

# Mapping and predicting electrical conductivity variations across southern England using airborne electromagnetic data

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ELECTRICAL CONDUCTIVITY ACROSS SOUTHERN ENGLAND

**Abstract:** Electrical conductivity is one of the fundamental geophysical properties of rock formations and can be measured at field and laboratory scales. A recent airborne geophysical survey of the Isle of Wight and part of the adjacent mainland has provided an assessment of the near-surface (close to outcrop) electrical conductivities associated with Palaeogene and Cretaceous formations. This study examines the degree to which the high resolution survey data contain distinctive geological and lithological signatures. The geostatistical nature of the conductivity distributions are examined in relation to two existing sedimentary bedrock schemes involving lithostratigraphical and simpler lithological descriptions. A close association between conductivity and bedrock geology is evident. It is then demonstrated how the central moments and dispersion statistics of the distributions may be used to predict the continuous, bedrock conductivity distribution across a large area of southern England, containing, as it does, a high population density and extensive infrastructure. The effectiveness of the method is demonstrated using the survey data obtained on the mainland and an existing database of Vertical Electric Soundings.

The electrical properties of UK soils and rocks were investigated during the 1930s in both the laboratory and using geophysical field measurements. These early measurements were intended to provide a framework for understanding the potential impact of ground conductivity on the then developing radio and telephone transmission systems. The laboratory experiments, typically using 'soil' samples to depths of about 3 m, are described by Smith-Rose (1933, 1935). In 1935 the British Electrical and Allied Industries Research Association (generally known as the Electrical Research Association, ERA) presented two electrical resistivity maps of England/Wales and southern Scotland. The maps show colour contours of apparent resistivity of the ground for an apparent depth of 500' (152 m). The indicated large investigation depth is thought to be due to the large separations and low frequency of the electromagnetic measurements carried out. The maps, apparently not available in the public domain, provide national scale information, and show a strong correlation with bedrock geology. Smith-Rose (1935) undertook a comparison of his laboratory measurements and the mapped information and notes a number of evident geological controls on both sets of information.

During the latter half of the last century more routine electrical and electromagnetic geophysical measurements provided a wealth of localised survey information for a variety of applications across the UK. Many of the measurements comprised vertical electric soundings (VES) for groundwater applications. The National Resistivity Sounding Database (Barker *et al.*, 1996) was developed from over 8,000 such soundings. The database information, comprising raw resistances, continues to be used in a geological context (Cuthbert *et al.*, 2009; Busby *et al.*, 2011). Electromagnetic measurements have also been used to guide geological mapping, usually in the near-surface (e.g. Zalasiewicz *et al.*, 1985; Cornwell & Carruthers, 1986) and these and other case studies indicate that clays and clay-rich units can be effectively distinguished from other lithologies such as sandstone and limestone.

In more recent times, 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 is acquired at four frequencies and the highest frequency provides information on the bulk electrical conductivities of near-surface formations. Due to their sensitivity to enhanced pore-fluid conductivities, the data have been used in a wide-range of localised environmental investigations in relation to industrial sites, coal-mine spoil and both open and closed landfills (Beamish, 2002, 2003). The impact of colliery spoil

zones across the Permo-Triassic aquifer of Nottinghamshire has been described by Beamish & Klinck (2006).

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 Isle of Wight (IoW) survey (Figure 1) was the first survey to acquire conductivity information in the south of England and the impact of industrial features that might interfere with the measurements are minimal. The Palaeogene and Cretaceous bedrock formations encountered on the IoW are some of the youngest bedrock lithologies to be assessed by the HiRES surveys. Since the lithologies are also representative of much of the southern, central mainland of England, the new information has a wider relevance. Beamish & White (2011a) used the IoW conductivity data to conduct a GIS-based assessment of the electrical conductivity information in relation to geological bedrock classification. The analysis used over 104,000 measurements across onshore IoW and established statistical and average electrical properties as a function of bedrock geology. Here the conductivity information obtained at the highest frequency (most relevant to outcrop geology) is reprised using a revised statistical framework together with a consideration of superficial geology. The geological classification of a geophysical measurement may take several forms and relies on existing classifications within a geological lexicon. Here the 1:50k digital lexicon DiGMap-GB50 (BGS, 2008) is used to investigate two forms of geological attribution. The first scheme considered uses a LEX-RCS (Rock Characterisation Scheme) procedure that provides a basis for standard lithostratigraphical geological map attribution with geophysical values. The second scheme considered uses a simpler RCS procedure that embodies a lithology-only classification of the bedrock units present. This second scheme may be considered more appropriate to geophysical attribution in that it represents a more generic description of the rock lithologies present (e.g. chalk, sandstone, limestone, etc).

Having established the statistical behaviour of the near-surface conductivity of the geological units across the IoW, the ability of these data to perform predictive mapping across a large central area of southern England is considered. The effectiveness of this procedure is demonstrated using both survey data obtained on the mainland and an existing database of Vertical Electric Soundings. The extended bedrock conductivity map has the potential to allow assessments of the degree to which localised measurements are consistent with, or represent departures from, the norm. The GIS-based predictive mapping of geophysical information is particularly significant across this area due to the high spatial density of the built environment with large population centres and associated infrastructure which tend to hamper systematic geophysical surveying.

## Background

Geophysical measurements provide volumetric estimates of total formation conductivity  $\sigma_t$  or its reciprocal, resistivity  $\rho_t$ . 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. Assuming negligible clay content, an empirical relationship developed by Archie (1942) indicates the bulk material conductivity is related to pore fluid conductivity ( $\sigma_f$ ), fractional porosity ( $\phi$ ) and degree of saturation ( $S$ ) as:

$$\sigma_t = a' \sigma_f S^n \phi^m \quad \dots(1)$$

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  $\sigma_t$ . A second term, due to mineral surface conduction can be introduced into equation (2) to allow for this (Glover *et al.*, 2000; Kirsch, 2006). In the near-surface, with materials displaying similar porosities and saturations, clay content is often the most significant factor in determining the bulk conductivity.

## The airborne survey

The Isle of Wight (IoW) is England's largest island; situated off the south coast of Hampshire it offers a diverse range of geology for an area of its size (380 km<sup>2</sup>). The island and part of the mainland were surveyed in 2008 as part of the HiRES airborne geophysical program (Figure 1). The IoW airborne survey area is contained within a rectangle of 36 x 22 km with flight lines spaced at 200 m in a N-S direction, orthogonal to the major structural trends of the region. A nominal survey altitude of 56 m was adopted, but over the built environment a regulatory flight altitude of 240 m was required. The primary aim of the survey was to determine the geophysical responses of specific geology, characteristic of much of southern England, in relation to geologic map revision. The acquisition parameters and processing procedures applied to the survey data are described by Beamish & Cuss (2009) and White *et al.* (2009). The survey obtained over 4,500 line km of data and provided the first airborne EM (AEM) measurements obtained across southern England.

The geology of the Isle of Wight can be fairly evenly divided into a northern zone of Palaeogene sands, clays and limestones and a southern region of Cretaceous strata. The structure is dominated by a prominent east-west trending monoclonal fold or ramp structure (White, 1921; Melville & Freshney, 1982). The two zones are divided by the east-west trending chalk beds of the late-Cretaceous. Geological units across the survey area are discussed in detail later.

## **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 highest frequency provides the shallowest depth of investigation and the half-space conductivity assessments at a frequency of 25 kHz are used here to assess bedrock formations at outcrop.

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. The depth of investigation depends on frequency and the vertical distribution in conductivity. In order to summarise the behaviour of the depth of investigation of the 25 kHz data, centroid depth estimates (Siemon, 2001) have been calculated across a range of uniform half-spaces. Centroid depths can be regarded as the mean depth of the in-phase current system at each frequency and are shown in Figure 2. For conductivities greater than 100 mS/m, centroid depths are confined to the upper 10 m yet exceed 30 m at conductivities less than 10 mS/m. Thus the potential for variations in formation thickness to influence the conductivity estimates is most pronounced in resistive environments.

## **Data screening**

The principal analysis conducted here is a geological/geostatistical appraisal of a conditioned set of the conductivity data. The full survey rectangle provided 289,068 onshore and offshore AEM measurements. The survey area is coastal and 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 500 mS/m to the data and restricting the data to locations where the survey altitude is less than 100 m, removing 6% of the data. This condition also has the equivalent effect of restricting the data set over urban areas.

## **IoW conductivity data**

This study uses the highest frequency (25 kHz) survey data converted to half-space, apparent conductivity values following the rejection and screening procedure discussed previously. The apparent conductivity values based on a natural-neighbour grid using a cell size of 50 x 50 m across the IoW are shown in Figure 1 alongside the geological boundaries (black lines) from the corresponding 1:50k bedrock geological map (discussed below). The urban-centres (high-fly) areas are identified by black zones. The conductivity data provides both structural edge information and, at the broader scale, an assessment of the intrinsic conductivity of the geological formations. In broad terms, there is a clear division in the very high and variable conductivities observed in the north (the younger Palaeogene rocks) and the far more resistive formations observed in the south (the Cretaceous rocks). The Palaeogene formations across the survey area are the youngest bedrock formations to be assessed by AEM measurements in the UK and the high degree of variability is noteworthy. Given the nature of the lithologies encountered it is likely that the data reflect a highly variable percentage clay content. Being a coastal survey, there is also potential for a consideration of the conductivity data in relation to saline conditions. These are most evident, at the scale used in Figure 1, across portions of the low-lying coastal strip of the mainland in the north-west corner.

