition, 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.

4.2 STATISTICAL CONDUCTIVITY DISTRIBUTIONS

Beamish & 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 & 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 & Filzmoser 2000). Although the data distributions are, in a strict sense, neither normally nor log-normally distributed, there is a general tendency for the distributions to be closer to log-normally distributed when standard statistical tests are applied. Here is 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 & White, 2012). Here only a limited set of examples is considered. Figure 6 shows 4 lithological histograms obtained from the 625k analysis. The data were all obtained from the NI 625k analysis and comprise:

- RCS = LATM (MAFIC LAVA AND MAFIC TUFF). The largest lithology sampled (the Antrim basalts). N=1, 1,119,650.
- RCS = COSD (CONGLOMERATE AND [SUBEQUAL/SUBORDINATE] SANDSTONE, INTERBEDDED). A 2-way mixed lithology sedimentary rock. N=4,147.
- RCS = SCAR (SANDSTONE, CONGLOMERATE AND [SUBORDINATE] ARGILLACEOUS ROCKS). A 3-way mixed lithology sedimentary rock. N= 52,701.
- RCS=MSLS (MUDSTONE, SILTSTONE, LIMESTONE AND SANDSTONE). A 4-way mixed lithology sedimentary rock. N=8,778.

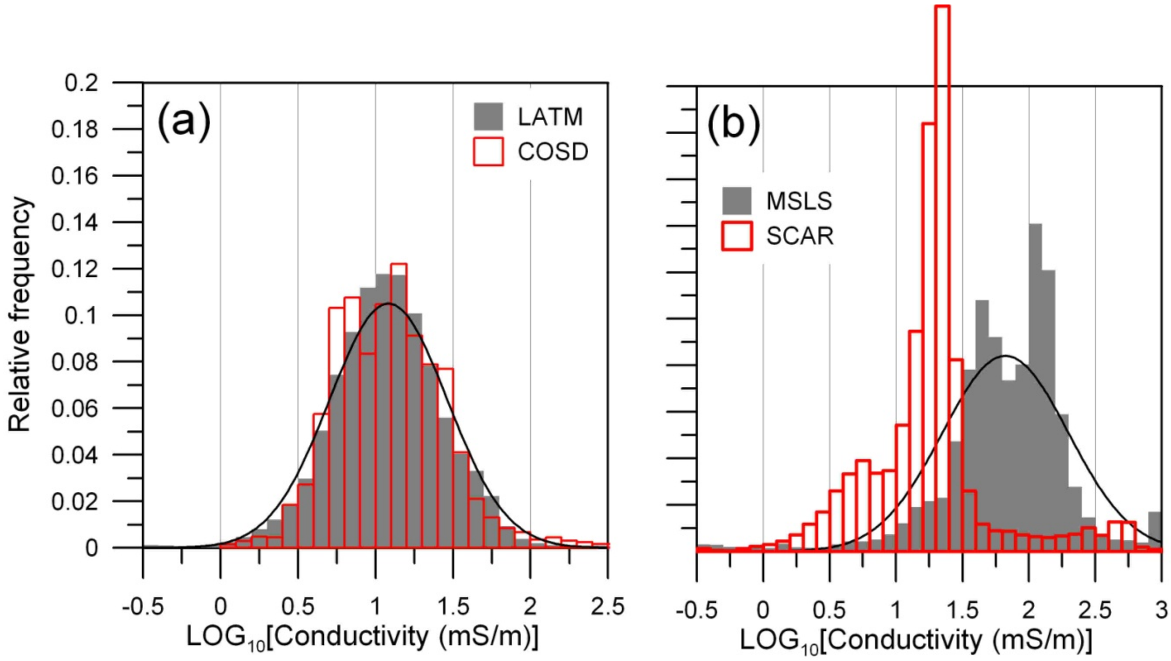

Figure 6. *Histogram of conductivities (LOG transformed) of 4 lithologies discussed in the text. (a) LATM with best-fitting normal distribution and COSD. (b) MSLS with best fitting normal distribution and SCAR.*

Despite the large sampling area (9,688 km^2) the LATM distribution appears unimodal and close to log-normal (the best-fitting log-normal is displayed in Figure 6a). The distribution is compared with that of COSD which has a similar form but a 2-peak distribution is observed in the central peak 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 MSLS and SCAR are shown in Figure 6b. Highly peaked, highly skewed multimodal behaviour is observed together with long tails 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 large majority of distributions however have an apparent unimodal character.

