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Mixed Method Approaches to the Investigation and Mapping of Buried Quaternary Deposits: Examples from Southern England

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ABSTRACT The lower reaches of major river valleys usually present archaeologists with considerable problems where thick sequences of stratified alluvium bury archaeology. These situations are typical of the lower reaches of major river systems that are currently under intense pressure from urban development where the archaeological resource is consequently at risk. Here we demonstrate how mixed method approaches, utilizing a range of borehole methods, cone penetration testing and surface and subsurface geophysics coupled with microfossil assessment (foraminifera/ostracoda), can be used to model these deposits and predict locations and depths at which important archaeological remains may be located. The novelty of this approach is not in the application of individual techniques to the problem but in the combined methodology, which enables a structured and cost effective programme of works to be formulated and provides the best chance to understand the subsurface. Although this approach has been developed to facilitate the location of archaeological sites buried at depth within the route corridor of development projects it is also suitable for locating fossil-bearing sequences and mapping stratigraphical units in Quaternary science. We demonstrate the approach using two examples from southern England. Copyright © 2007 John Wiley & Sons, Ltd.

Key words: alluvial archaeology; subsurface mapping; geophysics; cone penetration testing; boreholes; microfossils; Pleistocene; Holocene

Introduction

Quaternary researchers in the late nineteenth and early twentieth centuries were fortunate that the extent of the quarrying industry in northwest Europe allowed them unprecedented access to a

large number of sites containing Pleistocene sands and gravels. Today, however, terrestrial quarrying operations are much reduced and consequently it is often difficult to directly observe many important Quaternary deposits. Furthermore the limited numbers of new quarries opening restrict the opportunity to discover new bodies of sediment. Alternative methods for examining the subsurface are available and include test pits and trenches but they are limited

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because of the considerable depth of sequences encountered in many terrestrial and formerly marine situations. Alternatively, boreholes and other geotechnical sampling techniques such as cone penetrometers have been used in such situations to recover information on the nature of the buried sediment bodies as well as to recover samples for analysis in these deeper sequences.

Today a wide range of boreholing techniques and equipment exist (and vary between countries) and are commonly used to: (i) sample sediment bodies that are known to contain geologically important sequences (i.e. with faunal, floral or geochronological properties); or (ii) sample sequences thought to be 'characteristic' of a mappable sediment body.

For financial reasons it is less common to use borehole methods extensively to sample the subsurface in Quaternary research. This is particularly the case where the deposits are more than 5 m thick and when sequences are composed of hard sands and clays as well as gravels. In Britain the relatively restricted use of boreholes in exploratory Quaternary research is a result of high costs and difficult logistics (access to land, etc.). Unfortunately, it is often the case that during the occasions when high density sampling is carried out as a routine part of investigations associated with mineral extraction or ground engineering, the sampling strategies may not be ideal for Quaternary scientific investigation.

One area in which speculative (often large scale) subsurface investigations are undertaken and where the prime objective of the study is to determine the nature, distribution and formation history of the subsurface sediment package, is in contract, or developer funded, archaeology where the ultimate goal of subsurface modelling is the identification of locations at which archaeological remains may be buried (Bates *et al.*, 2000). In such situations investigations are devised in order to identify foci for trenching for artefact recovery (often costly) in areas of high archaeological potential. To allow for varying site surface and subsurface conditions as well as the individual requirements of the site (in terms of both developers, contractors and curatorial staff) a mixed method approach to investigating the subsurface has been developed involving bore-

holes, surface and subsurface geophysics (Bates and Bates, 2000) and ground geotechnical testing. This is integrated with rapid assessment of contained microfaunas (Foraminifera/Ostracoda) to allow a flexible and cost-effective response to development and hence subsurface investigation. The novelty of this approach is not in the application of individual techniques but in the combined methodology that enables a structured and cost-effective programme of works to be formulated that provides the best chance to understand the subsurface.

A mixed method approach is equally applicable to defining the likely subsurface foci of past human activities as it is to predicting the distribution and location of important interglacial deposits or in generating depositional models for regional landscape evolution. Here we describe two case studies in different regions with varying geological/geomorphological situations in southern England (Figure 1).

Investigating and mapping subsurface deposits

Geological investigations of areas containing thick, and complex, sequences of Quaternary sediments (e.g. Holocene alluvium found in the lower reaches of major river valleys (Devoy, 1979) or Pleistocene raised beach and river gravels on southern England's coastal plains (Bates *et al.*, 1997) typically begins with the examination of extant borehole data followed by mapping the surface expression of the deposits using quarry exposures, cliff sections, etc. Such an approach may be augmented by the occasional purposive borehole in areas known or thought to include sequences likely to contain geological or biological data required for palaeoenvironmental reconstruction, correlation or dating. This is typically the case in Britain, however, it contrasts with the situation in The Netherlands where the understanding and mapping of the geology throughout much of the country has been based on a large archive of borehole data that is available (Ebbing *et al.*, 2003; Weerts *et al.*, 2005). However, it is much rarer for subsurface investigations to be undertaken on a large scale where the objective is more speculative;

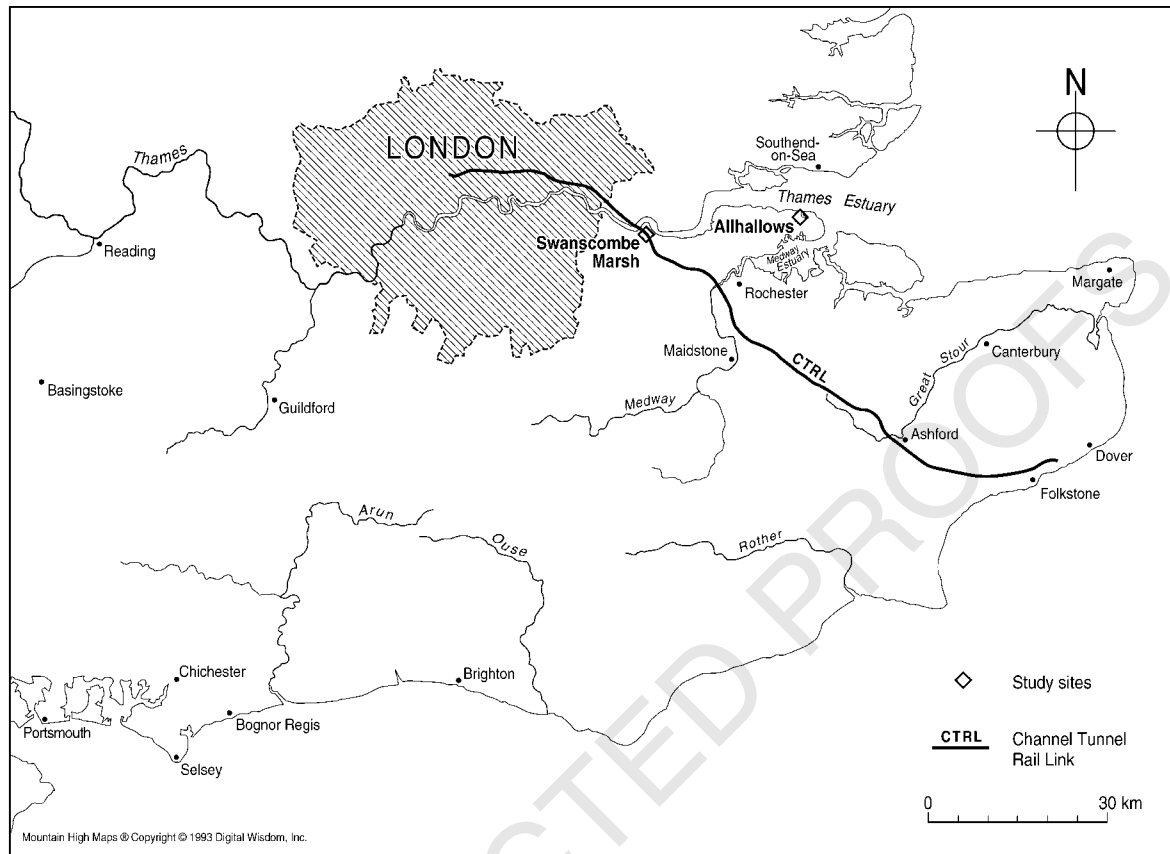


Figure 1. Site location plan for southern England showing the study sites at Swanxcombe Marsh and Allhallows.

exceptions to this are the surveys undertaken to characterize the potential of areas for mineral aggregate extraction. Recent evidence suggests the situation is now changing in the UK (Culshaw, 2005).

The rationale for the use of point-specific data (boreholes and test pit information) is that such information may be used to model and understand the geometry and topography of these subsurface sediment bodies (Chew, 1995) that are then linked together by assumptions about litho- or chronostratigraphical correlations. However, building confidence in these models is crucial because we are unlikely to have a complete knowledge of the systems either across space or through time (Bowden, 2004). Today it is increasingly common to visualize these bodies using geological modelling systems which allow the construction of integrated three-dimensional

models that provide the user (and reader) with pictorial images of the subsurface (Culshaw, 2005). The three-dimensional geological models consist of a structural framework of two-dimensional surfaces representing stratigraphical boundaries, chronostratigraphic horizons, etc., that aim to produce a three-dimensional representation of subsurface deposits allowing the researcher the opportunity to investigate the relationships between deposits and the ability to predict sequence occurrence away from known data positions (Jones, 1992). Images produced from the models imply a robustness with respect to the 'hardness' of the surfaces being created as well as the reliability of the relationship between data points when, in fact, our understanding of these surfaces and correlations are based upon often inadequate sampling intervals (of boreholes) and interpretations of sequences based on

the application of facies models to the stratigraphies coupled with the surface expression of the associated sediment bodies.