## **Geology**

### **Superficial Geology**

The classification of superficial geology across the survey area is based on the current 1:50k scale digital data for DIGMap-GB50 version 5.18 (BGS, 2008). The Lexicon Rock Characterisation Scheme (LEX-RCS) identifies 5 superficial units across the 36 x 22 km survey area (see Figure 3) and these are described in Table 1. Three of the units have content that is described as clay, silt, sand and gravel. In broad terms the superficial deposits are relatively sparse and considered to be thin (typically < 5 m). The superficial deposits have the potential to interfere with assessments of the conductivity

properties of underlying bedrock units in cases where they present a significant thickness and a marked contrast in conductivity.

Background information (from boreholes) on the depth to bedrock variations across the area indicates that the clay with flints formation (CWF, red polygons in Figure 3a) may have thicknesses that exceed 10 m. The degree to which the CWF formation may interfere with conductivity assessments of the bedrock formations was investigated across the Upper Chalk formation (identified in Figure 3). The Upper Chalk is estimated have the lowest conductivity of the bedrock formations encountered on the IoW (see later) and the extent of the CWF formation provides a large sample test. The issue investigated is whether the thickness of the at-surface CWF formation coupled with a potential enhancement in the conductivity of the formation due to, say, increased clay content influences the estimation of the conductivity of the underlying bedrock.

Two conductivity distributions were extracted from the 25 kHz apparent conductivity data samples across the Upper Chalk. The first distribution occupies the area of the CWF formation above the Upper Chalk and provides 1626 data points. The second distribution occupies the whole outcrop of the Upper Chalk, and this sampling provides 8621 data points. As discussed later, 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 distributions conform to neither. This is a common situation when dealing with large scale regional data sets (Reimann & Filzmoser, 2000). The statistics of the linear distributions of apparent conductivity are summarised in Table 2.

From Table 2, it is evident that the central moments of the 2 test distributions are equivalent with a suggested slight marginal increase in the estimate (see geometric mean) of the LPCK conductivity in the presence of overlying superficial deposits. The results indicate that estimation of bedrock conductivities in the presence of superficial deposits for the IoW data can be conducted solely on the basis of bedrock classification.

## **Bedrock Geology**

The bedrock classification across onshore IoW is based on the current 1:50k scale digital data for bedrock geology DIGMap-GB50 version 5.18 (BGS, 2008). The LEX-RCS classification identifies 22 bedrock units across onshore IoW on the basis of lithostratigraphical type; these are described in



Table 3. Table 3 also shows the number of data samples available across each formation. The distribution of bedrock units is shown in the geological map of Figure 3b. As can be seen using Table 3, the data sampling of some of the formations is limited particularly across the near-vertical beds associated with the central ramp structure. Considering the volumetric footprints associated with airborne measurements, any derived statistical results may not be significant in the poorly sampled units.

A bedrock classification of all the four frequency apparent conductivity data was conducted by Beamish and White (2011a) using the LEX-RCS classification discussed above. Here the analysis of the geological classification uses only the 25 kHz data and the analysis takes place using the logarithm (base 10) of the conductivity data. As noted previously, although the data distributions are, in a strict sense, neither normal 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. Figure 4 provides an example of the histograms of apparent conductivity (logarithm) obtained for 3 of the larger bedrock formations which possess distinctly separate conductivity levels. The formations considered are the resistive Upper Chalk (LPCK-CHLK, with 8621 samples), the Lower Greensand (FRS-FGST, with 18,546 samples) and the conductive Bembridge Marls (BMBG-CAMU, with 7109 samples). The best fitting normal distributions to the observed distributions are indicated. It can be seen that all 3 distributions are highly peaked with different effects observed in the tails of the distributions. The LPCK-CHLK distribution has a particularly long low value tail. A detailed examination of the conductivity values of  $< 1$  mS/m indicates that they are not associated with spatially persistent zones and the data in the tail may reflect the presence of localised zones of highly competent (tight) chalk. The high data value screening limit of 500 mS/m is observed in the BMBG-CAMU distribution and indicates, it could be argued, that 500 mS/m is too low a limit for the intrinsic high conductivities associated with this formation. The obvious accumulation of high values in the final bin below 500 mS/m shows, however, why this limit has been applied. Non-geological (cultural) perturbations have a tendency to produce localised high values, and these, together with some unrepresentative values from coastal locations (i.e. due to the influence of sea water) combine to produce the behaviour observed. It can also be noted that despite the large spatial sampling involved in the assessment, the distributions appear unimodal.

The bedrock classified distributions of the 25 kHz apparent conductivity for all 22 formations across onshore IoW are summarised in the box-whisker plot shown in Figure 5. The leftmost 10 units comprise the northern Palaeogene formations while the remaining 12 units are the southern Cretaceous formations. In Figure 5, the infilled 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 and the discrete symbols, beyond the terminating bars indicate outliers. Within the Palaeogene the first 3 formations comprising the Hamstead Beds and Bembridge Marls (clays and mud) provide the highest conductivity levels (discounting the small sampling associated with the Headon Formation, HE-CLSS). The lowest conductivity within the Palaeogene is associated with the limestone formation (HEOS-LMST). The lack of outliers is probably related to the small sampling population (85 data points). Within the Cretaceous the 2 uppermost chalk units (LPCK-CHLK and WNPCK-CHLK) provide the lowest conductivities observed across the IoW. As identified in Figure 5, there is a progressive and distinct increase in conductivity with increasing age across the 3 chalk units. Since a similar trend is also observed in the radiometric data obtained from the airborne survey (Beamish & White, 2011b) the behaviour is interpreted as indicating an increasing mineralogical (e.g. clay) content with increasing age. Increasing values of conductivity with age are also observed across the oldest formations on the island from the Lower Greensand (FRS-FGST) through to the Wealdon Formation (W-MDST and W-SDST).

As noted previously the observed distributions of classified conductivity values appear slightly unusual due to the behaviour of the tails of the distributions. Non-geological effects producing high values were noted previously however the behaviour of the outliers at low values should also be noted. The apparent conductivity data are estimated on the basis of a uniform, half-space assumption and there is the potential for interference from lateral effects between adjacent formations that exhibit contrasting conductivities. From a theoretical perspective, it is possible to buffer/remove data points within a fixed radius of a geological contact however due to the outcrop pattern across the IoW many data points would be omitted. In these circumstances it seems preferable to retain such data to be accumulated in the high and low tails of the distributions. There is then a case for trimming the data as discussed later.

## **Predictive comparison of classified values**

Two bedrock formations underlie the mainland component of the survey area. The first unit is the Becton Sand Formation (BECH-SSCL) which outcrops along the low lying coastal strip of the

mainland. The conductivity data appear strongly influenced by seawater saturation (e.g. Figure 1) which extends significantly inland (up to 1 km). The resulting conductivity distribution is highly bimodal and it is therefore difficult to assign a representative conductivity for this formation.

The second unit, the Headon and Osborne Beds (HEOS-CLSS), also outcrops on the IoW and can be used to compare the statistical sampling behaviour of two spatially distinct areas of the same bedrock formation. A statistical analysis of the HEOS-CLSS distribution on the IoW used 4839 samples whilst an equivalent assessment across this formation on the mainland provided 10,607 samples. It should also be noted that the HEOS-CLSS distribution on the mainland (Figure 3b) is overlain to a significant extent by superficial sand and gravel deposits (RTDU-XSV, Figure 3a). Figure 6 shows the histograms of apparent conductivity (logarithm) obtained for both the mainland and IoW data sets. The best fitting normal distributions to the observed distributions are also indicated. It can be seen that the 2 distributions are highly peaked and both retain an accumulation of high values in the final bin due to the reasons discussed previously. The proposition that the statistical analysis of the IoW data can be used to predict the behaviour on the same formation outcropping on the mainland is supported by the equivalence of the central moments observed in Figure 6. Transformation to the results to linear apparent conductivity provides population means of 48.8 mS/m (IoW) compared with 41.7 mS/m (mainland).

## **A detailed example**

Due to the large single outcrop (67.12 km<sup>2</sup>) on the IoW, the Lower Greensand Formation (FRS-FGST) is particularly well sampled (Table 3). The conductivity distribution shown in Figure 1 contains highly significant spatial information when examined in detail. Figure 7 shows the location of the outcrop of the FRS-FGST and the distribution of apparent conductivities observed. The gaps in the sampling points are due to the broad data screening applied (roads and high-fly zones) together with other more specific data exclusion areas. The conductivity values shown in Figure 7 can be seen to define spatially persistent zones of low, medium and high values that represent significant changes in the near-surface electrical properties across the formation. There are reported to be five cycles of sedimentation in the FRS-FGST, each going from glauconitic clay (with the potential to increase bulk conductivity above the norm) to clean sands (with the potential to decrease bulk conductivity below the norm). Although such detailed information provides a basis for further interpretation of the localised behaviour, the summary distribution shown in Figure 4 can be seen to provide a

geologically relevant assessment of the central moments and variance of the data in relation to the distributions obtained for other formations.