5 Results

The central moments of the conductivity distributions obtained from the RCS analysis (Tables 2 and 3) 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 conductivity map of the UK. The linear conductivity values used the initial map are listed in the final column of Table 3. The three most conductive lithologies are obtained for MYCFB (145 mS/m, an assumed value for fault zone rocks), SDSL (129 mS/m, a value for sandstone/siltstone) and CLISA (126 mS/m, a value for clay, silt, sand). The three most resistive lithologies are obtained for PYRR (0.32 mS/m, pyroclastic rocks), 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 using the values of Table 3, is shown using a 5 range, non-linear colour scale in Figure 7.

The conductivity attributed polygons follow the behaviour of the 625k lithological map of Figure 2. At the scale shown, there is an evident association between the larger scale terranes found in northern Scotland (omitting the Midland Valley), the Southern-Uplands-Down-Longford terrane, the Lake District, NW Wales (particularly Anglesey) and the south west granitic terrane which are all associated with the lowest conductivities (<5 mS/m). The general areas of eastern and southern England, associated with younger formations are generally associated with the highest conductivities.

The 625k conductivity map is digital and capable of further manipulation. In order to demonstrate some of the detail available within the map, 3 areas 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.

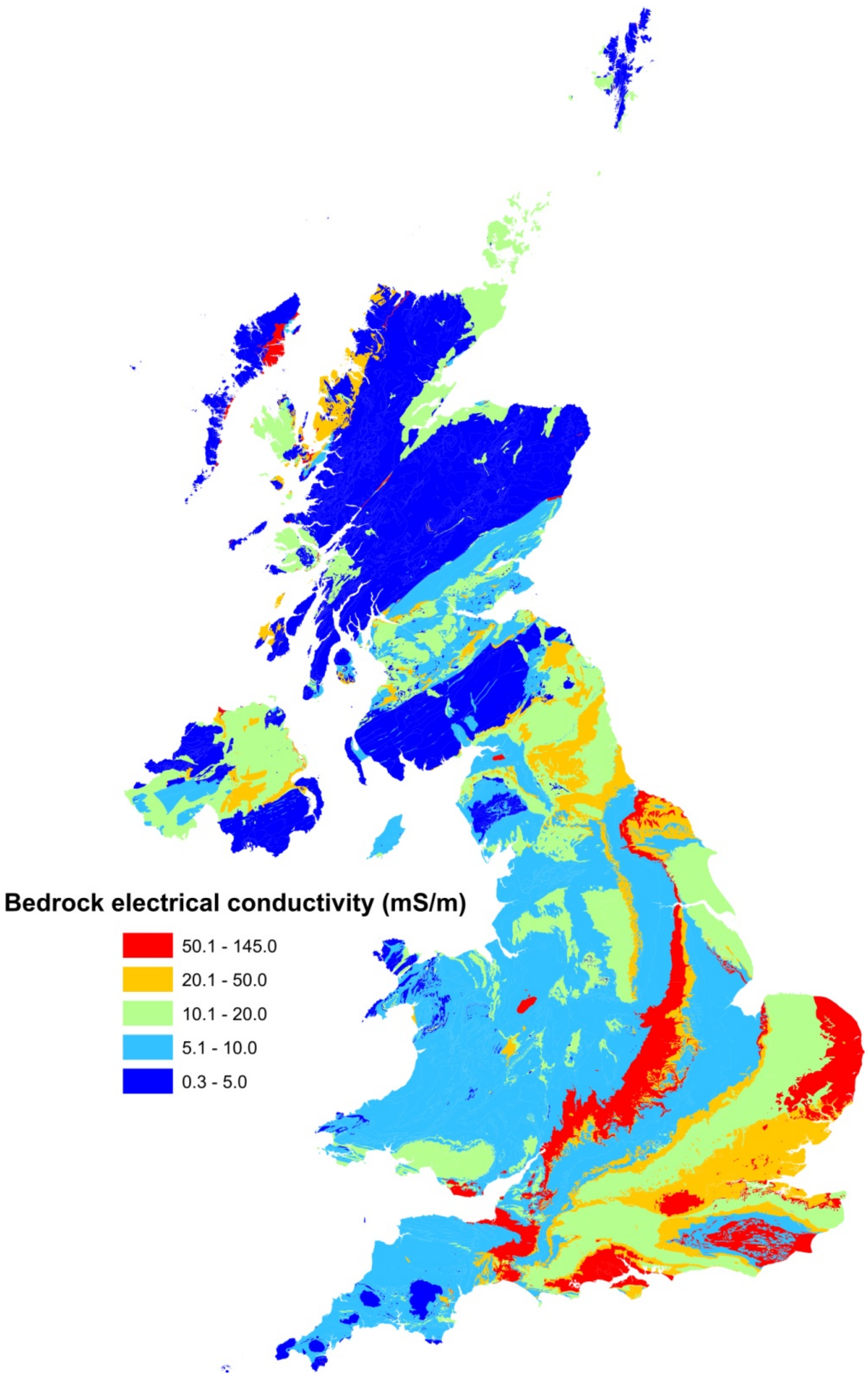

Figure 7. *The 625k near-surface bedrock conductivity distribution produced by lithological classification.*

5.1 LAKE DISTRICT

The conductivity map across this 90 x 90 km area is shown in Figure 8. The highest conductivity range is from 15.2 to 75 mS/m and thus this large area is predominantly resistive (< 15 mS/m). The large central area is dominated by the Lake District volcanics (lavas 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.

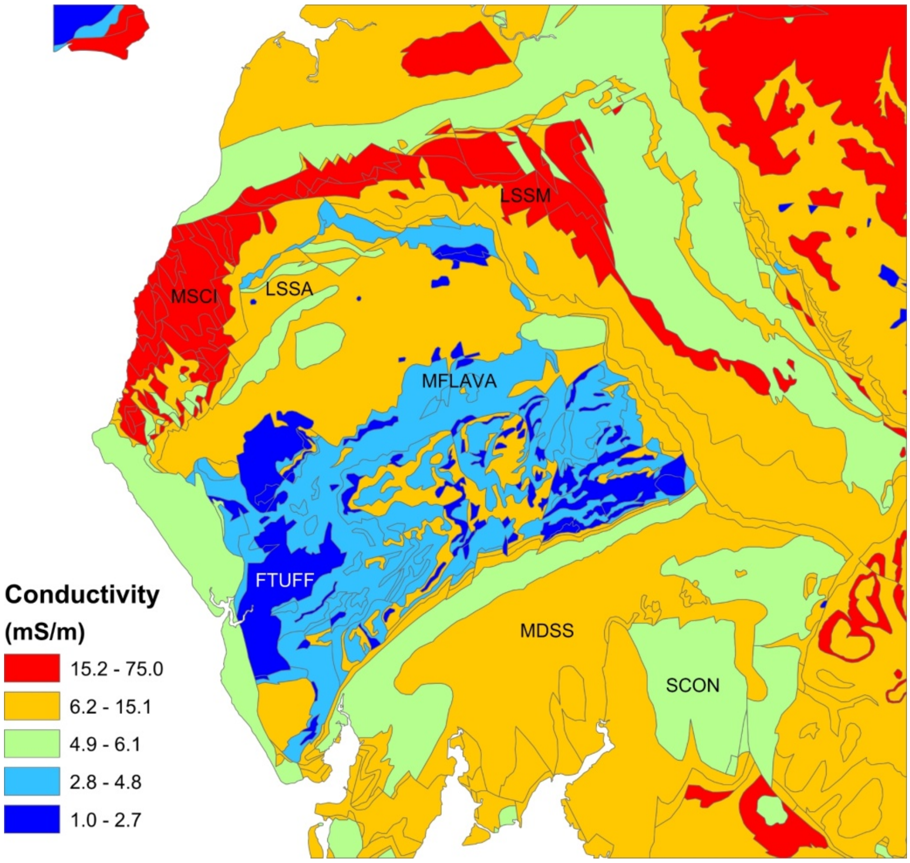

Figure 8. *Conductivity distribution across a 90 x 90 km area centred on the Lake District. A five band colour scheme, using natural breaks across the data subset, is used.*

5.2 VALE OF YORK

The conductivities obtained across an area of 120 x 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 Figure 9. Bedrock across a large area of the eastern coast is dominated by Chalk. 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 Chalk from the more conducting Dolomitised Limestone (DLDO) to the west and the highly conducting Mudstone-Siltstone-Sandstone (MSLS) formation to the east.

