Palaeogeographic Reconstruction in the Transition Zone: the role of geophysical forward modelling in ground investigation surveys

C. R. Bates¹ and M. R. Bates²

¹Department of Earth and Environmental Sciences, University of St Andrews,
St Andrews, Fife, Scotland. KY16 9AL

²School of Archaeology, History and Anthropology, University of Wales Trinity Saint David,
Lampeter, Ceredigion, Wales. SA48 7ED

Abstract

Geophysical survey techniques are commonly used as part of studies to reconstruct past geographies in archaeological and palaeoenvironmental landscape investigations onshore and offshore. However, their use across the intertidal zone for constructing contiguous models is far more challenging. In order to enhance the interpretation of the recovered data forward modelling is used here to demonstrate the effective use of a staged approach to site investigation. Examples of data from electrical and electromagnetic techniques have been modelled and tested with ground truth measurements including trial pits, coring and cone penetrometer testing. This combination of forward modelling and testing has proved to be particularly effective at mapping key geological situations of archaeological interest. The approach is demonstrated by reference to varying sub-surface sediment types exemplified by two field examples from the UK coast where typical palaeolandscapes features, namely incised channels and deeply buried topographies are encountered. These palaeogeographic features were chosen as they have high potential for association with the evidence of past human activity.

Key words

Geophysics; boreholes; palaeogeography; buried channels; peats; modelling

Introduction

Over the past four decades an increasing number of geophysical techniques have been applied to archaeological studies (David et al., 2008). This has mainly been undertaken with regard to investigation of structured archaeological sites containing substantial features such as walls, ditches, pits and burnt structures. More recently, the use of geophysics has extended to the investigation and reconstruction of past landscapes, both onshore and offshore (Bates et al., 2009). Few of these investigations however have attempted to link the onshore and offshore landscapes across the intertidal zone (Bates et al., 2007). The difficulty in using geophysical techniques to understand sedimentary sequences in the intertidal or transition zone has been previously documented by Missiaen et al. (2008) and no single technique is either wholly appropriate for every type of buried landscape or is readily deployable in every situation. Rather, different techniques are appropriate under different scenarios. Techniques that have consistently found application are seismic, electrical (in particular Electric Resistivity Tomography – ERT) and electromagnetic (in particular Frequency Domain Electromagnetic ground conductivity – FDEM). Each has its limitations but all have some benefits.

Despite such studies there remains an equivocal attitude towards geophysics in many quarters (Jordan, 2009). For example in archaeology/environmental sciences results that do not clearly reflect the preconceptions of the site are often dismissed as failures of geophysics while in engineering geology geophysics is typically viewed as providing imprecise data on ground conditions by comparison to the perceived precision from a borehole study (Butler, 2005). The short-comings are however a function of a number of factors including unrealistic expectations of techniques, poor field application of methods and insufficient consideration given to the likely ground conditions and the most appropriate methodology for investigation. For this reason our paper discusses the role of forward modelling within electrical techniques to allow geological scenarios of different conditions and of particular archaeological relevance to be articulated prior to fieldwork. The geological scenarios are then used as a basis to create geophysical test sections based on standard ranges of electrical resistivity that can be forward-modelled for comparison with field data. This approach is tested at two coastal sites

in the UK (Figure 1) where typical sequences likely to be encountered in the transition zone are present.

Geophysics in the transition zone

Geophysical investigations across the intertidal, or transition zone tend to be divided in those based either on marine methods or those on terrestrial methods. Both have advantages and disadvantages within this zone, where rapidly changing environmental conditions make it particularly difficult to survey. The difficulties include large tidal ranges that often limit surveying to only short periods of time at low tide when conditions expose a firm surface to walk on or conversely at high tide when the submerged surface can be over flown by a shallow-draft boat. Geophysical methods for effective survey in the transition zone must therefore be rapid to acquire data and light and readily transportable. The coastal zone is also characterised by high levels of noise, for example for seismic methods noise from ocean swell and the action of waves creating undesirable vibrations. The presence of saline water, and the changing saturation associated with semi-diurnal tides also has significant impact on electrical and electromagnetic signatures. For example in material that has high porosity and permeability (i.e. sands) and is thus susceptible to the changes in electrical conductivity.