### **Lithological classification of the data**

Beamish & White (2011a) used medians of the linear apparent conductivity data distributions for each of the 22 bedrock units to generate baseline geological conductivity maps for the IoW. Since the analysis was conducted using the four available frequencies it was also possible to summarise the average behaviour of conductivity with depth. While such an analysis provides specific geological conductivity information it is also possible to consider whether the LEX-RCS lithostratigraphical characterisation of conductivity information is the most appropriate choice for this type of analysis. Thus in Figures 1 and 5, it can be noted that the youngest and oldest formations, HM-CLSS and W-SDST respectively, both provide elevated conductivities in excess of 100 mS/m. Given the established dependence of bulk conductivity on porosity together with fluid and clay content, a rock characterisation scheme based on the type(s) of material should, in theory, offer a more relevant assessment. The use of a simpler material type classification should also offer a more generic approach to the prediction of material electrical properties elsewhere.

The rock classification scheme for UK sediments and sedimentary rocks is described in detail by Hallsworth & Knox (1999). The current digital bedrock geology DIGMap-GB50 version 5.18 (BGS, 2008) provides a rock characterisation material attribute referred to as RCS (a code) together with RCS-X (an enhanced code) and a further associated descriptive attribute referred to as RCS-D. This classification protocol identifies 11 units across the IoW and these are listed in Table 4. Table 3 provides a cross-reference of the RCS and LEX-RCS codes. Obviously the reclassification according to lithological content alone has resulted in a simplification of bedrock characterisation; in this case by a factor of 2.

The RCS bedrock attribution for the 11 units is shown in Figure 8a in association with the linework of the previous LEX-RCS classification. As can be seen in Table 4 the CLAY-SAND-SILT formation (CLSISA) provides over 34,000 samples while the limestone (LMST) unit provides only 85. As previously the distributions of the 25 kHz apparent conductivity (logarithmic units) for the 11 RCS formations are summarised in the box-whisker plot of Figure 8b. Again the scale of conductivities spans 4 orders of

magnitude. Three sets of associated behaviour are indentified by the dotted lines. In the first instance it is observed that the CLAY and CLAY-SAND-SILT units (circled) provide similar high conductivity levels. The central moments of the CLAY unit are also similar to those of the CAMU (Calcareous mud) unit. Secondly the limestone unit (LMST), although sampled at only 85 points provides a conductivity value significantly below that of the limestone with subequal amounts of interbedded argillaceous rocks (LMST-AROC). This indicates, as would be expected, that the clay component significantly enhances the bulk conductivity of the limestone. The third observation relates to the mudstone unit (MDST) which, by definition, would be considered a fine-grained sedimentary rock formed from silt and clay. This unit provides an enhanced conductivity over those associated with both the MDST-SDST-SLST unit and the SDST unit, which have similar conductivities.

The majority of the distributions appear unimodal, although none can be regarded as log-normally distributed, yet they can be described by a combination of their central moments together with measures of their dispersion (e.g. quartile or decile intervals). Two of the distributions however display behaviour associated with mixtures. The histograms for the CHLK and CLAY-SAND-SILT distributions (logarithmic units) are shown in Figure 9. The CHLK distribution indicates the onset of bimodal behaviour and this is not unexpected given the previous results that used the full 3 formation grouping (upper, middle and lower) of the Chalk sequence. Detailed examination of the behaviour observed in Figure 9 indicates that the lower value (leftmost) peak in the CHLK distribution is formed by the combined distributions associated with the Upper Chalk (LPCK-CHLK) and the Middle Chalk (WNPK-CHLK). The higher value peak is associated with the Lower Chalk (WZCK-CHLK).

The CLAY-SAND-SILT distribution is taken from a large spatial area (Figure 8a) and is obtained from 34050 samples. The low value tail displays evidence of at least two knees that may be present due to data sampling across areas with much reduced clay content. Although the spatial detail of this is potentially useful (e.g. Figure 7) , the overall distribution can still be considered representative of the bedrock formation sampled as long as the central moments together with the details of the variance behaviour are retained. While the cautionary notes on the observed distributions should be noted, the results of the log-distributed analysis have been converted to linear conductivity and the conductivity median together with first and third quartiles of the distributions are tabulated against the 11 unit RCS codes in Table 4.

## **Analysis of variance (ANOVA)**

The observed variations of conductivity across geological units have been summarised in the box-whisker plots of Figures 7 (LEX-RCS classification) and 11 (RCS classification). The results demonstrate the degree to which conductivity signatures for mapped geological units are different. ANOVA was used to further assess the contribution of geology to 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.

Using the logarithms of the conductivity data, the data were first statistically trimmed by rejecting the upper and lower deciles of the classified data sets to remove outliers. Table 5 summarises the analyses conducted and shows the percentages of the conductivity data variability that can be explained by the geological attribution. As expected, the percentages are remarkably high. In the case of the LEX-RCS classification, the results indicate a slightly higher proportion of variability is obtained across the older Cretaceous units. The high percentage obtained across all 22 units in the LEX-RCS classification is reduced but still remains high in the simpler 11 unit RCS scheme.

### **Predictive use of geologically-classified conductivity**

In order to investigate some of the issues involved in assigning bulk conductivity values on the basis of the lexicon descriptions of rock characterisation, a large area of southern England containing the loW was selected. The test area contains geological attributes across a total area of 16,297 km<sup>2</sup> and the sampling of the area in terms of geologic period is summarised in Table 6.

Table 6 indicates that the Cretaceous and Palaeogene formations, such as those outcropping on the loW, account for a large percentage (86.1%) of the total area. It is however the characterisation of the bedrock formations in terms of either lithostratigraphy (LEX-RCS) or the simpler rock material description (RCS) that is relevant here. Two studies were performed to consider the issues involved when performing an attribution according to these classifications.

When examined in relation to the larger test area, it can be noted that a number of the LEX-RCS classifications are confined to the loW (HM-CLSISA, BMBG-CAMU, BMBG-CLAY, BEL-LMAR, HEOS-LMST, BRBA-CLSISA, CAW-SDSM, SIOW-SDSM and FRS-FGSST). In effect the original 22 units reduce to 11 in terms of their wider application to the test area. The spatial sampling provided by the 22 unit classification across the test area is summarised in Figure 10a. The area sampled is 3,760.7 km<sup>2</sup>

which amounts to 23% of the total area. The spatial sampling provided by the 11 unit RCS classification is summarised and compared with the previous LEX-RCS sampling in Figure 10b. The sampling area increases to 93% of the total using this broader classification.

The median values of the lithologically-derived distributions of the apparent conductivity have been used to generate an observed (IoW) and predicted (mainland) bedrock apparent conductivity map (1:50k) as shown in Figure 11. The map uses a simplified 5 range colour scheme. The resistive chalk outcrop is a dominant feature across the mainland while the IoW displays the largest range of values by virtue of the conductive Calcareous Mudstone formation. The map represents an estimate of the baseline near-surface bedrock conductivities as defined by their central moments. According to the analysis conducted it does not include the effect of any superficial deposits. The map, together with associated measures of the dispersion statistics, allows the degree to which localised measurements represent correspondence with, or departures from, the norm to be assessed. The departures could arise, for example, from distinct geological conditions (specific mineralogies) and/or environmental influences.

The distribution of bedrock formations, classified according to their RCS descriptions (Figure 10b) potentially represents the maximum amount of geological information, across the test area, that can be attributed with the geophysical properties derived from the airborne survey of the IoW. The most extensive omissions within the RCS classification are due to formations within the Jurassic and Palaeogene periods.

## Discussion

It is possible to investigate the predicted conductivity values using existing data contained in the National Resistivity Sounding Database (Barker *et al.*, 1996). Seven clusters of such soundings are available across the test area as shown in Figure 11. In order to compare like-with-like, it is necessary to model/invert the database information (resistances) to provide vertical model assessments of bedrock values (i.e. below any superficial deposits present). In a number of cases the soundings are too limited (shallow) to provide this information. In other cases, the bedrock models appear inconsistent across the local scales of the soundings. The investigation conducted has generated models for 3 sets of VES soundings (A, B and C, Fig.11) that allow a limited comparison with the predicted bedrock conductivity values. The comparisons are obtained for (A) Mudstone (RCS=MDST), (B) Clay, Silt and Sand (RCS=CLSISA) and (C) Chalk (RCS=CHLK). The latter uses the information from just 4 soundings. The values of bedrock conductivity obtained from the VES soundings within the

MDST group range from 72 to 98 mS/m which compares with a predicted interquartile range of 40 to 96 mS/m. The values of bedrock conductivity obtained from the VES soundings within the CLSISA group range from 42 to 120 mS/m which compares with the predicted interquartile range of 60 to 174 mS/m. Finally the values of bedrock conductivity obtained from the 4 VES soundings within the CHLK group range from 7 to 9 mS/m which compares with a predicted interquartile range of 4 to 17 mS/m.