One of the major outcomes of subsurface modelling are the two-dimensional/three-dimensional surfaces that may be used (where appropriate) to reconstruct palaeogeographies for areas of the landscape for which surface sediment expression bears little or no relationship to those buried at depth. Within the framework of archaeological investigations associated with development/destruction of sites such an approach has considerable practical use due to its ability to enable the user to identify buried landsurfaces and reconstruct local or regional palaeogeographies through a multidisciplinary palaeoenvironmental investigation that allows a sequence of palaeogeographic maps to be constructed. Examining these maps with a knowledge of the preferred loci of human activity allows those locations at which such evidence may exist to be identified (Deeben *et al.*, 1997; Bates *et al.*, 2000). Other studies have a more geological objective (Chen *et al.*, 1996; Berendsen and Stouthamer, 2001; Culshaw, 2005).

In the course of many archaeologically orientated projects, correctly predicting the distribution of certain subsurface deposits with a high archaeological potential has considerable financial implications for the developers. Unexpected archaeological finds may cost construction projects tens of thousands of pounds per day in project down-time while excavation proceeds and consequently the need to 'best guess' the archaeological significance of sites is paramount. However, it has been found that to achieve the goals of subsurface modelling applying only borehole based surveys is often an inadequate response in many situations. This is particularly the case where approaches need to be flexible and vary from site to site depending on both the geological conditions as well as project budgets and practical limitations imposed by ground conditions and the site infrastructure. Additionally, extra information may often be required from areas of the site between sample (borehole) locations and consequently it has been necessary to use not only boreholes but other approaches such as cone penetration testing (CPT) as well as surface and subsurface geophysics to meet the

requirements at individual sites and fill in gaps between boreholes.

Similar arguments have been made by those involved in geotechnical studies associated with engineering construction activities (Culshaw, 2005; Lenham *et al.*, 2005). Characterization of the ground conditions in order to determine appropriate construction methods generally occurs in the initial stages of project development and may involve a range of techniques including borehole, CPT and geophysical techniques. However, it is recognized (Zhu *et al.*, 2003) that ground behaviour cannot be established and forecasted with 100% accuracy and that in order to minimize uncertainties of ground conditions careful consideration should be given to understanding the limitations of the information sources and the ways in which the information is combined to formulate models and interpretations. The limitations of a typical ground investigation survey are discussed in detail by Salvany *et al.* (2004).

In many cases an integrated approach to archaeological investigation using a range of geological, geomorphological and palaeoenvironmental perspectives derived from direct and indirect observations of subsurface stratigraphies is desirable prior to developing a conceptual model containing palaeosurface information. In some cases this information can be then used to place the archaeological site/area of investigation within a (pre)historical context as well as defining areas in which evidence of *in situ* activity by past human groups/environments may occur. In individual cases the mixed method approach needs to be structured in order to address the needs of the site/problem and an important element of the investigation is the clear articulation and discussion of the methods used. In particular, the limitations of the sampling approaches and the impact that that approach may have on the interpretation derived from the investigation (i.e. the confidence limits that may be placed on the conclusions of the investigation that relate to the location of sample points and correlations made between sample points) need to be articulated in order for confidence to be placed in the conclusions drawn. Discussion of this kind is rarely seen in the published literature, however, although this is of particular

importance where complex frameworks for site and sequence correlations may be based on individual classes of data (e.g. small mammals, etc.).

Methods

Boreholes

Information from boreholes is often available in geotechnical reports (Clayton *et al.*, 1995; Terra Nova, 2004) undertaken for a range of site investigation purposes and can provide information suitable for deriving predictions relevant to understanding the three-dimensional geometry of the buried sediment bodies. However, it should be remembered that the distribution of borehole data across a given site (as well as the methods and techniques used) is typically dependent on the geological conditions and the type of structure and construction design and methods to be used (Bell, 1993). Additionally, because such data collection is driven by commercial requirements, it may have only restricted predictive value in geological terms. In such situations, preliminary models derived from engineering boreholes may be usefully supplemented by “purposive boreholes” during a second phase of drilling investigation.

A range of equipment is available for investigation of subsurface contexts from unpowered manually driven devices such as Hiller borers and Russian (D-section) corers which retrieve variably undisturbed sediment cores to powered mechanical corers with a number of interchangeable coring heads (e.g. Eijkelpkamp system), small portable drill rigs including the Terrier 2000 self-propelled drill rig with a windowless liner sampling system and wireline percussive drilling (Clayton *et al.*, 1995; Bates *et al.*, 2000). Selection of appropriate drilling equipment varies dependant on a number of factors including costs, site ground conditions, nature of the overburden, the type of sediment likely to be encountered in the subsurface and the nature of the samples required for analysis.

Applications of coring and augering methods in archaeology (Barham and Bates, 1994a) include tracing the lateral extent of near-surface sites as part of cultural resource evaluations

(Stein, 1991), investigation of deposit depth and composition prior to excavation on middens, mounds and tells (Reed *et al.*, 1968; Barham, 1993), the coring of rockshelter deposits (Bailey and Thomas, 1987), assisting in reconstructing off-site palaeoenvironments (Barham, 1999) and understanding the development of urban areas (Densem and Doidge, 1979; Ammerman, 2000). Coring has also been deployed to assist in mapping archaeologically significant facies environments beneath urban areas, e.g. tufas in the lower Dour, Kent (Bates and Barham, 1993), and to stratigraphically link excavated sequences into adjacent palaeolandforms and landsurfaces (Barham and Bates, 1994b). In Europe, coring coupled to excavation trenching has recently been used in the study of agricultural systems buried beneath alluvium (Martín-Consuegra *et al.*, 1998).

Non-archaeological uses include the construction of lithostratigraphical models of Quaternary-age sediment bodies, including Holocene alluvium members and formations (Bridgland, 1988; Gibbard, 1985, 1994) and the recovery of samples for biostratigraphical analysis, radio-carbon dating and palaeoecological reconstruction of floodplain environments (Devoy, 1979). Good examples of the use of large datasets in the construction of subsurface models include the work of Chen *et al.* (1996) on the North China Plain, Berendsen and Stouthamer (2001) in the Rhine–Meuse delta region, Weerts *et al.* (2005) in The Netherlands and Culshaw (2005) in Manchester and the Neath/Swansea area of South Wales.

Cone penetration testing

The cone penetrometer was developed in The Netherlands in 1934 (Vermeiden, 1948) and has gained a wide acceptance within geotechnical engineering for determination of soil properties and stratigraphy. The method is based on the interpretation of the resistance of the tip of the cone rods and friction on the trailing sleeve as the cone is advanced into the ground. The technique is fast and economic and useful for subsurface sediment characterization and stratigraphical analysis (Figure 2). It is especially suited to fine-grained soil types, but caution must be given

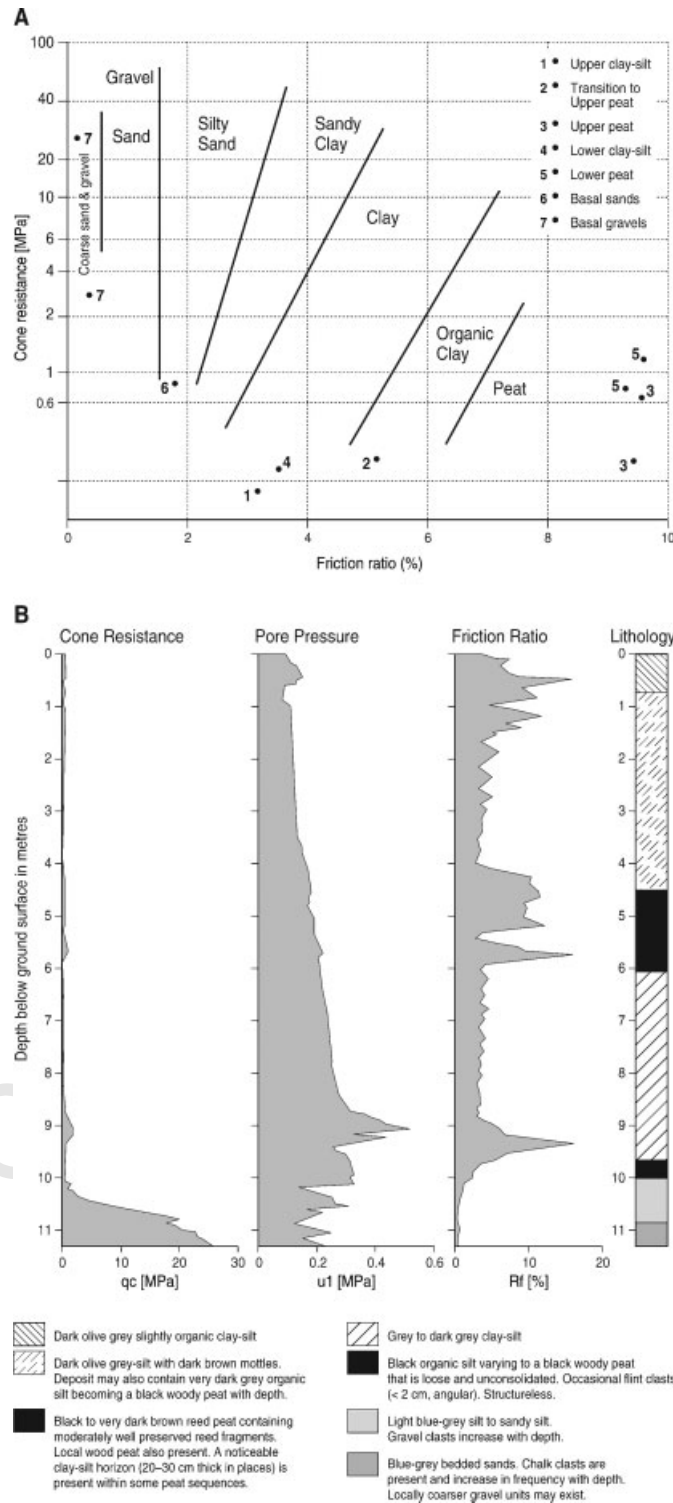


Figure 2. Cone penetration test (CPT) data log and interpretation. (A) Guide for estimating sediment types from cone resistance/friction ratio plots. (B) Cone resistance, pore pressure and friction ratios from sample location in Swanscombe Marsh and lithology as revealed by adjacent borehole.

to interpretation of CPT data in coarse sand or gravel, with the latter often causing complete cone rejection.

