A geological and hydrogeological assessment of the electrical conductivity information from the HiRES airborne geophysical survey of the Isle of Wight

David Beamish and James C. White

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

Published in PGA, Special Issue, November 2011

Proceedings of the Geologists' Association 122 (2011) 800–808

Corresponding author:

David Beamish (dbe@bgs.ac.uk)

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

Tel: +44(0) 115 936 3432

Fax: +44(0) 115 936 3437

Email: dbe@bgs.ac.uk

Keywords: airborne geophysics, electromagnetic, conductivity, Isle of Wight, bedrock geology, aquifer

Right running head: electrical conductivity IoW

ABSTRACT

A recent high resolution airborne geophysical survey across the Isle of Wight (IoW) and Lymington area has provided the first electromagnetic data across the relatively young geological formations characterising much of southern England. The multi-frequency data provide information on bulk electrical conductivity to depths of the order of 100 m. A GIS-based assessment of the electrical conductivity information in relation to bedrock geological classification has been conducted for the first time. The analysis uses over 104,000 measurements across onshore IoW and has established average and statistical properties as a function of bedrock geology. The average values are used to provide baseline maps of apparent electrical conductivity and the variation with depth (measured as a function of frequency). The average conductivity as a function of depth within the main aquifer units is summarised. The data indicate that the majority of the Palaeogene is characterised by values consistently in excess of 100 mS/m and with a surprisingly high degree of spatial heterogeneity. The youngest (Oligocene) Hamstead Member displays some strong edge effects and the largest localized values in conductivity. The central Upper Chalk is associated with the lowest observed conductivity values and, unexpectedly, mineral content and/or porosity appears to increase with decreasing age. The large central outcrop of the Lower Greensand Group, Ferruginous Sand Formation provides persistently low (< 30 mS/m) conductivity values which imply a relatively uniform distribution of clean sand content. Non-geological (e.g. environmental) responses are contained within the data set and examples of these in relation to a closed municipal landfill and an area of potential coastal saline intrusion are discussed. In the south, the Gault clay/mudstone of the Early Cretaceous appears as a distinctive conductive unit. Cross sectional modeling of the data has been undertaken across the aquifer units of the Southern Downs. The results indicate that the Gault Formation, acting as an aquitard, can be traced as a distinct unit under the more resistive Early Cretaceous Upper Greensand and Late Cretaceous Chalk formations. The conductivity modeling should therefore allow an estimation of the subsurface configuration of the aquifer and aquitard units.

1. Introduction

A number of modern, high-resolution, multi-parameter geophysical surveys have been conducted over the past decade across onshore UK (Peart et al., 2003; Beamish and 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 present study considers the airborne electromagnetic (AEM) data set acquired over the Isle of Wight (IoW) and part of the Lymington area (location map in Figure 1) in 2008.

One of the main uses of AEM data worldwide is in relation to resource and, in particular, mineral exploration. In the UK context, the HiRES AEM data set across Northern Ireland has been used to reassess Early Palaeozoic geological structure (Beamish et al., 2010a). The utility of the AEM data arises due to the conductivity contrasts generated by the largely concealed carbonaceous mudstones of the Moffat Shale Group; an analogous situation arises on the IoW in relation to the conductive Gault Formation. The HiRES AEM UK data sets have, however, largely supported and emphasised environmental assessments. This stems from the sensitivity of the measurement to pore fluid conductivity (discussed later) and the enhancements made to this by site specific concentrations of total dissolved solids (TDS).

The ability of the data to detect subsurface TDS enhancements and their movement in association with typical UK environmentally sensitive zones (e.g. former industrial sites, coal-mine spoil and both open and closed landfills) has been described previously (Beamish, 2003, 2004a). The impact of colliery spoil zones across the Permo-Triassic aquifer of Nottinghamshire has been described by Beamish (2003) and Beamish and Klinck (2006).

When compared to the industrial legacy issues contained within the other HiRES survey areas, the IoW is a relatively clean area in terms of heavy industry. One of the more significant local environmental pressures is in relation to the groundwater bodies largely contained within the Chalk Group , Upper Greensand Formation and Lower Greensand Group. The sustainable use of groundwater resources on the island continues to be challenging as described in recent publications (e.g. Entec, 2008). The

IoW AEM data set provides a framework for investigating the bulk electrical properties of all the formations to depths of the order of 100 m.

The baseline classification of the electrical properties of UK geological formations using HiRES AEM data has yet to be consolidated. The Palaeogene and Cretaceous bedrock formations encountered on the IoW (Figure 1) are some of the youngest lithologies to be assessed by the HiRES surveys. Since the lithologies are also representative of much of the southern mainland of England, the new information afforded by the electromagnetic survey is of wider relevance.

A Geographical Information System (GIS) based approach has been adopted in order to arrive at an assessment of the baseline data (e.g. the statistical averages for each of the formations) together with their variations across individual formations. The investigations are particularly relevant since the properties of the Palaeogene formations are found to be totally distinct in relation to the older and less conductive Cretaceous formations. As anticipated, the Chalk units provide some of the lowest conductivities but, unexpectedly, display a progressive increasing conductivity with age.

2 Location and survey details

The Isle of Wight is England’s largest island; situated off the south coast of Hampshire and it offers a diverse range of geology for an area of its size (380 km^2). In 2008 the island was surveyed in 10 flying days as part of the HiRES airborne geophysical program. The acquisition parameters and processing procedures applied to the Isle of Wight HiRES survey are described in Beamish and Cuss (2009) and White et al. (2009). A review of the Isle of Wight HiRES survey parameters is provided in Beamish and White, *this issue*, but it is worth repeating that the data were collected with 200 m line separations along a N-S direction, although along-line sampling of the electromagnetic field is about every 15 m. The sampling of the electromagnetic data across the 36 x 22 km survey area provided 289,068 measurements at each of the 4 frequencies of the AEM system.

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 and Freshney, 1982). The two zones are divided by the east-west trending chalk beds of the late-Cretaceous. The youngest identified bedrock unit on the island is the Oligocene succession of the Hamstead Member (HM-CLSS, Figure 1).

The main component of the present study comprises an assessment of the electrical conductivity information obtained from the AEM measurements in relation to the current 1:50 000 scale digital data for bedrock geology (BGS, 2008). The 22 bedrock units, together with the rock lexicon codes used here are shown in Figure 1. The map also shows polygons (in cross-hatch) that identify the major urban areas and a series of contours (in red) within which the survey altitude was greater than 100 m. The central vertically elongate ellipse is due to the avoidance of a major mast, and this zone forms a small hole in an otherwise uniform data set.

It is worth remarking that the complete survey rectangle (36 x 22 km) contains a large extent of seawater. The magnetic component of the survey is unaffected by water bodies however the conductivity of seawater is excessively high with respect to geological materials. The precise value of seawater conductivity is a function of salinity and temperature; a typical value for offshore IoW would be in excess of 3000 mS/m. When only onshore electromagnetic data is assessed across the IoW, the number of available EM measurements (IoW only) is reduced to 126,292.

3 The electromagnetic (conductivity) data

The four frequency EM system used on the survey is described in detail by Leväniemi et al. (2009). The four frequencies (0.9, 3, 12 and 25 kHz) provide depths of investigation which decrease with increasing frequency. The EM data acquired at 0.25 second intervals comprise the coupling values of secondary to primary field ratios at individual frequencies. 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 transform (Fraser, 1978). Inversion procedures may also be used to estimate the half-space conductivity (Beamish, 2002a,b). Such estimates are models with a validity that depends on a vertically uniform, one-dimensional (1D) assumption. The 4 frequency mapping and geological classification procedures applied here are based on an accurate implementation of the Fraser transform.

3.1 Conductivity Assessments

Geophysical measurements provide volumetric estimates of total formation conductivity σ_t or its reciprocal, resistivity ρ_t. The volumes involved in the airborne case are discussed below. 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/hydrogeological setting. It has long been established that the formation resistivity (ρ_t) of a clean (a rock matrix that is perfectly insulating) saturated formation is proportional to the conductivity (σ_f) of the fluid. The constant of proportionality is referred to as the formation factor (FF):

$$FF = \sigma_f / \sigma_t \qquad \ldots(1)$$

In practice, even the cleanest formations contain small amounts of clay, or mudstone bands, which can exert a significant influence on σ_t. Assuming negligible clay content, an empirical relationship developed by Archie (1942) indicates the bulk material conductivity is related to pore fluid conductivity (σ_f) and fractional porosity (ϕ) as:

$$\sigma_t = a' \sigma_f \phi^m \qquad \ldots(2)$$

where a' is an empirically determined constant. The exponent m is also an empirically determined parameter that depends on the geometric factor of grain shape and packing (typically in the range 1.2–2.0). More recently, effective medium models (Berg, 2007) have successfully described conductivity-porosity and saturation relationships, without the constraint of a non-conducting, fully saturated matrix inherent in Archie's approach. In the near-surface, with materials displaying similar porosities and saturations, clay content is often the most significant factor in determining the bulk conductivity.