5.3 SW ENGLAND

The conductivities across a large area (217 x 149 km) of SW England encompassing the Cornubian granite batholith are shown in Figure 10. The majority of the SW area is resistive with the 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. 10). In the NE of the area, large areas of conductive Mudstone-Siltstone-Limestone-sandstone (MSLS) lithologies occur in association with Lias group rocks.

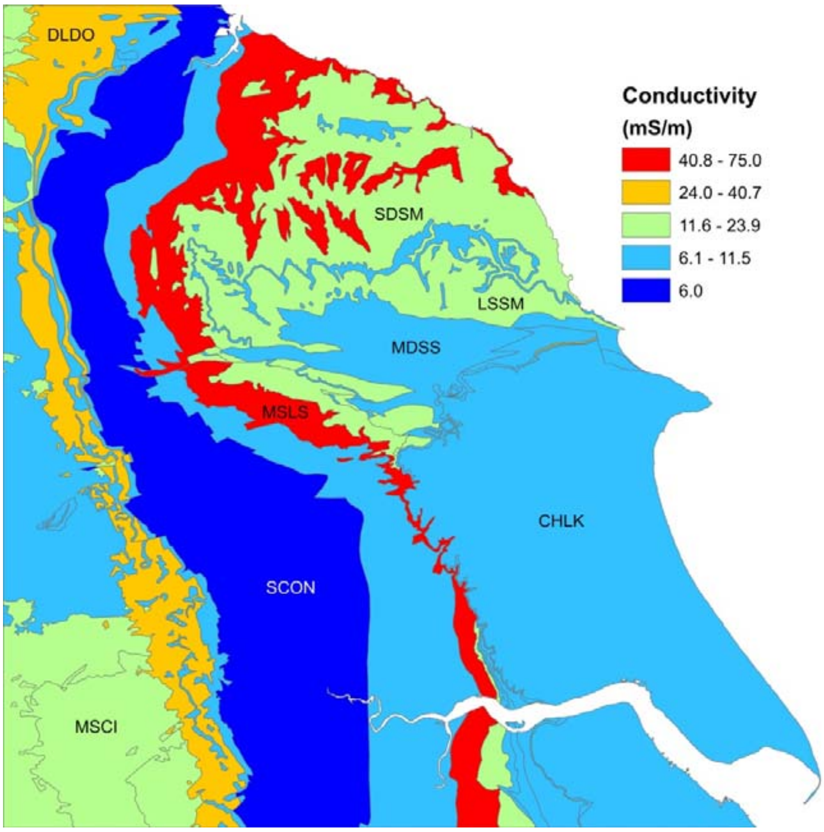

Figure 9. *Conductivity distribution across a 120 x 123 km area centred on the Vale of York. A five band colour scheme, based on the natural breaks across the data subset, is used.*