## **Conclusions**

A HiRES airborne geophysical survey of the IoW has provided an assessment of the near-surface (close to outcrop) electrical conductivities associated with Palaeogene and Cretaceous formations. The purpose of the present investigation has been to examine the degree to which the high resolution survey data contain distinctive geological and lithological signatures. The geostatistical nature of the conductivity distributions have been examined in relation to two existing sedimentary bedrock schemes involving lithostratigraphical and lithological descriptions. An examination of the central moments and dispersions of the classified data (ANOVA analysis) indicates that 80% of the variability observed can be accounted for by lithological characterisation and that this increases to 87% when a lithostratigraphical characterisation is used. The ability of the baseline data on the IoW to predict corresponding conductivity values on the nearby mainland has been examined and confirmed. The simpler lithological characterisation possesses a far greater ability to predict, and thus map, equivalent baseline conductivities across the south of England. The conductivity distributions for two of the lithologies (CHALK and CLAY-SAND-SILT) display behaviour associated with mixtures. The CHALK behaviour is due to a detectable increasing conductivity with age from the Upper to Lower Chalk sequence. The large sampling of the CLAY-SAND-SILT lithology appears to identify areas of clay-content deficiency with respect to the norm. Accurate prediction requires a knowledge of the observed (non-parametric) distributions and this can be accommodated by recording decile intervals. A lithological-based bedrock conductivity map of a significant portion of the south of England has been obtained. The baseline conductivity map, and associated statistics, allows the degree to which localised measurements represent departures from the norm to be assessed. The extent to which the methodology described here can be supplemented by existing or additional geophysical measurements is the subject of ongoing studies.



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## Tables (6)

**Table 1.** Superficial rock lexicon codes (LEX\_RCS) together with lexicon descriptions (LEX\_D) and rock characterisation descriptions (RCS\_D) for the IoW.

LEX_RCS	LEX_D	RCS_D
ALV-XCZSV	Alluvium	Clay, silt, sand and gravel
BTFU-XCZSV	Beach and tidal flat deposits (undifferentiated)	Clay, silt, sand and gravel
CWF-XCZSV	Clay-with-flints formation	Clay, silt, sand and gravel
PEAT-PEAT	Peat	Peat
RTDU-XSV	River terrace deposits (undifferentiated)	Sand and gravel

**Table 2.** Statistics of the apparent conductivity (AC at 25 kHz) distributions observed across the Upper Chalk (LPCK) in two areas. Clay With Flints (CWF) above Upper Chalk, and whole of the Upper Chalk. N refers to number of samples.

	AC (mS/m) CWF + LPCK	AC (mS/m) All LPCK
N	1626	8621
Minimum	0.52	0.11
Maximum	20.96	300.37
Mean	5.78	6.78
Median	5.07	5.09

25% percentile	3.82	3.37
75% percentile	7.15	7.7
Geometric mean	5.05	4.85

**Table 3.** The LEX-RCS bedrock geological classification for the Isle of Wight. Codes are as described in the text. *N* refers to number of data samples.

LEX_ROCK	NAME	N	RCS	RCS_X	RCS_D
HM-CLSS	Hamstead Beds	23951	CLSISA	CLAY+SANDU+SILT	Clay, silt & sand
BMBG-CAMU	Bembridge Marls	7108	CAMU	CAMU	Calcareous mud
BMBG-CLAY	Bembridge Marls	4759	CLAY	CLAY	Clay
BEL-LMAR	Bembridge Limestone	2679	LMAR	LMST+AROC	Limestone & interbedded argillaceous rocks
HE-CLSS	Headon Formation	20	CLSISA	CLAY+SANDU+SILT	Clay, silt & sand
HEOS-CLSS	Headon and Osborne Beds	4839	CLSISA	CLAY+SANDU+SILT	Clay, silt & sand
HEOS-LMST	Headon and Osborne Beds	85	LMST	LMST	Limestone
BRBA-CLSS	Bracklesham Group	3592	CLSISA	CLAY+SANDU+SILT	Clay, silt & sand
LC-CLSS	London Clay	983	CLSISA	CLAY+SAND+SILT	Clay, silt & sand
LMBE-CLSS	Lambeth Group	660	CLSISA	CLAY+SANDU+SILT	Clay, silt & sand
LPCK-CHLK	Upper Chalk (White)	8621	CHLK	CHLK	Chalk
WNCK-CHLK	Middle Chalk	3551	CHLK	CHLK	Chalk
WZCK-CHLK	Lower Chalk (Grey)	3017	CHLK	CHLK	Chalk
UGS-SDST	Upper Greensand	5288	SDCH	CHRT+SDST	Sandstone & chert
UGS-SDCH	Upper	432	SDST	SDST	Sandstone

	Greensand				
GLT-MDST	Gault	4242	MDST	MDST	Mudstone
CAW-SDSM	Carstone	2840	SDSM	MDST+SDST+SLST	Sandstone, siltstone & mudstone
SIOW-SDSM	Sandrock	5183	SDSM	MDST+SDST+SLST	Sandstone, siltstone & mudstone
FRS-FGST	Lower Greensand	18546	FRS_FGSST	FGSST	Ferruginous sandstone
AC-MDST	Atherfield Clay	965	MDST	MDST	Mudstone
W-MDST	Wealdon	3156	MDST	MDST	Mudstone
W-SDST	Wealdon	110	SDST	SDST	Sandstone

**Table 4.** The RCS bedrock geological classification for the Isle of Wight. Codes are as described in the text. *N* refers to number of data samples. The final 3 columns contain the results of the statistical analysis described in the text.  $\sigma$  med is median conductivity,  $\sigma$  Q1 is the first quartile and  $\sigma$  Q3 is the third quartile in units of mS/m.

RCS	RCS-X	RCS-D	N	$\sigma$ Q1 mS/m	$\sigma$ med mS/m	$\sigma$ Q3 mS/m
CLSISA	CLAY+SANDU+SILT	Clay, silt & sand	34050	60.1	120.2	174.5
CAMU	CAMU	Calcareous mud	7109	99.8	145.2	196.5
CLAY	CLAY	Clay	4759	81.3	132.7	208.9
LMAR	LMST+AROC	Limestone & subequal argillaceous rocks, interbedded	2679	30.4	43.4	68.9
LMST	LMST	Limestone	85	6.1	11.4	13.7
CHLK	CHLK	Chalk	15191	4.3	7.6	16.9
SDCH	CHRT+SDST	Sandstone & chert	432	18.4	23.5	28.8
SDST	SDST	Sandstone	5398	19.4	26.4	36.4
MDST	MDST	Mudstone	8365	16.0	63.6	95.8
SDSM	MDST+SDST+SLST	Sandstone, siltstone & mudstone	8024	17.6	28.4	49.8

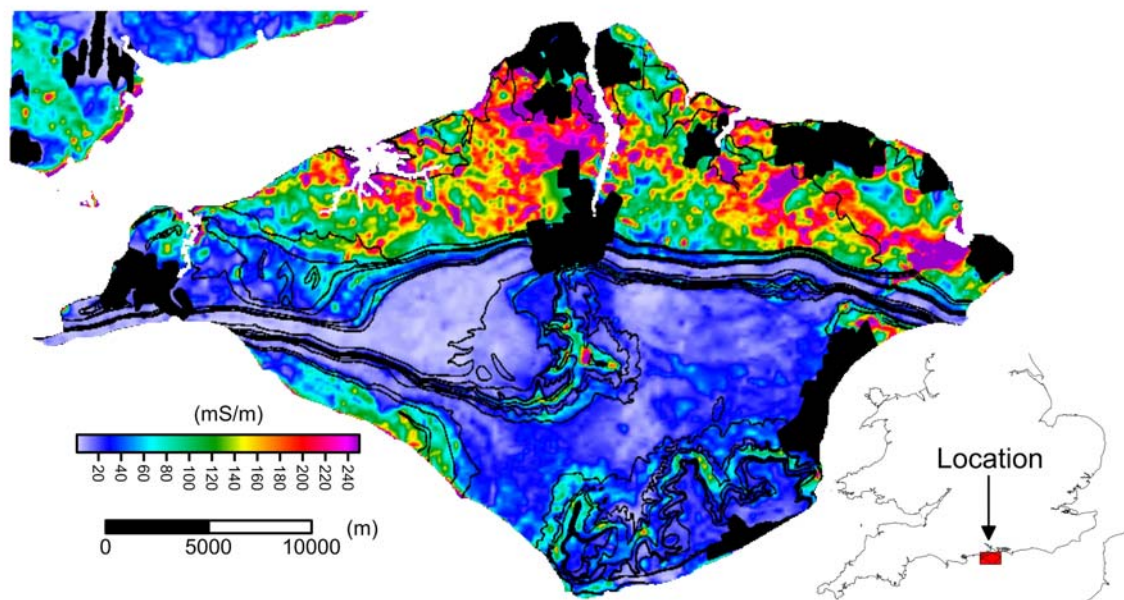
FRS_FGSST	FGSST	Ferruginous sandstone	18546	13.4	20.5	27.4
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**Table 5.** Results of ANOVA analysis applied to trimmed distributions of the logarithms of the conductivity data. Percentage of conductivity variability explained by geological classification. The two classifications considered are LEX-RCS and RCS.