It is important to understand that each AEM measurement is a volumetric average of the bulk subsurface conductivity. The lateral and vertical distances involved are technically complex (Beamish, 2004b) but are typically contained within a central area of sensitivity of less than 100 x 100 m over the ground surface. Each AEM measurement may then estimate electrical conductivity over a subsurface volume of over 60,000 m^3 (Beamish, 2004a).

3.2 Data conditioning

The conductivity of sea-water is far in excess of that arising from geological materials and the IoW data set is first restricted to onshore data values only (the data set is cut to the coast). The airborne EM data acquired is also subject to a range of non-geological perturbations and localized cultural interferences. Many of these perturbations are large amplitude and positively-biased i.e. they produce high conductivity outliers in the data distributions. The data set used in this analysis has been limited (clipped) to a maximum value of 500 mS/m. The airborne EM data may also be less reliable in urban areas because a significant proportion of the ground area is covered by a variety of structures, and the flight altitude is in excess of 200 m compared with about 56 m over rural areas. In the following analysis the data set has first been restricted to locations where the survey altitude is less than 100 m. This condition also has the equivalent effect of restricting the data set over urban areas (e.g. Figure 1). The condition produces gaps in the survey coverage. The road network and associated service routes may also produce low amplitude, localised perturbations to the EM data. Using a GIS-based approach, a pre-existing road network route was used to define a buffer zone (150 m of data exclusion around A and B-roads) to enable a cut procedure to be applied to the data set. The resulting gaps in the data coverage may be subsequently reconstituted by interpolation when gridding procedures are applied. The conditioned data set comprises 104,704 measurements.

3.3 Survey Results

The half-space apparent conductivity data are first summarised in terms of colour images obtained from natural-neighbour grids obtained at a cell size of 50 x 50m. The grids have been determined using the conditioned data set described above. Four images are produced; one for each frequency. Figure 2 shows the results obtained at the two lowest frequencies of 0.9 and 3 kHz using the same linear scale of conductivity. Shaded-relief is applied from the NW to emphasise gradients. The urban centres are identified by black zones. The lowest values in the gridded data are 0.7 mS/m (0.9 kHz) and 0.4 mS/m (3 kHz). Maximum values, due to the data conditioning, are both 500 mS/m and the data ranges span over three orders of magnitude. Even with the data conditioning applied a range of localised cultural perturbations exist within the data set. The residual cultural interference generally increases with decreasing frequency i.e. its influence is greatest at the lowest frequency.

The conductivity data provide both structural edge information and, at the broader scale, an assessment of the intrinsic conductivity of the geological formations. It is very evident that the Palaeogene in the north is characterised by values consistently in excess of 100 mS/m and a surprisingly high degree of spatial heterogeneity. The youngest (Oligocene) Hamstead Member (HM-CLSS) displays some strong edge effects and the largest localized values in conductivity. The LEX-ROCK codes identified on the geological map of Figure 1 are also shown alongside formation names in Table 1.

The central Upper Chalk unit (LPCK-CHLK) is associated with the lowest conductivity values across all geological formations. The older Chalk sequences (WNCK-CHLK and WZCK-CHLK) appear to be slightly more conductive and this implies a degree of increased mineral content or reduced porosity. The extensive Lower Greensand Group, Ferruginous Sand Formation (FRS-FGST) within the

Cretaceous is also associated with low conductivity values. Since these units contain a major portion of the groundwater resources on the IoW, the low amplitude spatial variations in the conductivity that are detected may have special relevance. The Atherfield Clay Formation (AC-MDST) together with the adjacent Wealden Group (W-MDST and W-SDST) display the highest conductivities within the Cretaceous. In the centre and south of the images, the Upper Greensand Formation (UGS-SDST and UGS-SDCH) together with the Gault Formation (GLT-MDST) are also associated with conductive responses. The lowest frequency data provide the deepest assessments, well below surface outcrop. The highest frequency data (25 kHz) are more readily associated with outcrop features. Figure 3 shows the conductivity data for 25 kHz with the geological line work defined by the currently available 1:50,000 scale bedrock geology. The linear colour scale is the same as that used previously. Shaded relief has been omitted for clarity. The image confirms that the localized, high conductivity features evident in the Hamstead Member (HM-CLSS) are continuous across adjacent formations (e.g. in the east). The Bembridge Marls (BMBG-CAMU and BMBG-CLAY) are associated with a decline to lower ambient conductivities within the Palaeogene in the west.

Within the Cretaceous formations, the high conductivities of the Wealden Group (W-MDST and W-SDST) are associated with a high degree of heterogeneity and significant variations are detected across the outcrop. The 25 kHz data provide a much clearer association of localized elevated conductivities within the thin outcrops of the Gault Formation (GLT-MDST), in the centre and south of the image in Figure 3 (see also Figure 1). The ability of the data to map the subsurface distribution of this unit is discussed later. The large central outcrop of the Lower Greensand Group, Ferruginous Sand Formation (FRS-FGST) provides persistently low conductivity values that continue to depth (Figures 2 and 3). This is indicative of a relatively uniform distribution of clean sand content. Within the low values recorded there are however some intriguing large scale features resolved and these are modified with depth/frequency. The 25 kHz image reveals an arcuate soft edge feature extending over 8 km in the northern area of the outcrop. The information has relevance to the internal properties of the Lower Greensand aquifer.

Being a coastal survey, there is also potential for a consideration of the conductivity data in relation to saline intrusion. The most obvious potential feature detected in relation to this issue is the high conductivity zone extending inland from Bembridge Harbour (BH, Fig. 3) in the east and following the course of the eastern river Yar (Yar, Fig. 3) beyond the village of Brading. The high conductivity continuous feature is also clearly visible across the Chalk escarpment further to the south-west. Potential zones of saline intrusion are the subject of more detailed ongoing studies.

When considering the information as half-space conductivity values at the four measurement frequencies, it is useful to consider the depths of investigation involved. These depths are quite complex and depend on the vertical conductivity distribution as well as frequency and altitude. The information is reviewed as part of the detailed geological assessment considered below

4 Geological Classification of the conductivity data

One of the purposes of this study is to summarise the conductivity data in terms of the young geological bedrock formations found on the IoW. Superficial deposits are not extensive on the IoW but could be included in an equivalent assessment. The methodology used here is GIS-based, and to our knowledge the procedure adopted has not been previously used on airborne conductivity data sets.

The 1:50 000 scale digital data for bedrock geology: DiGMap-GB50, BGS (2008) is shown in Figure 1. The 22 bedrock units, and their lexicon codes are described in Table 1; a more extensive lithological description of the units is provided by Beamish and White, 2010, *this issue*. The geological polygons were attributed with the apparent conductivity data at each of the 4 frequencies. The procedure enables a statistical assessment of the conductivity data according to geological classification. The analysis uses the 104,704 measurements of the conditioned data set.

Table 1.

Medians of conductivity-bedrock classification analysis for each of the four frequencies. AC refers to Apparent Conductivity and the associated numbers are measurement frequencies in kHz.

LEX_ROCK	NAME	No.data	AC 0.9 (mS/m)	AC 3 (mS/m)	AC 12 (mS/m)	AC 25 (mS/m)
HM-CLSS	Hamstead Member	23951	170	154	118	146
BMBG-CAMU	Bembridge Marls	7108	141	123	113	145
BMBG-CLAY	Bembridge Marls	4758	170	161	145	133
BEL-LMAR	Bembridge Limestone	8679	106	94	58	43
HE-CLSS	Headon Formation	20	207	210	210	174
HEOS-CLSS	Headon and Osborne Beds	4839	87	76	66	53
HEOS-LMST	Headon and Osborne Beds	85	52	39	22	11
BRBA-CLSS	Bracklesham Group	3592	59	46	38	34
LC-CLSS	London Clay	983	55	41	36	34
LMBE-CLSS	Lambeth Group	660	45	32	22	21
LPCK-CHLK	Upper Chalk (White)	8621	13	4	6	5
WNCK-CHLK	Middle Chalk	3521	34	17	13	10
WZCK-CHLK	Lower Chalk (Grey)	3017	41	26	22	25
UGS-SDST	Upper Greensand	5288	85	57	28	26
UGS-SDCH	Upper Greensand	432	91	61	26	24
GLT-MDST	Gault	4242	63	64	48	54
CAW-SDSM	Carstone (Monk's Bay Sandstone Formation)	2840	36	32	20	21
SIOW-SDSM	Sandrock	5184	35	33	28	32
FRS-FGST	Lower Greensand Group(Ferruginous Sands)	18546	29	23	18	21
AC-MDST	Atherfield Clay	965	135	86	75	46
W-MDST	Wealden	3156	151	116	77	79
W-SDST	Wealden	110	165	126	108	109

It is evident from Table 1 that the lowest conductivity medians are associated with the Chalk formations with the Upper Chalk (LPCK-CHLK) recording the lowest values. The Headon Formation (HE-CLSS) is sampled at only 20 points (in two separate zones) and the result obtained may not be statistically significant. In the Palaeogene succession, the Bembridge Marls (BMBG-CAMU and BMBG-CLAY) with a high clay content record large values together with the extensive Hamstead Member (HM-CLSS).