Solutions for shallow marine survey have resulted in the development of a number of shallow water survey platforms from manned vessels (Bates and Fenning, 2012) to autonomous boats (Danforth et al., 2007; Neal et al., 2012). These sonar platforms typically include instrumentation for acquiring very high resolution bathymetric models using singlebeam sonar, multibeam sonar and bathymetric sidescan sonar. Acquiring subsurface information in the shallow intertidal zone is often more challenging, especially if target horizons are deeply buried and/or the material is acoustically absorbing thus inhibiting the penetration of acoustic energy. In such cases, the physical size of both the wet-side of the sonar device and that of the dry-side instruments with their associated need for a significant electrical power supply can dictate that a relatively large survey vessel is necessary for deployment. Despite these limitations, some considerable success has been demonstrated in mapping shallow and intertidal areas using 3D chirp sonar for buried archaeological object detection (Vardy et al.,

2008) and also with non-linear sonar by Wunderlich et al. (2005). A 3D seismic approach to mapping buried foundations within sediments overlying rugged bedrock in a drowned coast line in western Turkey by Muller et al. (2009) further demonstrates the potential of seismic in very small area mapping.

Towed electrical resistivity arrays have been successfully deployed in marine environments where the array is either towed in the water column (Kwon et al., 2005) or dragged on the seafloor (Evans et al., 1999). In both cases the subsurface resolution obtained is often compromised by the water salinity. For the towed arrays, the survey requires that water depth is less than twice the electrode spacing.

Approaching the transition zone from the dry-side Missiaen *et al.* (2008) used a combined geophysical method approach to understand complex estuary sedimentation patterns in the Netherlands with acoustic methods providing the highest resolution results. They also demonstrated the necessity of a ground truth sampling program based on Cone Penetration Testing (CPT) and coring that could be quickly deployed over the short tidal windows. In the transition zone direct sampling is also confronted with many of the logistical difficulties faced by the geophysics, in particular the very soft, water-saturated, unstable sediments such as soft muds and liquefying sands that can rapidly collapse around test pits or drill holes.

One of the key issues commonly encountered in the transition zone is that of saltwater intrusion where the use of electromagnetic instruments for mapping ground conductivity changes can be limited. Electromagnetic induction instruments produce a time-varying electromagnetic field that in turn induce currents in the subsurface. Most instruments base their measurements on the assumption of low induction numbers in the subsurface where true conductivity is proportional to the ratio of recorded primary to secondary magnetic fields (McNeill, 1990). However, it has been noted that as true conductivity in an area increases, the skin depth decreases causing the induction number to increase (Spies, 1989). As skin depth decreases in high conductivity environments so does the depth of penetration (Callegary et al., 2007). Various calibration corrections have been proposed for EM in the intertidal zone that include adjustment with respect to high salinity levels, compensation for change in temperature and also for instrument drift (Delefortrie, 2014). There is a point however, when

ground conductivity increases beyond the level where the assumption of low induction number is valid (McNeill, 1990) and at this point, without the increase in separation of transmitter-receiver pair then absolute value of conductivity cannot be relied on rather, it is only the relative contrast in conductivity that can be used (Barker, 1990). In the two studies reported here, it is the relative contrasts in conductivity (or resistivity) that are shown to be important for discrimination of subsurface geology and thus palaeogeographic reconstruction. McDonald *et al.* (1998) clearly demonstrated the influence of geology, and in particular the effect of porosity and permeability, on saltwater intrusion in a study of coastal wetland at Langstone Harbour, UK. Here a buried channel complex consisting of muds, sand, peats and gravels on an undulating chalk bedrock was investigated with ERT and FDEM. Both methods were chosen as they could be rapidly deployed in order to investigate the degree of saline intrusion as a time-dependant variable over a tidal cycle. The wetland sediments showed the least amount of saline intrusion due to their relatively limited permeability with buried gravel channels showing highest changes in conductivity during high tide and thus intrusion of salt water. This study concludes with some simple and insightful models for interpretation of electrical and electromagnetic results over typical geological sequences with saline intrusion in the intertidal zone that are of particular relevance to our studies.