	All units	Palaeogene units	Cretaceous units
LEX_RCS	87 %	67 %	79 %
RCS	80 %	-----	-----

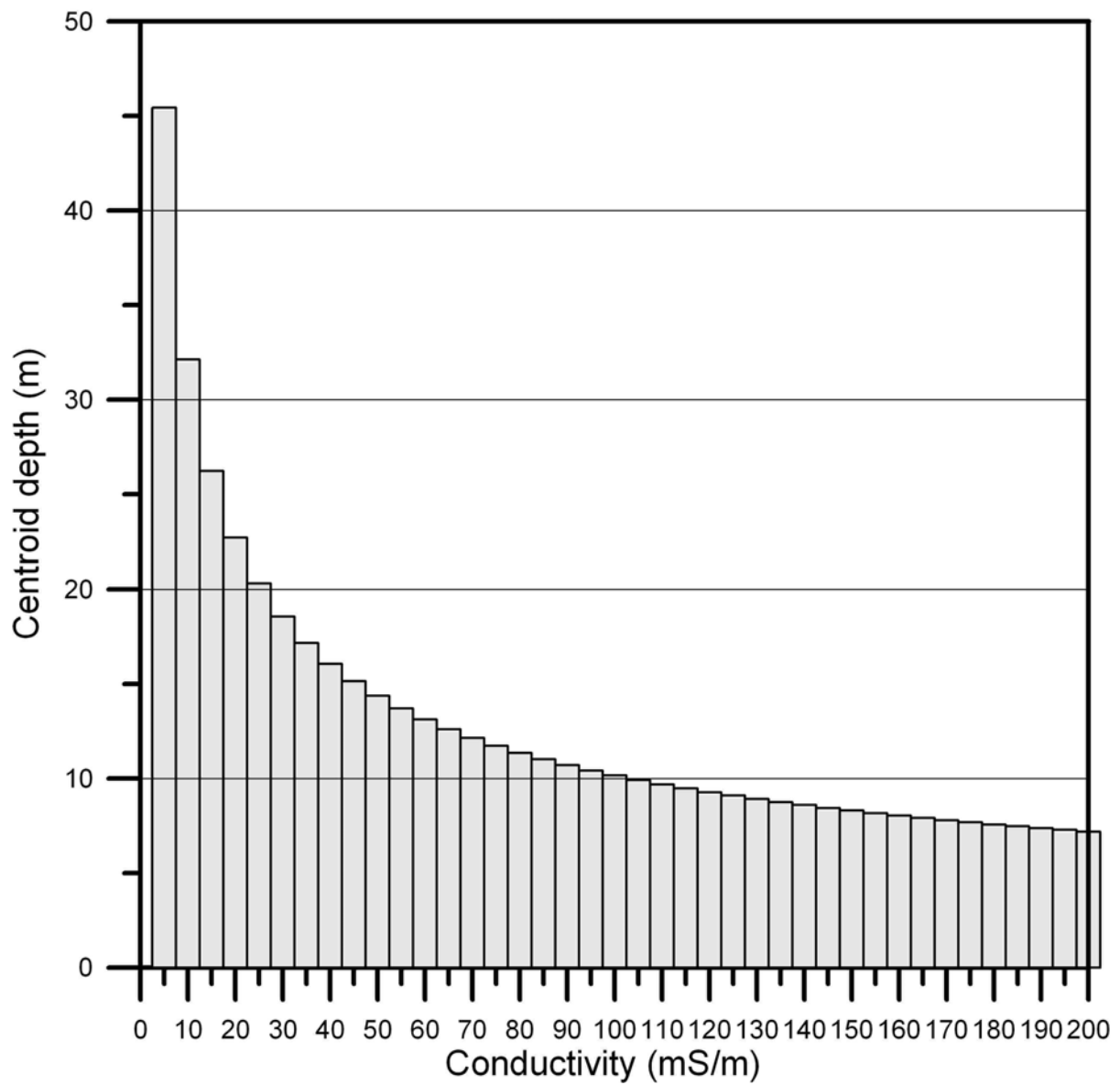
**Table 6.** Summary of geological bedrock formations and their areal extent within the test rectangle (150 x 136 km) across southern England.

Geological Period	Area (km <sup>2</sup> )	% of Total Area
Devonian	0.15	0.0009
Carboniferous	0.44	0.006
Triassic	11.0	0.09
Jurassic	2255.7	13.8
Cretaceous	9122.8	56.0
Palaeogene	4906.7	30.1

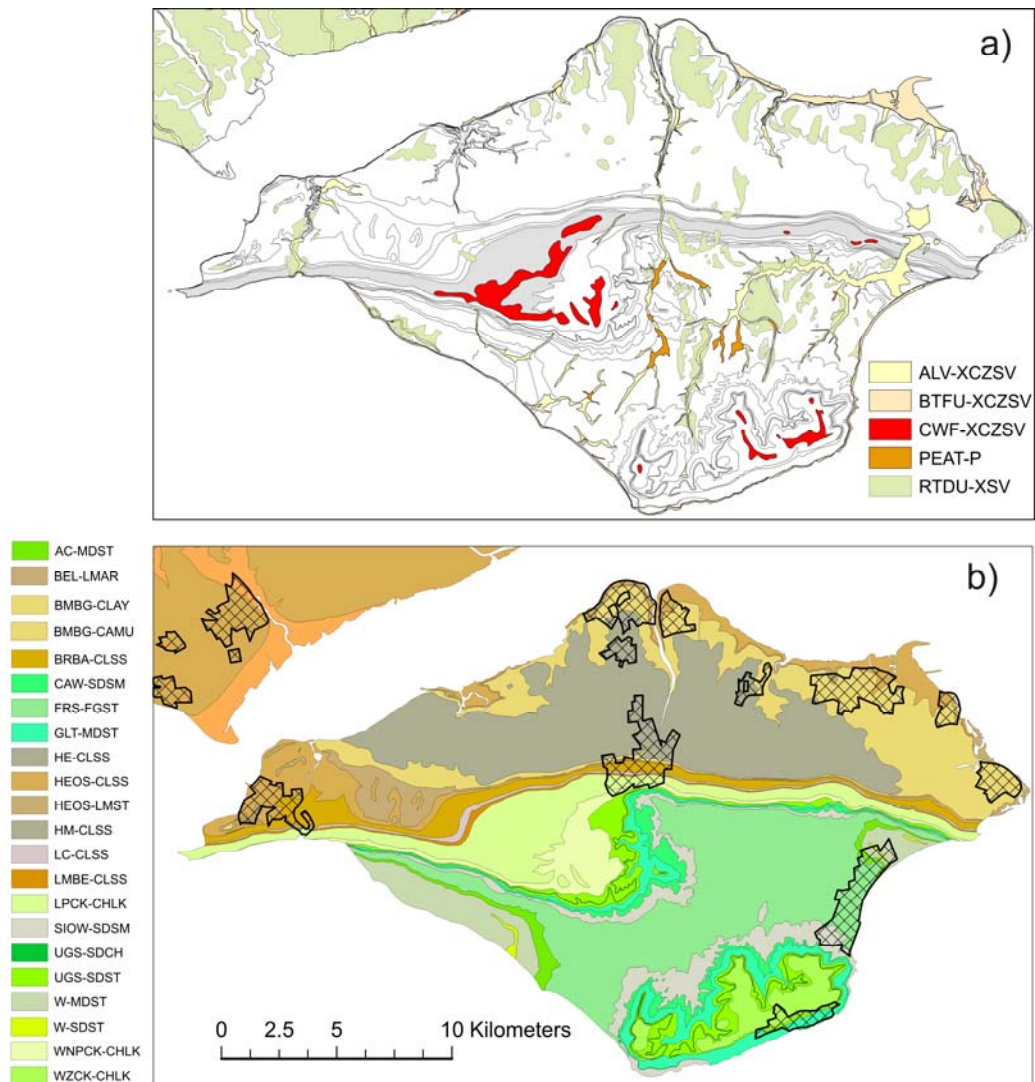


**Figure 1.** Image of the gridded apparent conductivity data obtained at 25 kHz with the geological line-work (LEX-RCS) superimposed. Black zones denote urban/fly-high areas. Inset map shows location of survey rectangle off the south coast of England.