A typical setup consists of a 20 t capacity hydraulic penetrometer mounted in a heavy tracked vehicle ballasted to produce a reaction weight of about 14 t. A 7.5 or 5 t capacity electric cone may be selected such as the Fugro piezocone penetrometer. In this case the cone has a 60° apex at the tip, a 10 or 15 cm² base area and a 150 or 200 cm² sleeve surface area combined with a pore-water pressure element (and resistivity probe). The cones are vertically advanced at a standard rate of 2 cms⁻¹ for readings of tip resistance and sleeve friction. Both tip resistance and sleeve friction are related to soil type and moisture content and the ratio of the tip resistance to the sleeve friction provides information that can be used to classify soil type (Figure 2A; Table 1). Pore pressure readings can also be taken during the cone drive. Resistivity of the sediment can be measured using an array of electrodes that record the bulk resistivity of the soil around and between the electrodes. Bulk resistivity represents the total electrical resistance contributed from all sources (grains, matrix material and water) and is a useful downhole check on surface-measured ground resistance properties (see below). Output from the cone penetrometer includes curves of tip resistance, sleeve friction, pore content and electrical resistivity with depth. An example of a CPT log and interpreted lithostratigraphy is shown in Figure 2B.

Examples of the application of CPT data to Quaternary geological/palaeoenvironmental or archaeological projects are limited but it has been used to construct large-scale stratigraphical models of the Po Plain (Amorosi and Marchi,

1999), produce cross-section data (Howie *et al.*, 1998) and locate the presence of buried structures under the Metropolitan Cathedral in Mexico City (Ovando-Shelley and Manzanilla, 1997).

Electrical geophysical investigation techniques

Electrical techniques are used extensively in near-surface geophysical investigations and include both direct current (DC) resistivity methods and indirect electromagnetic (EM) methods. All electrical techniques induce electrical currents in the ground, which are used to measure the variation in ground conductivity, or its inverse, resistivity. Different materials (solid rock and drift deposits), and the fluids within them, show different response to an applied electrical current. In general, sequences with high clay contents show higher conductivity as do saturated sequences, especially sequences where saline waters are present. Conversely sequences with low clay content, sands and gravel or bedrock such as limestones and chalks, show low conductivity or high resistivity (Table 1). Direct current resistivity is one of the most common methods for field practice, relying on directly placing an electrical current into the ground using two electrodes and measuring the response (the electrical potential) to that current over a set distance between two additional electrodes. By combining measurements made at a number of different electrode locations and separations it is possible to construct geo-electric pseudosections. These sections can then be interpreted as geological sequences when correlated with borehole or CPT ground-truth data. A number of commercial systems have been designed for the

Table 1. Sediment classification based on cone penetration testing data (based on Clayton *et al.*, 1995) and approximate ranges of physical properties for some common materials. (After Telford ^{Q1} *et al.*, 1990; Reynolds, 1997; Guegiem ^{Q2} and Palciauskas, 1994.)

Sediment type	Cone resistance	Friction ratio	Excess pore pressure	Density	P velocity	S velocity	Resistivity
Organic sediments/peat	Low	Very high	Low	1.1–2.4	100–500	100–500	10–300
Normally consolidated clay	Low	High	High	1.6–2.6	1000–2500	500–1500	1–100
Sand	High	Low	Zero	1.7–2.3	200–2000	100–1500	50–500
Gravel	Very high	Low	Zero	1.7–2.4	400–2500	200–1500	50–500

Q1	100
Q2	101
	102
	103
	104
	105
	106
	107
	108
	109
	110
	111
	112

rapid acquisition of two-dimensional pseudo-electrical resistivity sections and include the Lund System (Abem Ltd), Campus Instruments and SYSCAL (Iris Ltd) systems.

Electromagnetic techniques have been developed and adapted extensively over the past 15 yr to map lateral and vertical changes in conductivity (Reynolds, 1997). Two types of electromagnetic survey are currently practised: (i) time domain electromagnetic (TDEM) surveys, which are mainly used for depth soundings and more recently in advanced metal detectors; and (ii) frequency domain electromagnetic (FDEM) surveys that are used predominantly for mapping lateral changes in conductivity. Both electromagnetic survey types rely on inducing electrical currents in the ground by creating an electromagnetic field in a coil of wire located at the surface. In FDEM, the secondary electric currents are recorded by an additional electrical coil located at the surface. The FDEM survey has proved particularly successful in mapping near-surface and surface changes in conductivity because at low electrical induction numbers the ratio of the secondary and primary magnetic fields is linearly proportional to the terrain conductivity (McNeill, 1980). The FDEM survey potentially represents one of the most useful geophysical techniques in archaeological investigations, as changes in conductivity are often associated with differences between archaeologically significant lithological sequences (see Table 1) and also disturbed ground. Instrumentation exists to survey to a range of depths by using different source and receiver coil separations (see Table 2).

Both DC and EM approaches have been successfully used to map lithology and channel-belts and valley fills by Baines *et al.* (2002), to study the palaeohydrography and subsurface geology of sites in the Nile Delta (Ibrahim *et al.*,

2002) and in Sussex to map and model buried marine sediments associated with the Goodwood-Slindon and Brighton-Norton Raised Beaches (Lewis and Roberts, 1998; Bates *et al.*, 1999). Dalan (1991) used instrumentation with 3 m and 0.75 m coil separations to map features on an archaeological site in Illinois

Designing a survey strategy

Developing a methodology for implementation within projects either associated with archaeological investigation works or speculative ground investigation for Quaternary research should be approached on a site by site basis. However, a number of elements may be combined together to facilitate investigation. Desk-based study of extant data sources, in particular records held by national geoscience bodies (Culshaw, 2005) as well as local authorities, often provide substantial quantities of data from previous geotechnical investigations. Design of the field programme will be influenced by both this extant data as well as project-specific aims and objectives. Commonly a two-step approach to field investigation is recommended commencing with field trials for the techniques proposed (in order to clarify their suitability as well as to obtain preliminary data sets). This stage will allow appropriate techniques to be selected and provide a first-order subsurface model. The precise timings of works (i.e. geophysical survey, borehole drilling, etc. will be dependant on a number of factors but typically geophysical surveys would be concluded prior to, or during, the final phase of ground-truth drilling and sampling). Finally recovery and laboratory logging of cores coupled with assessment of the contained microfossil context (in this case Foraminifera and Ostracoda) allows initial

Table 2. Approximate depth of investigation ranges for Geonics Ltd, electromagnetic survey instruments

	Instrument				
	EM-38	EM-31	EM-34	EM-34	EM-34
Coil spacing (m)	1	3.7	10	20	40
Horizontal dipole (m)	0.75	3	7.7	15	30
Vertical dipole (m)	1.5	6	15	30	60

environments of deposition to be assigned to each sedimentary unit.

The successful design of a mixed-method approach to investigation is dependent on the careful construction of the survey methodology based on the consideration of a number of key geological and practical (finance/accessibility) factors. Key points to consider are:

- (i) the nature of the geological/geomorphological system;
- (ii) field study size area;
- (iii) project aims and objectives and the goals of the project in terms of information required and models being tested;
- (iv) sequence recovery or sequence logging;
- (v) depth of sequences;
- (vi) target size;
- (vii) measurement/sampling station interval.

While many of these points are likely to be very familiar to readers they are rarely discussed in the literature. Considered discussion of the sampling strategies used, their strengths and weaknesses and the limitations in the study should form an essential part of the discussion of the project and write-up. Failure to inform the reader and consider such information will make it difficult to address the success of a project. For example, the failure to locate certain deposits or certain classes of palaeoenvironmental data need to be considered in the light of the methodology used to obtain the samples as well as on the systems from which the material came, etc. The dangers of inadequate survey design have recently been discussed by Salvany *et al.* (2004) in the Agrio River valley, Spain.

Case Study 1: Thames River Crossing south site, Kent

This site was investigated as part of work associated with archaeological mitigations on the Channel Tunnel Rail Link and lies on the south bank of the river Thames downstream of the major crossing point at Dartford (Figures 1 and 3). Construction impacts here consisted of the excavation of a 450 m long box (including a tunnel boring machine launch chamber) taking

the railway through the Holocene floodplain deposits and underlying Pleistocene river gravel sediments into the basement Chalk beneath the river. Desktop evaluation of borehole records from the area identified the site as a likely area for preserving archaeological remains within the Holocene alluvial sequence of peats and clays. However, insufficient information existed to adequately understand the nature and location of possible archaeological sites. Because of sequence depths (5–10 m of Holocene deposits) trial trenching in advance of construction activity, following standard archaeological practice, was both impractical and costly. Furthermore, excavation during the construction window would be an expensive exercise that also ran the risk of major delays following unexpected discoveries. Consequently a mixed-method approach was adopted in order to attempt to precisely define areas of high archaeological potential and/or interesting palaeoenvironmental sequences and therefore focus excavation attention to limited areas of the construction footprint. These areas could then be examined either in advance, in targeted trenching exercises, or excavated during planned time slots within the overall construction timetable.