The use of electromagnetic frequency domain instrumentation for mapping landscape features has seen increased interest since the introduction of multi-frequency sensors. In a study of buried channels De Smedt *et al.* (2011) were able to model the channel depths with a high degree of confidence when compared to both auger ground truth and ERT data. Saey *et al.* (2009) further suggest that ground truth augering may not be necessary if a sufficient number of frequencies are used, however, their study is limited to a simple 2-layer subsurface model.

A more recent approach to the difficulty of choosing between wet and dry survey methods has been made to mapping salt water intrusion in the transition zone by the British Geological Survey (Beamish, 2011) using airborne-based electromagnetic methods. These tests with multi-frequency Electromagnetic (EM) mapping demonstrated increased conductivity up to 10km inland from the coast in valleys on Anglesey, UK. The variations in conductivity were associated with variations in the range of Holocene deposits present. While the approach was

successful over large areas, the availability of multi-frequency airborne EM is not readily accessible to many projects and further, the scale at which measurements are made would only be at the broadest, regional value.

In summary, geophysical and direct sampling programmes have been successful for the discrimination of channel sequences, peat beds, gravel bodies and buried palaeo-cliffs both onshore and offshore, however, integration of results is necessary. These scenarios are discussed further with the use of geological-geophysical models and test data.

The Geological Model and its archaeological relevance

As part of routine site investigations, for archaeological, palaeoenvironmental or geotechnical reasons, practitioners typically conduct surveys with preconceived scenarios for site formation (Bates and Stafford, 2013). These might simply be derived from a basic understanding of mapped data (geological maps) or may be more sophisticated and include complex ground models derived from earlier phases of work. These geological scenarios serve to allow the data recovered from site investigation to be evaluated against a baseline as we test and compare our data with the perceived scenarios. However, rarely are these scenarios articulated formerly and therefore comparing the results of a study to them is difficult if not impossible. Additionally without a formal scenario different practitioners may hold different interpretations of a particular geological sequence resulting in confusion when the results of an investigation are discussed and the implications of the study taken forward. The same practice is true within geophysics where the presence of a forward geophysical model is rarely articulated and therefore similar problems exist when addressing the results of a survey.

Geological scenarios are commonly used in geology and archaeology in order to make predictions regarding patterns of sedimentation or human activity (spatially or temporally) (Bates and Stafford, 2013). Geological sequences, of archaeological interest, have built up (and survived) in a number of palaeogeographic situations. Many of these situations are of relevance to human activity and consequently traces of past human activity may be preserved

in association with particular palaeotopographic situations. For example the cliff base at Boxgrove in West Sussex (Roberts and Parfitt, 1999) or the edge of floodplains (Bates and Stafford, 2013). Locating and examining these situations is now crucial both for academic field projects as well as developer funded archaeology where locating areas of archaeological importance are fundamental to the success of a project (Bates and Stafford, 2013). Consequently the rise in geoarchaeological activity associated with ground investigation in order to locate deeply buried sites has gained importance in the last 20 years.

Linking palaeogeographies to human activity through ground investigation models is prevalent in Prehistoric archaeology and good examples include documenting human presence on the floodplains of major river and estuary systems at places such as Happisburgh in Norfolk (Parfitt et al., 2010; Ashton et al., 2014), associated with channels and gravel bars of rivers (Conway et al., 1996; Bates et al., 2014) and along shore lines and at the base of cliff sequences (Roberts and Parfitt, 1999). All these types of geographic situation are encountered along coastal corridors and their mapping becomes an important objective for geoarchaeological study, the first part of which is the construction of the geological scenario. While the number of past geological scenarios it is possible to construct is infinite, a selection of the most common that are associated with human activity are listed in Table 1. A typical model for a major southern UK estuary is shown in Figure 2A.