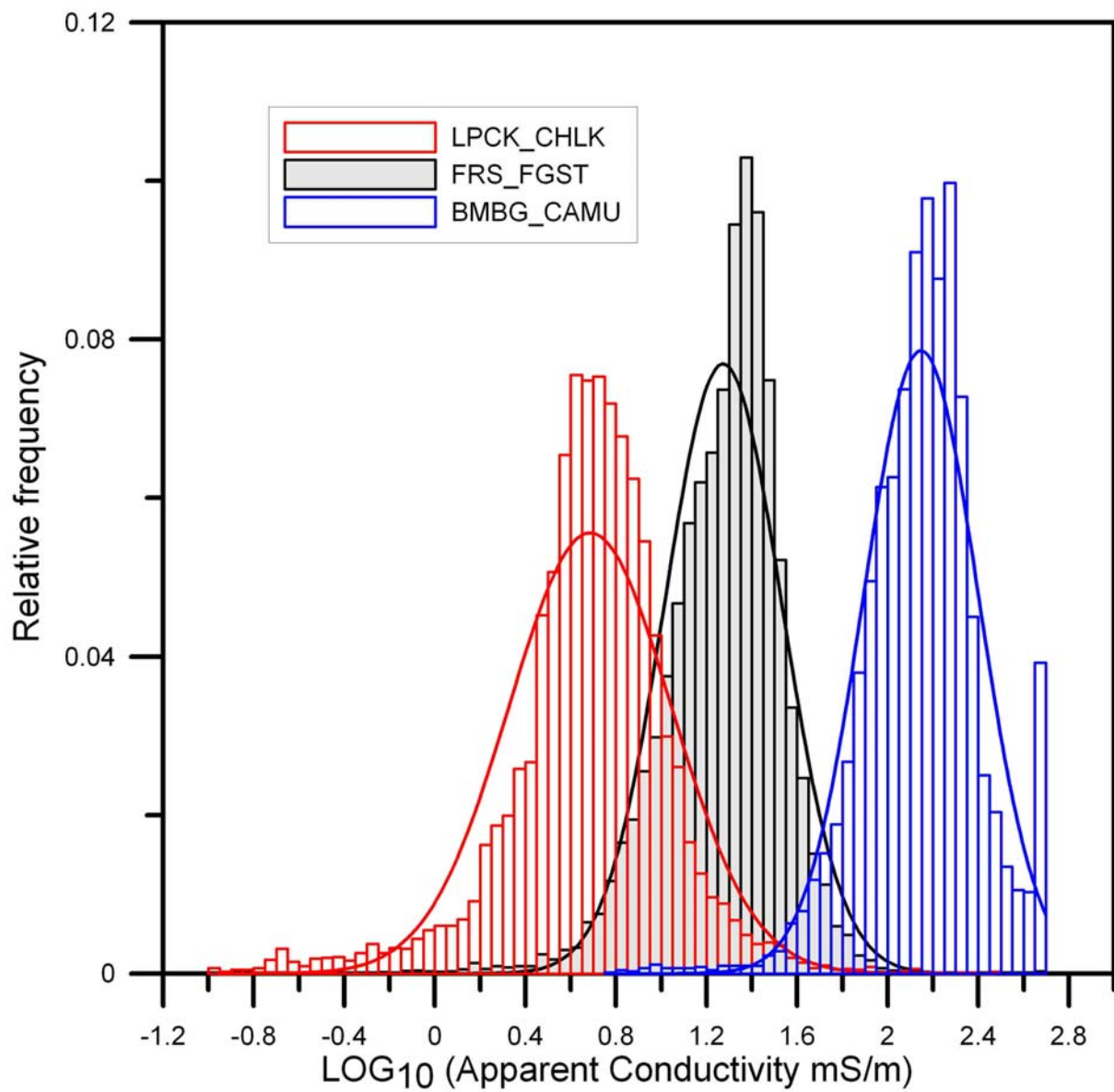




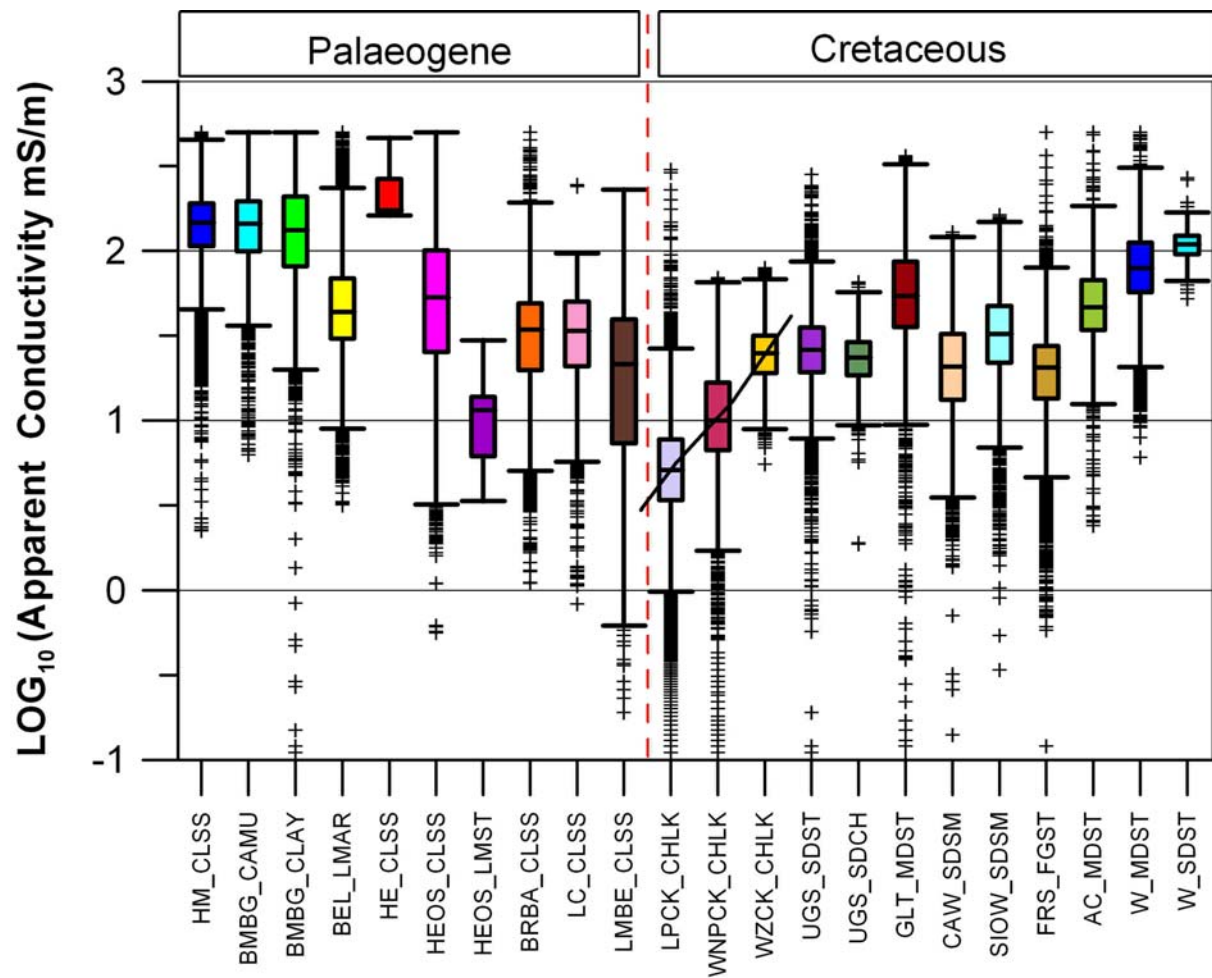
**Figure 2.** Electromagnetic centroid depths as a function of half-space conductivity.



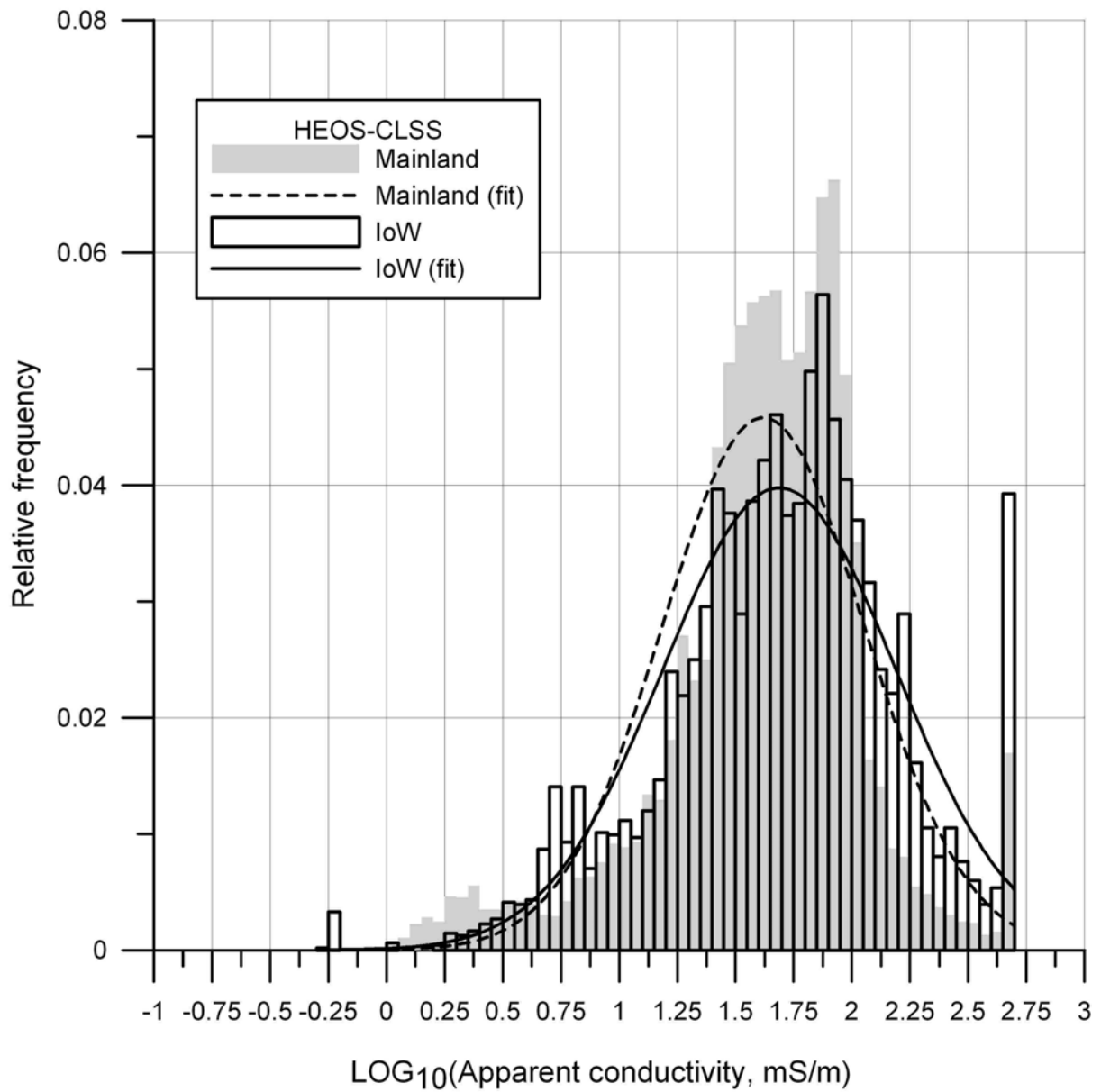
**Figure 3.** Geological maps across survey area. (a) Superficial deposit map with bedrock (LEX-RCS) line-work superimposed. See Table 1 for further details of the codes used. The Clay-with-flints formation (CWF) is highlighted in relation to the bedrock outcrop of the Upper Chalk (shown in grey). (b) Bedrock (LEX-RCS) map. See Table 3 for further details of the codes used. Urban areas are identified in cross-hatch.