The investigation strategy developed was based on a review of the geotechnical information from the site (boreholes, CPT data) in order to develop a field programme comprising a combined borehole survey utilizing both shell and auger (percussion) drilling and Mostap (continuous undisturbed sampler system) core sample techniques, cone penetration testing (CPT) and surface and subsurface geophysics in a structured approach maximizing the information return on each technique within the area of the major excavations associated with the box construction (Figure 3). The intensity of survey points and transects and the number of sample locations was limited to an extent by cost implications and access constraints, but the final sampling resolution (in this case beyond the construction footprint in order to adequately understand the subsurface stratigraphy) was predicted to be adequate to enable a detailed reconstruction of the buried stratigraphy and to identify the subsurface location of the key topographic locations for archaeological activity.

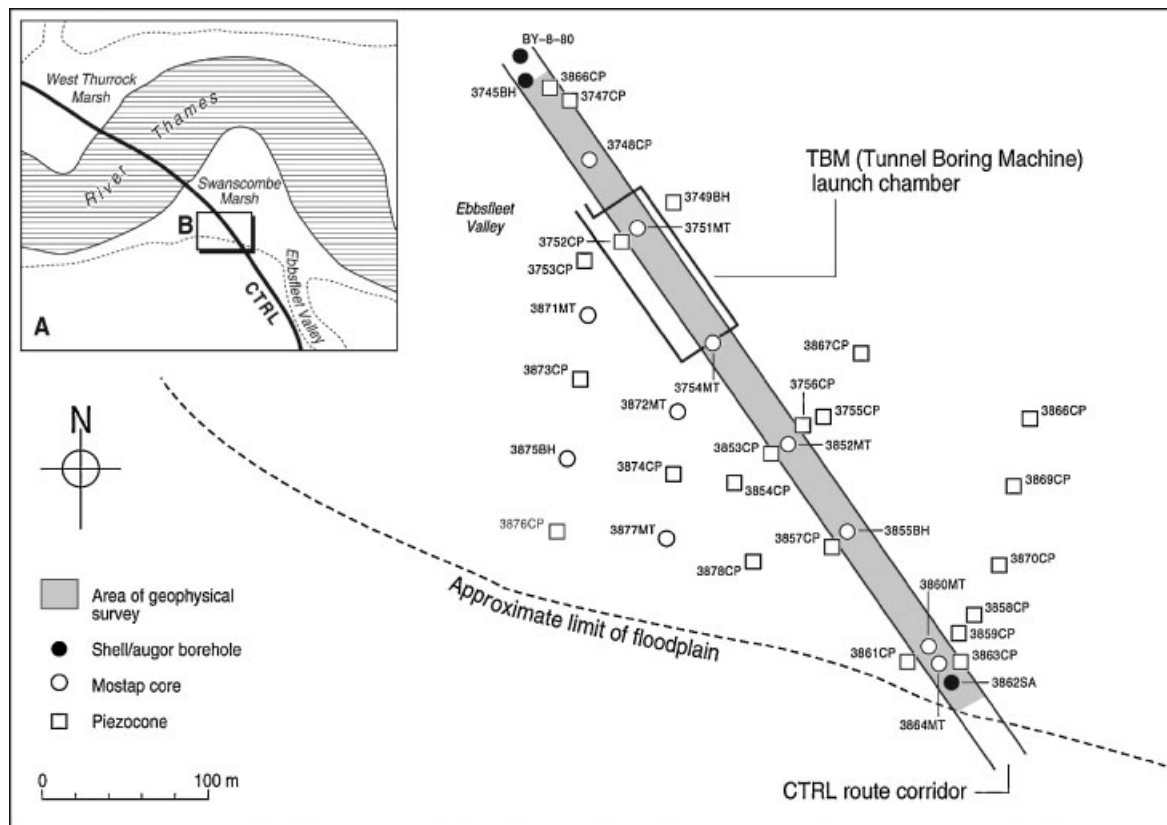


Figure 3. Thames River Crossing (Swanscombe Marsh) borehole, cone penetration test (CPT) and surface geophysics location points.

The initial geophysical survey (Figure 4) was conducted in order to investigate the subsurface electrical properties of the deposits and provide more localized targets for CPT and borehole sample recovery. An electromagnetic survey was conducted using the Geonics EM-31 and EM-34 terrain conductivity instruments across the full width of the route corridor and an Abem Lund electrical resistivity instrument along the central line of the route (Figure 4, upper and lower). The results of both electromagnetic surveys indicated lower conductivity at the southeast end of the section (shown as darker shades on the figure). This decrease in conductivity corresponds with the known decrease in depth to chalk surface, as it dips steeply north beneath the site from approximately 4 m depth to greater than 20 m depth. Above the chalk, a gravel layer was identified on the CPT data by cone refusal (base

of logged data) (Figures 2B and 5A) and this was correlated with a small increase in resistivity on the two-dimensional geoelectric pseudosection data (Figure 4, middle). Furthermore, the pseudosection indicated two possible steps in the gravel profile and it is proposed that these might represent palaeoterraces.

Following the non-invasive geophysical survey, targets for subsurface investigation were noted and it was decided that ground investigation techniques to rapidly characterize sedimentary properties of the deposits (CPT) and recover sediment samples (Shell and Auger boreholes and Mostap holes) (Figures 3 and 5) were also required. The principle considerations in selecting techniques involved the need to recover sample material for characterization and dating as well as the need to cover large areas of the site to recover proxy information on

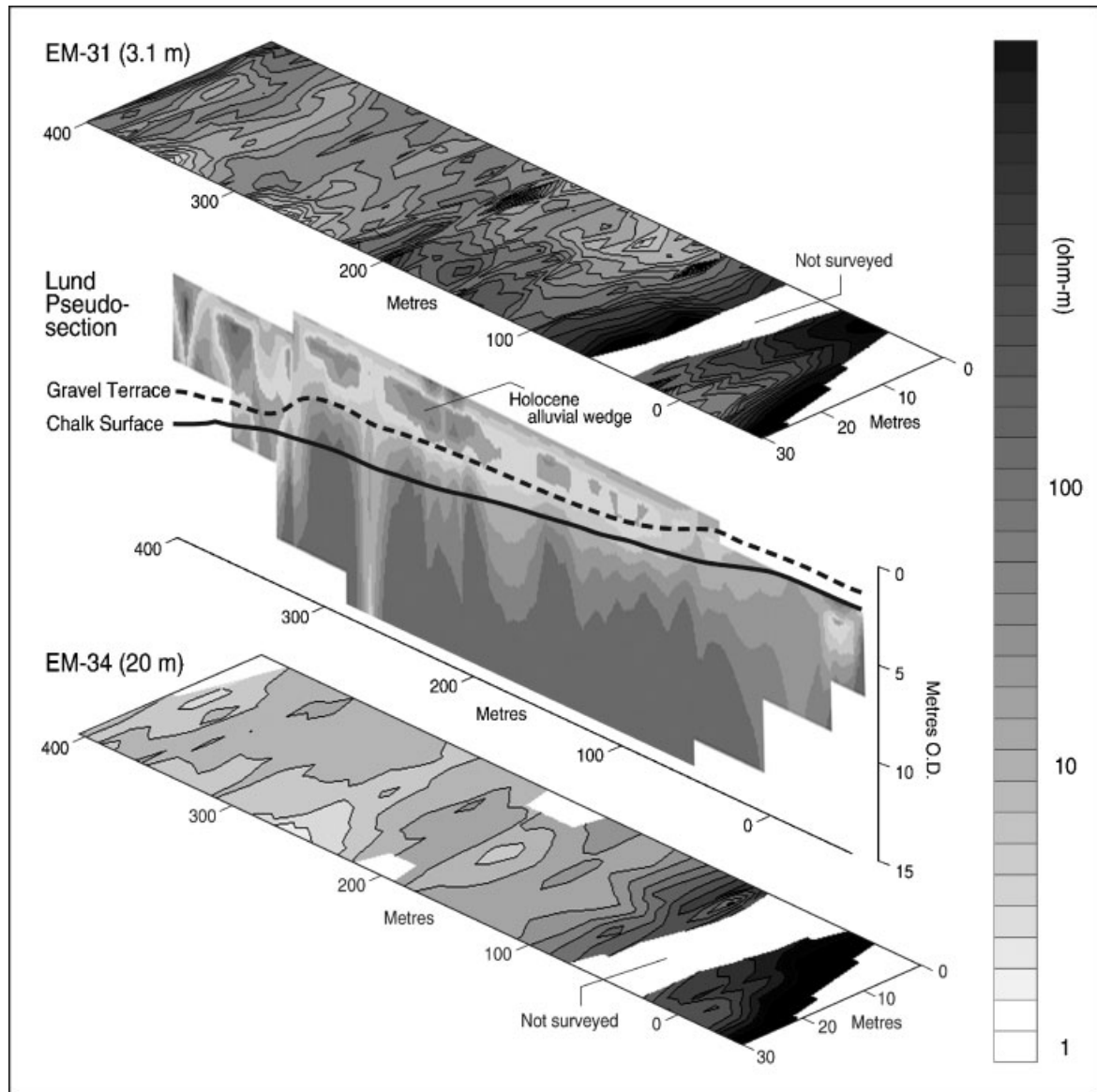


Figure 4. Geophysical data from Thames River Crossing (Swanscombe Marsh) survey area: (top) EM-31 surface geophysics; (middle) Lund pseudo-section; (base) EM-34 surface geophysics.

subsurface sediment types. This was undertaken by the CPT survey (Figure 5A), which provided the information for locating the Mostap cores (Figure 5B) in order to obtain samples for palaeoenvironmental analysis and absolute dating. The use of shell and auger boreholes at either end of the sample transect was governed by the need to penetrate the underlying gravels (which

CPT/Mostap cores cannot) and record the level of the chalk rockhead. Consequently a combination of sampling techniques was used to recover 1.5 m continuous cores through the soft sediments (Mostap sampling), 0.45 m cores through the soft sediments and bulk samples from the underlying gravels (Shell and Auger sampling).