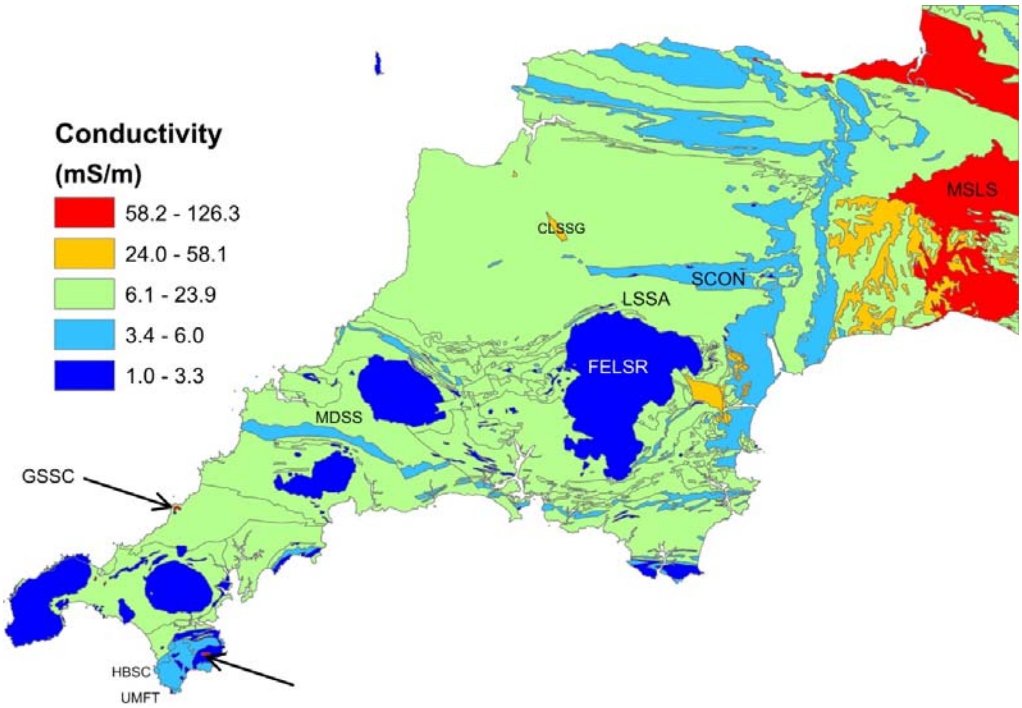

Figure 10. *Conductivity distribution across a 217 x 149 km area of SW England. A five band colour scheme, based on the natural breaks across the data subset, is used.*

6 Summary

A classification of the current 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 baseline map of the conductivity distribution of near-surface bedrock across the UK.

The conductivities obtained range from 0.3 to ~130 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 south west granitic terrane which are all associated with the lowest conductivities (<5 mS/m). The general areas of eastern and southern England, associated with younger formations, are generally associated with the highest conductivities.

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.

7 References

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Appendix 1.

The following notes refer to classification procedures indentified in Table 3. The numbering system used is referenced in Table 3.

Note 2. ANO (ANORTHOSITE). Examined other lithologies connected to Anorthosite Suite rocks. This was reassigned GB (GABBRO) from NI_250k.

Note 3**.** BCSD refers to BRECCIA, CONGLOMERATE AND SANDSTONE. Use BRSS (BRECCIA AND SANDSTONE, INTERBEDDED) from NI 250k.

Note 4. BRCMBR refers to BRECIA AND METABRECIA, This was reassigned using BRSS (BRECCIA AND SANDSTONE, INTERBEDDED) from NI 250k.

Note 11. CSSM refers to CONGLOMERATE, SANDSTONE, SILTSTONE AND MUDSTONE. This was reassigned using COSD (CONGLOMERATE AND [SUBEQUAL/SUBORDINATE] SANDSTONE, INTERBEDDED) from NI 625k.

Note 14. DBAT refers to DOLERITE AND THEOLIITIC BASALT. Dolerite is synonymous with microgabbo. This was reassigned using MCGB (MICROGABBRO) from NI_250k.

Note 15. DIAMIT (DIAMICTITE). DIAMICTITE is non-sorted conglomerate or breccias. Use CONG (CONGLOMERATE) (single-lithology) from NI 250k.

Note 16. DLDO refers to DOLOMITISED LIMESTONE AND DOLOMITE. This was reassigned using DLDO (same lithology) from A2 625k.

Note 17. DOLO refers to DOLOSTONE, another name for dolomitic rock. . This was reassigned using DLDO (same lithology) from A2 625k.

Note 21. GNMSF refers to MAFIC GNEISS. This was reassigned using GN (GNEISS) from NI 250k.

Note 22. GNSS refers to GNEISS. This was reassigned using GN (GNEISS) i.e. a different code but the same named lithology from NI 250k.

Note 24. GSSC refers to GRAVEL, SAND, SILT, CLAY covering the Neogene to Quaternary across the eastern area of East Anglia. This was reassigned using the CLISSA (CLAY, SILT, SAND), Eocene lithology.

Note 28. LATU refers to LAVA AND TUFF. This was reassigned using LATU (same lithology) from NI 250k.

Note 30. LMCM refers to LIMESTONE, MUDSTONE AND CALCAREOUS MUDSTONE. This was reassigned using MDLM (MUDSTONE AND LIMESTONE, INTERBEDDED) from NI_250k.