The Geophysical Model

From the initial geological scenario (Figure 2A) it is possible to construct a geophysical model based on average (bulk) properties for different materials. Typical ranges of geophysical properties such as electrical resistivity for unconsolidated and consolidated materials together with their varying pore water types are given in a number of standard texts (see Table 2 after Telford et al., 1991 and Reynolds, 2011). Of particular importance to working in the transition zone, as we have already noted, is the large influence that saline saturation has on the relative resistivity of different materials (McDonald et al., 1998) where up to 4 orders of magnitude difference can be seen between salt-saturated sand and dry sand. The empirical relationship presented by Archie (1942) demonstrates that bulk resistivity (or its

inverse bulk conductivity) is related to pore fluid conductivity, porosity and degree of saturation where a material contains little or no clay. A modified version of this relation (e.g. Kirsch, 2006) can allow for small amounts of clay but additional measurements are required to fully distinguish between the influence of fluid conductivity and those of the clay components (Gabriel et al., 2003). Nonetheless, most electrical and electromagnetic instrumentation have been developed on these relations.

In order to demonstrate some of the issues with contrasting resistivity resulting from different geology typical palaeogeographic situations are presented (Figures 2 and 3) together with their derived geoelectrical sections. The geoelectrical sections were forward-modelled for all cases using the 2D forward-modelling programme RES2dMOD (Loke and Barker, 1995). This programme uses a finite-difference method to divide the subsurface into a number of unit blocks in a rectangular mesh together with typical resistivity acquisition arrays such as Wenner-Wenner, Schlumberger, dipole-dipole and pole-dipole arrays to derive apparent resistivity pseudosections. The results of the forward modelling are shown beneath each block scenario. In Figure 2A we present a geological model based on an estuarine sequence of deposits as represented in a typical tide dominated estuary (*sensu* Dalrymple et al., 1992). Figures 2B and 2C represent geoelectrical scenarios and associated forward models for the geological scenarios under freshwater and saline conditions. In a similar manner in Figure 3 we present an example of a buried channel incised into bedrock under freshwater and saline conditions with varying sediment cover.

In the case of the estuary example (Figure 2A) the geoelectrical models for both fresh and saline conditions show that the steeply dipping bedrock should be clearly imaged. The imprecise representation of both channel edge dip and the depth to which the modelled data is able to predict resistivity changes is limited by the electrical array used in the model, a limitation of the modelling software. However despite this and the fact that individual units representing subtidal sands and gravels were not fully resolved with either model their presence is suggested by both models, especially when the sands are saline-saturated.

In the case of the buried channel scenario (Figure 3) different results are noted depending on the contrast in resistivity between the channel and surrounding materials and depending on

the relative size/depth of the channel. Where the channel occurs to the surface of the section (Figure 3A and 3B) then its presence is manifest in both fresh and saline models with the latter more distinctly showing the shape of the channel. In the case of a buried channel (Figures 3C and 3D) then in neither the fresh nor saline situation does the model match the shape of the channel but its presence is still noted. Where the channel is buried beneath a resistive layer of similar material to the channel the margins are poorly imaged with the depth and geometry of the channel not manifest in the model. Case 3F takes the same situation but decreases the channel resistivity by saline intrusion to demonstrate that the channel cannot be imaged in this case. The geo-electrical scenarios serve to demonstrate the sensitivity of the method to not only changing resistivity in the subsurface but also to the geometry of the units. Furthermore, although not shown here, imaging the various scenarios is also sensitive to the type of electrical array used for modelling, and by inference that which would also be used for field survey. Changing degree of saline-saturation will thus clearly have a profound influence on the apparent resistivity recorded in the field as would be the situation for changes during a survey over a tidal cycle.