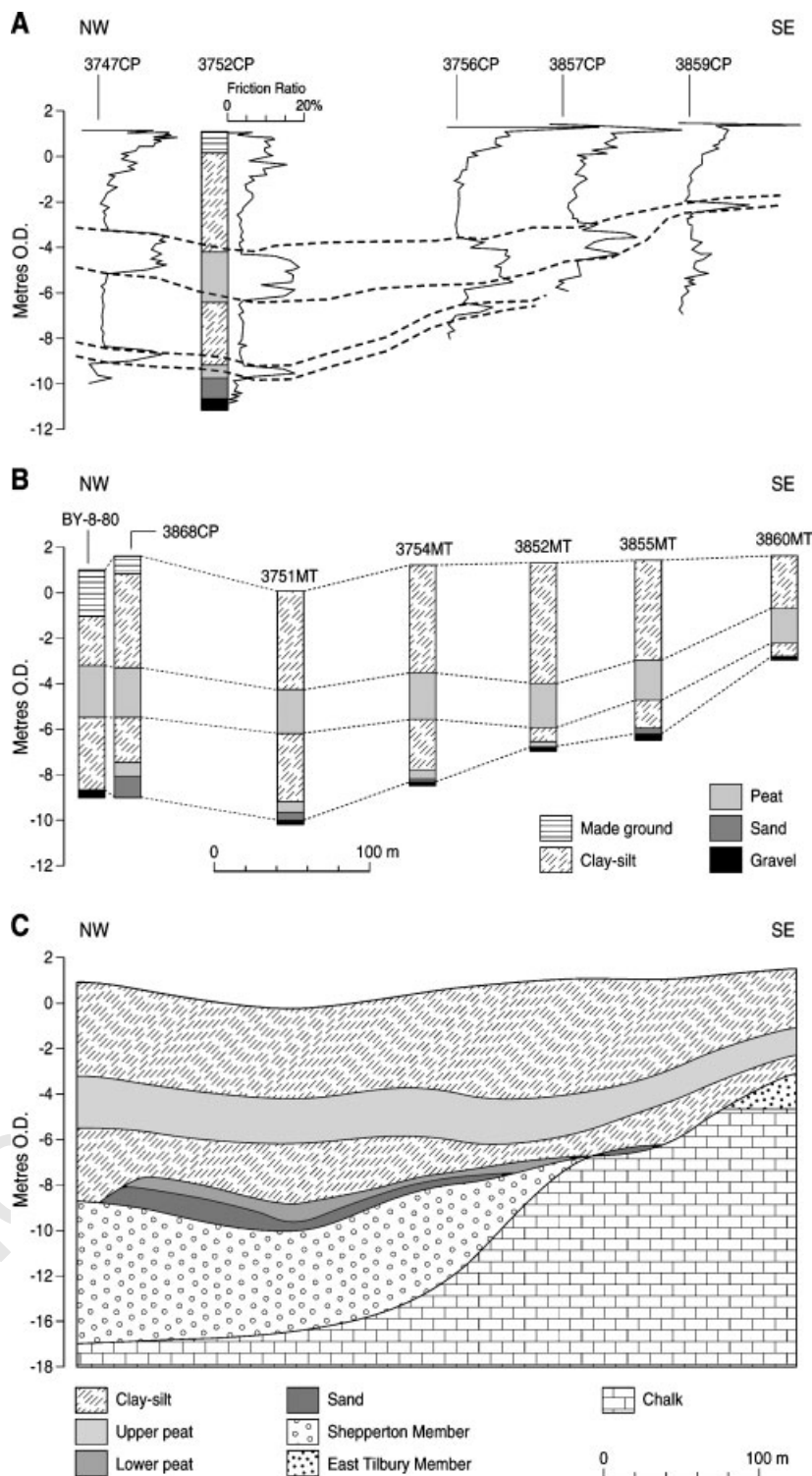


Figure 5. (A) Cone penetration test (CPT) results from selected test locations in Thames River Crossing (Swanscombe Marsh) area. (B) Lithology of selected boreholes. (C) Interpreted lithostratigraphical section based on CPT and borehole information for the Thames Crossing area.

In order to understand the nature of the sequences, and compare results between techniques, the information from the CPT testing (Figure 5A) and Mostap/Shell and Auger drilling (Figure 5B) have been combined and a number of key stratigraphic units identified within the study area (Figure 5C; Table 3). Many of these units can be traced laterally across the site and provide a framework for the interpretation of site history and archaeological potential.

The CPT data (Figure 5A) clearly shows the presence of two peaks in friction ratios below the high associated with the modern ground surface. Of these peaks the uppermost (VII), occurring between depths of -3 m and -6 m OD towards the northern end of the box and rising in the southerly direction, is the most prominent. In places the upper peak can be seen to be a double peak (3752CP, 3857CP) with a corresponding dip in values in the middle. The lower peak (-9 m rising to -7 m OD southwards before disappearing, V) is less marked. Both peaks can be inferred to represent peat units (Figure 5B). These results match closely those obtained from the direct observation of the sequences through the recovered drill cores (Figure 5B), where two major peat units can be traced southwards along the route corridor. They are both overlain by clay-silt units (VI and VIII).

The results of the investigation have produced significant quantities of data that enhance our knowledge of the geometry of the major sediment bodies within the area of the southern approaches to the tunnel and in particular define the nature of the early Holocene topographic template (*sensu*^{Q3} Bates, 1998; Bates and Whittaker, 2004) marked by the gravel-chalk interface (Figure 6). The topographic template is underlain by sands and gravels below -8 m OD (III) throughout much of the northern area of investigation (as evidenced in the shell and auger boreholes at the northern end of the box). This sand and gravel is likely to correlate with the Shepperton Member and the formation of the gravel post-dates 15 ka (Gibbard, 1994). To the south a rise in this surface is noted and a thin gravel spread is present at the southern margins of the site (II). The sediments capping this higher ground are probably equivalent to older Thames gravels, probably part of the East Tilbury Marsh

Member (*sensu* Gibbard, 1994). A denuded chalk (I) surface connects these two zones and is likely to consist of patches of soliflucted chalk and exposed bedrock (Figure 5C).

The majority of the sediments overlying the gravel/bedrock topography consist of alternating peat/organic silts and clay-silts similar to those previously described in the area (Devoy, 1979) (Figure 5B). In the case of both peat/organic units (V and VII) they can be seen to thin out south against the rising valley margins. The basal peat is underlain by slightly sandy clay-silts (IV). The presence of a twofold subdivision of the uppermost peat (VII) (with an intervening clay-silt) indicates that a phase of channelling or temporary submergence within the peat-forming period may have occurred. This peat appears to become patchy towards the southern margins of the floodplain. Of particular significance from the archaeological perspective was the identification at the southern end of the route corridor of a topographic high or headland feature (Figure 6). This promontory was considered a likely location for human activity pre-dating the period of submergence of the landscape beneath the ever encroaching alluvial envelope. On the basis of previous work in the Thames (Bates and Whittaker, 2004) this is likely to have occurred around ca. 5600 yr BP (i.e. early Neolithic).

Confirmation of the nature of the stratigraphical sequences within the study area was subsequently possible through direct observation of the deposits. A single, sheet piled, trench was sited and excavated by mechanical excavator through the alluvium. Borehole data indicating the presence of the intermittent peat unit (VII) resting on the gravel high potentially sealing any artefacts beneath the peat provided target depths for excavation. As a result it was decided that mechanical excavation should cease some 20 cm above the base of the peat. Hand excavation followed to expose the peat base and the contact with the underlying clastic sediments. The excavation produced (Table 4) a significant number of artefacts associated with a disturbed landsurface (developed in IV) beneath the peat (VII) confirming the predications made on the basis of the various phases of ground investigation (the lowermost peat (V) and overlying

Q3

Table 3. Major lithostratigraphical units identified at the CTRL Thames Crossing south site and CPT/EM characteristics

Unit number	Lithological description	EM characteristics	CPT characteristics			Inferred environments of deposition	Geological Member
			Cone resistance	Friction ratio	Excess pore pressure		
VIII						Modern topsoil.	
VII		Moderately resistant Conductive		Rising to high Low		Intertidal or subtidal mudflats	
VI		Moderately resistant		High		Alder carr or reedswamp wetlands	Tilbury Member
V		Conductive		Low		Intertidal or subtidal mudflats	
IV		Moderately resistant		High		Alder carr or reedswamp wetlands developing from freshwater channel system	
III	Poorly sorted flint gravel with subangular to angular flint clasts and variably sandy matrix	Resistant				Cold climate periglacial braided channel system	Shepperton Member
II	Poorly sorted flint gravel with subangular to angular flint clasts and variably sandy matrix	Resistant					
I	Hard, dense chalk that is soft, mixed clay-silt, chalk and angular flint clasts towards top	Highly resistant				Cold climate periglacial braided channel system	East Tilbury Marsh Member
							Chalk bedrock