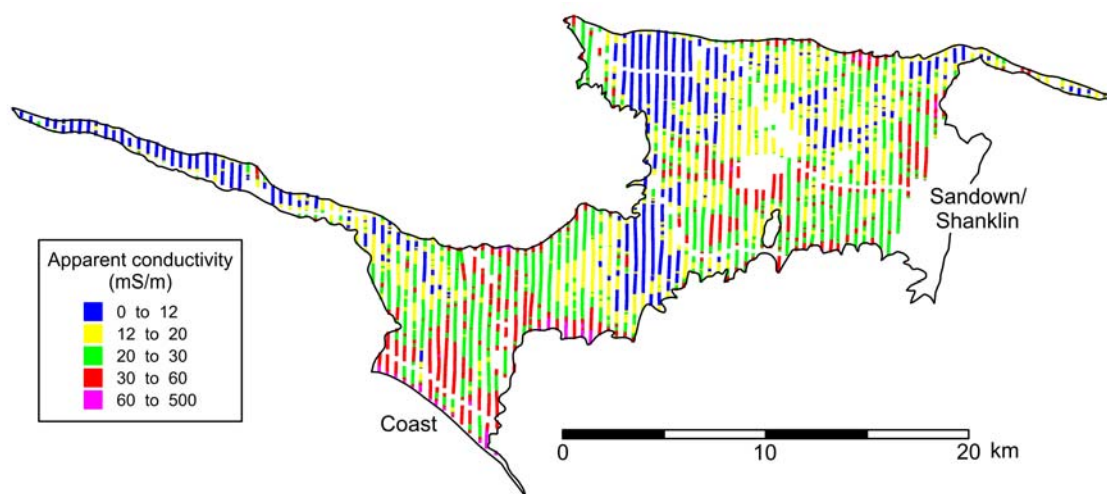
**Figure 4.** Normalised distributions of 25 kHz apparent conductivity (logarithmic scale) for 3 bedrock formations. Upper Chalk (LPCK-CHLK), Lower Greensand (FRS-FGST) and the Bembridge Marls (BMBG-CAMU). The best-fitting normal distributions are also shown.



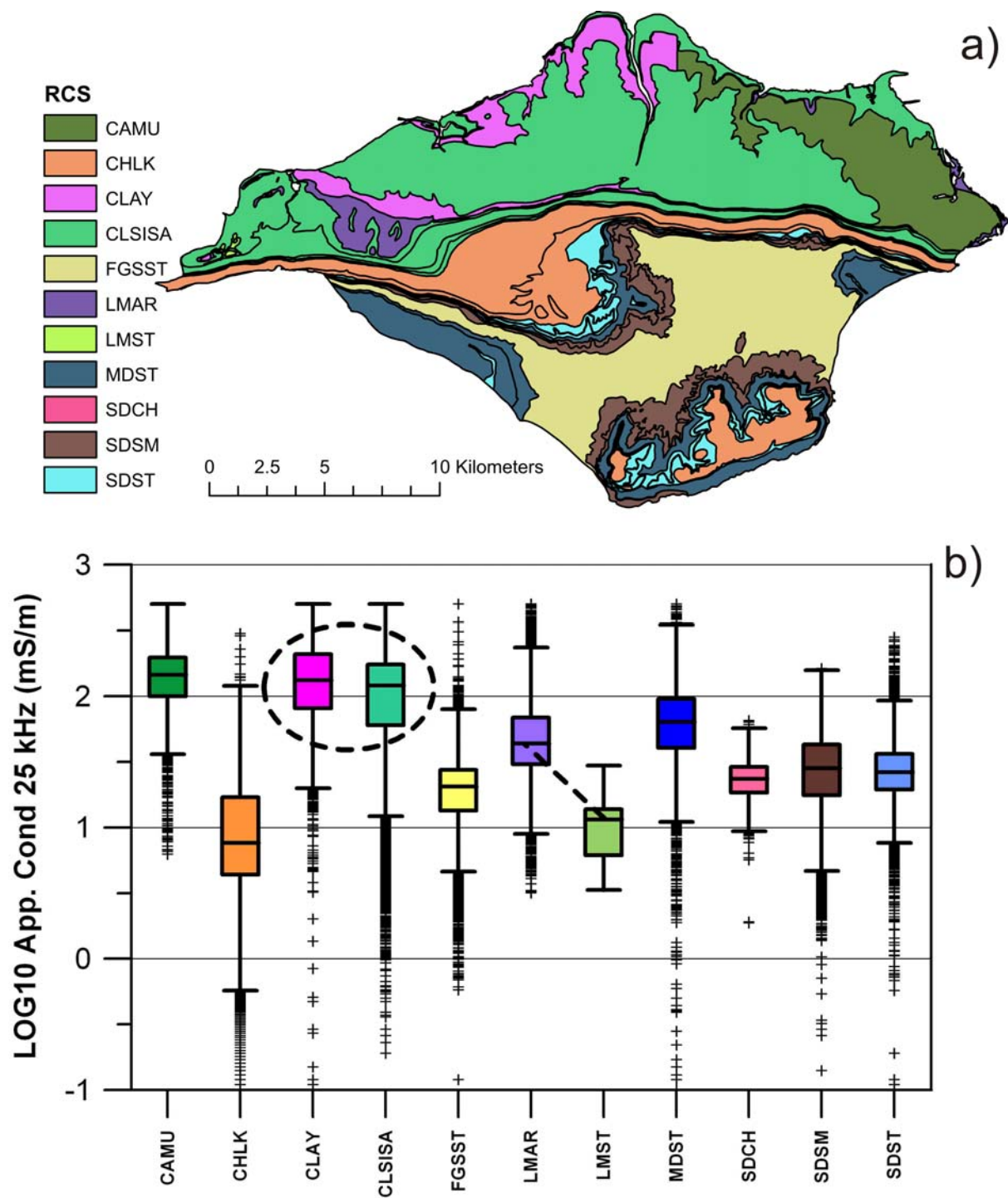
**Figure 5.** Box and whisker plot summarising the statistical behaviour of the 25 kHz apparent conductivity values (logarithmic scale) classified according to bedrock (LEX-RCS) geology. See Table 3 for details of the codes used. A trend, of increasing conductivity with increasing age, across the three Chalk units is indicated.



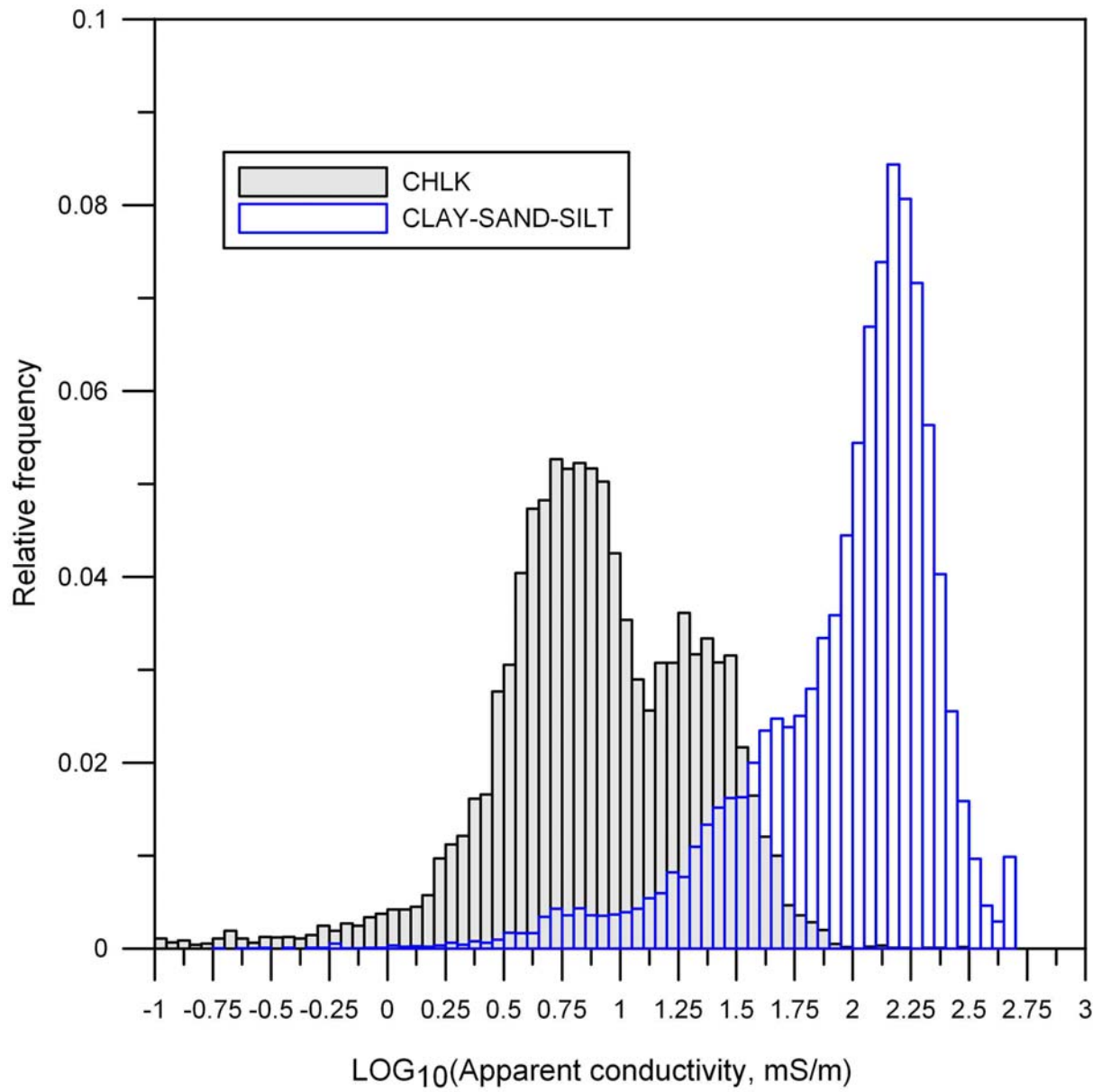
**Figure 6.** Normalised distributions of 25 kHz apparent conductivity (logarithmic scale) for the same bedrock formation, the Headon and Osborne Beds (HEOS-CLSS) obtained on the mainland and on the loW. The best-fitting normal distributions are also shown.