Case Histories

Two case histories are given to demonstrate typical scenarios in transition zone palaeolandscape investigations. The first at West Street, Sussex, England (Figure 4) represents a typical small scale (2-4m deep) channel preserved in the intertidal zone that is usually buried beneath the beach sand. The geophysical objective here was to delineate the buried channel and gain insight into the internal structure of the channel in order to target test pitting for the recovery of palaeoenvironmental and dating samples. The second investigation at Borth in West Wales (Figures 5 - 7) has a focus imaging deeply buried topography (10-30m) overlain by tidal/sub-tidal, estuarine and freshwater (including peats) sediments.

At both sites, electrical resistivity tomography (ERT) surveys were conducted using an ABEM Terrameter SAS4000 with 5m, 2m, and 1m electrode spacing chosen dependant on the scale of features to be mapped. A modified Wenner-Schlumberger gradient array was used for data

acquisition in order to gain increased resolution in the near surface while improving data cover for the largest depths of investigation. Electrode locations were surveyed using dGPS. The measured apparent resistivity data were converted to pseudo-section images (electrical resistivity tomograms) of modelled resistivity using finite-difference forward modelling with the RES2DINV software (Geotomo Software, Malaysia) following the method of Loke and Barker (1995). It is important to note that the method assumes a 2D distribution of resistivity variation and thus is compromised when the geology changes rapidly out of this plane. However, for most scenarios targeted in the transition zone, the survey line direction is chosen to cross-cut the major geological changes or to be sympathetic to the transient features such as the salt water intrusion.

Frequency domain electromagnetic (FDEM) surveys were conducted with the Geonics EM31, Geonics EM38 and a CMD Explorer. All instruments were used in both horizontal and vertical dipole orientations and thus penetration depths of up to 6m were possible in non-saline saturated sequences but limited to less than this in the fully saline-saturated sediments. All EM instruments were deployed with dGPS for positioning with accuracy better than 0.1m in horizontal and vertical. Typical survey patterns described grids with line spacing not greater than 5m and along line sampling of a minimum of 3 samples per second (approximately 50cm at walking pace). The instruments were all hand-carried as the uneven beach surfaces did not allow for any mechanised approach. Survey results were analysed using ArcMap (ESRI) and are presented as contoured maps of ground conductivity. Ground truth methods included CPT, coring, trial pits and hand sampling as individually described.

West Street, Selsey Channel (Figure 4)

The West Sussex coastal plain on the south coast of England is marked by extensive Pleistocene deposits that include a series of high sealevel events that are truncated by a complex sedimentary sequence associated with a series of north-south trending valleys (Bates et al., 1997, 2010). On the foreshore and intertidal zone today smaller scale channels relating, in a way that is currently difficult to ascertain, to the main marine sequences, are buried by thin modern beach deposits. These channels allow the possibility to investigate the channel morphology and sedimentology with respect to palaeoenvironmental signature and

associated archaeological deposits (Bates et al., 2009). These channels are typically less than 4m deep, 100-200m wide and contain a variety of sediments from gravels and sands to clays and organic silts/peats (West and Sparks, 1960; Stinton, 1985; Bates et al., 2009, 2010; Bates, 2011). The model scenarios were illustrated in Figure 3B.