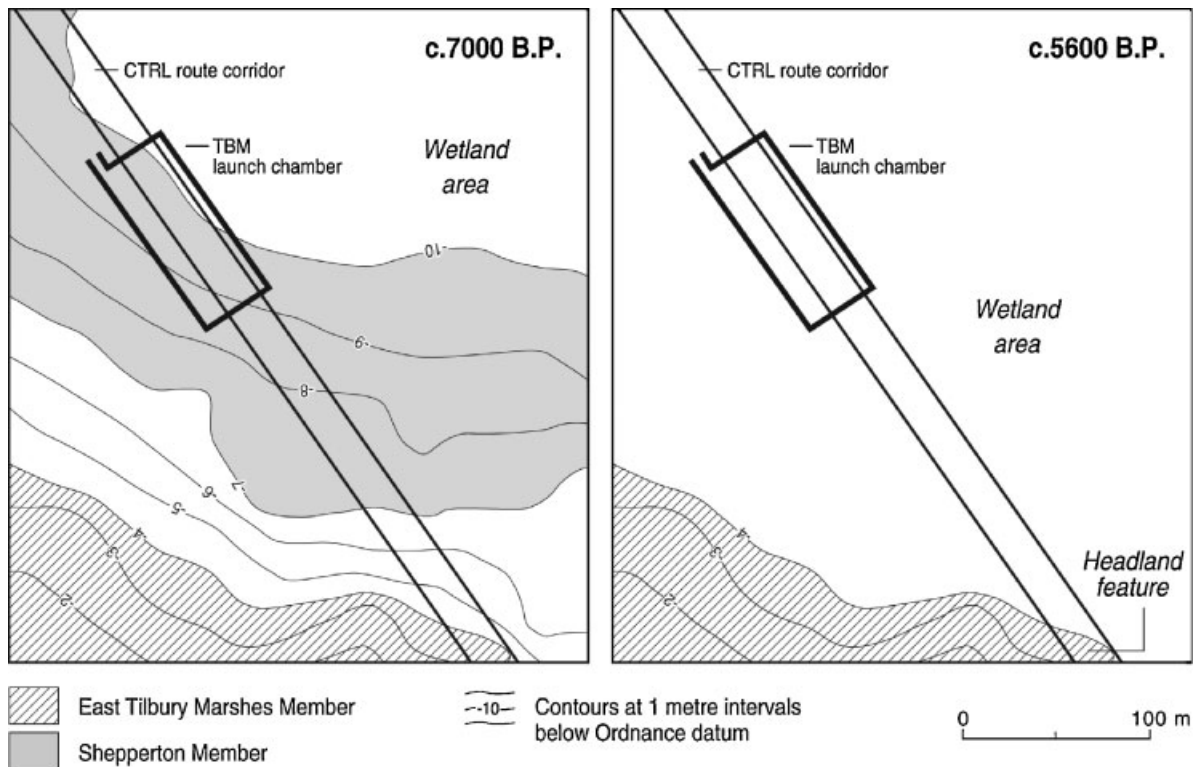


Figure 6. The topographic template (gravel/bedrock surface) constructed from borehole and cone penetration test (CPT) data within the route corridor. Two maps showing the possible distribution of wetland and dry ground associated with the early Holocene landsurface at -10 m (ca. 7000 yr BP) and -4 m OD (ca. 5600 yr BP). The map for 5600 yr BP indicates the position of the headland feature thought likely to be associated with Neolithic human activity.

clay-silt (VI) is missing in this part of the site). As a result of this strategy being adopted minimal risk to development was taken and the works were scheduled into a complex construction programme from an early stage. An additional check on the broad patterns of sediment accumulation was possible through careful monitoring of the deposits excavated during the construction of the cut and cover works associated with the railway. These observations confirmed the patterns identified from the borehole/CPT and geophysical surveys.

Case study 2: Allhallows, Kent

Allhallows lies at the northern end of the Hoo Peninsular close to the confluence of the River Medway and the Thames Estuary (Figure 1).

Pleistocene deposits including fine-grained fossiliferous deposits at the Allhallows Golf Course (Bates *et al.*, 2002) and gravels beneath Binney Farm (Bridgland, 2003) lie adjacent to a branch of the modern floodplain (Figure 7). Despite recent work investigating the Medway sequences the Pleistocene deposits of the Medway remain poorly known and understood in relation to the better known sequences of the Lower Thames (Bridgland, 2003). This is, in part, a function of the scarcity of faunal and floral remains from the Medway sites. Until the discovery of the Allhallows Golf Course site, the interglacial deposits at Kingsnorth (Bates, 1999) and now additional interglacial deposits here at Allhallows, the only site in the lower Medway with faunal remains pre-dating the Devensian was located at Upnor where the remains of a straight-tusked elephant was discovered in

Table 4. Thames River Crossing South archaeological excavation trench stratigraphy and associated archaeological remains

Depth (m OD)	Lithological description	Context number	Unit number	Archaeological finds	Inferred environments of deposition
0.32 to 0.10	Mid-orange-brown clay-silt with frequent rooting	01	VII		
0.10 to -0.20	Mid-grey clay-silt with occasional root canals	02	VII		Intertidal or subtidal mudflats
-0.2 to -0.65	Mid-grey clay-silt.	03	VII		
-0.65 to -1.40	Dark greyish brown peat	04	VI	26 flint flakes and 4 pieces of burnt flint (mainly from lowermost 100 mm). Occasional animal bone fragments	Alder carr or reedswamp wetlands
	-----Surface-----			27 flint flakes, 62 pieces of burnt flint, 4 pieces of burnt flint flakes and 1 sherd of shell-tempered pottery	Weathering horizon (?) representing stable surface developed on surface cut into underlying deposit by ?fluvial channelling
-1.40 to -1.90	Mid-greenish-grey clay-silt containing occasional roots and small pieces of wood	06	?V	37 flint flakes and 5 pieces of burnt flint (from upper 100 mm of unit)	Either floodplain fluvial overbank situation or cold climate solifluction conditions
-1.90 to -2.30	Mid-grey/white silty clay and chalk clasts, occasional sharp, angular fragments of flint. Becomes chalk rich with depth	05	?I		Degraded upper part of Chalk bedrock

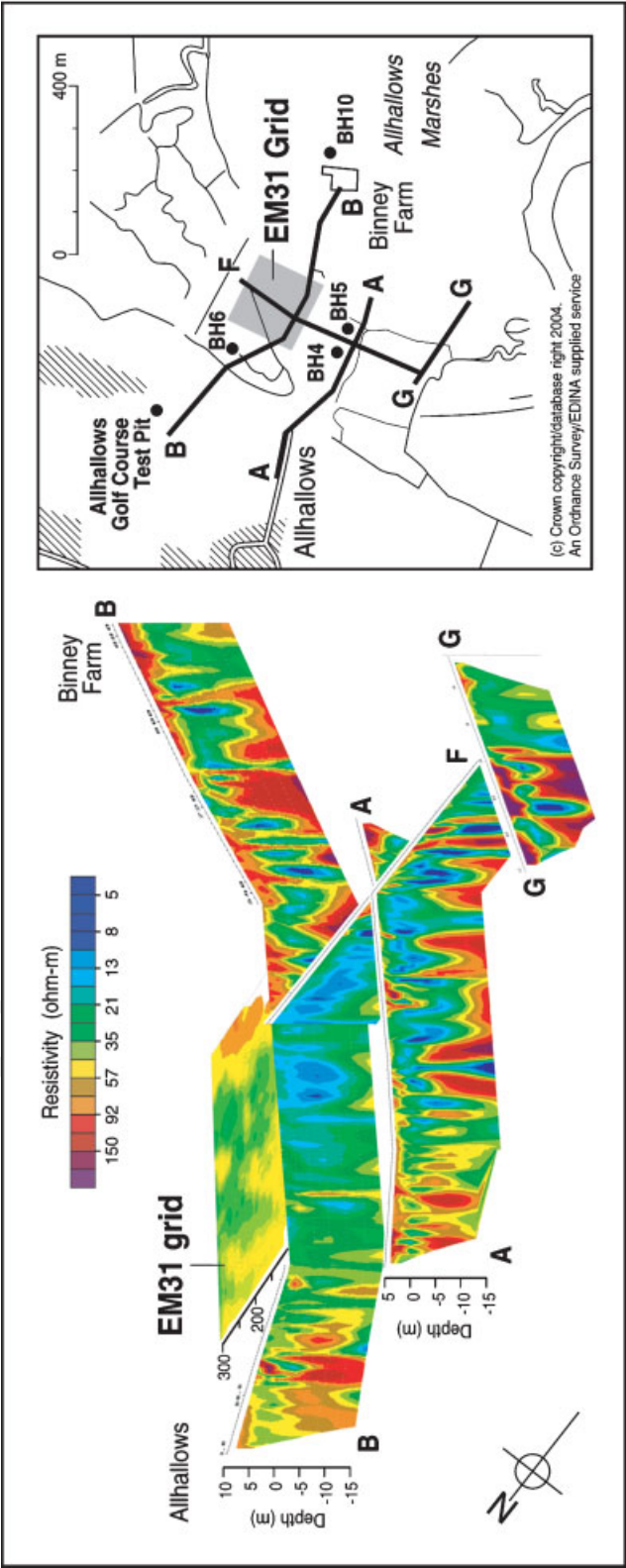


Figure 7. Allhallows site. Inset map showing distribution of transects, survey grid and boreholes. Fence diagram showing EM31 grid results and electrical pseudosections.

TPC

solifluction deposits in the early 20th century (Andrews, 1928).

The site at Allhallows was initially selected for investigation in order to examine relationships between sediment bodies at the edge of the Holocene estuary and their contained post-glacial archaeology. Understanding the relationship between deposits flanking the edges of the floodplain (colluvium) and the Holocene deposits of the floodplain, possibly containing evidence from human activity, was also considered likely to provide proxy information on changes to the estuary in the later Holocene. The Holocene sediments had been mapped by the BGS (1997) in the vicinity of the site but the mapped depth of Holocene sediments (3 to 4 m) appeared anomalously low given the downstream location of the site within the Medway Estuary. Furthermore the discovery of interglacial sediments of unknown age immediately to the west of the site (Bates *et al.*, 2002) at the Golf Course and beneath the floodplain at Kingsnorth (Bates, 1999) had indicated that a complex subsurface stratigraphy was present beneath the west bank of the Medway and it was considered likely that elements of some or all of these Pleistocene sequences may also extend downstream or downslope into the study area. In particular the investigation set out to use surveying techniques to differentiate near-surface differences in sediment types within typical Holocene sequences (upper 3 m of stratigraphy) and electrical resistivity sectioning to produce sequences that matched the EM survey techniques in the near-surface zone (upper 3 m) and to extend the electrical sectioning into the deeper subsurface zone (3–15 m). It was hoped that the electrical sectioning could differentiate bedrock sequences from Pleistocene and Holocene deposits and that careful placing of ground-truthing locations (boreholes/test pits) could therefore significantly enhance the understanding of the regional site stratigraphy.