The geological classification of the data is shown graphically in the box-whisker plots of Figure 4. The analysis provides one such plot for each of the four frequencies. Only the results for 2 frequencies (3 and 25 kHz) are shown since similar characteristics are repeated in the results for the other 2 frequencies. A logarithmic (base 10) axis is used as the ordinate since data values span several orders of magnitude.

In these plots, the box with infill indicates the first and third quartiles of each distribution with the enclosed bar denoting the median value. The terminating bars denote the range of the data and the discrete symbols indicate outliers. It should be noted the majority of the distributions are non-normal. A number of the distributions are closer to log-normal however the majority of distributions have excessively long high value tails, terminating in the limiting value of 500 mS/m. The complex behaviour reflects the high degree of cultural interference that remains within the data set. The medians of the analysis provide a useful summary of the bulk electrical properties of each formation. Some of the limiting (high/low value) conductivity behaviour of the formations has already been described and Figure 4 further reveals that trends are more apparent in the Cretaceous than the Palaeogene. Within the Palaeogene, the successive London Clay (LC-CLSS) and Bracklesham Group (BRBA-CLSS) formations provide equivalent results between 34 and 60 mS/m. When examining the results shown in Figure 4, the small number of data points involved in some of the estimates (e.g. HE-CLSS and HEOS-LMST) should be noted. Progressive behaviour with age is observed across the Chalk units with conductivities unexpectedly increasing with age through the sequence as indicated in Figure 4. In a similar manner, increasing values of conductivity with age are observed through the Lower Greensand (FRS-FGST) to the Wealden Formation (W-MDST and W-SDST), as indicated in Figure 4.

4.1 ANOVA analysis

The information on the ability of the conductivity data to discriminate geological bedrock units can be further analysed using an analysis of variance (ANOVA). The ANOVA model operates by comparing the amounts of dispersion in each of the groups to the total amount of dispersion in the data. The ANOVA analysis tests the hypothesis that the means of two or more of the populations are equal. The ANOVA results indicate that across all 22 geological formations the percentage of the apparent conductivity data variability that can be explained by bedrock geology is remarkably high and is 58% (0.9 kHz), 60% (3 kHz), 48% (12 kHz) and 52% (25 kHz).

4.2 Baseline apparent conductivity maps

The geological classification of the conductivity data provided statistical average behaviours which can be used to generate new baseline conductivity maps for the IoW. Such maps also provide a summary of the analysis conducted. The conditioned data set used in the analysis contains gaps and holes due to the altitude condition applied. These omitted zones are now populated with their associated bedrock mean values. Figure 5 shows two examples of the new baseline apparent conductivity maps produced. Figure 5a shows the results at 0.9 kHz which provides the deepest ranges of investigation depths and Figure 5b shows the results at 25 kHz with the shallowest range of investigation depths, closest to outcrop. A slight amount of shaded-relief has been applied to reveal the bedrock boundaries; the degree of shade increases with conductivity contrast. The images summarise the behaviour of the average electrical properties of the bedrock formations with frequency/depth. Thus the extensive outcrop of the Lower Greensand Group (FRS-FGST) shows little variation with depth while the Palaeogene formations in the west display significant increases with depth.

4.3 Depths of investigation and average behaviour in aquifer units

The volume (i.e. the lateral and vertical dimensions) of the subsurface involved in each measurement is quite complex since it depends both on altitude and the conductivity of the subsurface. Beamish (2004b) describes the volumetric footprints (skin-depths) of the airborne system used here. To provide a measure of the depths of investigation we apply the modified half-space inversion model introduced by Beamish (2002b) and use the results to calculate centroid depths (Siemon, 2001). Centroid depths can be regarded as the mean depth of the in-phase current system at each frequency; they do not constitute maximum depths of investigation. Following the geological classification considered above we used the inversion results to calculate the statistics and means of the centroid depths for each bedrock formation. The results are summarized in Table 2 using one of the most conductive formations of the Palaeogene (the Hamstead Member, HM-CLSS) and the most resistive formation (the Upper Chalk, LPCK-CHLK). Other depths of investigation will typically fall within the limiting values of Table 2.

Table 2

Depths of investigation (centroid depths in m) obtained as mean values across the conductive Hamstead Beds (HM-CLSS) and the resistive Lower Chalk (LPCK-CHLK) for the four frequencies.

	0.9 kHz	3 kHz	12 kHz	25 kHz
HM-CLSS	24	16	9	8.5
LPCK-CHLK	118	104	26	25

As can be seen there is a considerable variation with frequency, but more significantly, with the conductivity of the formation (see Table 1). The geological classification of the conductivity data can also be used to construct and compare the depth dependence of the average apparent conductivity of individual formations. Figure 6 shows the properties of the 5 bedrock classifications making up the main aquifer units (the Upper and Lower Greensand and the three Chalk units). The Upper Chalk (LPCK-CHLK) and Upper Greensand (UGS-SDST) clearly form distinct and limiting behaviour, while the Lower Greensand (FRS-SDST) shows behaviour closest to that of the Middle Chalk (WNCK-CHLK).

5 Localised conductivity mapping

As discussed previously, the IoW EM data set, even after conditioning, retains a range of localized non-geological perturbations. In cases where the response is not simply due to a noise source (e.g. radiation or cultural coupling), the behaviour can be investigated in detail, to provide further subsurface assessments. Here we consider a small, 1.5 x 1.5 km area in the vicinity of a former municipal landfill. The location of the landfill, to the east of Newport, is shown in Figure 1. We have no specific technical information on the history of the Lynnbottom site considered here nor the number and location of disposal cells. The mapping of the conductivity information at this site is assisted by the addition of five further survey lines which were acquired to allow a limited zone of 100 m spaced lines to be obtained.

The 1.5 x 1.5 km study area, largely confined to the conductive Palaeogene Hamstead Member (HM-CLSS) , is shown in Figure 7. The area shown is covered by BNG Eastings from 452500 m to 454000 m and by BNG Northings from 8800 m to 89500 m. The information is shown as a 3D perspective view with the relief provided by an accurate 5 x 5 m resolution DTM. The survey lines and AEM measurement points are shown as discrete symbols. Figure 7a uses an Ordnance Survey (1:50k) topographic map and the apparent conductivities at the highest frequency of 25 kHz are shown contoured. Due to high background conductivities the contours shown are values greater than 100 mS/m. In Figure 7a, we observe 4 zones with only the two southernmost areas showing values in excess of 200 mS/m. It is a matter of interpretation as to whether the elevated conductivities are associated with shallow geological and/or artificial sources. With decreasing frequency (increasing penetration depth), only the two main southernmost areas are found to retain elevated conductivities. This is indicated in Figure 7b which uses an orthorectified aerial photograph together with contours of the 3 kHz apparent conductivities. The detailed mapping information obtained is indicative of the identification of 2 zones of leachate accumulation. The two zones display features that indicate attenuation of bulk conductivity with depth and the zones appear laterally compact. Further modelling/inversion of the four frequency data set would better indicate the degree to which vertical migration/attenuation is taking place.

6 Conductivity models

The assessments of the data thus far have involved the mapping capabilities of the 4 frequency information. The 4 component EM data can also be used to construct 1D models of the vertical conductivity distribution at each measurement location. Various multi-layer inversions have been used to provide 1D conductivity models for the IoW data. Some of the techniques involving few- and many-layer inversions of the AEM data have been described by Leväniemi et al. (2009) and by Beamish and Leväniemi (2010). The inversion of the 4 frequency data takes place along flight line profiles where the lateral sampling is high (~ 15 m). The 1D models may then be stitched together and used in a number of 3D visualisation packages. In the first instance, 1D Occam inversions (Beamish and Leväniemi, 2010) were undertaken to determine the broad resolution of the data and the continuity of the subsurface features. Initial model explorations of the complete data set are also required to assess the sea/land conductivity behaviour and the issue of high-fly zones (holes in the model data set) together with the influence of cultural noise on the data and the resulting models.