Figure 4A shows the results of a FDEM survey over the beach, the location of ERT transect and the test pits. The FDEM (Figure 4A) showed ground conductivity varying between 50mS/m and 500mS/m (20-2 ohm.m) over the beach sands with values less than 30mS/m (>33 ohm.m) across the gravel deposits at the top of the beach above high tide. The channel margins were constrained by conductivity values above approximately 400mS/m where the Tertiary clay bedrock extends close to the surface (Figure 4B). Internal variation in conductivity suggests higher conductivities in the northern part of the channel (values above 465mS, associated with test pits 3 and 6) with lower conductivities in the southern part of the channel (test pits 4 and 7). The lithology of the sediments determined from test pits are shown in Figure 4D and show sand dominated sediments in the northern part of the channel that are replaced by clay-silt or organic silt overlying gravel in the southern part of the channel. The FDEM results (Figure 4A) that show the highest conductivity is associated with sediments in test pits 3 and 6 consisting predominantly consisting of sands (with the highest porosity and permeability) that are saline-saturated. In contrast lower porosity sediments (clays), and beyond the margins of the channel, associated with the Tertiary bedrock are associated with lower conductivities.

The ERT transect (Figure 4C) exhibits a near surface layer of very low resistivity that thickens within the middle part of the profile exhibiting two pod-like features extending down some 5m from the surface. These defined the channel form. The recorded apparent resistivity of less than 1 ohm.m in the ERT (Figure 4C) compares well with the surface FDEM results and is likely a result of saltwater saturating the coarse sediments that fill the channel.

Borth: deeply buried estuarine and freshwater sequences (Figures 5 - 7)

The existence of submerged landscapes surrounding the island of Britain has been recorded and discussed since Clement Reid published *Submerged Forests* in 1913 (Reid, 1913). The west coast of Wales contains a substantial number of drowned forests that have been reported on frequently since the mid 19th century when Keeping (1878) first recorded the presence of peats overlying marine clays at Borth (Figures 5 and 6). The sediments between Borth and Ynyslas consists of a sequence of tidal and estuarine sands and silts overlain by peat containing a substantial number of trees (Figures 2A, 6A). The southern margin of this sequence was re-exposed in 2012 during sea defence construction and the Silurian bedrock Borth Mudstones Formation was seen to plunge steeply down beneath the modern beach and the underlying Holocene sediments. Peat was exposed at the surface (Figure 6B) and consists of 'forest peat' at least 1m thick with common tree stumps at the south end of the beach. Archaeological evidence, in the form of broken, burnt beach pebbles and human footprints, were also found in this area (Figure 6D). 500m to the north the forest peat is cut by a large, East to West trending channel-like feature that consists of thin organic silts capping a series of well laminated sediments (Figure 6C) that appear to exhibit bar like structures rich in reworked peat. Further north forest peat is re-established (Figure 6A) and this extends to Ynyslas. The southern margin of the sequence where it onlaps to the bedrock was clearly imaged using FDEM as was the northern margin of the channel sequence (Figure 5).

In order to understand the topography of the pre-inundation landscape ERT forward-modelling of the foreshore (Figure 7A/B) was conducted and indicated that it should be possible to map the contrast in bedrock with salt-saturated sand, the channel sequences and possibly also the thin peat layers given that the resistivity contrast to surrounding salt-saturated sands is high. The ERT data was acquired along a continuous profile from south to north along the foreshore (Figure 7A). Ground truth methods included test pits, boreholes and CPT. The inversion results of an ERT field transect is shown together with CPT and boreholes results (Figure 7C) and overall interpretation in Figure 7D. The underlying bedrock, with resistivity greater than 80 ohm.m, was clearly mapped in the ERT and showed a strong northerly dip with an associated increase in thickness of the Holocene sediments (10-30 ohm.m) and beach material (<15 ohm.m). Direct resistivity measurements made on the peat recorded values of between 100 and 400 ohm.m. The presence of this within the overall silt/sand channel sequence is mapped with both the forward model and the ERT. Further

investigations on the site has demonstrated that there is a reasonable correlation with the CPT data down to the depth of maximum CPT penetration and also good correlation in the near surface with test pits. The EM ground conductivity data showed (Figure 5) that the dipping bedrock at the south end of the beach provided a distinct and mappable unit.