The survey instrument used to map the near-surface geo-electric units was the Geonics EM-31 with digital acquisition (Figure 7). The site was surveyed with data being recorded at 1-m intervals along lines spaced at 20 m intervals perpendicular to the projected lines of any channels. The lines were surveyed using sur-

vveyors tape and compass with the corner points surveyed using electronic distance measurement (EDM) and a differential global positioning system (DGPS).

Two-dimensional electrical sections were surveyed using a Syscal Junior 2D resistivity geo-electric profiler (Figures 7 and 8). Electrode spacings from 1 m to 5 m were tested at the site with different survey configurations and offset programs. All profiles illustrated were surveyed with electrode spacings of 5 m. Ground-truthing of geo-electric units was achieved using boreholes drilled either by a Terrier or a shell and auger drill rig (Figure 9).

The EM31 survey (Figure 7) was conducted across nearly the full width of the low-lying floodplain between the Hoo Peninsular and Binney Island to the east. The results suggest the presence, within the top 3–4 m, of low-resistance (conductive) units (green colour) narrowing in a southwesterly direction and being replaced by fingers of more resistant sediments (non-conductive, yellow colour). A zone of very high resistance exists to the south-eastern parts of the site (red or hot colour) suggesting the presence (close to the surface) of coarse, relatively resistive sediments (?perhaps gravels or sands). These results can be interpreted as depicting the distribution of Holocene channels within the marsh system with more conductive units representing finer grained channel fills. These appear to equate with recent drainage features on the marsh surface to the north of the survey area. Confirmation of the fine grained texture and organic nature of the sediments close to the surface within the zones postulated to be occupied by Holocene channel sediments was made during the drilling of boreholes 3, 4 and 5 (Figure 9). Microfossil evidence from the upper part of BH 5 (Table 5A) suggested accumulation of the deposits in brackish, intertidal conditions in the middle to high saltmarsh with few freshwater indicators present. This evidence would predict the location of sediments of finer grained texture (clays/silts/organic sediments) within the green/low resistance zones that might be suitable for palaeoenvironmental investigation. The edges of these zones are likely to be those zones in which channel marginal structures (jettys, trackways,

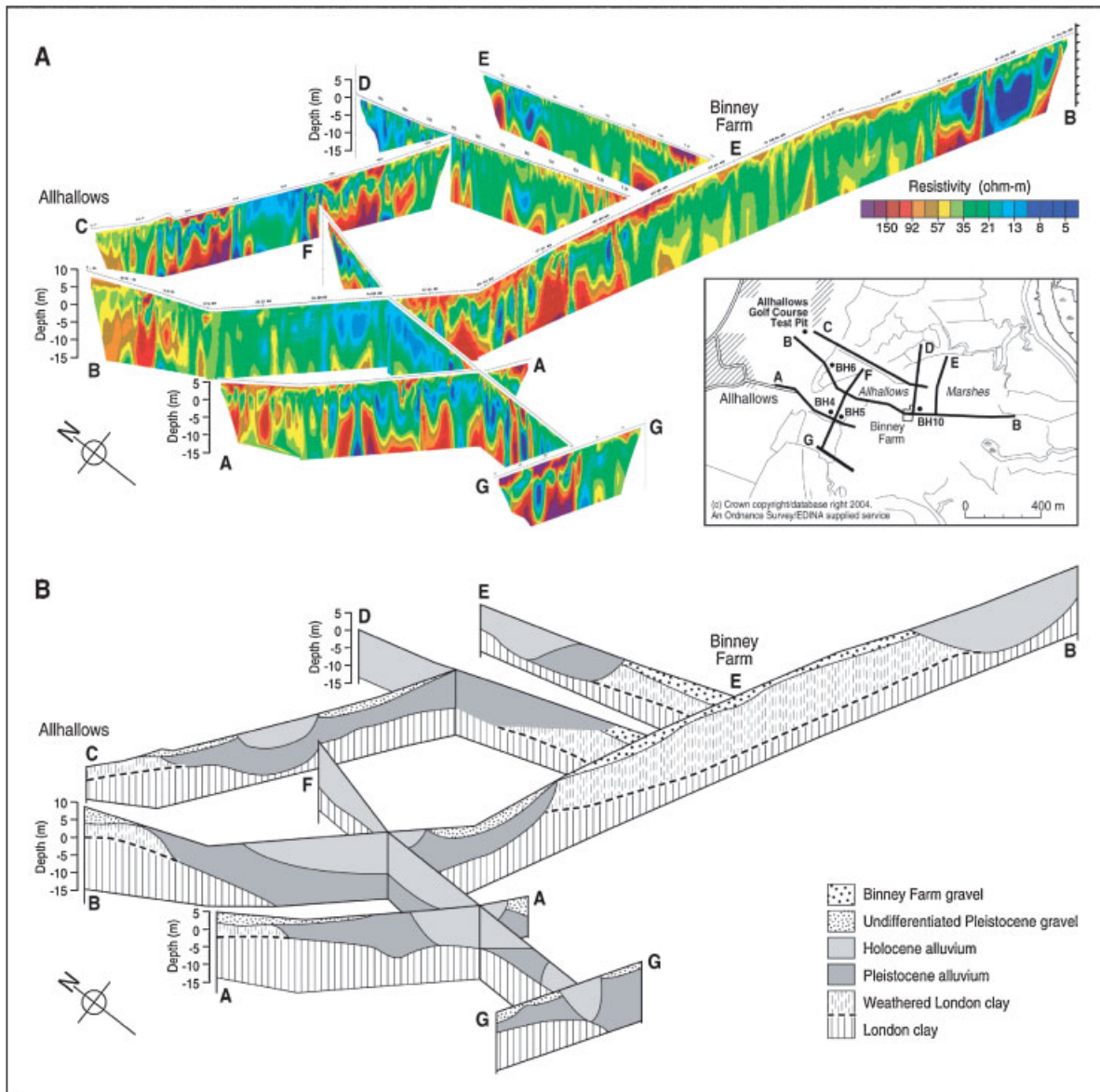


Figure 8. (A) Electrical pseudosection fence diagram. (B) Inferred stratigraphy from Allhallows study area.

etc.) may be present, providing targets for archaeological investigations.

To enhance our understanding of the deeper parts of the stratigraphical sequences, below the 3 m depth tentatively suggested to represent the base of the Holocene by the BGS (1997), two-dimensional electrical sections were surveyed along seven transects typically in a northwest to southeast trend or north-south

trend (Figures 7 and 8). The survey lines were designed to cut across mapped sediment unit boundaries. The final geo-electric sections have been placed into a fence diagram (Figure 8A) and the data interpreted in terms of sedimentary units through a comparison with borehole information (Figure 8B). Units with higher apparent conductivity are coloured blue while those with relatively higher resistivity are

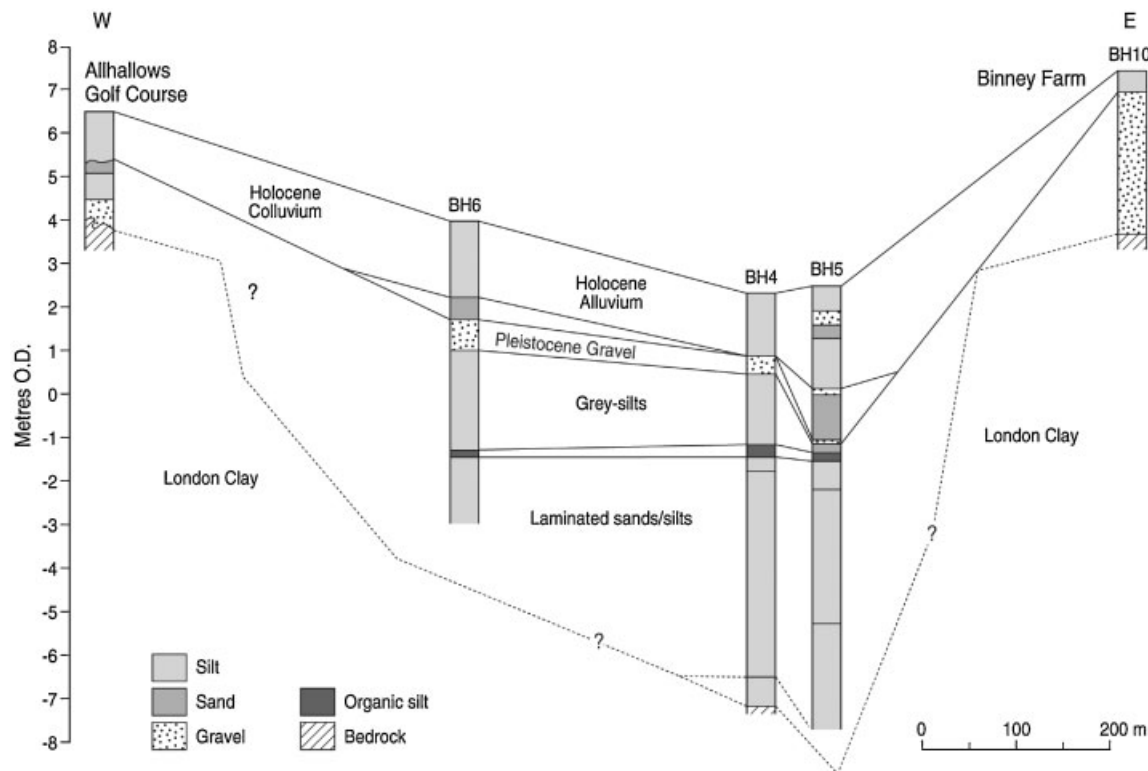


Figure 9. Lithology of key boreholes from the Allhallows study area.

coloured red. The relationship between the surface EM 31 survey data and the evidence present in the geo-electric sections is shown in Figure 7. Units with the greatest electrical resistance (red) are interpreted to represent gravels or unweathered bedrock (London Clay). Consequently at the western end of the main transect B a thin resistive unit is seen to overlie a sequence of conductive then resistive deposits. This sequence is interpreted as indicating the presence of near-surface Pleistocene sands or gravels resting on bedrock that may be weathered at the top (evidence from the Golf Course site described by Bates *et al.* (2002) confirms this interpretation). A similar sequence is present beneath Binney Farm where the upper resistive unit has been demonstrated to be flint gravel (Binney Gravel, *sensu* Bridgland, 2003) in BH 10 while the conductive/resistant package below consists of weathered London Clay above hard, unweathered London Clay (Figures 7 to 9).