**Figure 7.** The 25 kHz apparent conductivities within the Lower Greensand Formation (FRS-FGST). Posted values of apparent conductivity using a 5-range classification.

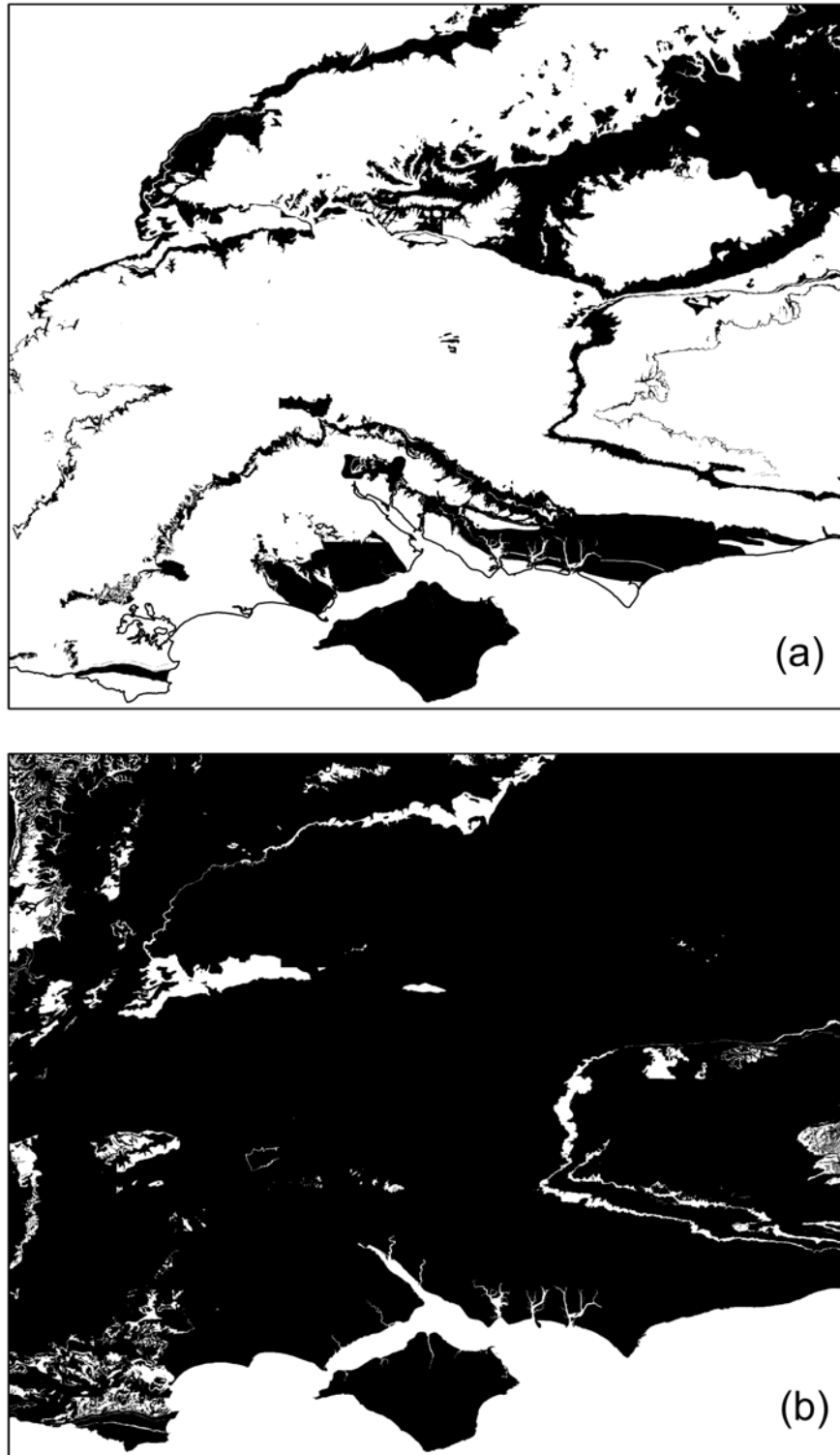


**Figure 8.** (a) Lithological (RCS) units observed on the IOW. Detailed descriptions of the codes are given in Table 4. (b) Box and whisker plot summarising the statistical behaviour of the 25 kHz apparent conductivity values (logarithmic scale) classified according to bedrock (RCS) geology. See Table 4 for details of the codes used. Dotted lines are referred to in the text.

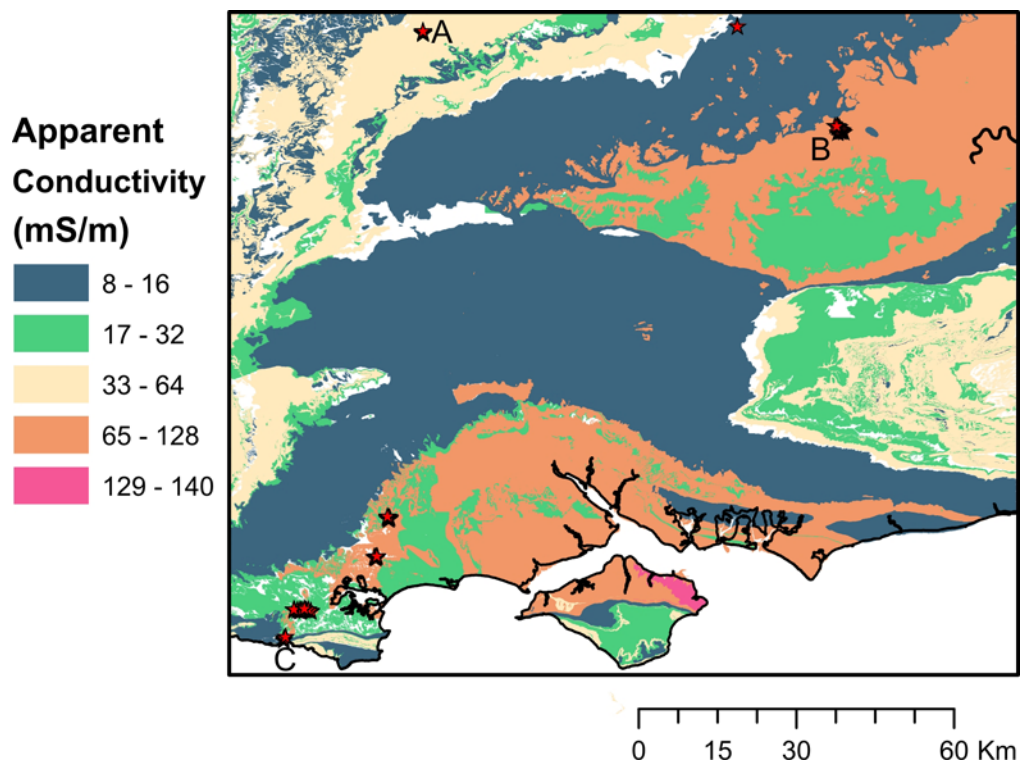


**Figure 9.** Normalised distributions of 25 kHz apparent conductivity (logarithmic scale) for two bedrock RCS lithologies, the CHLK and CLAY-SAND-SILT formations.





**Figure 10.** Area within test area rectangle (150 x 136 km) sampled by (a) a lithostratigraphical (LEX-RCS) classification and (b) a lithological (RCS) classification. Sampled area is in black.



**Figure 11.** Near-surface, bedrock apparent conductivity distribution across test area (150 x 136 km) obtained by a lithological (RCS) attribution scheme. Onshore white areas denote no data. The red stars identify the locations of the available VES soundings from the UK national database. The location of three of the clusters are identified as A, B and C and discussed in the text.