The layered inversion procedure used here is the one-dimensional inversion methodology referred to as Laterally Constrained Inversion or LCI (Siemon et al., 2009). The procedure performed here is a laterally constrained inversion using a small number of layers. The methodology and its application to two of the central areas on the IoW that include the resistive Chalk has been described by White and Beamish (2009). Here we consider a 5 x 5 km case study across the Southern Downs area which contains the Chalk and Upper Greensand aquifers. The area considered is covered by BNG Eastings from 452150 m to 457150 m and by BNG Northings from 76700 m to 81700 m.

In this area, the conductive Gault Formation clay unit (GLT-MDST), acting as an aquitard, forms a continuous boundary to the Upper Greensand Formation (UGS-SDST) at outcrop (Figure 1). The bedrock geology across the case study area is shown and identified in Figure 8a. The map has been rotated so that the abscissa (x-axis) is horizontal and along that of the N-S flight direction. The 6 bedrock units outcropping across the area are identified together with the median values of apparent conductivity at 25 kHz (values in brackets, from Table 1) are shown in Figure 8a. It is evident that 4 of the formations provide a relatively resistive environment (apparent conductivity < 30 mS/m) while the apparent conductivity of the Sandrock Formation (SIOW-SDSM) is slightly elevated (32 mS/m). Within this general context the Gault Formation (GLT-MDST) appears distinctly more conductive, by a factor of about two. The horizontal red line in Figure 8a identifies the location of the conductivity cross-section shown in Figure 8b.

In the perspective view of Figure 8b the bedrock geology across the area to the east of the cross-section (Fig. 8a) is shown draped on a DTM surface with vertical exaggeration (x3). The N-S conductivity cross-section is then shown draped below this surface, again with a high degree of vertical exaggeration (x10). The length of the cross-section is 5 km and the vertical extent of the cross section (depth below surface) is 100 m. The conductivity range in the colour bar is from 0 to 100 mS/m and conductivity values are no longer ‘apparent’ but represent a set of vertical distributions that best-fit the 4 frequency observations. In detail, the cross-section will inevitably contain elements of noise.

There are 3 outcrops of the Gault Clay along the cross section and each is associated with at- and near-surface conductivity values in excess of ~60 mS/m. We note that, in detail, the correspondence is not precise. Given the context however, we would argue that the high conductivity values (in excess of 60 mS/m) should be associated with the Gault Formation . The three outcrops appear then to be associated with three southerly-dipping zones which are isolated from each other and which show a progressive thickening and deepening to the south. Along the chosen cross-section, the resistive units would then largely represent the configuration of the Upper Greensand aquifer. To the north of the Gault/Upper Greensand outcrop a vertically-compact, localized near-surface conductive zone shows a degree of correspondence with the outcrop of the Sandrock Formation (SIOW-SDSM). It should be appreciated however that both the at- and sub-surface configurations of both geological and conductivity units are likely to be fully three dimensional and our assessment of the conductivity distribution is inherently only one-dimensional.

7 Summary

This study has presented and considered the high resolution AEM survey data acquired across the IoW. The main purpose of the present study has been to provide a geological assessment of the electrical conductivity information in the near-surface.

Due to population density, the EM data are impacted by a number of high-fly zones above conurbations and are subject to a range of general cultural interferences. A degree of data conditioning has been applied that attempts to remove some of non-geological responses and provide a more robust geological assessment. The geological assessment has used a GIS-based framework to investigate the statistical behavior of the conditioned data set in relation to the bedrock geology. The survey data used in the analysis comprise over 104,000 values at each of four frequencies. The analysis provides both stable averages for each of the formations together with information relating to spatial variability. An ANOVA analysis indicates that a significant percentage (~ over 50%) of the apparent conductivity information can be explained by bedrock geology. We have presented the results of the statistical analysis as baseline apparent conductivity maps which summarise the behaviour of the average electrical properties of the bedrock formations over the depths of investigation provided by the four frequencies. Under the uniform half-space assumption, the depths of investigation achieved by the data vary with the conductivity of each formation and may range from values of 25 m to over 100 m.

The data have also been used in quite localized mapping assessments of their information content. A detailed example in the vicinity of a former municipal landfill has been presented and the detailed response characteristics that may be contained in the data have been noted.

Due to inherent dependancy on mineral content, porosity and fluid conductivities the data may be used in both geological and hydrogeological assessments. An example of the conductivity models (cross sections obtained from 1D data inversion) obtained across the Southern Downs have been developed and presented. The results indicate to the degree to which conductivity contrasts within the Cretaceous sequence can be imaged to depths of the order of 100 m.

8 Conclusions

The HiRES survey has provided information on the Palaeogene and Cretaceous bedrock formations encountered on the IoW. These are some of the youngest lithologies to be assessed by the sequence of HiRES surveys. Since the lithologies are also representative of much of the southern mainland of England, the new information afforded by the electromagnetic survey is significant.

The results indicate that the majority of the Palaeogene is characterised by values consistently in excess of 100 mS/m and a surprisingly high degree of spatial heterogeneity. The youngest (Oligocene) Hamstead Member (HM-CLSS) displays some strong edge effects and the largest localized values in conductivity. In the absence of additional control information, the high conductivity zones would normally be associated with subsurface volumes of high mineral (e.g. clay) content. Within the Palaeogene, the successive London Clay (LC-CLSS) and Bracklesham Group (BRBA-CLSS) units display similar electrical properties. The central Upper Chalk is associated with the lowest conductivity values across the Cretaceous formations. The older Chalk sequences (WNCK-CHLK and WZCK-CHLK) appear to be more conductive indicating increasing mineral content and/or porosity. The Atherfield Clay Formation (AC-MDST) together with the adjacent Wealden Group Formation (W-MDST and W-SDST) display the highest conductivities within the Cretaceous. The large central outcrop of the Lower Greensand Group, Ferruginous Sand Formation (FRS-FGST) provides persistently low conductivity values that continue to depth. This is indicative of a relatively uniform distribution of clean sand content. Within the low conductivity values observed some large scale features are resolved. The observations, yet to be interpreted, have relevance to the internal properties of the Lower Greensand aquifer. The information presented here may therefore be developed in relation to obtaining a more complete understanding of the local hydrogeology.

A detailed case study of the mapping information in the vicinity of a closed municipal landfill was undertaken. The results indicate the presence of two zones of leachate accumulation. The two zones display features that indicate attenuation of bulk conductivity with depth and the zones appear laterally compact. Being a coastal survey, there is also potential for a consideration of the conductivity data in relation to saline intrusion. One obvious feature has been noted extending inland from Bembridge harbour following the course of the eastern River Yar.

The primary conductor identified in the southern area of Isle of Wight is the Gault clay/mudstone of the Early Cretaceous. This is prominent at outcrop across the Southern Downs and can be traced as a distinct unit under the more resistive Early Cretaceous Upper Greensand and Late Cretaceous Chalk formations. In regions where the bedding is significantly non-vertical this should allow estimation of the local strike and dip of the boundaries and hence the configuration of the aquifer and aquitard units.

Acknowledgements

Our thanks go to Jon Busby and Peter Hopson for internal reviews and helpful comments. Topographic base maps are reproduced from the OS by British Geological Survey with the permission of Ordnance Survey on behalf of the Controller of Her Majesty's Stationery Office, Crown copyright. All rights reserved. A newscast of the Isle of Wight airborne geophysical survey is available on the BGS YouTube channel at http://www.youtube.com/watch?v=D4ECcUPNi_E , last accessed 01 September 2010. This paper is published with the permission of the Executive Director, British Geological Survey (NERC).

References

Archie, G. E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Transactions of the American Institute of Mining, Metallurigical and Petroleum Engineers 146, 54-62

Beamish, D., 2002a. Airborne EM applied to environmental geosciences in the UK. First Break 20, 618–23.

Beamish, D., 2002b. The canopy effect in airborne EM. Geophysics 67, 1720-1728.

Beamish, D., 2003. Characterising landfills from the air. First Break 21, 67-72.

Beamish, D., 2004a. 3D modelling of near-surface, environmental effects on AEM data. Journal of Applied Geophysics 56, 263-280.

Beamish, D., 2004b. Airborne EM skin depths. Geophysical Prospecting 52, 439-449.

Beamish, D., Cuss, R.J., 2009. The HiRES airborne geophysical survey of the Isle of Wight: Logistics Report. British Geological Survey Internal Report IR/09/54.

Beamish, D., Kimbell, G.S., Stone, P., Anderson, T.B., 2010. Regional conductivity data used to reassess Lower Palaeozoic structure in the Northern Ireland sector of the Southern Uplands–Down-Longford terrane. Journal of the Geological Society London 167, 1-9.