Blue (highly conductive) deposits are clearly visible close to the centre of transect line B

(Figure 8) and these have been matched with the conductive units seen in the EM31 survey (Figure 7) that represent the extent of the Holocene incursion into the region through which the upper part of BH 5 penetrates (Figure 9). This is reflected in the nature of the microfossil assemblages reported from BH 5 (Table 5B). Green coloured units adjacent to the Holocene channel are interpreted as fine grained Pleistocene sediments that have been shown in boreholes 4 to 6 to be laminated sands and silts (Figures 8 and 9). Microfossil assessment (Tables 5 and 6) revealed the presence of several freshwater species as well as the noded form of *Cyprideis torosa* suggesting slightly brackish waters. The overall impression given by this fauna is of a river system close to the upstream edge of the brackish water limit where inwash of material from adjacent freshwater parts of the system commonly occurred. The presence of both *Ilyocypris salebrosa* and *Scottia tumida* indicates that these deposits are certainly of pre-Holocene date, and possibly as old as MIS 9 and clearly

Table 5. Summary of initial scan of BH 5 microfossil results, Allhallows

Depth (m)	Organic remains						Ecology
	Plant debris/ seeds	Insects	Ephippia of cladocera	Brackish forams	Fresh-water ostracods	Brackish ostracods	
							Tubes ^a
1.49–1.51	x	x	x	x			Brackish: tidal
1.65–1.67	x	x	x				
1.79–1.81	x	x	x	x			
1.97–1.99	x	x	x	x			
2.09–2.11	x	x	x	x	x	x	
2.15–2.17	x	x	x	x	x	x	
2.29–2.31	x	x	x	x			
3.67–3.69					x	x	Tidal/freshwater
3.82–3.84					x		
3.88–3.90							
3.97–3.99							
4.08–4.10							
4.37–4.39							
4.65–4.67							
5.37–5.39							
5.70–5.72							
6.10–6.12							
6.50–6.52							
6.80–6.82							
7.60–7.62							
8.24							
8.45							
8.54							
8.63	x						
8.81	x	x					
9.00	x						
9.80	x	x					
9.95	x	x					

^a Precipitate around stems/rootlets.

(Continues)

Table 5. (Continued)

Fauna	Depth (m)								Ecology (Age)
	1.49–1.51	1.65–1.67	1.79–1.81	1.97–1.99	2.09–2.11	2.15–2.17	2.29–2.31	3.67–3.69	3.82–3.84
Foraminifera									Brackish: tidal (Holocene)
<i>Trochammina inflata</i> (Montagu)	x				x				
<i>Elphidium williamsoni</i> Haynes			x		x				
<i>Haynesina germanica</i> (Ehrenberg)			x		x				
<i>Jadammina macrescens</i> (Brady)				x	x				
<i>Ammonia limnetes</i> (Todd & Bronnimann)				x					
<i>Quinqueloculina</i> sp.					x				
Ostracoda									
<i>Leptocythere laceritosa</i> (Hirschmann)					x				
<i>Cypris pubera</i> O.F. Muller					x				
<i>Cyprideis torosa</i> (Jones) (noded)							x		Tidal/freshwater (Pleistocene)
<i>Ilyocypris gibba</i> (Ramdohr)								x	
<i>Ilyocypris salebrosa</i> Stepanaitys ^{*Q6}							x		
<i>Candona</i> sp. (juveniles)							x		
<i>Scottia tumida</i> (Jones) [*]							x		
<i>Paralimnocythere compressa</i> (Brady & Norman)								x	

Table 6. Summary of detailed microfossil assessment of Pleistocene levels in BH 5, Allhallows

Depth (m)	Organic remains ^a					Fish remains
	Brackish ostracods	Freshwater ostracods	<i>Bithynia</i> operculi	Charophyte oogonia		
3.60–3.62						
3.62–3.64	x	x				
3.64–3.66	x	x	x			
3.66–3.68	x	x	x			
3.68–3.70	x	x	x	x		x
3.70–3.72	x	x	x			
3.72–3.74		x	x	x		
3.74–3.76		x	x			
3.76–3.78		x	x			
3.78–3.80		x	x			
3.80–3.82		x	x			
3.82–3.84		x	x			x
3.84–3.86		x	x			x
3.86–3.88		x	x			x

^a Occurrences are given on a presence (x)/absence basis only.

(Continues)

Table 6. (Continued)

Ostracoda												
(b) Distribution of Ostracoda species												
Depth (m)	<i>Cyprideis</i>	<i>Ilyocypris</i>	<i>Ilyocypris</i>	<i>Candona</i>	<i>Limnocythere</i>	<i>Scotia</i>	<i>Herpeto-</i>	<i>Pseudo-</i>	<i>Fabaeformis-</i>	<i>Cyclo-</i>	<i>Ilyocypris</i>	<i>Paralimno-</i>
	<i>torosa</i>	<i>gibba</i>	<i>salebrosa</i>	<i>neglecta</i>	<i>inopinata</i>	<i>tumida</i>	<i>cypris</i>	<i>candona</i> sp.	<i>candona</i>	<i>cypris</i> sp.	<i>inermis</i>	<i>cythere</i>
	(Jones)	(Ramdohr)	Stepanaitys*	Sars	(Baird)	(Jones)*	reptans	(juveniles)	balatonica		Kaufmann	(Brady & Norman)
	(noded)				(sexual population)		(Baird)		(Daday)			(Brady & Robertson)
(b) Distribution of Ostracoda species												
3.60–3.62												
3.62–3.64	x											
3.64–3.66	xx	xx	x	x								
3.66–3.68	xx	xx	x	x								
3.68–3.70	x	x		xx								
3.70–3.72	x	xx		xx								
3.72–3.74		xx		x								
3.74–3.76		xx		x								
3.76–3.78		xx		xx								
3.78–3.80		xx		x								
3.80–3.82		x		xx								
3.82–3.84	x	x		x								
3.84–3.86		x		x								
3.86–3.88				x								

o, one specimen only; x, present (several specimens); xx, common.

* Either not part of the today's European fauna or extinct.

distinguishes the deposits from those of Holocene date in BH5.

The results clearly demonstrate that the EM surveying techniques are able to differentiate near surface differences in sediment types within typical Holocene sequences (upper 3 m of stratigraphy) and Pleistocene sequences. Matching results from the electrical resistivity sectioning and the EM survey techniques in the near-surface zone (upper 3 m) has been achieved (Figure 7) and extended using the electrical sectioning into the deeper subsurface zone (3–15 m) (Figure 8). Although often difficult to determine without the use of ground truthing (achieved here with boreholes and confirmed by the microfossil results), electrical sectioning can be used to differentiate bedrock sequences from Pleistocene and Holocene deposits.

Conclusions

These case studies demonstrate that a structured programme of site investigation works borrowing and adopting methods and techniques from a variety of disciplines can significantly enhance our ability to understand the subsurface stratigraphy at a site. In particular the case studies confirm that:

- (i) geophysical techniques can provide useful information on the distribution of near-surface (3–20 m depth) sediment packages in a rapid and cost-effective fashion;
- (ii) there is broad agreement between the results obtained from the geophysical investigation and the geotechnical (borehole) ground investigations;
- (iii) CPT investigation can rapidly characterize the major sediment sequences and is a cost-effective approach to modelling the subsurface;
- (iv) CPT data can 'fill in gaps' between sample location points (boreholes/test pits) to allow correlations to be based on a secure foundation.

While it is recognized that many projects investigating Quaternary sequences are often conducted with minimal financial backing the

ability to undertake more extensive surveys and the implications of a wider knowledge base is an important concern to Quaternary scientists when attempting to 'weight up' the evidence from key-hole investigations that often typify investigation programmes. Adopting frameworks developed from wide ranging site surveys reconstructing sequence geometries, in which sample location points may be placed within the landscape context, avoids the dangers of reconstructing landscape contexts from detailed observations from point-specific data.

Acknowledgements

The authors would like to thank staff at Union Railways (North)/(South) Ltd and Wessex Archaeology for support during the Thames River Crossing works. The estate manager and local residents for help and patience during the field programme at West Wittering and English Heritage for a grant from the Aggregates Levy Sustainability Fund to allow us to undertake the project work. To Ms Lys Dyson, staff at Kent County Council and those who participated in the field programme at Allhallows as well as the European Union who funded this work. Finally we would like to thank Su Bates for sample preparation and the drawing office in the School of Geography and Geosciences at the University of St Andrews for the production of drawings.

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