Discussion

The use of electrical and electromagnetic techniques in these studies illustrates that they can successfully be used to obtain meaningful data to facilitate palaeoenvironmental reconstructions in the intertidal zone when ground truth information is available for cross-reference. Further, the geophysical surveys not only allow for ground truth data to be extrapolated but also for speculative surveying to be undertaken prior to targeted ground truth methods. Modelling and application of the methods also show how conditions across the zone that change from freshwater saturated to saline saturated have a profound and measureable effect on electrical and electromagnetic results and thus they allow onshore and offshore reconstructions to be linked. As the techniques become more rapid for data acquisition it is anticipated that their use will become more widespread and cost effective. With the advance of towed electric arrays such as the Ohmmapper (Groom, 2008) for onshore investigation and multi-electrode arrays for offshore investigation results for the same beach locations can be directly compared at different states of the tide.

Perhaps more importantly we hope to have demonstrated how the construction of geological and geophysical scenarios can be used for forward-modelling as an important part of palaeogeographic studies. It is important both to recognise that this happens subliminally, as well as purposively, and if carefully articulated through worked up models it can provide useful insight both prior to field survey and when evaluating models held by the discipline. As pointed out by others (for example Missiaen et al., 2008) there is no easy geophysical solution or no 'plug and play' adoption of methods for the investigation of any one site; certainly experience in data interpretation and ground truthing data in a variety of settings is of vital importance in the creation of a reflective approach to modelling, data collection and interpretation. Rather, as Jordan (2009) has urged the use of a 'reflective project

development' in which forward modelling with site tailored programs and staged, informed interpretation of results are needed to ensure success in this zone. Such an approach was adopted during the palaeoenvironmental works associated with the construction of High Speed 1 in southern England (Bates and Stafford, 2009) and should be rolled out in a more flexible way. Here we have demonstrated how such a structured approach can be useful within geophysics in the transition zone to understand this challenging place but also as the first step in attempting to join together survey results from onshore to offshore.

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Table 1. Buried topographic feature, size, sedimentary contrast with adjacent sediment bodies and examples of features likely to be encountered beneath the ground.

Table 2. Resistivity ranges of some common materials. From Telford, 1991; Reynolds, 2011.

Buried topographic feature	Vertical dimensions	Dimensions (width x length)	Likely contrast	Example	Reference
Cliffline	2-200m	m's x km	Cut into bedrock and overlain by superficial sediments	Goodwood/Sindon Raised beach cliffline	Bates et al., 1997, 2009
Channel	2-8m	5-200m x km	Cut into bedrock or superficial sediments, filled with superficial sediments and overlain by superficial sediments	West Street, Selsey Channel	Bates et al., 2009 and this paper
Floodplain edge	2-20m	<50m x km	Cut into bedrock or superficial sediments and overlain by superficial sediments	Thames floodplain edge	Bates and Stafford, 2013
Islands in floodplain	<20m	10's x 100's m	Grave highs overlain by superficial sediments	Sub-floodplain islands in Thames	
River terrace	2-6m	<200m x km long	Sand, gravel and silt/clay packages resting on bedrock and overlain by superficial sediments	Lower Thames/Thames estuary	
Beach	<10m	<100m x km long	Gravel and sand resting on bedrock	Goodwood/Sindon Raised beach cliffline	Roberts and Parfitt, 1999

Material	Resistivity – Dry (ohm.m)	Resistivity - Saline Saturated (ohm.m)
Sand	10^1 - 10^2	10^{-1} - 10^0
Gravel	10^2 - 10^3	10^{-1} - 10^0
Sandy-Silt	10^0 - 10^1	10^{-1} - 10^0
Clay	10^{-1} - 10^1	10^{-1} - 10^1
Peat	10^1 - 10^2	10^{-1} - 10^0
Sandstone	10^1 - 10^4	10^{-1} - 10^1
Siltstone	10^1 - 10^3	10^{-1} - 10^1
Granite	10^2 - 10^4	10^2 - 10^4
Limestone	10^2 - 10^4	10^1 - 10^2
Shale	10^0 - 10^2	10^{-1} - 10^1