Beamish, D., Klinck, B., 2006. Hydrochemical characterization of a coal mine plume detected by an airborne geophysical survey. Geofluids 6, 82-92.

Beamish, D., Leväniemi, H., 2010. The canopy effect in AEM revisited: investigations using laser and radar altimetry. Near Surface Geophysics 8, 103-115.

Beamish, D., White, J.C., *XXXX*. A radiometric airborne geophysical survey of the Isle of Wight. Proceedings of the Geologists' Association XX, *This issue*

Beamish, D., Young. M., 2009. Geophysics of Northern Ireland: the Tellus effect. First Break 27, 43-49.

Berg, C. R., 2007. An effective medium algorithm for calculating water saturations at any salinity or frequency. Geophysics 72, E59-E67.

British Geological Survey, 2008. Digital Geological Map of Great Britain 1:50 000 scale (DiGMapGB-50) data. Version 5.18. Keyworth, Nottingham: British Geological Survey. Tiles EW330_Lymington; EW331_ Portsmouth; EW344_Chale; EW345_Ventnor. Release date 30-09-2008.

Entec UK Limited, 2008. Environment Agency – Southern region, Groundwater Body Groundwater Quality Reports, Isle of Wight Lower Greensand Body Final Report,1-106.

Fraser, D.C., 1978. Resistivity mapping with an airborne multicoil electromagnetic system. Geophysics 43, 144– 172.

Leväniemi, H., Beamish, D., Hautaniemi, H., Kurimo, M., Suppala, I., Vironmäki, J., Cuss, R.J., Lahti, M., Tartaras, E., 2009. The JAC airborne EM system AEM-05. Journal of Applied Geophysics 67, 219-233.

Melville, R.V., Freshney, E.C., 1982. British Regional Geology: Hampshire Basin and adjoining areas (Keyworth, Nottingham: British Geological Survey).

Peart, R.J., Cuss.R.J., Beamish, D. and Jones, D.G., 2003. Locating and mapping potential environmental hazards in the UK with high resolution airborne geophysics. Geoscientist 13, 4-7.

Siemon, B., 2001. Improved and new resistivity-depth profiles for helicopter electromagnetic data. Journal of Applied Geophysics 46, 65–76.

Siemon, B, Auken, E., Christiansen, A.V., 2009. Laterally constrained inversion of helicopter-borne frequency-domain electromagnetic data. Journal of Applied Geophysics 67, 219-233.

White, H.J.O., 1921. A short account of the geology of the Isle of Wight. British Geological Survey Memoir.

White, J.C, Beamish, D., Cuss, R.J., 2009. The HiRES airborne geophysical survey of the Isle of Wight: Processing Report. British Geological Survey Open Report OR/09/060.

White, J.C., Beamish, D., 2009. A 3D Conductivity Model of the Isle of Wight, UK, from Airborne EM Data. Near Surface 2009 – 15th European Meeting of Environmental and Engineering Geophysics, Dublin, Ireland, 7 - 9 September 2009, Abstract B03.

Figure Captions

Figure 1. The 1:50 000 scale digital data for the bedrock geology,BGS (2008) of the Isle of Wight, and inset location map. The red contours denote areas where the survey altitude was greater than 100 m. The polygons with cross-hatch in black denote urban areas. The letter L (circled) denotes the location of a detailed study of the Lynnbottom landfill site.

Figure 2. Images of the gridded apparent conductivity data obtained at (a) 0.9 kHz and (b) 3 kHz. The same linear conductivity scale is used and shading is applied from the NW. Black zones denote urban areas.

Figure 3. Image of the gridded apparent conductivity data obtained at 25 kHz with the geological line-work (Fig. 1) superimposed. Black zones denote urban areas. BH denotes Bembridge Harbour. Yar (arrowed) indicates the inland route of the eastern River Yar.

Figure 4. Box and whisker plots summarising the statistical behaviour of the apparent conductivity values classified according to bedrock geology (a) 3 kHz and (b) 25 kHz. Trends, with age, within the 3 Chalk units and across the Lower Greensand Group (FRS-FGST) to the Wealden Formation (W-MDST, W-SDST) are indicated

Figure 5. Average (median) baseline apparent conductivities of the 22 bedrock formations obtained by statistical analysis (a) 0.9 kHz and (b) 25 kHz. A slight amount of shaded-relief has been applied from the north to emphasise the geological contacts.

Figure 6. Variation of average apparent conductivity with average centroid depth for the 5 bedrock formations making up the principal groundwater aquifer.

Figure 7. Conductivity variations across an area of 1.5 x 1.5 km containing the former Lynnbottom landfill site shown as a perspective view looking north.. Conductivity values in excess of 100 mS/m are contoured. (a) 25 kHz data, with an

OS 1:50,000 topographic map overlaid on a DTM as background. (b) 3 kHz data, with an ariel photograph overlaid on a DTM as background. The N-S sampling points of the airborne data set are shown with symbols (the majority of lines are ~100 m apart).

Figure 8. Example of the conductivity modelling (inversion) results obtained across a 5 x 5 km area of the Southern Downs. As indicated, the rectangle is rotated so that North appears to the left. The upper frame shows the geological units present across the full 5 x 5 km area. The numbers in brackets refer to the average apparent conductivity for each formation at 25 kHz. The lower image shows the conductivity cross-section along the N-S profile indentified in the upper frame. The cross-section is draped beneath a DTM with the geological units superimposed. The length of the cross-section is 5 km and the depth extent (highly exaggerated) is 100 m.

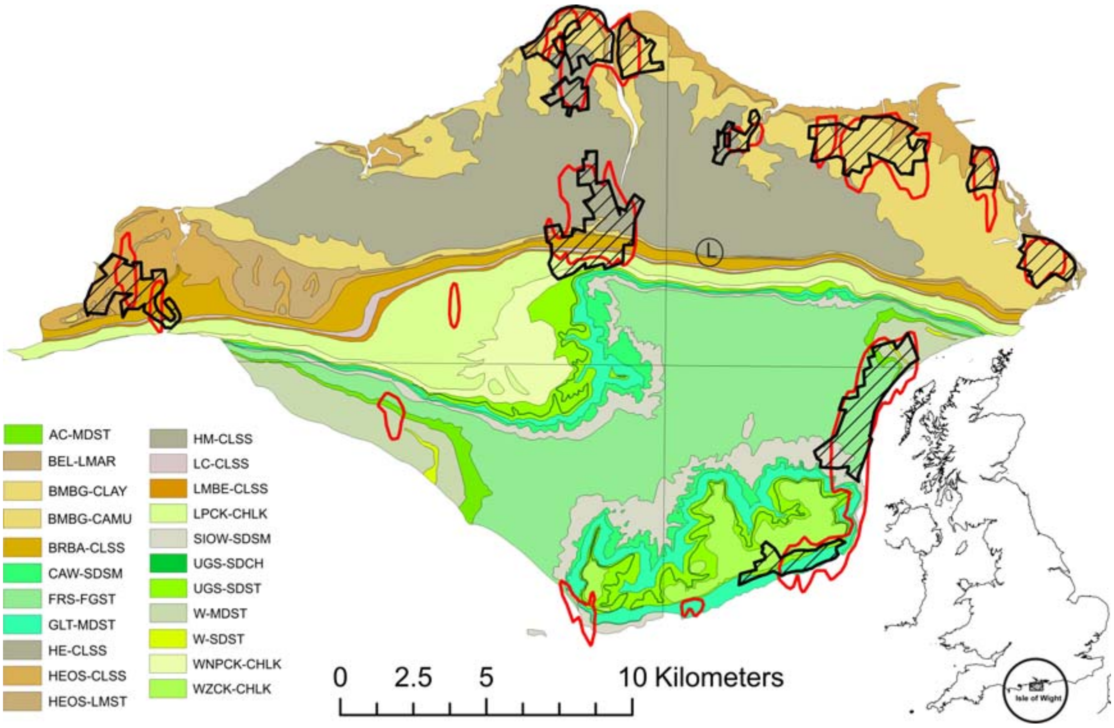

Figure 1. The 1:50 000 scale digital data for the bedrock geology BGS (1980) of the Isle of Wight, and inset location map. The red contours denote areas where the survey altitude was greater than 100 m. The polygons with cross-hatch in black denote urban areas. The letter L (circled) denotes the location of a detailed study of the Lynnbottom landfill site.