Note 31. LMCS refers to LIMESTONE AND CALCAREOUS SANDSTONE. This was reassigned using LMAS (INTERBEDDED LIMESTONE, ARGILLACEOUS ROCKS AND SUBORDINATE SANDSTONE) from NI 250k.

Note 33. LSMD refers to LIMESTONE AND MUDSTONE, INTERBEDDED. This was reassigned using LSMD (INTERBEDDED LIMESTONE AND MUDSTONE) from NI 250k.

Note 35. LSSM refers to LIMESTONE, SANDSTONE, SILTSTONE AND MUDSTONE and is the Carboniferous Oolite formation. This was reassigned using the Carboniferous SDSM (SANDSTONE, SILTSTONE AND MUDSTONE) lithology.

Note 37. MAFI refers to MAFITE. This was reassigned using MCGBR (MAFITE) from ANG 250k.

Note 39. MDSC refers to MUDSTONE, SANDSTONE, CONGLOMERATE. This was reassigned using MDSL (MUDSTONE, SANDSTONE, LIMESTONE) from NI 250k.

Note 44. MFTUF refers to MAFIC TUFF. This was reassigned using TUF (TUFF) from ANG 250k.

Note 45. MIGM refers to MIGMATIC ROCK which is an interface lithology between igneous and metamorphic rock formations. It forms part of the Neoproterozoic Moine Supergroup rocks. This was reassigned using GN (GRANITE) since MIGM grades into granite.

Note 50. MSSP refers to GNEISSOSE SEMIPELITE AND GNEISSOSE PSAMMITE. This was reassigned using GN (GNEISS) from NI_250k.

Note 52. MYCFB refers to MYLONITIC-ROCK AND FAULT-BRECCIA. The highest conductivity obtained by this analysis is ~130 mS/m (SCGS, Table 3). To ensure a more conductive assignment for MYCFB a value of 145 mS/m was assigned.

Note 54. PGCP refers to GRAPHITIC PELITE, CALCAREOUS PELITE, CALCSILICATE-ROCK AND PSAMMITE. This was reassigned using PSPE (PSAMMITE and PELITE) from NI 625k.

Note 55. PPSPC refers to PSAMMITE, PELITE, SEMIPELITE AND CALCSILICATE-ROCK. This was reassigned using PSPE (PSAMMITE and PELITE) from NI 625k.

Note 59. PSSP refers to PSAMMITE and SEMIPELITE. This was reassigned using PSPE (PSAMMITE and PELITE) from NI 625k.

Note 61. QAREN refers to QUARTZ-ARENITE. This was reassigned using QZITE (QUARTZITE) from NI 625k.

Note 65. SCGS refers to SANDSTONE WITH SUBORDINATE CONGLOMERATE AND SILTSTONE). This was reassigned using SDSL (SANDSTONE AND SILTSTONE) from IoW_50k.

Note 69. SCSM refers to SANDSTONE WITH SUBORDINATE CONGLOMERATE, SILTSTONE AND MUDSTONE. This was reassigned using SMSC (SANDSTONE, MUDSTONE, SILTSTONE AND CONGLOMERATE) from NI 625k.

Note 77. SEMPEL refers to SEMIPELITE. This was reassigned using PSP (PSAMMITE, SEMIPELITE AND PELITE) from NI_625k.

Note 78. SISDM refers to SILTSTONE AND SANDSTONE WITH SUBORDINATE MUDSTONE. This was reassigned using SMSC (SANDSTONE, MUDSTONE, SILTSTONE AND CONGLOMERATE) from NI 625k.

Note 80. SMLP refers to SERPENTINITE, METABASALT, METALIMESTONE AND PSAMMITE). This was reassigned using SEPITE (SERPENTINITE) from NI 250k.

Note 82. SPPE refers to SEMIPELITE AND PELITE. This was reassigned using PSP (PSAMMITE, SEMIPELITE AND PELITE) from NI_625K.

Note 85. SYR refers to SYENTIC ROCK. This is an unnamed igneous intrusive rock (ORDOVICIAN). This was reassigned using IGRU (IGNEOUS ROCK) from ANG_50k (NEOPROTEROZOIC).