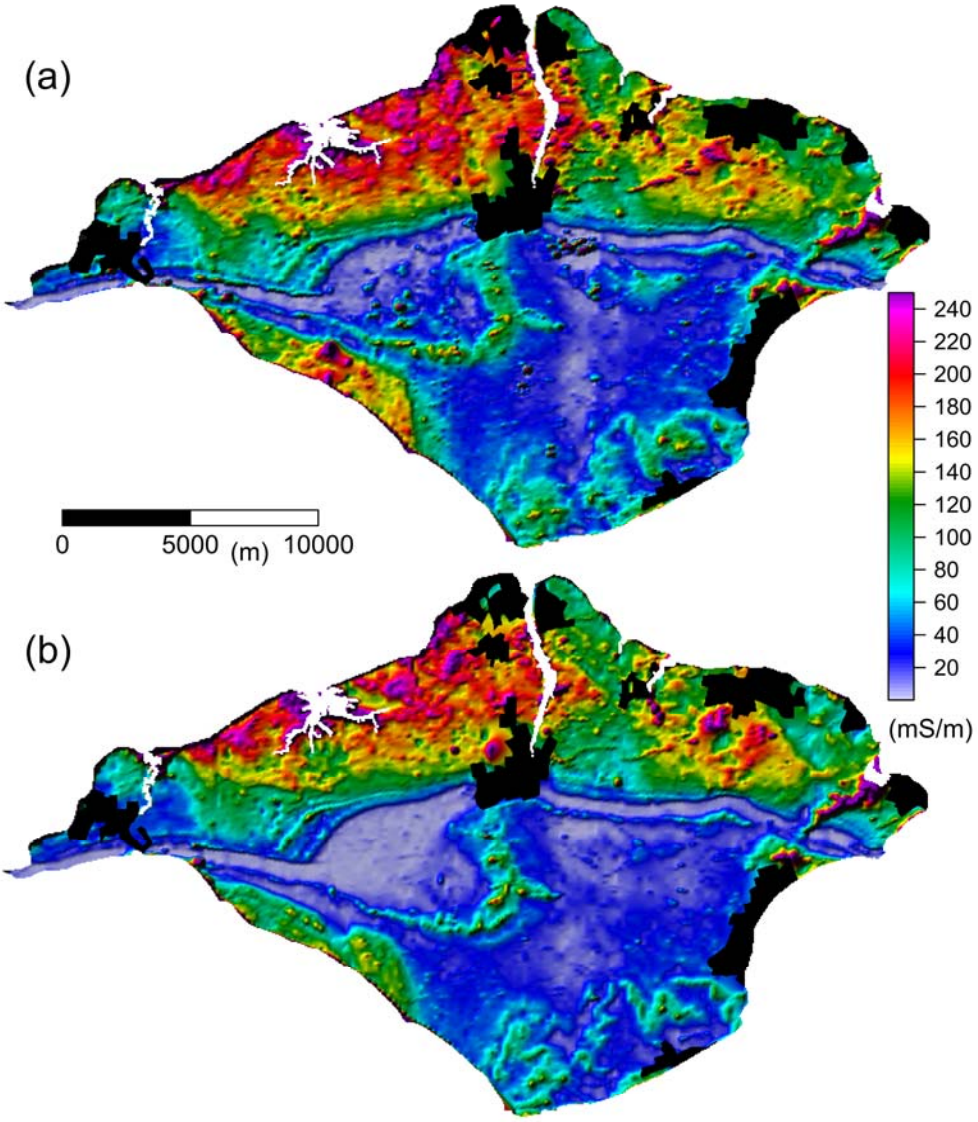

Figure 2. Images of the gridded apparent conductivity data obtained at (a) 0.9 kHz and (b) 3 kHz. The same linear conductivity scale is used and shading is applied from the NW. Black zones denote urban areas.

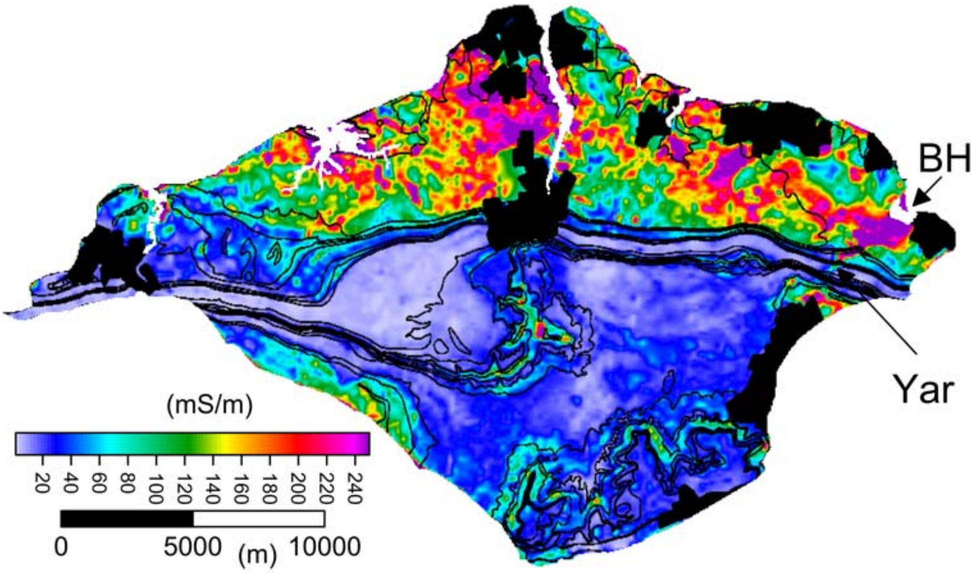

Figure 3. Image of the gridded apparent conductivity data obtained at 25 kHz with the geological line-work (Fig. 1) superimposed. Black zones denote urban areas. BH denotes Bembridge Harbour. Yar (arrowed) indicates the inland route of the eastern River Yar.

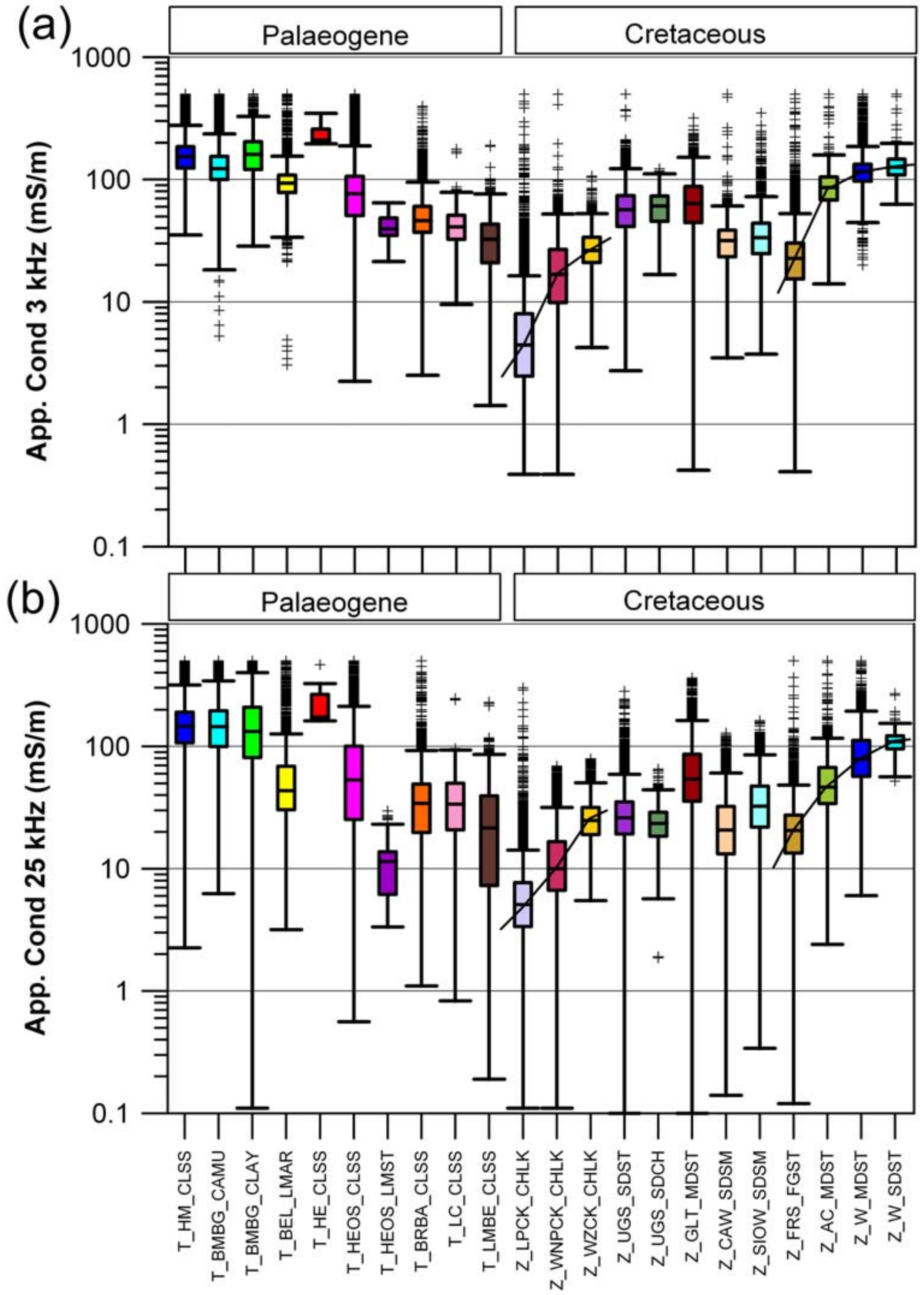

Figure 4. Box and whisker plots summarising the statistical behaviour of the apparent conductivity values classified according to bedrock geology (a) 3 kHz and (b) 25 kHz. Trends, with age, within the 3 Chalk units and across the Lower Greensand Group (FRS-FGST) to the Wealden Formation (W-MDST, W-SDST) are indicated

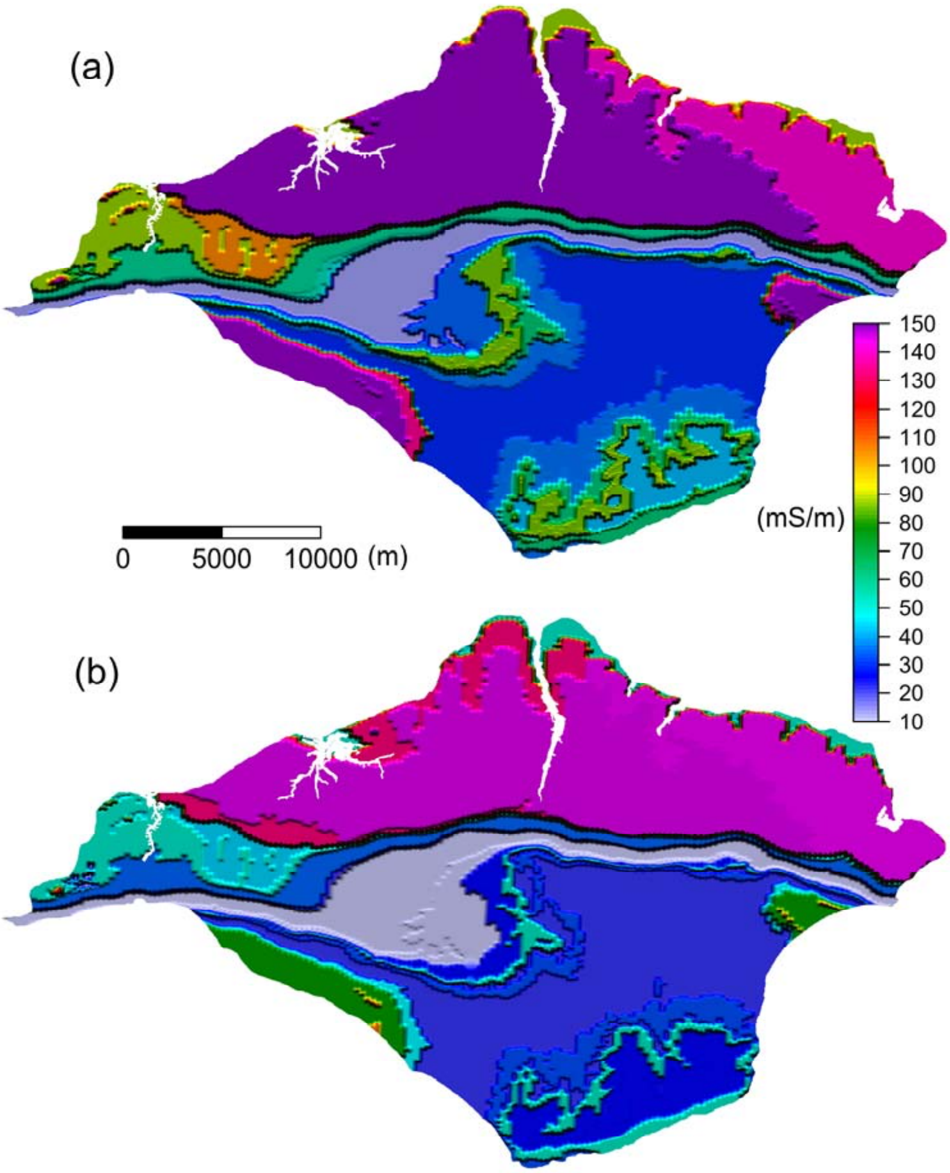

Figure 5. Average (median) baseline apparent conductivities of the 22 bedrock formations obtained by statistical analysis (a) 0.9 kHz and (b) 25 kHz. A slight amount of shaded-relief has been applied from the north to emphasise the geological contacts.

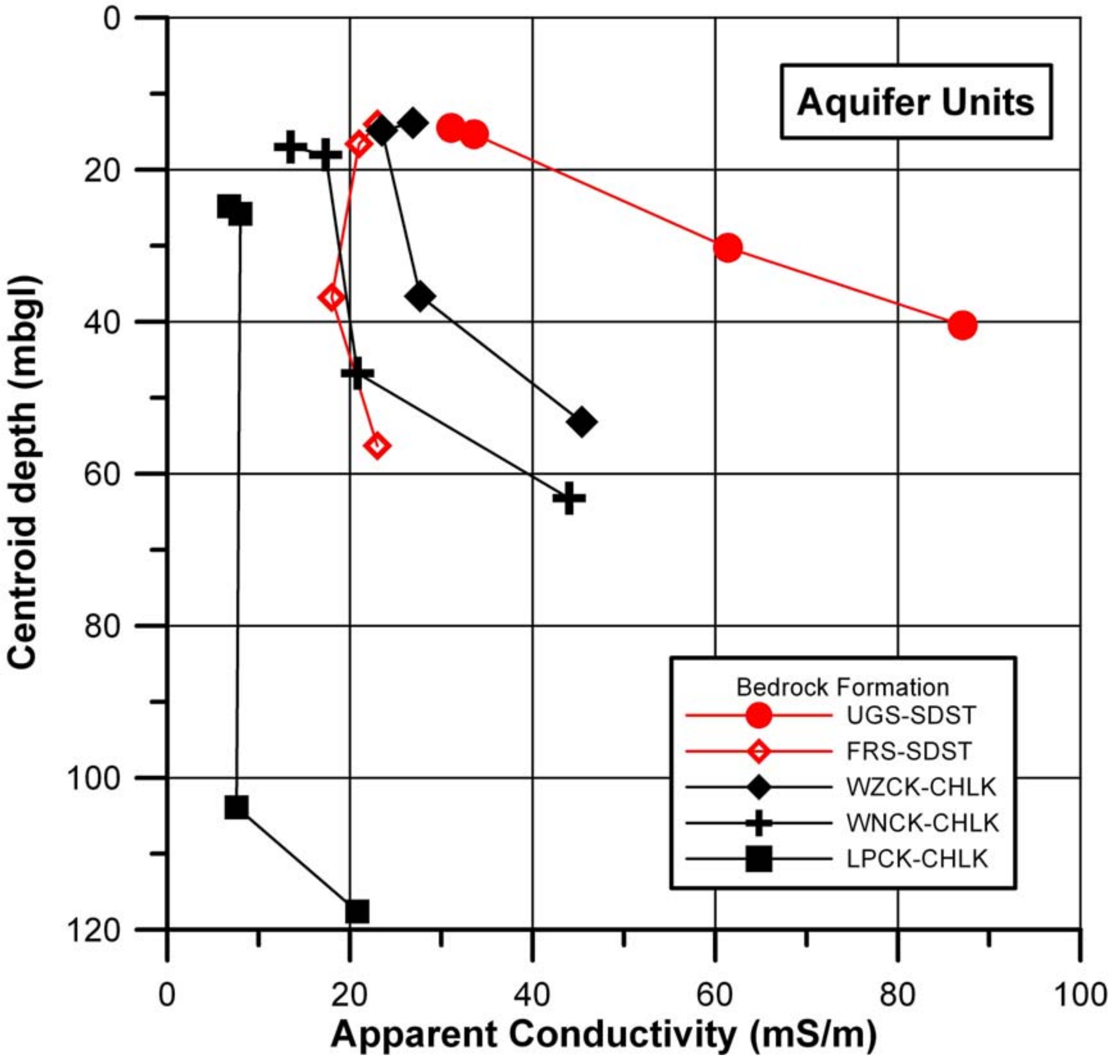

Figure 6. Variation of average apparent conductivity with average centroid depth for the 5 bedrock formations making up the principal groundwater aquifer.

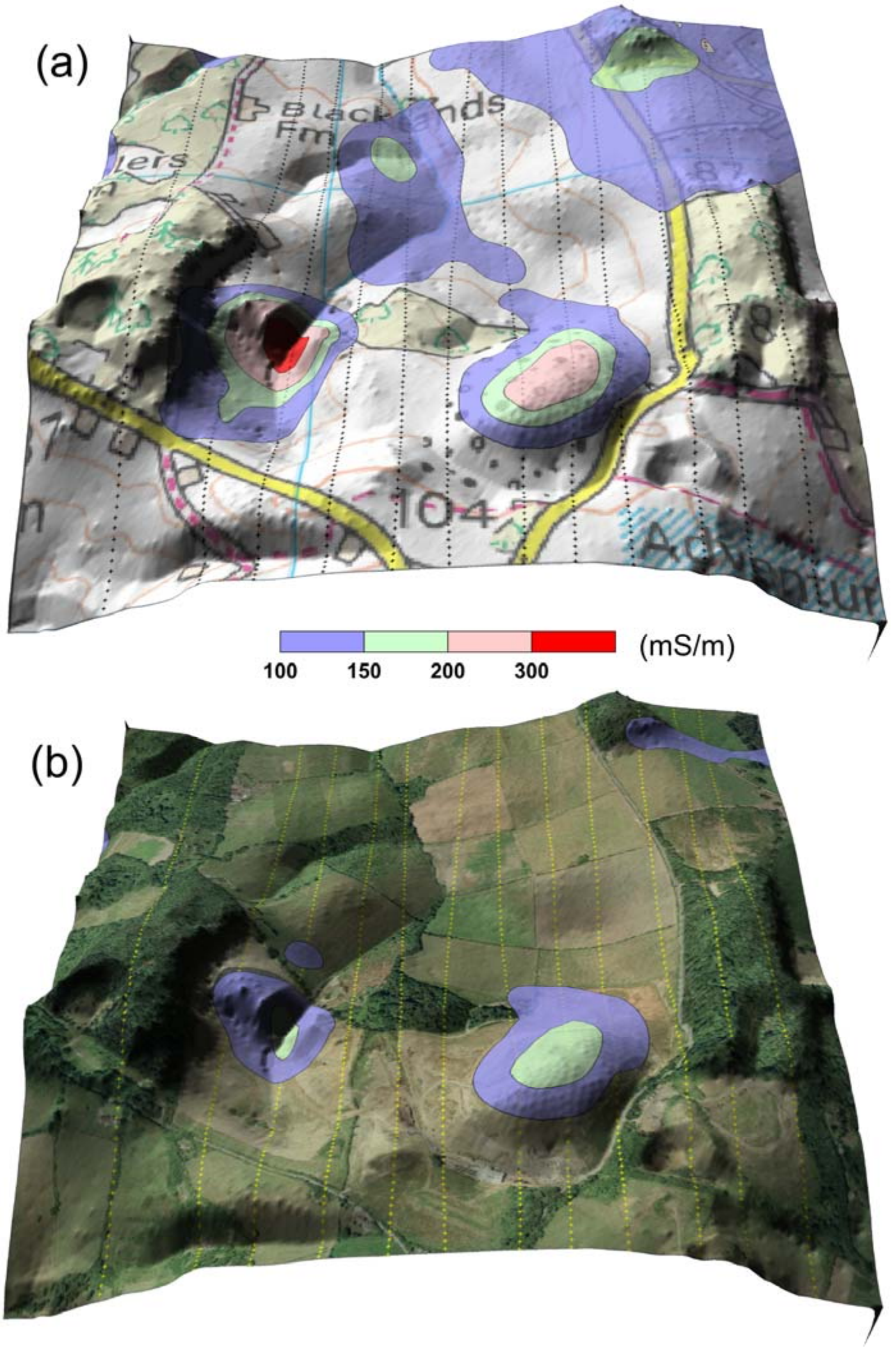

Figure 7. Conductivity variations across an area of 1.5 x 1.5 km containing the former Lynnbottom landfill site shown as a perspective view looking north.. Conductivity values in excess of 100 mS/m are contoured. (a) 25 kHz data, with an OS 1:50,000 topographic map overlaid on a DTM as background. (b) 3 kHz data, with an ariel photograph overlaid on a DTM as background. The N-S sampling points of the airborne data set are shown with symbols (the majority of lines are ~100 m apart).

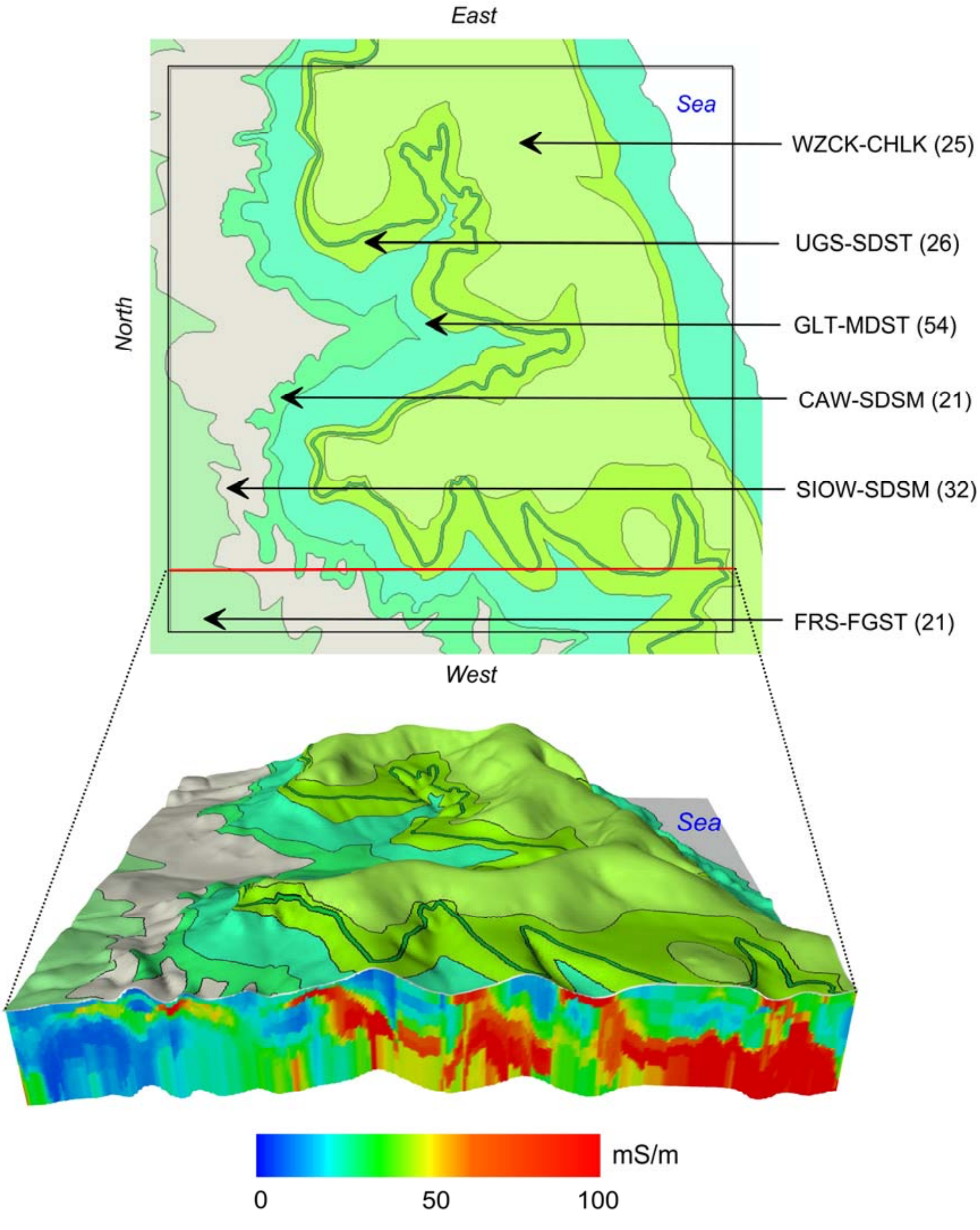

Figure 8. Example of the conductivity modelling (inversion) results obtained across a 5 x 5 km area of the Southern Downs. As indicated, the rectangle is rotated so that North appears to the left. The upper frame shows the geological units present across the full 5 x 5 km area. The numbers in brackets refer to the average apparent

conductivity for each formation at 25 kHz. The lower image shows the conductivity cross-section along the N-S profile indentified in the upper frame. The cross-section is draped beneath a DTM with the geological units superimposed. The length of the cross-section is 5 km and the depth extent (highly exaggerated) is 100 m.